Agent Based Control of Electric Power Systems with Distributed Generation

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Summary

Distributed generation, decentralized and local control, self organization and autonomy are evident trends of today's electric power systems focusing on innovative control architectures such as MicroGrids, Virtual Power Plants, Cell based systems, plug-in electric vehicles and real time markets. Situation in Denmark is even more interesting, with a current 20% penetration of wind energy it is moving towards an ambitious goal of 50% penetration by the year 2050. Realization of these concepts requires that power systems should be of distributed nature – consisting of autonomous components and subsystems that are able to coordinate, communicate, cooperate, adapt to emerging situations and self organize in an intelligent way.

At the same time, rapid development in information and and communication technologies (ICT) have brought new opportunities and elucidations. New technologies and standards have been developed particularly in the area of communication and distributed control. Electric power industry is eager to explore, evaluate and adopt these new advancements in ICT for improving its current practices of automation and control in order to cope with above mentioned challenges.

This thesis focuses on making a systematic evaluation of using intelligent software agent technology for control of electric power systems with high penetration of distributed generation. The thesis is based upon a requirement driven approach. It starts with investigating new trends and challenges in electric power systems brought by introduction of distributed generation (DG). It reviews innovative control architectures and precisely identifies the requirements in these control architectures which are interesting for application of the intelligent agents and maps them to the capabilities of the intelligent agents. It suggests a multiagent based flexible control architecture (subgrid control) suitable for the implementation of the innovative control concepts. This subgrid control architecture is tested on a novel distributed software platform which has been developed to design, test and evaluate distributed control strategies. The results have been discussed from case studies of multiagent based distributed control scenarios in electric power systems.

The main contribution of this work is a proposal for system design methodology for application of intelligent agent technology in power systems. The methodology consists of suggestions for redesign of control architecture, a prototype for a software platform which facilitates implementation of multiagent control and results from case studies of specific scenarios. The work also contributes to agent based control with an approach of model based agents. In this approach the agents contain a model of their environment in order to select and reason about implications of a control action. This approach has showed promising results to improve the fault diagnosis and automation in electric power system.

Resumé

Decentral produktion og distribueret styring og regulering anvendes i stigende grad i nutidens elektriske kraftsystemer. Der er derfor øget interesse for innovative systemarkitekturer såsom microgrids, virtuelle kraftværker, cellebaserede systemer, plug-in elbiler og realtid markeder. Danmark står overfor store udfordringer i denne udvikling. Fra den nuværende 20% dækning af energibehovet ved hjælp af vindenergi stiler Danmark mod et endnu mere ambitiøst mål, nemlig at opnå en 50% dækningsgrad i året 2050. Realisering af dette mål forudsætter, at styringssystemerne er distribuerede og består af autonome subsystemer, der er i stand til at koordinere, kommunikere, samarbejde samt at tilpasse sig nye situationer og selvstændigt at organisere sig på en hensigtsmæssig og intelligent måde.

Samtidig tilbyder den eksplosive udvikling indenfor informations- og kommunikation teknologi (ICT) helt nye muligheder for realisering af automationsløsninger. Nye teknologier og standarder er blevet udviklet specielt inden for kommunikation, distribueret software og kunstig intelligens. Elforsyningen er derfor interesseret i at anvende disse nye ICT teknologier til at forbedre den nuværende praksis ved automatisering for at kunne håndtere udfordringerne ved den øgede decentralisering af produktionen.

Denne afhandling undersøger anvendelsen af agentteknologi ud fra en systemdesign synsvinkel med særlig henblik på intelligent styring af elsystemer med høj anvendelse af decentral produktion. Afhandlingen omfatter en detaljeret undersøgelse af de nye tendenser og udfordringer i automatiseringen. Afhandlingen gennemgår innovative styringsarkitekturer og identificerer styringskrav, som er relevante for anvendelserne og udnyttelse af agentteknologiens særlige fortrin ved realisering af intelligente funktioner, herunder anvendelse af videnbaseteknologi. Der udvikles en multiagentbaseret fleksibel styringsarkitektur (subgrid control), som er velegnet til realisering af innovative systemarkitekturer. Denne subgrid styringsarkitektur er afprøvet på en distribueret softwareplatform, som er udviklet til test og evaluering. Forskningsresultaterne er vurderet gennem casestudier, hvor multiagentteknologi platformen anvendes i udvalgte scenarier fra elsystemer.

Preface

This thesis was prepared at Center for Electric Technology CET, Department of Electrical Engineering, the Technical University of Denmark in partial fulfillment of the requirements for acquiring the Ph.D. degree in engineering.

The thesis deals with distributed control in electric power systems with distributed generation. The main focus is on a systematic evaluation of multiagent technology for for distributed control of electric power systems with high penetration of distributed generation.

The thesis consists of a summary report and a collection of ten research papers written during the period 2007–2010, and elsewhere published.

Lyngby, May 2010

Arshad Saleem

Papers included in the thesis

I. Saleem, A. and Lind, M. Requirement analysis for autonomous systems and intelligent agents in future Danish electric power systems International Journal of Engineering, Science and Technology 2010. vol. 1. No.2

II. Saleem, A. Heussen, K. and Lind, M. Agent Services for Situation Aware Control of Power Systems With Distributed Generation. Proceedings of IEEE PES General Meeting, 2009, Calgary, Canada

III. Saleem, A. and Lind, M. Reasoning about Control Situations in Power Systems. Intelligent System Applications to Power Systems. International Conference on Intelligent System Application in Power Systems 2009, Curitiba, Brazil.

IV. Saleem, A. Lind, M. and Veloso, M. Multiagent based protection and control in decentralized electric power systems. Proceedings of the ATES Work Shop of the 9th International Conference on Autonomous Agents and Multiagent Systems 2010, Toronto, Canada.

V. Saleem, A. and Lind, M. Knowledge based support for multiagent control and automation. Submitted to Cigre International Symposium on Electric Power Systems of the Future, Integrating Supergrids and Microgrids. Bologna, Italay, 2011.

VI. Heussen, K. Saleem, A. and Lind, M. Control architecture of power systems: Modeling of purpose and function. Proceedings of IEEE PES General Meeting, 2009, Calgary, Canada

VII. Saleem, A. Us, T. and Lind, M. Means-end based functional modeling for intelligent control: modeling and experiments with an industrial heat pump system. In proceedings of the 10th IASTED International Conference on Intelligent Systems and Control,2007. Cambridge, USA

VIII. Saleem, A. Lind, M and S. Singh. Modeling Control Situations in Power System Operations. In proceedings of the International Conference on Autonomous and Intelligent Systems AIS 2010, Porto, Portugal

IX. A. Saleem, M. Lind, N. Honeth and L. Nørdstrom. A case study based Interoperability model of Multiagent Systems and IEC 61850. In proceedings of the IEEE PES Conference on Innovative Smart Grid Technologies Europe 2010, Gothenburgh, Sweden

X. Heussen, K. and Saleem, A. and Lind, M. System-Awareness for Agent-based Power System Control. In proceedings of the IREP Symposium- Bulk Power System Dynamics and Control, VIII (IREP) 2010. Rio de Janeiro, Brazil

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Finally and most importantly, I am greatly thankful to my family and friends. Your love, care and attention made my life worth living, struggling and progressing. Love you all.

Contents

Chapter 1

Introduction and Background

1.1 Drivers of Change in Electric Power Systems

Electric power systems is one of the most critical and strategic infrastructures of industrial societies and is currently going through a revolutionary change. Deregulation, security of supply, environmental concerns and rapid growth in ICT are basic driving factors which have given rise to development trends in power systems like renewable and distributed generation, free markets, decentralized control, self healing and automatic (dynamic) reconfiguration systems.

1.1.1 Deregulation in Electric Power Industry

Deregulation in Electric Power Industry with other commonly used concepts of re-regulation, liberalization, restructuring and privatization all under a general umbrella of *market reform* is a complex phenomenon ultimately aiming at providing a competitive market based environment which can offer energy to customers at reduced price. The deregulation has eliminated or significantly reduced the monopolies in electric power generation and distribution functions.

Several players have resulted in increased availability, stability of fuel supply, less requirement for idle capacity (because of the presence of spot market), increased service quality and choice for customers and innovation in technologies and standards [1].

Participation of several players in energy production and distribution has lead to complex economic structures resulting in more complex power flow pattern and increased number of interconnections. In turn it has also resulted in the introduction of *nodal pricing* which is a market-pricing approach used to manage the efficient use of the transmission system when congestion occurs on the bulk power grid. The idea of nodal pricing will be discussed later in the context of *real time markets*.

1.1.2 Distributed Generation

Distributed energy resources are defined as small, modular electric energy generation or storage systems located relatively close to the customer. Distributed generators (DG) can include a number of operating technologies and sizes, ranging from several kW to hundreds of MW. DGs can be operated interconnected with a grid, or operate in stand alone mode, without grid support. The latter approach is usually taken in remote areas having difficulty in connecting with the main grid. Fuel based DG technologies include industrial gas turbines, gas fired combined heat and power plants (CHPs and micro CHPs) and fuel cells. In addition, the variety of renewable energy based DGs include photovoltaic (PV) generators, wind generators, biomass, and small hydro turbines.

The penetration of DG has been defined on three levels of evolution[1]:

Accommodation:
This is the first stage of DG penetration where DG is accommodated into the current electricity market and centralized coordination remains in domination.

Decentralization:
At this stage the share of DG increases, virtual utilities optimize the service of DG through centralized coordination systems and DG start to participate in control of the system.

Dispersal:
The DG becomes predominant in the grid. Regional distribution network become self content local grids or the Subgrids. Distributed coordination plays

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[1] ECN vision on smart grid: `www.ecn.nl`

the main role in systems control and operation. Systems balancing becomes increasingly dependent on DG capabilities which itself brings new challenges to the control.

The impact of DGs on the grid primarily depend on the level of penetration and is two fold. It has provided the opportunity for introduction of new control paradigms such as distributed and local control, the ability to continue serving customers locally in the case of a fault on the transmission grid, increased efficiency by reduction in transmission, and reduced CO2 emission in the case of the renewable DGs. At the same time, it has also brought new challenges to the control, automation, and protection of the system. This require development of concepts and methods that can take advantage of opportunity and adequateness address the challenges.

1.1.3 Climate Change and Environmental Concerns

Climate change and environmental concerns with CO2 emissions and global warming have impacted all aspects of electric power systems including generation, transmission, distribution and consumption. It has resulted in high feed-in tariffs and purchase subsidies in many countries. Increasing pressure from public side due to environmental concerns has made it very difficult to build any larger primary equipment assets both on the generation (power plants) and transmission side (lines, substations).

1.1.4 Emergence of Real Time Energy Markets

The real time energy market is a balancing market for energy in which the locational marginal prices (LMPs) at a pre-determined locations are calculated every short interval of time [2] based on the actual system operations security-constrained economic dispatch. The real-time dispatch process satisfies the system-wide energy requirement and operating reserve requirements using linear optimization algorithm to minimize the energy, congestion, and transmission loss costs, given system conditions and constraints.

A Real time markets can smooth-out the durational load pattern in order to reduce the impact of binding unit operating and system constraints on intermittent energy sources, e.g., wind turbines. It can also allow demand to increase

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[2] duration for this interval of time currently varies. Example can be found from 6 seconds to up to 5 Minutes

in response to the availability of costless wind generation [2]. Moreover, it provides ways to activate small scale distributed energy resources (DERs or DGs) during intra hour regulation for the normal operation. The new resources can be industrial or commercial electricity demand as well as household electricity demand like heat pumps, direct electric heating, electrical vehicles and other types of demand that can be controlled with no or little consequences to the end-users. Moreover, small scale generations can be activated in the proposed market.

The over all impact of the real time markets is improved market dynamics with minimum administrative over-heads to deliver a stable and predictable outcome. The real time market mechanism activates the DERs and make the relevant technologies compete based on technical and economic features.

1.1.5 The Current Situation in Denmark

The current situation in Denmark is of particular interest where in recent years large amount of small and distributed energy resources have replaced large centralized power plants (Figure 1.1). Denmark has already achieved the world highest (20%, 2007 data) of renewable energy resources (RES) into its power systems; and is now targeting an even higher ambitious goal. The new energy strategy by the Danish government, *A visionary Danish energy policy*, published on 19 January 2007, outlined the energy development policy towards year 2025[3].

The goal is to increase the share of renewable energy to at least 30% of the total energy consumption by 2025. This is expected to require wind power generation in 2025 equal to 50% of the national electricity consumption, which will lead to tremendous changes for the Danish electric power system in the future. [3].

1.1.6 Development in Information and Communication Technology

Another important and interesting driving factor for change in electric power systems is rapid growth in Information and Communication Technology ICT . Electric power industry has traditionally been slower in adopting modern ICT as compared to some other industries e.g., telecommunication. But recently rapid growth and significant reduction in price of ICT tools and technologies

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[3] Energy Strategy 2025, Danish Ministry of Energy and Transport: `http://www.ens.dk`

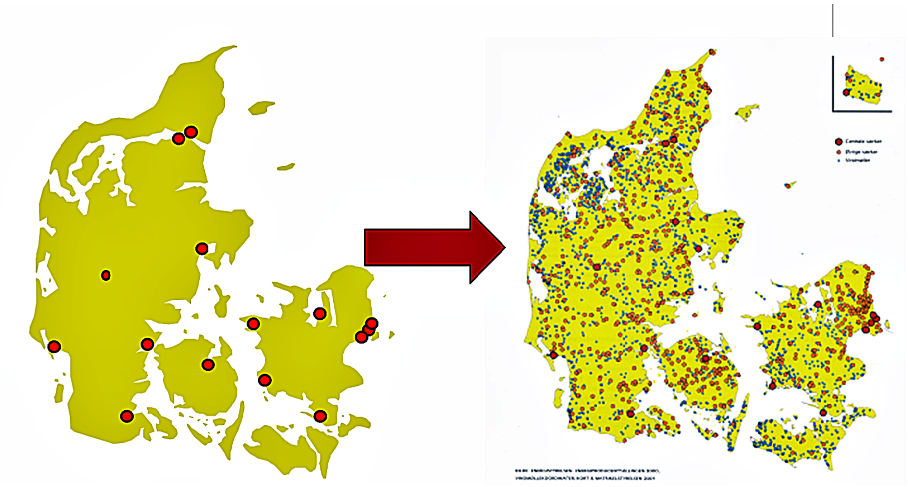

Figure 1.1: Transition in Electric Power Systems of Denmark

has made it tempting for electric power industry to take initiatives to adopt ICT more effectively.

ICT is used for various power system applications such as monitoring and control, protection coordination, and other vital functions. It has the potential of further improving system operation, flexibility, security margins and overall cost. But at the same time it is also subject to threats (both malicious and accidental) not fully understood, especially those deriving from the interaction with the power system infrastructure, thus introducing additional vulnerabilities that should be accurately assessed.

While a quick and seamless adaptation of ICT is crucial for enlargement, open access and progressive integration of cross border electricity markets, it's adaptation within existing control infrastructures and practices is a real challenge and require a new approach to system design and operation.

1.2 Intelligent Control and Multiagent Systems

The intelligent control paradigm has emerged from the merger of disciplines such as artificial intelligence, control systems, and operations research (Figure 1.2). It models the complex systems with several components, non-linear interactions and partially defined boundaries. It is supposed to be robust, self aware and flexible [4].

Today's electric power systems have evident trends of increased complexity, growing interconnections, heterogeneous nature of generation sources as well as operation paradigms, and open structure. Thereby they have attracted interest for application of *multiagent systems* which are combination of intelligent control and distributed systems and often referred to as *a distributed artificial intelligence product*. Following sections provides an introduction to the fundamental concept of intelligent agent technology and multiagent systems in general computing theory as well as its implication in the control of electric power systems.

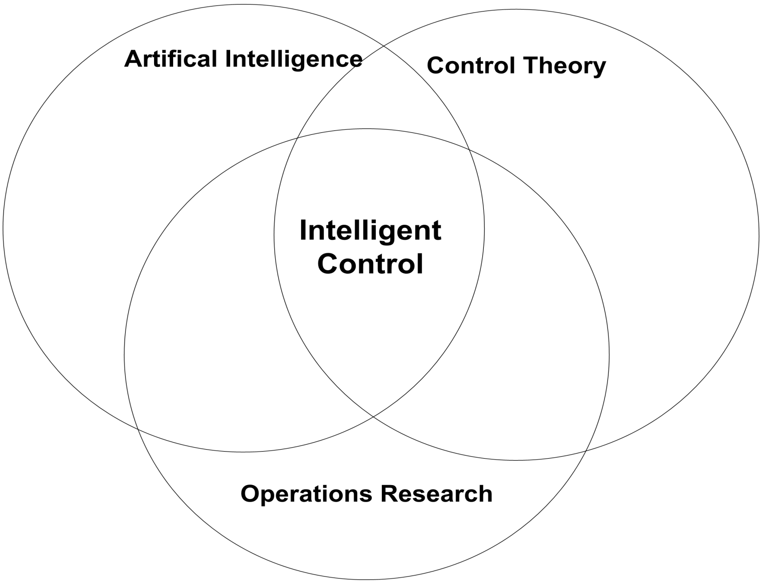

Figure 1.2: Intelligent control as merger of artificial intelligence, control theory, and operations research

1.2.1 Intelligent Software Agents

The fundamental concept of software agent is defined as follows:

An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives[5].

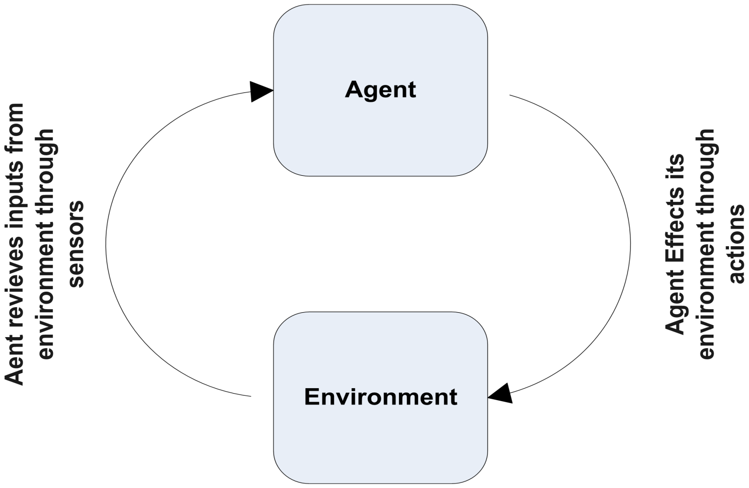

Figure 1.3: Agent in its environment with sensors and effectors

Figure 1.3 shows a software agent interacting with its environment through sensors and effectors. Agents observe their environment through sensor and update their internal data base, and they effect the environment through actions. This fundamental view of agent as an integrated entity with sensors and effectors often leads to relating agents with classic control loop of control theory. But in reality agents though having control theory as one of its parent field inherits many aspects from other fields such as artificial intelligence, distributed systems and knowledge based systems.

Agents are specified more precisely by a metaphore commonly known as BDI (Belief, Desire, Intention). The beliefs represent knowledge of an agent about its environment. The *Beliefs* are captured through sensors of the agent and stored in an internal data base. This data base (also commonly called knowledge base) should be properly organized, updated and synchronized to other functions, e.g., decision making of the agent architecture. Usage of rule based systems [6] and ontologies [7] are some of the suggestions for this purpose. The *Desires* are goals or *design objectives* of an agent. Desires not only sets the criteria for rationality of an agent but also defines the nature and level of autonomy for agents. *Intentions* is the way agents attempt to achieve their goals. In agent oriented software engineering intentions are modeled as *behaviors*. A behavior of an agent may consists of a single or multiple *actions* and lead to a achievement of a goal or a sub goal. Figure 1.4 describes the BDI model with an example and explains what beliefs, desires and intention could be in a concrete power systems scenario.

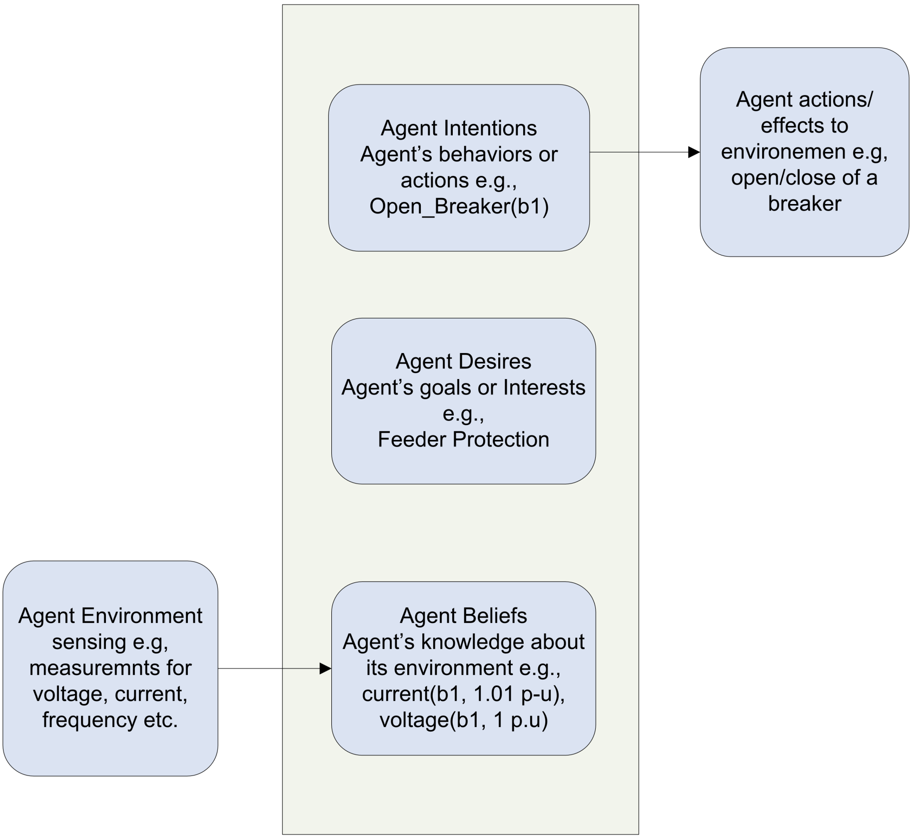

Figure 1.4: Belief Desire Intention BDI based abstract agent architecture

In this example a *Breaker Agent* has a *desire or goal* of protecting a feeder. It collects information such as voltage and current measurements through its sensors and saves it as its *beliefs*. In order to achieve its design goal of protection it reviews its beliefs and in a specific situation utilizes its *intentions* which is the opening or closing of a breaker.

The BDI architecture is also related to *Means-Ends based modeling* approach which has been used in process control, diagnostic reasoning and and plant automation [8, 9, 10]. The intentions of an agent are its means to achieve the goals or the ends: Efficient use of the means require proper maintenance and updation and utilization of agent beliefs.

Agents are *situated* in physical or virtual environments. Agents represent specific entities in their environment and implement its control. Agents in general continue to remain in their environment with *mobile agents*[11] as an exception because they can move from on environment to another and take their current state of execution with them.

Autonomy is one of the most important characteristics of agents which differentiates it from traditional software e.g., objects. Autonomy brings a higher level of choice for agents over selection of their actions in specific situations. In other words, an autonomous agent is only told its objective and not how to achieve it through programmed behaviors. The agent has a choice in selecting specific actions and a sequence to execute these action. Level of autonomy in agents is usually limited by its design objectives i.e, agents have freedom to choose any action which leads them to achievement of design objectives in one way or the other.

Flexibility in agents refers to the proactive behaviors i.e, agents not only passively react to changes in their environment rather they can take initiatives and perform in a preemptive way. Moreover flexibility refers to the ability of agents to work together in groups or societies i.e, Multiagent Systems.

1.2.2 Multi Agent Systems

Multiagent systems MAS are systems consisting of more than than one agent. Agents in a MAS can either be cooperating with each other. In a multiagent system, individual agents are supposed to keep a balance between their own interest and the overall interest of the system. The agents focused on their own interests are called *self interested agents* and the agents more focused on the interest of the overall system are called *altruistic agents*.

Multiagent systems are useful to implement in application areas that are naturally distributed, decentralized and are easy to be decomposed in their design. As shown in figure 1.5, a system architecture based upon multiagent systems provides a natural way of decomposing a software system into subsystems and to model interactions between these subsystems and individual components (agents) within the subsystems.

FIPA (The Foundation for Intelligent Physical agents) standards [4] defines a framework for inter-agent interaction in multiagent systems. FIPA standards

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[4] FIPA, The Foundation for Intelligent Physical Agents:`http://www.fipa.org/`

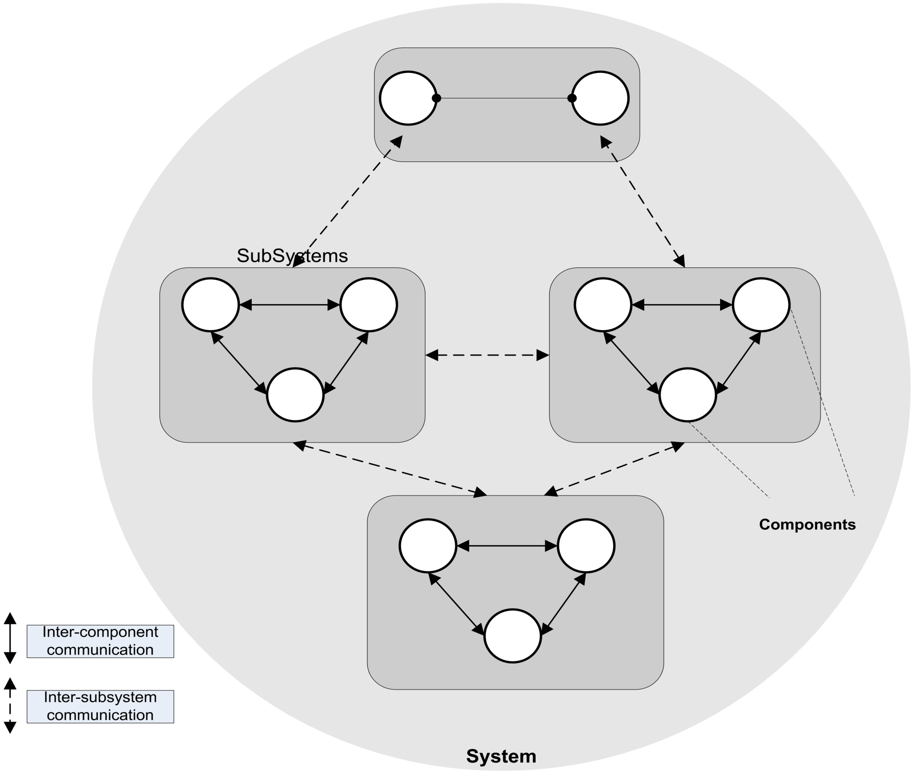

Figure 1.5: System decomposition based upon Multiagent Systems

also specifies abstract architectures for multiagents system implementation. Figure 1.6 describes this abstract architecture.

Besides the application of agents, this architecture includes several services. A Directory Facilitator (DF) provides yellow page services i.e. different agents interact with this service to register and discover available agent services. Agent Management Services (AMS) provide white page services. This agent is responsible for creating, destroying and managing agents and containers in a multiagent platform. The Message Transport Service (MTS) is responsible for message transportation between agents. This service also enables synchronization of messages when several messages are sent and received from different agents in parallel. FIPA also provides a language specification for communication between agents. This language specification is called the FIPA agent communication language (FIPA ACL).

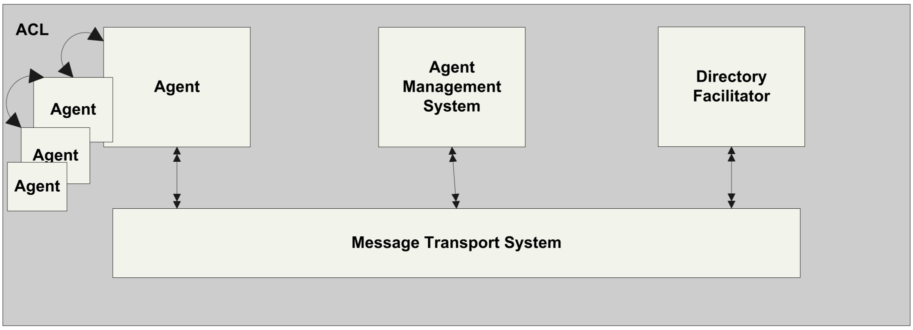

Figure 1.6: FIPA abstract architecture for MAS implementation

1.2.3 Agent application view in electric power systems control

In electric power systems control, agents can be applied at different levels of control. Starting from a low level control of devices it goes to higher level of planning and optimization. This is shown in figure 1.7 which presents a view of agents at different levels of control in electric power systems.

The agents at the *device layer* interact directly with devices at physical system layer. In most cases an agent acts as the controller of a physical device and performs control functions, e.g., a generator agent control active and reactive power set points of a generator, and a breaker agent would perform functions of opening and closing a breaker. Agents at this level of control have a higher requirement for timely execution of actions and thereby usually do not implement high level mechanism for decision making. Agents at this level may communicate with other agents at same level and to the agents at higher level of control. The so called local or distributed control is implemented at this level. Though being able to communicate with other agents at same level as well as higher level, agents at this level, should be able to make local decision independently.

The agents at the *control coordination level* usually do not directly interact with physical electric power system devices, instead they communicate with agents at lower level of control i.e. device level agents. Status information is communicated from lower level to the high level whereas control commands are send from higher level to the lower. Agents at this level implement less time critical requirements and more sophisticated decision making mechanisms for system planning and control.

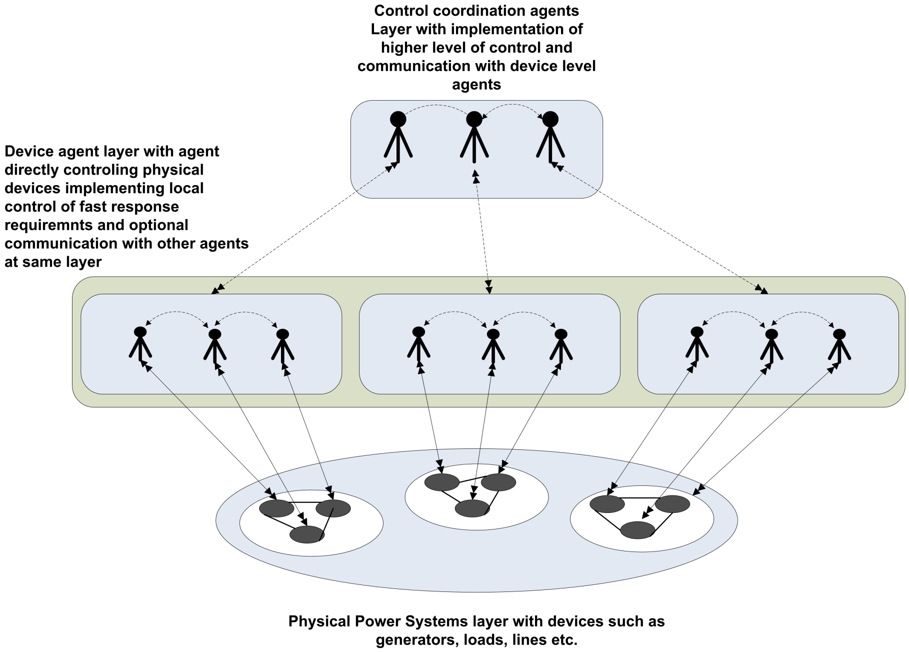

Figure 1.7: Application of agent technology at different levels of control and coordination

1.2.4 How Agents can help facilitate in future power systems

Inherent capabilities in the concept of agents and multiagent systems have potential to address current and future challenges in control of electric power systems. This section reviews such capabilities and explains their potential for application.

1.2.4.1 Decomposition

The concept of multiagent systems provides a natural way for decomposition of systems into subsystems and to model interactions among these subsystems as well as interactions among individual entities (agents) inside the subsystems. This characteristic of agents and multiagent systems can be used to cope with the challenges brought up by deregulation and introduction of distributed generation in electric power systems. Particularly, the modern control architectures such as *microgrids*, *virtual power plants* and real time *cell based systems* have obvious potential for application of multiagent systems since they represent different kind of aggregations and decomposition of the system.

1.2.4.2 Abstraction

Abstraction can assist in coping with the complexity of future electric power systems. It can be used to to define a simplified model of the system that emphasizes some of the details or and suppresses others. This can significantly simplify the process of design for complex systems and help understand the interactions between subsystems.

Moreover, It is important to note that while use of agent technology in control systems can simplify the design process e.g, by choosing appropriate levels of abstraction, at the same time, it can reduce the transparency of operation. It may be argued though that reduced level of transparency is a problem brought by automation in general. This problem is not specific to the agent technology but may be amplified by it if not used carefully.

1.2.4.3 Socialability

Multiagent systems have mature mechanism for implementation of cooperative and competitive mechanisms. Protocols have been developed for standardized high level communication. Such capabilities can be efficiently utilized in implementation of *real time markets*, *commercial virtual power plants* and *energy hubs* etc., where control objectives are achieved by a joint effort of several entities and require negotiations, cooperation and (or) competition mechanisms.

1.2.4.4 Greater level of Autonomy and Intelligence

Current trends of distributed generation, decentralized and distributed control, heterogeneous energy resources and short time scale control operations have brought a significantly increased level of complexity both in structure and operation of electric power systems. This problem has also limited the operator's ability to cope with complex disturbances. A greater level of autonomy and intelligence provided by agents can be a potential in this case. Moreover, the capability of agents to explicitly model and reason about organizational structures such as roles, aggregations and hierarchies also helps to cope with increasing complexity in power systems.

1.2.4.5 Evolutionary Transition

Wrapping Agents facilitates the implementation of systems in evolutionary way rather than a revolutionary all at once change. This is crucial to achieve transition from gigantic traditional power systems to the future distributed agent based system. The wrapper agent brings an interface to the other non-agent components of the system. This wrapper agent performs a two-way translation function: taking external requests from other agents and mapping (translating) them into standard messages understood by other non-agent components, and taking the non-agent components's external requests and mapping them into the appropriate set of agent communication commands. This ability to wrap legacy systems means agents may initially be used as an integration technology and as new requirements are placed on the system, more components may be converted to an agent based module and added to the system.

1.2.4.6 Binding Glue for other enabling Technologies

Multiagent systems have a potential to be used as a binding tool for several potential software technologies for implementation in control of electric power systems such as service oriented architectures, communication technology and knowledge based systems. Figure 1.8 shows that intelligent agent technology by enabling efficient implementation of relevant technologies facilitates implementation of control architectures such as microgrids, virtual power plants and cell based systems. This in turn helps achieve different operational requirements and constraints as described in figure 1.8.

1.3 Current state of the art – Agents in Power Systems

Intelligent agent technology has been of great interest for application in different areas of the control of electric power systems in recent years. The interest includes academic research efforts, large projects and industrial applications.

Jennings [12] portrays a general case of using agent in modern control systems. It

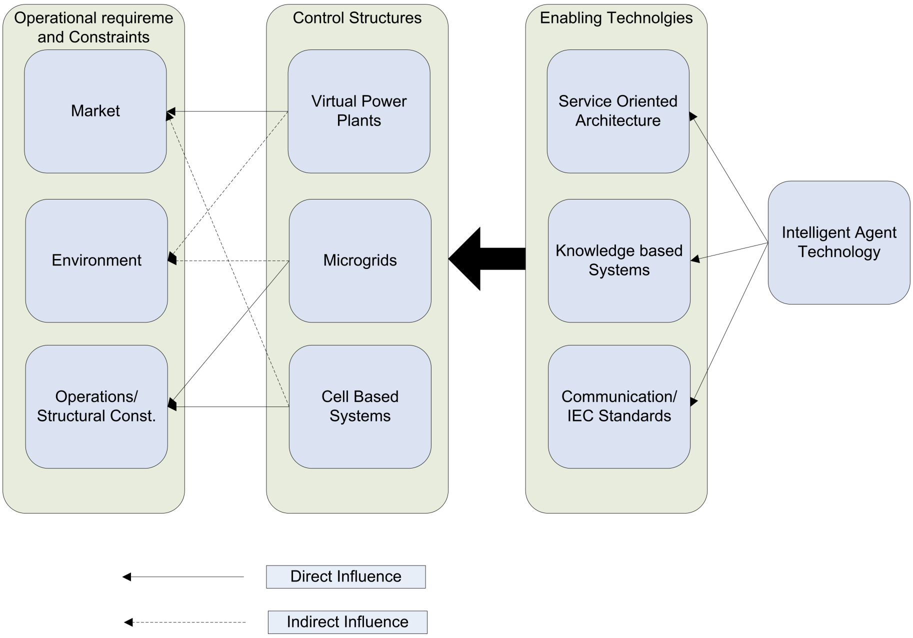

Figure 1.8: agent technology as binding glue for other promising technologies

gives direction on interesting capabilities of multiagent systems and significance of their application in industrial control systems. Moreover it describes software engineering credential of agent oriented approach from a application perspective.

Initial efforts in application of intelligent agent technology in control of electric power systems has been described by Jennings [13] and [14]. A multiagent systems part of larger Europe project ACRHON was developed and deployed by Spanish electric utility Iberdrola [5]. The multiagent system presented ensure that Iberdrola's transport network remains within the desired safety and economical constraints. Also the system has been used to help operators working with supervisory control e.g., by reducing the complex process of alarm handling.

So called HOMEBOTS were also an early application of multiagent systems for energy management. Gustavsson et. al. [15, 16, 17, 18] presents a multiagent based system which calculates the market equilibrium to achieve optimal energy use. It also presents the idea of Intelligent Buildings in the context of home services, such as energy saving, comfort of living, and safety. The system presented consists of a collection of software agents that monitor and control

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[5] Iberdrola:`http://www.iberdrola.es`

an office building. It uses the existing power lines for communication between the agents and the electrical devices of the building, such as sensors and actuators for lights, heating, and ventilation. The objectives are energy saving and increased customer satisfaction through value-added services.

Electric power system restoration is one of the areas which have attracted much attention for application of multiagent systems. Nagata have developed and presented multiagent based systems for restoration of distribution systems [19, 20, 21] and for bulk power systems [22, 23]. The approach for distribution system restoration has agents at two levels of control. The first layer consists of load agents, that represent power customers in the network. The second layer of agents consists of feeder agents that perform control coordination at feeder level. Feeder agents coordinate communication among load agents and are modeled based on the operator's experience. It has been shown that agents using local information and with coordination to other agents can achieve efficient restoration. The approach for bulk power system restoration consists of a two-level hierarchical architecture. Several local-area management agents and remote-area management agents are located at the upper level, which are corresponding to the local/remote area management system, while several load agents and generator agents are located at the lower level.

Another area with large interest for application of intelligent agent technology has been local control of isolated electric power networks. This includes control of Microgrids [24, 25, 26, 27, 28] and cell based systems [29, 30, 31, 32]. The Microgrids are supposed to be isolated from from the main grid always or most of the times, whereas cells in a cell based system are connected to the main grid in normal conditions and islanding operation is performed only in emergency situations. Agents in the control of Microgrid and cell based systems are used to implement local intelligence and autonomy where different device agents execute autonomous control actions. Different distributed resource allocation algorithms are implemented for optimal energy exchange between energy demand and production.

Introduction of distributed generation in low and medium voltage grids have brought several challenges to the traditional protection systems based upon unidirectional flow of power and fault current. New solutions are sought actively to cope with this situation and multiagent systems solutions are are one of most promising ones among under consideration recently [33, 34, 35, 36, 37]. Most important aspect of these solutions is that they implement communication based agent coordination mechanisms. Moreover, such communication based solutions normally divide network into zones and make identify and isolate faulted zone and protect rest of the network. Agent based local intelligence is implemented at distributed generators and loads in order to maintain balance protected part of the network.

Multi agent systems have also been of interest in modeling and analyzing electricity markets in recent years both for traditional day ahead markets [38, 39, 40, 41, 42, 43] as well as in a comparatively new concept of so called virtual power plants, or market motivated aggregations, where different energy resources form aggregation in order to enable their participation in markets [44, 45, 46, 47, 48, 49].

Advantage of using multiagent systems in traditional day ahead markets is convenient modeling of complex behavior of system participants in the underlying environment and suitability of agent based systems for large-scale systems involving various types of interacting system participants with distinct roles, functionalities, behavior, and decisions, which depend on the participants objectives and interactions with other system participants [50].

In market oriented aggregation structures, the agent based approach enables clustering numerous distributed generators, responsive loads and electricity storages in a single aggregation unit. Such units, some times refereed to as virtual power plants, are able to provide flexibility services for the balancing markets. Intelligent agents take up roles such as device agents and auctioneer agent. Negotiation takes palace among different agents in order to achieve price equilibrium.

McArthur et al. in [51, 52] have summarized potential and challenges for application of intelligent agent technology in electric power system. First part of this work describes fundamental concepts of and approaches in multiagent systems having potential for application in electric power systems control. The second part focuses on implementation techniques, tools and standards. It reviews various available options and gives recommendations on best approaches. It also describes methodology for agent based system development with example of a selected application.

Some of the agent based solution have successfully been transformed to industrial application. The ARCHON project [14] brought the first of such applications and it was adopted by Spanish electric utility Iberdrola. This application integrates diagnostic reasoning with multiagent architecture and implements decision support for control room environment.

An agent based system called protection engineering diagnostic agents (PEDAs) [53, 54, 55] has been developed at University of Strathclyde for automation of management and analysis of supervisory control tasks (SCADA). This application has been under the use of British transmission system operator since 2004. It Supports protection engineers by integrating an intelligent SCADA analysis system and digital fault recorder (DFR) data. Protection engineers are supported by online availability of interpreted data and which assists them in decision making.

IntelliTEAM II [56, 57] is another industrial application based on multiagent systems developed by S&C Electric Company [6]. Several utilities in North America including ENMAX Power Corporation [7] have adopted this application into their operation. IntelliTEAM II is an agent based modular distribution automation system. It uses agent based distributed control and peer-to-peer communication to dynamically track system conditions on overhead and underground distribution systems, and provide fully automatic fault isolation and service restoration.

Lastly, Agent based solutions have also been suggested for application in many of the large projects. some of these project include CRISP [8], GridWise [9], EcoGrid-dk [10], INEGRAL [11] and FENIX [12].

The European project CRISP investigated the use of ICT for application in modern smart grid and proposed an architectures of the distributed power grid. The proposed architecture consisted of models of ICT based strategies and was applied in several operational scenarios. Application of intelligent agent technology in this project primarily focused on inter stake holder communication based upon agent based dialogue models. Such dialogue models ensure execution of dependable and secure businesses services. CRISP also suggests the application of agent technology for application in electricity markets and for control of cell based structures such as virtual power plants.

The GridWise initiative aims at using advanced communications and modern information technology for improving coordination between supply and demand, and enabling a smarter, more efficient, secure and reliable electric power system. This initiative have adopted an agent-based computational economics modeling for incorporating market mechanisms that allow the system to evolve over time in response to market dynamics. In this agent based approach the agents interact with each other and with their environment according to the programmed logic, i.e, the knowledge and behaviors.

The INTEGERAL project aims at developing ICT platfrom for distributed control in electric power systems based on commercially available tools, technologies and standards. It motivates to establish the control architecture of different aggregation levels (e.g, the Microgrid control) as a software intensive system. It

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[6] S&C Electric Company:`http://www.sandc.com/`

[7] ENMAX Power Corporation, Alberta, Canada:`http://www.enmax.com//`

[8] CRISP Project:`http://www.crisp.ecn.nl/`

[9] GridWise Consortium :`http://gridwise.pnl.gov/`

[10] Ecogrid-dk Project:`http://www.energinet.dk/EcoGrid/`

[11] INTEGERAL Project:`http://www.integral-eu.com`

[12] FENIX project: `http://www.fenix-project.org/`

defines an aspect oriented heterogeneous agent architecture and proposes to implement control functions delivered by agents as services. This service based implementation of control functions aims to provide reusability, flexible access and adaptability.

The FENIX project focuses on efficient integration of DER (Distributed Energy Resources) into the electric power system by aggregating them into large scale virtual power plants. In FENIX, the virtual power plant (VPP) operation is characterized at two levels: the Commercial VPP and the Technical VPP, characterizing commercial wholesale market operation and system management services respectively. Intelligent agents are used to implement such commercial and technical functionalities in VPP aggregations. For commercial VPP operation the agents acts on behalf of an aggregation of DER units to generate optimal commercial value in the wholesale electricity markets. For the technical operation of VPP, it has been suggested that the distribution system operator DSO implements an agent to characterize the optimal operational parameters of DER units, behavior of controllable loads and local network constrainers.

The EcoGrid-dk project addressed the question of how should the Danish power systems be designed to securely accommodate 50% wind power generation? The project investigated different measures to be taken in control, operation and market mechanism; and potential tools and technologies to be applied in answering this question. The work package 2 *System Architecture* of this project investigated measures to be taken to improve control architecture of future power systems with 50% wind power. It suggested to adopt an agent based flexible control based upon loosely coupled autonomous aggregation structures (the subgrids). The agents inside these aggregations represent different electric power system components and perform 0functions of automation and control.

The overall state of the art of intelligent agent technology in electric power systems is quite promising. But at the same time, most of the applications and concepts are application specific and are therefore not flexible enough to be generalized for a range of application domains. Therefore there is a need for development of a system design approach that can facilitate all aspects including specification, functional design, architecture, implementation and testing in order to transform of today's centralized electric power systems into the future distributed, decentralized, robust and flexible system. The need for such system design approach has motivated the choice of research questions for this Ph.D. project.

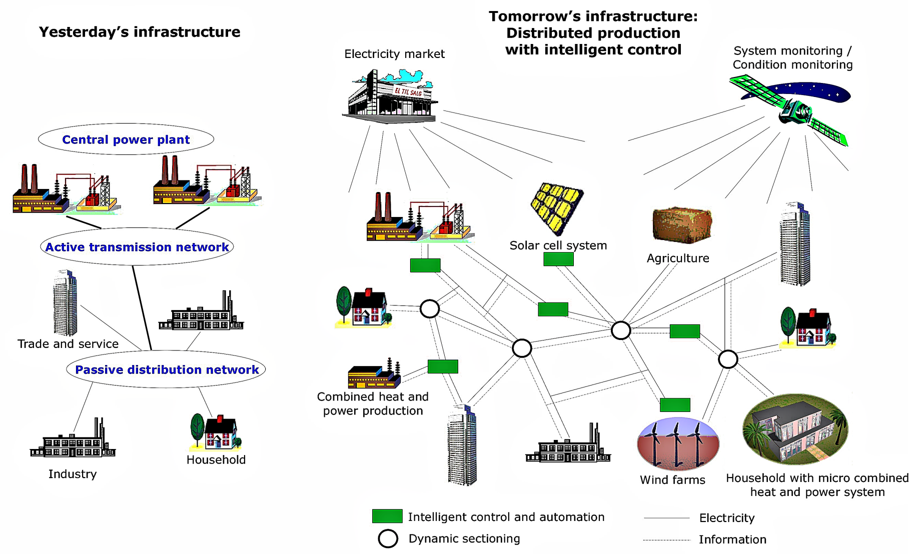

Figure 1.9: Future challenge is to utilize emerging ICT technologies to provide flexible control mechanisms for complex electric power system

1.4 Challenges Ahead

The challenges ahead for electric power systems is to efficiently utilize modern ICT technologies in the operation and control (Figure 1.9). Security of supply is the primary concern. It has been argued [58] that insufficient or even counterproductive control actions caused by deficiencies in information management, communication or the performance of the control system itself has been common to all recent blackouts. System blackouts could have been averted or confined to a smaller area had there been a proper and timely control response. in order to address this problem there is need for a consistent and systematic approach for design of control system strategies.

Increased penetration of DG, heterogenous energy sources, and emerging distributed control architectures such micrograds, virtual power plants and cell based systems have further transformed electric power systems from being hierarchies into complex networks (figure 1.9).

For the automated entities in such systems it has become increasingly difficult to properly analyze emerging situations and choose an appropriate set and sequence of control actions to be executed because of the increased complexity of subsystem interactions. There is a need to reorganize current information systems. Today's control and information systems including the majority of existing agent application are modeled strictly based upon physical topology and behavior of the systems. But the interaction in intelligent distributed systems are not only on the level of physical entities. It is also on the level of intentions and goals. One approach could be to use the novel approaches of means-ends modeling of complex system reflecting the functional organization of the system.

Another relevant part of the challenge is the lack of platforms to design and test new control strategies. This includes both software based simulation platform and the physical platform for laboratory testing. Current simulation and testing facilities do not have capabilities to test control strategies that fully benefit from e.g., intelligent systems, high level communication and efficient information representation.

These challenges have directly influenced the choice of research question for this P.hD.work. The research questions addresses issues spanning all phases of system design and can therefore contribute to a methodology for multiagent system design and its application in control of electric power systems.

Chapter 2

Research Questions and Contributions

The work in this thesis is based upon a number of research questions derived from of the current state of the art in the electric power systems and the new challenges and requirements faced by the industry. The research questions are defined within a system design perspective covering all phases from requirement specifications to testing. This perspective has served as framework for the work done during the Ph.D. and provides an outline for the research work. Following part of this section describes each research question, its relevance and to the the work done and briefs on how it has been answered in the papers produced as part of this Ph.D. work.

Following are the papers included in this thesis:

I. Saleem, A. and Lind, M. Requirement analysis for autonomous systems and intelligent agents in future Danish electric power systems International Journal of Engineering, Science and Technology 2010. vol. 1. No.2

II. Saleem, A. Heussen, K. and Lind, M. Agent Services for Situation Aware Control of Power Systems With Distributed Generation. Proceedings of IEEE PES General Meeting, 2009, Calgary, Canada

III. Saleem, A. and Lind, M. Reasoning about Control Situations in Power Systems. Intelligent System Applications to Power Systems. International Conference on Intelligent System Application in Power Systems 2009, Curitiba, Brazil.

IV. Saleem, A. Lind, M. and Veloso, M. Multiagent based protection and control in decentralized electric power systems. Proceedings of the ATES Work Shop of the 9th International Conference on Autonomous Agents and Multiagent Systems 2010, Toronto, Canada.

V. Saleem, A. and Lind, M. Knowledge based support for multiagent control and automation. Submitted to Cigre International International Symposium on Electric Power Systems of the Future, Integrating Supergrids and Microgrids. Bologna, Italay, 2011.

VI. Heussen, K. Saleem, A. and Lind, M. Control architecture of power systems: Modeling of purpose and function. Proceedings of IEEE PES General Meeting, 2009, Calgary, Canada.

VII. Saleem, A. Us, T. and Lind, M. Means-end based functional modeling for intelligent control: modeling and experiments with an industrial heat pump system. In proceedings of the 10th IASTED International Conference on Intelligent Systems and Control,2007. Cambridge, USA.

VIII. Saleem, A. Lind, M and S. Singh. Modeling Control Situations in Power System Operations. In proceedings of the International Conference on Autonomous and Intelligent Systems AIS 2010, Porto, Portugal.

IX. A. Saleem, M. Lind, N. Honeth and L. Nørdstrom. A case study based Interoperability model of Multiagent Systems and IEC 61850. In proceedings of the IEEE PES Conference on Innovative Smart Grid Technologies Europe 2010, Gothenburgh, Sweden.

X. Heussen, K. and Saleem, A. and Lind, M. System-Awareness for Agent-based Power System Control. In proceedings of the IREP Symposium- Bulk Power System Dynamics and Control, VIII (IREP) 2010. Rio de Janeiro, Brazil.

Table 2.1 summarizes contribution of each research paper to the specific part of the PhD research i.e, the research questions[1]

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[1] Papers I- V and VII IX have been written as main contribution to this Ph.D. work, whereas paper VI and X have partial contribution from the the Ph.D. work.

Research Questions	Publication									
	I	II	III	IV	V	VI	VII	VIII	IX	X
Requirements	X									
Control Architecture	X					X				
Applicability of Agent Technology		X		X					X	
Knowledge Based Systems		X	X	X	X	X	X	X		X
Software Platform		X		X		X		X		X
Demonstration in case Studies		X		X		X		X		X

Table 2.1: Relevance of research questions to publications

2.1 Identification of Control Requirements

What are control requirement in electric power systems that could exhibit potential for use of Agent Technology?

Deregulation, high penetration of distributed generation and environmental concerns have led to the introduction of innovative control architectures such as microgrids, virtual power plants, cell based systems and real time markets in electric power systems. These trends have brought interesting changes both in physical and control structure of the electric power systems. Fundamental motivation behind this Ph.D. work is to evaluate the use of intelligent agent technology to cope with the challenges caused by these changes. The First part of this work deals with precisely identifying the specific needs and requirements in changed scenarios of electric power systems which could be interesting for application of intelligent agent technology. Requirements identification determines the needs or conditions to meet for a new or altered system, taking account of the possibly conflicting requirements of the various stake holders, such as beneficiaries or users and provides evaluation for applicability of specific technologies. Current work on requirement identification, e.g. smartgrid road map of the national institute of science and technology NIST [2] and in [59], primarily focuses on identification and explanation of general drivers, needs and motivations for application of decentralized electric power systems and the smartgrid. Some other works [60] directly start with specification of control architecture and implementation strategies. Paper I in this thesis addresses this part of the research work. This paper reviews three example cases (micrograms, virtual power plants and cell based systems) of innovative control architecture in electric power systems. It precisely identifies different requirements in each of these cases and maps them to the specific capabilities of autonomous systems and intelligent agents.

The result of this work is a framework for understanding the applicability of autonomous systems and intelligent agents in electric power systems. Moreover, this part provides input for the rest of the research work. It provides basis for

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[2] National Institute of Science and Technology Smartgrid road map: `http://www.nist.gov/smartgrid/`

design of a control architecture and puts qualifications for the development of the software platform.

2.2 Control Architecture

What is a suitable agent based control architecture for decentralized electric power systems?

Decentralization, communication, increased level of autonomy are central to the challenges and requirements of today's electric power systems. A multi agent based flexible control architecture should be envisioned which maps the capabilities of intelligent agents to the identified requirements of electric power systems. Parts of paper I and paper VI, address this question. A control architecture is the conceptual model that defines the structure, behavior and multiple views of a system. It also describes interaction between subsystem components and interfaces with other systems. The GridWise architecture specifications[3] provides basis for organization of systems framed across technical, economic, operational, standardization and implementation aspects. It also provides guidelines for moving from architecture towards implementations. nevertheless it does not incorporates any aspects of applicability of intelligent systems such as the intelligent agent technology. The work in [60] describes a basic functional architecture enabling application of intelligent agent technology in order to achieve a higher degree of automation and more reliable operation. It also proposes information technology based framewwork for the implementation of system based upon the proposed architecture.

In paper I of this thesis, a generic flexible control architecture is envisioned for future scenarios where the electric power system is a loose aggregation of units that could be a microgrid, virtual power plant or cell like structure. These subgrids not only have to optimally perform local control within the subgrid, but also must comply with responsibilities towards the main grid. This two way responsibility is particularly interesting for scenarios of electric power systems with very high penetration of distributed generation and where a large part of the grid are sub-aggregated units – the subgrids. Central to idea of the subgrid control architecture is fulfilment of the requirements such as flexibility, reorganization and decentralization.

Paper VI addresses another relevant aspect of control architecture. It suggests an improvement to the traditional approach to design of control architecture which is based on the physical structure of the systems and have difficulty

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[3] GridWise Architecture Tenets and Illustrations: `http://www.gridwiseac.org//`

in capturing the underlying functional semantics. It suggests a mechanism to organize control architecture in a means-ends way i.e. based on functions and purpose of power systems. This approach helps to model implicit control knowledge which is difficult to formalize otherwise. The approach has been compared with traditional ones with the help of an example of power balancing.

The contribution of this part of the research work is recommendation on how a control architecture should be organized that addresses new challenges and requirements in electric power systems and utilizes capabilities of intelligent software agent technology.

2.3 Applicability of Agent Technology

What benefits Agent Technology can offer in order to satisfy identified requirements (research question 1)?

Intelligent agents and Multiagent Systems posses capabilities such as autonomy, proactivity, high level communication and cooperative decision making. This part of the research investigate how such capabilities are relevant for electric power engineering application, especially in the context of distributed generation and innovative control architectures, and what is a suitable framework for their application. The papers II, IV, IX and X address this question.

Paper II describes a service oriented mechanism for multiagent cooperation. In this mechanism control agents represent different components of the electric power systems are able to offer and utilize control services. Request and provision of these services is done autonomously based on a service oriented architecture. This mechanisms demonstrates the capabilities of intelligent agents such as autonomy, decision making and cooperative problem solving.

In the paper IV, a novel multi-agent planning framework is presented in which control plans are developed through a dynamic auction mechanism. Upon any changed situation, agents calculate the utility for different control roles and bid for specific roles based upon calculated utility. The final control plan assigns specific roles to each agent according to the bids received for each role. This mechanism demonstrates capabilities of agents such as explicit negotiation, coping with emerging situations and dynamic reorganization.

The paper IX presents an interoperability model for multiagent systems and the IEC 61850 standard. The IEC 61850 is the most promising standard for the design of substation communication automation systems. On the other hand multi agents systems are attracting growing interest for different applications of substation automation systems [61, 62, 63]. Therefore it is important to demonstrate and evaluate the interoperability of these two technologies. This paper does this through a case study and demonstrates how in a specific scenario, a multiagent system should be designed that efficiently conforms to the IEC 61850 standard.

The paper X presents a concept for the representation and organization of control and resource-allocation, enabling computational reasoning and system awareness. The principles are discussed with respect to a recently proposed subgrid operation concept.

The overall contribution of this part of the research is demonstration of different efficient mechanisms of applying multiagent systems in electric power systems control and automation demonstrating capabilities of multiagent systems and their applicability.

2.4 Application of Knowledge Based Systems

How knowledge based systems can be exploited for decision making, self awareness and [re]organization in power systems?

Growing penetration of distributed generation, increased interconnection and communication, and introduction of distributed and local control paradigms have increased the complexity of structure, operation and control of electric power systems. Recently a large amount of research efforts has been made to utilize knowledge based techniques in order to model domain knowledge and decision making expertise to build expert decision support systems that can support human decision making as well as automation. Traditionally, the motivation for application of knowledge based systems ranges from coping complexity of interconnection to the flexibility of rule based systems in changed environments. The strength of knowledge based systems have been investigate in particular in the problems areas of inconsistent data, complexity of network structure and re-organization, Combinatorial nature of the solutions and restoration in the power systems [64]. Some of the major application application examples include alarm processing and system diagnosis [65, 66, 67], contingency analysis and control [68, 69], and power system restoration [70, 71, 66]. This thesis investigates usability of knowledge based techniques in power systems in the context of multiagent systems. This part of the research has been addressed in papers III, V, VII and VIII. The Paper III discusses the problem of interpretation of control situations. It demonstrates how to use explicit means-ends model based reasoning about complex control situations in maintaining consistent perspectives and selection of appropriate control action for goal driven agents in a multiagent environment. Effectiveness of this mechanism has been demonstrated with an example of electric power distribution network consisting of several load and DG agents and a connection to utility grid. The example demonstrates that in the case of a fault and loss of connection to the utility grid, the load and DG agents can evaluate their environment and select an appropriate action to maintain balance in isolated part of the distribution network. Paper VIII applies the same method in a different application of power dispatch and evaluates results.

The Paper VII presents the use of qualitative model based reasoning and fault diagnosis in industrial control systems. With example of an industrial heap pump system, it presents a mechanism of modeling control systems and shows its application in fault identification and diagnostic control in different scenarios. The Objective of this work was to gain a general understanding for implementation of knowledge based system in industrial control systems and to investigate it's implications of it for further development in specific areas of electric power system control.

The paper V presents a method for using model based reasoning in electric power systems protection and control. It describes how agents using a model of their environment can perform reasoning in order to be aware of a situation and to choose right actions to perform.

The over all contribution of this part of the research is development of methods for using knowledge based techniques for agent based control and automation. Applicability have been demonstrated in examples from power systems control.

2.5 Testbed/Platforms Development

What implementation technologies and simulation tools are best suited for using agent technology in power systems?

In order to design, test and evaluate multiagent based solutions in electric power systems it is crucial to have a proper software platform which can facilitate implementation of multiagent systems with their full potential. Current use of intelligent systems techniques in electric power system control falls into two categories. The first approach models the electric power systems in some dynamic modeling platform such as PSCAD[4] or DigSILENT Power Factorey[5] etc. This approach enables efficient modeling of dynamics of electric power systems but is not efficient for implementing aspects of intelligent systems. The second approach uses high level tools and languages, e.g, JADE[6] or JESS[7] to implement intelligent systems and lacks a dynamic model of electric power systems and hence the electromagnetic dynamics and their effect on proposed control techniques. In this Ph.D. work a comprehensive experimental software platform was developed. The platform consists of several components and provides modeling of dynamic electric power networks as well as implementation of intelligent systems such as multiagent systems based on standard protocols. It also included components for support of knowledge based system such as means-ends modeling and model based reasoning. A middleware software was developed for real time communication among different components of this software platform.

Paper I and II describes development of the electric power network modeling component and the software agent component where different control agents are designed and programmed. It also describes development of a middleware for real time communication between these two components. The software agent component supports design of service oriented architecture (SOA) where different agents can offer, search and subscribe specific control services for electric power systems control and balancing.

Paper V describes integration of a rule based system into the software platform which facilities qualitative means-ends based modeling of systems and reasoning about control situations to choose right action and situation awareness. Development of this software platform considered very carefully the requirements identified in previous parts of the research and ensured that platform is capable of implementing such requirements.

The overall contribution of this part of the research is development of a flexible software platform which can facilitate design, development and testing of multiagent based control strategies for implementation in electric power systems.

2.6 Demonstration in Case Studies

How can the capability of agent based control demonstrated in some innovative control architecture scenarios? Finally it is important to demonstrate in some

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[4] PSCAD Simulation Environment: `https://pscad.com/`

[5] DIgSILENT GmbH: `http://www.digsilent.de/`

[6] Java Agent Development Framework (JADE): `http://jade.tilab.com/`

[7] JESS, rule based engine for the JAVA platfrom: `http://www.jessrules.com/`

application scenarios how capabilities of multiagent systems, implemented in a flexible control architecture and aided by model based reasoning can cope with emerging challenges of electric power systems. This part of research is primarily addressed in paper II and IV.

Paper II presents results from using multiagent systems in a scenario of distribution system islanding. Recently, a large amount of distributed generation have been connected to low and medium voltage networks and there is a growing interest for activating these DGs in control and automation and of the system. This paper presents how agents bring local intelligence to different components of distribution systems such as DG and loads and for their participation in control during islanding operation of the distribution system. Results have been presented from simulations of different scenarios depending on amount of available distributed generation and participation loads in control. One important aspect of this study is to show application of a greater level of autonomy – which is an important characteristic of multiagent system – in electric power systems control. In the presented study all agents take decisions autonomously e.g. DG agents decide to offer and render *regulation services* and load agents offer *loadshedding services* in a completely autonomous way. High level agent characteristics such as autonomy and negotiation were tested in dynamic electric power simulations in order to test their feasibility, robustness and time scale compliance with electric power systems operations. Moreover it has demonstrated that during such a scenario agents can utilize a model to be aware of their environment and choose appropriate control actions consistently.

Paper IV describes usage of multiagent systems in a specific problem of distribution system protection. Introduction of distributed generation has brought challenges to current distribution protection systems and industry is actively seeking new solutions to improve their current practices. This paper utilizes enhanced communication among different agents and a novel role selection mechanism for agents. Results from different experiments has shown the effectiveness of multiagent systems to improve current practices.

Paper V concentrates on utilization of knowledge based systems. The study case shows application of qualitative modeling and diagnostic reasoning in a distribution system protection. It also describes integration of the knowledge base systems module into the software platform. Results from this paper show effectiveness of knowledge based systems and improvement in current practices.

This part of the research exemplifies and provides feed back on applicability of research work carried out during the Ph.D. work. Some of the key challenging areas of today's power systems have been selected for testing and evaluation of proposed mechanisms. Promising results show that proper application of multiagent system can effectively address the challenges in of today's electric power systems.

2.7 General Contributions

The general contribution of this research work is an *evaluation and demonstration of the intelligent agents technology* for application in control of electric power systems with high penetration of distributed generation. Intelligent agent technology falls in a broad category of information and communication technology ICT. Therefore considerations have also been given to understand intelligent agent technology in a *broader ICT context.* Application of intelligent agent technology has been evaluated together with other ICT technologies such as service oriented architecture, high level communication, and knowledge based systems.

A special emphasis has been given to *study current trends and understand requirements* which make intelligent agent technology a potential for application in power systems.

During the course of the research work a *comprehensive software platfrom* was developed. This software platform enables design, test and verification of agents based control strategies that incorporates power systems dynamics and allows to implement ICT technologies. Development of this software platform is an important achievement since currently available software tools provides either modeling of dynamic electric power networks or implementation of intelligent systems techniques such as intelligent agents. The software platform enables development of dynamic power system networks, implement agent based techniques and knowledge based systems. Usefulness of the software platform has been demonstrated in a number of *case studies.*

Investigations have been made and mechanisms have been proposed to utilize *knowledge based techniques* such as rule based systems, qualitative modeling, situation awareness, selection of appropriate control actions and diagnostic reasoning in electric power systems.

New trends in electric power systems are suggesting increased use of communication based solution for control in electric power systems. This research work has *suggested intelligent control mechanisms based upon coordination and communication* and have investigated their integration with multiagent systems.

The research work has contributed with a general system design methodology covering all phases from requirement specifications to testing.

Chapter 3

Conclusions and Directions for Future Work

This section concludes the dissertation work by presenting general conclusions and giving directions for possible future work in continuation of the current research.

3.1 Conclusions

Electric power systems of today are facing several challenges. Environmental concerns, security of supply and accommodation of growing amount of distributed generation are some of the primary ones. Addressing these challenges require current control and information systems to be re-evaluated and redesigned. Large amounts of distributed generation as well as demand side resources should be actively integrated into the operation and control of the system. Intelligent agent technology is one of the promising ICT technologies that can be used to provide required local intelligence, pro-activity and cooperativeness based upon high level communication structures, for this purpose.

The first important step in this direction is to investigate and understand the key areas where application of intelligent agent technology could be useful. This has been addressed in the current research work concluding that emerging control architectures such as microgrids, cell based systems, virtual power plants and real time markets have a good case for application of intelligent agent technology.

Future control architectures should be based upon aggregation structures to support required flexibility, grater level of autonomy, local and distributed control and robust interactions.

Level of intelligence and autonomy in agents for application in control of electric power systems must be selected very carefully considering the time scales and operational criticality of the specific application domains.

Complexity will increase significantly in future decentralized electric power systems. Autonomous entities (agents) in such systems will face a challenge in selection of appropriate control (counter)actions in emerging situations of complex scenarios. Dealing with such situations requires the utilization of knowledge based techniques to facilities such entities with a model of their environment. These models can be used to analyze and reason about control situations and to select appropriate control actions, i.e., implementation of situation awareness.

Efficient implementation of intelligent agents as well as other ICT technologies require a suitable software platform. Such platforms should be able to facilitate modeling of dynamic electric power networks as well as high level intelligent system mechanisms.

In order to benefit from the full potential of intelligent agent technology it is important to utilize it together with other ICT technologies such as service oriented architectures, knowledge based systems and power systems communication standards such as IEC 61850.

3.2 Future Work

The research work dealt with a comparatively open and new field of study. There is a large scope for continuing the current work in the directions given in this dissertation. Some of such directions are as follows:

Response time is a critical concern for any multiagent based solution. A possible future study could be to evaluate proposed mechanisms in some real time simulation environment e.g, Real Time Digital Simulators (RTDS).

The proposed multiagent based mechanisms in this work has been tested in simulation based studies. It shall be interesting and useful to test these methods in real world demonstrations with real customers and electric power system components.

Verification and validation is a difficult task in multiagent based systems due to their inherent decentralization, autonomy and localization. Therefore it should be useful to further investigate for verification and validation of the solutions proposed in the current work.

Agent based solutions proposed in the current work are highly communication dependant. Studies should be made on further investigation of fault tolerance of communication (communication failure scenarios).

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Requirement analysis for autonomous systems and intelligent agents in future Danish electric power systems

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Abstract

Denmark has already achieved a record of 20% penetration of wind power and now moving towards even higher targets with an increasing part of the electricity produced by distributed generators (DGs). In this paper we report work from a sub activity "subgrid design" of the EcoGrid.dk[1] project. First we review innovative control architectures in electric power systems such as Micrograds, Virtual power plants and Cell based systems. We evaluate application of autonomous systems and intelligent agents in each of these control architectures particularly in the context of Denmark's strategic energy plans. The second part formulates a flexible control architecture for electric power systems with very high penetration of distributed generation. This control architecture is based upon the requirements identified in the first part. We also present development of a software framework to test such flexible control architectures.

Keywords: Electric power system, distributed control, autonomous systems, intelligent agents

1. Introduction

Electric power systems is one of the most critical and strategic infrastructures of industrial societies and is currently going through a revolutionary change. Deregulation, security of supply, environmental concerns and rapid growth in Information and Communication Technologies (ICT) are basic driving factors behind trends like renewables and distributed generation, free market, decentralized control, self healing and automatic (dynamic) reconfiguration in today's' power systems. Deregulation aims at ultimately providing a competitive market based environment which can offer energy to customers at a favorable price. Environmental Concerns primarily deals with CO2 emissions and global warming. Security of supply ensures the smooth delivery of energy to customers. Electric power industry has traditionally been slower to adopt modern ICT compared with other industries e.g. telecommunication. But recently, a rapid growth and significant reduction in price of ICT tools and technologies has made it inevitable for electric power industry to take initiatives to adopt ICT more effectively. This situation has created an incentive among both distribution utilities as well as network operators to develop long term strategies and plans that address above mentioned challenges.

Denmark has already achieved a record of 20% penetration of wind power (2007 data), and innovative control architectures like microgrids, virtual power plants (VPP), cell based systems, vehicle to grid, are under consideration and development in electric power system. Furthermore, Denmark is now moving towards a target set out by a new national energy strategy which implies 50% wind power penetration for the electric power system by 2025.

With the valuable experiences accumulated so far, it has been anticipated that the technical challenges for a 2025 scenario of 50% wind penetration will be in balancing the power system, development of new market services and the need for new strategies for

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[1] EcoGrid project: http://www.ecogrid.dk/

operational security and control. Accomplishing these challenges require that future power systems are of a distributed nature, consisting of autonomous components or subsystems, are able to coordinate, communicate, compete and adapt to emerging situations and self heal themselves. Efforts are underway to meet these challenges. EcoGrid.dk is a principal research program on the national level initiated by the Danish TSO (Transmission System Operator) Energinet.dk, and comprised a consortium of stake holders including power distribution and generation companies, manufacturers, consultants and research institutes both in and outside Denmark, to propose a strategy for transforming the Danish power system into the world best renewable based electricity network. In this paper we report work from a sub activity "subgrid design" of the Ecogrid.dk project (phase 1). This activity is part of the work package II dealing with System Architecture.

The paper is composed of three main parts. In the first part we make a review of innovative control architectures in electric power systems such as microgrids, virtual power plants and cell based systems. In the second part we evaluate the approach of using autonomous systems and intelligent agents in each of these control architectures particularly in the context of Denmark's strategic energy plans. We identify specific requirements and respective capabilities of intelligent agents for each of these control architectures. In the third part we formulate a generic and flexible subgrid control architecture for the future Danish electric power system. We base this architecture on the requirements identified in the second part and suggest that power systems with high penetration of distributed generation may be controlled as a loose aggregation of energy units -- *the subgrid control*. Finally we present a multiagent software platform for design and test of the subgrid control concept which is currently under development.

The structure of the paper is as follows: section II presents the review of innovative control architectures in the context of the Danish Power System and a requirement analysis for the use of intelligent agents and autonomous systems. Section III presents the generic sub-grid based control architecture and section IV presents our work on developing a software framework for designing and testing the flexible control strategies mentioned in section III. Section V contains conclusions of the work.

2. Review of Innovative Control Architectures

The objective of this section is to review existing Danish and international proposals for future systems structures e.g. microgrids, cell based systems and virtual power plants and perform a requirement analysis for the use of intelligent agents and autonomous systems in these architectures. One purpose of this task within the EcoGrid.dk project was to provide input to other tasks in the project and to provide inputs to the electric power industry for their future planning and application of intelligent control technologies.

2.1 Intelligent Agents and Multiagent Systems:

“An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives” (Wooldridge 2002).

To further explain:

- Agents are encapsulated in a belief, desire, intention BDI metaphor
- Agents are situated in physical or software environments
- Agents are autonomous and can exercise control over their state and behavior
- Agents are proactive and can take initiatives by themselves rather than passively responding to changes in their environment
- Agents are social and can communicate in high level dialogues

This definition of agents and the metaphore presented in Figure 1 is analogous to the notion of engineering autonomous systems which can react intelligently and flexibly on changing operating conditions and demands from the surrounding processes (Rehtanz 2003). Such intelligent and autonomous systems provide capabilities like decomposition, reasoning, dynamic, flexibility (dynamic reconfiguration) and cooperation modeling. The remaining part of this section indicates that such capabilities are critical for realization of innovative control architectures in electric power systems.

It has been suggested to use intelligent agents and multiagent systems from a requirements rather than a technological perspective. Intelligent agents are considered appropriate for applications that are modular, decentralized, changeable, ill-structured, and complex (Wernstedt & Davidsson 2002) because multiagent architecture directly supports design and development of systems with such features.

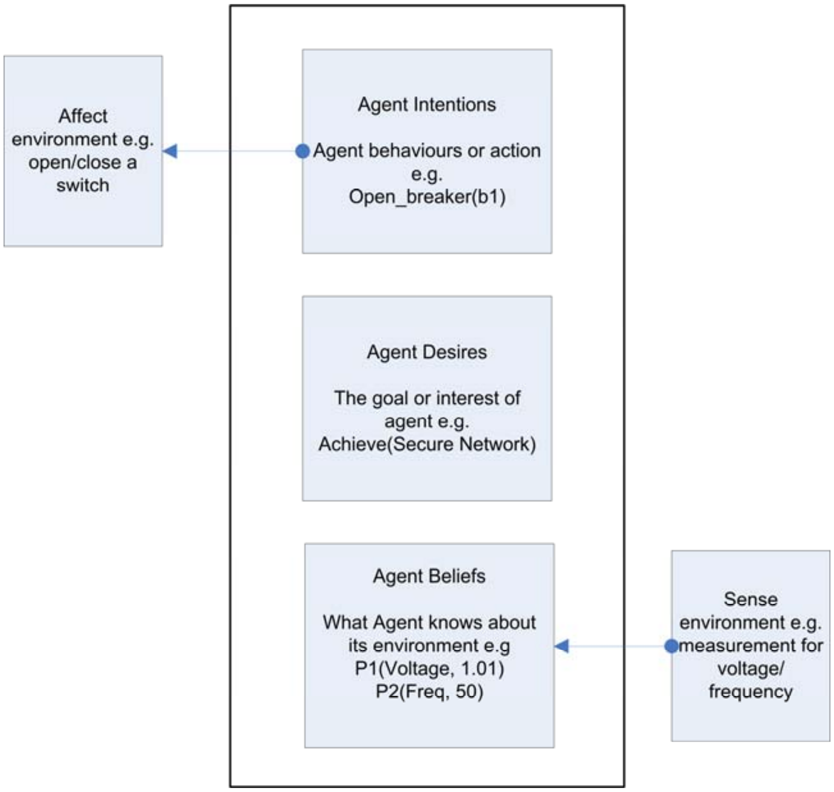

Figure 1. *Belief, Desire, Intention BDI* based abstract intelligent agent metaphor

We investigate innovative control architectures in electric power systems and argue that they have specific characteristics which makes them candidates for application of intelligent agents. We base our analysis primarily on the three most noteworthy and emerging concepts: microgrids, virtual power plants and cell based systems. It is important to note that the terminology *cell based systems* has been used in very general meaning in electric power system literature. For our study we refer to a concept applied by *the cell project*[2] of Danish TSO Energinet.dk, which falls within the general notion of cell based energy systems.

2.2 Microgrids:

Microgrids are small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage. A microgrid can be connected to the main power network or be operated autonomously, similar to an island operation. Sources in a microgrid are usually small (< 100 kw) units with power electronic interfaces (Hatziargyriou 2008). Microgrids can be characterized by following specifications based upon current implementation and test efforts:

- Different resources in a microgrid may be owned by different owners, thus making environments where the components have competing goals, while still serving the common goal of ensuring “security of supply”
- Resources in a microgrid are of a heterogeneous nature
- In a grid connected mode, all the resources in microgrid participate in the market, whereas in islanded mode microgrid have its own market managed by local microgrid controller
- A microgrid has to be able to shift to (and from) islanded mode to grid-connected mode

Considering this characterization, intelligent software agents have a very obvious case for application in microgrid control and operation. Intelligent agents have sophisticated cooperation mechanism (Jennings 1995; Liu et al. 2006) which could help implement the required cooperation between different DGs in a microgrid. The adaptive nature of intelligent agents (Bernon et al. 2003) can help to implement dynamic adaptability in microgrids e.g., from grid-connected to islanding mode. The autonomous nature of agents is vital for the local and distributed control of microgrids and to facilitate the economic interest of individual DG owners. The ability of agents to coordinate, communicate and resolve issues can help to implement market mechanism. Also agents have the capability to strike a balance between individual and collective system goals which is relevant for implementing the above scenario of maintaining a balance between individual economic goal of DG owners and overall system goal of security of supply and balancing.

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[2] The Danish Cell Project: www.energinet.dk

There are several efforts and demonstrations for utilizing intelligent agents and autonomous systems for design and control of microgrids (Dimeas 2004; Farred 2008).

2.3 Virtual Power Plants:

Unlike a microgrid which is a geographical aggregation, a virtual power plant is a commercial aggregation of distributed energy resources. VPP is a group of DG units which are controlled to function together like a single power plant, thereby improving the market function and providing valuable flexibility to the power system. Through the VPP concept, individual DGs will be able to gain access and visibility across the energy markets, and benefit from VPP market intelligence in order to get their revenue maximized, which otherwise would have not been able to participate in the market due to their small size or stochastic energy supply. Virtual power plants can be characterized further as following:

- Same as microgrids, different components in a VPP may be owned by different owners with competing goals/interests
- The resources in a VPP may be geographically dispersed at long distances, making the communication requirements more significant
- All nodes participate in the market, individually in the local market and in the main grid through a central facilitator (controller) of VPP
- Nodes of a VPP should have enough level of intelligence to take local decisions and perform well in the market

Besides the requirement of autonomy, local control capability, high level communication and decision making as in microgrids, it is apparent that VPP has a higher requirement for (real time) market mechanisms. Current research has shown that economic feasibility of VPP is very much dependent on good local market mechanisms, ability of the DGs inside a VPP to respond intelligently to price signals, and negotiation patterns of DGs for participating in the market (Shi 2009). Intelligent agents and other reasoning mechanism has been used widely in different market processes e.g., stock exchanges and has great potential to be used in VPP particularly enabling for individuals DGs to participate effectively in the market.

2.4 Cell based systems:

A cell is defined as the portion of a distribution system below 150/60 KV sub station typically consisting of 20-100 MW of conventional loads and a mix of CHP and wind turbine generators (Lund 2007; Cherian & Knazkins 2007).
A cell has two main operational modes:

- In the case of a cell-area operating in parallel with the HV-grid, the main focus of control is a fully automated VPP operation on existing and the future market conditions. It should also be possible for TSO to interact with cells from a control center just as they would interact with a conventional power plant

- In emergency situations in a 400 KV grid, it performs intentional islanding i.e., on receiving a signal from the control center it quickly manages a balance between generation and load within the cell and restarts itself using local resources (< 60 KV)

In the case of a cell-area operating in parallel with the HV-grid, the focus of control can be fully automated VPP operation on existing and the future market conditions. It should also be possible for TSO to interact with cells from a control center just as they would interact with a conventional power plant. In emergency situations in a 400 KV grid, it performs intentional islanding i.e., on receiving a signal from the control center it quickly manages a balance between generation and load within the cell and restarts itself using local resources (< 60 KV)

In the first case of VPP operation the control is commercially motivated and can incorporate both active and reactive power at the same time. Furthermore the controller can be asked to do voltage control in a certain grid point utilizing all available generators under its control. During the second case of emergency islanding situations, islanding occurs and control is transferred to local cells. In such cases each cell behaves like a microgrid (or island) which is not connected to the main network. When cells are islanded (in emergency situations) they are disconnected from the main grid and are no longer able to participate in the normal market.

It is clear that cell operation can either be commercially motivated, the first case of VPP operation where more centralized approach and competitive market mechanisms are required, or it can be technically motivated, the second case of emergency islanding where a decentralized (or local) control with cooperative behavior of individual resources is anticipated.

Cell based systems have a high requirement for situation awareness and being able to reconfigure in a changed situation e.g., when going to cell mode. The behavior of cell components has to be different during islanding and VPP operation modes. Thus it is anticipated that characteristics of intelligent agent technology like knowledge representation, situation reasoning and cooperative decision models can facilitate realization of this concept. Aspects of agent technology are already under testing in the cell project

Table 1. Mapping of intelligent system capabilities into innovative power systems control requirements

Agent Capabilities	Innovative power systems control architectures			
	Microgrid	Virtual Power Plants	Cell based Systems	
			VPP operation	Emergency Islanding
Local/Distributed Control	H	H	L	H
Modularity	H	H	H	H
Self organization/Adaptability	L	H	L	H
High level cooperation and communication structures	H	H	H	H
Market mechanism	H	H	L	H
Robust/no single point of failure	H	H	H	H
Hybrid control mechanisms	L	L	H	H
H: high requirement	**L: low requirement**			

demonstrations (Lund 2007; Cherian & Knazkins 2007). Because of the requirement for more centralized nature of control during VPP operation and more decentralized one during islanding, it should be interesting to consider heterarchical control strategies where different modes of control are implemented at different control levels.

Table 1 summarizes a mapping of intelligent capabilities into innovative power systems control requirements. It shows the important characteristics of intelligent based systems which have a potential for application in innovative control architectures. The application cases have been analyzed with two levels of significance: high requirement and low requirement.

3. Subgrid Architecture

As the second part of this work, a generic flexible control architecture was envisioned for future scenarios where the electric power system is a loose aggregation of units that could be a microgrid, virtual power plant or cell like structure. These subgrids not only have to optimally perform local control within the subgrid, but also must comply with responsibilities towards the main grid. This two way responsibility is particularly interesting for scenarios of electric power systems with very high penetration of distributed generation and where a large part of the grid are sub-aggregated units -- the subgrids. The subgrid control architecture tries to organize the grid in a flexible way which allows dynamic aggregation and de-aggregation of resources at different control levels. The process of (de)aggregation is supposed to be flexible enough to incorporate both technical and commercial motivations for aggregation and should have a mechanism for capturing semantics for differentiating these modes. Figure 2 shows a symbolic presentation of such a scenario. The concept of subgrid based control has been motivated and based upon the capabilities of intelligent systems e.g., modularity, decomposition, local/distributed control and its implementation is anticipated to be done using sophisticated mechanisms of coordination, cooperation and competition provided by multiagent technology.

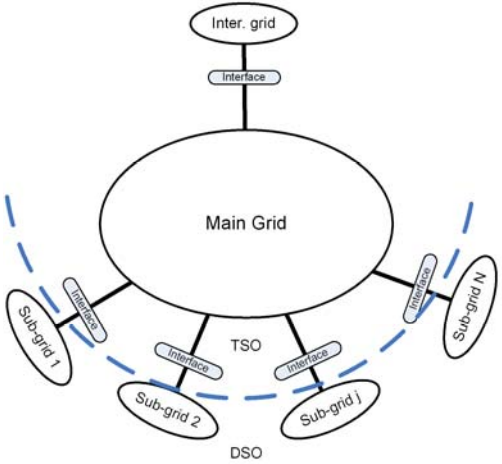

Figure 2. Decomposition of the power grid into a main grid interconnected with a number (N) of sub-grids (Lind et al. 2008; Xu et al. 2008)

Figure 3 presents different the modes of operation, and transition among these modes for a subgrid. In the following we briefly describe these modes and their operation. It should be noted that "connected", "islanding" and "commercially aggregated" are stable modes, whereas "blackout", "connected alert", "synchronization" and "aggregated alert" are modes of transition.

3.1 Connected:

This is a mode of normal operation when the subgrid is part of the main grid and taking part in normal operations. From this state the subgrid can either go to "connected alert ", in the case where early warning systems work (emergency), directly go to "blackouted" state when early warning systems does not work, or to "aggregation alert" state where it starts planning/synchronizing for commercial aggregation.

3.2 Connected Alert:

An alert message may come from a PMU based early warning system informing about some disturbance or fault and the subgrid goes to the connected alert state. The subgrid controller suggest an optimized plan for islanding operation at this state which may include reconfiguration and load shedding schemes based on the current situation. From "connected alert" mode the subgrid can go to one of following states:

- Connected mode: In the situation when a disturbance is not very severe, e.g., under-voltage signal and the grid was able to overcome it without any need to go in islanded mode (restoring)

- Islanded mode: In the situation when the system has prepared a (partial) optimized plan for islanding operation and goes safely to islanding (optimized islanding)

- Blackouted mode: in the case of a very severe disturbance and there was not enough time to prepare a plan for islanding.

3.3 Islanded:

The sub-grid may enter this mode from one of following:

- Connected mode: when early warning systems don't work and subgrid directly goes to islanded (non optimized islanding)

- Connected alert mode: when an alert message from early warning system takes subgrid to connected and it comes to islanded state with already prepared (semi) optimized plan for islanding operation

- Blackouted mode: when system was blackouted initially but then was able to prepare an optimized plan for islanding operation and blackstarts later

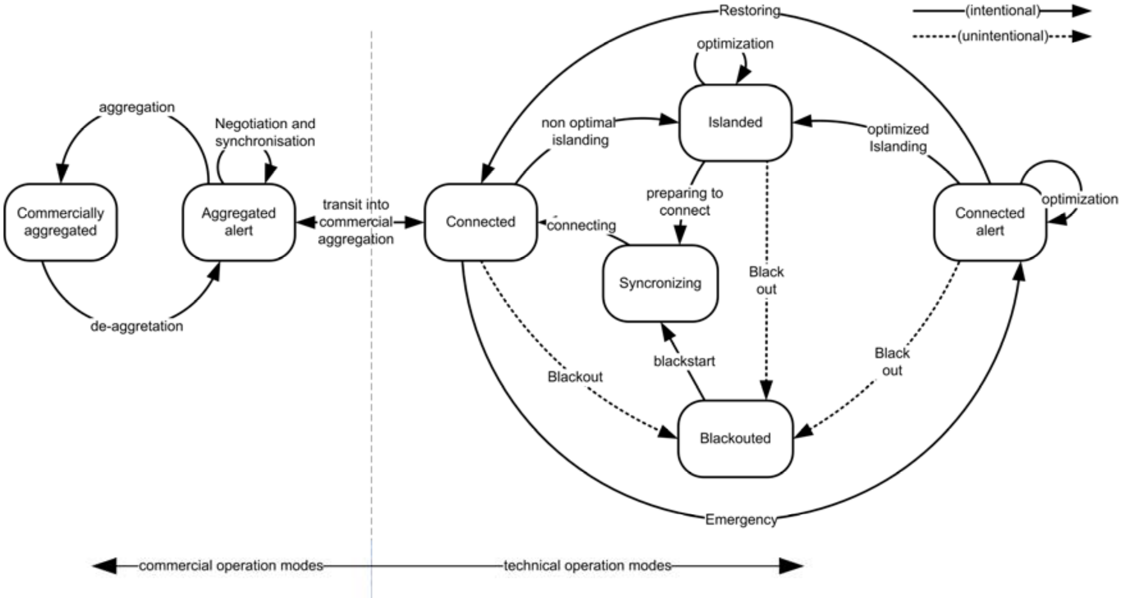

Figure 3. Control modes and transition for subgrid operation

3.4 BlackOuted:

In this subgrid operating mode there is no operation going on in the subgrid and the power is lost by all the loads. The system tries to make an optimal islanding plan at this state and tries to blackstart.

3.5 Aggregated alert:

It is a transitional mode and is reached when some agents controlling the grid resources decide to create a dynamic aggregation based upon some commercial motives. During this mode synchronization and planning is performed to prepare for commercial aggregated operation.

3.6 Commercially Aggregated:

This is a stable mode where aggregated resources perform a commercial operation e.g. VPP operation or market based intentional islanding of microgrid.

A more detailed description of the subgrid based control architecture and discussion on its usability in electric power systems with very high penetration of distributed generation can be found in (Lind et al. 2008).

4. Development of Software platform for design and testing of Flexible Control

Section II performed a requirement analysis for applying intelligent agents and autonomous systems in electric power systems with high penetration of distributed generation, a flexible control architecture was presented for such systems in section III. This section describes development of a software platform to design and test such multiagent based flexible control strategies. A dynamic multiagent platform has been implemented in the Java agent development framework (JADE)[3]. The platform consists of one main container, and several sub containers. Each sub container represents a sub-aggregation unit in a electric power network consisting of one load shedding agent LS and several DG and load agents. Both DG and load agents can join or leave the network dynamically according to the changes in the network. New such sub-aggregation units can also be created following any situation in the network. The software platform also includes JADE utility agents and services. Some of the important utilities and agents are: i) DF (directory facilitator) agent which provides yellow page services. DG and load agents interact with this agent to register and discover agent services, ii) AMS (agent management services) agent which provide white page services. This agent is responsible for creating, destroying and managing agents and containers in a JADE platform, iii) MTS (message transport service) is a service responsible for message transportation between agents within a container and across containers. This service also enables synchronization of messages when several messages are sent and received from different agents in parallel. In order to take full advantage of agent capabilities such as autonomy, local control, scalability and high level communication, the software platform is implemented as fully compliant with FIPA (foundation for physical intelligent agents)[4] standards. Figure 4 shows the structure of the software platform. It presents a symbolic representation of containers which represent electrical islands in a distribution system, the agents inside these containers and the JADE utility services described above. Detailed discussion on development and effectiveness of this platform has been described in (Saleem et al. 2009), where results have been presented from several experiments of using this platform in distributed control scenarios.

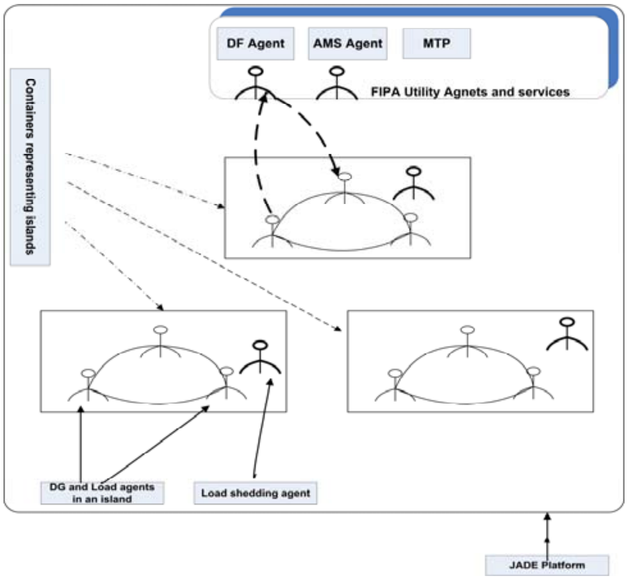

Figure 4. Software platform for design and testing of flexible control strategies

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[3] Java Agent Development Framework (JADE): http://jade.tilab.com

[4] Foundation for Physical Intelligent Agents (FIPA): http://www.fipa.org

5. Conclusions

A requirement analysis has been performed for utilization of intelligent agents and autonomous systems in innovative control concepts of electric power system. A flexible subgrid based control architecture has been proposed for control of electric power systems with very high penetration of distributed generation. A multiagent software platform has been described. The purpose of this software platform is to support design and test of multiagent based flexible control strategies. This platform has been based on the requirement identified in section II and the control architecture envisioned in section III.

The approach of the paper is to identify requirement and to map them into the capabilities of intelligent systems. Subsequently, to suggest a control architecture based upon these requirements and present the development of a software platform for design and test of such control architecture.

Nomenclature

DG	Distributed Generation
VPP	Virtual Power Plant
JADE	Java Agent Development Framework
FIPA	Foundation of Physical Intelligent Agents
PMU	Phasor Measurement Unint

Acknowledgement

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Agent Services for Situation Aware Control of Power Systems With Distributed Generation

Arshad Saleem, *Student-Member, IEEE,* Kai Heussen, *Student-Member, IEEE*, and Morten Lind

***Abstract*—Electric Power system of Denmark exhibits some unique characteristics. An increasing part of the electricity is produced by distributed generators (DGs). Most of these DGs are connected to the network at the distribution level. At the same time the concept of vehicle to grid (V2G) is already in the process of realization. This situation has created an incentive in electric power industry to utilize modern information and communication technologies (ICT) for improving the distribution system automation. This paper describes our work on how significantly increased amount of distributed generation could be exploited for the robust control of electric power systems. In particular, we present our work on the implementation of a dynamic service oriented system, in which autonomous agents represent different components of low voltage grid. These agents could offer and utilize electric power control services. We present results from several experiments where agents offer and utilize services in order to achieve distributed and autonomous control for subgrid operation of a distribution system. Finally it is discussed how the service oriented architecture can be combined with knowledge based reasoning to implement situation awareness required in complex control situations.**

***Index Terms*—Intelligent Control, Smart Grid, Autonomous Agents, Services, Situation Awareness**

I. INTRODUCTION

DISTRIBUTED generation, decentralized and local control, self organization and autonomy are evident trends of future's electric power systems focusing on innovative control architectures like MicroGrids, virtual power plants, cell based systems and grid connected electric vehicles.

Realization of these concepts require that power systems should be of distributed nature – consisting of autonomous components – which are able to coordinate, communicate, compete, adapt to emerging situations and self organize themselves. Intelligent Software Agents which are autonomous software entities posses most of these capabilities in their design metaphor and have already proved a potential for providing such capabilities in other fields e.g. e-commerce. This fact has made agents a very interesting technology for design, control and operations of the smart electric power systems – the smart grid.

This paper describes our work on how significantly increased amount of distributed generation could be exploited for the control of electric power systems. In particular, we present our work for the implementation of a dynamic service oriented system. In this system autonomous agents represent different components of low voltage distribution grid, and both offer and utilize electric power control services. We present results from several experiments on distributed and autonomous control in subgrid operation where a part of the distribution network is islanded form the utility grid. We also motivate a mechanism for situation awareness in agents. It is described why it is critical for agents to be aware of the semantics of situation before being able to request,invoke or provide control services in complex situations.

Intelligent systems and autonomous agents have been of great interest for the control of electric power systems in recent years. Jennings [1] portrays a general case for using agent in control systems. In [2] a multiagent approach has been presented for restoration of electric power distribution networks with single source of power. It motivates the use of agents at different control levels e.g. feeder agents and load agents. This approach brings the ideas of hierarchal and distributed control together. McArthur et al. [3] suggests the use of agents in a services oriented manner for development of electric power engineering applications specially in the context of a shift from energy as product to energy supply as a service. Solanki et al. [4] presents a multi agent mechanism for islanding operation of distribution systems with DGs. It suggests an under voltage load shedding schema in the electrical islands for maintenance of energy balance.

In this paper we present a fully decentralized and service oriented approach where autonomous agents represent physical electric power system components like distributed generators (DG agents), electric power loads (Load agents) and a load shedding agent (LS agents). In our approach DG agents register regulation services, and load agents register shedding services for the provision of power balance. Load shedding is performed when not enough regulation services are available to restore energy balance in the islanded subgrid. For load shedding, we adopt the idea of performing under voltage load shedding [4] because voltage drop is more severe then frequency drop in islanding scenarios of low voltage grid.

An important aspect of our approach is that both the provision of non-scheduled power from DGs for power balance, and the load shedding, is performed in a service oriented manner. DG agents choose to provide service of regulation, and load agent choose to shutdown themselves autonomously as a provision of service. This is critical for the realization of innovative architectures like microgrids and virtual power plants, where electric power components are owned by different owners with specific economic interest, and which also requires plug and play capabilities.

The present paper is organized as follows. Section II describes a dynamic model of low voltage grid which has been used in simulations. Section III describes a software platform developed for the implementation of autonomous agents and

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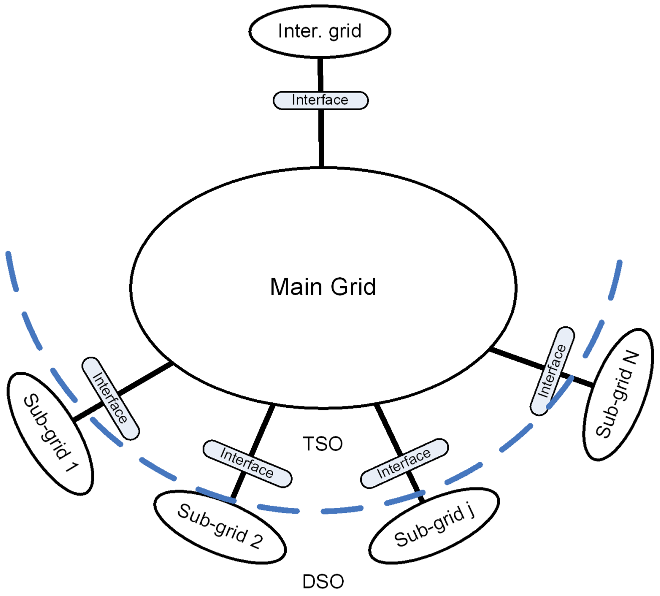

Fig. 1. Increased penetration of DGs in (Danish) electric power systems provides opportunity to control the electric power network as a subgrid based system, e.g. during islandng scenario [5], [6]

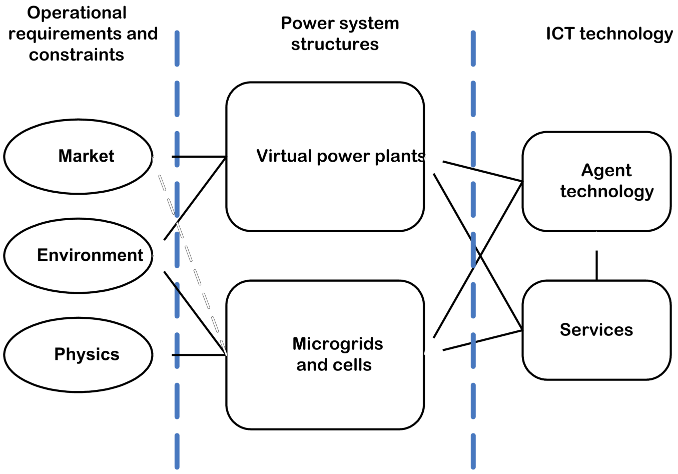

Fig. 2. Agents and service oriented technology can be used to implement intelligence and autonomy required for the realization of innovative architectures like MicroGrid and Virtual Power Plants [5], [6]

services. It also describes development of a middleware for real time communication between the software platform implemented in JAVA and dynamic simulation model developed in DigSILENT PowerFactory [1]. Section IV describes simulations and results. Section V discusses how the service oriented architecture can be used to realize control agents which are situation aware. Section VI is conclusion section.

II. NETWORK MODELING

A dynamic model of a part of the distribution grid has been modeled in DigSILENT PowerFactory for simulation and experiments purpose. Figure 3 shows a single line diagram of the model. It consists of three local DGs and four

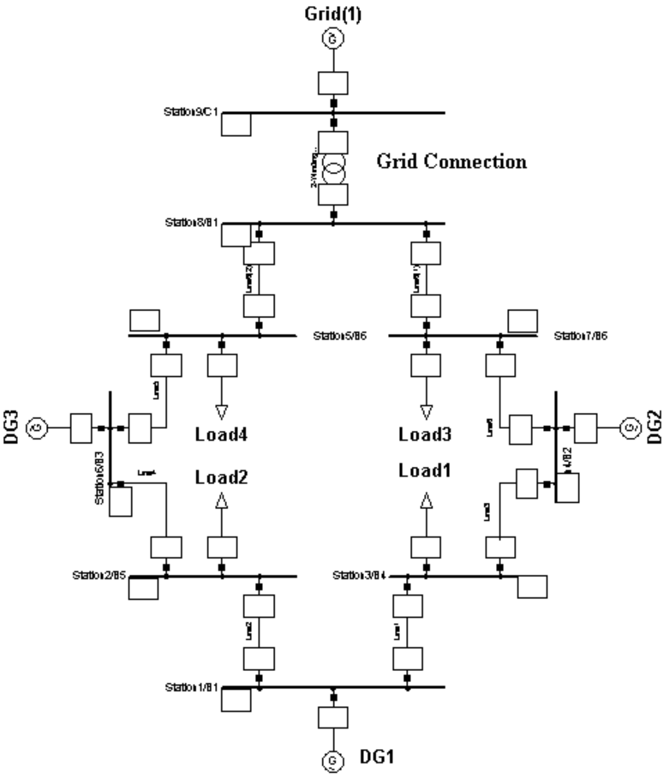

Fig. 3. Single line diagram of test model developed in DigSILENT PowerFactorey

(aggregated)loads. DGs are modeled using built-in type ”*4.9 MVA DG*” of DigSILENT PowerFactory. A connection to the utility grid has also been simulated in the model. Initially three different scenarios have been simulated based upon this network model.

III. SOFTWARE PLATFORM AND MIDDLEWARE DEVELOPMENT

A dynamic multi-agent platform has been implemented in the Java agent development framework (JADE)[2]. The platform consists of one main container, and several sub containers. Each sub container represents an island in a distribution network consisting of one load shedding agent LS and several DG and load agents. Both DG and load agents can join or leave the network dynamically according to the changes in the network. New islands can also be created following any situation in the network. The software platform also includes JADE utility agents and services. Some of the important utilities and agents are: i) DF (directory facilitator) agent which provides yellow page services. DG and load agents interact with this agent to register and discover agent services, ii) AMS(agent management services)agent which provide white page services. This agent is responsible for creating, destroying and managing agents and containers in a JADE platform, iii) MTS (message transport service) is a service responsible for message transportation between agents with in a container and across containers. This service also

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[1] DIgSILENT GmbH: http://www.digsilent.de/

[2] Java Agent Development Framework (JADE): http://jade.tilab.com/

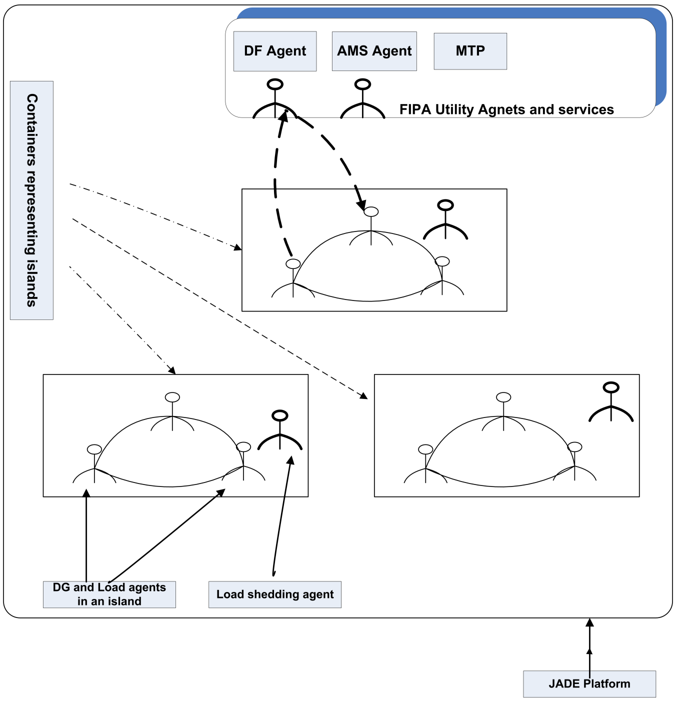

Fig. 4. Software platform developed in JADE

enables synchronization of messages when several messages are sent and received from different agents in parallel. In order to take full advantage of agent capabilities like autonomy, local control, scalability and high level communication, the software platform is implemented as fully compliant with FIPA (foundation for physical intelligent agents) standards[3]. Figure 4 shows the structure of the software platform. It presents a symbolic representation of containers which represent electrical islands in a distribution system, the agents inside these containers and the JADE utility services described above.

A. Development of middleware software for communication between JADE and DigSILENT model

Real time communication between the software platform and a dynamic simulation of physical network in "DigSILENT Power Factory" is implemented using a middleware based upon OPC (open connectivity via open standards) DA(real time data access) standard[4]. This middleware is implemented using java native interface (JNI) and fully conforms to the OPC standard. Through an OPC server, software agents can connect to respective devices in dynamic model and perform control actions during the simulations. Each agent in the software platform creates its own instance of connection and has an individual channel of control commands, which ensures that decentralized nature and robustness of the control mechanism is not compromised. Figure 5 shows structure of this middleware.

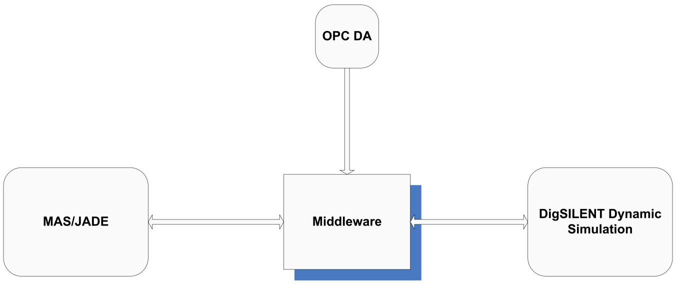

Fig. 5. Middleware development for realtime communication between dynamic simulation in Digsilent PowerFactorey and software platform

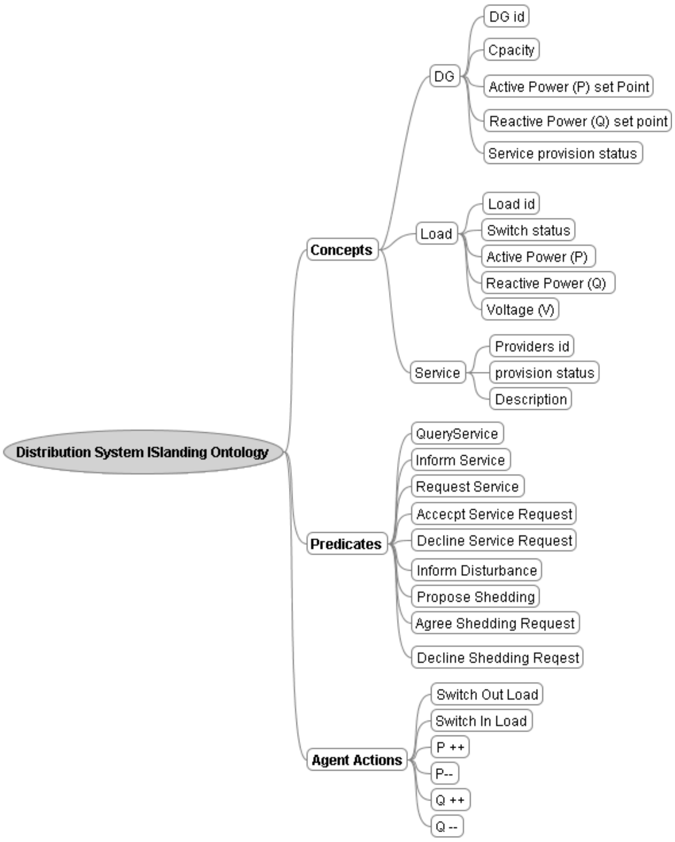

Fig. 6. Structure of ontology developed for agent knowledge realization and communication

B. Development of Ontology for agent Communication

Ontologies provide a way to structure information for several agents to understand the semantics of knowledge and to agree upon the terminologies used in communication. An ontology has been created to structure information transferred between agents. Basic components of this ontology are *concepts*, *predicates* and *agent actions*. The structure of this ontology called Distribution System Islanding Ontology is shown in figure 6. During the development of this ontology it has been made sure that it fully conforms to FIPA and W3C standards[5].

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[3] Foundation for physical Intelligent Agents (FIPA):http://www.fipa.org/

[4] OPC Foundation:http://www.opcfoundation.org/

[5] W3C - The World Wide Web Consortium :http://www.w3.org/

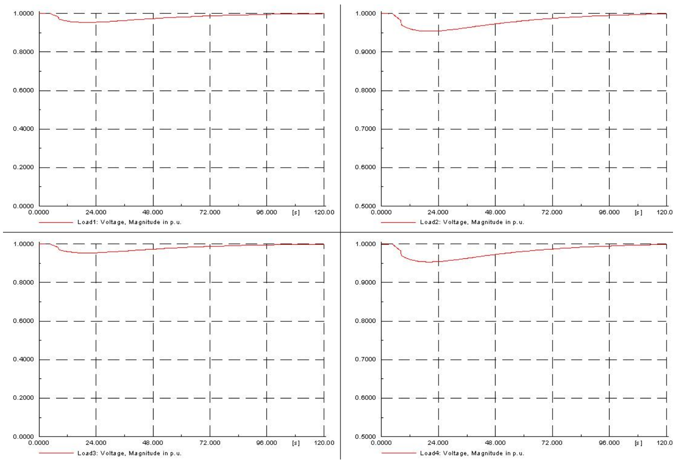


Fig. 7. Voltage response for all four loads during case I

IV. SIMULATIONS

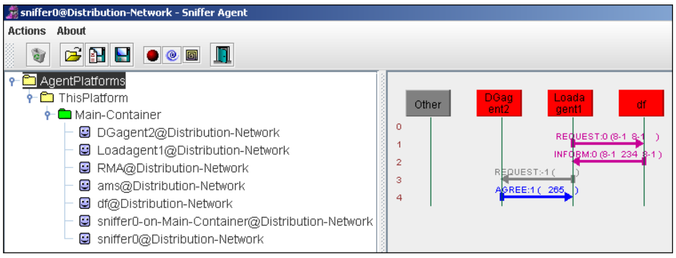
In this paper we present results from three different scenarios which have been simulated according to different patterns of service availability in the network presented in figure 3. In all three scenarios, during the simulation, a part of the distribution network is islanded due to an outage at utility grid. Initially the system have three DGs connected, four loads and a connection to utility grid. Systems is balanced and voltage at the nodes of all loads is 1 p.u. Load agents at each load are continuously monitoring voltage to response to any disturbance.

A. case I: Only one DG providing regulation service

In first scenario, only one DG (DG2 in this case) is providing regulation service. Which means that it can provide extra active power if required for balancing in the islanded part of system (the subgrid). The control flow in the system goes as follows in this scenario:

- Outage occurs at utility grid and a part of distribution network is islanded
- An amount of power coming from grid is lost which creates an imbalance in the islanded part of network
- Load agents observe voltage drop at their nodes
- Load agents contact DF agent to look for any regulation service
- DF agents informs about regulation service currently provided by the DG2 agent and provides its reference
- Load agents request the DG2 agent for provision of service
- The DG2 agent accepts this request and provides the service by increasing its active power setpoint accordingly
- Voltage is restored at nodes of all loads

Figure 7 shows voltage at loads 1 to 4 (starting from top left and moving clockwise) during the simulation. It shows an initial steady voltage of 1 p.u, a voltage drop due to outage and restoration after the provision of regulation service from DG2. Figure 8 shows communication of agents during the simulation of this case. For simplicity, only load agent1 has been shown in the communication. It can been seen that first load agent sends a ”*Request*” message to DF agent asking for the information about any available regulation service. In reply, DF agent sends an ”*Inform*” message with information about available service and provider reference of this service. Load agent then sends a ”*Request*” message to DG agent for provision of this service and DG agent replies with an ”*Accept*” message.



AgentPlatforms
ThisPlatform
Main-Container
DGagent2@Distribution-Network
Loadagent1@Distribution-Network
RMA@Distribution-Network
ams@Distribution-Network
df@Distribution-Network
sniffer0-on-Main-Container@Distribution-Network
sniffer0@Distribution-Network

REQUEST:0 (8-1 8-1)
INFORM:0 (8-1 234 8-1)
REQUEST:-1 ( )
AGREE:1 (265)

Fig. 8. Communication between agent during case I

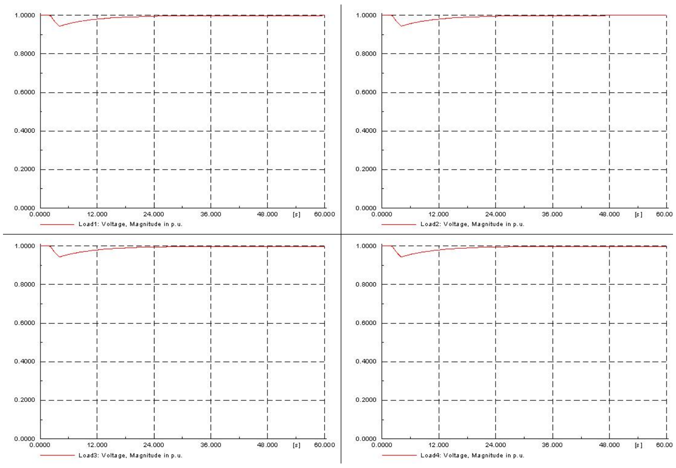
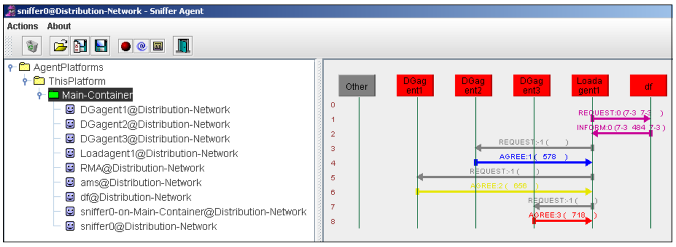


Fig. 9. Voltage response for all four loads during case II

B. Case II: All three DGs providing regulation service

In this case, all three DGs in the islanded part of distribution network are providing regulation service and subsequently accept the request from Load agent for provision of this service. Figure 9 shows the voltage response during the simulation of this case. It can be observed that voltage restoration is efficient in this case because regulation has been shared by three DGs. Figure 10 shows communication between agents during this case. It shows ”*Request*” of load agent to all three DG agents which are currently providing regulation service and a subsequent ”*Accept*” response from DGs



AgentPlatforms
ThisPlatform
Main-Container
DGagent1@Distribution-Network
DGagent2@Distribution-Network
DGagent3@Distribution-Network
Loadagent1@Distribution-Network
RMA@Distribution-Network
ams@Distribution-Network
df@Distribution-Network
sniffer0-on-Main-Container@Distribution-Network
sniffer0@Distribution-Network

REQUEST:0 (7-3 7-3)
INFORM:0 (7-3 484 7-3)
REQUEST:-1 ( )
AGREE:1 (578)
REQUEST:-1 ( )
AGREE:2 (656)
REQUEST:-1 ( )
AGREE:3 (718)

Fig. 10. Communication between agent during case II

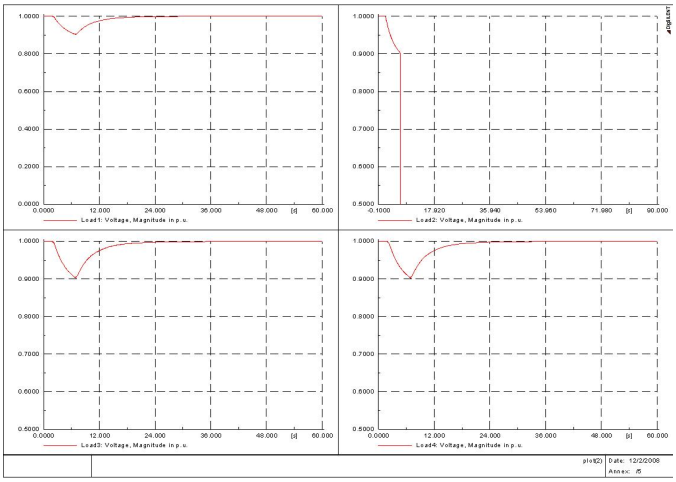


Fig. 11. Voltage response for all four loads during case III

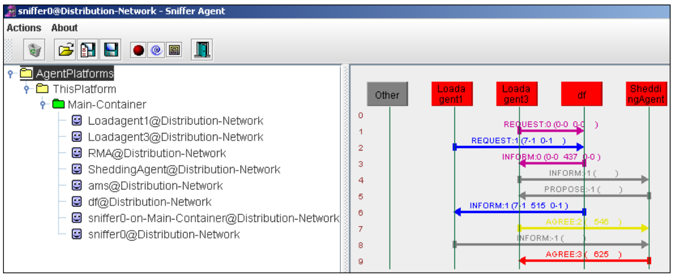


Fig. 12. Communication between agent during case III

C. *Case III: No regulation service available – Load Shedding*

This is the case where none of the DGs are providing regulation service at the time of outage when a part of distribution network is islanded from the utility grid. Load agents are informed about unavailability of any regulation service by the DF agent. Load agents inform this situation to the LoadShedding agent. LoadShedding agent proposes one of the the load agents, Load agent3 in this case, to shed itself in order to achieve balance in the island. Load agent3 agrees on this proposal and sheds itself. Voltage is restored as a result. Figure 11 shows the voltage response during simulation in this case. It shows an initial voltage drop due to outage and restoration after the load3 agent sheds itself. As a result, voltage goes down to zero at node of load3 and is restored at rest of the loads. Fig.12 shows communication between agents in this case. It can been seen that load agents send an "*Inform*" message to LoadShedding agent in order to inform it about situation of unavailability of any regulation service. LoadShedding agent then sends a "*proposal*" message to load3 agent which replies with an "*Agree*" response.

V. SITUATION AWARENESS IN AGENTS

In experiments presented in previous section and in most of the work found in literature about using agents for developing industrial control systems, agents are assumed to be situation aware i.e. they have capability to respond adequately to inputs from the physical systems and from other agents. Two problems must be addressed here:

- How to define the situation or context of an agent's control actions?
- How is the agent informed about the situation?

In the following part of this section we present our ongoing work on how to make agents situation aware particularly in the context of control of distributed power systems and with reference to the case studies presented in previous section.

A. *Defining awareness in control situations*

When an agent delivers a control service, such as provision of balancing power, the action is always a part of context or situation. The action can be part of a plan that the agent has devised in order to accomplish its own goal or it can be seen as the agent's contribution to a community of several agents cooperating to achieve a common goal. As an example we consider the situation of failure of an action i.e. when an action of the agent is failed to produce intended results. In this case, it would be desirable that the agent could:

- Reconsider the objectives of the action and the means used
- Derive possible remedial actions and predict their consequences
- Plan and execute a (new) action

The agent may not make these decisions based on local knowledge alone. It may also be necessary to consider the global situation including knowledge about the role played by the agent as member of a community of agents and the purposes and functions of the physical power system components and subsystems. By getting situation aware, a requesting agent can ensure that services it requests will solve it's problem, whereas agent delivering services can ensure that the services it is delivering are dependable and that the requestor can rely on them.

Awareness about control situations can be ensured if the agent has an internal model representing the context of its actions. Ideally, the agent should not only have a library of behaviors but should also have knowledge base representing contextual knowledge required for handling abnormal situations. Such a knowledge base representing information about the control situation in a power system can be developed using multilevel flow modeling (MFM) [7]–[9]. The advantages of MFM is the ability to choose level of abstraction in the model so that it matches the particular need or perspective of each agent and that relations between perspectives are logically defined. In this way it can be ensured that the perspectives of each agent are consistent.

Figure 13 presents three views on the control situation in the example cases, presented in previous section, using the concepts of the MFM language for modeling means-end relations in complex systems. Three views are: systems's view, the view of one of the DG agents (DG3 agent) and a load agent (Load4 agent). Views for the other generators and loads are not included for simplicity of the presentation in figure 13.

1) System's view – overall balancing: The part of the model comprising G1, F_{SCH1}, G2 and F_{SCH2} represents the view of system – the overall balancing. This is a view of regulation of grid resources. Grid resources comprises three distributed generators represented by MFM source functions So_{DG1}, So_{DG2} and So_{DG3} and four loads represented by MFM sink functions Si_{L1}, Si_{L2}, Si_{L3} and Si_{L4}. Furthermore the storage function labeled St represents the total rotating inertia in the system. The functions included in flow structure represent accordingly the resources involved in the balancing of power in the example case. The transfer of power from the generators to the loads is represented in MFM by the transport functions Tr_{DG1}, Tr_{DG2}, Tr_{DG3}, Tr_{L1}, Tr_{L2}, Tr_{L3},Tr_{L4}. Since the control strategy adopted is decentralized so this view gets realized by the individual actions of agents.

2) The view of DGs: The view of DG3 is representing how the generator agent may see the control situation. From the perspective of the system, DG3 is simply a power source So_{DG3}. But from the perspective of the generator agent, the grid is a power consumer or sink represented by Si_{DG3} and the power source feeding the generator is So^1_{DG3}. The inertia of generator DG3 is represented by an energy storage function St_{DG3}. The goal to be achieved by the generator agent is represented by G_{DG3}. The goal specifies the power to be delivered to the grid.

3) The view of L4: The view of Load4 is representing how the load agent may see the control situation. From the perspective of the system, Load4 is simply a power consumer or load Si_{L4}. But from the perspective of the load agent, the grid is a power source represented by So_{L4} and the power consumer is represented by Si^1_{L4}. Note that Si_{L4} in F_{SCH1} is not the same as Si^1_{L4} in F_{L4}. The conversion of the power in the load from the electric energy e.g. to another form of energy is represented by the conversion function Cn_{L4}.

4) Relations between the three views: The relations between the views are indicated above. However, the MFM language allows systematic expansion and aggregation of functions so that e.g. the system's view may be expanded by incorporating the views of DG3 and/or Load4. In a service oriented agent architecture, this expansion could be done either as a demand from the system or could be done by the DG3 and Load4 agents explaining how they see the situation.

In this way the MFM models can be used to realize distributed situation awareness. This concept may appear conflicting with the basic agent paradigm which assumes that the agent is autonomous and takes actions based on local information only. But in reality MFM gives only a model of the world and not complete information. An agent, by using its local information, can perform reasoning on this model in order to decide e.g. which service it requires in current situation(from the load's perspective) or how to deliver a service so that it incorporates all dependabilities (from DG's perspective). An introduction to MFM and its application to power system is discussed in detail in [10] by current authors.

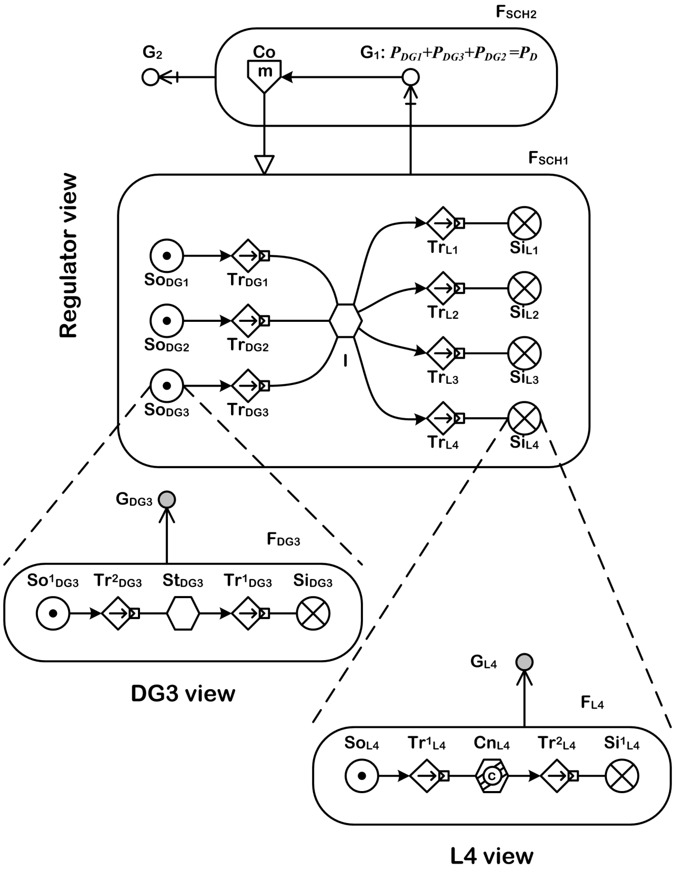


Fig. 13. Three views of the control situations

VI. Conclusions and Discussion

A dynamic software platform is developed to implement autonomous and local control of electric power systems with high penetration of DGs. A middleware software is implemented for real time communication between JAVA and DigSILENT power Factory simulation software. Results have been presented from experiments of using this system in islanding operation of the low voltage distribution grid. It has also been described that how situation awareness is critical for agents to understand and reason about their environment specially in the action failure scenarios. A mechanism has been demonstrated for bringing situation awareness in agents during control situations. The work done and the results demonstrate that a careful use of agent technology and the service oriented architecture have great potential for designing control systems for the power system with significant amount of distributed generations. Also, increased autonomy in control systems requires that autonomous components should be able to grasp and understand the semantics of emerging control situations.

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Paper III:

Saleem, A. and Lind, M. Reasoning about Control Situations in Power Systems. Intelligent System Applications to Power Systems. International Conference on Intelligent System Application in Power Systems 2009, Curitiba, Brazil

Reasoning about Control Situations in Power Systems

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***Abstract*—Introduction of distributed generation, deregulation and distribution of control has brought new challenges for electric power system operation, control and automation. Traditional power system models used in reasoning tasks such as intelligent control are highly dependent on the task purpose. Thus, a model for intelligent control must represent system features, so that information from measurements can be related to possible system states and to control actions. These general modeling requirements are well understood, but it is, in general, difficult to translate them into a model because of the lack of explicit principles for model construction. Available modeling concepts for intelligent control do not assist the model builder in the selection of model content i.e. in deciding what is relevant to represent for a particular reasoning task and thereby faced with a difficult interpretation problem. In this paper, we present our work on using explicit means-ends model based reasoning about complex control situations which results in maintaining consistent perspectives and selecting appropriate control action for goal driven agents.**

***Index Terms*—Power Systems, Intelligent Control, Multiagent Systems, Means-Ends reasoning, Situation Awareness, Control Situations**

I. INTRODUCTION

In decentralized multi-agent systems, such as de-regulated electric power systems, the world model or perspective of individual agents is based upon the goal or interest of the agent. Actions of each agent bring changes in its environment with consequences reflected in the perspective of other agents. The classic agent behaviors which are primarily based upon discrete situation-action rules may not be sufficient to cope with control situations in a dynamic environment. As an example consider the situation when a control action of the agent is failed to produce the intended result. In this case, it would be desirable that the agent could:

- Reconsider the objectives of the action and the means used
- Derive possible remedial actions and predict their consequences
- Plan and execute a (new) action

The agent may not make these decisions based on local knowledge alone and by executing behaviors based on discrete situation-action rules. It may also be necessary to consider the global situation including knowledge about the role played by the agent as member of a community of agents and the purposes and functions of the physical power system components and subsystems. Awareness about control situations can be ensured if the agent has an internal model representing the context of its actions. Ideally, the agent should not only have a library of behaviors but should also have a knowledge base representing contextual knowledge required for handling abnormal situations. Such a knowledge base representing information about the control situation in a power system can be developed using multilevel flow modeling (MFM) [10], [13], [15]. The advantage of MFM is the ability to choose level of abstraction in the model so that it matches the particular need or perspective of the agents and that relations between perspectives are logically defined. In this way it can be ensured that the perspectives of the agents are consistent and are coherent with a global perspective of the system. MFM provides concepts for semantically rich modeling of agent's context of action and mechanism to perform reasoning on this model for diagnosing and developing action plans in dynamic control situations.

A. The modeling problem

Power system models used for reasoning tasks such as intelligent control are highly dependent on the task purpose. The level of detail and abstraction of the model must comply with the needs of the task to be solved. Thus, a model for intelligent control must represent system features, so that information from power system measurements can be related to power system disturbances and possible counteractions. These general requirements to models for intelligent control are well understood, but it is in general difficult to implement the requirements into a model. The main problem is the general lack of explicit principles for model construction which take into account task requirements.

A variety of modeling concepts for intelligent control has been proposed and several types of modeling tools have been developed for representing power systems. However, these tools do not assist the modeler in solving the fundamental modeling problem which is a problem of interpretation. The model builder is not assisted in the selection of model content i.e. in deciding what is relevant to represent for a particular reasoning task and for a specific power system. The model builder is therefore faced with a difficult interpretation prob-

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lem. Within AI research this modeling challenge is referred to as the knowledge acquisition. The interpretation problem is accordingly not unique to power systems control but is a generic problem. Lind [12] discuss the modeling problem in the context of process control.

In the present paper, these interpretation problems in building models for intelligent control will be analyzed. Results of the analysis indicates that power system knowledge that can be captured in a means-end and part-whole framework.

B. Multilevel Flow Modeling

Multilevel Flow Modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [8]–[10], [13], [14], [16]. MFM has been developed to support functional modeling [15] of complex dynamic processes and combines means-end analysis with whole-part decompositions to model system functions at different levels of abstraction. System functions are represented by elementary flow functions interconnected to form flow structures representing a particular goal oriented view of the system (Figure 1). Flow structures are interconnected in a multilevel representation through means-end relations, causal relations, control functions and structures. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types [14]. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive model of the functional organization of the system represented as a hyper graph. It should be noted that MFM provides a formalized conceptual model of the system which supports qualitative reasoning about control situations [11], [23].

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [6], [17], [18], oil refineries [3], chemical engineering [20] and biochemical processes [1].

Application of MFM includes model based situation assessment and decision support for control room operators [19], hazop analysis [21], alarm design [24] and alarm filtering [7] and planning of control actions [2], [6]. MFM is supported by knowledge based tools for model building and reasoning [16]. The MFM concepts shown in Figure 1 will be demonstrated below with a simple modeling example.

1) An MFM example: Application of the MFM concepts shown in Figure 1 is illustrated in the following for the simple example shown in Figure 2 below. The example is a heat transfer system with a water circulation loop and associated support system for lubrication of the circulation pump. It should be noted that the example has been selected in order to serve the specific needs of the present paper. Thus we will only consider the functions involved in circulation of lube oil and the water and ignore the functions associated with the transfer of heat through the heat exchangers. By including the means-end relations between the mass flow and energy flow functions in the heat transfer system the models would have been more complex and representative for MFM models in general. Another aspect of MFM which of the same reason is not illustrated strongly by the example is the principal differences between physical and functional topology. The interested reader can find more complex and "interesting" examples elsewhere [1], [3], [20], [21]. An MFM model of a power system model is described below.

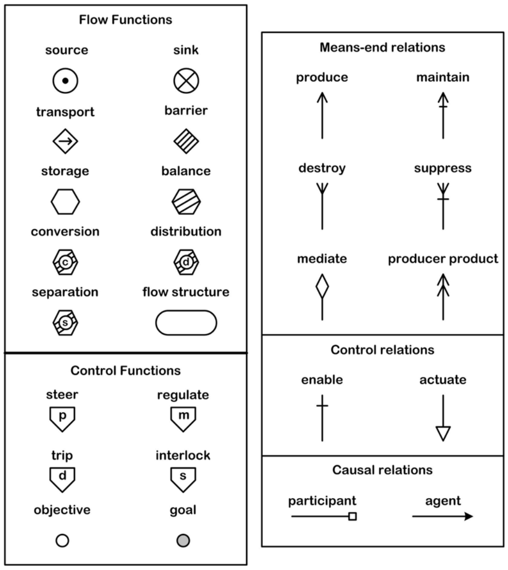

Fig. 1. MFM concepts

The water circulation loop and the lube oil system are equipped with flow measurements FM1 and FM2 and associated controllers CON1 and CON2 dealing with lube oil and water flow regulation. The purpose of the example is to demonstrate how control and process functions are integrated in the MFM models.

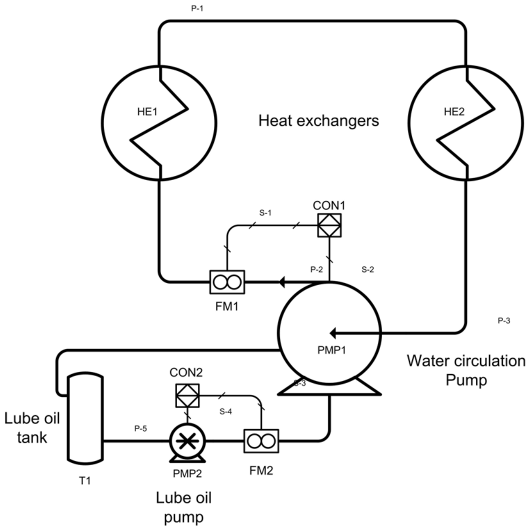

Fig. 2. The MFM model example

a) The MFM model: The model in Figure 3 represents the objectives and functions of a water circulation loop in a heat transfer system as they are represented in MFM. The example illustrates how the MFM model provides a comprehensive understanding of the purpose and functions of the circulation loop and its subsystems. On an overall level the model can be seen as composed of three sub-models representing different views on the water circulation system.

The first view (starting from the top) represents systems aspects related to water circulation and comprises the flow structure labeled MFS1, a maintain relation and the objective O1. This part of the models represents the overall objective of the water circulation, which is to maintain a flow of water. The flow structure contains the functions provided to circulate the water. In this simplified model the transport function T1 is the means used for water circulation.

The second view is partially overlapping with the first view because what is seen here as a means (the transport T1) is in the second view seen as an end. Transport T1 is related to the means of transport which is the pumping represented by the energy flow structure EFS1. T1 and EFS1 are related by a type of means-end relation called a producer-product relation in MFM. The flow structure EFS1 is decomposed into the flow functions representing the services provided by components of the pump system (including the energy supply) in order to achieve the end, the transportation of water represented by T1.

The third view is related with the second view through the energy transport T2, an enable relation and an associated objective O2 which is the end to be maintained by the functions contained in the flow structure MFS2. The flow structure MFS2 represents the functions involved in the lubrication of the pump and the objective O2 represents the condition that should be fulfilled in order to ensure that the pump is properly lubricated. A condition which should be satisfied in order to enable the pump to provide its functions. The flow functions inside MFS2 accordingly represent the functions of the pump lubrication system.

Even though the simple example does not utilize all the concepts of MFM, it demonstrates the power of MFM to represent in a clear and logical way relations between the goals and functions of a system. The MFM modeling language has a strong syntax which defines rules for combining the different entities and relations of the language into a consistent model.

The model in Figure 3 show the functions of the components and subsystem which contributed to the overall objective of the system (deliver water flow). No consideration was accordingly given to the purpose and function of control systems in meeting this objective. As is well known control systems are important for ensuring that process objectives are met in spite of uncertainty and disturbances in the process. MFM has a set of functions which can be used to represent control system functions (see Figure 1).

II. INTELLIGENT CONTROL OF POWER SYSTEMS

The overall purpose of intelligent control of power system is to detect and interpret the significance of deviations in power system states from their normal expected values and to provide an appropriate remedial action to restore normal or safe operation. Usually, several interpretations are possible of a given situation depending on the specific goal that may be dependent on the situation. Three main types of operating goals can be distinguished.

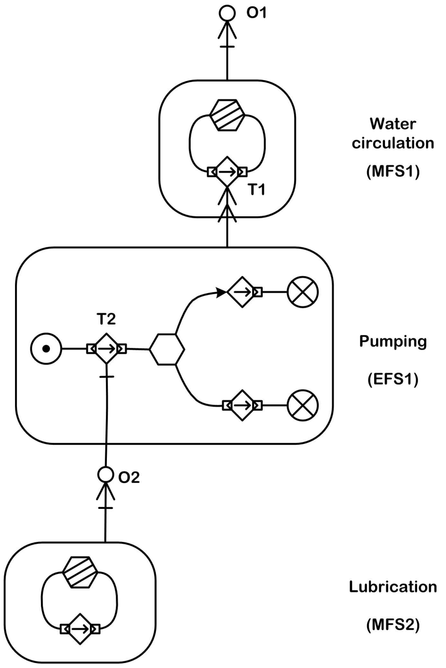

Fig. 3. The MFM model example

(1) In some situations the goal is to relate the symptoms of a power system disturbance to a possible failed component or subsystem. In this case the goal of the intelligent controller is to exchange the failed component or utilize redundancy. It is clear that such a goal would only be acceptable, if the controller is allowed to take the failed entity out of service and that there is enough time to make the repair.

(2) These conditions are not met if there are no spare parts or alternatives or if overall requirements to power system operation cannot be satisfied during the period of change. In such situations it would be necessary to find means of compensation for the disturbance that avoid the removal of the failed component.

(3) However, in situations with high risk and uncertainty it can even be a dangerous decision to compensate the disturbance. Under such circumstances the goal of the intelligent control should be to derive and evaluate possible consequences of the disturbance and to provide protective action (e.g. shut down). In this case the decision to act could be done without knowing the prime cause of the failure. Taking into account the uncertainty and the possible risks this may be the best strategy.

These examples illustrate a variety of problems that typically should be handled by an intelligent power control system. In order to satisfy these demands the control system must maintain an overview of the situation in order to choose a proper control strategy and decide how to act. Skilled human supervisors that can keep the power system running under a variety of disturbance situations, have apparently such an ability to adapt their control actions to the actual power system operating situation. This capability is difficult to model and simulate in artificial intelligence programs because of the range of situations to be considered and because of the difficulties of defining the strategies that control the interdependent concurrent reasoning processes that are required.

The modeling problem is further complicated by the fact that power system knowledge required for the intelligent control would be dependent on the overall operational goal. If the goal is to compensate for a failed component there would be a need for knowing possible redundant standby components or other means to remediate the failure. If the goal is to protect the power system operation in order to ensure reliability of supply, knowledge about means of protection would be required. The power system knowledge to be used is therefore dependent on the task to be solved, i.e. it is determined by an interpretation of the power system physical features within a task context.

A. The Power System Example

For the purpose of a study case, we take an example from a distribution network. Figure 4 shows a single line diagram of the example. It consists of three local DGs, four (aggregated) loads and a connection to the utility grid. It is assumed that both loads and DGs are controlled by smart controllers (Load and DG agents), and that there is a regulator agent, responsible for overall balancing. These agents have the capability to react to changes in environment and choose appropriate action to respond the the changes. We consider the scenario when this part of the network is disconnected form the main utility grid. The role of the regulator agent is to maintain overall power balance in this isolated part of network. The DG agents may provide regulation service by delivering extra active power. The load agents continuously monitor voltage at their nodes, and if find any disturbance, they start looking for availability of regulation services.

1) A control situation: In the following we consider a control situation in the power system as depicted in Table I and show that a representation of the power system in an MFM model can be used to represent the perspectives of the three agents and to reason or negotiate about alternative control actions for the same situation. Table I depict the goals of the regulator, load and DG agents and show that each agent has a different interpretation of the same situation depending on the goal. The table show also that there are four different ways of responding in order to control the situation.

B. MFM model of the Power System Example

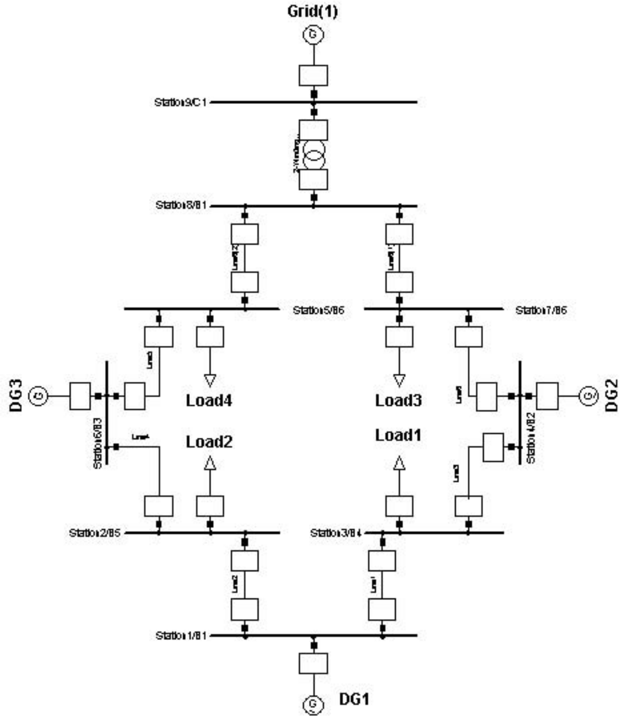

Fig. 4. The power system example

Figure 5 present a MFM model of the power system example based on the modeling principles presented above. The model contains three views of the power system: an overall systems's view, the view of one of the DG agents (DG3 agent) and a load agent (L4 agent). Views for the other generators and loads are not included for simplicity of the presentation. In the following we will describe the model and demonstrate that the model provides a coherent representation of the different views of the agents and a representation of the relations between the views which can be used for reasoning about alternative control actions. The example and the MFM model has also been discussed in [5], [22]. A detailed discussion of views and perspectives in MFM with power system examples is presented in [4].

1) System's view - overall balancing: The part of the model comprising G1, F_{SCH1}, G2 and F_{SCH2} represents the view of system - related to the task of overall balancing. This is a view of regulation of grid resources. Grid resources comprises three distributed generators represented by MFM source functions So_{DG1}, So_{DG2} and So_{DG3} and four loads represented by MFM sink functions Si_{L1}, Si_{L2}, Si_{L3} and Si_{L4}. Furthermore the storage function labeled St represents the total rotating inertia in the system. The functions included in the flow structure represent accordingly the resources involved in the balancing of power in the example case. The transfer of power from the generators to the loads is represented in MFM by the transport functions Tr_{DG1}, Tr_{DG2}, Tr_{DG3}, Tr_{L1}, Tr_{L2}, Tr_{L3},Tr_{L4}. Since the control strategy adopted is decentralized, this view gets realized by the individual actions of agents.

2) The view of DGs: The view of DG3 is representing how the generator agent sees the control situation. From the perspective of the system, DG3 is simply a power source So_{DG3}. But from the perspective of the generator agent, the grid is a power consumer or sink represented by Si_{DG3} and the

TABLE I

THE INTERPRETATION OF A POWER SYSTEM STATE AND THE CONTROL ACTION TO BE TAKEN DEPENDS ON THE AGENTS GOAL. THE SAME SITUATION OF IMBALANCE MAY THEREFORE CALL FOR DIFFERENT ACTIONŤS DEPENDING OF THE AGENT

Agent	Goal	State	Control intention
Regulator	overall balancing	load-demand imbalance	dispatch new set-points to DGs
L4 Agent (global perspective)	voltage stability at node	voltage drooped at node	look for regulation service
L4 Agent (local perspective)	consumption of required power	un-availability of required power	request more active power
DG3 Agent (global perspective)	deliver of power to network	frequency drop at node	inertia response
DG3 Agent(local perspective)	maximize production / earn profit	demand for more power from network	provide more power

power source feeding the generator is So_{DG3}. The inertia of generator DG3 is represented by an energy storage function St_{DG3}. The goal to be achieved by the generator agent is represented by G_{DG3}. The goal specifies the power to be delivered to the grid.

3) The view of L4: The view of L4 is representing how the load agent may see the control situation. From the perspective of the system, L4 is simply a power consumer or load Si_{L4}. But from the perspective of the load agent, the grid is a power source represented by So_{L4} and the power consumer is represented by Si^1_{L4}. Note that Si_{L4} in F_{SCH1} is not the same as Si^1_{L4} in F_{L4}. The conversion of the power in the load from the electric energy e.g. to another form of energy is represented by the conversion function Cn_{L4}.

4) Relations between the three views: The relations between the views are indicated above. However, the MFM language allows systematic expansion and aggregation of functions so that e.g. the system's view may be expanded by incorporating the views of DG3 and/or L4. In a service oriented agent architecture, this expansion could be done either as a demand from the system or could be done by the DG3 and L4 agents explaining how they see the situation.

C. Representing the control situations in MFM

The imbalance situation and its interpretations by the three agents presented above in table can be expressed explicitly by the MFM model in Figure 5. How this is done will be explained briefly in the following.

1) The regulator agent: The goal of the regulator agent is to ensure overall balancing. With his goal in view the agent will perceive the situation as a load-demand imbalance. The imbalance can be expressed in the flow structure F_{SCH1} as a deviation from the normal pattern of energy flows delivered by the three sources So_{DG1}, So_{DG2}, So_{DG3} and consumed by the four sinks Si_{L1},Si_{L2},Si_{L3},Si_{L4}. Within the view of the regulator agent the control action will be to restore the situation by dispatching new set points G_{DG1},G_{DG2},G_{DG3} to the DG's.

2) The agent L4: The agent Load4 has two alternative goals as shown in Table I. Depending on the goal chosen the agent will take appropriate action.

If the goal is to ensure voltage stability and the situation therefore is interpreted as a voltage droop problem, the control action of the agent is to request a regulation service. The voltage is here seen as an attribute of the source So_{L4} which represent the network as seen in the view of L4.

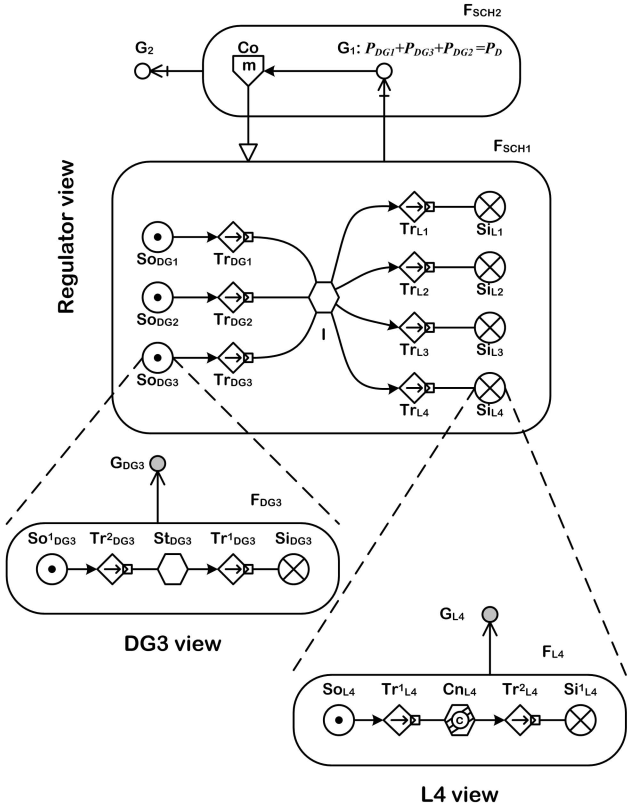

Fig. 5. The views of the regulator, generator and load agents represented in MFM

If the goal of the agent is to ensure consumption of required power and the situation therefore in this case is interpreted as a problem if unavailability of required power, the control action of the agent is to request more active power. The power is here seen as an attribute of the source.

3) The agent DG3: The agent DG3 has also two alternative goals as shown in Table I and again depending on the goal chosen the agent will take appropriate action.

If the goal is to deliver power to the network and the situation therefore is interpreted as a frequency drop problem, the control action of the agent is to execute an inertia response. The inertia is represented by the storage function St_{DG3} and the response will be a temporary increase in the power flow represented by the transport Tr_{DG3} caused by an increase in the energy stored by St_{DG3}. This causal relation is represented in the MFM model by an arrow pointing towards the transport function (the agent relation shown in Figure 1).

If the goal of the DG3 agent is to maximize production in order to earn profit and the situation therefore is seen as a demand for more power from the network, the control response will be to provide more power by increasing the flow attributed to the source So_{DG3}. The network is in this view seen as a sink Si_{DG3} and the power demanded is an attribute of this function.

III. CONCLUSIONS

Work presented in this paper presents the problem of interpretation in complex control situations of electric power systems. The importance of being able to reason explicitly about different views on a control situation is explained. It is shown that Multilevel Flow Modeling can provide model based support to explicit means-ends reasoning and handling of views. The application of explicit means-ends models provides a novel extension of the classic belief-desire-intention BDI paradigm of multiagent systems. A power system example demonstrate the importance of means-end and part-whole concepts in modeling and intelligent control of complex power systems.

IV. ACKNOWLEDGEMENT

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Paper IV:

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Multiagent based protection and control in decentralized electric power systems

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ABSTRACT

Electric power systems are going through a major change both in their physical and control structure. A large number of small and geographically dispersed power generation units (e.g., wind turbines, solar cells, plug-in electric cars) are replacing big centralized power plants. This shift has created interesting possibilities for application of intelligent systems such as multiagent systems for control and automation in electric power systems. This paper describes work on designing a multiagent system for protection and control of electric power distribution networks.It demonstrates how explicit modeling of capabilities, states, roles and role transition in agents can capture the control and automation in electric power systems. We present illustrative results from using our proposed schema in realistic simulations.

Categories and Subject Descriptors

C.3 [**Special-purpose and application-based systems**]: Process control systems, Real-time and embedded systems.

General Terms

Experimentation, Reliability, Security

Keywords

Multiagent systems, power systems control and protection, industrial application

1. INTRODUCTION

Distributed generation, decentralized and local control, self organization and autonomy are evident trends of future's electric power systems focusing on innovative control architectures like MicroGrids, Virtual Power Plants, Cell based systems, and plug-in electric vehicles. Realization of these concepts requires that power systems should be of distributed nature - consisting of autonomous components that are able to coordinate, communicate, cooperate, adapt to emerging situations and self organize in an intelligent way. Intelligent Software Agents that are autonomous software entities have most of these capabilities in their design metaphor and have already proved a potential for providing such capabilities in other fields.

In this paper we present our work in devising a multiagent system for protection and control of electric power systems with distributed generation (DG). In the attributed mechanism, intelligent agents represent different components in electric power distribution grid such as distributed generators, electric power loads and relays. The work demonstrates how explicit modeling of capabilities, states, roles, and role transition in agents can apply to the control and automation in electric power systems. We have tested our new schema for application in the specific problem of protection and control of electric power systems. The aim of such a system is to identify the fault location, isolate it from the network and restore supply of power in rest of the system. This problem is of particular interest in a changed scenario of electric power systems because it requires distributed components to communicate and cooperate with each other and perform a collective decision making. The rest of this paper is organized as follows:

Section 2 describes the problem background including how the traditional protection systems work and what challenges are brought by the introduction of DGs.

Section 3 presents our new mechanism. It presents in detail the decision models of different agents involved, formulation of the control plan and assignment of roles to specific agents.

Section 4 presents results of using the new mechanism in experiments and section 5 concludes the paper.

2. BACKGROUND

The objective of a electric power protection system is to identify and isolate faulted section of the electric power network[3]. Traditional protection in electric power systems works on the assumption that whenever a fault occurs, fault current flows from the source of power towards the fault location. This assumption holds because of the fact that flow of power has traditionally been unidirectional, i.e., from large power plants to the loads consuming this power. But with the introduction of distributed generators in low voltage grids, this assumption no more holds; and whenever there is a fault, a multidirectional fault current flows into the network, leaving the traditional protection systems not effective any more. This problem has been illustrated in figure 1. Electric power utilities have been showing great interest in development and acquisition of new mechanisms to cope with this situation.

Most common practice among utilities today is to disconnect a complete feeder containing any DGs whenever a fault occurs in it. This is primarily because of the inability to locate the exact fault location by traditional protection

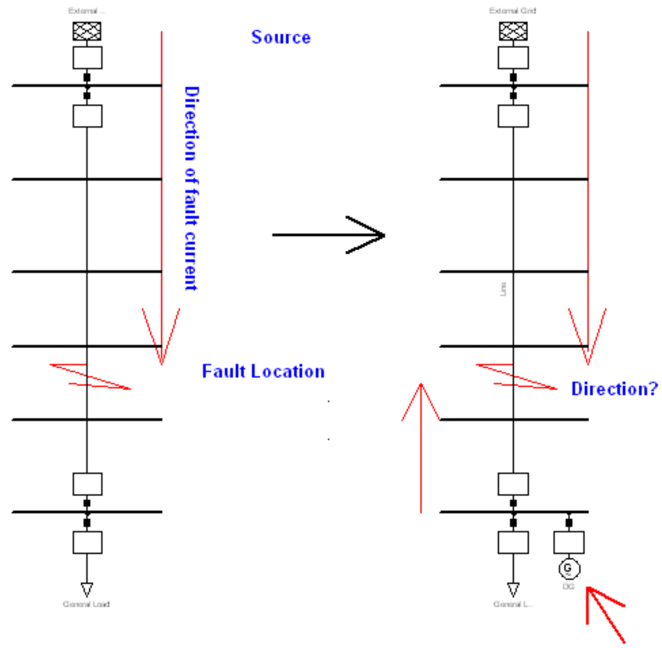

Figure 1: Problem of fault location identification in systems with DGs.

systems. But this practice is causing lost revenues both to utilities and DG owners [10, 1]. Moreover with increased penetration of DGs into electric power networks, stability of the systems itself is depending on the DGs. Hence it is not straightforward to disconnect a large number of DGs in a fault scenario. This problem is particularly important for the grids with very high penetration of DGs, e.g., the situation in Denmark [13]. Traditionally, protection and control have been two different tasks in electric power systems, but these scenarios of very high penetration of DGs also require that protection and control have to be performed together [13, 4, 6].

Current work on addressing this issue primarily falls in two categories: offline calculation based methods, e.g., [2, 7] and communication based methods, e.g., [8, 14, 11].

Offline calculation based methods try to perform large amount of offline calculations to calculate characteristics for all possible type of faults at all locations of the network. These methods are very much dependent on the structure of network as well as the nature of power generators and loads in the network. Any change in either of these two leaves the applicability of such methods very limited.

Communication based methods motivate to have communication among different components in the network for exchange of information like local current and voltage in order to identify and isolate a fault. Such methods primarily focus only on protection and do not address the requirement of integrating protection and control as mentioned earlier. Secondly these methods assumes fixed capabilities of different components, and do not suggests a mechanism for explicitly specifying capabilities of such components.

There is a general understanding in both offline calculation and communication based methods that with the introduction of DGs it is not possible to identify and isolate the exact location of fault. Rather the network has to be divided in different zones based upon the availability and placement of DGs and efforts should be made to protect these zones. Moreover, in all communication based methods it is considered that information should be exchanged to insure that direction of fault current is towards a particular zone. Our approach adopts these two general considerations.

3. PROPOSED MECHANISM

Our proposed schema consists of a number of agents. Each agent represents some of the physical elements in electric power network. The sample network used for the experiment purpose is shown in figure 2. It consists of a section of typical medium voltage (11 kv) distribution network. It includes 6 load agents (load 1-6), 5 distributed generator agents (DG 1-5, and 4 relays agents (Relay 1-4).

The network is divided into three parts (zones) based upon the availability of distributed generation. There is no distributed generation available in the first zone; the second zone has two distributed generators, whereas the third zone has three distributed generators. Corresponding relay agents are responsible for all the balancing and fault isolation tasks in their respective zones.

Table 1 describes different possible roles, states, capabilities and actions for all three kind of agents. The aim of the multiagent systems is to define a distributed mapping function from agents to roles, based upon current state and capabilities of agents.

3.1 Control plans and role assignment

Generation of a control plan and assignment of specific roles to agents are two different tasks. Accomplishment of a specific goal in a control scenario requires successful execution of a number of roles. A set of such roles defines a control plan. A transition function maps a role set i.e. a control plan to specific world situations. This mapping is done based upon domain principles [15]. In our case such domain principles are the laws of electromagnetism and control theory. Detailed description of these laws and how they determine the role sets are out of the scope of this paper.

Such transitions are defined during the design phase. The Relay agent determines best situation to control plan mapping every time there is a new situation. The decision of assigning specific roles to agents is taken dynamically through explicit communication. This is done distributedly through an auction mechanism. Whenever there is a new situation, e.g. a fault scenario in the network, the relay agent analyzes the current situation and determines a best control plan that maps to the current situation. Then the relay agent communicates with DG and Load agents for specific role assignment in chosen control plan. DG and Load agents calculate their local cost functions based upon their current state and capabilities. Based upon the value of this cost function DG and Load agents send a bid to Relay agent, and Relay agent in response assigns a role to every agent in the selected control plan.

Figure 3 shows the process of control plan determination and roles assignment. It should be noted that realization of different roles requires specific capabilities. These capabilities may be offered by one or more agents, but for simplicity, here we consider scenarios where a role is realized by capabilities offered by a single agent.

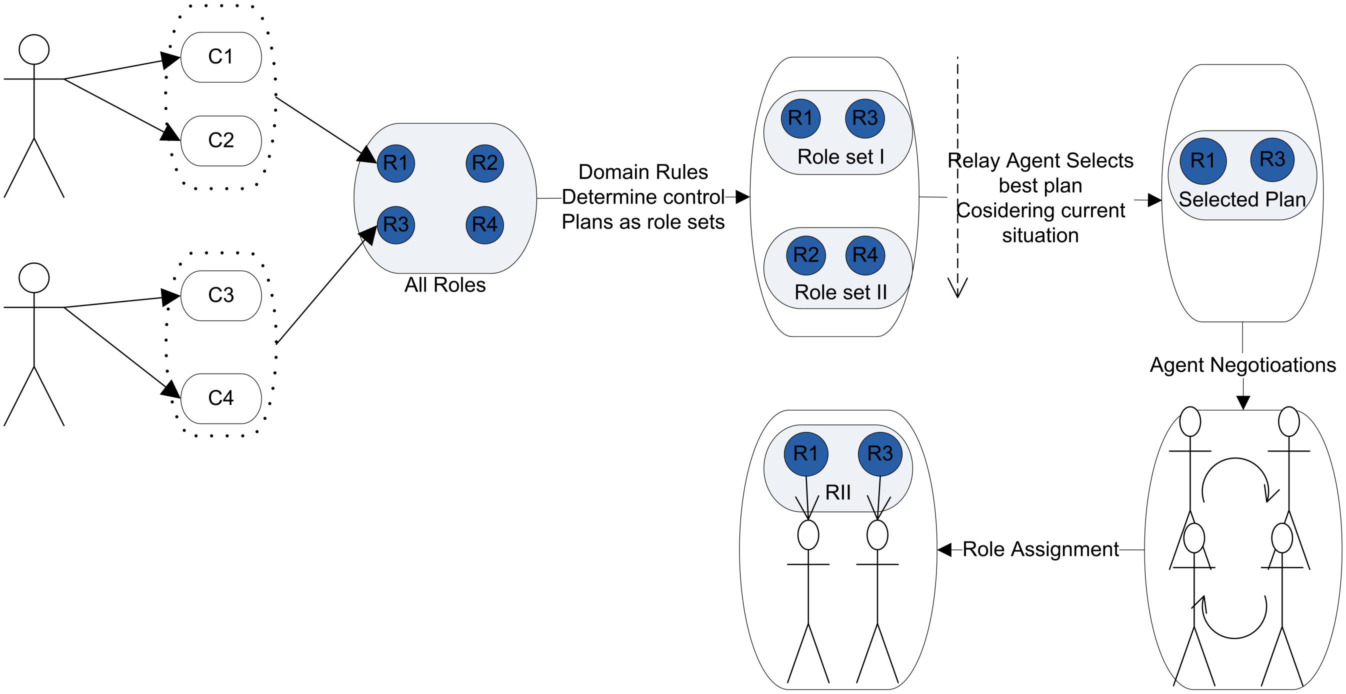

Figure 3: Control plan and role transition process in agents.

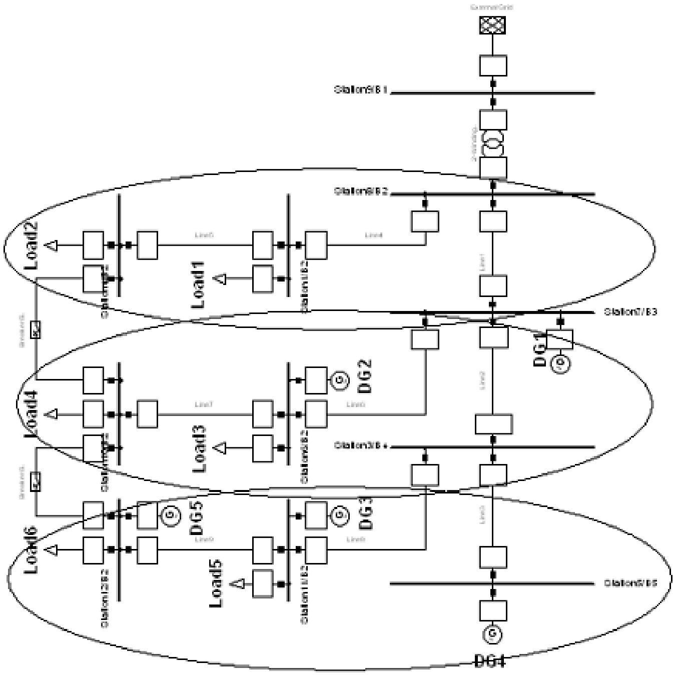

Figure 2: Example power system network used for experiment purpose.

3.2 Control Plan Transition Properties

Once role assignment is performed and the selected control plan is in execution there are a number of transition properties which trigger a change in the current control plan. Following are the list of such transition properties in our case.

3.2.1 An agent is no more present in the network

For example one of the DGs gets disconnected from network due to some fault. The role assumed by this agent has to be assigned to a some other agent in the network. This may require negotiation between agents and recalculation of their cost functions.

3.2.2 A new agent joins the network

An example of this transition property could be a new load getting connected to the network. Capabilities of this new agent might be more suitable for a specific role and may consequently require reorganization of the control plan.

3.2.3 Change in capability of one or more of the agents

For example a DG agent looses its capability to regulate the frequency of network due to some fault and consequently is no more able to perform specific role of regulator.

3.2.4 The state of one of the agents is changed

For example a DG agent goes from state of relaxed to the state of stressed due to change in its fuel level.

3.2.5 External events

An external event may also cause a trigger for change in the current control plan in execution. For example a tree falls on one of the lines in network causing a shortcircuit event. Another example of an external trigger could be a price signal in a market based scenario.

3.3 Agent Decision Models

This subsection describes the decision models of three types of agents.

3.3.1 *Relay Agent*

The relay agent has a central role in proposed schema. There is one Relay agent at the start and end of each zone in the network e.g. R2 and R3 for zone II. They continuously monitor the state of the network, identify and respond to any changes or transition triggers. Relay Agents work as zone disconnecters with responsibility to separate a zone from the network. In normal condition, there is a steady state current flowing into the network and whenever a fault occurs due to, e.g., a shortcircuit, a high current (fault current) flows into the network. The value of this fault current is significantly higher than the normal current value in steady state. The relay agent gets triggered upon observing an unusual high current value and has three main tasks:

i. Direction of fault current

In a fault scenario, current always flows form the current source to the fault location. Thus, to ensure that fault is inside the primary zone of a relay, the relay agent has to make sure that the direction of the fault current is into its primary zone at two zone connecting breakers i.e. the breakers which connect a zone to its neighboring zones, and at the DG connection breakers for all DGs inside the zone.

ii. Magnitude of fault current

The relay agent has to ensure that one of the fault current measurements either from the zone connecting breakers or from the DG connecting breakers is greater than a certain threshold. This is necessary because in case some of the loads in the zone are served from DGs outside the zone, the current flows into the zone even in normal situation when there is no fault.

iii. Role assignment

After a fault has been confirmed inside one of the zones, the job of each relay agent with the zone of its primary responsibility isolated from the main grid is to calculate energy balancing in its primary zone and assign new roles to DGs and loads inside the zone. This requires calculation of total generation and consumption of energy inside the zone and negotiation with DG and Load agents for participation in balancing. DG agents and Load agents calculate local cost functions based upon their current state and capabilities and communicate it with Relay agent. The relay agent based upon the value of cost function of each of these agents assigns them new roles. Thus, the job of Relay agent, in this case, is to determine a mapping function that takes current state and maps roles to specific agents based upon their capabilities.

$$f_{tr}(S_{cur}, T_i, CP_{ini}) \Rightarrow CP_{fn} \qquad (1)$$

Where f_{tr} is the function that takes current state S_{cur} and a transition property T_i, to map chosen control plan CP_{ini} into a final control plan $CP_{fn}$with all roles assigned to specific agents. T is the set of transition triggers described in the section 3.2. Figure 4 describes the decision model of Relay agent.

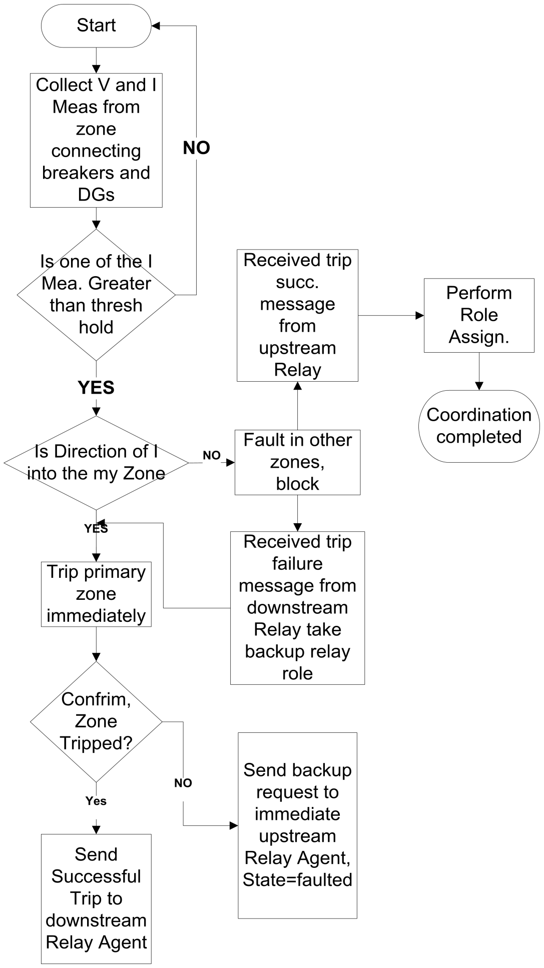

Figure 4: Relay agent decision model.

3.3.2 *DG Agent*

DG agents represent distributed power generators in electrical network. Every DG agent, on receiving message from Relay agent, calculates its cost function. The cost function of DG agent is based upon its current state e.g. relaxed/average/stressed, and its capabilities e.g. ability to control frequency. The cost function of a DG agents is defined as:

$$\delta_c(S_{cur}, C_{cur}) \Rightarrow U_{role} \qquad (2)$$

i.e., the cost function is a function that maps current state of DG agent S_{cur}, and current capabilities C_{cur} into a role utility U_{role}. DG agent sends a bid based on the value of this cost function. Relay agent cumulates bids from all DG agents and sends back a message with a new role. DG agents upon receiving this message takes up the new role and start executing actions related to this role. A flow chart for decision model of DG agents is given in figure 5.

3.3.3 *Load Agent*

Load agents represent electric power loads in the network. Load agent, on receiving message from Relay agent, calculates its cost function. The cost function of load agent is based upon its current state e.g. critical/non-critical and

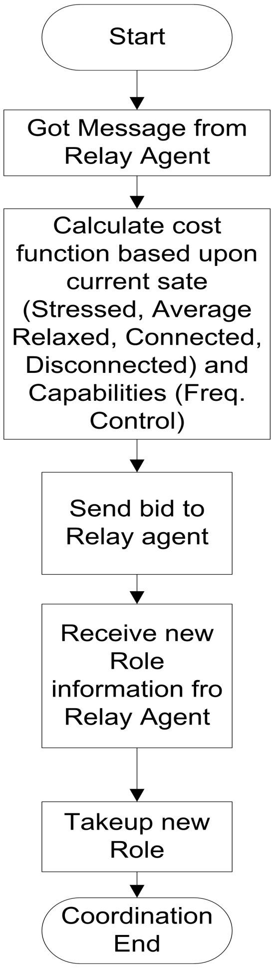

Figure 5: DG agent decision model.

the capabilities e.g. auto-shed. The cost function of load is given as:

$$\delta_c(S_{cur}, C_{cur}) \Rightarrow U_{role} \tag{3}$$

it is a function that maps current state S_{cur} and current capabilities C_{cur} of a load agent into a role utility.

After calculation of the cost function, load agent sends a bid based upon value of this cost function to Relay agent. Relay agent cumulates bids from all Load agents and sends back a message with a new role. Load agent on receiving this message takesup the new role. The decision model of load agents is same as that of DG agent with only difference of different set of capabilities and current states. Different possible states, roles, capabilities and actions for Relay, DG and Load agents are described in table 1.

3.4 Software Testbed Used

The proposed schema is tested and verified in a testbed. The testbed consists of two layers: a physical power systems layer and a software layer. The physical layer consists of a dynamic model of the electric power network. The description of this layer is in section 1 (see also figure 2). The software layer has been developed in JAVA and JADE (JAVA Agent Development Framework). It consists of several containers of agents. Each such container represents a zone in electric power network and contains a number of DG and load agents. There is also one relay agent in each zone. The detailed description of this software testbed, its capabilities and utilization in different scenarios of multiagent cooperation has been presented in [12].

Table 1: Description of agents, sates, roles and capabilities

Agents	States	Roles	Capabilities	Actions
DG	stressed average relaxed disconnected	generator regulator	produce power freq. control	P++ P- - disconnect reconnect
Relay	faulted functioning faulted-zone cleared-zon	primary facilitator neutral blocked	monitor current monitor voltage	close reclose(open)
Load	critical non-critical	connected disconnected	self-shed	(re)connect disconnect

4. EXPERIMENT AND RESULTS

We simulated a scenario when a short-circuit i.e. an external event of change occurred in zone II of the electric power network. Relay agents execute their control logic as described in figure 4. Relay Agent 2 identifies a fault in its zone and isolates the zone from rest of network. Relay Agent 3, on evaluating current situation comes up with an initial control plan, consisting of a set of roles for balancing of power and safe operation in its zone. The initial control plan selected by Relay Agent 3 consists of following roles:

CP_{ini} = {1x Primary Relay, 1x Facilitator Relay, 1x Regulator, 2x Generators, 1x Connected Load, 1x Disconnected Load}

Note that in normal condition the main grid was performing the role of regulator and all DGs had the role of generators. Now since the main grid has been disconnected from this part of network, one of the DGs has to take up the role of regulator. Also to keep generation and consumption balance after disconnection of main grid, it is necessary for one of the load agents to take the role of disconnected. Assignment of roles to specific agents has to be done by negotiation between different agents. In this case following are the available candidate agents and a set of all roles:
Agents= {DG3, DG4, DG5, Relay2, Relay3, Load4, Load5}
Roles = {Regulator, Generator, Connected Load, Disconnected Load, Primary Relay, Backup Relay}

Relay agent 3 initiates negotiation for the assignment of roles, and all agents calculates the values for their local cost functions.

4.1 Cost Function Calculation for Agents

All agents participating in negotiation process calculates

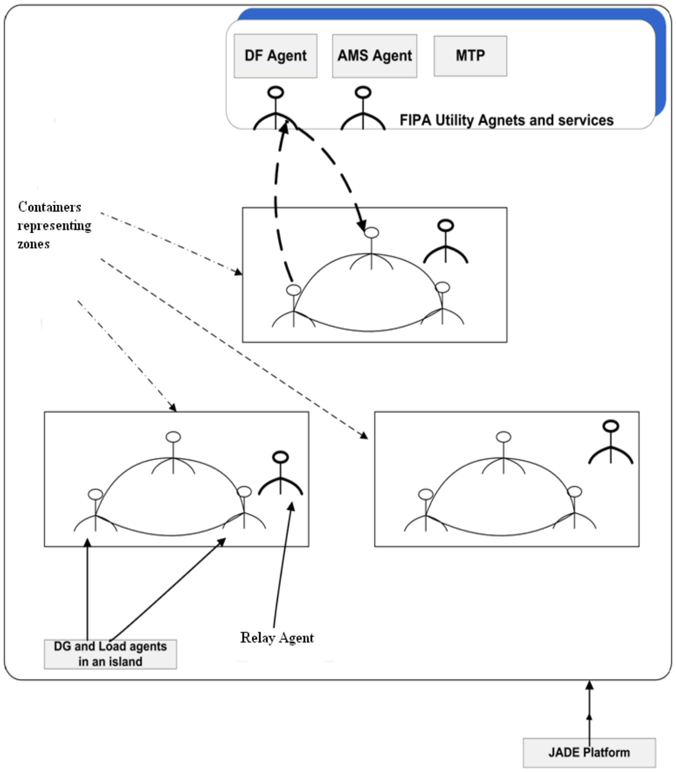

Figure 6: Software test bed used for experiments.

cost functions to calculate utility of specific roles. In our case all agents in a zone calculate cost function only for their own utilities and based upon this value sends a bid to Relay agent. This is different from some approaches e.g. [9] where all agents calculate cost functions for all other agents. In such approaches firstly, there is a great burden of processing power and time. Secondly a full visibility of every agent for all other agents is assumed, which may not be practical in all scenarios, especially in our case of electric power systems where different agents are geographically dispersed.

4.1.1 Cost Function Calculation for DG Agents

DG agents calculate cost function for the utility of roles regulator and generator. DG3 agent is in the state of stressed at the time of fault occurrence and it has the capability of frequency control. Using its cost function described in section 3, the utility value is calculated as 10 for the role of generator and 5 for that of regulator. Table 2 summarizes cost function calculation for all DG agents.

4.1.2 Cost Function Calculation for Load Agents

Load agent calculates cost function for the utility of roles connected and disconnected loads. Load 5 currently is in the state of non-critical and has the capability of self-shed. The cost function calculation results in the utility value of 5 for the role connected and 8 for disconnected. Cost function calculation for both load 4 and load 5 is summarized in table 3.

4.1.3 Cost Function Calculation for Relay Agents

Relay agents calculates cost functions for the utility of roles primary, and facilitator. Relay2 agent is currently in the state of faulted-zone. This means that the fault is within its primary zone of responsibility. Moreover it is functioning and have the capabilities of monitoring voltage and monitoring current. Based upon this information it calculates the utility of 10 for the role of primary relay and 5 for facilitator relay.

Table 2: Cost function calculation for DG agents

Agents	Current state	Current capabilities	Cost function calculation: $\delta_c(S_{cur}, C_{cur}) \Rightarrow U_{role}$
DG3	stressed	freq. control = yes	$U_{role} = (Generator) = 10$ $U_{role} = (Regulator) = 5$
DG4	average	freq. control = no	$U_{role} = (Generator) = 15$ $U_{role} = (Regulator) = 0$
DG5	relaxed	freq. control = yes	$U_{role} = (Generator) = 15$ $U_{role} = (Regulator) = 15$

Table 3: Cost function calculation for Load agents

Agents	Current state	Current capabilities	Cost function calculation: $\delta_c(S_{cur}, C_{cur}) \Rightarrow U_{role}$
Load4	critical	self-shed = yes	$U_{role} = (connected) = 10$ $U_{role} = (disconnected) = 5$
Load5	non-critical	self-shed = yes	$U_{role} = (connected) = 5$ $U_{role} = (disconnected) = 8$

4.2 Final Role Assignment

Relay agent cumulated all received bids and made an assignment of roles to specific agents. In this case following was the final role assignment:

CP_{fn} = {Primary Relay = Relay Agent 2, Facilitator Relay = Relay Agent3, Regulator = DG5 Agent, Generator = DG3 and DG4, Connected Load = Load4 Agent, Disconnected Load = Load5 Agent}

4.3 Communication Robustness

If communication fails at any point and Relay agent does not hear back from any of DG or Load agents, the state of Relay changes from functioning to faulted and the value of the cost function is changed. As a result the current relay takes up the role of blocked whereas the next upstream agent takes the role of backup relay. In a worst case of all the relays in feeder going faulted, the whole feeder will be tripped. Current common practice in distribution system protection is tripping a complete feeder with DGs whenever there is a fault. It means that in the worst case of communication failure in whole feeder, our proposed approach will work as good as current common practice.

5. CONCLUSIONS

In this paper we have shown the applicability of multi-agent systems for control and protection in decentralized electric power systems.

Recent changes in structure and control of electric power systems has made it a complex system consisting of distributed components interacting with each other. Explicit modeling of capabilities, states, roles and actions have shown promising results to address these challenges.

We have applied the proposed multiagent system in the specific case of protection and control for which electric power industry is actively seeking new solutions. The experiments showed that it was possible to identify the zone with fault, isolate it from network and most importantly to perform a simple yet non-trivial role transition in agents in order to maintain balance in rest of the systems.

Traditionally, the protection systems in electric power industry have utilized very little communication. This is one reason that the industry is very careful while adopting new solutions based upon communication. We have therefore provided a mechanism which is robust to communication failure. In the worst case of total communication failure the result will be as good as that of from current common practice.

6. FUTURE WORK

After having promising results in simulations, the proposed systems is to be tested at SYSLAB of Denmark's Risø national labpratory. This laboratory has small scale but real electric power grid for test and experiments purposes [5].

7. ACKNOWLEDGMENT

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Paper V:

Saleem, A. and Lind, M. Knowledge based support for multiagent control and automation. Submitted to Cigre International Symposium on Electric Power Systems of the Future, Integrating Supergrids and Microgrids. Bologna, Italay, 2011

Knowledge based support for Multiagent Control and Automation

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***Abstract*—This paper presents a mechanism for developing knowledge based support in multiagent based control and diagnosis. In particular it presents a way for autonomous agents to utilize a qualitative means-ends based model for reasoning about control situations. The proposed mechanism have been used in different scenarios of electric power distribution system protection and control. Results show that agents can use local models of their environment and coordinate with other agents to analyze and understand a disturbance situation and choose an appropriate control action. The paper also introduces Multi Level Flow Modeling (MFM) which has been used to model agent environment and describes development of multiagent implementation of MFM Workbench.**

***Index Terms*—Power Systems, Intelligent Control, Multiagent Systems, Means-Ends reasoning, Situation Awareness, Control Situations**

I. INTRODUCTION

Today's industrial control and automation systems are of increasing level of complexity both in their structure and operation. Electric power systems is one such system where deregulation, high penetration of distributed generation and introduction of heterogeneous energy sources have brought several new challenges.

Deregulation primarily aims at providing a competitive market based environment for availability of energy at a reduced price. It eliminates monopolies and allow participation of several participants in energy production and distribution. Introduction of several participants and resulting economic implications have caused complex power flows as well increased number of interconnections [8].

Distributed energy resources (DGs) are small, modular electric energy generation or storage systems located relatively close to the customer. Example of distributed generation include wind turbines, photovoltaics, micro combined heat and power plants, fuel cells etc. In several countries of the world, including Denmark, a large amount of DG have replaced large central power plants. The intermittent nature of some of the DGs (e.g., wind turbines and photovoltaics) have brought challenges to control and in particular balancing of the system. In the same way the heterogeneous nature of energy sources means that each of them has a specific dynamic behavior and a resulting impact on the system.

In response to these challenges efforts are underway to redesign the current electric power system into a modular, flexible and intelligent system i.e., the smart grid. Application of information and communication technologies is one of the tool to achieve this goal. Multiagent Systems is one such technology that have attracted a lot of interest for application in control of electric power systems and have produced promising result [20], [21]. At the same time several challenges remain to achieve the full potential of the intelligent agent technology. These challenges have been reported and partially addressed in previous work of current authors [28], [29], [31].

In decentralized multi-agent systems, such as de-regulated electric power systems, the world model or perspective of individual agents is based upon the goal or interest of the agent. Actions of each agent bring changes in its environment with consequences reflected in the perspective of other agents. The classic agent behaviors which are primarily based upon discrete situation-action rules may not be sufficient to cope with control situations in a dynamic environment and the agent may not make these decisions based on local knowledge alone (the situation). The action can be part of a plan that the agent has devised in order to accomplish its own goal or it can be seen as the agent's contribution to a community of several agents cooperating to achieve a common goal.

It is also necessary to consider the global situation including knowledge about the role played by the agent as member of a community of agents and the purposes and functions of the physical power system components and subsystems. Awareness about control situations can be ensured if the agent has an internal model representing the context of its actions. Ideally, the agent should not only have a library of behaviors but should also have knowledge base representing contextual knowledge required for handling abnormal situations.

In this paper we build on our previous work and demonstrate the applicability of knowledge based qualitative modeling for situation awareness of agent and assistance in control action selection in a practical scenarios of electric power distribution systems protection. The rest of this paper is organized as follows:

Section II introduces MFM and explains its concepts with the help of an example. Section III describes concepts of intelligent agent technology and its application in electric power systems. Sections IV describes problem of protection in electric power distribution networks. Section V explains our modeling methods and presents its applicability in a case study. Section VI conclude the paper.

II. MULTILEVEL FLOW MODELING

Multilevel Flow Modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [11]–[13], [15], [16], [18]. MFM has been developed to support functional modeling [17] of complex dynamic processes and combines means-end analysis with whole-part decompositions to model system functions at different levels of abstraction. System functions are represented by elementary flow functions interconnected to form flow structures representing a particular goal oriented view of the system (Figure 1). Flow structures are interconnected in a multilevel representation through means-end relations, causal relations, control functions and structures. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types [16]. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive model of the functional organization of the system represented as a hyper graph. It should be noted that MFM provides a formalized conceptual model of the system which supports qualitative reasoning about control situations [14], [32].

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [9], [19], [23], oil refineries [5], chemical engineering [25] and biochemical processes [3].

Application of MFM includes model based situation assessment and decision support for control room operators [24], hazop analysis [27], alarm design [34] and alarm filtering [10] and planning of control actions [4], [9]. MFM is supported by knowledge based tools for model building and reasoning [17]. The MFM concepts shown in Figure 1 will be demonstrated below with a simple modeling example.

A. An MFM example

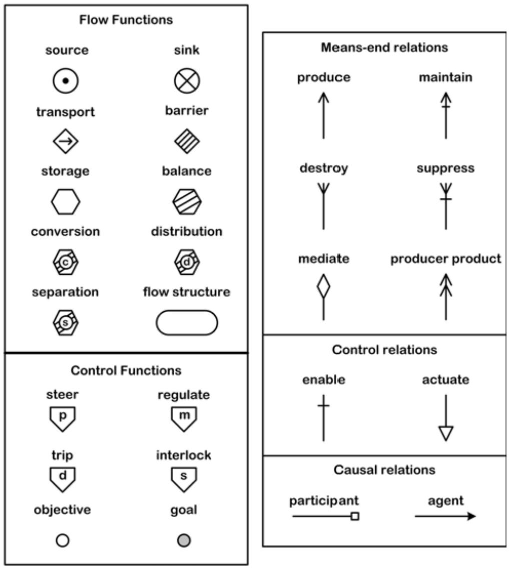

Fig. 1. MFM concepts

Application of the MFM concepts shown in Figure 1 is illustrated in the following for the simple example shown in Figure 2 below. The example is a heat transfer system with a water circulation loop and associated support system for lubrication of the circulation pump. It should be noted that the example has been selected in order to serve the specific needs of the present paper. Thus we will only consider the functions involved in circulation of lube oil and the water and ignore the functions associated with the transfer of heat through the heat exchangers. By including the means-end relations between the mass flow and energy flow functions in the heat transfer system the models would have been more complex and representative for MFM models in general. Another aspect of MFM which of the same reason is not illustrated strongly by the example is the principal differences between physical and functional topology. The interested reader can find more complex and "interesting" examples elsewhere [3], [5], [25], [27]. An MFM model of a power system model is described below.

The water circulation loop and the lube oil system are equipped with flow measurements FM1 and FM2 and associated controllers CON1 and CON2 dealing with lube oil and water flow regulation. The purpose of the example is to demonstrate how control and process functions are integrated in the MFM models.

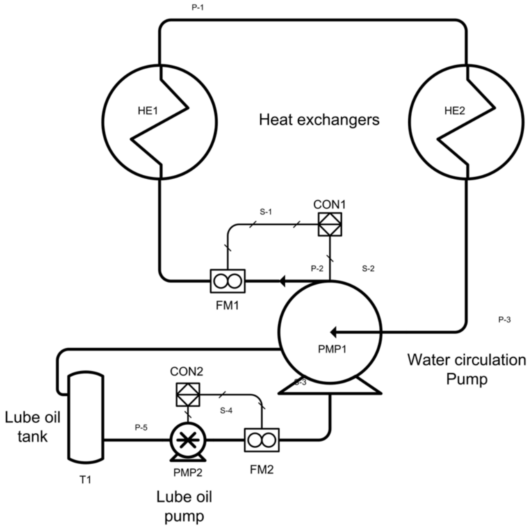

Fig. 2. The MFM model example

a) The MFM model: The model in Figure 3 represents the objectives and functions of a water circulation loop in a heat transfer system as they are represented in MFM. The example illustrates how the MFM model provides a comprehensive understanding of the purpose and functions of the circulation loop and its subsystems. On an overall level the model can be seen as composed of three sub-models representing different views on the water circulation system.

The first view (starting from the top) represents systems aspects related to water circulation and comprises the flow structure labeled MFS1, a maintain relation and the objective O1. This part of the models represents the overall objective of the water circulation, which is to maintain a flow of water. The flow structure contains the functions provided to circulate the water. In this simplified model the transport function T1 is the means used for water circulation.

The second view is partially overlapping with the first view because what is seen here as a means (the transport T1) is in the second view seen as an end. Transport T1 is related to the means of transport which is the pumping represented by the energy flow structure EFS1. T1 and EFS1 are related by a type of means-end relation called a producer-product relation in MFM. The flow structure EFS1 is decomposed into the flow functions representing the services provided by components of the pump system (including the energy supply) in order to achieve the end, the transportation of water represented by T1.

The third view is related with the second view through the energy transport T2, an enable relation and an associated objective O2 which is the end to be maintained by the functions contained in the flow structure MFS2. The flow structure MFS2 represents the functions involved in the lubrication of the pump and the objective O2 represents the condition that should be fulfilled in order to ensure that the pump is properly lubricated. A condition which should be satisfied in order to enable the pump to provide its functions. The flow functions inside MFS2 accordingly represent the functions of the pump lubrication system.

Even though the simple example does not utilize all the concepts of MFM, it demonstrates the power of MFM to represent in a clear and logical way relations between the goals and functions of a system. The MFM modeling language has a strong syntax which defines rules for combining the different entities and relations of the language into a consistent model.

The model in Figure 3 show the functions of the components and subsystem which contributed to the overall objective of the system (deliver water flow). No consideration was accordingly given to the purpose and function of control systems in meeting this objective. As is well known control systems are important for ensuring that process objectives are met in spite of uncertainty and disturbances in the process. MFM has a set of functions which can be used to represent control system functions (see Figure 1).

III. AGENT BASED INTELLIGENT CONTROL OF POWER SYSTEMS

An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives [36].

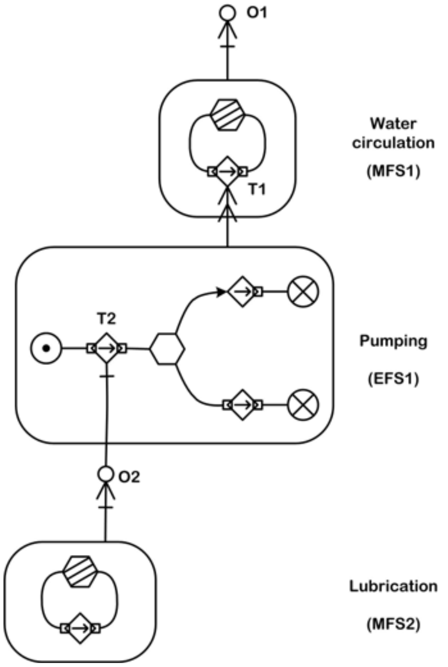

Fig. 3. The MFM model example

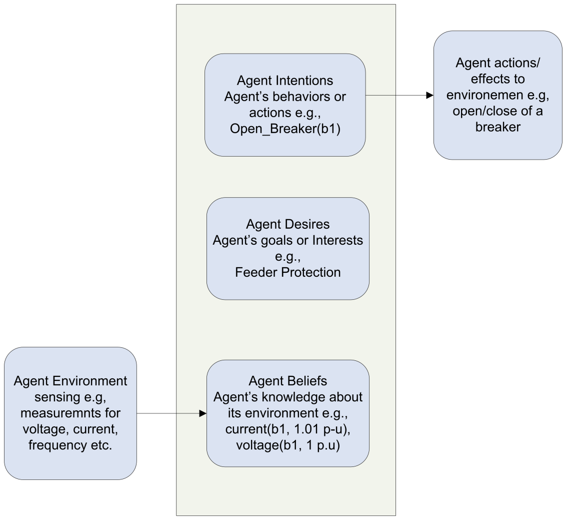

Fig. 4. Belief Desire Intention BDI based abstract agent architecture

Agents are defined by a metaphore commonly known as BDI (Belief, Desire, Intention). The beliefs represent knowledge of an agent about its environment. The *Beliefs* are captured through sensors of the agent and stored in an internal data base. This data base (also commonly called knowledge base) should be properly organized, updated and synchronized to other functions, e.g., decision making of the agent architecture. Usage of rule based systems [22] and ontologies [2] are used for this purpose. The *Desires* are goals or *design objectives* of an agent. Desires not only sets the criteria for rationality of an agent but also defines the nature and level of autonomy for agents. *Intentions* is the way agents attempt to achieve their goals. In agent oriented software engineering intentions are modeled as *behaviors*. A behavior of an agent may consists of a single or multiple *actions* and lead to a achievement of a goal or a sub goal. Figure 4 describes the BDI model with an example and explains what beliefs, desires and intention could be in a practical scenario.

Multiagent systems (MAS) are systems consisting of more than than one agent. MAS are useful to implement in application areas that are naturally distributed, decentralized and are easy to be decomposed in their design. A system architecture based upon MAS provides a natural way of decomposing a software system into subsystems and to model interactions between these subsystems and individual components (agents) within the subsystems.

A. *Agent application view in electric power systems control*

In electric power systems control, agents can be applied at different levels of control. Starting from a low level control of device agents it goes to higher level of coordination and planning. The agents at the *device layer* interact directly with devices at physical system layer. Agent behaviors implement control functions of a device e.g., a generator agent control active and reactive power set points of a generator and breaker agent would perform functions of opening and closing a breaker. The agents at the *control coordination level* usually do not directly interact with physical electric power system devices, instead they communicate with agents at lower level of control i.e, devices level agents facilitate coordination and higher level operations such as planning.

IV. PROBLEM OF PROTECTION IN DECENTRALIZED ELECTRIC POWER SYSTEMS

The objective of a electric power protection system is to identify and isolate faulted section of the electric power network. Traditional protection in electric power systems works on the assumption that whenever a fault occurs, fault current flows from the source of power towards the fault location. This assumption holds because of the fact that flow of power has traditionally been unidirectional, i.e., from large power plants to the loads consuming this power. But with the introduction of distributed generators in low voltage grids, this assumption no more holds; and whenever there is a fault, a multidirectional fault current flows into the network, leaving the traditional protection systems not effective any more. This problem is illustrated in figure 5. Electric power utilities have been showing great interest in development and acquisition of new mechanisms to cope with this situation.

Several solutions have been suggested for application to this problem ranging from offline analysis based mechanisms [1], [6] to the ones that utilize communication based techniques [7], [26], [37]. Challenges faced to current systems and suggestions for improvements have been given in [33].

V. MODELING FOR INTELLIGENT CONTROL

A. *Software Platform*

This section describes the development of software platform for the purpose of agent based modeling and diagnostic control. A comprehensive approach has been taken for this purpose. Figure 6 presents the different components of software platform. The modeling component utilizes human expert knowledge from specific domains and facilitates with development of qualitative models based on goals and objectives of a systems. The models developed here are implemented in the multiagent software platform where different agents can utilize this model and can reason about different control situation. More on modeling will be explained in next subsection.

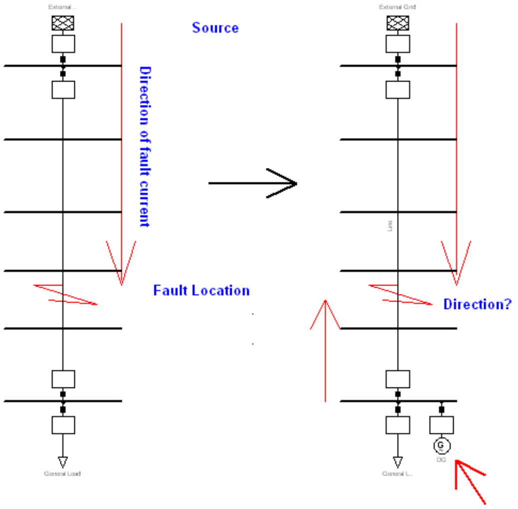

Fig. 5. Problem of fault location identification in systems with DGs.

The multiagent software platform has been implemented in the Java agent development framework (JADE)[1]. The platform consists of one main container, and several sub containers. Each sub container represents an aggregation of relevant agents. The agent in a container can join or leave dynamically according to the changes in the environment. New containers can also be created following any changed situation. The software platform also includes some utility and service agents. Detailed description of this specifications of utility agents has been given in [30].

An agent in the software platfrom embodies an instance of a reasoning engine and utilizes it in order to perform reasoning and diagnosis.

Real time communication between the software platform and a some representation of the physical environment is implemented using a middleware based upon OPC (open connectivity via open standards) DA(real time data access) standard[2]. This middleware is implemented using a java native interface (JNI) and fully conforms to the OPC standard. Through an OPC server, software agents can connect to respective devices in the physical environment and perform control actions during the simulations. Each agent in the software platform creates its own instance of connection and has an individual channel of control commands, which ensures that decentralized nature and robustness of the control

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[1] Java Agent Development Framework (JADE): http://jade.tilab.com/

[2] OPC Foundation:http://www.opcfoundation.org/

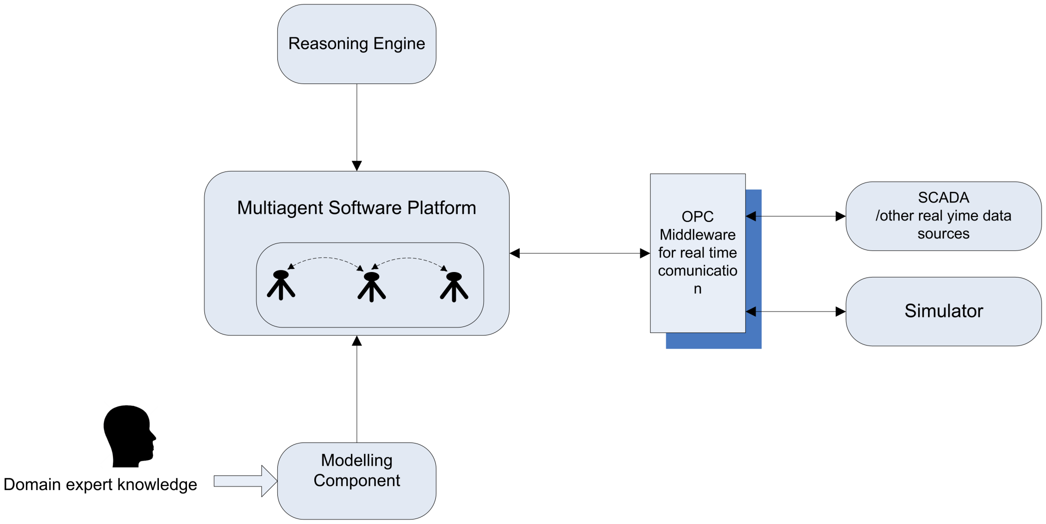

Fig. 6. Multuagent based software platfrom

mechanism is not compromised.

There are several options for representation of the physical world. For the results presented in the current paper, a dynamic simulation model of a distribution systems network was developed in DigSILENT PowerFactory [3]. Alternatives include online connectivity to a SCADA systems or to some process plant.

B. Modeling of Distribution System Feeder

The overall purpose of intelligent control of power system is to detect and interpret the significance of deviations in power system states from their normal expected values and to provide an appropriate remedial action to restore normal or safe operation. Usually, several interpretations are possible of a given situation depending on the specific goal that may be dependent on the situation. The advantages of MFM based modeling is the ability to choose level of abstraction in the model so that it matches the particular need or perspective of each agent and that relations between perspectives are logically defined. In this way it can be ensured that the perspectives of each agent are consistent. In this section we show how the concept of MFM is applied for modeling different components if electric power distribution network.

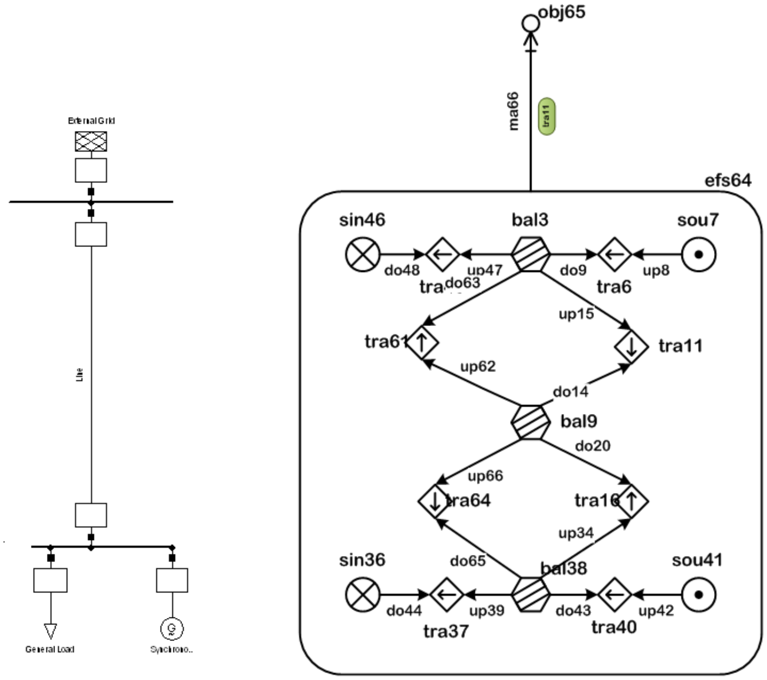

Fig. 7. Modeling of a simple network

Figure 7 shows a simple example of such modeling where a simple electric power network (left side of the figure) is modeled using MFM (right side of the figure). In this example external grid is modeled with MFM function of energy *source* and *sink* (sou7 and sin46 respectively), two bus bars are modeled as *balances* (bal3 and bal38), the load as a *sink* (sin36), the generator as a *source* (sou41). The transmission line is modeled as *transport* function. Note that for a possible two way transportation of power (or current) one transmission line is modeled with two transport functions of MFM each representing one of upstream and downstream flow of power (current). Moreover, a balance function has been used to join the upstream and downstream flows. The direction of flow in a specific situation is determined by using values of current and voltage at two sides of a line. These values are transmitted from the simulator (or e.g., SCADA) through the middleware layer. The goal of this small system is modeled with an

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[3] DIgSILENT GmbH: http://www.digsilent.de/

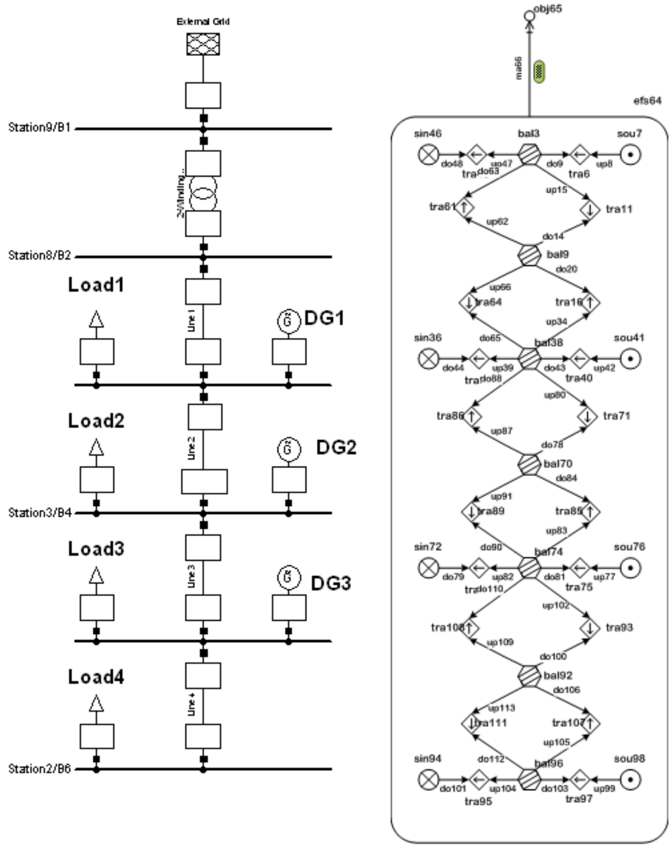
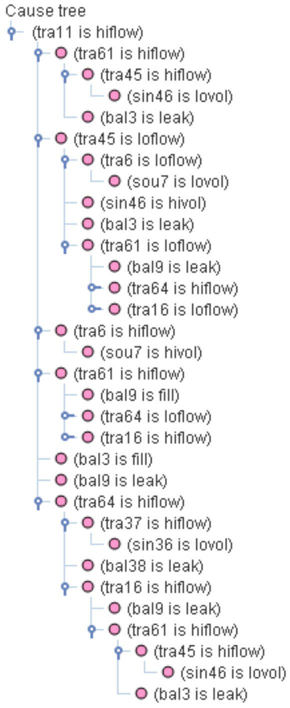


Fig. 8. Modeling of a distribution feeder



Cause tree

- (tra11 is hiflow)
  - (tra61 is hiflow)
    - (tra45 is hiflow)
      - (sin46 is lovol)
    - (bal3 is leak)
  - (tra45 is loflow)
    - (tra6 is loflow)
      - (sou7 is lovol)
    - (sin46 is hivol)
    - (bal3 is leak)
    - (tra61 is loflow)
      - (bal9 is leak)
      - (tra64 is hiflow)
      - (tra16 is loflow)
  - (tra6 is hiflow)
    - (sou7 is hivol)
  - (tra61 is hiflow)
    - (bal9 is fill)
    - (tra64 is loflow)
    - (tra16 is hiflow)
  - (bal3 is fill)
  - (bal9 is leak)
  - (tra64 is hiflow)
    - (tra37 is hiflow)
      - (sin36 is lovol)
    - (bal38 is leak)
    - (tra16 is hiflow)
      - (bal9 is leak)
      - (tra61 is hiflow)
        - (tra45 is hiflow)
          - (sin46 is lovol)
        - (bal3 is leak)

Fig. 9. Cause tree generated after simulation of fault in the network

objective function (obj65). Section II of this paper should be consulted for understanding of the basic MFM functions.

Figure 8 presents modeling of small distribution feeder (MV, 11kv) with three distributed generators (4.9 MVA each), four loads (1.5 MW each) and connection to the utility grid. Modeling of this systems in MFM has been done on the same principles described for modeling of a small example previously. Note that a detailed dynamic model of the network is developed in Digsilent Power Factory (left side of the figure 8) and is used as representation of the physical environment. This model provides measurements for agents in order to perform reasoning using the MFM model (right side of the figure 8). A discussion on why the problem of protection is not trivial and can not be managed by traditional methods have been given in [35].

C. Support in decision making and analysis of reasoning paths

Experiments were performed to evaluate applicability of the proposed modeling method on the presented network. In this paper we discuss how agents can utilize models based upon means and ends and perform reasoning to select control actions. Relevant discussions of problem of protection in distribution systems and has been given in [33] and a general discussion on the problem of situation interpretation and control action selection in multiagent systems is given in [30] by the current authors.

A short circuit fault was simulated in at line 2 (corresponding to tra37 of MFM model) of the simulated distribution feeder. As a result a bidirectional fault current flows in the network. The control agent (such as generator agents and load agents) update measurement from the network simulation and utilize it in the MFM model in order to perform reasoning about this situation. Figure 9 shows a cause tree generated as a result. It is showing several possible causal paths for the simulated disturbance in the network. Note that number of causal paths produces depend on the information available. In scenarios of least available information all all possible paths will be generated. This situation is not realistic as well as challenging to handle computationally. On the other hand in an ideal situation situation of full full visibility i.e., measurements available from all nodes of the network a single causal path (a set of postdictions) can be achieved. This is also not a realistic scenario. In the current study experiments are made with realistic number of measurements available and a number of causal paths are generated.

D. Analysis of a causal Path

Here we describe one of the causal path generated as a result of reasoning performed on the model. A short circuit fault was simulated at bus 4 of the distribution feeder which in modeled as bal 74 in the MFM model. As result a bidirectional fault current flows into the network and measurement of fault is observed at line 1 (tra11 in the MFM model) and is sent to reasoning system. Several causal paths are generated based upon this information. One of the causal path is presented in

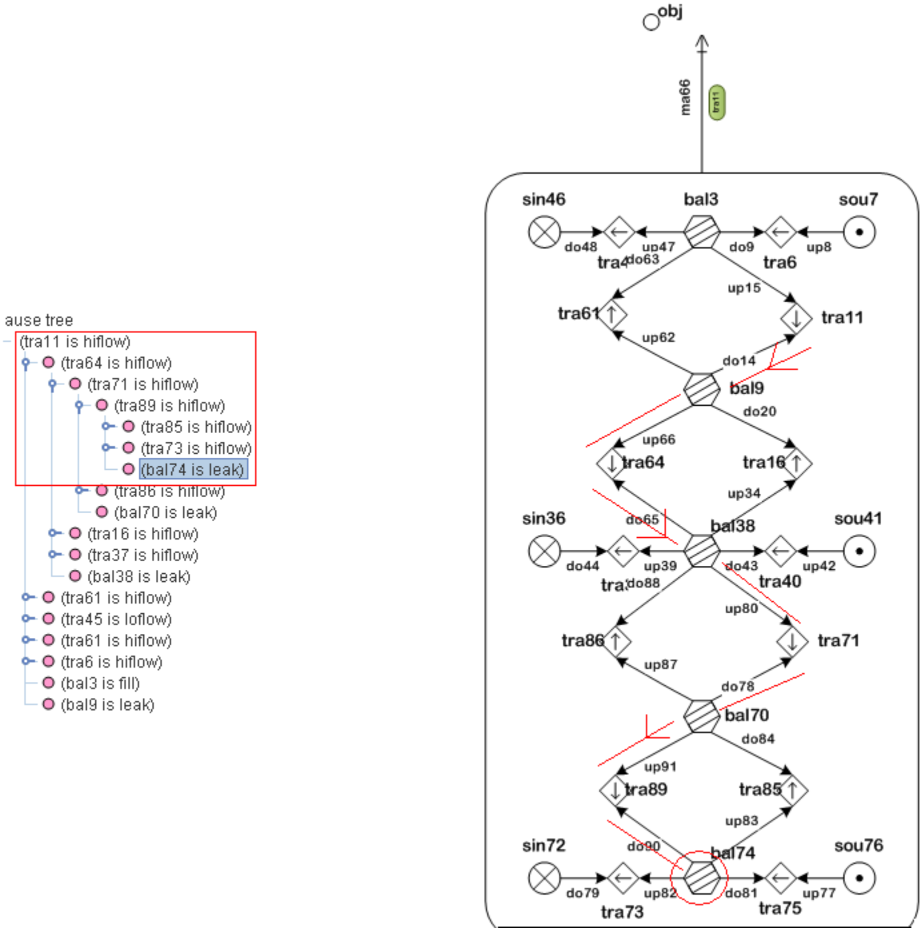


Fig. 10. One of the causal path presenting a postdiction

the figure 10.

This causal path suggests that the high current at line (tra11) may have been caused by a high current current in line 2 (tra71) and this turn may have been caused by a fault on bus 4 i.e., a leak on function bal74. Note that for the implementation of two way flow of power and current a single distribution line is modeled with two MFM transport function e.g., line 1 with tra11 and tra 64. This has been explained and exemplified in the subsection B. and figure figure 7 previously. Several other causal paths are also generated which can cross checked and ignored when comparing with available information.

VI. CONCLUSIONS

The work presented in this paper presents the problem of interpretation in complex control situations of electric power systems in the context of multiagent systems. Current work builds on the previous work where the problem of control situation interpretation was discussed in general. In the current work the proposed mechanisms of explicit means-ends reasoning on control situation is explained and have been applied on an example of protection in electric power distribution systems with distributed generation. An architecture of a comprehensive software platform for design, implementation and testing has been presented. This software platform facilitates with modeling, simulation based testing and online streaming of data from simulators as well as physical environments such as SCADA system or a plant. Results shows that the application of explicit means-ends models provides a novel extension of the classic belief-desire-intention BDI paradigm of multiagent systems and enhances its applicability in complex industrial control systems. A power system example demonstrate the importance of means-end and part-whole concepts in modeling and intelligent control of complex power systems.

VII. ACKNOWLEDGEMENT

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Paper VI:

Heussen, K. Saleem, A. and Lind, M. Control architecture of power systems: Modeling of purpose and function. Proceedings of IEEE PES General Meeting, 2009, Calgary, Canada

Control Architecture of Power Systems: Modeling of Purpose and Function

Kai Heussen, *Student-Member, IEEE*, Arshad Saleem, *Student-Member, IEEE*, and Morten Lind

***Abstract*—Many new technologies with novel control capabilities have been developed in the context of "smart grid" research. However, often it is not clear how these capabilities should best be integrated in the overall system operation. New operation paradigms change the traditional control architecture of power systems and it is necessary to identify requirements and functions. How does new control architecture fit with the old architecture? How can power system functions be specified independent of technology? What is the purpose of control in power systems? In this paper, a method suitable for semantically consistent modeling of control architecture is presented. The method, called Multilevel Flow Modeling (MFM), is applied to the case of system balancing. It was found that MFM is capable of capturing implicit control knowledge, which is otherwise difficult to formalize. The method has possible future applications in agent-based intelligent grids.**

***Index Terms*—Functional Modeling, Requirement analysis, Modeling methods, Frequency Control, Smart Grid Concepts**

I. Introduction

THE transition of power systems today to the "smart" energy systems of the future has received much attention from industry, research and public institutions in recent years. The interest is a result of the need for replacement of old equipment on one side, and of new requirements associated with sustainability for future energy systems, on the other.

In this context, particularly in the US and Europe, many projects have been started that aim at developing new technologies and concepts to shape the idea of the "Smart Grid". US projects tend to emphasize on the development of new concepts and architectures[1] for grid components, business interoperability as well as restructuring markets for more realtime operation. In comparison, the focus in the European Smart Grids platform[2] is rather on the active integration of renewable energies (REN)[3] and distributed resources (DR)[4] and to bring about an evolution of the existing system architecture.

In Denmark specifically, the political goal of 50% share of wind energy by 2025 has inspired the ECOGRID project. This project, funded by the danish transmission system operator[5], aims at preparing the danish power system for this challenge [1].

The recently ended Phase I of the ECOGRID project included a work package on "System Architecture". This work package was comprised of a review of "innovative technologies", a "requirement analysis", and an outlook on "possible solutions". It has been emphasized that there is a need for identifying the requirements to define the architecture of the future system [1], [2]. When discussing system architecture, enabling technologies should be known. It is crucial, however, to assess the technologies and to analyze the anticipated needs in order to redefine the overall goals and to specify the functions required of solutions. This specification of functional requirements must be clear, concise and generic to leave freedom for future design innovations, especially for the adoption of future sustainable technologies. Further, it was concluded that concepts, methods and tools are needed that enable design and evaluation of system architecture.

A. Accommodating New Technology

Major shifts in technology motivate system redesign. For instance, power electronics revolutionize the way energy flows can be controlled, both in power generation and transmission. Also, with the increased amount of REN and DR, a large number of technologies have been and are being developed that enable a controllable consumption and generation of energy in general (e.g. frequency responsive demand, demand clusters, vehicle to grid, etc.). Another class of new technologies regards the supervisory control of power systems on the larger scale [1], such as PMU measurements and online state estimation. Here, also control theory has brought potential for "smarter" power system automation, improving both stability and resource utilization [3]. Information and communication technology (ICT) can be regarded as an enabling technology for many of the new concepts listed here.

Many of these new technologies bring desirable capabilities [4], which are not naturally supported by the traditional power system and energy markets. And often they are of a scale too small to be recognized by energy markets or to be controlled by grid operators.

B. Challenges for Control Architecture

A major issue for system integration is manageability or controllability of these technologies in the context of an already complex power system. The active integration of these additional resources requires new concepts for control and supervision.

In recent years many new concepts have been developed that aim at tackling this challenge. Most of these concepts can be categorized as aggregation approaches of two kinds:

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[1] e.g. EPRI's Intelligrid http://intelligrid.epri.com/ or the GridWise Alliance (http://www.gridwise.org/)- particularly the associated Architecture Council (http://www.gridwiseac.org/)

[2] http://www.smartgrids.eu/

[3] e.g. EWIS (http://www.wind-integration.eu/) and TradeWind (http://www.trade-wind.eu/)

[4] e.g. the projects FENIX (http://www.fenix-project.org/) or ADDRESS (http://www.addressfp7.org/).

[5] Energinet.dk

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(1) Aggregation based on the physical location of resources (in the grid)[6], and (2) commercial aggregation concepts rather based on the generation patterns and capabilities resources [5], [6][7]. The former are aimed at improving the technical operation of the system, and research in this area is of rather technical nature. Whereas, the latter are striving for a profitable participation in energy markets, such that research in this direction focuses on the economical and market-operation principles.

It is generally difficult to evaluate and integrate such complex technologies, particularly when originating from different backgrounds. In order to do that one needs to understand purposes and functions these systems.

In this paper, we present a framework and modeling approach for describing the relations between purpose and functions. A particular strength of the modeling tool used here, called Multilevel Flow Modeling (MFM), is that it provides a meaningful representation of control functions.

By applying this functional modeling approach to the frequency control mechanism, as described in the literature, we show how the network of control objectives and functions composes the system to function as one unit. The modeling technique can be a bridge from values to design as it makes possible to explicate the relation between purposes and functions of the technical system.

In Section II the modeling method is introduced and explained. The rest of the paper is devoted to illustrating the application of functional modeling to power systems. In Section III-A we analyze power system goals on the highest level, in order to gain a clear formulation of the "ends" of electrical energy systems. Next, as the main contribution, a MFM model of frequency control is developed in Section III-B. Finally the presented results and are discussed and future work is motivated in Section IV.

II. MULTILEVEL FLOW MODELING

Multilevel Flow Modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [7]–[12]. MFM has been developed to support functional modeling [13] of complex dynamic processes and combines means-end analysis with whole-part decompositions to describe the functions of the process under study and to enable modeling at different levels of abstraction. Process functions are represented by elementary flow functions interconnected to form flow structures representing a particular goal oriented view of the system (Figure 1a)). Flow structures are interconnected in a multilevel representation through means-end relations, causal roles and control functions and structures (Figure 1b)). MFM is founded on fundamental concepts of action [11] and each of the elementary flow and control functions can be seen as instances of more generic action types. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive model of the functional organization of the system represented as a hypergraph. It should be noted that MFM is a formalized conceptual model of the system which supports qualitative reasoning about control situations [14], [15].

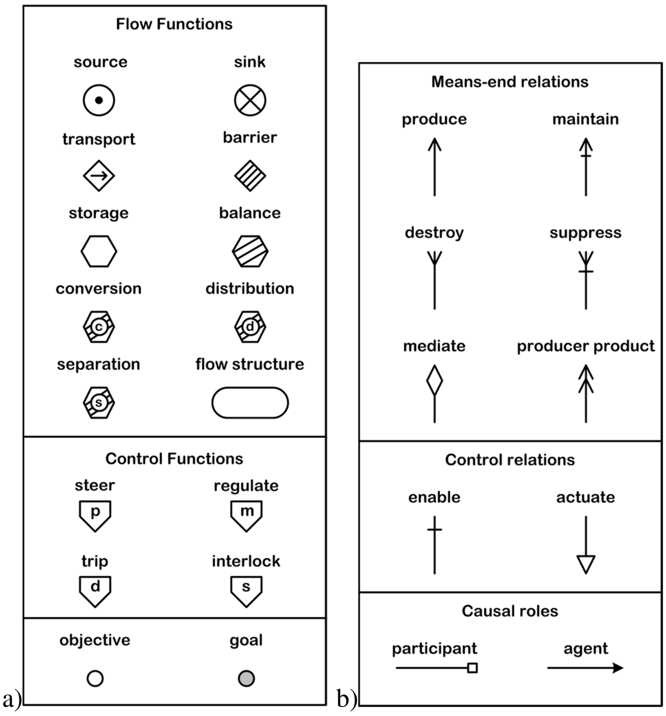

Fig. 1. a) MFM entities and b)MFM relations

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [16]–[18], oil refineries [19], chemical engineering [15], [20] and biochemical processes [21].

Application of MFM includes model based situation assessment and decision support for control room operators [22], hazop analysis [23], alarm design [24] and alarm filtering [25] and planning of control actions [16], [26]. MFM is supported by knowledge based tools for model building and reasoning [12].

MFM has been applied in power systems by Larsson [27] without explicit representation of control functions. Here we show that the capability of representing control is essential for capturing the functional complexity of power systems.

Application of MFM in power systems is envisioned to further intelligent agent solutions in power systems control. MFM models could support situation-awareness of agents, for example to enable reasoning about appropriate responses in fault situations.

A. *Demonstrating MFM principles by a small example*

Application of the MFM concepts is illustrated in the following by a simple example in Figure 2 below. The model represents the objectives and functions of a water circulation loop in a heat transfer system. It is assumed that the water is circulated by an oil lubricated pump. The example illustrate how the MFM model provides a comprehensive understanding of the purpose and functions of the circulation loop and its

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[6] i.e. MicroGrids, Cells, Technical Virtual Power Plants, ...
[7] e.g. (Commercial) Virtual Power Plants

subsystems. On an overall level the model can be seen as composed of three sub-models representing different views on the water circulation system.

The first view (starting from the top) represents systems aspects related to water circulation and comprises the flow structure labeled MFS1, the produce relation and the objective O1. This part of the models represents the overall objective of the water circulation, which is to produce a flow of water. The flow structure contains the functions provided to circulate the water. In this simplified model the transport function T1 is the means used for water circulation.

The second view is partially overlapping with the first view because what is seen here as a means (the transport T1) is in the second view seen as an end. Transport T1 is related to the means of transport which is the pumping represented by the energy flow structure EFS1). T1 and EFS1 is therefore related by a type of means-end relation called a producer-product relation in MFM. The flow structure EFS1 is decomposed into the flow functions representing the services provided by components of the pump system (including the energy supply) in order to achieve the end, the transportation of water represented by T1.

The third view is related with the second view through an enabling relation and an associated objective O2 which is the end to be achieved by the functions contained in the flow structure MFS2. The flow structure MFS2 represents the functions involved in the lubrication of the pump and the objective O2 represents the condition that should be fulfilled in order to ensure that the pump is properly lubricated. A condition which should be satisfied in order to enable the pump to provide its functions. The flow functions inside MFS2 accordingly represents the functions of the pump lubrication system.

Even though the example does not utilize all the concepts of MFM, it demonstrates the power of MFM to represent in a clear and logical way knowledge about the goals and functions of a system. The MFM modeling language has a strong syntax which define rules for combining the different entities and relations of the language into a consistent model.

B. Control Functions

The modeling example above described the functions of the components and subsystem which contributed to the overall objective of the system (deliver water flow). No consideration was accordingly given to the purpose and function of control systems in meeting this objective. As is well known control systems are important for ensuring that process objectives are met in spite of uncertainty and disturbances in the process. This is actually the basic reason for using control systems. MFM has a set of functions which can be used to represent control system functions. We will use the example above to illustrate how some these concepts are used.

Assume that we need to keep the lubrication flow in the pump within specified limits in order to avoid pump problems. An engineering solution to this problem could be to use a regulator measuring the oil flow and controlling the speed of the oil pump. The function of the regulator is to maintain oil flow within limits. This function can be modelled in MFM as shown in Figure 3.

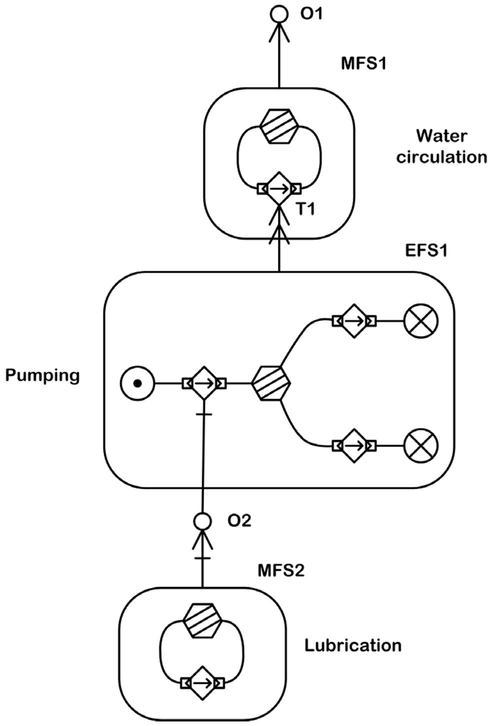

Fig. 2. MFM model of a water circulation loop

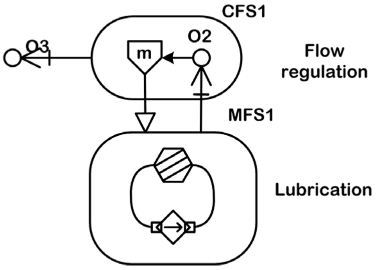

Fig. 3. MFM model of the regulated lubrication system

Note that we have introduced a new objective O3 in addition to the original objective O2. It is very important to emphasize the fundamental difference between these two objectives. O2 is ”process” objective specifying the value range within the lubrication flow should be kept. In contrast O3 in a ”control” objective specifying the performance required of the regulated process. The control objective could specify stability margins etc. and other control attributes specifying the desired performance of the regulator (see also Lind [9]).

It should be stressed that the ”loop” formed by the maintain and the actuate relations connecting the mass flow and the control flow structures are conceptual relations and is therefore not a representation of the function or structure of a feedback loop. The concept of feedback is connected with signal or information flow. Control functions shown here do not describe information flow but the purpose of the control action (to regulate).

III. PURPOSE AND FUNCTIONS OF POWER SYSTEMS

In the following we will demonstrate, how MFM can be applied to power systems. In order to refer to a rather generic power system the modeling was based on the descriptions derived from reference [28].

The process of modeling in MFM is an iterative process, it can be started in principle at any level of means-ends decomposition. An outcome of the modeling is a clear understanding of functions at various levels of abstraction.

The results of the analysis are presented in two stages: First, high-level system objectives are discussed, and then the it will be shown how MFM can be used to model the frequency control hierarchy.

A. Objectives of an Electrical Power System

Usually the location of energy sources is distant from where energy is needed. Electricity is a natural choice for energy delivery, because it can be transported effectively and it can be converted from and to mechanical energy with high efficiency[8].

The *purpose* of electrical energy systems is thus the timely provision of electrical energy to satisfy the demand for different forms of energy. The *function* of the electrical energy system describes how the system serves its purpose. That is,

> *the function of an electric power system is to convert energy from one of the naturally available forms to the electrical form and to transport it to the points consumption.* [28]

Kundur further elaborates that the power system should meet "fundamental requirements" as follows (p.9, [28])

1) *... meet the continually changing load demand of active and reactive power ...* [while considering that, *(edt.)*] *electricity cannot be stored conveniently in sufficient quantities.* [...]
2) *... supply energy at minimum costs and minimum ecological impact*
3) *The "quality" of power must meet minimum standards with regard to* [...]
    (a) *constancy of frequency*
    (b) *constancy of voltage;*
    (c) *level of reliability*

The scope of these requirements encompasses different time ranges and scopes of planning and comprises technical, economical and societal (ecological) goals.

Technical objectives tend to dominate the operational requirements, whereas economical objectives tend to be oriented more on scheduling and planning. Ecology considers the whole life cycle, but it is not always straightforward how this requirement is to be interpreted in practice. Let us therefore further differentiate objectives by: *operation*, *scheduling*, *planning* and *system design*.

The categorization of requirements and goals into "economical" and "technical" can actually be derived from different values that are associated with these goals [29]. In abstraction from economical, technical and societal categories the authors identified the following values in the context of energy systems:

1) Security of energy supply;
2) Overall resource efficiency of the energy system; and
3) Sustainability of system structure, operation and planning.

These values express the most fundamental sources of "requirements" we could derive, and they are technology independent. The suggested prioritization was observed for instance by how these values have been considered historically in the electrical power systems context[9].

Let us elaborate a bit on the interpretation of these three values:

1. *Security (availability) of energy supply* relates to the basic human value of security, the security that energy is available when needed. In a more long term perspective, it also means *security of access* to energy resources, for example.

2. *Resource efficiency* relates to the general understanding that resources are limited and that efficient utilization frees resources for other purposes. Resources could be natural (e.g. energy or material), but could also be human or monetary resources. A typical means of evaluating system efficiency is the creation of institutions or market instruments to enable means of monetary resource allocation and evaluation. Economical evaluation is however limited to the extent in which costs and benefits can reasonably be quantified.

3. The concept of *sustainability* is rather new in the context of power systems, but it has a long tradition in the provision of energy resources. It is important to include objectives of this kind to give space for reasoning about appropriateness of technologies and the application of methodologies that go beyond the capacity of econometric tools.

Criteria formulated in terms of values are pervasive in principle. That means, they affect all system objectives, functions and realization independently.

Now, given these value-criteria and categories, how do we interpret the "fundamental requirements" quoted above?

1) "Meeting the continually changing demand" clearly is an operational objective and it relates to *security of energy supply*. We take this as the central goal of a power system:
    $\mathbf{g_1}$: *Supply electrical energy as demanded.*
2) The requirements regarding "costs" and "ecology" are high-level criteria and are basically equivalent to the value statements on *resource efficiency* and *sustainability*, respectively.
3) The requirements relating to the "quality of power", are rather mixed. Quality requirements (a) and (b), constancy of voltage and frequency, respectively, are strictly functional requirements. Point (c) "reliability", however, can be interpreted in many ways:
    - If subordinated to power quality it is a functional requirement.

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[8] The transformation of thermal or chemical energy is not as efficient. District heating systems are a good counter-example, that illustrates that electricity is not always the most efficient form of energy distribution.

[9] It may not be a "natural" prioritization, but it is unclear if a such a "natural" prioritization exists after all.

- It can also be seen as a high-level objective, derived from *security of supply / availability*.
- Some aspects of reliability could characterize the specification of control objectives, such as *performance*, or *stability*, which includes those objectives related to stabilizing the network as a whole. These objectives which would be subordinated to $\mathbf{g_1}$ as a purpose.

The following modeling focuses on achieving an *operational* understanding of objective $\mathbf{g_1}$.

B. Control Functions for Balancing Generation and Demand

Following the discussion above, we now start developing a functional model of the control structure of electrical energy systems. The focus is on the frequency control mechanism, which is directly related to the high-level goal of supplying as much energy as demanded. To put this model in context, we shall first analyze common representations of these control structures from the literature as given in [28].

A common and detailed illustration of the power system control functions is given in Figure 4. It shows a composition of several subsystems (boxes) interconnected by signals (arrows). It may be interpreted as follows: On the top of the diagram we find the "System Generation Control" which receives a set of input signals and issues "supplementary control" signals to as inputs to generating units. One of the input signals is called "generation schedules", which should represent the operating points of all generators participating in the system control. The other inputs comprise information on the system operating state, received from the "Transmission Controls". The central part of the diagram shows subsystems of a power plant (Generation unit) considered relevant for power system control. This includes the prime mover as source of energy and generating torque and the associated generation control system, which receives the rotor speed and supplementary control as control inputs. The generator, receiving this torque from the prime mover (shaft power), feeds back the rotor speed. The generator further receives inputs and feeds back to its excitations system and controls, and finally, it emits an electrical power and voltage as outputs of the power plant subsystem.

Further, the "transmission controls" receive this electrical power as input information for their control responsibilities, which includes the control of voltage and reactive power. This simplified view suggests a subordinated role of the transmission controls , for example, omitting the role of the generation units in voltage control. In this paper we also limit the scope of modeling to the active power / energy related system functions. That means the subsystems and signals marked with thin dash-dotted lines are only included implicitly in the following.

The model in Figure 4 is based on the signal-flow type of diagram, where the arrows present *signals* and the boxes represent *systems* which generate or transform signals. This type of diagram origins from signal processing and is often used to explain the composition of control systems. The naming of the boxes and signals ascribes meaning to them, and their relation with each other can be interpreted as command-chain or physical interconnection. This kind of interpretation of Figure 4 was given above.

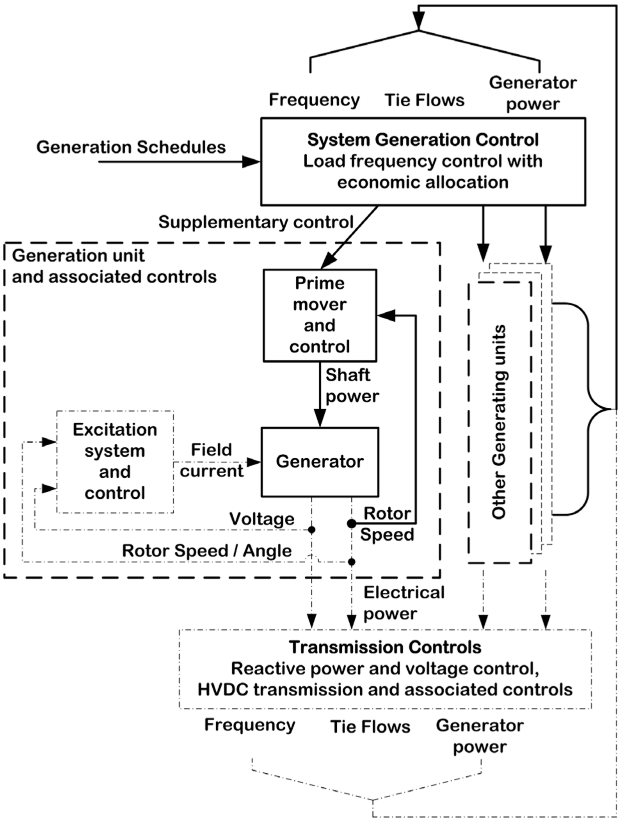

Fig. 4. Subsystems of a power system and associated controls (adapted from [28], Fig.1.2). The subsystems shown with dash-dotted lines are not modeled explicitly in this paper.

However, the functions represented in this type of diagram can formally only be interpreted as signal processing functions. One could argue that it is often possible to interpret the intentions implemented in the design of a control system from a signal-flow diagram. In this case, the intentions are then inferred from conceptual schemes of control engineering. Yet, the intentionality is only *implicit* in the ordering of signal flow structures. In fact this type ordering is prone to misinterpretation, for example when a system redesign is attempted without considering the underlying design objectives [11].

Signal-flows are also used to suggest control hierarchies and control roles in the modeled system. Figure 5 illustrates the hierarchical structure of power system control by a flow of command signal flows and a command hierarchy in an organigramme. This control hierarchy can be divided systematically into control levels, depending on level of abstraction, the relevant time scales and type of control tasks performed [3], [30], [31]. This approach is meaningful for complex automation systems and it can also be found in other industrial automation systems [32].

1) Functional Structure of the Energy System: In contrast to the types of diagrams used above, functions and purposes of systems and subsystems are modeled explicitly in functional

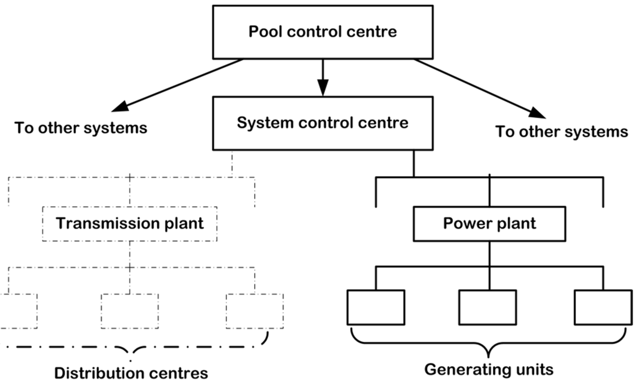

Fig. 5. A representation of control hierarchy in power systems from the literature (adapted from [28], Fig. 1.4).

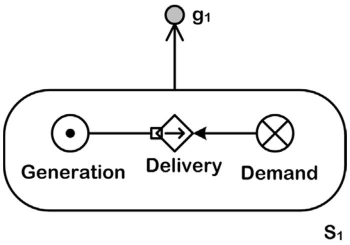

Fig. 6. High-level view of the energy system (MFM model).

models. Multi-level Flow Modeling (MFM) provides rich semantics to model the relations of utility between systems and subsystems. The means-ends decomposition is possible both in terms of intention, as goal-oriented action, and in terms of intentional composition of physical functions in energy and mass flow functions.

The most high-level view of the multilevel flow model is shown in Figure 6. The energy system is here described by an *energy flow structure* $\mathbf{S_1}$, describing the process view, and its association with *goal* $\mathbf{g_1}$: *Satisfy energy demand*, employing the means-ends relation: *produce*. $\mathbf{S_1}$ comprises three energy flow functions: A *source* (Generation), a *transport function* (Delivery), and a *sink* (Demand). The flow functions are interconnected by causal relations: Generation is a *participant*, supplying energy to the transport function, whereas Demand is an *agent* causing the energy flow. These causal roles imply that generation is supposed to be following the load demand. This causal role is realized by the frequency control functions that will be analyzed below. The transport function in $\mathbf{S_1}$ represents the action of power-delivery at any time.

2) Abstract Model of Frequency Control: The flow structure and goal introduced above represent the overall function of the electrical energy system. This function is of course dependent on mechanisms that bring about the intended causality, to satisfy the goal. That mechanism is frequency control.

The purpose of frequency control is accordingly represented by the causal relations between generation and demand in the flow structure $\mathbf{S_1}$ in Figure 6. This purpose is achieved by a cascade from centralized to decentralized control and coordination functions. The decentralized, low-level, control functions are implemented on the generators and are known as *frequency droop control* or primary frequency control. The more central control functions are associated with secondary frequency control, inter-area balancing, economical allocation *et cetera*. Control functions on this level have been generalized as "corrective control" in [3]; in the following we will refer to it as *system balancing*. The coordination of these two control functions is possible due to the kinetic energy stored ($\mathbf{E_{kin}}$) in the generators of the power system and the associated synchronous[10] frequency f_{sys}.

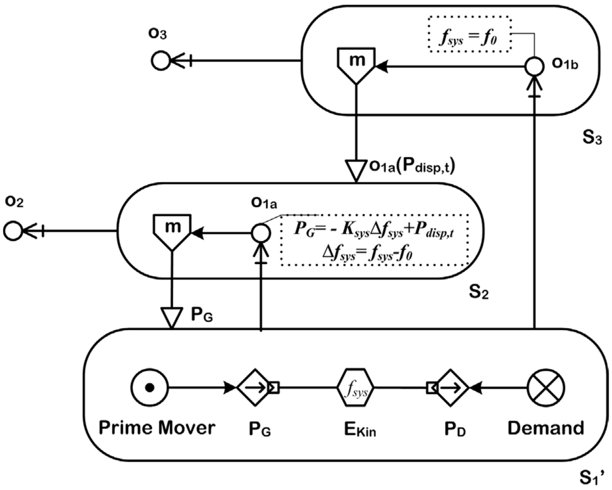

Fig. 7. Abstract MFM model of the system balancing hierarchy.

An MFM model of this composition is shown in Figure 7. Here, the flow structure $\mathbf{S_1}'$ shows an expansion of the flow structure $\mathbf{S_1}$ in Figure 6, where the energy source (Generation) has been expanded. The frequency droop control is represented by the *control flow structure* $\mathbf{S_2}$ and system balancing is modeled as control structure $\mathbf{S_3}$. The objectives associated with $\mathbf{S_1}'$, $\mathbf{o_{1a}}$ and $\mathbf{o_{1b}}$, are a decomposition of the above stated purpose of frequency control. This purpose can be formalized as follows:

$$\mathbf{o_1}: \quad P_G \overset{!}{=} P_D \ , \tag{1}$$

where P_D is the power consumed by the demand, and P_G is the shaft power of the generators. This equation is a statement of intention, which is expressed by the exclamation mark ($\overset{!}{=}$).

The separation between frequency droop control and system balancing is based on a decomposition of (1):

$$P_G = -K_{sys}\Delta f_{sys} + P_{disp,t} \ , \tag{2}$$

with $\Delta f_{sys} = f_{sys} - f_0$ is the frequency deviation, $K_{sys} = \frac{1}{R_{sys}}$ is the system droop constant and $P_{disp,t}$ is the total power dispatch by the system balancing function. This decomposition leads to the objectives $\mathbf{o_{1a}}$ and $\mathbf{o_{1a}}$ of droop control and system balancing, respectively.

Droop control or primary frequency control is necessary for the mitigation of larger short-term deviations in the balance between load and demand. The response is coordinated by an adequate stetting of the droop constants, such that a required system droop constant $R_{sys} = \frac{1}{K_{sys}}$ is achieved

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[10] This synchronous operation is a load-sharing mechanism, realized by lower-level functions.

(Section III-B3). The objective is thus to achieve the droop characteristic:

$$\mathbf{o_{1a}}: \quad \Delta f_{sys} \overset{!}{=} P_G = R_{sys} \cdot (P_{disp,t} - P_D)\ , \tag{3}$$

The primary frequency-control ($\mathbf{S_2}(\mathbf{o_{1a}})$, $\mathbf{o_2}$) ensures that the frequency deviation matches the droop setting and power dispatch. It does so by means of adjusting the prime mover $\mathbf{P_G}$, the shaft power input to the generators, using control according to the performance specified in $\mathbf{o_2}$. As a result, the frequency reflects the mismatch between demand and dispatched power. The power dispatch is to be adjusted by the system balancing $\mathbf{S_3}$.

Following (2), the objective $\mathbf{o_1}$, i.e. matching dispatched generation with demand, is equivalent to returning the frequency to its nominal value:

$$\mathbf{o_{1b}}: \quad f_{sys} \overset{!}{=} f_0\ , \tag{4}$$

Thus, system balancing is aimed at bringing the frequency back to its nominal value by means of adjusting the power dispatch. The performance objective $\mathbf{o_3}$ specifies *how* the control structure $\mathbf{S_3}$ should achieve the control objective $\mathbf{o_{1b}}$, which could be, for example, a formulation of the time-scales associated with primary, secondary and tertiary frequency control, or economic allocation criteria.

3) De-aggregation to Represent Individual Units: Above, all generators were aggregated into one. In this section we show the system view of frequency control for an individual generator. The aggregation of the previous section is split into two sources and two transport functions: G1, P_{G1} and P_{Grest}. The inertia (energy storage) remains aggregated in this view (Figure 8).

For this case, equation (2) can be decomposed into

$$P_G = -(\sum_{i=1}^{N} K_i)\Delta f_{sys} + \sum_{i=1}^{N} P_{disp,i}\ . \tag{5}$$

We have therefore two system constants that can be coordinated independently on the higher aggregation levels:

$$1)\ \frac{1}{R_{sys}} = K_{sys} = \sum_{i=1}^{N} K_i \qquad 2)\ P_{disp,t} = \sum_{i=1}^{N} P_{disp,i}\ . \tag{6}$$

The coordinated droop of all synchronous generators is the sum of the individual responses. The balancing control $\mathbf{S_3}$ actuates the generators independently of their contribution to primary control. The frequency gets restored by balancing control, as a result all primary controllers get back into balance.

IV. DISCUSSION AND CONCLUSION

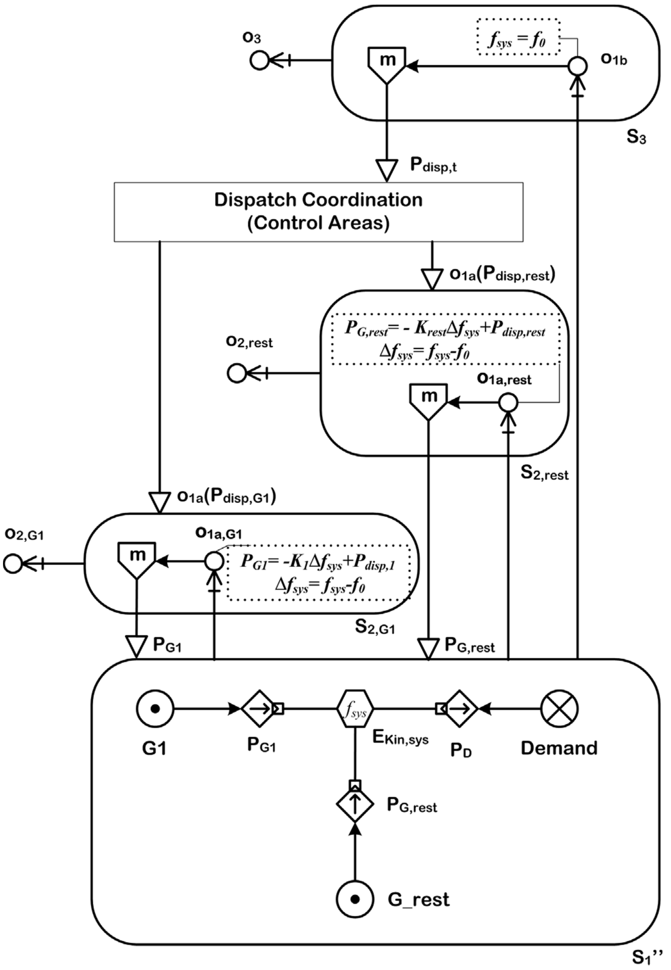

Fig. 8. Distributed frequency control. The generator control structures $\mathbf{S_{2,G1}}$, $\mathbf{S_{2,Grest}}$ locally adjust their generation according to their respective power setpoint and local droop setting, based on the common system frequency.

The analysis of power systems presented here presents a new angle on control design starting with the question: What is purpose of power systems? This seemingly remote analysis of values revealed two important facts: (1) there is a hierarchy among the typically believed standard objectives of power system operation; and (2) whenever new power system (control) objectives are defined, a choice based on values is made. This rigorous ends-means approach set an anchor for the analysis using MFM. The following analysis of the frequency control clarifies the concepts of frequency control. Seen in the larger picture, this model could contribute with categories of control functions for new active power control technologies (for example for of Wind Turbines).

So far, with frequency control, only a model of one of the simplest control functions in the domain has been presented. Some of the further modeling challenges addressed in future work are:

- Load-angle stability: a deeper analysis of control functions that enable synchronous operation.

- Reactive power and voltage control: this modeling task comprises two challenges: (1) a MFM model of reactive energy flows needs to be developed that is consistent with the common understanding of reactive power; and (2) a model of the spatially distributed control of voltage.

- Even though the balancing functions described here are in line with the description derived from [28], the complex coordination patterns of inter-area balancing and program responsibility require a more detailed modeling of the control structures.

This is the first study of control functions in power systems using MFM. The study is part an ongoing work and will be expanded to more control functions in order to obtain a comprehensive understanding of control architecture in power systems. We conclude that MFM can be an effective analytical tool in the development and evaluation of new technologies for existing and future power systems.

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Paper VII:

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MEANS-END BASED FUNCTIONAL MODELING FOR INTELLIGENT CONTROL: MODELING AND EXPERIMENTS WITH AN INDUSTRIAL HEAT PUMP SYSTEM

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ABSTRACT

The purpose of this paper is to present a Multilevel Flow Model (MFM) of an industrial heat pump system and its use for diagnostic reasoning. MFM is functional modeling language supporting an explicit means-ends intelligent control strategy for large industrial process plants. The model is used in several diagnostic experiments analyzing different fault scenarios. The model and results of the experiments are explained and it is shown how MFM based intelligent modeling and automated reasoning can improve the fault diagnosis process significantly.

KEY WORDS

Intelligent Control, Means-Ends Based Reasoning, Fault Diagnosis, Industrial Heat Pump System

1. Introduction

Diagnosis of fault scenarios is a demanding task in complex industrial processes because of their dynamics and uncertainty caused by insufficient sensor information. Typically, control room operators use their cognitive abilities, past experience, heuristics and contextual knowledge to muddle through such situations. But due to the increased complexity in present process plants, operators need decision support systems for effective diagnosing of fault situations.

The application of information and communication technology in industrial process automation has made it possible to process and present comprehensive amount of data to the operators. Applications can now collect, store, organize and perform reasoning upon data from several sources. These capabilities are crucial to cope with increased demands of uncertainty, dynamism and flexibility of process plants. But it has also increased the complexity of such systems significantly [1] by presenting operators with an overwhelming amount of information. There is therefore a risk that operators are unable to cope with complex incidents and fault scenarios [4].

MFM which is a functional modeling method can be used to reduce the incompatibility between increasing system complexity and the human cognition ability. It makes it possible to build software which model systems on the basis of natural cognition model of human beings – the means-ends modeling. It assists control room operators in visualizing the system in terms of its capabilities – the means; and its goals – the ends. Thus, when a disturbance occurs, it guides the control room operator about why the system has ended up in this situation and what capabilities of the system that can bring it back to the normal state and continue achieving the overall desired goal of the system. The MFM language is accompanied with a software tool called MFMWorkbench, which provides intelligent reasoning for the diagnosis. The MFMWorkbench is a research prototype and has been developed in JESS Rule Based Systems environment [5].

In this paper we show how MFM can be used to perform an explicit mean-ends based modeling of an industrial heat pump and how this model and the accompanying MFMWorkbench can be used for diagnosis in intelligent control. Several experiments have been performed and documented in order to describe how this modeling makes the diagnosis task more efficient in different fault scenarios. In next section we will briefly describe the MFM language and the MFMWorkbench. Detailed description of functional modeling should be found in [2]. More elaborated discussions and semantics of MFM language are available in [3, 6, 9].

2. Multilevel Flow Modeling (MFM) and the MFMWorkbench

Multilevel Flow Modeling MFM is, as mentioned above, a functional modeling method which has been developed to support intelligent control, human supervisory control and decision making in industrial process plants involving the interaction of material, energy and information flows. Different functions in MFM are represented by elementary flow functions interconnected to form flow structures representing a goal oriented view of the system. As shown in Figure 2.1, the views represented by the flow structures are related by means-ends and part-whole relations and comprise together a comprehensive model of the functional organization of system [2].

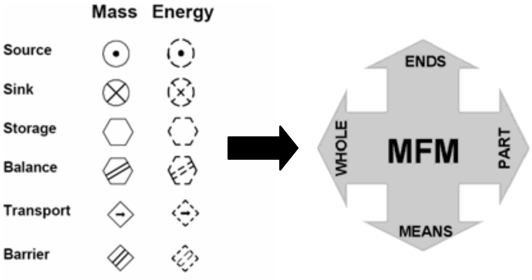


Figure 2.1: Flow Function Concepts and Symbols of MFM

Using these concepts and symbols in Figure 2.1, MFM represents goal structures and their relationship to underlying causal mechanism of the process in formalized way [6]. The MFMWorkbench together with its built-in inference engine performs reasoning on the knowledge represented in model and comes up with diagnostic suggestions in fault scenarios. It helps the user to construct and analyze different fault scenarios on the system. The MFMWorkbench has been developed using the JAVA based expert system shell called JESS [5]. In order to use MFMWorkbench an MFM model of the system must be created first. To build the MFM model, a MSVisio template is provided. The template contains all MFM functions, relations and structures. The user is then able to construct the individual flow structures with appropriate relations (see explanations of the MFM model of the heat pump system in the following). The MFM model build in MSVisio is compiled and imported into the MFMWorkbench. The Workbench uses an MFM diagnostic rule base and the constructed MFM model file to present the implications of chosen scenarios in the user panel of the workbench (Figure 4.1). MFM has recently shown its potential in fields as diverse as chemical engineering [12, 13], bio-informatics [10, 14] and nuclear power process plants [15].

3. MFM model of the Heat Pump System

In this section we briefly describe structure and function of an industrial heat pump for the familiarity of readers. A detailed description of the heat pump, its working and control requirements should be found in [7, 8, 11]. Later in this section we will describe how this heat pump system is conceptualized using the means-ends concepts and how modeling is done. In next section we document our experience from the diagnostic experiments and intelligent reasoning using the MFMWorkbench.

3.1 Structure and Function of Heat Pump System

The purpose of a heat pump is to move heat from one location to another by means of work. Generally, heat pump technology is applied to move heat from a low temperature heat source to high temperature heat sink. We performed modeling and executed experiments with a particular type of heat pump which operates within a Heat Integrated Distillation Pilot Plant [7]. A basic heat pump consists of an evaporator, compressor, condenser, throttle valve (for expansion) and a liquid refrigerant. Very basically, in our case, the liquid refrigerant Freon R-114 is evaporated by the heat transferred from the distillation column condenser. Afterwards, Freon is compressed by the compressors to achieve a high pressure and high temperature. Then, it is condensed via the re-boiler heat exchanger by transferring heat, followed by returning to the initial state by the throttle valve. Figure 3.1 below shows the actual heat pump configuration including a cooling system attached after the re-boiler and the safety valves. Red flow lines express the increased heat content of Freon and blue flow lines the decreased heat content.

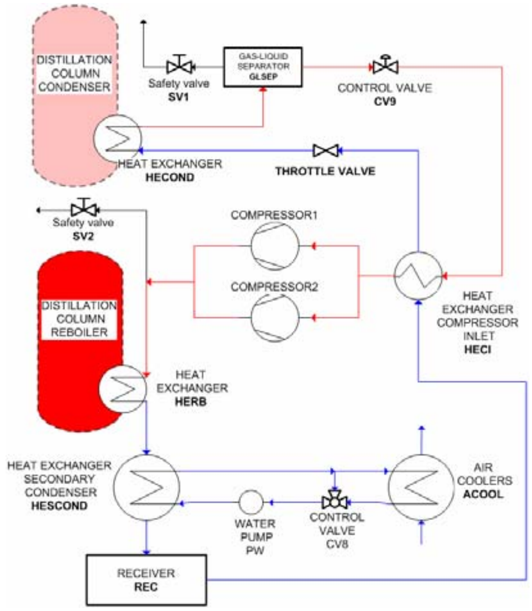


Figure 3.1: Process flow sheet of the industrial heat pump system located at DTU [7].

3.2 The Means-Ends Modeling

MFM modeling brings forward the qualitative functional principles of the system – abstracting from its physical structures. The primary purpose of an industrial heat pump system is to upgrade the low temperature heat released from the distillation column condenser to high temperature media in the re-boiler via work input. To achieve this goal, the objectives which are associated with the goal must be satisfied. Moreover, every objective is realized by related system components and this is expressed in the means-ends structure depicted in Figure 3.2. For simplicity, some objectives and functions are disregarded here and the functions shown in the means-end structure are overall functions.

3.3 MFM Model of Heat Pump System

On the basis of the means-ends structure presented in Figure 3.2, a complete model has been developed for the heat pump system. Figure 3.3 presents a part of this model whereas the complete model is shown in Appendix A. Detailed descriptions of the complete model and its elements are available in [11].

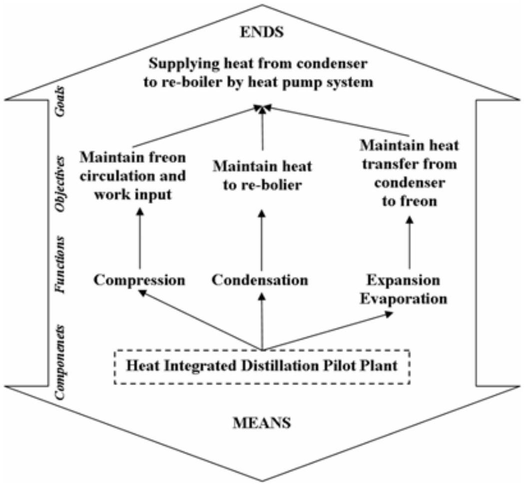


Figure 3.2: Means and ends of the industrial heat pump system

The purpose of the cooling water circulation section of an industrial heat pump system is to control and/or decrease the temperature of the Freon coming from re-boiler heat exchanger. In the MFM model presented in Figure 3.3, these purposes are represented as objectives (O1 and O8). The capabilities of the system to achieve these objectives are represented by functions (FW1, FW2, FW7) whereas the casual relations (the links between the functions) determine the causal directions of the propagation of changes in the state of flow functions. It is important to note that the MFM based means-ends modeling is an abstraction from the physical structure which provides an overall qualitative understanding of the intended behavior of the system.

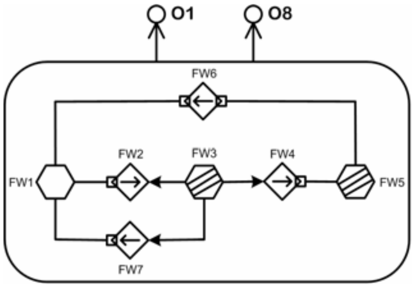


Figure 3.3: An excerpt from the MFM model of the Heat Pump System showing the cooling water circulation process

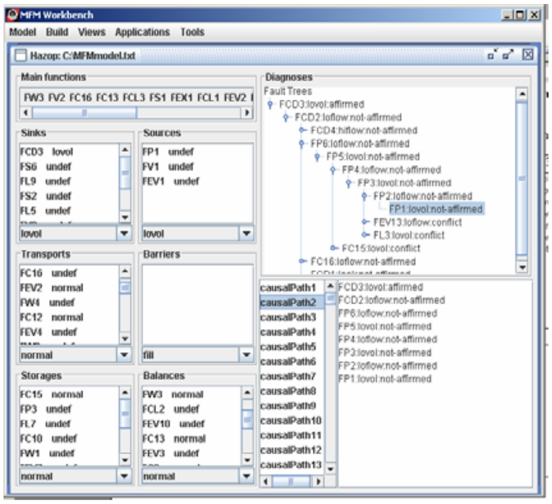
4. Diagnostic Scenarios

Several experiments have been performed with the model to evaluate its performance in different fault scenarios. In this section we document some of them to present how this kind of modeling can complement the human diagnosis and decision making process and thereby improve it significantly. For complete understanding of the scenarios presented in following parts of this section it is important to read the description of the functions and goals presented in Appendix B. Also to interpret different abbreviations in this section, readers should refer to Figure 3.1.

4.1 Scenario 1: Low Temperature in Re-Boiler

In this scenario we assume that the operator finds the temperature of re-boiler decreasing. The temperature of the distillation column and the states of control valves, the air cooling and water circulation were found normal. The safety valves are closed and oil pressure in the compressors is normal too. To simulate this situation in our model and perform diagnosis using the MFMWorkbench (Figure 4.1), the sink function FCD3 is set to the state of low volume (lovol) which means the energy content (temperature) in the re-boiler is low. After setting FCD3 to lovol, 371 causal paths are generated by the diagnosis. Then, the state of functions FV2, FL3, FW3, FEV2, FC12, FC13, FC8, FC15, FC6, FS5, FEV13 are set to normal and the number of valid causal paths without conflicts decrease to 5.

The causal path is produced by searching through the causal relations in the MFM model. The search will start at the triggering node (FCD3 in this example) and propagate the state information. A propagated state may conflict with state information which is assumed for a node in which case the causal path leading to that node is invalid. If the state of a node is propagated it may be confirmed by other information in which case it is labeled “affirmed”. If such information is not available it is labeled “not-affirmed”. In the following, we describe these valid casual paths and their interpretations.



FW3 FV2 FC16 FC13 FCL3 FS1 FEX1 FCL1 FEV2

Sinks:
FCD3 lovol
FS6 undef
FL9 undef
FS2 undef
FL5 undef
lovol

Sources:
FP1 undef
FV1 undef
FEV1 undef
lovol

Transports:
FC16 undef
FEV2 normal
FW4 undef
FC12 normal
FEV4 undef
normal

Barriers:
fill

Storages:
FC15 normal
FP3 undef
FL7 undef
FC10 undef
FW1 undef
normal

Balances:
FW3 normal
FCL2 undef
FEV10 undef
FC13 normal
FEV3 undef
normal

Fault Trees:
- FCD3:lovol:affirmed
  - FCD2:loflow:not-affirmed
    - FCD4:hiflow:not-affirmed
    - FP6:loflow:not-affirmed
      - FP5:lovol:not-affirmed
        - FP4:loflow:not-affirmed
          - FP3:lovol:not-affirmed
            - FP2:loflow:not-affirmed
              - FP1:lovol:not-affirmed
            - FEV13:loflow:conflict
            - FL3:lovol:conflict
        - FC15:lovol:conflict
    - FC16:loflow:not-affirmed

causalPath1
causalPath2
causalPath3
causalPath4
causalPath5
causalPath6
causalPath7
causalPath8
causalPath9
causalPath10
causalPath11
causalPath12
causalPath13

FCD3:lovol:affirmed
FCD2:loflow:not-affirmed
FP6:loflow:not-affirmed
FP5:lovol:not-affirmed
FP4:loflow:not-affirmed
FP3:lovol:not-affirmed
FP2:loflow:not-affirmed
FP1:lovol:not-affirmed

Figure 4.1: Representation of casual paths and diagnosis in MFMWorkbench for scenario 4.1.

4.1.1 Causal Path 1

This path informs the operator that the primary cause of the temperature decrease in the re-boiler is a failure of the balance (FCD1) between the heat transfer to the re-boiler and to HESCOND. This means that the Freon does not condense properly so that more vapor phase Freon, which should be condensed in HERB, is flowing (FCD4) to HESCOND compared to the normal state. Consequently, this result in a low transfer of heat to the re-boiler (FCD2) and the temperature in the re-boiler is decreased. From the causal path shown in Figure 4.1.1, it can be interpreted that the Freon condensing capability of HERB is decreased due to some malfunction of the heat exchanger.

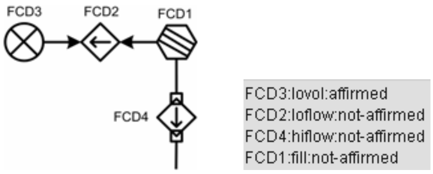


Figure 4.1.1: Casual path 1 (right hand side) and corresponding MFM functions (left hand side) for scenario 4.1.

4.1.2 Causal Path 2

This path informs the operator that the primary cause of the temperature decrease in re-boiler is a decrease in power supply to the electric motors (FP1) of the compressors. Then, the transfer of electric energy to the compressors as mechanical work (FP2) is decreased following a decline in compression (FP3) of Freon and transport of energy to the distillation column re-boiler via FP4, FP5, FP6, FCD2. From this causal path shown in Figure 4.1.2, it can be interpreted that the *electricity supply capability of the power supply is reduced* and this has caused a low temperature in re-boiler.

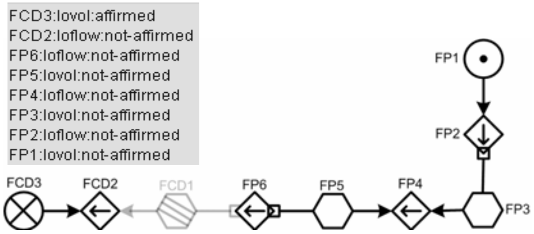


Figure 4.1.2: Casual path 2 and corresponding MFM functions for scenario 4.1.

4.1.3 Causal Path 3

This path informs the operator that the primary cause of the temperature decrease in the re-boiler is a release of Freon from the safety valve SV1 caused by high pressure in GLSEP (FC10:hivol). Then, the mass flow rate of Freon via HECOND, the throttle valve, the receiver and HESCOND is decreased. From the causal path shown in Figure 4.1.3, it can be interpreted that the temperature in re-boiler has decreased due to a lack of Freon in the system which is caused by a Freon release from the safety valve SV1 due to a high pressure in the connected GLSEP.

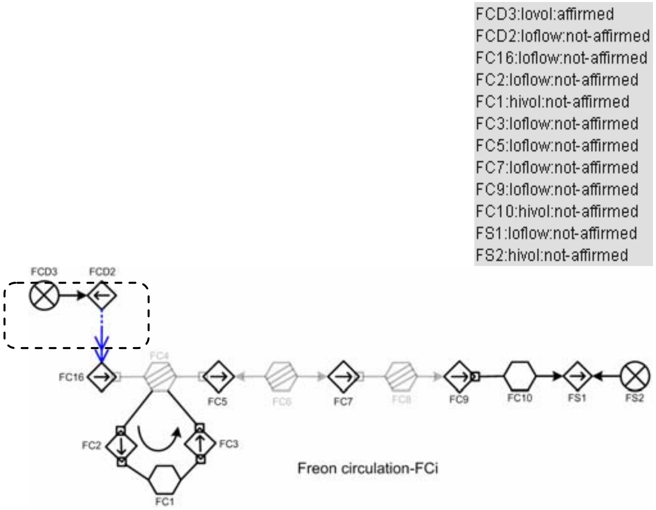


Figure 4.1.3: Casual path 3 (right hand side) and corresponding MFM functions (left hand side) for scenario 4.1.

4.1.4 Causal path 4

This path informs the operator that the primary cause of the temperature decrease in the re-boiler is the failure of the balance function (FC4) between the Freon uptake and discharge in receiver REC. Because of the balance failure, the amount of Freon stored in the receiver is increased (FC1:hivol), the transport of Freon via condensers FC16 also decreases and this causes a low heat transfer (FCD2) to the re-boiler. From the causal path shown in Figure 4.1.4, it can be interpreted that the temperature in the re-boiler has decreased due to a decrease in Freon circulation caused by an increase of the amount of Freon kept in receiver REC.

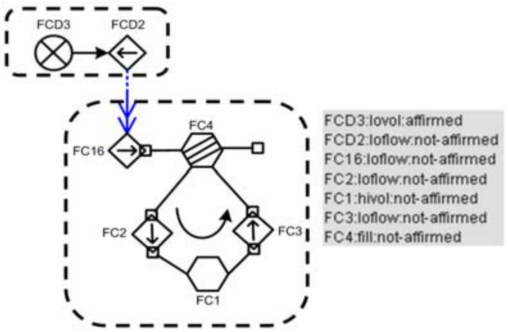


Figure 4.1.4: Casual path 4 (right hand side) and corresponding MFM functions (left hand side) for scenario 4.1.

4.1.5 Causal Path 5

This causal path shown in Figure 4.1.5 informs the operator that the primary cause of the temperature decrease in the re-boiler is a release of Freon from the safety valve SV1 connected to GLSEP caused by high pressure in the gas liquid separator (FC10:hivol) (same as the causal path 3 in Figure 4.1.3). However, in this case, the dynamics of FC2, FC1, and FC3 does not play any role.

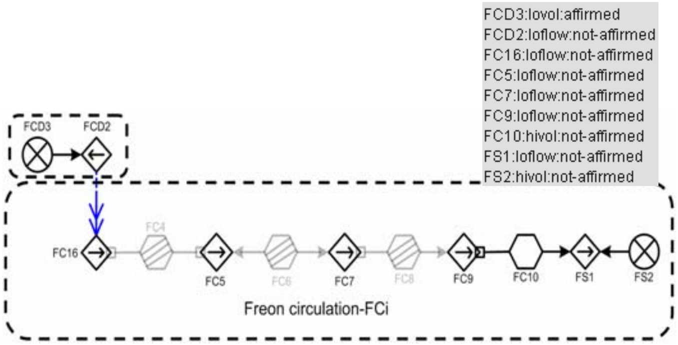


Figure 4.1.5: Casual path 5 (right hand side) and corresponding MFM functions (left hand side) for scenario 4.1.

4.2 Scenario 2: High Temperature in Cooling Water System

In this scenario the operator finds that the temperature of the cooling water is increasing. The first reaction of the operator is to check the re-boiler and the distillation column condenser temperature but they are normal. Then the number of the cylinders used in compressors are checked by the operator to see whether there is high work-input or not; and it is constant also. Then the amount of water in the cooling system is checked to see whether there is a leak or not but there is no problem. Also the Freon circulation flow is at normal values and there is no deviation. Lastly, the compressors are checked whether there is a lubrication problem or not. Every parameter seems to be alright in the heat pump system. To implement this scenario with our model, firstly, the transport function FCL1 is set to loflow which means that the heat transfer from Freon to the cooling water has decreased because of high temperature in the cooling water. After setting FCL1 to loflow, 370 causal paths are generated in the diagnosis. Then, the functions in FCi, FEVi, FLi, FCDi, FPi, FEXi are set to normal and the number of valid causal paths without conflicts decreases to three. In the following we describe these three paths.

4.2.1 Causal Path 1

This path informs the operator that the primary cause of the temperature increase in the cooling water is the decrease in the suction of air by propellers from ambient air (FV1). This causes low flow of air through ACOOL (FV2) and a decrease of the heat transfer from the cooling water to the air via ACOOL (FCL3). From this causal path, shown in Figure 4.2.1, it can be interpreted that the increase in cooling water temperature is caused by insufficient air suction to ACOOL and a corresponding lack of cooling for the circulating water.

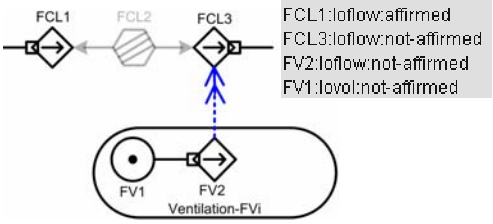


Figure 4.2.1: Casual path 1 (right hand side) and corresponding MFM functions (left hand side) for scenario 4.2.

4.2.2 Causal Path 2

This path informs that the primary cause of the temperature increase in the cooling water is the increase in temperature of the ambient air passing through ACOOL (FCL4). This has reduced the heat transfer from the cooling water to ACOOL (FCL3). From this causal path, shown in Figure 4.2.2, it can be interpreted that the increase in cooling water temperature is caused by an increase in the temperature of the ambient air circulated through ACOOL.

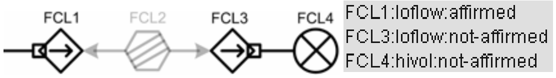


Figure 4.2.2: Casual path 2 (right hand side) and corresponding MFM functions (left hand side)

4.2.3 Causal Path 3

This path informs that the primary cause of the temperature increase in the cooling water is the failure of balance (FCL2) between by-passed water and water sent to ACOOL. From this causal path shown in Figure 4.2.3, it can be interpreted that the three-way control valve CV8 should be set to another operational condition where less cooling water is by-passed.

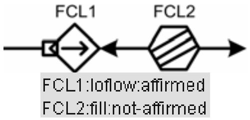


Figure 4.2.3: Casual path 3 (below) and corresponding MFM functions (above) for scenario 4.2.

5. Conclusion and Future Work

MFM based means-ends functional modeling is highly useful in assessment and diagnosis of disturbance situations. It models a system on the basis of its objectives and capabilities and provides explicit constructs for representing casual relations which determines the flow of control and disturbances. This kind of modeling is showing promising results for development of intelligent supervision and control systems in various industrial fields like chemical process plants, nuclear power plants, bio-informatics and electricity transmission networks; particularly in complex situations where limited human cognition abilities are unable to cope with the growing complexity of industrial process plants and systems. Continuous and sustainable research is going on in this field for further advancements. One of the desired goals for near future is to use diagnosis advice provided by the current system and generate a plan for restoration. Also work is going on to improve the MFMWorkbench software in order to make the modeling process easier for users.

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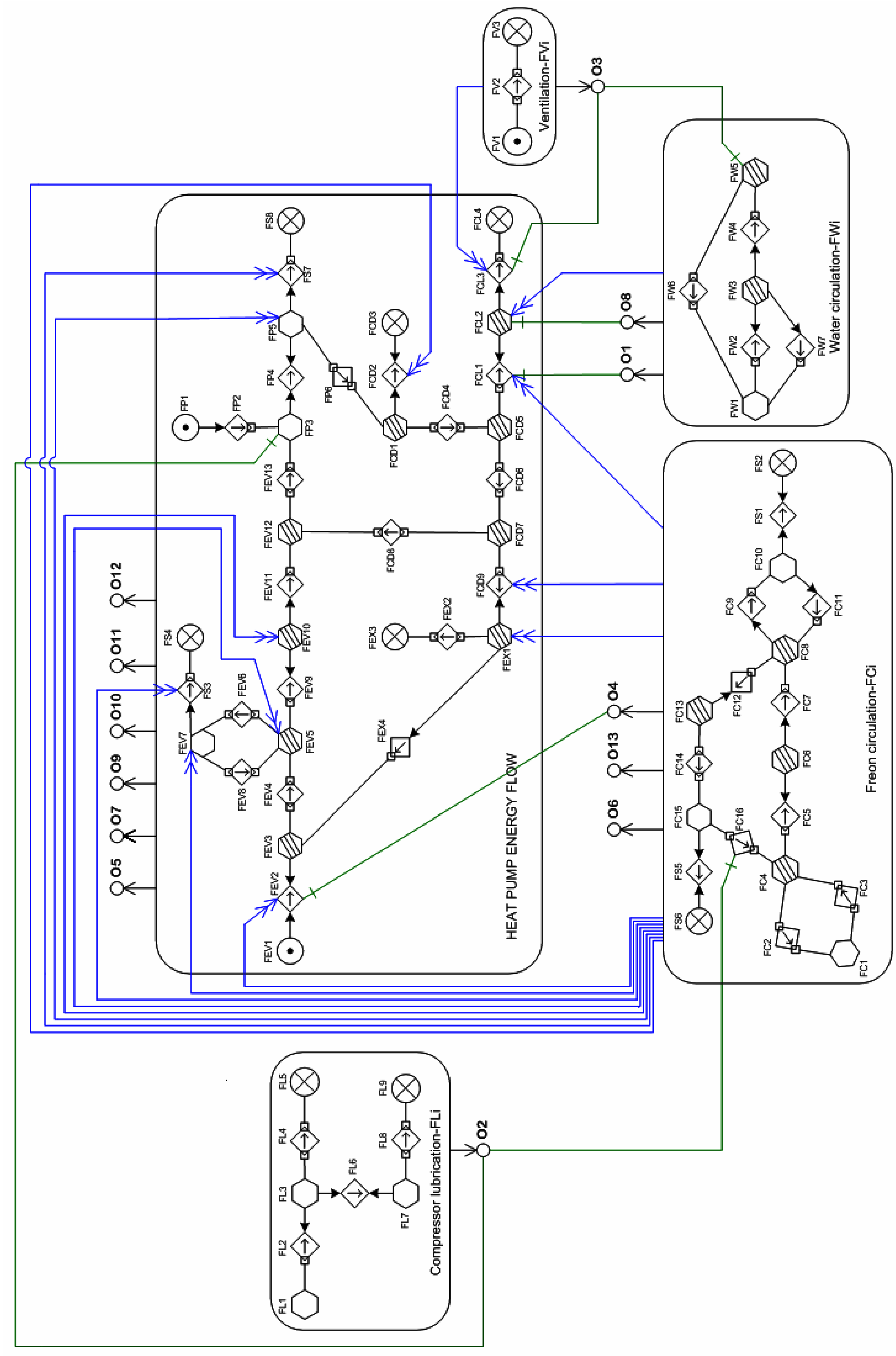
Appendix A



Multilevel Flow Model of Industrial Heat Pump System

Appendix B

Table B1: Descriptions of flow function in MFM model of the Industrial Heat Pump System

FVi	**Ventilation**
FV1	Suction of air by propellers from environment
FV2	Transport of air through air coolers
FV3	Ventilation of hot air to atmosphere
FWi	**Cooling Water Circulation**
FW1	Presence of cooling water in the system
FW2	Transport of cooling water to CV8
FW3	Allowing circulation through air fans or by-passing
FW4	Transport of cooling water to air coolers
FW5	Cooling of water while circulating in the ACOOL
FW6	Transport of cold water coming from air fans to HESCOND
FW7	Transport of by-passed water to HESCOND
FLi	**Compressor Lubrication**
FL1	Storage of compressor oil for supplying additional oil
FL2	Oil suction via inlet valve to compressor
FL3	Storage of oil in compressor while splash lubricating
FL4	Transport of oil to environment when undesirable leaks occur
FL5	Oil leaking to environment
FL6	Transport of shared excess oil to the other compressor
FL7	Storage of oil in other compressor while splash lubricating
FL8	Transport of oil to environment when undesirable leaks occur
FL9	Oil leaking to environment from the other compressor
FCi	**Freon Circulation**
FC1	Storage of Freon in the receiver
FC2	Taking of excess Freon to the receiver
FC3	Releasing certain amount of Freon to throttle valve
FC4	Feeding system with liquid Freon
FC5	Transport of sub-cooled Freon to the throttle valve
FC6	Expansion of high pressure Freon by means of throttle valve
FC7	Transport of Freon liquid vapor mixture to GLSEP
FC8	Separation of vapor phase Freon from liquid phase
FC9	Transport of liquid Freon to the collecting vessel
FC10	Storage of liquid Freon in GLSEP
FC11	Transport of possible Freon vaporizing from collecting vessel
FC12	Transport of Freon vapor to control valve CV9
FC13	Manipulation of Freon flow rate entering to HECI
FC14	Transport of Freon after compressors before SV2
FC15	Presence of Freon after compressors till receiver
FC16	Transport of Freon passing through condensers entering receiver
FEVi	**Freon Evaporation**
FEV1	Providing heat to Freon for evaporation (heat transfer from distillation column condenser)
FEV2	Transfer of heat from distillation column condenser to Freon via HECOND
FEV3	Evaporation of low pressure Freon due to heat transfer from distillation column condenser
FEV4	Transfer of energy to GLSEP as gas-liquid mixture because of partial evaporation
FEV5	Separation of Freon gas from the mixture
FEV6	Collection of liquid Freon droplets in the collecting vessel
FEV7	Storage of liquid Freon in the collecting vessel
FEV8	Vapor Freon evaporating from collecting vessel
FEV9	Transfer of freon gas to the control valve CV9
FEV10	Manipulation of Freon energy entering to HECI by means of Freon flow rate manipulation
FEV11	Transfer of heat of Freon to r HECI (cold side)
FEV12	Transfer of heat coming from receiver outlet high pressure Freon (hot side) to compressor inlet low pressure Freon (cold side)
FEV13	Transfer of superheated Freon vapor to the compressors
FPi	**Freon Compression**
FP1	Supplying electricity to electric motors of compressors
FP2	Transfer of electric power to compressor engines
FP3	Compression of superheated Freon vapor via conversion of mechanical work to heat by means of cylinders
FP4	Transfer of freon after compression before safety valve SV2
FP5	Presence of freon after compression
FP6	Transport of superheated high pressure freon vapor to HERB
FCDi	**Freon Condensation**
FCD1	Partial condensation of superheated high pressure Freon through HERB
FCD2	Transfer of heat released from Freon condensation to the re-boiler
FCD3	Supply heat to re-boiler
FCD4	Transfer of partially condensed Freon energy to HESCOND
FCD5	Total condensation of Freon vapor through HESCOND by means of releasing heat to the cooling water
FCD6	Transfer of totally condensed Freon to HECL (hot side)
FCD7	Heat transfer from high pressure liquid Freon (hot side) to low pressure Freon vapor (cold side) through HECI
FCD8	Heat exchange between receiver outlet high pressure Freon (hot side) and CV9 outlet low pressure Freon (cold side)
FCD9	Transfer of sub-cooled high pressure liquid Freon energy to throttle valve
FCLi	**Freon Cooling**
FCL1	Heat transfer from partial condensate freon to cooling water
FCL2	Manipulation of cooling rate by means of CV8
FCL3	Heat transfer from cooling water to air coolers
FCL4	Release of heat to atmosphere
FEXi	**Freon Expansion**
FEX1	Expansion of high pressure low temperature subcooled Freon by means of throttle valve
FEX2	Transfer of friction loss during expansion
FEX3	Release of lost energy to environment
FEX4	Transport of low pressure low temperature Freon gas liquid mixture to HECOND
FSi	**Safety Functions**
FS1	Transport of Freon via SV1 to environment from GLSEP
FS2	Release of Freon from safety valve 1
FS3	Transfer of Freon energy to environment by means of SV1
FS4	Release of Freon energy
FS5	Transport of freon via SV2 to environment after compressor
FS6	Release of freon from safety valve 2
FS7	Transfer of freon energy to environment by means of SV2
FS8	Release of freon energy via SV2

Table B2: Explanations of objectives ans their main functions in MFM model of the Industrial Heat Pump System

Objective	**Main function**	**Explanation**
1	FW3	Maintain cooling water flow
2	FL3	Maintain compressor lubrication
3	FV2	Maintain air flow through air coolers
4	FC16	Maintain freon circulation
5	FCD3	Provide indirect heat transfer from condenser to re-boiler
6	FC13	Avoid feeding compressors with liquid freon
7	FCD8	Provide heat exchange between REC outlet and HECI inlet
8	FW3	Provide cooling rate manipulation
9	FEV2	Maintain heat transfer from distillation column condenser to freon
10	FCL1	Maintain heat transfer from freon to cooling water
11	FCL3	Maintain heat transfer from cooling water to air coolers
12	FEX1	Maintain expansion of freon through throttle valve
13	FS1	Provide operation between safety limits

Table B3: Explanations of goals in MFM model of the Industrial Heat Pump System

Goal	**Explanation**
G0	Proper, stable, flexible and safe heat pump operation
G1	Upgrading the low temperature heat released from the distillation column condenser to high temperature media re-boiler via work input given by compressors
G2	Flexible operation for changing demands in heat pump operation
G3	Protection of compressors from malfunctioning

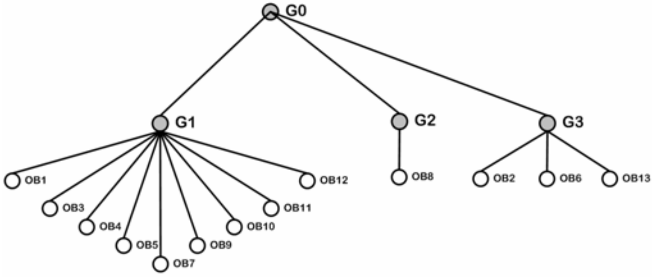


Figure B1: Goal-objective structure in MFM model of the Industrial Heat Pump System

Paper VIII:

Saleem, A. Lind, M and S. Singh. Modeling Control Situations in Power System Operations. In proceedings of the International Conference on Autonomous and Intelligent Systems AIS 2010, Porto, Portugal

Modeling Control Situations in Power System Operations

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***Abstract*—Increased interconnection and loading of the power system along with deregulation has brought new challenges for electric power system operation, control and automation. Traditional power system models used in intelligent operation and control are highly dependent on the task purpose. Thus, a model for intelligent operation and control must represent system features, so that information from measurements can be related to possible system states and to control actions. These general modeling requirements are well understood, but it is, in general, difficult to translate them into a model because of the lack of explicit principles for model construction. This paper presents a work on using explicit means-ends model based reasoning about complex control situations which results in maintaining consistent perspectives and selecting appropriate control action for goal driven agents. An example of power system operation and control has been described using the multilevel flow modeling approach.**

***Index Terms*—Power system operation, Intelligent control, Multi-agent systems, Means-ends reasoning, Situation awareness, Multilevel flow modeling.**

I. INTRODUCTION

DUE to the deregulation of the electricity markets, the operation and control philosophy of the power system has been changed from the traditional power systems (centralized to decentralized decision making). The operation and control of power system is becoming more complex due to its distributed nature, multiple interactions and uncertainties. The modeling of power systems for intelligent control is therefore challenged in coping with the increased complexity. Thus, available modeling concepts for intelligent control do not assist the model builder in the selection of model content i.e. in deciding what is relevant to represent for a particular reasoning task and thereby faced with a difficult interpretation problem.

Power system models used for intelligent operation and control are highly dependent on the task purpose. The level of detail and abstraction of the model must comply with the needs of the task to be solved. Thus, a model for intelligent operation and control must represent system features, so that information from power system measurements can be related to power system disturbances and possible counteractions. These general requirements to models for intelligent control are well understood, but it is in general difficult to implement the requirements into a model. The main problem is the general lack of explicit principles for model construction which take into account task requirements.

For representing power systems, a variety of modeling concepts for intelligent operation and control has been proposed and several types of modeling tools have been developed. However, these tools do not assist the modeler in solving the fundamental modeling problem which is a problem of interpretation. The model builder is not assisted in the selection of model content i.e. in deciding what is relevant to represent for a particular reasoning task and for a specific power system. The model builder is therefore faced with a difficult interpretation problem. Within artificial intelligence (AI) research, this modeling challenge is referred to as the knowledge acquisition problem. The interpretation problem is accordingly not unique to power system operation and control but is generic. Lind [1] discussed the modeling problem in the context of process control.

In electricity markets [15], the perspective of the individual agent in decentralized multi-agent systems is based upon the goal or interest of the agent. Actions of each agent bring changes in its environment with have consequences reflected in the perspective of other agents. The classic agent behaviors which are primarily based upon discrete situation-action rules may therefore not be sufficient to cope with control situations in a dynamic environment. The agent may not make these decisions based on local knowledge alone and by executing behaviors based on discrete situation-action rules. It may also be necessary to consider the global situation including knowledge about the role played by the agent as member of a community of agents and the purposes and functions of the physical power system components and subsystems.

Awareness about control situations can be ensured if the agent has an internal model representing the context of its actions. Ideally, the agent should not only have a library of behaviors but should also have a knowledge base representing contextual knowledge required for handling abnormal situations. Such a knowledge base representing information about the control situation in a power system can be developed using multilevel flow modeling (MFM) [2]-[4]. The advantage of MFM is the ability to choose level of abstraction in the model of the power system so it matches the particular need or perspective of the agents and that relations between perspectives are logically defined. In this way, it can be ensured that the perspectives of the agents are consistent

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and are coherent with a global perspective of the system. MFM provides concepts for semantically rich modeling of agent's context of action and mechanism to perform reasoning on this model for diagnosing and developing action plans in dynamic control situations.

In the present paper, the interpretation problems in building models for intelligent power system operation and control are analyzed. Results of the analysis indicate that power system knowledge can be captured in a means-end and part-whole framework.

II. Multilevel Flow Modeling

Multilevel flow modeling (MFM) is an approach to modeling goals and functions of complex industrial processes involving interactions between flows of mass, energy and information [2]–[3], [5]. MFM has been developed to support functional modeling [4] of complex dynamic processes and combines means-end analysis with whole-part decompositions to model system functions at different levels of abstraction. System functions are represented by elementary flow functions interconnected to form flow structures representing a particular goal oriented view of the system (Fig. 1). Flow structures are interconnected in a multilevel representation through means-end relations, causal relations, control functions and structures. MFM is founded on fundamental concepts of action and each of the elementary flow and control functions can be seen as instances of more generic action types [6]. The views represented by the flow structures, functions, objectives and their interrelations comprise together a comprehensive model of the functional organization of the system represented as a hyper graph. It should be noted that MFM provides a formalized conceptual model of the system which supports qualitative reasoning about control situations [5],[10],[16].

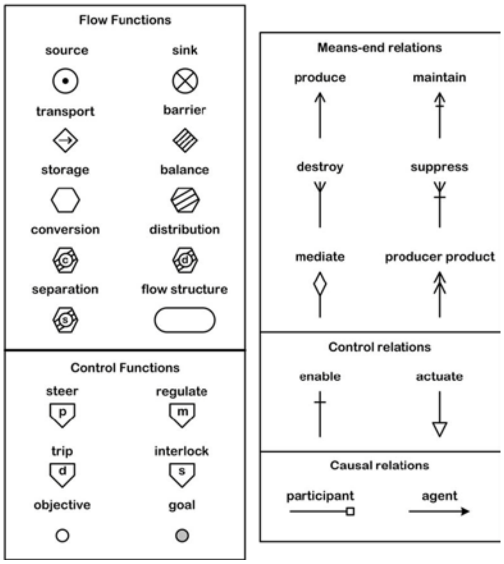

Fig. 1. MFM concepts

MFM has been used to represent a variety of complex dynamic processes including fossil and nuclear power generation [8], [9], oil refineries [10], chemical engineering and biochemical processes [11]. Application of MFM includes model based situation assessment and decision support for control room operators [16], alarm design [7] and planning of control actions [8], etc. MFM is supported by knowledge based tools for model building and reasoning [5]. The MFM concepts shown in Fig. 1 will be demonstrated below with a simple modeling example.

Application of the MFM concepts for modeling control functions is illustrated with a simple heat transfer system comprising a water circulation loop and associated support system for lubrication of the circulation pump as shown in Fig. 2. The example has been selected in order to serve the specific needs of the present paper. Thus we will only consider the functions involved in circulation of lube oil and the water and ignore the functions associated with the transfer of heat through the heat exchangers. The water circulation loop and the lube oil system are equipped with flow measurements FM1 and FM2 and associated controllers CON1 and CON2 dealing with lube oil and water flow regulation. The purpose of the example is to demonstrate how control and process functions are integrated in the MFM models.

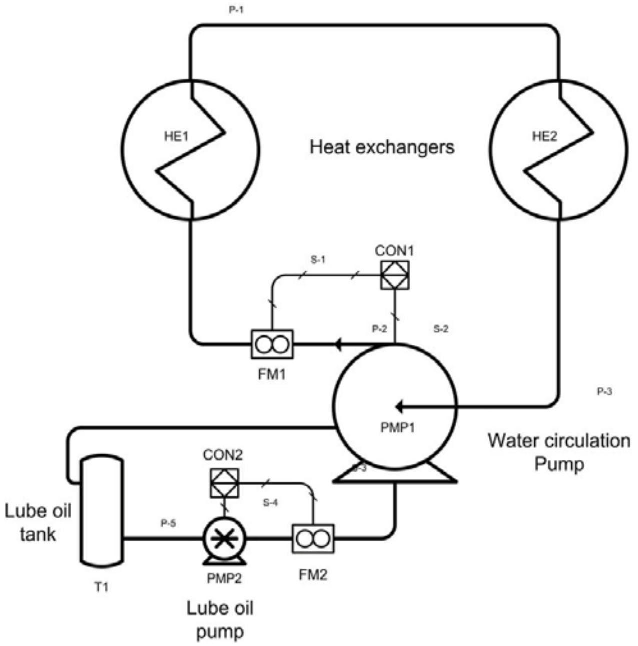

Fig. 2. Water circulation pump

Two models of the example system are presented. The first model excludes functions of the control systems. The second model show how the model is modified when the control system in the lube oil system and the water flow control are taken into account.

A. MFM model without control functions

The model in Fig.3 represents the goals and functions of the heat transfer system without control systems using MFM modeling concepts. On an overall level the model can be seen as composed of three sub-models representing different views on the water circulation system. The first view (starting from the top) represents systems aspects related to water circulation and comprises the flow structure labeled MFS1, a maintain relation and the objective O1. This part of the model represents the overall objective of the water circulation, which is to maintain a flow of water. The flow structure contains the functions provided to circulate the water. In this simplified model the transport function T1 is the means used for water circulation.

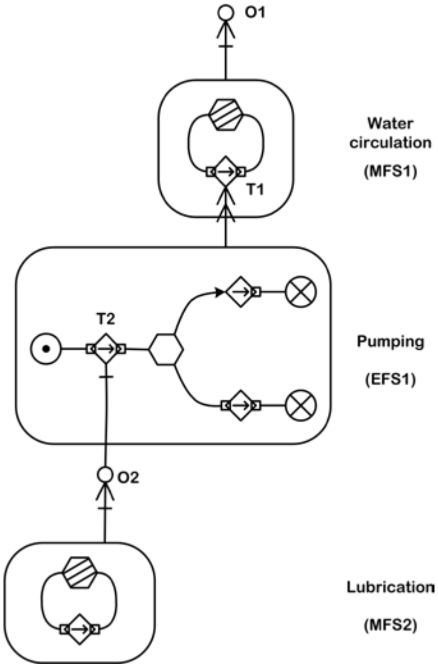

Fig. 3. MFM model without control functions

The second view is partially overlapping with the first view because what is seen here as a means (the transport T1) is in the second view seen as an end. Transport T1 is related to the means of transport which is the pumping represented by the energy flow structure EFS1. T1 and EFS1 are related by a type of means-end relation called a producer-product relation in MFM. The flow structure EFS1 is decomposed into the flow functions representing the services provided by components of the pump system (including the energy supply) in order to achieve the end, the transportation of water represented by T1.

The third view is related with the second view through the energy transport T2, an enable relation and an associated objective O2 which is the end to be maintained by the functions contained in the flow structure MFS2. The flow structure MFS2 represents the functions involved in the lubrication of the pump and the objective O2 represents the condition that should be fulfilled in order to ensure that the pump is properly lubricated. The flow functions inside MFS2 accordingly represent the functions of the pump lubrication system. Even though the simple example does not utilize all the concepts of MFM, it demonstrates the power of MFM to represent in a clear and logical way relations between the goals and functions of a system.

B. MFM model with control functions

The model shown in Fig. 4 describes the functions of the components and subsystem which contributed to the overall objective of the system (deliver water flow) [12]. No consideration was given to the purpose and function of control systems in meeting this objective. As is well known control systems are important for ensuring that process objectives are met in spite of uncertainty and disturbances in the process. This is actually one of the basic reasons for using control systems. We will now show how the concepts for modeling control functions in MFM are used.

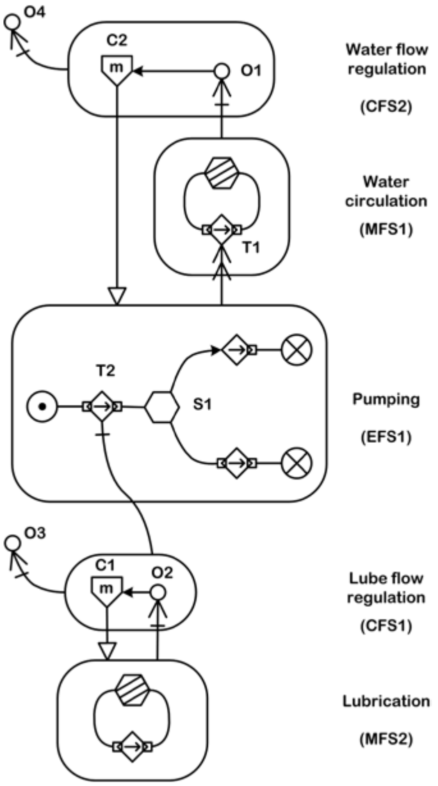

Fig. 4. MFM model with all control functions

C. Regulation of lubrication flow

Assume that we need to keep the lubrication flow in the pump within specified limits in order to avoid pump problems. An engineering solution to this problem could be to use a regulator measuring the oil flow and controlling the speed of the oil pump (FM2 and CON2 in Fig. 1. The function of the regulator is to maintain oil flow within limits. This function can be modeled in MFM as shown in Fig. 4. The regulator function is represented by C1.

Note that we have introduced a new objective O3 in addition to the original objective O2. It is very important to emphasize the fundamental difference between these two objectives. O2 is a “process” objective specifying the value range within the lubrication flow should be kept. In contrast O3 in a “control” objective specifying the performance required of the regulated process. The control objective could specify stability margins etc. and other control attributes specifying the desired performance of the regulator.

D. Regulation of water flow

Assume that we also must to keep the water flow in the circulation loop within specified limits in order to support the heat exchange process. The solution is here to use a regulator measuring the water flow and controlling the speed of the circulation pump (FM1 and CON1 in Fig. 2. The function of the regulator is to maintain water flow within specified limits. The MFM model shown in Fig. 4 shows how this control function can be represented by an extension of the model shown in Fig. 3. The function of the water flow regulator is represented by C2. The actuation relation is pointing towards T2 representing the means of control used (transport of energy to the pump rotor whose function is represented as an energy storage S1). Objective for C2 is represented by O4.

III. MFM MODEL OF THE POWER SYSTEM

To demonstrate the effectiveness of MFM model, a small power system having four generators and four (aggregated) loads is considered as shown in Fig. 5. It is assumed that both loads and generators are controlled by smart controllers (load and generator agents), and that there is a regulator agent, responsible for overall power balancing while maintaining the power system security. These agents have the capability to react to changes in environment and choose appropriate action to respond the changes.

A. MFM Model of the Power System

Fig. 6 presents a MFM model of system shown in Fig. 5, based on the modeling principles presented in section II. The model contains three views of the power system: an overall systems' view, the view of one of the generator agents (Gen-3 (G3) is shown) and a load agent (L4 agent). Views for the other generators and loads are not included for simplicity of the presentation. The model which provides a coherent representation of the different views of the agents and a representation of the relations between the views to be used for reasoning about alternative control actions has been described below [13],[14].

1) System's view: overall balancing and secure optimal dispatch: The part of the model comprising O_2, F_{SCH1}, O_4, F_{SCH2} and F_{SCH3} represent the view of system related to the task of overall balancing and secure optimal dispatch. This is a view of regulation and operation of grid resources. Grid resources comprise four generators represented by MFM source functions So_{G1}, So_{G2}, So_{G3} and So_{G4}; and four loads represented by MFM sink functions Si_{L1}, Si_{L2}, Si_{L3} and Si_{L4}. Furthermore the storage function labeled Ba_1 represents the total rotating inertia in the system. The functions included in the flow structure represent accordingly the resources involved in the balancing of power in the example case. The transfer of secure and optimal power from the generators to the loads is represented in MFM by the transport functions Tr_{G1}, Tr_{G2}, Tr_{G3}, Tr_{L1}, Tr_{L2}, Tr_{L3}, Tr_{L4}. Since the control strategy adopted is decentralized, this view gets realized by the individual actions of the agents.

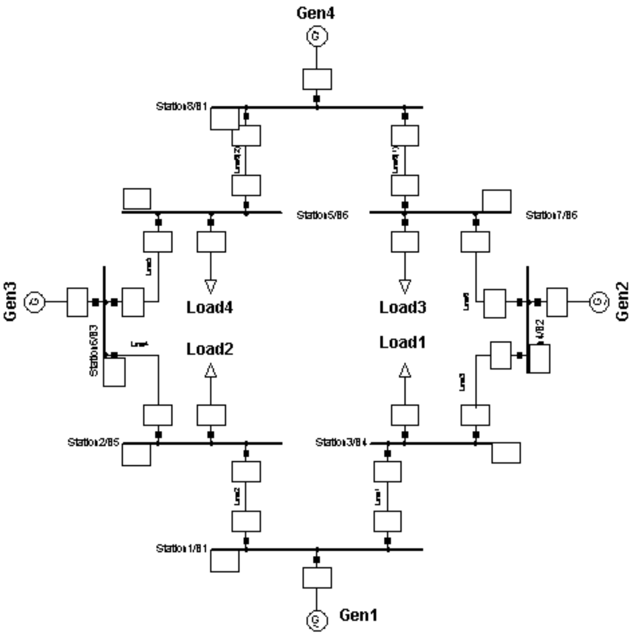

Fig. 5. The power system example

2) The view of Generators: The view of Gen-3 (G3) is representing how the generator agent sees the control situation. From the perspective of the system, Gen-3 is simply a power source So_{G3}. But from the perspective of the generator agent, the grid is a power consumer or sink represented by Si_{G3} and the power source feeding the generator is So_{G3}. The inertia of generator Gen-3 is represented by an energy storage function St_{G3}.

Table I
THE GOAL, STATE AND CONTROL ACTION OF THE POWER SYSTEM

Agent	Goal	State	Control intention
Regulator	balancing and secure optimal dispatch	network congestion	dispatch new set-points to Gens
		load-demand imbalance	
L4 Agent (global perspective)	voltage stability at node	voltage drooped at node	look for regulation service
L4 Agent (local perspective)	consumption of required power	un-availability of required power	request more active power
Gen-3 Agent (global perspective)	deliver of power to network	frequency drop at node	inertia response
Geh-3 Agent(local perspective)	maximize production / earn profit	demand for more power from network	provide more power

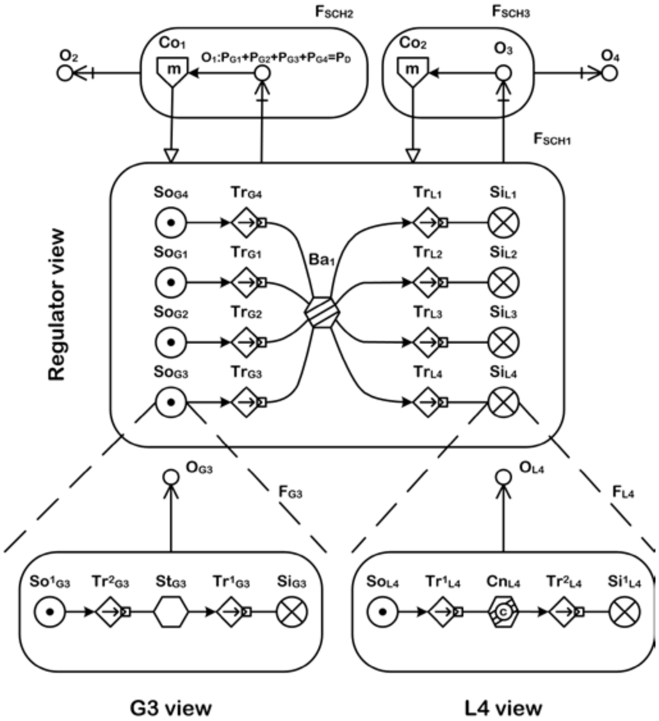

Fig. 6. Views of the regulator, generator and load agents

The goal to be achieved by the generator agent is represented by O_{G3}. The goal specifies the power to be delivered to the grid.

3) The view of Loads, L4: The view of L4 is representing how the load agent may see the control situation. From the perspective of the system, L4 is simply a power consumer or load Si_{L4}. But from the perspective of the load agent, the grid is a power source represented by So_{L4} and the power consumer is represented by Si^1_{L4}. Note that Si_{L4} in F_{SCH1} is not the same as Si^1_{L4} in F_{L4}. The conversion of the power in the load from the electric energy e.g. to another form of energy is represented by the conversion function Cn_{L4}.

4) Relations between the three views: The relations between the views are indicated above. However, the MFM language allows systematic expansion and aggregation of functions so that e.g. the system’s view may be expanded by incorporating the views of G3 and/or L4. In a service oriented agent architecture, this expansion could be done either as a demand from the system or could be done by the G3 and L4 agents explaining how they see the situation.

B. Representing the control situations in MFM

The imbalance situation and its interpretations by the three agents presented above in table can be expressed explicitly by the MFM model in Fig. 6. How this is done will be explained briefly in the following.

1) The regulator agent: The goal of the regulator agent is to ensure overall balancing and perform secure and optimal dispatch of power. With its goal, the agent will perceive the situation as a load-demand imbalance in a secure and optimal way. The imbalance can be expressed in the flow structure F_{SCH1} as a deviation from the normal pattern of energy flows delivered by the four sources So_{G1}, So_{G2}, So_{G3} and So_{G4}; consumed by the four sinks Si_{L1},Si_{L2},Si_{L3} and Si_{L4}. Within the view of the regulator agent, the control action will be to restore the situation by dispatching new set points of four generators under any imbalance. F_{SCH3} solves the network congestion problem for optimal dispatch whereas F_{SCH2} assigns new set-points to respective generators.

2) The agent L4: The agent Load4 has two alternative goals as shown in Table I. Depending on the goal chosen the agent will take appropriate action. If the goal is to ensure voltage stability and the situation , therefore, is interpreted as a voltage droop problem, the control action of the agent is to request a regulation service. The voltage is here seen as an attribute of the source So_{L4} which represent the network as seen in the view of L4.

If the goal of the agent is to ensure consumption of required power and the situation, therefore, in this case is interpreted as a problem if unavailability of required power, the control action of the agent is to request more active power. The power is here seen as an attribute of the source.

3) The agent Gen-3: The agent G3 has also two alternative goals as shown in Table I and again depending on the goal chosen the agent will take appropriate action. If the goal is to deliver power to the network and the situation therefore is interpreted as a frequency drop problem, the control action of the agent is to execute an inertia response. The inertia is represented by the storage function St_{G3} and the response will be a temporary increase in the power flow represented by the transport Tr_{G3} caused by an increase in the energy stored by St_{G3}. This causal relation is represented in the MFM model by an arrow pointing towards the transport function (the agent relation shown in Fig. 1).

If the goal of the G3 agent is to maximize production in order to earn profit and the situation therefore is seen as a demand for more power from the network, the control response will be to provide more power by increasing the flow attributed to the source So_{G3}. The network is in this view seen as a sink Si_{G3} and the power demanded is an attribute of this function.

IV. CONCLUSIONS

This paper presents the problem of interpretation in complex control situations of electric power systems. The importance of being able to reason explicitly about different views on a control situation is explained. It is shown that multilevel flow modeling can provide model based support to explicit means-ends reasoning and handling of views. The application of explicit means-ends models provides a novel extension of the classic belief-desire-intention BDI paradigm of multi-agent systems. A power system example demonstrates the importance of means-end and part-whole concepts in modeling and intelligent control of complex power systems.

V. ACKNOWLEDGEMENT

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Paper IX:

Saleem, A. Nicholas Honeth and Lars Nordstørm. A Case Study of Multi-Agent Interoperability in IEC 61850 Environments. In Proceedings of the Innovative Smart Grid Technologies Europe, Gothenburg, Sweden. 2010.

A Case Study of Multi-Agent Interoperability in IEC 61850 Environments

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*Abstract***—The IEC 61850 is the most promising standard for design of substation communication and automation systems. On the other hand multi-agents systems are attracting growing interest for different applications of substation automation systems. In multiagent systems agents represent different stake holders in the power system and based on implemented decision making logic they determine optimal operational conditions for the power system's given boundary conditions. Interoperability is of course a necessary pre-requisite for such architectures. Here we identify two aspects of interoperability; horizontal and vertical. Horizontal interoperability is relies on common semantic models of the power system that the agents can use to make decisions. One such semantic model is presented in the IEC 61970 Common Information Model (CIM). At this level, the IEC 61850 standard provides a model for access to information and control functions that has the necessary flexibility needed. In this paper we discuss the mapping between a multi-agent based architecture for power system control and the IEC 61850 standard for utility automation. The mapping is based on a use-case drive approach, in which the information exchange need is defined by the multi-agent system.**

*Index Terms***— multi-agent systems, power systems control and protection, industrial application multi-agent systems, power systems control and protection, industrial applicationa**

I. INTRODUCTION

The development towards a sustainable energy system in the electric power industry has lead to the emergence of a set of market models and new concepts for optimized operation and control of power systems, e.g. Virtual Power Plants and Microgrid. In these new concepts, the traditional stake holders are complemented by new actors that take roles such as aggregator, prosumer, dispatchable load etc. Common to all these concepts is that they assume a more flexible and loosely coupled ICT system architecture. In such architectures, ICT components communicate to implement optimization, control and protection functions. One approach to such architectures is the use of multi-agent system. The agents represent different stake holders in the power system and based on implemented decision making logic they determine optimal operational conditions for the power system given boundary conditions.

Interoperability is of course a necessary pre-requisite for such architectures. Here we identify two aspects of interoperability; horizontal and vertical. Horizontal interoperability is relies on a common semantic models of the power system that the agents can use to form decisions. One such semantic model is presented in the IEC 61970 Common Information Model (CIM). The CIM has the constructs necessary to represent knowledge about the complete power system that the agents need for optimized decision making. Vertical interoperability is concerned with making the agent-based architecture interact with contemporary automation, protection and control systems in substations and power plants. At this level, the IEC 61850 standard provides a model for access to information and control functions that has the necessary flexibility needed. In this paper we discuss the mapping between a multi-agent systems MAS based architecture for power system control and the IEC 61850 standard for utility automation. The mapping is based on a use-case drive approach, in which the information exchange need is defined by the multi-agent system. Based on this need, interaction patterns with logical nodes (LN) as defined in the IEC 61850 are identified. The mapping also enables interaction at different levels of abstraction with the IEC 61850 based systems.

Rest of this paper is organized as follows:

Section II introduces fundamental concepts of agents, multi-agent systems, IEC 61850 and related standards. It also introduces the problem of protection and control in electric power systems with distributed generation which provides the study case used in this paper. Section III describes our approach for MAS to IEC 61850 mapping. Section IV presents application of our approach in a study case and discusses the results. Section V concludes the paper.

II. RELATED WORK

This paper combines the formalisms of agent-based control with the nomenclature of IEC 61850. In this section, these topics are dealt with separately after which other work that combines them is discussed.

A. Multi-Agent Systems

The fundamental concept of software agent is defined as:

An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives.[10]

Agents are elaborated by a metaphore commonly known as BDI (Belief, Desire, Intention). Beliefs represent knowledge of an agent about its environment. The Beliefs are captured through sensors of the agent and stored in an internal data base. This data base (also commonly called knowledge base) should be properly organized, updated and synchronized to other functions, e.g. decision making of the agent architecture. The Desires are goals or design objectives of an agent (or of the systems agent is part of). Desires not only sets the criteria for rationality of an agent but also defines the nature and level of autonomy for agents. Intentions is the way agents attempt to achieve their design goals. In agent oriented software engineering intentions are modeled as behaviors. A behavior of an agent may consists of a single or multiple actions and lead to a achievement of a goal or a sub goal.

Multi-agent systems (MAS) are systems consisting of more than than one agent. MAS are useful to implement in application areas that are naturally distributed, decentralized and are easy to be decomposed in their design. A system architecture based upon MAS provides a natural way of decomposing a software system into subsystems and to model interactions between these subsystems and individual components (agents) within the subsystems.

B. Protection and Control in Electric Power Systems with Distributed Generation

Introduction of distributed generation in medium and low voltage grids has brought challenges in functions of protection and control. New approaches suggest increasing use of modularity and communication. The methods presented in [6], [9], [5], [8], [4], [7] are among many works that propose the use of multi-agent systems for protection and control in electric power systems. Both [6] and [9] propose methods that utilize agent-based zoning for use in distribution networks. In these schemes, agent-controllers are placed at the zone borders and at DG sources withing the network. By interactively comparing measurement data and coordinating effector capabilities at different locations in a distribution network, various protection, monitoring and control functions can be implemented. Such distributed functions can include fault location and restoration [9], [4], current differential protection [6], islanding [7], adaptive load shedding [2] and voltage regulation [8].

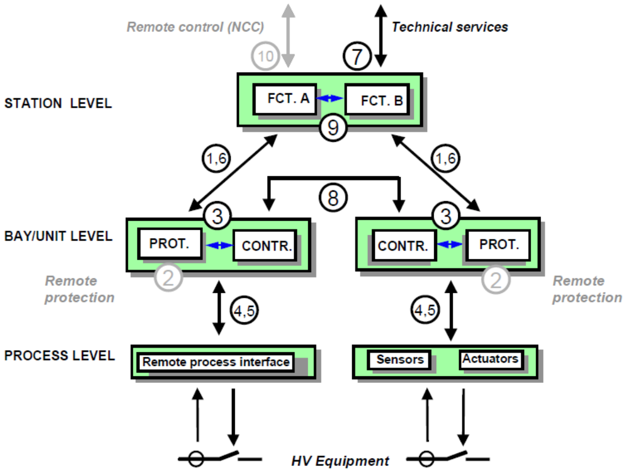

Fig. 1. Functional levels and logical interfaces defined in the IEC 61850 standard.

C. IEC 61850 and related standards

The IEC 61850 series of standards for communication networks and systems is intended to provide interoperability between Substation Automation Systems (SAS) [1]. It provides a specification for the communication between Intelligent Electronic Devices (IEDs) and related SAS equipment. Furthermore, it describes the requirements of the functions implemented in SAS, not to attempt to standardize the functions themselves but to specify the communication between them.

A subset of the functions that are described in [1] fall into the category of distributed functions. The standard defines these as the set of functions where it's subparts, called Logical Nodes (LNs), are located on different physical devices. While all functions communicate with each other, the process that they are controlling, monitoring or protecting, distributed functions are dependent on the execution of a set of defined functional steps for their functionality. The loss of any of the constituent LNs could mean that the function would be blocked or that it would be functionally degraded.

The IEC 61850 standard also defines a functional hierarchy where functions are classified in terms of how closely they are situated to the substation process. Three main levels are defined:

- *bay level functions* - refers to the group of functions that are predominantly associated with a specific bay in the substation instance.
- *process level functions* - interface directly with the process, namely I/O functions such as data acquisition and issuing of commands.
- *station level functions* - refer to functionality that concerns the substation as a whole.

Figure 1 from [1] illustrates the functional hierarchy as well as shows the numbering of the standard interfaces between

LNs in different levels and between LNs situated on the same functional hierarchy level. Interfaces 2 and 10, shown in gray, are not defined in the standard. Interface 2 is reserved for use in remote protection functions on the same level on the control plane while interface 10 is the undefined vertical communication to SCADA or other remote control. The specification of communication via the remaining interfaces is the core of the IEC 61850 standard.

Communication between LNs at the station and bay levels occurs through interfaces 1 and 6, while between LNs within a station or bay are 9 and 3 respectively. Interface 8 supports direct communication between LNs in different bays, this is used to support functions such as interlocking.

Finally, interfaces 4 and 5 provide the communication channel between process and bay level functions. The use of a process bus specified in IEC 61850 is discussed in detail in [3]. The benefits that are pointed out are the increased level of interoperability between low-level devices that is achievable as well as the possibility for cost and operational optimizations that are not possible using more traditional methods where extensive copper wiring is required.

D. *Multi-Agent Systems and IEC 61850*

General objectives of this paper is similar to that of the work done in [2] which proposes the view of IEC 61850 and CIM to provide a standardized framework for application of MAS to electrical power protection, control, monitoring and recording. In [2] the author proposes a 1:1 mapping of agents to LNs in a SAS. Vertical interoperability is achieved by implementing LN functionality as an agent while the horizontal agent interoperability is by definition maintained. Agents are categorized by the functional level at which they are placed, these include the process, logical device, bay and substation level. The type of inter-agent communication and the interfaces used are defined by the functional level at which the distributed function implemented by the MAS is situated.

III. MAS TO IEC 61850 MAPPING

When considering the method for the extension of [2] in this paper, we use [9] as the basis for deployment of agents and the assignment of agent functionality. Figure 3 illustrates the agent placement used in the example in [9] that is described in section IV where a Distributed Generation (DG) agent is placed at each DG source and a relay agent is deployed at each zone border. The geographical locations of the the agents are also the location of the host physical devices or servers as they are referred to in [2].

The horizontal communication in the functional hierarchy occurs through logical interfaces 2, 3, 8, 9 and 10. All except interfaces 2 and 10 are specified by the IEC 61850 standard for communication between LNs. Interface 2 is allocated for implementation of remote protection functions. This bay-level horizontal communication should by definition be both reliable and low latency. The remote control interface 10 for vertical communication is intended for communication with SCADA or other high-level control.

The formalism proposed here is that a set of LNs are implemented in each MAS agent, this allows MAS integration to remain consistent with the IEC 61850 standard. More specifically, LNs that are implemented in the MAS (mostly at the station functional level) appear as standard LNs to all other LNs and communicate via the same interfaces using the protocols specified by the IEC 61850 standard. This allows complex distributed functions to utilize the cooperative, autonomous and pro-active capabilities of MAS-based control interoperably with IEC 61850-based SAS.

A. *Roles and control plan*

The control strategy presented in [9] specifies that an agent can assume a set of different roles. These roles fill different functionalities defined in a control plan. The role assigned to an agent can change due to changes in the state of the system control plan such as disappearance of an agent, appearance of a new agent, changes in agent capability, external trigger events or scheduled activities. The roles assumed by the agent and LNs assigned to each role are defined in the control plan.

The processes of generating a control plan and allocating roles proposed in [9] makes use of a transition function. The transition function maps a control plan, defined as a set of related roles, to specific world situations. The transition function is based on domain principles such as the laws of electromagnetism and control theory. Transitions are determined at design time. At run time, role assignment to agents based on the transition function are determined by means of an auction mechanism. A coordinating agent mediates the communication required to perform the role assignment. The assignment and realization of the roles to agents depends on the capabilities of the agent physical host devices.

B. *Logical Node Assignment*

Depending on the required functionality of the agent, sets of LNs that implement the functionality must be assigned to it accordingly. IEC 61850 LNs are selected such that they form the low-level ”atomic” functional units of control, monitoring and protection. Each agent must therefore implement IEC 61850 LNs for all of the low level functionality required by all roles that the agents are capable of assuming. Not all LNs are used simultaneously, different subsets of an agent’s LN set are used depending on the current role.

The LNs that the agent is capable of implementing will depend on the capabilities of the agent host physical device as well as which LNs lower in the functional hierarchy it can communicate with. Figure 2 illustrates the relationship between the agent itself, the roles it can assume, the LN set associated with a specific role and finally, how the

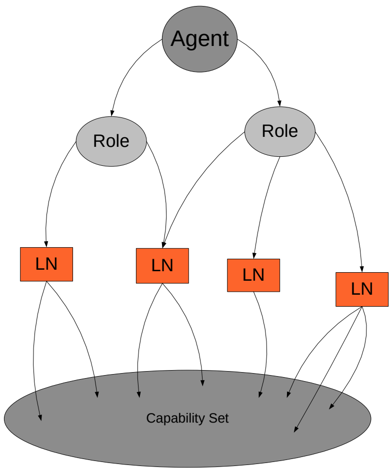

Fig. 2. Illustrates how an agent can assume various roles containing a set of LNs each which use different capabilities.

LNs are interact with the capabilities of the physical host device. Communication between LNs strictly follows IEC 61850 specification using for instance, logical interface 3 if the communication occurs between bay-level LNs in the same bay or interface 8 if the communication is between bays.

The scope of the functionality available to an agent LNs is determined by the capabilities accessible to the agent. Most of the capabilities are enabled through the process level LNs like XCBR, TVTR and XSWI. These LNs do not need to be implemented on the same device but need to be in communications with the agent physical host device using the IEC 61850 specified process interfaces. Communication between the process level LNs and bay level LNs occurs through the process bus labeled as IF4 and IF5 in the standard. Some bay level function LNs could be implemented by IED bay controllers as per the current norm while more complex distributed functions become well suited to implementation as agent LNs.

This method is consistent with the IEC 61850 standard for substation automation but allows complex functionality or functionality where stakeholders should be represented to be implemented on an agent platform that supports a high level of local control intelligence incorporated into LNs as well as the ability to negotiate and cooperate with other agents. Some larger distributed function LNs could be implemented on a group of individual but related agents while similarly, a group of closely related LNs could be implemented on a single agent platform logical device.

IV. EXAMPLE AND VALIDATION

In order to describe and validate the mapping formalism presented here, we apply it to the example agent-based protection and control scheme presented in [9]. Beginning with a brief explanation of agent decision models and description of the agent types used in the system. The portection and control system model is then mapped to the IEC 61850 formalism described in the preceding section.

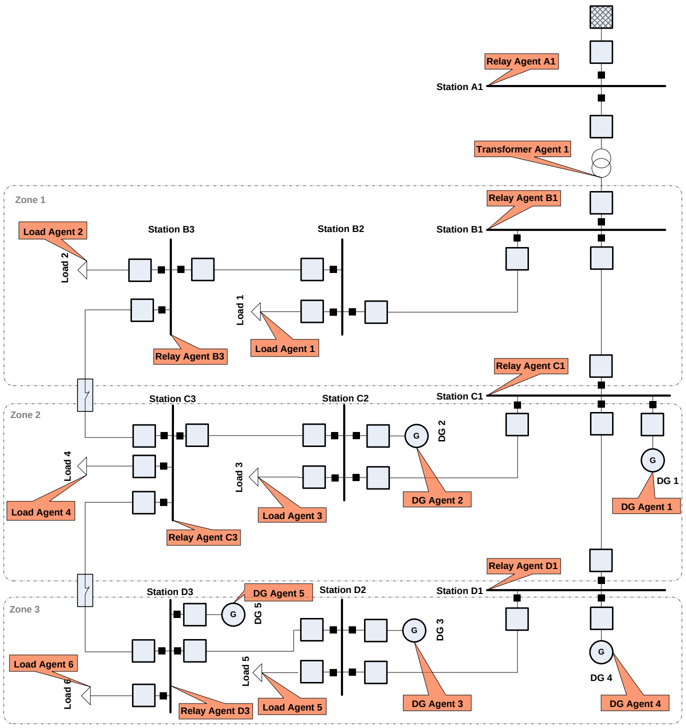

Fig. 3. Power system network used in example indicating assignment of agents.

A. *Agent Decision Models*

This subsection describes the decision models of three types of agents.

1) Relay Agent: The relay agent has a central role in proposed schema. There is one Relay agent at the start and end of each zone in the network e.g. R2 and R3 for zone II. They continuously monitor the state of the network, identify and respond to any changes or transition triggers. Relay Agents work as zone disconnecters with responsibility to separate a zone from the network. In normal condition, there is a steady state current flowing into the network and whenever a fault occurs due to, e.g., a short circuit, a high current (fault current) flows into the network. The value of this fault current is significantly higher than the normal current value in steady state. The relay agent gets triggered upon observing an unusual high current value and has three main tasks:

i: Direction of fault current:

In a fault scenario, current always flows form the current source to the fault location. Thus, to ensure that fault is inside the primary zone of a relay, the relay agent has to

TABLE I
DESCRIPTION OF AGENTS, SATES, ROLES AND CAPABILITIES

Agents	States	Roles	Capabilities	Actions
DG	stressed average relaxed disconnected	generator regulator	produce power freq. control	P++ P- - disconnect reconnect
Relay	faulted functioning faulted-zone cleared-zone	primary facilitator neutral blocked	monitor current monitor voltage	close reclose(open)
Load	critical non-critical	connected disconnected	self-shed	(re)connect disconnect

make sure that the direction of the fault current is into its primary zone at two zone connecting breakers i.e. the breakers which connect a zone to its neighboring zones, and at the DG connection breakers for all DGs inside the zone.

ii: Magnitude of fault current:

The relay agent has to ensure that one of the fault current measurements either from the zone connecting breakers or from the DG connecting breakers is greater than a certain threshold. This is necessary because in case some of the loads in the zone are served from DGs outside the zone, the current flows into the zone even in normal situation when there is no fault.

iii: Role assignment:

After a fault has been confirmed inside one of the zones, the job of each relay agent with the zone of its primary responsibility isolated from the main grid is to calculate energy balancing in its primary zone and assign new roles to DGs and loads inside the zone. This requires calculation of total generation and consumption of energy inside the zone and negotiation with DG and Load agents for participation in balancing. DG agents and Load agents calculate local cost functions based upon their current state and capabilities and communicate it with Relay agent. The relay agent based upon the value of cost function of each of these agents assigns them new roles. Thus, the job of Relay agent, in this case, is to determine a mapping function that takes current state and maps roles to specific agents based upon their capabilities, i.e.,

$$f_{tr}(S_{cur}, T_i, CP_{ini}) \Longrightarrow CP_{fn} \quad (1)$$

Where f_{tr} is the function that takes current state S_{cur} and a transition property T_i to map a chosen control plan CP_{ini} into a final control plan CP_{fn} with all roles assigned to specific agents. T is the set of transition triggers described in the previous section. Figure 4 describes the decision model of Relay agent.

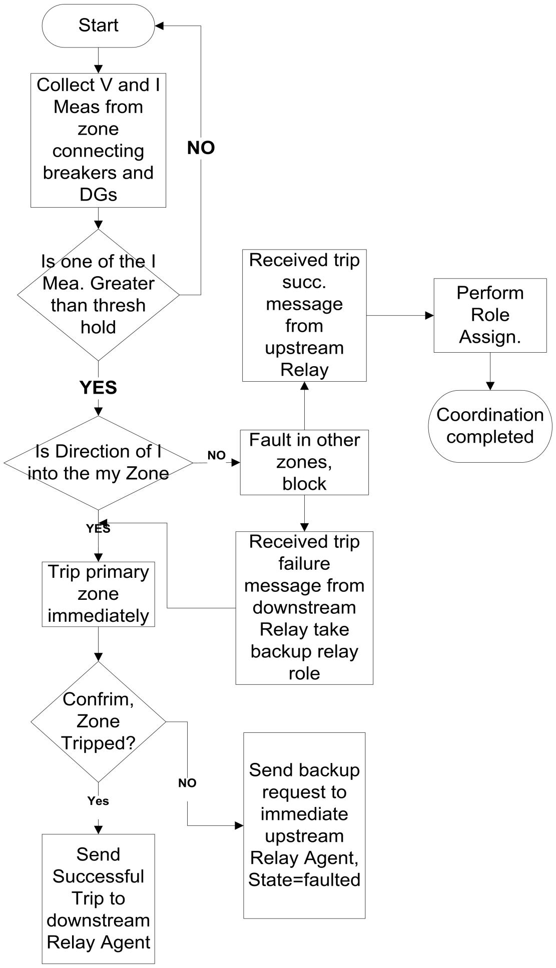

Fig. 4. Relay agent decision model.

2) DG Agent: DG agents represent distributed power generators in electrical network. Every DG agent, on receiving message from Relay agent, calculates its cost function. The cost function of DG agent is based upon its current state e.g. relaxed/average/stressed, and its capabilities e.g. ability to control frequency. The cost function of a DG agents is defined as:

$$\delta_c(S_{cur}, C_{cur}) \Longrightarrow U_{role} \tag{2}$$

i.e., the cost function is a function that maps current state of DG agent S_{cur}, and current capabilities C_{cur} into a role utility U_{role}. DG agent sends a bid based on the value of this cost function. Relay agent cumulates bids from all DG agents and sends back a message with a new role. DG agents upon receiving this message takes up the new role and start executing actions related to this role. A flow chart for decision model of DG agents is given in figure 5.

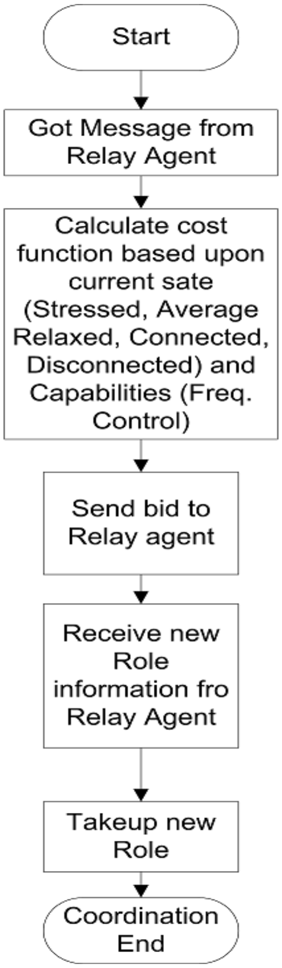

Fig. 5. DG agent decision model.

3) Load Agent: Load agents represent electric power loads in the network. Load agent, on receiving message from Relay agent, calculates its cost function. The cost function of load agent is based upon its current state e.g. critical/non-critical and the capabilities e.g. auto-shed. The cost function of load is given as:

$$\delta_c(S_{cur}, C_{cur}) \Longrightarrow U_{role} \tag{3}$$

it is a function that maps current state S_{cur} and current capabilities C_{cur} of load agent into a role utility.

After calculation of the cost function, load agent sends a bid based upon value of this cost function to Relay agent. Relay agent cumulates bids from all Load agents and sends back a message with a new role. Load agent on receiving this message takes up the new role. The decision model of load agents is same as that of DG agent with only difference of different set of capabilities and current states. Different possible states, roles, capabilities and actions for Relay, DG and Load agents are described in Table I.

B. MAS Protection and Control Mapped to IEC 61850

This section details the allocation of LNs in order to model the protection scheme from section IV-A. We begin by describing the LNs that are of interest after which the LN assignment and interaction is described.

The deployment of the various agents is shown in figure 3. For the Relay agents we assign the station-level LNs RFLO and PDIF, Load agents are assigned PIOC and MMTR while DG agents are assigned ZGEN and ARCO as shown in Figure 7. Relay agents are placed at the zone borders in order to monitor and control up and downstream flow from the zones.

Figure 6 shows the IEC 61850 style model of the collaborating parts of substations B1 and C1. It presents a modified version of figure 15 in the IEC 61850 standard which illustrates the LNs that define a distributed busbar protection system for a single substation. To illustrate the mapping onto the test scenario presented in this paper, the example is expanded to include two electrically connected substations which interact with each other in order to implement a distributed fault location LN RFLO.

In this case it makes sense to implement the lower level (process and bay level) LNs in dedicated logical device hardware such as IEDs and MUs . The closely related station level PDIF and RFLO LNs are collocated on the relay agent platform. The distributed function RFLO requires agent capabilities such as communication, negotiation, data consistency/quality management and intelligent pro-active control. The interaction between agents uses agent communication language (ACL) and utilizes the utility's IP-based wide-area-network for communication.

The process level LNs define the sensor and actuator equipment at the process level, a current measurement transformer in the example. Process level LNs are likely to use merging units (MU) as logical devices . Current samples are collected at process level and send via the process bus (most likely using GOOSE or GSE messages) to bay controller logical devices that are subscribers to the current sample data. Bay level LNs could be assigned to dedicated fast-response logical devices, they often include protection and safety functions

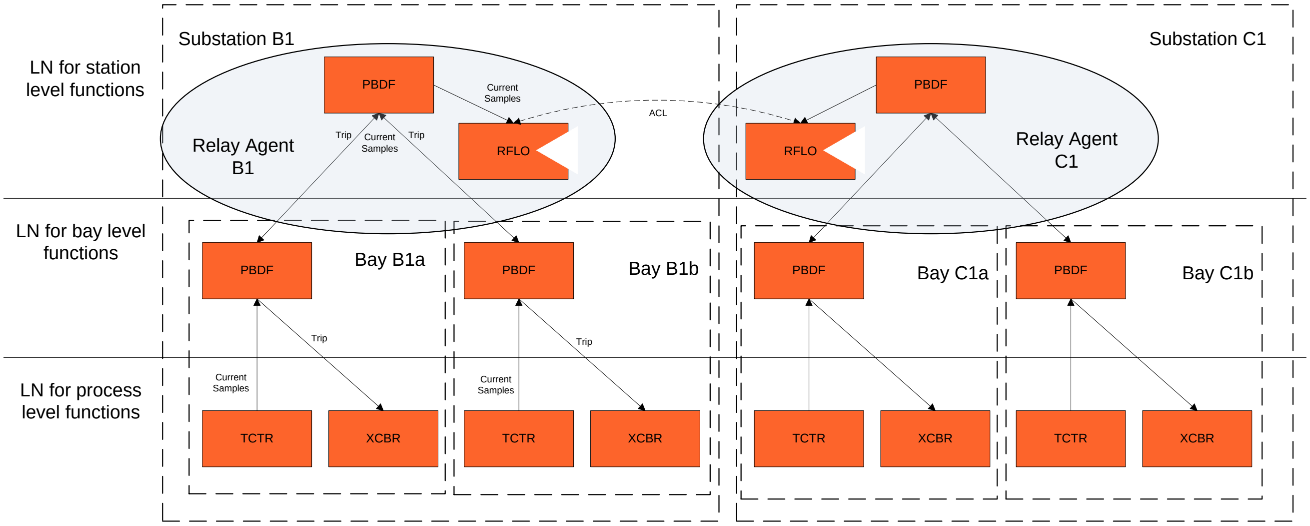

Fig. 6. Decomposition of functions into interacting LNs on different levels showing agent LN interaction.

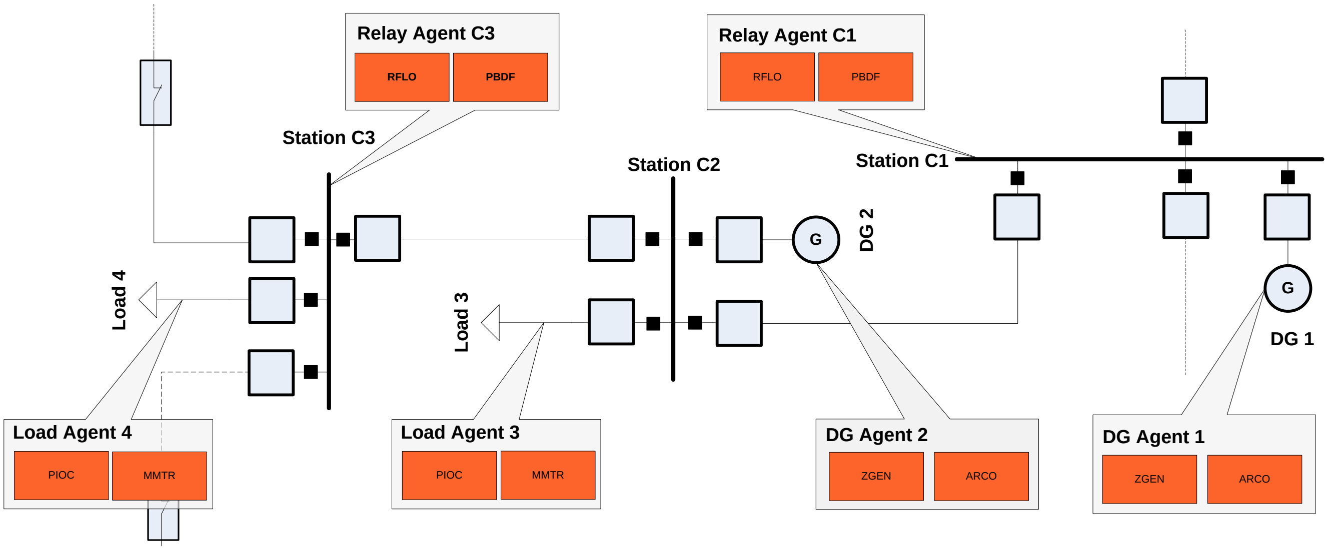

Fig. 7. Showing the mapping of high-level LNs to agents in zone C from Figure 3.

which must be verifiable in terms of reliability and response time. Station level LNs are more likely to require a high level of interaction and therefore are in some cases best assigned to agent platform based logical devices where distributed functions can be implemented across a set of agents.

V. CONCLUSIONS

In this paper we have shown the applicability of multi-agent systems for control and protection in electric power systems can be augmented by the integration of IEC 61850 communication principles.

By modeling the structure and communication of multi-agent functionality using IEC 61850 nomenclature there is the potential for seamless interoperability between modern SAS best-practices and sophisticated distributed intelligent control.

Applying the IEC 61850 functional hierarchy allows SAS design engineers the flexibility to make optimal choices in terms of the allocation of dedicated hardware for predictable response times or integration of functionality in general hardware to save costs and allow for integration for high-level distributed control.

Traditionally, the protection systems in electric power industry have utilized very little communication. With the adoption and integration of IEC 61850-enabled devices and the development of powerful, reliable distributed intelligent control methods that inter-operate transparently with these devices, the goal would be to realize a robust, scalable, secure and interoperable future electric power transmission and distribution system that adheres to well-developed and intuitive standards and best practices. We have therefore provided a mechanism which is robust to communication failure. In the worst case of total communication failure the result will be as good as that of from current common practice.

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Paper X:

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System-Awareness for Agent-based Power System Control

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Abstract

Operational intelligence in electric power systems is focused in a small number of control rooms that coordinate their actions. A clear division of responsibility and a command hierarchy organize system operation. With multi-agent based control systems, this control paradigm may be shifted to a more decentralized open-access collaboration control paradigm. This shift cannot happen at once, but must fit also with current operation principles. In order to establish a scalable and transparent system control architecture, organizing principles have to be identified that allow for a smooth transition.

This paper presents a concept for the representation and organization of control- and resource-allocation, enabling computational reasoning and system awareness. The principles are discussed with respect to a recently proposed Subgrid operation concept.

I. Introduction

Trends toward more renewable and decentralized power generation, small-scale demand controllability and ubiquitous energy storage challenge system operation as we know it. These elements increase requirements to operation flexibility. Even though they also increase control flexibility, the diversification of controllable resources would make it increasingly difficult for an operator to effectively utilize these resources. This paper presents a framework for addressing the complex interactions between System Operation & Control and associated resource allocation problems in the context of a more decentralized and flexible system operation paradigm.

Historically on the grounds of their business model, vertically integrated utilities would offer reliable electricity supply. The restructuring of electricity supply led to a separation of the reliability objectives from energy trade, which, as a side effect, led to a separation of market-aspects of energy-trade and engineering questions concerning security and control. Essential functions in the provision of electricity, known as Ancillary Services, had received less attention from market-oriented literature [1].

The primary objective of a power system operator remains to achieve and maintain secure system operation, reliably and economically. Intelligent analysis, design of control systems as well as operator support systems, including visualization, have enabled the continued secure operation of these systems.

In Denmark, which intends to supply about 50% of its electricity from wind power by 2025 [2], more frequent critical grid situations are expected. In the ECOGRID project[1], it has been suggested that distributed generation and additional controllable demand, such as heat pumps, should be actively integrated into grid operation [3]. This active contribution is expected to be facilitated by a more distributed control architecture that may also allow partial islanding operation, as demonstrated recently in the CELL project[2] [4].

These developments also imply a vision of an operation framework where changing grid conditions may lead to a decomposition of grid operation objectives. Operating responsibility would then be delegated to “subgrid-operators”, likely implemented by agent-based software. These agents would have to initiate control actions according to current system needs and allocate operating resources. Further, the local operating situation should be transparent to the higher-level operator.

In operation, deciding which information is relevant in a given situation, prioritizing operational objectives and keeping the overview of available control means, as well as informing higher-level operators about relevant changes in the operating situation are essential requirements. This is what we refer to as “system-awareness”.

With the goal of improving operator support systems, researchers in the domain of cognitive systems engineering have been looking into the information

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[1] http://www.energinet.dk/en/menu/R+and+D/EcoGrid/EcoGrid.dk.htm

[2] http://www.energinet.dk/en/menu/R+and+D/The+Cell+Project/The+Cell+Project.htm

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processes involved when operators make decisions (in process control). It was found that decisions about appropriate control actions require that information about the system state can be related to operational objectives. One influential approach, [5], established the relevance of whole-part and means-ends abstractions for operator decision-making. Moreover, the "decision ladder" explains lower and higher levels of information processing and how they relate to states of knowledge and decision-making, which has also been introduced in [5].

Future operator support systems will thus require representations, which are sufficiently simple and can be related to the overall grid situation. What is required to achieve this kind of transparency of intelligent control systems? Which types of decisions should be left to human operators, and what kinds of information do they require to make "good" decisions? These questions motivate our ongoing work on Functional Modeling and Intelligent Systems applications in Power Systems [6]–[8].

A. Relevance of ICKT for Distributed Resources

One common trend is to address these challenges to coordination and control of distributed resources by information, communication and knowledge technologies (ICKT) [3]. Notably, in the Homebots [9], CRISP[3] and INTEGRAL[4] projects the value of intelligent agents and knowledge modeling approaches for the integration of distributed generation has been developed. Also systems-of-systems engineering approaches, utilized in some American projects (e.g. Intelligrid[5], GridWise[6] and GridWise Architecture Council[7]), have been coining terms such as "interoperability" and "self-healing".

ICKT brings a different perspective into the Power Systems domain. Particularly the modeling of knowledge by classification of information is relevant to capture engineering-knowledge about the system.

Function-oriented classification and representation is useful for control-aggregation, because it allows in principle the aggregation of different types of devices into a common hierarchy, e.g. [10], and it enables the formulation of generic performance requirements [8].
Pooling and aggregation of small-scale resources is essential, both for participating in power markets and from an operation/control perspective. However, the reasons for these aggregations are motivated quite differently [11]. Essentially, it is suggested to create Commercial Virtual Power Plants (CVPP), conceived as risk-controlling aggregators toward given energy markets, independent of grid topology; and Technical VPPs (TVPP), ensuring communication with local Operators[8].

Again, a separation of security questions from market aspects and business models can be observed, as here often "market" and "technical" aspects are treated separately, and if combined, then the latter only as provider of constraints to the former. This practice becomes difficult when markets with shorter time-scales or even markets for balancing-control are suggested without specification of control performance requirements.

B. Multi-Agent-Systems Application to Power Systems

Modern control architectures in electric power systems such as Microgrids, Virtual Power Plants and Cell-based Systems etc. exhibit requirement for decomposition, modularity, decentralized/local control, self organization, high level communication and increased level of autonomy. Multi-agent systems have proven capabilities of implementing such requirements and thereby have attracted a great amount of interest for their application in operations, control and automation [3], [12].

Multi-agent-systems with intelligent software agents [13] are considered a likely software concept capable of providing useful characteristics such as modularity, distributed control and cooperation mechanisms [3], [14]–[16]. The ability to reason about possibly complex control situations is also within reach of agent technology [17].

An ICKT architecture based on software agents allows for a flexible modeling of interests, roles and behaviours of agents with respect to their embedding in the environment.
The specification of roles and required behaviours, however, cannot be based on the generic agent paradigm alone, but it must also be derived from an application-perspective.

In order to achieve a scalable architecture, it is necessary to have strong organizational principles that enable classification and organization of similar properties and tasks associated with different problem classes. For Power System operation, more "intelligence" should not imply that the operator is "out of the loop", but it should

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[3] http://www.crisp.ecn.nl
[4] http://www.integral-eu.com
[5] http://intelligrid.epri.com
[6] http://gridwise.pnl.gov
[7] http://www.gridwiseac.org
[8] The CVPP/TVPP-concept, coined in [4], was employed in the European FENIX project (http://www.fenix-project.org/) and is further pursued in the ADDRESS project (http://www.addressfp7.org).

simplify the operation of increasingly complex power systems by providing the necessary transparency.

C. Scope

Motivated by the anticipation of agent-based control architectures, this paper departs from a recently suggested Subgrid architecture in Section II.

With a perspective on operator decision-making derived from cognitive systems engineering, we conceptualize a Subgrid operation architecture based on intelligent software agents. It builds on the understanding of how means-ends-reasoning and the weighing of alternatives are intertwined in rational decision making [18]. The basic ingredients are the *representation* of low-level controls and power-system functions by Functional Models, agent-based *role-allocation* concepts and *performance evaluation* on the basis of the Functional Model.

In the following Section, a Subgrid architecture is motivated and the concept from [3] is outlined. Section III will introduce the relevant concepts from cognitive systems engineering and functional modeling, multi-agent system and reliability evaluation. The architecture is then developed in Sections IV and V.

II. Subgrid Operation Concept

The current literature on integration of distributed resources frequently points to an operation scenario where the power exchanges between different sub-grids would be negotiated and fixed at limited levels (e.g. [19]), a suggestion which seems to be conceived mostly in bottom-up (distribution level) control design perspectives.

However, from a market-only perspective, for example for the integration of large amounts of wind power, it would be most effective to consider regions as large as possible for mutually smoothing (predicted and unpredicted) wind power variations [20]. From a market-perspective, the only barrier to trade should be transmission limitations. Why would the power-exchange between any two parts of the power system be fixed or capped? What is the value of being able to limit the power variations in the exchange between grid regions?

The first answer is that even though energy markets allow the trade of energy across country borders, it is the responsibility of System Operators (TSOs) to keep these exchanges close to scheduled values and the acceptable deviations are defined by agreements between neighbouring TSOs. Whereas exchange and mutual support is beneficial, large unplanned variations make system operation difficult and threaten stability. The question of valuation of limiting power exchange is thus also a question of valuation of operational stability.

Measures of operational stability depend on the control architecture. In [3] it has been suggested that under challenged operating conditions it could be beneficial to utilize the high penetration of distributed generation in Denmark by introducing a “Subgrid” architecture [12], in which control authority is partly delegated to Subgrids, preparing for partial islanding situations.

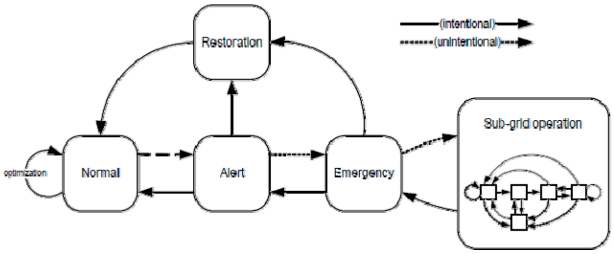

Fig. 1 High-level operating states with Subgrid operation mode.

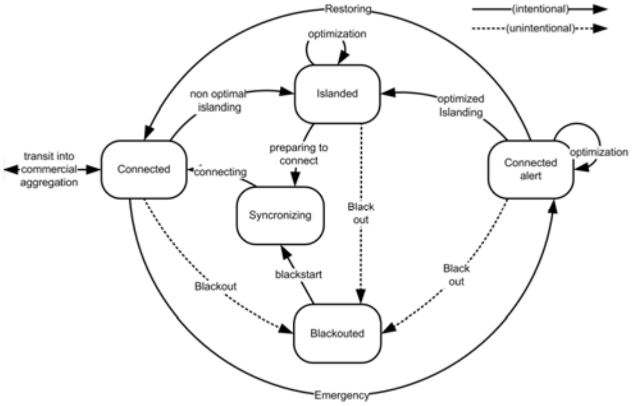

Fig. 2 Transitions within the Subgrid operation model [12].

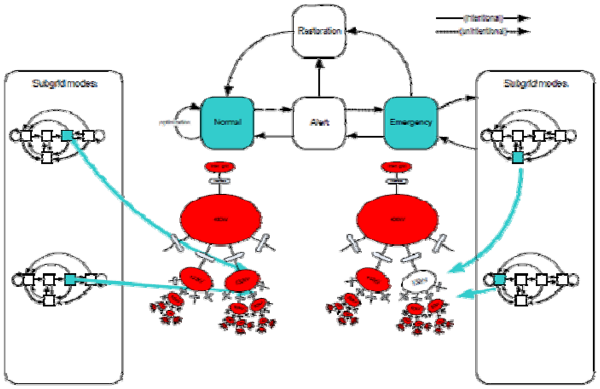

Fig. 3 Operation scenario: Interconnected operation and partial blackout with Subgrid operation.

Figures 1, 2 and 3 illustrate the interleaved operating states suggested for the subgrid operating modes. The overall operating modes (Figure 1) are described in the following:

- *Normal operating mode*. The system is prepared for a disturbance.
- *Alert mode*. System OK but not ready for additional disturbance which will transfer it to the emergency mode. State for system operators' control actions.
- *Emergency mode*. The system collapses if immediate control action is not taken; one additional contingency leads to a collapse without enough time for the system operator to intervene.
- *Subgrid operation mode*. The system is divided in smaller islands (sub-grids) in order to survive on local resources during an emergency period.
- *Restoration mode*. System collapsed. State for black-start procedure.

This Subgrid operation concept is envisioned to be realized by an arrangement of intelligent software agents. In order to realize such a scenario, a supervisory control agent – a Subgrid operator agent - is necessary for every Subgrid. It should be equipped with intelligence features that resemble human operator intelligence.

The following sections outline some underlying principles and modeling approaches required for the realization of such Subgrid operator agents and the related roles.

III. Background

Central features of multi-agent technology are its versatility and knowledge-base capabilities. This also means that a proper domain and problem understanding is required before a multi-agent architecture can be drafted. With a focus on the control problems an operator-agent will have to address, this section introduces: System operation, system-awareness and supervisory control; the means-ends dimension and functional modeling; the multi-agent concept; reliability valuation in power systems.

A. Supervisory Control by Operators

The power system operator has control authority for the system he is responsible for. Control authority implies that every entity providing system services is liable to activate its resources according to contracted performance requirements. Further on, the operator may disconnect parts of the system if critical grid conditions require this. At the same time, the operator is also liable to compensate the loss, which is an incentive for secure operation.

As the system operator oversees the system operation by identifying critical aspects of any given operating situation, it is crucial that he is aware of both, his available reserves (resources, control-means) and the need for control. Software and display panels support system operators to make informed decisions. Data relevant in the same decision context should be displayed close enough together, the distinction between measured and estimated information should be noted, etc. On the other hand, too detailed information can easily lead to information overflow in the supervision of complex processes. Filtering the relevant data is fundamental to successful supervision.

In attempting to model relevant information for a given operation scenario, it is apparent that information about the system state needs to be valuable with respect to the operational objective [5]. Information about objectives is just as important for a situation-awareness model as data from the process.

Situation-awareness in supervisory control is thus made up of awareness of control needs and control-means [21], [22]. Supervisory control is about relating lower-level control objectives to higher-level and overall operation goals. System security is the overall goal of power system operation.

B. Decision Ladder for Supervisory Control

As noted earlier, situation-awareness is not generated from solely communicating (displaying) measured data from the system. Both in the interpretation of signals and in the generation of control inputs, a number of abstraction levels can be distinguished between raw signals from and to instrumentations and their relation to the operating situations.

The decision ladder [5], given in Figure 4, stratifies these levels of abstraction both for state-analysis and planning of control actions. The decision ladder indicates that e.g. a system operator, upon observing certain data, must relate it to a (mental) model of the system before identifying the system state. To interpret this state as the operating situation, the state is related to an intended goal-state.

The role of representations in supervisory control can be read from this model as well: all kinds of intermediate states of knowledge require an appropriate representation, so that the information processing-activity may utilize it.

Different types of representations are relevant at each respective level. Seeing that an operator has a functional understanding (and intuition) about the system, an intelligent operator agent requires comparable high-level representation capabilities.

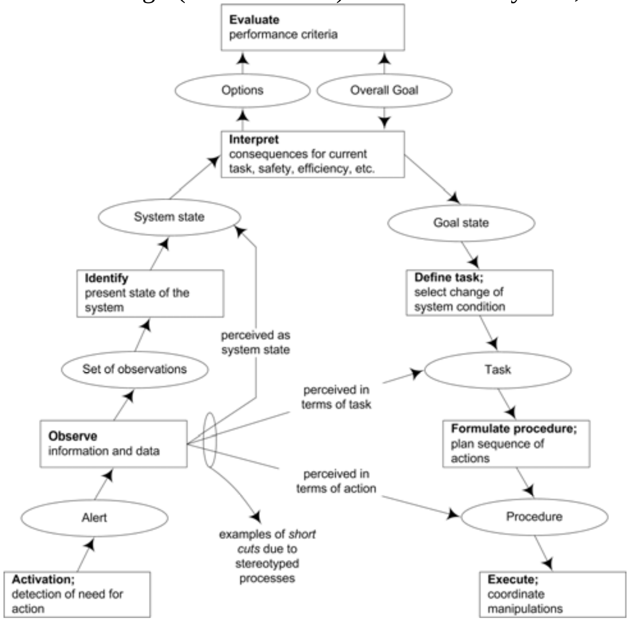

Fig. 4 Decision ladder (adapted from [5]). The boxes represent information-processing activities, while the ellipses represent intermediate states of knowledge. Classic closed-loop control corresponds to the lower “short cut” where the observation leads directly to procedure: Observed measured variables are translated by a controller (procedure) directly into control actions. For such controls, deliberation, task definition and procedure formulation belong to the control-design.

A system-state should be interpreted both with respect to control objectives and available resources. Reasoning and deliberation over alternative control objectives, tasks and procedures, choice of resources are all basic ingredients of operator intelligence.

C. Means, ends and Functional Modeling

Abstract models that represent lower levels of the control, relating control objectives to control-means, can be developed on the basis of a means-ends modeling approach.

Overall goals, process objectives and the realization of the process in components and their behaviour form a direction of ends and means. Consider a control action: In order to save the power line from overloading, the relay is programmed to open its breaker. In order to keep the system frequency at 50Hz, power system frequency control observes the frequency and alters the generators’ power input. For any control actions can be said that he intention to alter the state of a system is realized by means of observing it and manipulating it. Every control action entails concepts of the means-ends dimension.

In power systems, the overall goal of reliable operation is decomposed into a number of control objectives such as power-balance (frequency stability), optimal transmission operation (voltage stability, reactive power management), etc. This decomposition of control objectives cannot be derived directly from the overall objective, but it is rooted in the engineering principles and properties of the involved electromechanical process. However, in order to understand the decomposition, a high level of abstraction (i.e. a simple model) is sufficient, as for example in frequency control [7], [8].

Functional modeling provides context to overall goals, by introducing this intermediate level of abstraction along the means-ends dimension, relating objectives to functions:

Overall goals
|
process objectives
|
control- and process- functions
|
realization (behaviour–structure)

Functional modeling is thus the modeling of activities (behaviour) in relation to their purpose, and the context of the activity.

The word function can have several different meanings, including the mathematical concept of function, which is not considered here. A stone may have the function of keeping papers on the ground, or the function of being a weapon, depending on its use. These functions are not inherent in the properties of the stone, but they are attributes of its use (possibly related to the specific set of properties of the stone, yet not by the stone, but by an external purpose). As functions are attributed to things, their origin is external to the things but related to the purpose of their use.

D. Representation of Control via Functional Modeling

The functional modeling perspective can be formalized into a functional representation. Multilevel Flow Modeling (MFM) is a way to formalize the functional representation of a goal-directed process [23]–[25].

MFM models are composed of two dimensions: *means-ends* and *whole-part*. The means-ends dimension is vertical and is modeled via a set of relations interconnecting goals and process as well as functions and processes. The whole-part dimension is expressed via "flow-structures", grouping a set of interconnected symbols (process-functions) into a process.

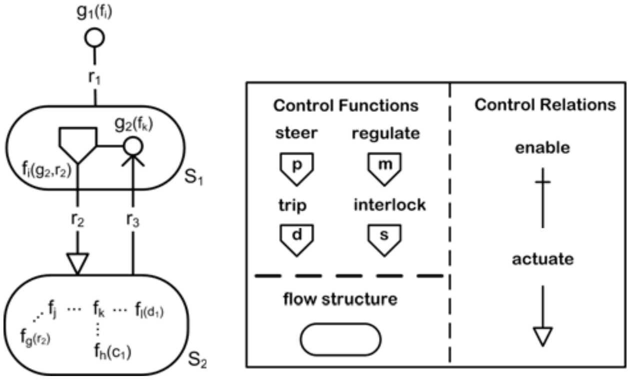

Fig. 5 Left: Control pattern with process-functions and associated roles. Right: Control functions and control relations. Modeling examples for the power systems domain can be found in [7],[8].

Semantics and symbols have been developed for control and flow-processes. That is, a library of functions and causal relations for their interconnection is available to model processes that include control-, energy- and mass-flows. The interconnection of processes to goals and process-to-process is expressed via means-ends relations. A process, enclosed by a *flowstructure,* is connected to a goal via an achieve-relation. More precisely, objectives are connected via a *maintain-*, *produce-*, *suppress-*, or *destroy*-relation. A flowstructure is an encapsulation of a process-part, composed of elementary flow- or control-functions. Employing this representation, a means-end decomposition of a process can be formulated as goals/-objectives, means-end-relations and (flow-) processes. The explicit process-decomposition enables the modeling at different levels of abstraction.

A basic pattern of an MFM model involving control functions is given in Figure 5. Flowstructure S_1 is a control structure with a control function actuating a process S_2, as a set of interconnected functions (f_g, f_j, f_k, f_h and f_l). For the process in S_2 there exists library of flow-functions to model energy and material flow-structures, which can be applied to power systems as well [7], [8]; for the sake of this paper, the process functions are kept generic.

Functions are associated with an internal state. This state is influenced by neighbouring functions and/or by external agents. For flow-functions, causal roles have been established that indicate, how a state-change is propagated through the system of functions (via the flow-object: energy, matter).

Note that $f_g(r_2)$, $f_h(c_1)$ and $f_l(d_1)$ are functions whose state is influenced by an external agent. In the given figure, the control function f_i actuates $f_g(r_2)$. Furthermore, the state of $f_l(d_1)$ is influenced by an external disturbance (d_1) and $f_h(c_1)$ is determined by a constraint/setpoint (c_1).

The pattern in Figure 5 reveals some essential attributes involved in modeling control:

- control objective $g_2(f_k)$
- control function $f_i(g_2; r_2)$
- performance of the control function $g1(fi)$
- relations between control process $S1$ and controlled process S_2: $r_2; r_3$
- disturbances to be encapsulated $f_l(d_1)$
- actuation and actuator location $f_g(r_2)$
- (dynamic) constraints $f_h(c_1)$
- configuration: relations between process functions, disturbances, actuators and constraints.

The functional model provides the relations between these objectives, roles, control- and process-functions. Also multivariable-, distributed- and cascaded control can be modeled within this framework.

This model can be employed for a number of purposes relating to supervisory control and control design. By relating the states of functions to system, control means and control objectives, MFM models enable situation-dependent dynamic reasoning about control situations. The causal relations combined with state-information enable powerful causal reasoning about causes and consequences of observed process deviations.

With respect to the decision-ladder, the model can serve as a representation of the execution-level control structures. A procedure for performance-evaluation of the represented control process can be derived directly from the means-end and causal structure of the model

1) MFM-based state identification: For root-cause analysis, function-states are discretized into normal and abnormal (high/low) states. An observed "abnormal" state will trigger the causal reasoning system, which then will generate possible causal explanations (root-causes), by matching functional information with observed data.

From a decision-ladder perspective, this reasoning function corresponds to analysis (interpretation) of the system state.

2) Causal Reasoning for Control-influence: If dynamic control functions are part of the system-in-view, the overall system-state can be evaluated directly with reference to the control-objective which is to be achieved. This corresponds to performance monitoring of a control loop. Using reasoning about causal influence, functions with the ability to influence the achievement of a control objective can be identified within the flow-structure, which may support the identification of control opportunities.

E. Operation Security: Valuation and Evaluation

Power system security is the concept that a power system operation should be resistant to failures. The classic approach to secure operation is *N-1 security*, which means that the power system operation should be able to withstand the impact of any single component outage. A system operator aims at maintaining this *N-1* criterion at all times, moving from day-ahead planning stages to minute-to-minute security assessment. It is also closely related to the state diagram of Figure 1, in which a single contingency corresponds to the transition from normal operation to alert mode. Power system operation is designed as a combination of automatic and manual reserves, which serve the operator in order to return to the normal operating condition.

The *N-1* criterion is a practical condition for estimating reserves with respect to power plant outages, where the time of outage is impossible to foresee. However, the reserve need for offsetting prediction errors of fluctuating renewable generation can only be measured on probabilistic grounds. A practical approach to scheduling reserves, here referred to as 3σ [26], is to schedule about three times the standard deviation of the prediction error. It has been shown that for high wind power penetration, the 3σ criterion may exceed the *N-1* criterion.

From an *outside* perspective, system security corresponds to reliability. Reliability is essentially a probabilistic concept estimating the likelihood of failure, in this case, the likelihood of insufficient reserves. A significant body of literature suggests that the need for reserves to provide operational security can be more effectively quantified on the basis of probabilistic approaches rather than by directly using the deterministic *N-1* criterion (e.g. [27]).

The value of access to electric energy is ultimately afforded by the value reliability has for the energy consumers (and producers) (Figure 7). The "value of lost load" (VoLL) [26], though hard to estimate, is the effective counterpart to the cost of providing reliable operation. Considering these two costs, an optimum reliability would theoretically be found at the minimum of the system cost function:

$$C_{system}(p_{rel}) = C_{LL}(1- p_{rel}) + C_{rel}(p_{rel}) \ ,$$

where p_{rel} is the reliability, and C_{LL} and C_{rel} are the costs of unreliability (Lost Load) and reliability provision, respectively. Whereas this concept explains valuation of operational security well, there is significant uncertainty and variance about the relationship between unreliability and its costs, such that it is common practice to set a target level of reliability instead of a comparative evaluation[9].

Even though it is hardly contested that probabilistic approaches are theoretically more accurate, there are practical issues inhibiting their use: a) a significant history of data is required to establish relevant statistics (for e.g. failure rates); and b) probabilistic approaches are complex: difficult to handle mathematically, require model simplifications and they are computationally expensive. Furthermore, probabilistic concepts are only descriptive, but not instructive. Real-time control room applications rely on practical consideration of worst-case outages and disturbances (*N-1,* sometimes *N-2,* for a set of selected contingencies).

A point often overlooked, particularly in stationary probabilistic estimation of reserve-capacities is the dependence of reserve needs on the structure of ancillary services markets and practical operation strategies. Not all kinds of technologies are suitable for all kinds of markets, so that the cost of some reserves will also depend on the market structure [28]. This market structure varies widely from system to system [29], [30].

On top the estimation of reserve needs, the way of allocating the resources is also relevant, as market design may also influence bidding strategies and available resources and cost [30], [31].

F. On Agent-Notions

Agent: Entity acting with intention. In the following discussion it is relevant to distinguish two separate meanings of the notion "agent". The first meaning of "agent" derives from semiotic theory of the act. In this context *agent* refers to the performing role of an action - as opposed to, e.g. the *object* role. Throughout this paper, the italic *agent* refers to this role-concept. The second is derived from the software-engineering notion of agent, which refers to an entity that has its own goals and the ability to actively pursue them. This notion will be noted plainly as agent or software-agent.

That is, a software-agent is an entity that has the ability to assume an *agent*-role. An example where the two notions come together, is the speech act, modeling the communication between software agents. Here a

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[9] A target level, such as 99,9%, could then be understood as an average of 0,01% of "load not served", but also as "ca. 87 hours with insufficient reserves".

software-agent can be both initiating *agent* and passive *receiver* with respect to the sending of messages. Notions in MFM refer to types of roles, not to self-interested entities.

G. Intelligent Software Agents

Intelligent software agents are a software concept based on a human-oriented model of distributed intelligence. Agents encapsulated in BDI (Belief, Desire, Intention architecture) are situated in some environment and can act flexibly and autonomously in that environment to meet their design objectives [13].

Agents can be considered individuals, each equipped with belief (i.e. world model, state information), desires (interests/goals) and intentions (intended actions/plans). Situated in a physical- as well as in a software-context, agents communicate with other agents and act in representation of a physical or organizational entity, according to interests associated with it.

Generally, there are a number of ways Multi-Agent-Systems (MAS) can be viewed. The generic and powerful perspective of agents portrayed above is particularly suitable for knowledge-based reasoning and communication. Agents based on the BDI-architecture exhibit reasoning capabilities, to decide about alternative ways to achieve their design goals (desires). MAS can also be seen as a means of solving distributed control problems, where each agent becomes a part of a distributed computation algorithm. This view usually entails the decomposition of an originally centralized control or optimization problem into a distributed problem, where agents may or may not exchange information. This mathematical decomposition has been applied for example in [33], [34]. In these contexts, agents are viewed under the umbrella of a common mathematical framework, used to derive e.g. optimality or stability conditions.

The main difference between multi-agent systems of one kind and the other is their supposed representational intelligence. Whereas the latter 'mathematical' view focus on a mathematically implicit representation of objectives, communication and cooperation, the former 'intelligent' type of agents employs explicit semantic concepts to describe their goals and to communicate with other agents. These two views are not fundamentally opposed to each other, but rather associated with different levels of autonomy. Also autonomous agents could deliberately join the 'umbrella' of a joint mathematical algorithm. For practical study of such algorithms, the benefits of autonomy are not always required.

1) Origin of BDI-model: The idea of the BDI architecture originates from the view of agents as individuals [18], who proposed a computation architecture that combines the AI perspective on intelligence as an integration of means-ends reasoning and valuation capabilities required of rational agents under the premise of bounded resources.

Originally this meant the integration of two facets of rational behaviour. The first aspect is the planning problem or means-ends reasoning, which is employed within artificial intelligence to construct plans (a sequence of actions) that will achieve a particular goal. Second is the problem of weighing alternatives and deciding upon them, that is, given a number of feasible plans, to choose one of them. For a rational agent, this choice requires an analysis of the utility on the basis of its beliefs and desires - and implicitly on a means-ends analysis in specifying the alternatives.

Any practical problem carries both of these aspects, choices about plans and the making and refinement of plans are nested and intertwined. A software architecture that incorporates both aspects under bounded resources must also include mechanisms that control and evaluate how deep either problem ought to be computed.

Here, the plans themselves assume a special role, becoming a subject of both evaluation and reasoning. We come to distinguish *plans as recipes* from *plans as intentions*.

2) Procedural Reasoning and the Role of Plans: A software-architecture that exhibits properties of the BDI paradigm is the Procedural Reasoning System (PRS) [13]. We introduce its basic idea here so that one can anticipate some of the control flow that can be implemented on an agent paradigm.

At its core, the PRS is based on pre-compiled plans which are stored in a library. These plans are made of a *goal* (postcondition), a *context* (precondition) and a *body* representing a recipe. The recipe may include both procedure calls (primitive actions) and other goals.

An agent is equipped with an interpreter, matching facts with conditions (goals with desires and intentions, contexts with beliefs), and four types of knowledge: The plan library mentioned above, beliefs (facts), desires (design objectives, goals) and intentions, which is implemented as a stack of goals that the agent wants to achieve.

Now, once a fact and a goal match a plan in the library, the agent can proceed with its execution, which may

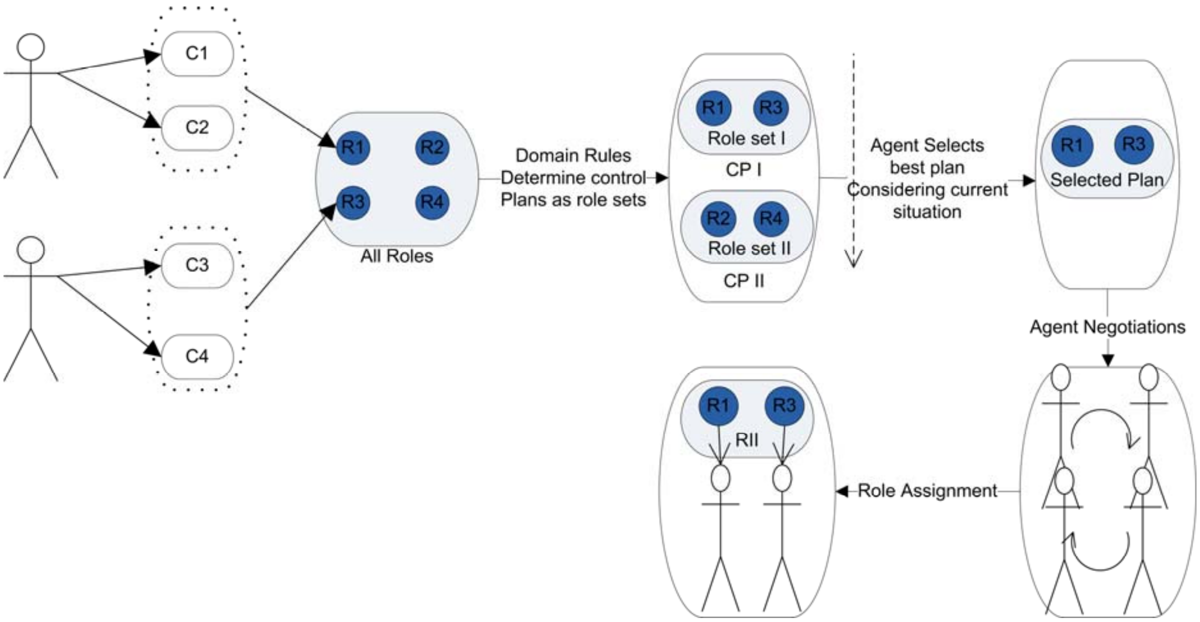

Fig. 6 Role-assignment process [32]. Abbreviations: Control Plan *CPi*, Capability *Cj*, Role *Rk*.

cause further goals to come on the intention-stack. In a dynamic environment new belief facts will be added and removed over time, causing different plans to be activated.

Note that a plan inherently is an ends-to-means structure, it can contain action sequences (function calls) and subgoals, and a plan can only be activated when its preconditions are satisfied. A comparison of the PRS to the original BDI architecture of [18], shows that PRS implements partial plans, as plan-refinement is implemented on the basis of intermediate goals. However, it is simpler with regard to the evaluation and filtering of opportunities and alternative plans, the valuation aspects [13].

3) Roles and Capabilities, Control Plans: In multi-agent problem solving, different roles can be assigned to individual agents based upon their capability to perform certain tasks. Roles and capabilities are formulated based upon a specific context. For example in the context of instrumentation there are two kinds of roles: sensor and actuator. A capability of an agent is its *ability* to function according to such a pre-specified role, here the ability to measure a required value; however, this capability may be unused at a particular time. Complimentarily, a role corresponds to a *slot* in a pattern of interactions, which would need to be filled by an entity with the respective capability. The role expresses a requirement, whereas the capability expresses a potential.

Assignment of roles to agents based upon their capabilities can be done in two fundamental ways:
i) predetermined/static role assignment and
ii) dynamic role assignment.
In predetermined or static roles assignment, roles are assigned to agents at the systems design phase and capabilities are considered permanent or unchanged. This approach results in fast execution but may suffer failure in case of agents loosing specific capabilities.

In dynamic role allocation, roles are assigned to agents dynamically based upon their current capabilities. A role-allocation process is performed whenever the current state of the system changes such that a conflict with the assumptions of the previous assignment appears.

Control roles are a representation of specific functions with respect to control, such as actuator, disturbance, constraint, including the functions providing different control tasks as well as the e.g. frequency/voltage controller as well as associated performance objectives. As well, relevant structural, topological and support roles may be included.

H. Dynamical Allocation of Agent Resources to Roles

In this paper we utilize an allocation mechanism suggested in [32], which, based on a control plan with pre-defined roles, allows allocation of agent capabilities to each role.

Generation of control plan and assignment of specific roles to agents are two different tasks. Accomplishment of a specific goal in a control scenario requires successful execution of a number of roles. A control plan defines set of such roles. Generally, a mapping between the roles and specific "world situations" is done based upon domain principles [35].

The decision of assigning specific roles to agents is taken dynamically through explicit communication, which, initiated by a facilitator agent, is done distributed through an auction mechanism.

For specific role assignment in a chosen control plan, the facilitator requests bids from all participating agents. Agents calculate their local cost functions based upon their current state and capabilities for each role they may assume. Based on the value of this cost function, agents send a bid to the facilitator, which then assigns a role to every agent in the selected control plan.

Figure 6 illustrates the process of control plan determination and role assignment. It should be noted that realization of different roles requires specific capabilities. These capabilities may be offered by one or more agents, and one agent may offer several capabilities. Essential for this algorithm is that both bidder and auctioneer have a common understanding of what the assumption of a role implies.

IV. Representation and Evaluation of System Operation

Given the role system operators have in power system operation, to ensure secure (reliable) operation, how can we value its services?

In terms of valuation of system operation cost, it is important to recognize the position of the operator in the valuation chain (see Figure 7): Grid reliability is valued both by consumers and producers; it has the character of a common good as long as its provision is indiscriminant[10].

Reliability cannot be provided without the means of a responsible entity, the system operator. The operational counterpart to reliability is the operators "certainty". The cost of system operation is a function of the resources dedicated to system operation, but the resource need cannot be quantified directly: It depends on how the system is operated, which types of resources are employed and which types of disturbances need to be counteracted.

Assume that the operational intelligence of an operator is driven by an aim for "certainty" (corresponding to a measure of security) and the cost comes from allocation of operation-resources. It is outlined in the following, how the control flow and resource allocation can be considered in a common framework, formulated in a functional representation as introduced in Section III-D.

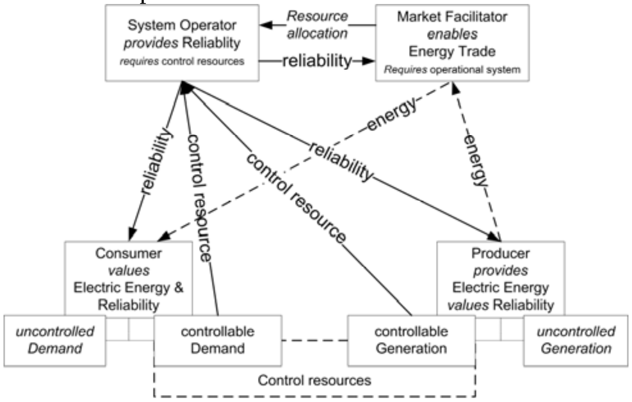

Fig. 7 Needs (ends) and resources (means) in electric energy systems. The arrow points toward the needs: Consumers value the availability of electric energy. Both consumers and producers value grid reliability - and both may offer "reliability-means" (controllable resources).

A. Tasks of an operator agent

Suppose a software agent would have to secure and coordinate Subgrid operation. Suppose also, active devices and control-function aggregators are represented by software agents. In order to design proper tasks and interactions for these agents, it can be useful to start from current system-operation approaches.

As a supervisory control agent, the Subgrid operator-agent oversees the operation of a local grid part. It is responsible for the secure operation of a local grid and is subordinated to a higher-level system operator.

System operation is also the art of securing the system by procuring control resources for uncertain future disturbances. Operation heuristics must therefore aim at "hedging" this uncertainty. Today, the main role of this hedging goes to the energy markets, yielding a scheduled dispatch. The remaining uncertainty is dominated by large power plant outages whose time of occurrence is particularly uncertain, such that the practical threat is covered by the largest unit outage. Probability concepts in operation are not so visible in the operation of

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[10] Based on the needs of high-reliability applications, for example for data centers, some recent architecture suggestions adopt a more discriminatory view of reliability provision, e.g. in [19]. These architectures, however, usually assume a locally decoupled grid operation through power electronic interfaces

conventional power systems[11]. In the case of high wind power penetration, however, it may not be the outage probability, but the uncertainty of prediction which could determine the need for reserves [26]. However, the quite different character of these disturbances might suggest that a different kind of reserve and activation model could apply for these more time-dependent disturbances.

The Subgrid architecture of [3], [12], outlined in Section II, suggests operating states analog to [36], and how the operating states and transitions of the high-level grid are coordinated and interleaved with the operating states of a Subgrid. This state-model is a practical discretization of grid situations that is consistent with the decision ladder introduced earlier. Each state implies a different prioritization of operation-objectives, according to the situation. In order to keep track of control objectives, asubgrid operator agent would internally represent the systemstates
as were given in Figure 2 and trigger transitions based on events observed directly as well as by reasoning about the observed information, as presented in Section III-D1. Events may be triggered by local observations only as well as in coordination with the high-level grid operation, for overlapping states or transitions.

On the basis of state information control actions need to be invoked. The type of actions accepted and necessary strongly depends on the respective state/transition. Deliberative planning, including the allocation of local controllers, is a part of the operator responsibility. To simplify the task of deciding and planning control actions, a number of control actions can be represented in the form of *control plans*. Especially for emergency situations, it cannot be expected that planning and resource allocation should be done in real-time. Such control plans should be prepared during uncritical system conditions.

B. Coordination problems

Coordination is a type of task that aims at distributing tasks and resources amongst a number of agents: Who is going to do what?

In a framework where software agents represent most relevant entities, the *who* can be identified as an agent, except for components serving non-interactive functions (e.g. a transmission-line). If tasks are modeled as a network of interactions or related actions, the *what* is a *role* to be assumed by an agent. The required coordination is thus a role-allocation problem.

As introduced above, there is static and dynamic role allocation. In the concept outlined here, the operator-agent role follows a static allocation. The system operation is also a coordination problem with respect to control, which may be decomposed into two questions: *a)* which control actions should be performed and maintained at the given state-transitions? And, *b)* which units will perform them?

The task at hand is a control problem; therefore all roles to be allocated are framed by the control task. As shown in Section III-D, control tasks can be decomposed by a functional model. The functional model can represent the structure of a control solution including also those functions that would not directly be represented by agents, such as a transmission line or other passive devices. If a functional model is employed to represent a control solution, the means-ends structure of a control problem would be defined.

According to the role-allocation mechanism presented in the previous section, a role-allocation can be performed on the basis of bids by agents that represent the respective device capabilities.

In this form, the role-allocation formulation is an abstraction, framing also solutions of ancillary-service dispatch problems such as that presented in [1].

C. Control Plans

A practical implementation to initiate actions on a state-transition can be analog to the PRS (Section III-G2). The structure of a plan is mapped by understanding a current Subgrid state as a precondition and the desired transition as a goal state (post-condition). Un-intentional transitions are triggered by a observations, and intentional transitions can be triggered by the successful execution of a control plan.

A control plan is a particular type of plan whose goals and preconditions are formulated with respect to the controlled system, specifying relevant control roles as well a system structure it applies to.

The execution of a control plan would be composed of two phases: a startup/transition phase and a state maintenance phase.

Apart from preconditions (related to activation state) and postconditions (related to goal state), a control plan has essentially two parts, according to the two phases:

1) a sequence of actions (“startup procedure”)

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[11] Load prediction is quite accurate, and load variations do not impact the reserve need as much as the N-1-criterion.

2) a (set of) functional model(s), defining the target topology and control structure

A startup/transition plan defines the structural and topological changes required to initialize the operating scenario described in part two. In part two, control roles would be specified analog to or directly by MFM models as introduced in Section III-D.

Such a plan could be constructed dynamically, but let us assume that all control plans parts are partially prepared. We suggest functional models to structure the second part of the control plan, and see the possibility of planning start-up sequences using functional models as well [37].

In order for the plans to be ready for activation and timely execution when needed, these plans need to be prepared proactively. Control resources need to be allocated and appropriate plans yielding the best utility will be chosen. As a basis for the generation of control plans, a plan-library (defining complete control structures, control recipes) should be prepared, with standard- or template-plans for all transitions, so that the range of possible control actions is confined.

A planning-algorithm may match the function-topology with the known system structure and formulate the necessary transition steps (e.g. opening and closing of breakers).

A resource allocation algorithm analog to that described in Section III-H could take bids on all these roles. A bid must include *a)* a cost-variable *b)* role-specific quantities constraining the extent to which a given role may be fulfilled.

The bid-structure has to be role-specific, that is for example, a load may offer curtailment for a critical grid-situation, whereas a generator may offer a primary frequency control function including droop, capacity limits, control performance, etc.

D. Evaluation for Resource Allocation

A control plan in the form of a functional model provides sufficient relational information to formulate an evaluation function out of the agent-bids. The role-specific quantities of the agent-bids are related through the functional model, using a mathematical formulation of the respective flow structures, e.g. a power balance can be calculated out of bids for a power generation and demand.

In the same way, control-specific information, such as control-ranges can be matched with expected disturbance behaviour. This part of the evaluation problem corresponds to the reserve allocation problem introduced in Section III-E. If probabilistic information is available for a disturbance characteristic, such as prediction error or variability expectations, evaluation of bids toward the performance evaluation of an associated control function would yield a probability with which the allocated resources are insufficient (e.g. expected load not served). If the control plan includes the expression of performance requirements, these could be matched with the respective evaluation of bids (an algorithmic approach could also be employed, adjusting the bids to match a requested performance, or optimality condition).

The overall *cost* of a given control plan after resource allocation is the sum of its allocated bids. Assuming that the performance of a control plan corresponds to a certainty with which the control plan matches the security-objectives of our operator-agent - this value is the *utility* of a given control plan. Key to this approach is the separation of the means-ends structure, as part of the control plan, from the weighing problem, which requires the evaluation. As control plans can thus be evaluated according to their performance, different control plans can be compared with respect to their cost and overall performance.

Control alternatives can thus be evaluated in a utility vs. cost framework.

V. Application to Subgrid Concept

The concepts outlined in the previous section, lend themselves for application to the Subgrid concept in an agent architecture. Here we discuss some aspects relevant for the design of this agent-based solution.

The control problems in each transition of the Subgrid concept are quite different and thus require also different capabilities and evaluation criteria. In this Section, only the states in the right part of Figure 2 are considered, that is, commercial aggregation and market aspects are left out here.

A. Agents in Consideration

Even though types of devices may vary widely, we may identify some characteristic capabilities. The use of these capabilities depends on the system organization and perspective. In the framework outlined in this paper, capabilities need to be represented by an agent in order to be acknowledged and activated.

For application in the outlined operation concept, we may consider the following types of representation agents:

- Operator Agent (reasoning & decision making)

- uncontrollable demand (offers shedding)
- controllable demand-aggregator (such as in [38])
- distributed generation (or -aggregator)
- local electric vehicles (or -aggregator)
- relay agents (topology changes and fault detection)
- market facilitator, market operator

Each agent represents a different entity and thus different capabilities. Different agents may offer the same capabilities, e.g. both a load and a generator may offer droop regulation capabilities. The list suggests that representation-agents are intended to combine interests (e.g. of a device owner) with a representation of (control-) functionalities that are relevant for the system. As these control functionalities (capabilities) are tied to the entities they represent, a further splitting by functionality seems inappropriate.

However, to increase the robustness of operation, this splitting may be considered for the different tasks that are combined in the operator agent. Here, for example, state-estimation-, reasoning- and planning- capabilities may be distributed on a number of coordinated agents.

B. Relation between Subsystem States and Control Plans

The intentional transitions (->) for each Subgrid state are

- *Connected* -> Islanded; -> Connected alert
- *Connected Alert* -> Islanded -> Connected
- *Islanded* -> Synchronizing.
- *Synchronizing*. -> Connected
- *Blackout* -(blackstart)-> Synchronizing

One can tell from these transitions, how different the control plans will be in type. For example, the “blackstart” transition is naturally a startup-plan that will bring the system into a control mode feasible for synchronization. Its precondition is Blackout, the postcondition is “Synchronizing”. A local grid may also be energized from neighbouring grid parts. Then the startup-plan would be based on an incremental control sequence for closing the appropriate breakers. The “non-optimal-islanding”-transition is a protection scheme, that should be triggered locally. Nevertheless, a control plan would also be required here, anticipating the built-in resulting topology after a disruption. The protection plan will likely also include demand-shedding to quickly establish the power balance, which suggests an important decision-variable for the evaluation of alternative protection scenarios (control
plans).

A synchronizing control plan will focus on the grid-forming unit(s) in the system, and possibly include PMU-roles, which would allow for a more smooth transition.

The connected to connected-alert transition will be initiated by fault observations, particularly at a higher-level transition, which leads to suspending market-operation and invoking of local control-reserves. Inside this mode, a redispatch is performed.

All transition control plans require preparation, so that their activation may happen immediately after fulfillment of pre- and post-conditions.

C. Operation in the Time-perspective

In the time-perspective it should be considered, when to renew the plans, both with respect to their means-ends structure and with respect to the resource-allocation. Generally, the timing should be as frequent as possible, but only as frequent as relevant changes can be expected in the system.

The allocation of roles to a control plan should be triggered when a sufficient number new resources becomes available, but also when the situation of the resources changes, for example when a allocated resource looses the capability to perform a previously allocated role.

Another trigger for new renewed planning are changing requirements, such as a new predicition that differs sufficiently from the prediction utilized in the previous plan. This predictive heuristic becomes especially important, when control logic will also be based on energy-storage.

The anticipation of disturbances also determines some of the system-subsystem relations. Operation plans ought to be prepared, depending on the anticipation of challenges, i.e. based on the prediction of uncertain variables. For example, if a storm-front is expected, operators might like to “stock up” on positive reserves.

D. System-subsystem relations

Power system operators on higher level may evaluate the situation in different subsystems, offering support for some or suggesting the trade of reserves across secured lines. A range of coordination possibilities can be considered on the basis of the means-end evaluation established above.

VI. Discussion and Conclusion

We have outlined an architecture of agent-based power system operation, framing operational objectives and related economic decision problems on different levels of system decomposition (from end-users to system operators). This framework enables the representation of alternative control plans, and their evaluation under a utility vs. cost perspective.

The autarky of the agent models employed in this architecture has been limited to reflect transparent operation principles. The means-ends modeling framework focuses on a description of control solutions, which opens up for different algorithmic implementations. Particularly mathematical models for ancillary service dispatch such as in [1] or distributed protection as in [34] could be modeled and implemented within this framework. Also more complex hierarchical resource allocation (e.g. PowerMatcher) could in principle be interfaced with this model.

The principles presented in this paper demonstrate how an agent-based control system can be structured to create a scalable power system operation concept, capable of distributing and aggregating control authority and yet remaining transparent from an overall system operation perspective.

Resource allocation - the market aspect - is here framed as subordinated to the control structure, thus creating open interfaces and the possibility for ad-hoc markets under dynamic system operation conditions.

Important aspects to be addressed in further work toward an implementation include:
- Building a library of control plans and roles
- Extensive classification of role types
- Norms for explicit performance evaluation
- Problem specific resource-allocation algorithms
- Interpretation and visualization of control plans

In the long run, also advanced control approaches such as model-predictive control should be modeled in the means-ends framework. Further development of functional representations in power systems will also enable further and explicit benchmarking of existing and future control and resource-algorithms.

Aspects of the outlined agent architecture may form a basis for next-generation operator support systems, including the integration of Artificial Intelligence methods, such as fault-location identification or counteraction-planning. The complexity of such reasoning systems indicates that tasks of an operator-agent will need to be split into a supervisory control agent and a number of supporting agents.

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