Final report

1.1 Project details

Project title	Control, Protection and Demand Response in Low Voltage Grids
Project identification (program abbrev. and file)	Energinet.dk project no. 10782
Name of the programme which has funded the project	Forskel
Project managing company/institution (name and address)	Professor Birgitte Bak-Jensen, Aalborg University, Department of Energy Technology, Pontoppidanstræde 111, 9220 Aalborg East
Project partners	KK-Electronics, Denmark A/S, now KK Wind Solutions A/S, Bøgildvej 3, 7439 Ikast SEAS-NVE, Hovedgaden 36, 4520 Svinninge
CVR (central business register)	29102384
Date for submission	31-03-2016

1.2 Short description of project objective and results

The purpose of the project is to find a solution for efficient integration of renewable energy at distribution level using demand side management of heavy loads. In the project a hierarchical control structure is set up and the method is simulated and verified for a distribution network grid at Zealand using control of charging of electric vehicles and heat pump loads. Protection issues at medium voltage level are also considered.
The results can if new legislation regarding costumer payments allows it, be used by the distribution companies to solve voltage and capacity issues along the radials when integration a huge amount of renewable energy and/or due to the electrification of the heating and transport sector. Thereby, they can avoid or delay investment in new lines with higher capacity.

Formålet med projektet er at finde en løsning til en effektiv integration af vedvarende energi i distributionsnettet ved smart lastforbrugsstyring på store laster. I projektet er der udformet en hierarkisk styringsstruktur og metoden er simuleret og verificeret på et distributionsnet på Sjælland ved at styre forbruget til opladning af el-biler og varmepumpelasten. Beskyttelsen på mellemspændingsnettet er også analyseret.
Resultaterne af projektet kan hvis nye love omkring forbrugernes betalings tillader det, anvendes af distributionsselskaberne til at løse spændings og kapacitet problemer langs linjerne ved stor integration af vedvarende energi og/eller ved elektrificeringen af varme og transport sektoren. Derved kan de undgå eller udsætte investeringer i nye linjer med større kapacitet.

1.3 Executive summary

The future challenges in the distribution network grid due to the increasing demand for instance from the electrification of the heating and transport sector together with more environmental concern and favorable government policies leading to a rapid growth of Renewable Energy Sources (RESs) calls for new control methods in a smart grid (SG) context not to overload the radials and at the same time create benefits for prosumers, retailers and distribution system operators (DSO). The smart grids are expected to integrate diverse types of generations and loads and provide an active demand side management to foster energy efficiency, grid stability and reliability. The rapidly increasing wind and solar energy penetration and thereby, high volatility in the electricity price in the Danish power system is expected to be facilitated through responsive demands, smart metering and dynamic pricing using new developed control methods, using the flexibility of the controllable large loads. Further, constantly changing generation and load alters the fault power of the system and may impact the protection schemes.

The aforementioned issues has traditionally resulted in building fast excess generation or grid scale storages to compensate the power imbalances resulting from intermittent generations and fluctuating demands. But this is a costly solution even though it performs technically well. One potential alternative is to control the electrical loads in an intelligent way and make them follow the intermittent generation. This should profit both the consumers getting reliable and cheap electricity and at the same time enable the utility to prevent huge investments in lines, generation or storage equipment. This means a paradigm shift from ‘generation following demand’ to ‘demand following generation’.

Therefore, this project has been developing and validating an intelligent control architecture and an adaptive protection method for the future distribution system which coordinates the elements of the smart grid, mainly using data from the smart meters and controllable loads (electrical vehicles (EV), heat pumps (HP) and electrical water heaters (EWH)), the network grid layout, the power generation data (here photovoltaic system (PV)) and which takes the information and communication technology(ICT) characteristics into account. The results from the projects are demonstrated mostly by simulations and partly by laboratory setups.

The research outcome will not only serve as a reference for ongoing research in this direction but can also if new legislation regarding costumer payments allows it, be used by the distribution companies to solve voltage, capacity and protection issues along the radials when integration a huge amount of renewable energy and/or due to the electrification of the heating and transport sector. Thereby, they can avoid or delay investment in new lines with higher capacity. The major contributions of this work are described in the following five stages:

- Stage 1: Development of an intelligent Demand Response (DR) control architecture coordinating the key SG actors, namely consumers/prosumers, network operators, aggregators, and electricity market entities to facilitate market participation of residential consumers and prosumers. A Hierarchical Control Architecture (HCA) with primary, secondary, and tertiary control loops is developed together with a heterogeneous communication network to establish coordinated control of widely distributed loads and generations. In the HCA each control loop are designed with specific control latency and time to establish coordination between the loops. The structure is demonstrated with a power and communication co-simulation and the results showed that the proposed architecture effectively integrate responses from widely distributed loads and generations.
- Stage 2: Development of detailed models of controllable loads namely EVs, HPs and EWHs, local generation in the form of PVs, and the distribution network. Different control strategies are developed to realize various DR techniques, such as autonomous, voltage, incentive based, and price based control. By use of the HCA developed in stage 1 and the set up models and control strategies, the performance of the method is demonstrated for a case study with a low voltage distribution networkfrom Zealand. Despite the actual study case network, the strategy and models are generic and can be applied to any network. The outcome from this part exploits the demand flexibility and the technic support from the consumers/prosumers as well as their possibility to trade the flexibility in electricity markets.
- Stage 3: Development and implementation of a scaled down SG testbed for physical demonstration of the developed DR models and control strategies. The testbed is a 1 kVA testbed built in a laboratory. The communication system is integrated in the testbed in the form of an optical fiber and TCP/IP based communication. Both a cen-

tralized and decentralized control approach is implemented in the testbed for optimized EV charging coordination. As practical demonstration of SG control and communication behavior is lagging, the developed scaled down testbed provides a novel economic and riskless approach for practical demonstration of the SG control and is a new research area in the SG field.
- Stage 4: Development of an adaptive overcurrent protection for the future distribution system having high share of RESs and Active Network Management (ANM) activities. This protection should be able to take bidirectional power flow and ANM activities such as demand response, network reconfigurations into account. Therefore, an approach to adapt relay settings based on dynamic network topologies and power in feed is developed in contradiction to the conventional protection methodology where the protective settings are made static. A two-stage protection strategy with an offline proactive stage combined with an online adaptive stage is designed. Settings of the relays for every mode of operation are done in the proactive stage based on offline short circuit analysis. The adaptive stage identifies the actual operating status the RES and the operating modes (grid-connected, islanded, network reconfiguration etc.) in real time to adapt and activate the right settings. The method is demonstrated with good results for a case study of a model of a medium voltage distribution network using a real time digital simulator in the laboratory.
- Stage 5: Development of an aggregated model and control structure for distribution systems. Aggregated models for HP and EV demands are created and a control-architecture is developed for activating the aggregated flexible demands and comparing the results with the results from situations where individual loads are simulated. The aggregation models can be used by the DSOs to assess the network conditions and the aggregators could use the aggregated values when bidding in the market.

To conclude the overall outcomes of the project provides a good method to exploit methods to ensure demand flexibility from controllable loads and establish integrated ANM and protection methods to ensure an effective control and protection of the future distribution grids, given that new legislation allows the set up method. If so, the end consumers will get reliable and cheap electricity and the utility can prevent or delay huge investment in network grid reinforcement. The DSO can implement the aggregation and control methods in their planning and operational stages to avoid grid bottlenecks, further the aggregators can use the results from the aggregated models when bidding on the market.

1.4 Project objectives

The initial objectives of the project were to:
- Build up and intelligent distributed architecture of the smart grid
- Set up operation and control strategies for demand response, storage management and home automation
- Set up smart metering algorithms for consumers to minimize their electricity costs
- Set up an intelligent and adaptive relay protection scheme in the smart grid environment
- Set up coordination and control strategies for the smart grid components to mitigate contingencies like overloading, generation deficiency etc.

During the project period the focus became on the hierarchical control structure for controlling heat-pumps, electric water heaters and electrical vehicles in a structured way to prevent overloading and too high voltage fluctuations on the distribution lines in systems with also a high PV penetration. The storage possibility and flexibility of these loads was explored in detail and tests were made both using simulation programs and laboratory experiments. Also the objective regarding the intelligent adaptive projection scheme, were appropriately addressed. The simulation of the system were based on actual metering data from at site under the SEAS-NVE network grid at Zealand, these were used as base load condition, and extra heat-pumps, electric water heaters and electrical vehicles were added in the simulation, to try to analyze the future conditions. This had low risk, since the data were available more or less already from project start, both for the low voltage system analyzed regarding the load-flow and the medium voltage system analyzed regarding the protection issues.

Quarterly meetings were held with the project partners to get input and feed-back regarding the analyzed models and to keep track on the project. This worked very well, and ensured that the proposed method would be realistic to implement for the DSO and that KK-electronics as control providers could see the ideas of the set up control strategies.

On the other hand the focus initially intended regarding the smart meter functionalities and home-automation has to be left only to simulations and laboratory work. First of all, due to the fact that the meters were only controllable so far via PLC (Power line carrier) and only used for billing purpose, whereas all other functionalities available in the meter were not used. It was found that it would be too time and cost-consuming and have too high risks to implement new control and measurements at the costumer site during the project. Therefore, the actual control of the heat-pumps available in the test area, could also not be controlled, and only the normal power consumption from these were used as a part of the base load given by the meter data from the area.

But in the end the objectives of the project were reached, though the control idea is not directly implemented in the smart meters as originally intended, only the ideas for what and how the control should be is set up.

After finalization of the Ph.D work in the project, where all the above issues were addressed, it was found, that there were still some hours and money left on the project. We therefore applied for a prolongation of the project to focus on demand flexibility from aggregated loads which could be used by the DSO for planning and operation of the grid and by aggregators when bidding on the market. This prolongation was approved by energinet.dk and the project was extended with 5 months, to fulfill this objective without extra costs supplied from energinet.dk. This work has resulted in some internal reports, from which the main results are also given in this final report.

1.5 Project results and dissemination of results

Most of the work done in this project is done in relation to a Ph.D work done by BishnU Prasad Bhattarai. Therefore, also most of the results are to be found in his Ph.d thesis report [1] This is a summary report based on 3 journal papers (one accepted [2], and two to be submitted) and 7 conference papers [3-9] and one conference paper accepted but not yet published [10]. Further two internal reports have been made regarding the aggregated models which were the focus for the extended part of the project. In the following the main activities and results during the project are described.

1.5.1 Setting the project into a general smart grid perspective

The project is started by setting the project idea in perspective to the ongoing transformation of the electric grid due to increased penetration of RES and the electrification of the gas, heating and transport sectors. The opportunities, such as using demand side management and exploring the flexibility due to the electrification of the gas, heat and transport sector, and challenges, in the form of fluctuating power generation from RES, integration of large loads from the same sectors as above with random fluctuations of demand, which challenge the balancing stability and security of the power system and influence the hosting capacity and the protection of the distribution network grid, are described. Also some international aspects are considered, such as Nordic market perspectives and how the flexibility of new larger loads can contribute here. There are also financial challenges, since a proper market framework is missing for how the costumers can participate and benefit if offering demand responses. This leads to the following objectives for the Ph.D project:

- Develop suitable control architecture for exploiting demand flexibility from residential consumers in LV distribution networks
- Develop proper models of potential flexible loads and suitable control strategies for activating DR considering a dynamic electricity market
- Coordinated control of active loads and local generation to provide economic and efficient operation of the LV grid
- Develop a smart grid testbed considering multi-disciplinary aspects of the smart grid for practical demonstration of the developed DR models and control strategies, and

- Develop an adaptive and proactive protection scheme to ensure protection coordination in a MV distribution grid during varied network topologies

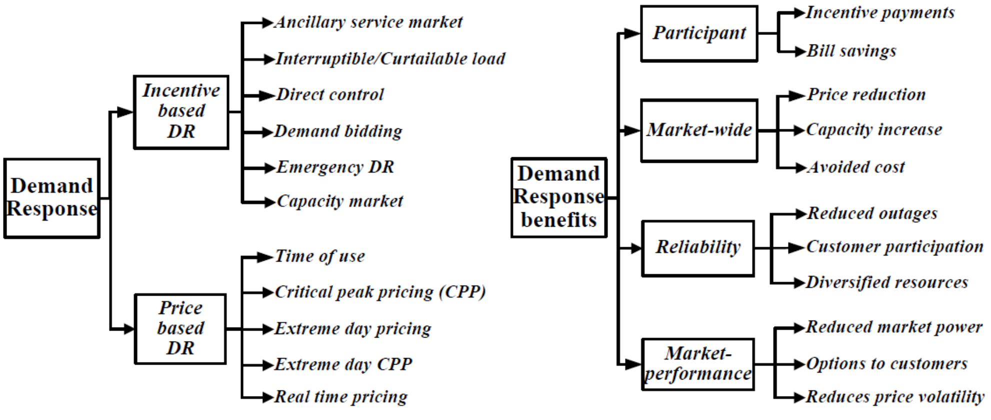
Further, as mentioned above the project period were extended to find aggregated models of the loading and generation with the following advantages:

- Demand flexibility from the aggregated load has less forecasting/prediction errors since the individual errors gets compensated by each other (are leveled out). This supports an effective decision making for both the aggregator when bidding at a market and distribution system operator (DSO) when planning new operation and extension of the network grid.
- The aggregation provides an effective approach to trade the consumer flexibility in the electricity markets since the individual consumers will have practical difficulties to trade their flexibility in the market if treated individually. A
- s the aggregation results in few larger loads having a less fluctuating and averaged behavior instead of many distributed very fluctuating small loads, it facilitates the DSO and aggregator in the analysis and planning process.

1.5.2 *State of the art analysis*

This part summarizes the major scientific contributions made in the smart grid context for distribution grids. The focus is on intelligent control architectures including ideas for demand side management, modeling of controllable loads and issues regarding protection of the distribution system with high penetration of RES.

The demand side management relates for instance to price based demand response (DR) often used to move loads from critical high peak period to off-peak periods. But also intensive based DR is discussed since they normally have a more dispatch able response than the price based methods. Finally, also automatic demand response is discussed, which acts on response due to variations in parameters like frequency or voltage. The benefits of the different methods are discussed seen from costumer, DSO and system operator point of view. The analyze result in the following overview of DR classification and possible benefits.



a) DR classification **b) Benefits of DR**

Fig. 1. DR classification and potential benefits (reference: M. H. Albadi and E. F. El-Saadany, "Demand response in electricity markets: An overview," in Proc. IEEE PES General Meeting 2007, pp. 1- 5, Jun. 2007).

Next part of the state of the art analyses concern the intelligent architecture. The main purpose is to keep the voltage and frequency within limit and many of the concepts operate with both centralized and de-centralized methods. Figure 2a illustrates advantages and disadvantages of centralized and decentralized controls. Also the concept of hierarchical control is discussed, since this will be applied during the project. Figure 2b is showing this kind of concept for a micro-grid, where the real-time support is controlled locally to support the network locally by a kind of primary control but the more overall set-points and balancing issues are dealt with from the central stage by a secondary or a tertiary controller. For the control systems also the ICT needs and performance are analyzed.

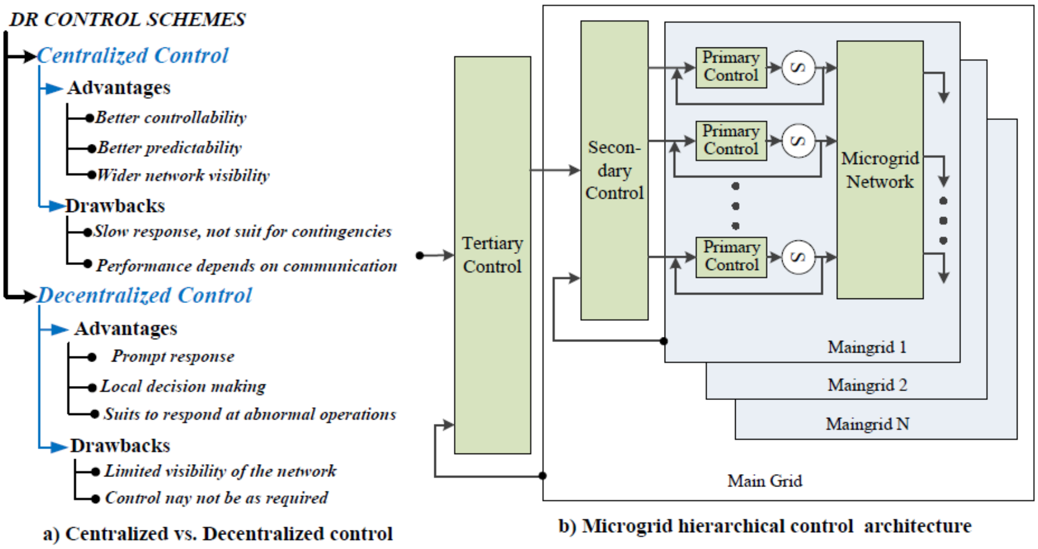


Fig. 2. Intelligent control architecture a) Centralized versus decentralized (reference: N. S. Lu et al., "Centralized and decentralized control for demand response," in Proc. IEEE PES Innovative Smart Grid Technologies, pp. 1- 8, Jan. 2011) and b) Hierarchical control architecture (reference: C. A. Canizares et al, "Trends in micro-grid control," IEEE Trans. Smart Grid, vol, 5, no. 4, pp. 1905-1919, Jul. 2014)

Third part of the state of the art analyses discusses the flexible loads and local generation. Key features of EVs are set up and different models are analyzed. Models of HPs and how they can support the electrical network and how the COP (coefficient of performance) factor are dependent of ambient conditions are investigated. PV systems models seen from an electrical point of view, is based on the state of the art analysis to be modeled as a static generating source which output varies with irradiance and ambient temperatures.

Fourth part of the state of the art analyses look into different control strategies to prevent voltage and capacity contingencies at the distribution level. To be able to perform the control different aspects like the type of resource, control perspective, the objective and application should be taken into account before setting up the method. This is presented in figure 3.

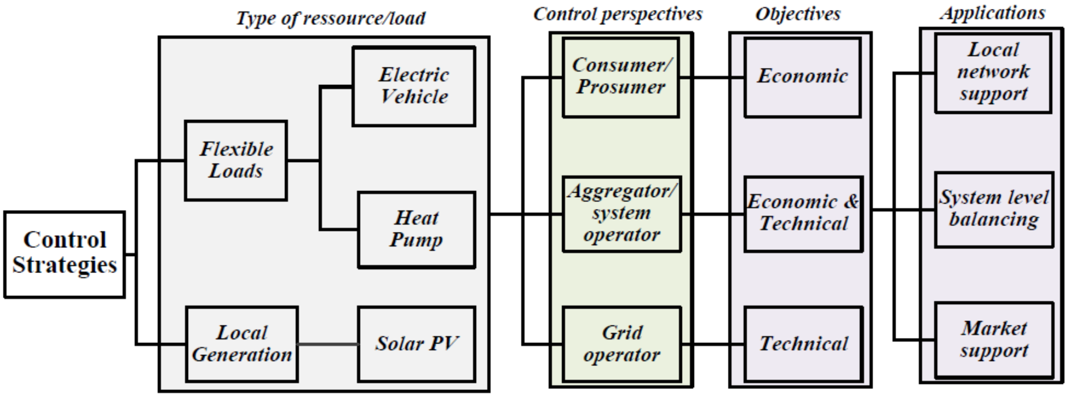


Fig. 3. Various perspective to develop DR control strategies.

The last section of the state of the art deals with ANM and protection, where the interaction between ANM and protection are discussed and where adaptive protection (AP) is introduced as a future solution for the distribution network grid with a high penetration of RES and where ANM are used for varying the network topologies.

1.5.3 Hierarchical control architecture (HCA)

The set up hierarchical control structures are documented in the Ph.D thesis [1], but also in the conference paper [3]. Some of the challenges so far in relation to HCA is that there are no standardized architecture for demand response (DR), further also the passive structure of the current low voltage network grid is a barrier for the implementation. Therefore, the idea in this project uses various types of DR programs to achieve both commercial and technical functionalities. The following interaction framework is set up as a starting point, where the demand response resource is a consumer with a directly controllable load which receives a control signal such as electricity price, power/temperature set point. The aggregator is a commercial actor, who ensures the coordination among the actors to execute the demand response. The aggregator is the link to the market and they also ensure coordination with the DSO to avoid grid bottlenecks.

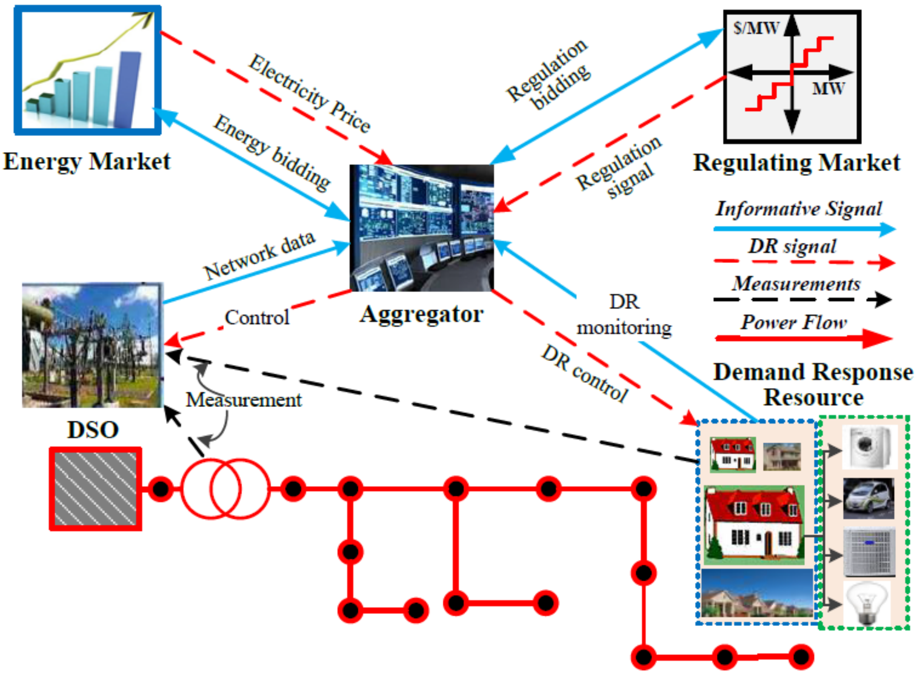


Fig. 4. Demand response interaction framework for smart grid actors.

The control methods as given in table 1 are considered for the hierarchical control method to be build. It is important that the response time of the difference control methods are coordinated, so it is possible to separate the different actions. Also the cauterization is done in a way so limitations of each DR method are compensated by the other.

Table 1. Categorization of different DR control methods. ADR= Autonomous Demand Response, DLCDR = Direct Load Control based Demand Response, DDDR= Demand Dispatch based Demand response, PDR=Price based Demand Response

DR Type	**Control Signal**	**Signal type**	**Decision place**	**Control action**	**Response time**	**Communication need**
ADR	Frequency/Voltage	Directive	Local	Local	< 1 sec	No
DLCDR	ON/OFF, Setpoints	Directive	Central	Central	sec. - min	Yes
DDDR	Demand dispatch	Instructive	Central	Local	min. - hour	Yes
PDR	Price	Informative	Central	Local	hour - day	Yes

Based on the methods mentioned in table 1 a HCA as shown in fig. 5 is set up for the project. The specific response time increases from the inner primary loop towards the outer tertiary loop and provides in this way back up in both directions for the next loop and increases the control and operational flexibility. The HCA loops are however not identical to the frequency regulations loops known from the power system balancing control, but the primary loop in the HCA can be used for primary frequency regulation and so on for the other loops. But the loops can also be used to serve the network grid in several ways such as for peak reduction, congestion management, local voltage support etc.

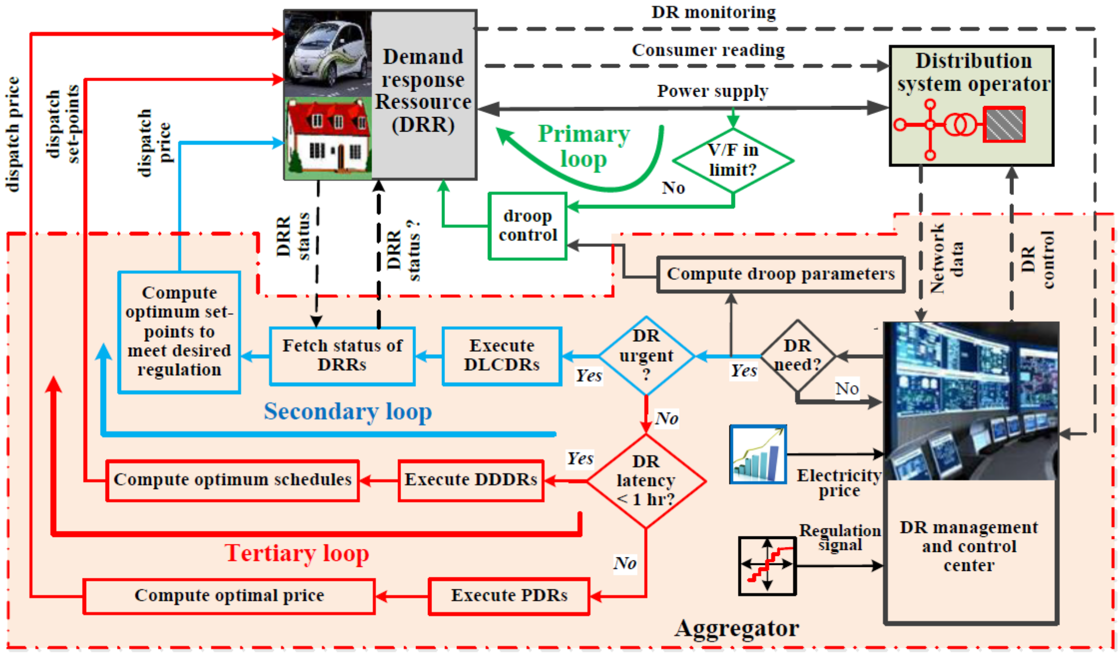


Fig. 5. Hierarchical DR control architecture.

The tertiary control loop is the slowest and is designed to execute PDR using informative control to optimally adjust the hourly electricity price to incentivize the consumers to use more or less energy or it can use DDDR as an instructive control to send out specific set-points to the consumers. Normally the PDR would have slow response time since the costumers should know the price maybe even the day ahead. The DDDR is in this project set to be updated every 15 minutes, to compensate uncertainties from the day ahead market. The secondary control is implemented to make direct control of the loads, and works as an intra-day/intra-hours balancing resource when the tertiary control is incapable to meet the regulation requirements. The primary control is using automatic demand control and is based on for instance local voltage measurements, and it is activated whenever the system parameters are outside the limits. It can perform almost real-time control (in order of seconds) and can be designed as a power-voltage (P_V) droop control.

The control architecture is used for simulation on a test LV network fed by a 10/0.4 kV, 400 kVA transformer as shown in fig. 6. More details about the test grid can be found in [1]. This network grid has a high integration of PV, so bidirectional flow is present. The yearly consumption and generation profile is seen in fig. 7.

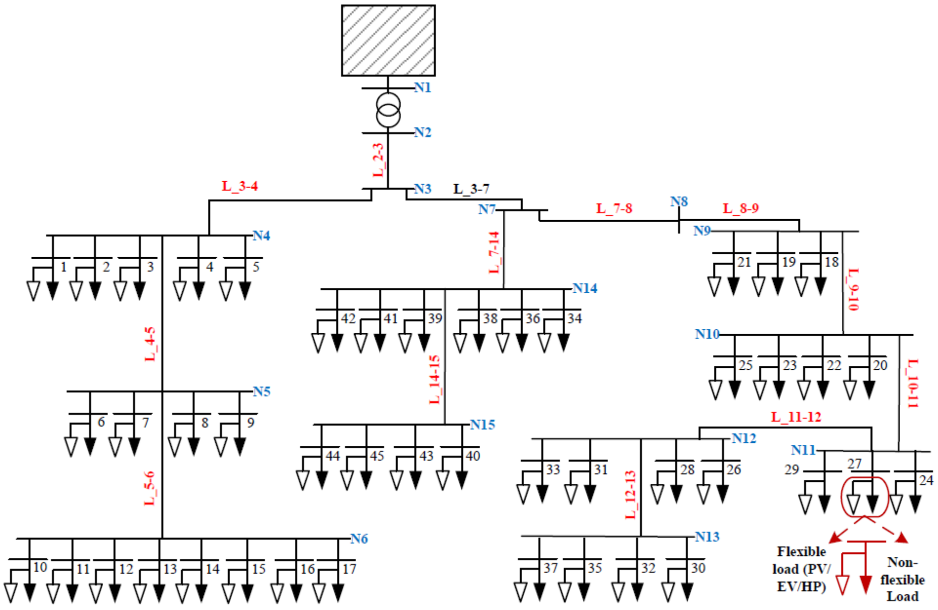
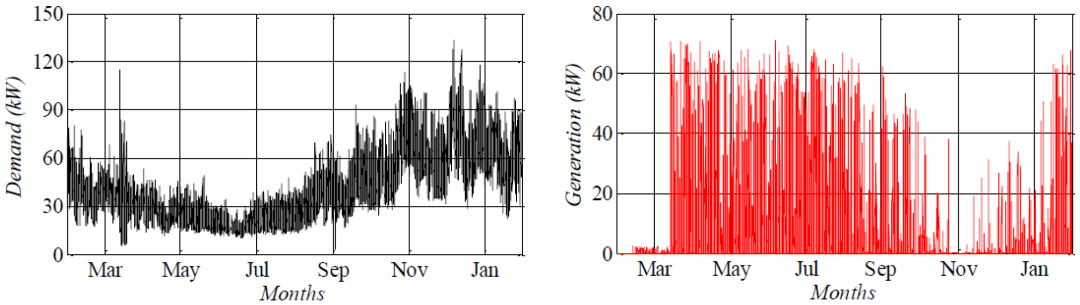
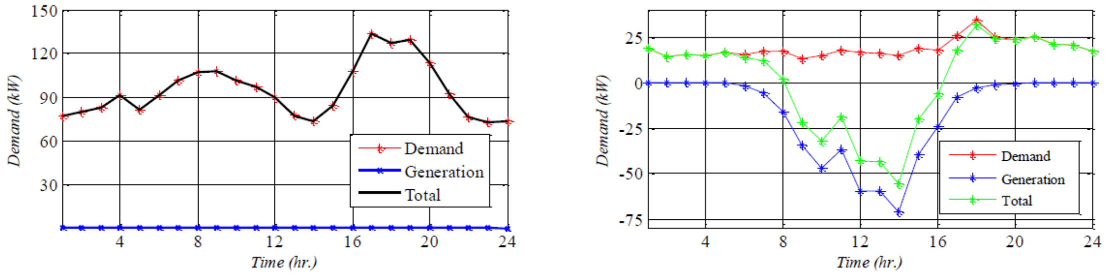


Fig. 6. Single line diagram of test network



Yearly consumption proflie

Yearly generation profile

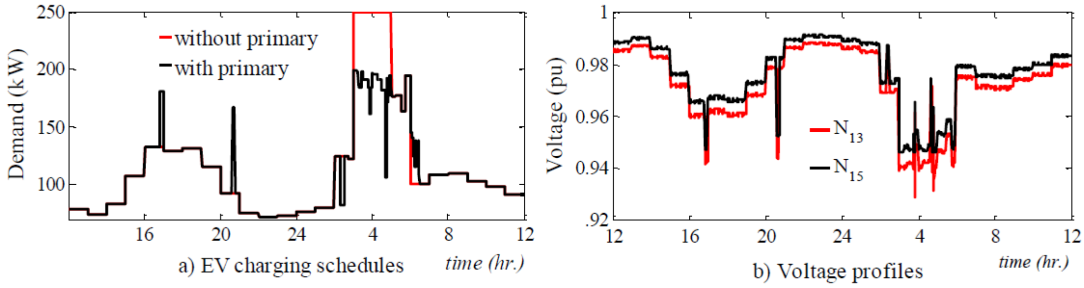


a). Maximum demand Day

b) Maximum generation day

Fig. 7. Upper curves yearly variation of demand and generation seen at the 10kV transformer. Lower curves maximum demand and maximum generation day.

For the test case EV-penetration are modeled as demand response loads. The performance of the HCA is simulated over 24 hours of power and communication co-simulation. In fig. 8 an example of the implementation of the primary control is shown. It is seen how the primary control counteracts the too low voltage ensuring that the minimum voltage is 0.95 pu. Other examples with the tertiary and secondary control is also shown in [1]



a) EV charging schedules

b) Voltage profiles

Fig. 8. EV charging profiled and voltage profiles demonstrating the primary control action.

1.5.4 DR control strategies

This part is based on the Ph.D thesis [1] and the conference papers [4, 5, 6 and 7]. First a method to manage constraint violations in the LV distribution grid is realized as a proactive centralized and a reactive decentralized control. The centralized control is based on estimated operational scenarios and operates every hour, while the decentralized control is used to react to voltage violations in real time. Given the consumers forecasted load, the centralized control performs a load flow calculation to see if any current or voltage problem occur. If so the control activated the minimum amount of flexible load to counteract the violation. This flexibility offer request is then send to the consumer. To ensure fair utilization of flexibility from all costumers their activation limits are different and computed using historic data. The decentralized control is implemented to give real time voltage support and is designed as a linear P-V droop and implemented at every consumer. Again to ensure fair participation of all costumers, different thresholds levels and minimum voltage levels for full activation are used at the different nodes (higher levels are set close to the substation). The test network grid for analyzing this control is shown in fig. 9. The flexibility limit of each consumer is set to 20% of the load. The results are shown in fig. 10, here the blue part is grid behavior without control. The green part is when the central controller is activated. The central controller is able to keep the voltage at 0.95 pu almost all times, however there are a few occasions where the central controller cannot keep the limit, seen as small grey spikes in the green area in fig. 10a. In fig. 10 also the overloading before the control, the total load at the transformer and the used activated flexibility compared to available flexibility are shown. It is seen that only a minor part of the flexibility is used, but that there are occasions where the flexibility is not enough. In fig. 11 is shown an example where also the decentralized control is activated. In this case random noise is simulated to create load variations. The usage of different voltage activation limits for the different costumers is also clear from this figure, and it is seen that the voltage limits are more violated if the control are not used, whereas the voltage is kept within limits for costumer 14 when the control is activated, there are however still few incidents for the costumer at node 26 with voltage violations due to missing flexibility from at the costumer location for these periods. In the figures the upper red curve is the voltage threshold for the activation, and the lower red curve is the minimum voltage level for full activation of the flexibility. To gain the full flexibility both centralized and decentralized based control should be used.

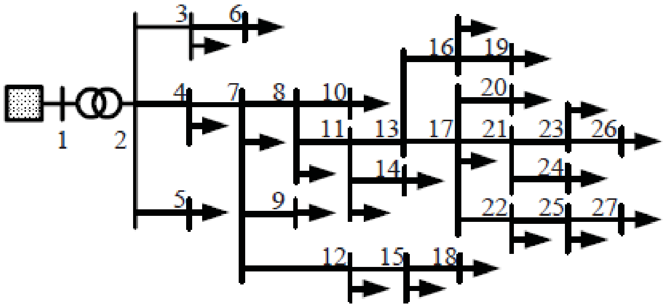


Fig. 9. Test network grid for demonstrating the DR-response method.

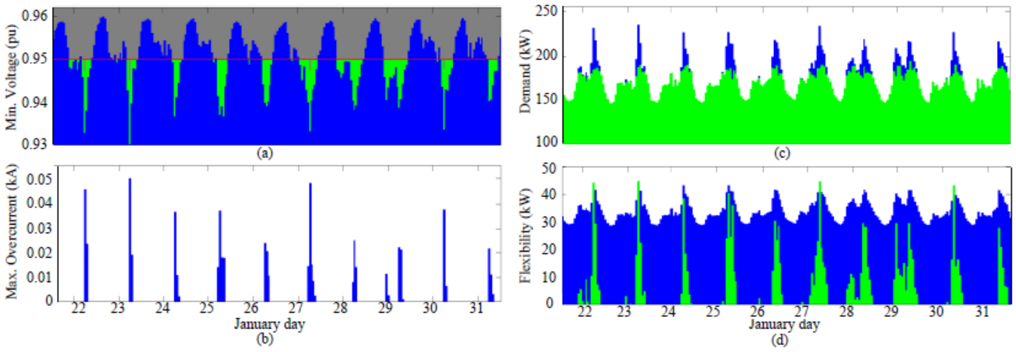


Fig. 10 Result for application of central DR control a) Minimum voltage at the feeder, b)Maximum overcurrent at the feeder c) Transformer load, d) Available versus activated flexibility

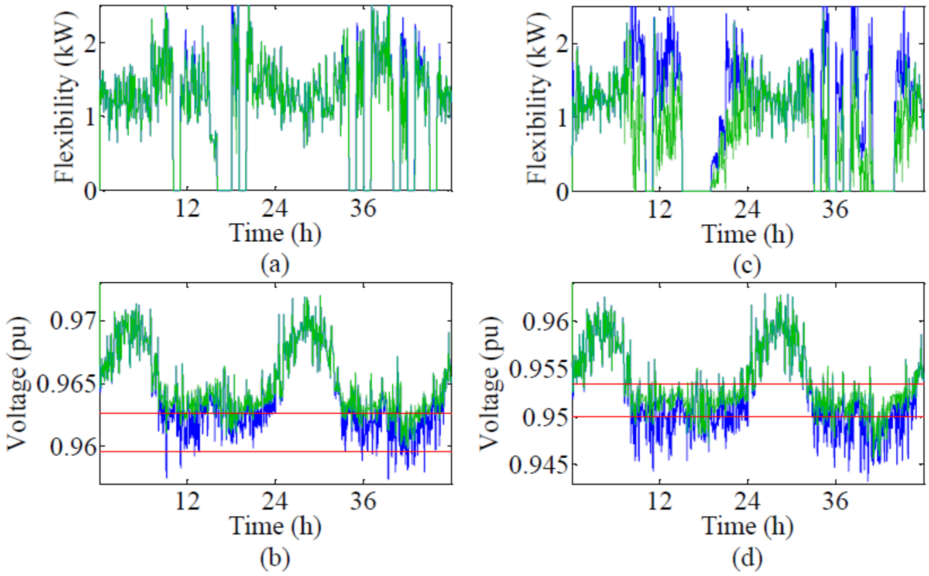


Fig. 11. Simulation results with (green) and without (blue) decentralized control a) flexibility of consumer 14, b) voltage at consumer 14, c)flexibility of consumer 26 and d) voltage at consumer 26.

In this part of the project also a novel voltage controlled dynamic DR strategy is developed. The methods first calculated near real-time the voltage dependency of the loads. To follow a dispatch demand, the required tap-setting of an intelligent MV/LV sub-station is computed using the computed voltage dependency of the loads. Then finally a simple adaptive voltage estimation technique is implemented to ensure that the voltages are within limits, this updates the voltage estimates based on periodic measurement data. For further details see [4].

Next results for DR control strategies for EVs are presented. Again the idea of a hierarchical control is used, but only with two stages. Here a local adaptive control is encompassed by a central coordinative control to use the flexibility from EVs. The central control could be managed by and aggregator who prepares optimum EV charging schedules taking both technical (network constraints) as well as economic aspect into account, and the local control adjust the actual EV-charging in real-time according to measured voltage. This is made as an on-off control. To prevent frequent switching the EVs which are activated by the local controller, are kept at the new settings until next slot from the central controller. More details of the control can be seen in [5]. The results for a case scenario where the EV penetration is set to 66% of all house hold and the today base load is increased by 50% for the test grid as in fig. 6 are illustrated in fig. 12a. In order to demonstrate adaptiveness of the proposed algorithm, the electricity price has been changes as shown in fig. 12b) and feeder load is increased as shown by dotted red line in fig. 12a. The EV schedules adapts to the variation in electricity price as well as according to the load. The local voltage control ensures real-time adjustments a time 24, due to the increased load, since the voltage at point of coupling (POC) was violated. This is shown as the blue dotted line in fig. 13, for the voltages at the deviated price in fig. 12b.

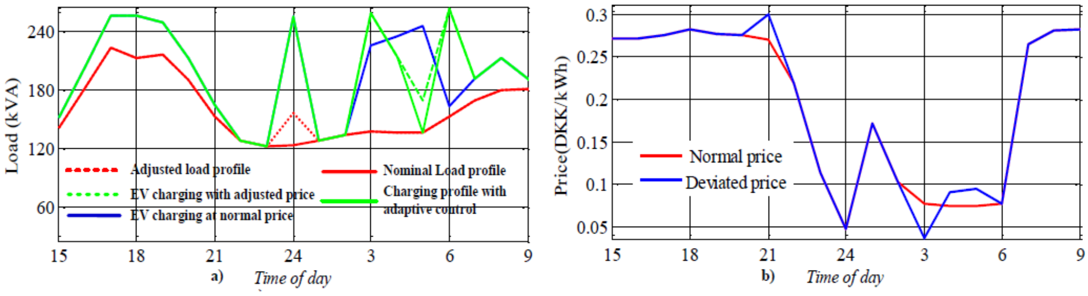


Fig. 12 EV-schedules a) EV charging profiles b) Electricity prices

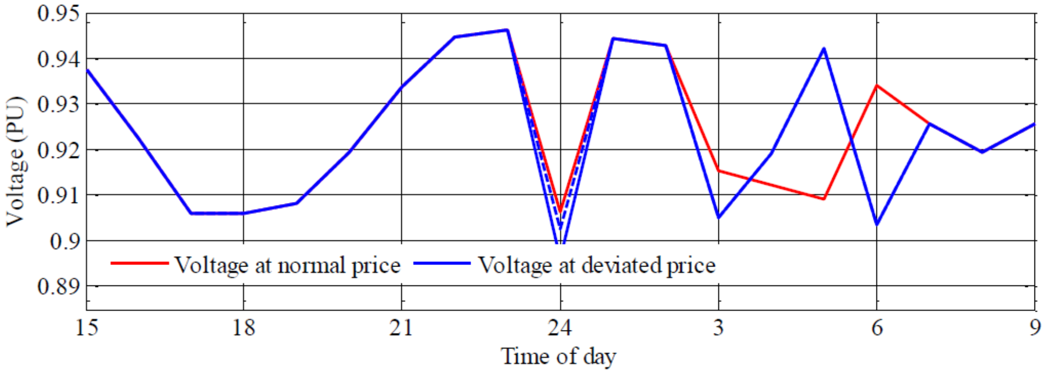


Fig. 13. Terminal voltage at the farthest node(N13) for different cases.

Also a study case for DR response using HP is investigated, also in this case a centralized and a local control is used. The centralized control in this case determines the schedules based on electricity price, heating demands and electric feeder criteria. The HP is on-off controlled and therefore a binary integer programming optimization is implements. Again the local controller performs adaptive control in real-time but here the control is based both on the voltage at POC but also the thermal demand of the costumer. The detailed description of the control is given in [6]. The results from a simulation for the network grids as shown in fig. 6 where 80% of the costumers are expected to have HP are shown in fig. 14 and 15. The aggregated HP operation is shown in fig. 14.a and the prices signal used in fig. 14.b. It is clearly seen that the central controller plans the operation schedule of the HP according to the prices. Fig 15 shows the impact on the HP schedules and voltage at N13 with and without the local adaptive control. It is seen that the local control adjust the voltage within limits (here set to 0.92) if needed.

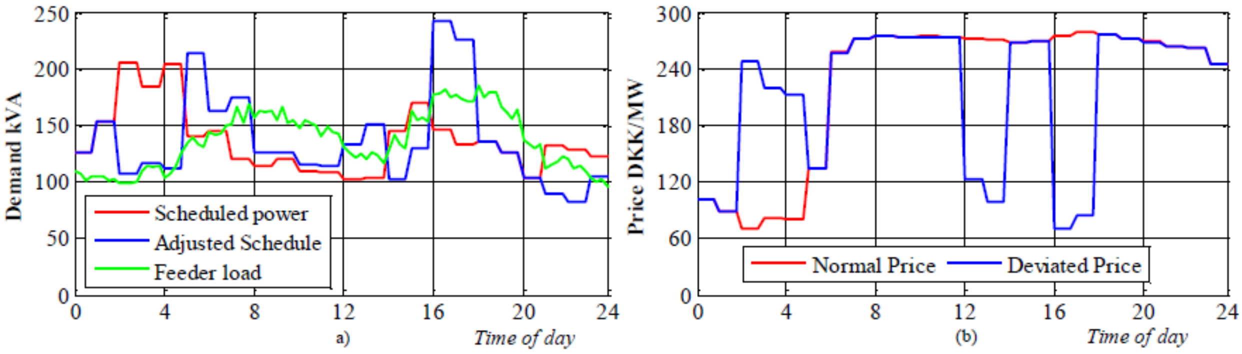


Fig. 14. HP scheduling with load a price variation, b) Normal and deviated prices.

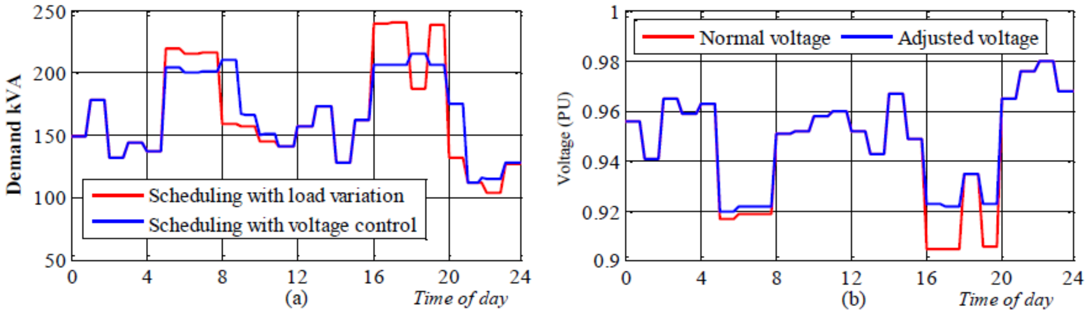


Fig. 15. Impact of local voltage control on a) HP schedules and b) voltage at node N13.

Based on the seen results it is also obvious, that if the prices change the consumption can be changed. Therefore, if also the price signals change according to either global or local conditions this can be effectively used to control the DR.

1.5.5 Control of active load and local generation

Different from the previous section this part describes the DR control systems for distribution grids which have both large active loads and local generation here especially in the form of PV system. The idea is to make a control system in such a way that the PV systems and the active loads become supportive to each other. Again a centralized and a decentralized control method are set up. The first case to be considered is again based on the network grid as shown in fig. 6 with integration of EVs and PVs in the grid. The EVs are modeled as three phase constant power loads at 11 kW and 25kWh. The PVs are modeled as static generators and are operated as constant power sources with specified PO set-points. The reactive power limit of the PVs are set by limiting the PF to ±0.95. An auto-regressive moving average model is used to forecast the consumer demand and PV production. More information of the models can be found in [8]. The central controller is doing the EV-scheduling as in previous section, first considering the PV power production as non-controllable. However, if this leads to congestions in the grid, rescheduling is done considering both the PV production and the EV-consumption. This favor the PV power production and let the PV contribute prior to the EV for under-voltage violations and the EV contribute prior to the PV for over-voltage violations. The central control provides periodic control with 15 min intervals, and any inter-slot variations cannot be dealt with by this. Therefore a decentralized control based on voltage measurements are implemented at every EV and PV location to adjust the power consumption/production in real-time. These controls are made as linear droop controls. These controls remain non-operational as long as the voltage limits are not violated. If the decentralized controls are activated, this is also taken into account at the next time-step optimization for the central controller. The coordination between the periodic centralized control and the decentralized real-time control is seen in fig. 16. The effect of the periodic centralized control for scheduling is compared to a system with without such a control in a case where changes in electricity price and load demands are changed as in fig. 17, and the results are shown in fig. 18.

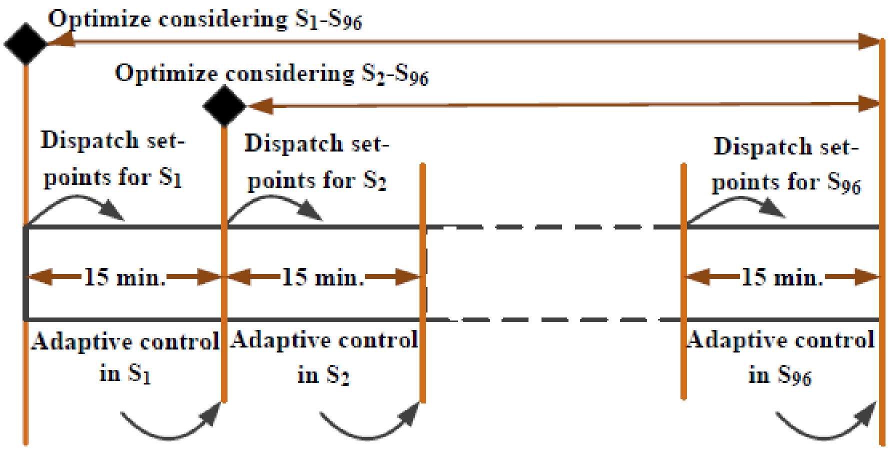
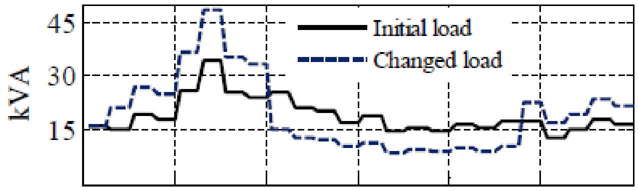
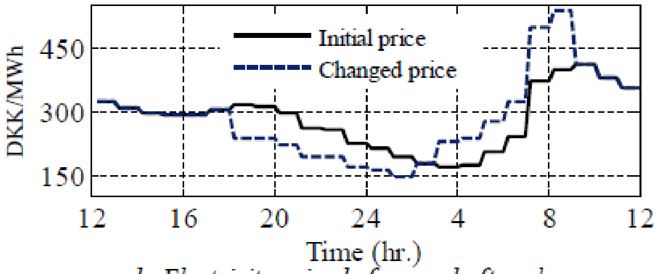


Fig. 16. Coordination between centralized and decentralized control



a. Feeder load before and after change



b. Electricity price before and after change

Fig. 17. Original and modified a)demand and b) electricigy price

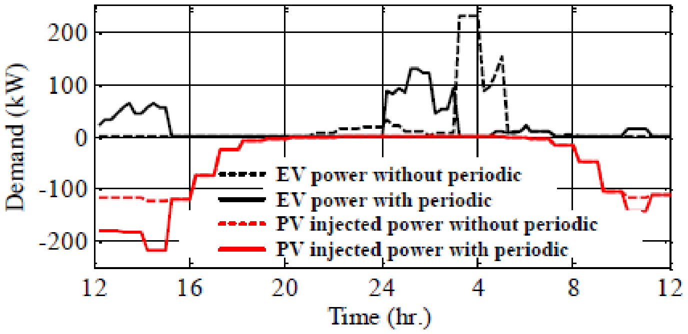


Fig. 18. PV oiwer injection and EV charging power to adjust to change in electricity price and load changes.

It is seen that the changes in loads and electricity price significantly changes the charging profiles of the EVs and also the power injections from the PVs in certain periods. Due to the price change, EVs scheduled originally to charge from 3:00 – 5:00 are shifted to day-time 13:00 to 17:00 to ensure increased PV power injection. The periodic optimization helps the EVs to adjust their charging according to the updated prices. To see the effect of the decentralized control some load changing events are shown in fig. 19c. From fig. 19.b it is seen that the first transient variability of the PV production (event 2 from 14-14:45) causes and overvoltage. However, with the control some of the PVs curtail their output and the problem is solved. Later at event 4 an increase in load causes and under voltage. Then the EV charging power is decreased to mitigate the problem. So both the centralized and the decentralized control work as intended.

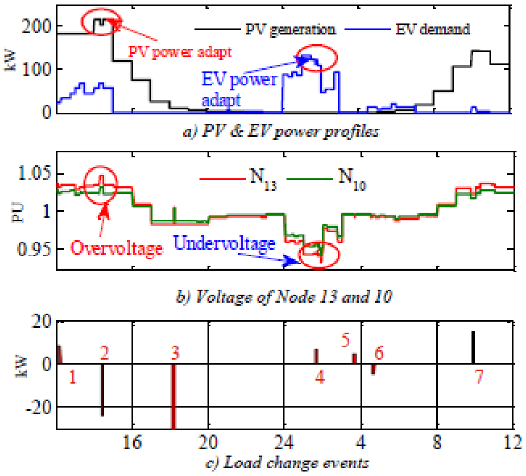


Fig. 19. Decentralized control with PV power curtailment and EV charging power change.

In the project also the effect of using EWH together with the PV systems are shown. The main contributions to this is described in [10]. Again the network grid used for the case studies are the one shown in fig. 6. In this case the EWH is modeled as a constant power thermostatic load with a thermal storage tank. The EWH provides flexibility both by adjusting the power consumption directly, but is can also be controlled adjusting the temperature settings of the EWH, so it consumes less power for lower temperatures and vice versa. The control is more or less set up like the one for the EV/PV control, so the EWH compensate over voltages from the PV and under-voltages are compensated scheduling the EWHs to operate during high PV generation periods. The flexibility is achieved through droop controls for both the active and reactive power whenever the voltage at the point of coupling (POC) is violated. The control is made such that reactive power control is done prior to active power control for under-voltage problems. But for over-voltage problems the active power control operate prior to the reactive power control letting the EWH use more power first. An adjustable temperature band is made to exploit extra flexibility when voltage violations occur.
Results for a case with both EWH and PV penetration is shown in fig. 20 for a case with light loading but high PV penetration. It is observed that the EWH first increases its active power consumption to mitigate the over-voltage. However, this is not enough and reactive power consumption is increased also. However, it is managed to do the control without PV curtailments.

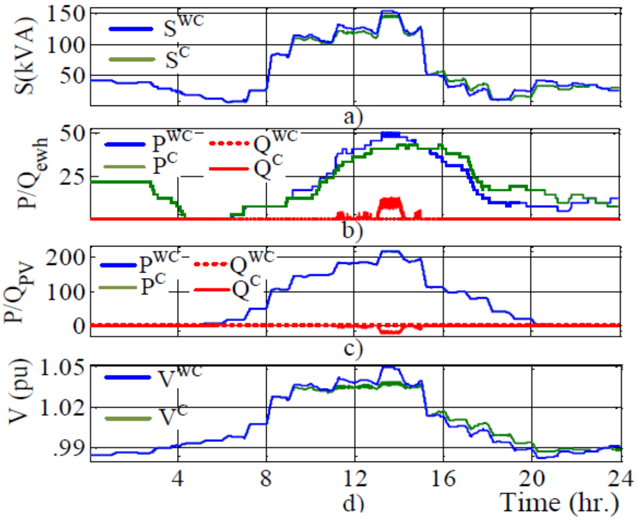


Fig. 20 Simulation results for both EWH and PV a) Total apparent power, b) Total active and reactive power of consumed by EWH, c) Total active and reactive power injected by PV, and d) Voltage at farthest end node, with and without adaptive control for lightly loaded case.

As a conclusion for this section, the interaction of active loads and RES has been shown and the flexibility of either EVs or EWHs has been used actively to ensure the voltage stability in the grid both for over-voltage and under-voltage conditions.

1.5.6 *Development of at test bed*

During the foreign stay of the Ph.D student at Optical Zeitgeist Laboratory, INRS, Canada a small scaled-down smart grid test bed was established. The system lay-out of this test bed is shown in fig. 21.

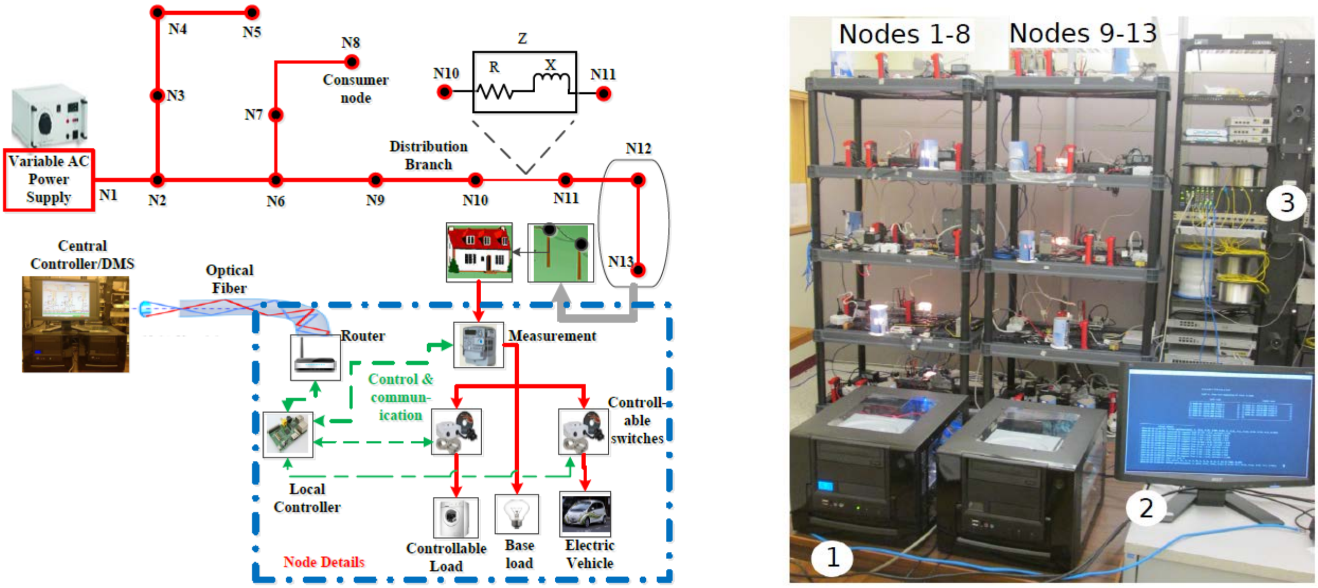


Fig. 21 13-node scaled down smart grid test-bed

The test bed is realized to demonstrate various novel smart grid solutions such as demand response, real-time pricings and congestion management. The setup is based on a 250kVA 0.4 kV radial network grid, which is scaled down to 1 kVA and O.22 kV. Further the ICT system is integrated in the system, to verify real-time monitoring and control capabilities of the real system. The test bed functionalities are demonstrated by optimizing the EV charging in the grid. More information about this test-bed can be gained from [2].

1.5.7 *Proactive and adaptive protection design.*

The main results achieved regarding proactive and adaptive protection idea for the future power system at MV, realized in this project is more detailed described in [9], here only the main findings will be given. The idea for the proactive and adaptive protection is based on the focus on increased integration of distributed energy resources (DER) in the grid, which might fluctuate a lot and thereby jeopardizing the existing protection system when producing power, maybe given reasons for bi-directional power flow or increasing fault current and they might also give reasons for blinding or false tripping of the relays. Another reason is due to Active Network Management issues (ANM) for instance in the form of network re-configuration, demand response etc. which might also affect the protection. Therefore, the conventional protection schemes might be insufficient to maintain selectivity and sensitivity if they only have a single parameter setting and proactive and adaptive protection are needed for the more dynamic behavior of the future MV grid. In this project a two-stage protection strategy is designed. First, an offline fault analysis is performed to find the relay settings seen from each relay for all possible operation modes of the grid i.e. with/without DERs connected, with different network configurations, in island or grid connected mode. These settings are stored in the relay memories. Next an on-line state detection algorithm is realized to detect the actual operation mode, network condition and DER availability after which the appropriate relay settings are chosen. To find the network status a combination of a local adaptive and communication assisted centralized protection scheme is implemented.

The new protection concept described above is illustrated in figure 22.

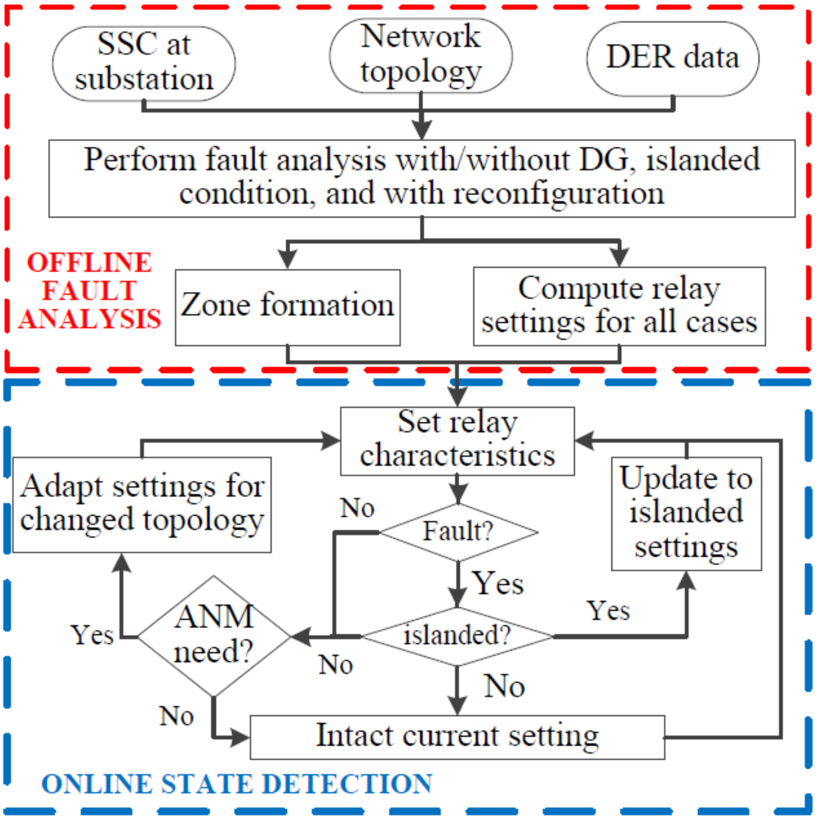


Fig. 22.Flow chart of proposed proactive and adaptive protection algorithm

From the flow chart it is also seen that a zone formation is to take place. This is based on a state detection algorithm (SDA) implemented for online identification of the operating states. The distribution network is decomposed into various zones as shown in fig 23, such that fault current contributions from the DERs in any zone will cause minimal impacts to the operation of the relays in the other zones.

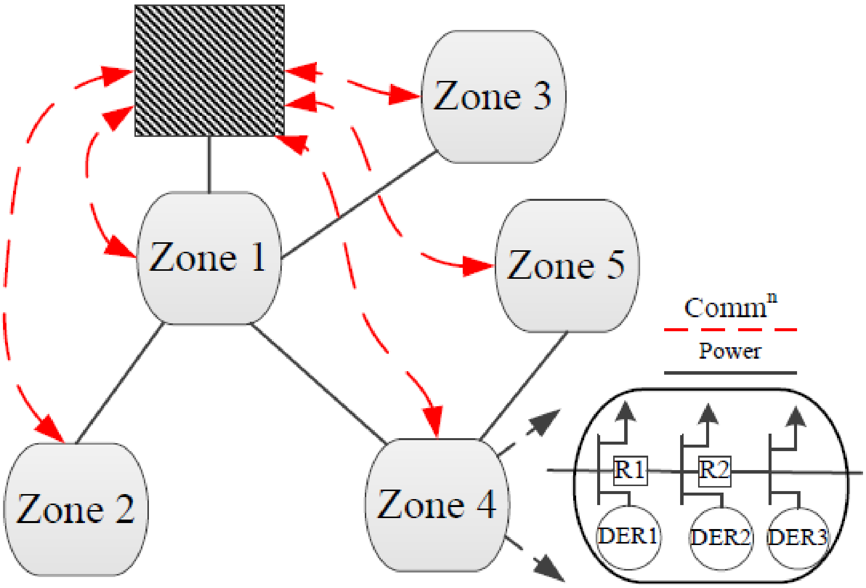


Fig. 23. Procedure of zone formation.

Each relay within a zone, called intra-zone relay (IZR), is designed to detect ON/OFF states of the DERs within the zone. The centralized protection unit is then designed to detect major changes in the network operation such as switching of modes (grid-connected/islanded), network recon-figuration etc. Thereafter, the central protection unit uses an event driven communication to update settings of respective relays.

The protection system is shown in a network grid like the one shown in fig. 24.

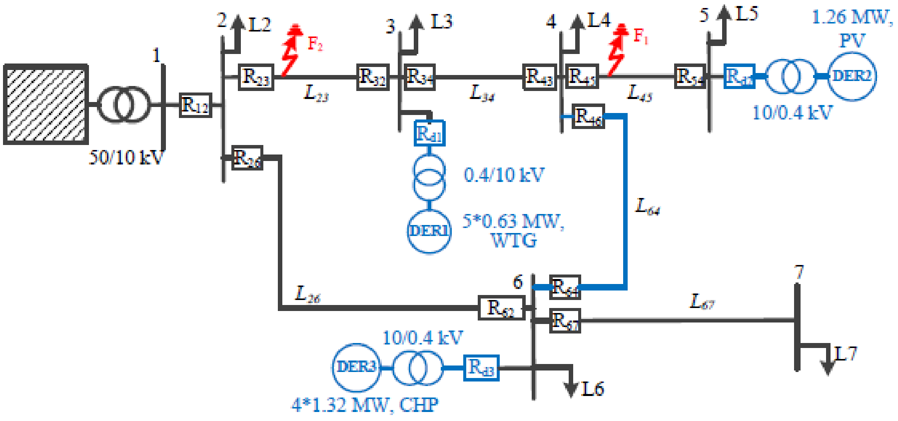


Fig. 24. Test MV network grid for the protection method

In fig. 25 different fault currents are shown for different situations in the network grid.

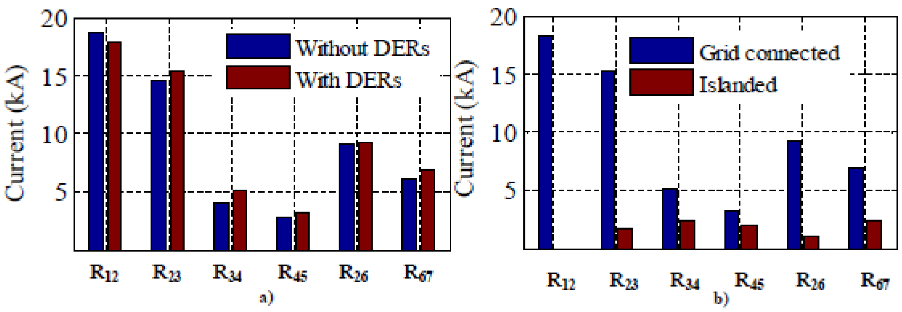


Fig. 25 Maximum fault current seen by different relays for different network conditions.

In fig. 26 results for a blinding situation is shown for the case with a normal protection with a single value setting and for the adaptive protection method. For a bolted fault F1 in Fig. 24, the fault current seen by R34 is greater than its instantaneous pickup current, thereby the relay undesirably face an overreach problem. In fact, F1 forced the relays R34 and R45 into instantaneous modes and R34 gets tripped as shown in Fig. 26 for out of zone fault. To overcome the protection blinding issue the relays pickup settings are updated adaptively on the basis of the connection status of the DERs. The DER connection status is identified on the basis of state detection algorithm presented fig. 22. In fact, the pickup current of relay R34 is increased to avoid overreach i.e. to enable discrimination of out-of-zone faults. It can be clearly observed that, to clear the fault F1, the proper relay R45 gets tripped, thereby avoiding the overreach of R34.

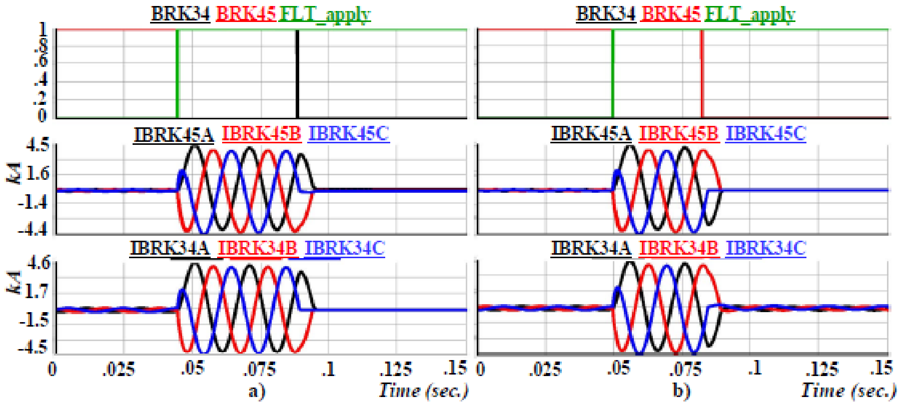


Fig. 26. a)Protection blinding of R34. b)solution using the proactive and adaptive solution

In the paper [9] also an example with false tripping is showed to verify the capability of the new algorithm.

1.5.8 *Aggregation of residential consumer demands in distribution feeders*

This part of the project is done in the prolongation period where the focus is on demand flexibility from aggregated loads which can be used by the DSO for planning and operation of the grid and by aggregators when bidding on the market. The results are detailed described in two internal reports, but since there are not published in papers, the results from this part is a bit more detailed here.

So far in the project the control techniques for the DR deployment has mainly been implemented on device or consumer level. This is very essential for the actual implementation of the control, but the question has been if it is really necessary to reach every consumer/device. First of all it needs an expensive ICT infrastructure, there is a large amount of data to be handled, and it may delay the control due to delays introduced in the data collection, computation and actual action, and in the end it gives a very complex calculation. Therefore, the key idea is to aggregate the electrical consumers connected to a node or nearby nodes in a distribution feeder to an equivalent aggregated load for each load types. For instance, 'n' Electric Vehicles (EVs) connected at a particular node (or nearby nodes) are represented by a single EV and 'm' heat pumps connected at nearby node(s) are modeled by a single HP and so forth. The aggregation results in few large aggregated loads instead of many small distributed loads. However, it is worth mentioning that the aggregated load should behave equivalently as the other normal non-aggregated loads. The advantage of this aggregation is a decreased data flow and data computations, and that aggregators can participate in various markets with less uncertainty since the aggregation levels out fluctuations from the individual customers. When a bid is accepted on the market, the aggregator should disaggregate the bid and dispatch the schedule for the targeted consumers. The setup is that a central aggregator disaggregates the demand flexibility among the local aggregator. The local aggregator then optimally disaggregates the received flexibility to the individual consumers within their service area for the practical implementation of actual control. Also the DSO can use the tool for planning. The set up can be illustrated as in fig. 27.

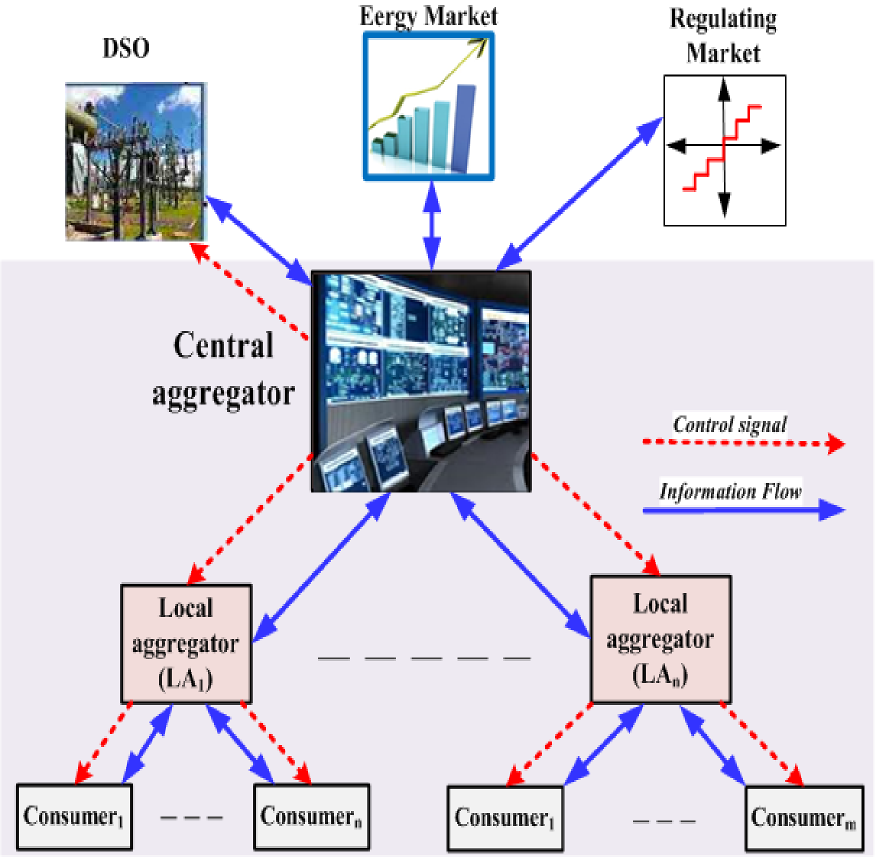


Fig. 27 Illustration of the implementation of the proposed aggregation model

The aggregation method proposed comprises the following parts:

- Determination of optimum aggregation area for a given distribution feeder
- Computation of equivalent aggregated load for each aggregation area including power profiles for EVs and HPs
- Determination of equivalent impedance and equivalent power of each aggregated area
- Implementation of control strategies

This is illustrated in fig. 28 and in the end of the section the method is illustrated by some performance analysis.

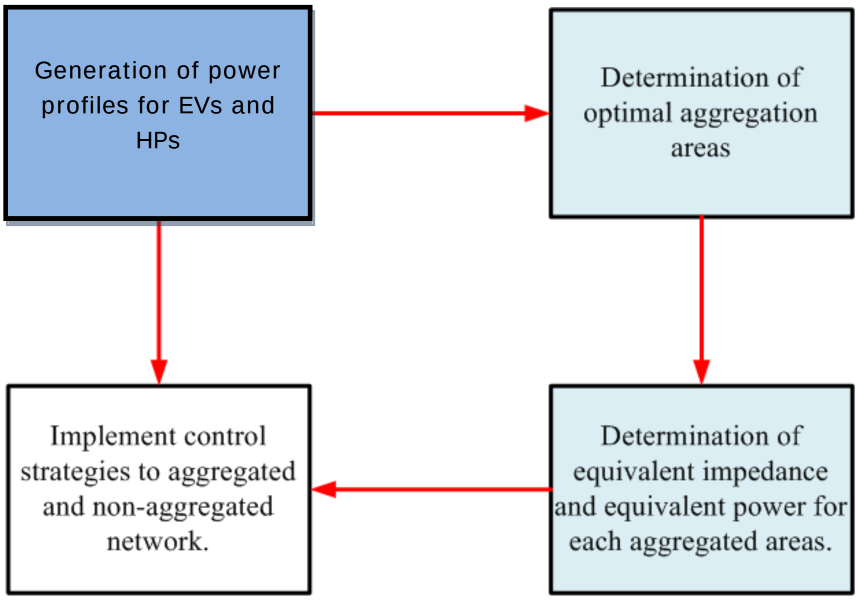


Fig. 28. Illustration of included parts in the aggregation method.

1.5.8.1 Determination of optimum aggregation area.

The formation of aggregation areas depends on the geographical aspects (how far the consumers are sparse), forecasting errors of the aggregated loads, cost associated with the aggregation such as installation of aggregation point etc. Therefore it is formulated as an optimization problem considering the following two aspects:

- The aggregation should give minimum communication distance to the substation (central aggregator)
- The aggregation points should result minimum cost

This is formulated as follows:

$$Obj\ Fun:$$

$$Min. \sum \left[\frac{\sum D_{ij}}{Max.D} + \frac{\sum N_k}{Total\ no.of\ \ Aggregation\ point} \right]$$

$$where,\ D_{ij} = b_i * X_{ii} + (1 - b_i) * X_{ij} + ... + b_i * X_{iT}$$

$$Subject\ to: X_{ij} < 85m \quad \forall\, i, j$$

where X_{ij} is distance for the ith node to communicate with the jth node, X_{ii} is the distance from the ith node to the aggregator location, b_i is the binary decision variable which indicates presence or absence of the aggregation point, N_k is the number of aggregation points. The first part of the optimization is used for minimizing the distance among aggregation areas. The second part represents the minimization of cost associated with the installation of aggregation points. It should be noted that the first part is distance whereas the second part is the cost. Therefore, it is needed to convert both into similar units before applying the optimization techniques. This is done using per unit values for the two parameters. The total communication distance required is converted into per unit by dividing it by its maximum dis-

tance which is the case when there is only one aggregation area meaning that all the consumers need to communicate with the central aggregator. Similarly, the total cost required for installation is converted into per unit by dividing it with the possible maximum number of aggregation point, i.e., the case when aggregation point is installed at each node.
After expressing both sections into per unit, the problem is converted into binary integer problem. The problem is then solved by using Genetic algorithm solver available in Optimization Toolbox of the MATLAB 2013a. To see how the method works it is applied to the network grid shown in fig. 6.
The obtained solution for the given network is expressed as follows, and the result is shown in fig. 29 with the reduced aggregated model shown in fig. 30 where each aggregated area has one aggregated load for each load type. As such, all the consumer loads are reduced into four load points each loaded with an aggregated EV load, and aggregated HP load and an aggregated basic load, thereby significantly simplifying the network.
:

```
Optimization terminated: average change in the penalty fitness value less than options.

Objective Function Value is 1.137101

Results: [1 0 0 0 1 0 0 0 0 1 0 1 0 1 0]

Agg Area 1 Consists of Nodes: [4 5 6]

Agg Area 2 Consists of Nodes: [9 10 11]

Agg Area 3 Consists of Nodes: [12 13]

Agg Area4 Consists of Nodes: [14 15]
```

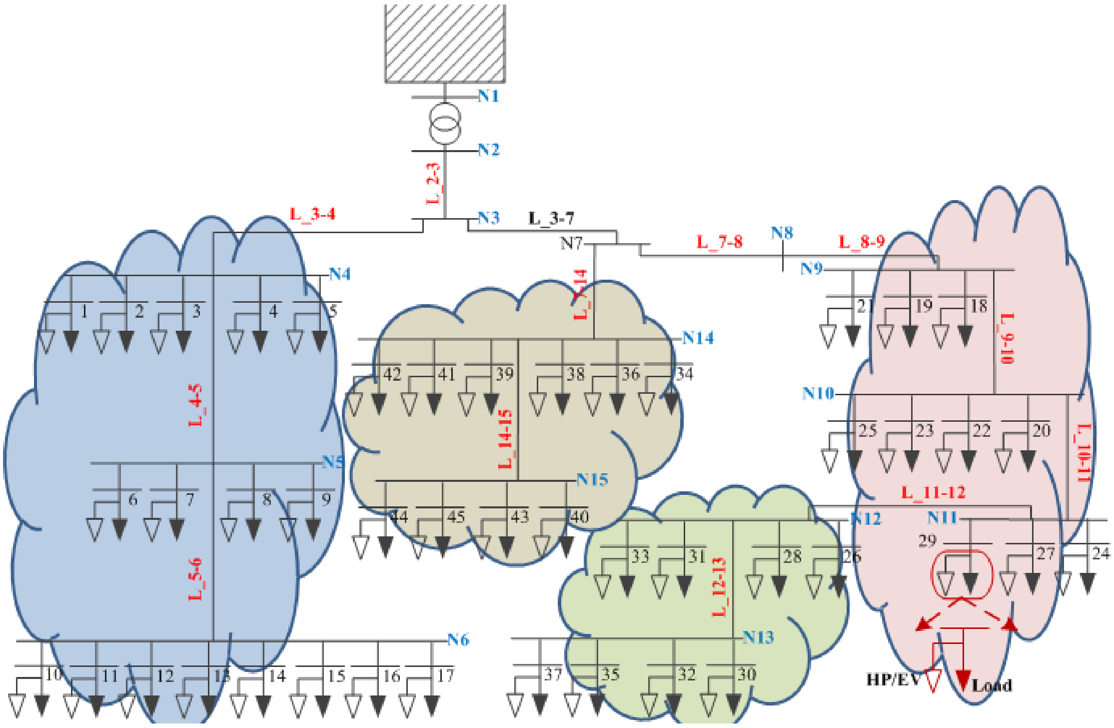


Fig. 29. Optimum Aggregation of the Børup distribution feeder

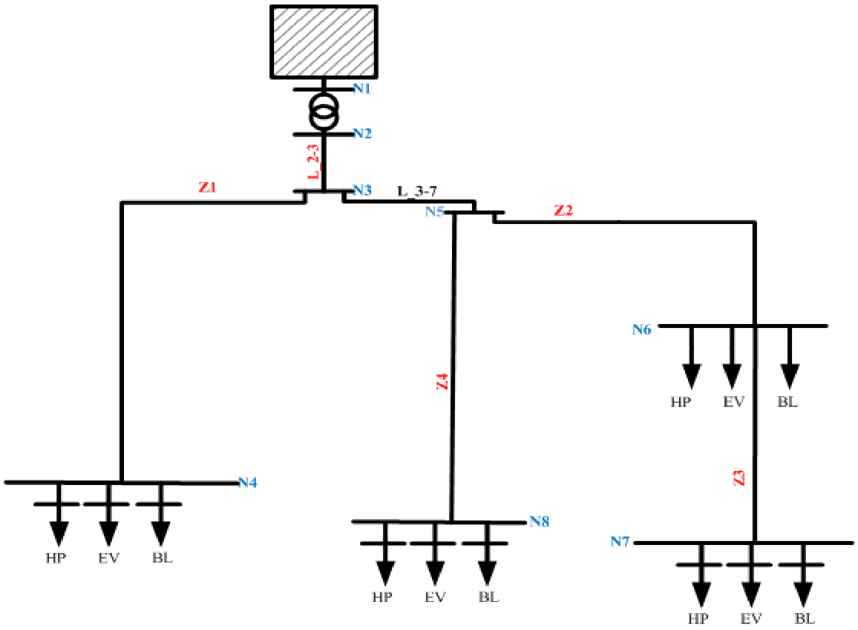


Fig. 30 Equivalent network topology for an aggregated load

1.5.8.2 Computation of equivalent aggregated load for each aggregation area including power profiles for Evs and HPs

Once the aggregation areas are defined based on the optimization problem, the load of each area should be estimated, both flexible and non-flexible, in order to be able to define the equivalent line impedances for the reduced network model. When applied for real networks, the estimation of total load for each of the defined areas can be made using any kind of forecast technique based on historical data of every load type involved. However, in this case, no historical data is available for the HP and EV consumption, so these have to be created by means of a stochastic procedure such as the one presented in following.

Fig. 31a shows a flow-chart summarizing the methodology employed for creating the power consumption profiles for each individual HP and EV load and the aggregated profile for each of the defined areas in the LV network. In order to provide this task and later on the analysis with a realistic approach, the first step is to find an appropriate model of the units to be used. Next the thermal demand and driving profiles are created based on relevant references. Then, the number of consumer in the LV system (nLVusers), the number of aggregation groups (ngroups), the number of consumer per groups/area, and the penetration of HP and PEV load in the LV system are defined.

After doing so, each HP and EV load designed according to the system penetration levels is assigned with its unit characteristic according to a random assignation process and then randomly assigned among the different areas determined across the network. To calculate the individual power consumption profiles for the number of flexible loads selected, both the individual model parameters and the individual input profiles are employed in the models proposed for the HPs and EVs. Finally, after generating all the individual profiles required, those related to each of the aggregation areas are summed in order to obtain the aggregated HP and EV consumption profiles for each of the areas determined.. For the actual network grid four aggregated areas were found. From the 45 users connected in total LV network, 17 users are assigned to area 1, 10 to area 2, 8 to area 3 and 10 to area 4. Based on this distribution, for a HP and EV load penetration of 100% (all customers have EV and HP) fig. 32 illustrate the individual consumption profiles generated for each HP and EV in each of areas and the corresponding aggregated profile after their summation. From the individual HP profiles depicted in fig. 32a all the HP units have the same rated power, however their operation pattern are completely different since they are characterized by having different storage tanks and different thermal consumptions. The power consumption profiles obtained for the different EVs in fig. 32b, clearly reflect the variety charging activities not only due to the different charging rates considered but also due to the battery sizes and driving profiles considered

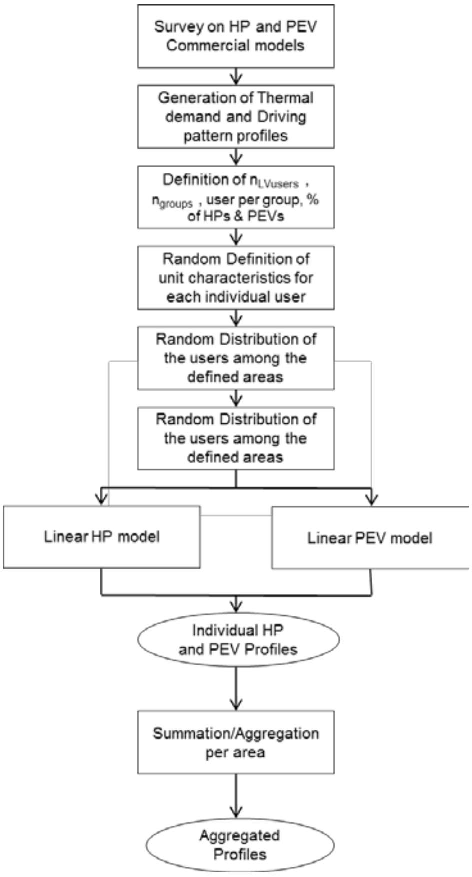


Fig. 31. Flow-chart summarizing the procedure used for the individual and aggregated power profiles from HPs and EVs

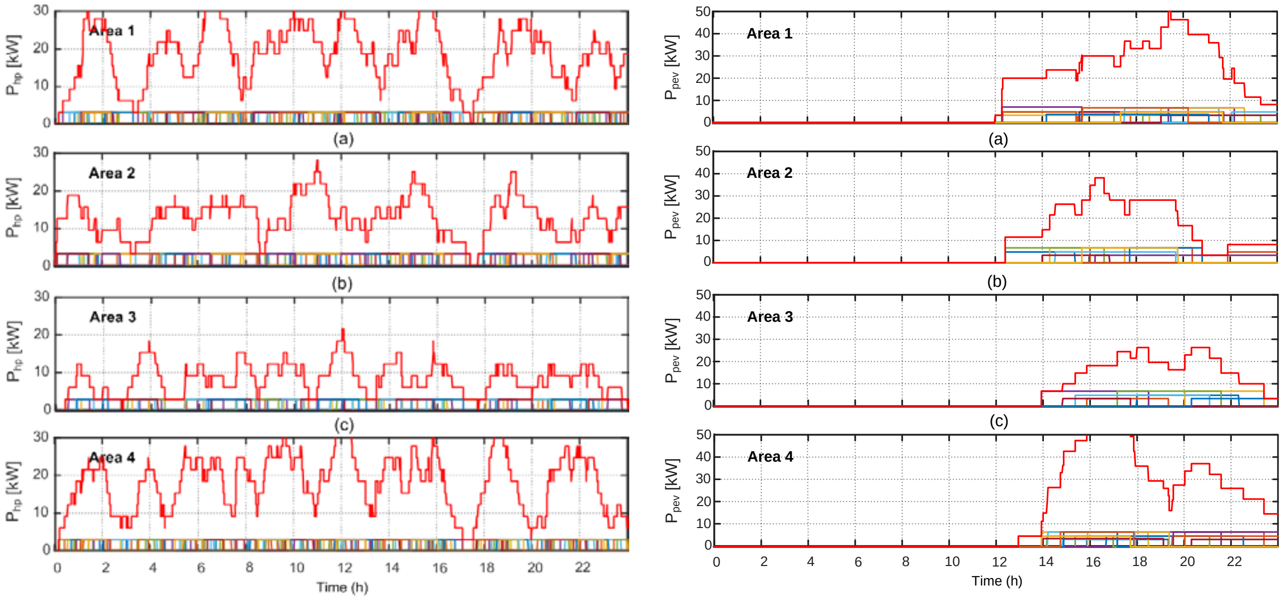


Fig. 32. Left. Individual and aggregated power consumption profiles for HPs per area. Right. Individual and aggregated power consumption profiles for PEVs per area.

1.5.8.3 Determination of equivalent impedance and equivalent power of each aggregated area.

Next step is to find the equivalent impedance of the network grid at different power consumption levels. If only the impedance normally seen at node N4 is also used in the aggregated network, then the power loss and voltage drop will not reflect the real system and both bee too small. So it is important that the voltage drop at the new N4 buss in the aggregated model is more like the voltage drop at the end of the lines like N6 for this case, and also that the power loss in the grid would be as in the real network in figure 29 before the aggregation. To ensure this a hierarchical clustering technique is used to cluster the power consumption throughout the given time period into a given number of clusters. In this study, 24 hours consumption from each consumer is clustered into three clusters , but depending on how much the load fluctuates during a day, this number for other networks might need to be higher. But here the 3 clusters are used for the total load (base load, EV and HP). The total load and the three clusters are shown in fig. 33. This information is then used to calculate equivalent impedances for each hour for the different aggregation areas. These are shown in fig 34. It is seen, that to have the right condition for minimizing the error between aggregated and real network grid in relation to voltage drop and power loss, the equivalent impedances are changed according to the cluster for the power demand. In this way, the clustering and impedance calculation can be done off-line depending on power level, and during real time operation only the cluster level and belonging impedance is used for the control. The voltage drop and power loss in real and aggregated models are shown in fig. 35 and 36 respectively, and it is seen that the error is very small.

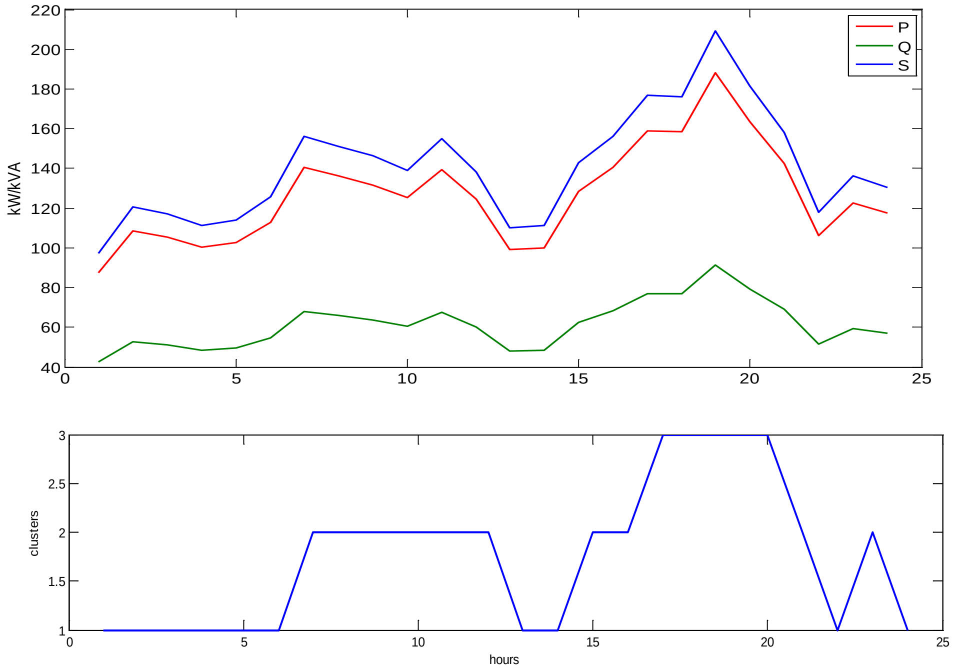


Fig. 33 Total load of the network grid and belonging clusters during a day.

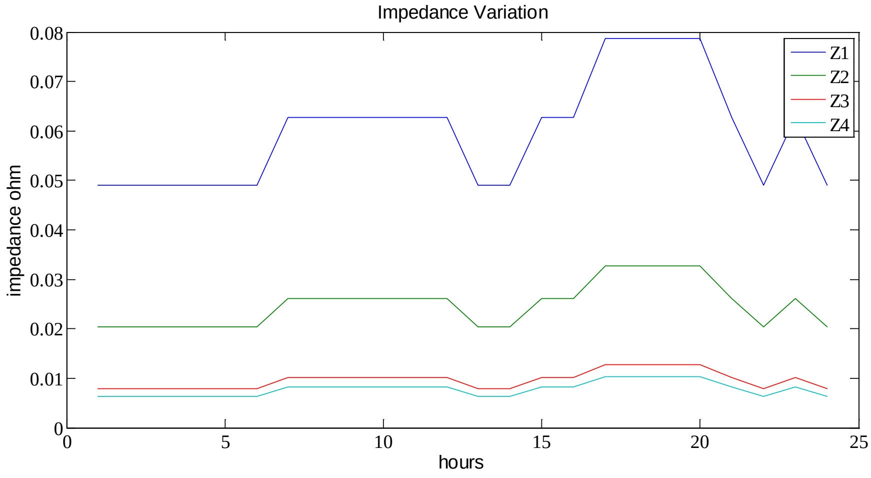


Fig. 34. Variation of Zeq for the four aggregated areas over a day with total load (base +flexible load)

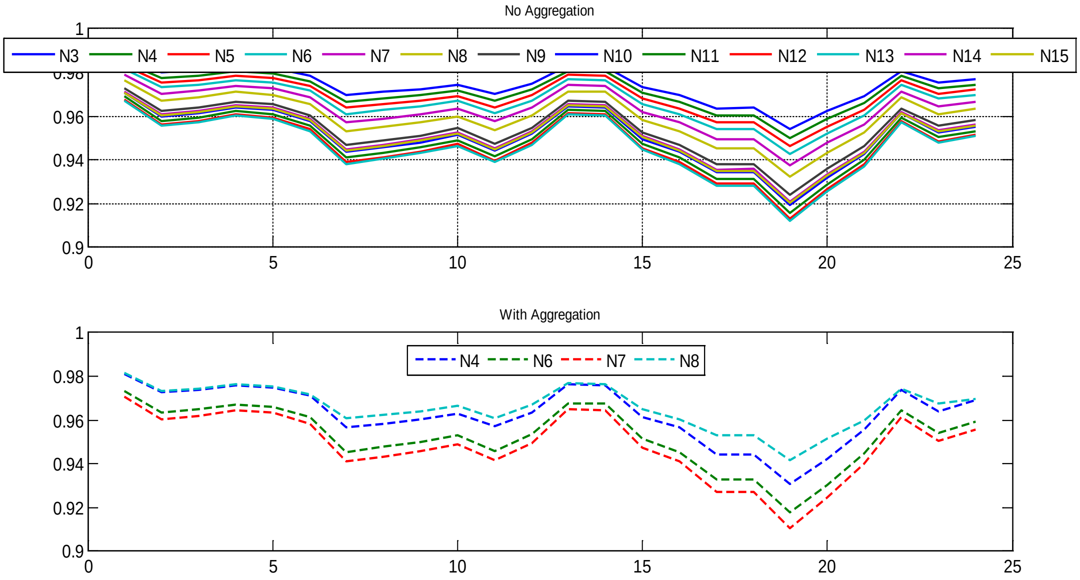


Fig. 35. Voltage with and without aggregation

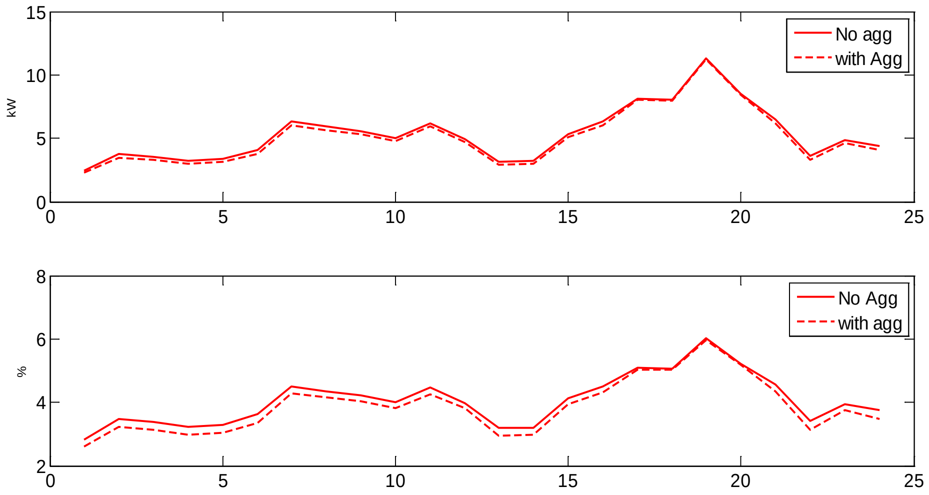


Fig. 36. Power loss with and without aggregation

1.5.8.4 Implementation of control strategies

The control architecture proposed for controlling the aggregated flexible demand in the LV network is based on a combination of centralized and decentralized approaches. Therefore, the idea is that each of the found aggregated areas are assigned with a distributed controller (DC) with the purpose to supervise and activate the local aggregated flexible demand when required. In the other hand, at the substation level the centralized controlled (CC) is placed not only to supervise the different DCs but also to activate their flexible demand when a more global interest requires it. This is illustrated in fig. 37, which is a kind of more detailed model seen from control perspective than fig. 27. By means of different measurement devices placed in strategic locations of the LV network the CC can interpret what the local system needs are and actuate in accordance. For example, if its objective is to maintain the loading of the secondary transformer below a given limit, whenever this is overpassed it reduces the aggregated consumption of the HP and PEV in the different areas by means of the DCs.

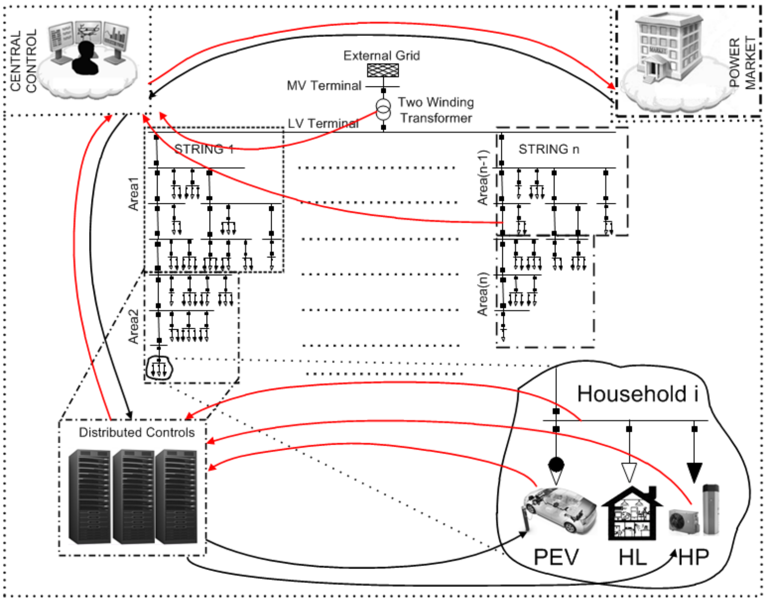


Fig. 37. Schematic representation fo the hierarchical control architecture

Fig. 38 illustrates a block diagram of the implementation of the mentioned hierarchical control architecture in DIgSILENT PowerFactory. Each of the DCs are able to monitor the aggregated power consumption from both the HPs and EVs in their domain as well as the voltage in their point of connection (POC). Furthermore, each of the DCs are able to receive a request signal form the CC in order to adapt their local flexible consumption according to the needs. So, as soon as an under-voltage occurs in a given area or a request is made from the CC, the power consumption of the HPs and PEVs will be change according to:

$$\Delta P_{HP}^{DC\#} = P_{HP}^{DC\#} - \mathrm{P}_{regHP}^{DC\#} \cdot A - \mathrm{P}_{regHP}^{CC}$$
$$\Delta P_{PEV}^{DC\#} = P_{PEV}^{DC\#} - \mathrm{P}_{regPEV}^{DC\#} \cdot B - \mathrm{P}_{regPEV}^{CC}$$

Where $\Delta P_{HP}^{DC\#}$ and $\Delta P_{PEV}^{DC\#}$ adapted power consumption from HPs and EVs within the DC number #, $P_{HP}^{DC\#}$ and $P_{PEV}^{DC\#}$ are their measured power consumptions at the aggregation level, $\mathrm{P}_{regHP}^{DC\#}$ and $\mathrm{P}_{regPEV}^{DC\#}$ are the power regulation required from HPs and EVs within a DC in order to keep the voltage of its POC within the stipulated limits and P_{regHP}^{CC} and P_{regPEV}^{CC} is the power regulation required from HPs and EVs within a DC in order to respond to the needs of CC. Finally, A and B are variables which define the share or the regulation according to the instantaneous consumption capacity form HPs and EVs. The power regulation required from HPs and EVs within a DC is calculated as:

$$\mathrm{P}_{regHP}^{DC\#} = \int (k_{a1} \cdot (1 - (\mathrm{V}_{\mathrm{poc}} - \mathrm{V}_{\mathrm{th}})) + k_{b1} \cdot (\mathrm{V}_{\mathrm{poc}} - \mathrm{V}_{\mathrm{th}})) \cdot dt$$
$$\mathrm{P}_{regPEV}^{DC\#} = \int (k_{a2} \cdot (1 - (\mathrm{V}_{\mathrm{poc}} - \mathrm{V}_{\mathrm{th}})) + k_{b2} \cdot (\mathrm{V}_{\mathrm{poc}} - \mathrm{V}_{\mathrm{th}})) \cdot dt$$

Where k_{a1} and k_{b1} are the parameters to tune the local voltage controller affecting the consumption of the HPs and k_{a2} and k_{b2} for the local voltage controller affecting EVs, V_{poc} is the voltage at the point of connection and V_{th} is the threshold stipulated by the DSO.

In Fig. 38, it is also illustrated how the CC monitors the flexible consumption among the different areas in the LV system as well as measures the loading of the power lines and calculates and defines which the most loaded one is. In this way, if the loading of the most loaded line in the system is overpassed the CC will calculate what is the total regulation power required in order to solve this constraint (P_{reg}^{CC}) and in consequence the regulation power required from each of the DCs. Therefore:

$$\mathrm{P}_{reg}^{CC} = \int (k_{c1}\cdot(1-(\mathrm{LL}_{\mathrm{th}}-\mathrm{LL}_{\mathrm{max}})) + k_{d1}\cdot(\mathrm{LL}_{\mathrm{th}}-\mathrm{LL}_{\mathrm{max}}))\cdot dt$$

Where k_{c1} and k_{d1} are the parameters to tune the response from this global controller, $\mathrm{LL}_{\mathrm{max}}$ is the line loading of the most loaded line in the LV network and $\mathrm{LL}_{\mathrm{th}}$ is the threshold established by the DSO.

Similarly, the share of P_{reg}^{CC} among the different DCs is made based on their instantaneous flexible consumption capacity using the following expression:

$$\mathrm{P}_{reg}^{DCA\#} = \mathrm{P}_{reg}^{CC}\cdot\left(\frac{\mathrm{P}_{HP}^{DC\#}+\mathrm{P}_{PEV}^{DC\#}}{\sum_{i=1}^{n_a}\mathrm{P}_{HP}^{DC\#}+\sum_{i=1}^{n_a}\mathrm{P}_{PEV}^{DC\#}}\right)$$

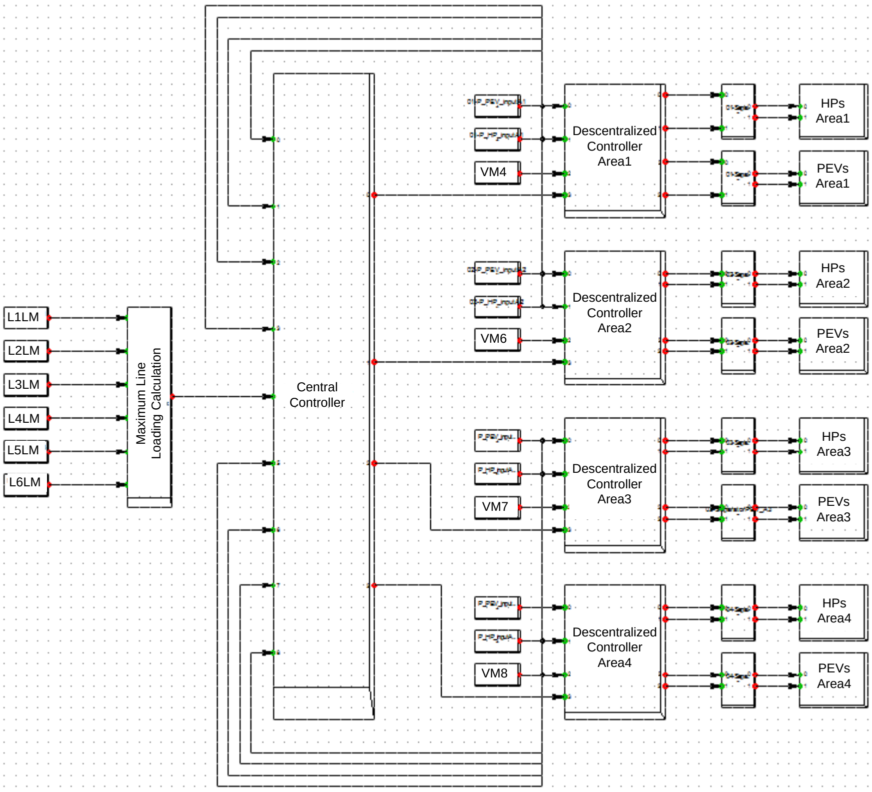


Fig. 38. Implementation of the hierarchical architecture in DigSilent

The following four cases has been analysed to see the benefits of the control procedure:

- Case I - Comparison of the current and future loading scenarios: For the penetration level selected, which is 50% of HPs and 25% of EVs for all customers, and where the flexible load have been distributed randomly across the LV network. This distribution of HP and EV load will provide the aggregated profiles for each of the defined aggregation areas which are required as input for finding the equivalent line impedance to determine the new reduced LV network model.

- Case II – Performance comparison of the detailed and reduced LV network models: The aim is to determine how similar or with which precision the reduced model is capable of representing the performance of the detailed LV network model.

- Case III – Comparison of the non-controlled and controlled version of aggregated model by means of the decentralized controller: The aim is to verify the effectiveness of the control mechanism proposed when the individual decentralized controllers act over the aggregated flexible demand in their specific area to solve under-voltage problems. In this way, the minimum voltage limit established for any existing LV bus is 0.935 p.u.
- Case IV – Comparison of the non-controlled and controlled version of aggregated model by means of the centralized controller: The aim is to verify the effectiveness of the control mechanism proposed when the centralized controller act over the decen-

tralized controllers and in consequence over the aggregated flexible demand of their specific area to solve overloading problems in an specific parts of the infrastructure. A maximum loading of 70% is allowed to the most loaded line in the network.

The results are shown in fig. 39- 42. In fig. 39 it can be noticed how the assumed penetration of flexible loads significantly stresses the LV system during the peak moments of the day. In this sense, the synchronization of the high HP demand due to the winter conditions and the high EV demand once the user arrive home leads this local distribution grid to be highly constrained in comparison to what it is nowadays. As it can be seen from fig. 39.g and h the nature of this bottleneck are an under-voltage situation originated between 18 and 20 hours at bus N7–in the reduced version of the LV grid considered(fig. 30) - and the overloading of line 1 originated in the same time frame.

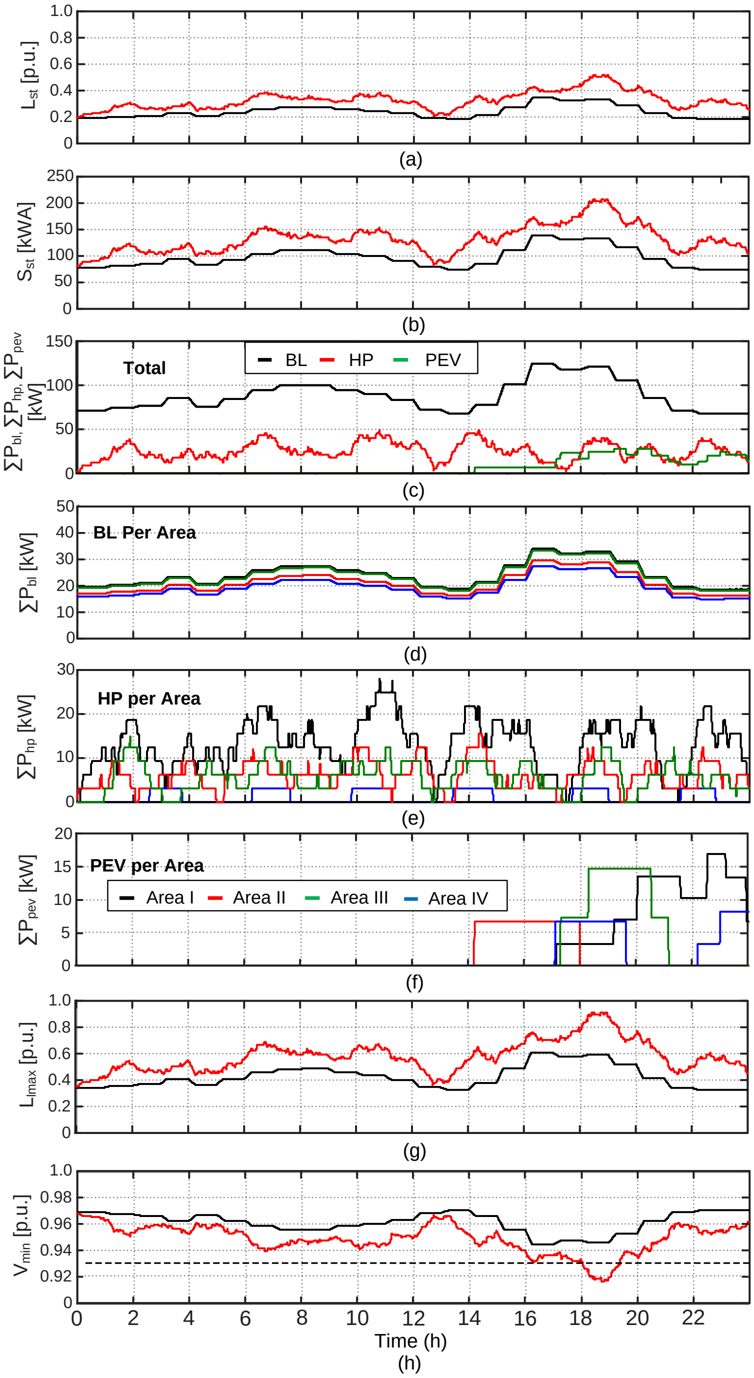


Fig. 39 Results for case I: (a) Loading of the ST (b) Apparent power at the ST level, (c) Aggregated active power consumption for all the BL, HP and PEV across the LV grid, (d) Aggregated active power consumption of BL per area, (e) Aggregated active power consumption of HPs per area, (f) Aggregated active power consumption of PEVs per area, (g) Loading of maximum loaded line in the LV grid, (h) minimum voltage in the LV grid. Black lines in (a, b, g and h)is current scenario, red is for future scenario.

For case II it is not possible in DigSilent to use different equivalent impedances for the different hours, so in this case only the peak values from all clusters are used. From the results from case II in fig. 40 the following conclusions can be drawn. It is seen that the difference between the aggregated and real model is very small, nearly only visible in fig. 40h where the voltage profile in red for the reduced network is slightly more elevated than the one from the original network (black)

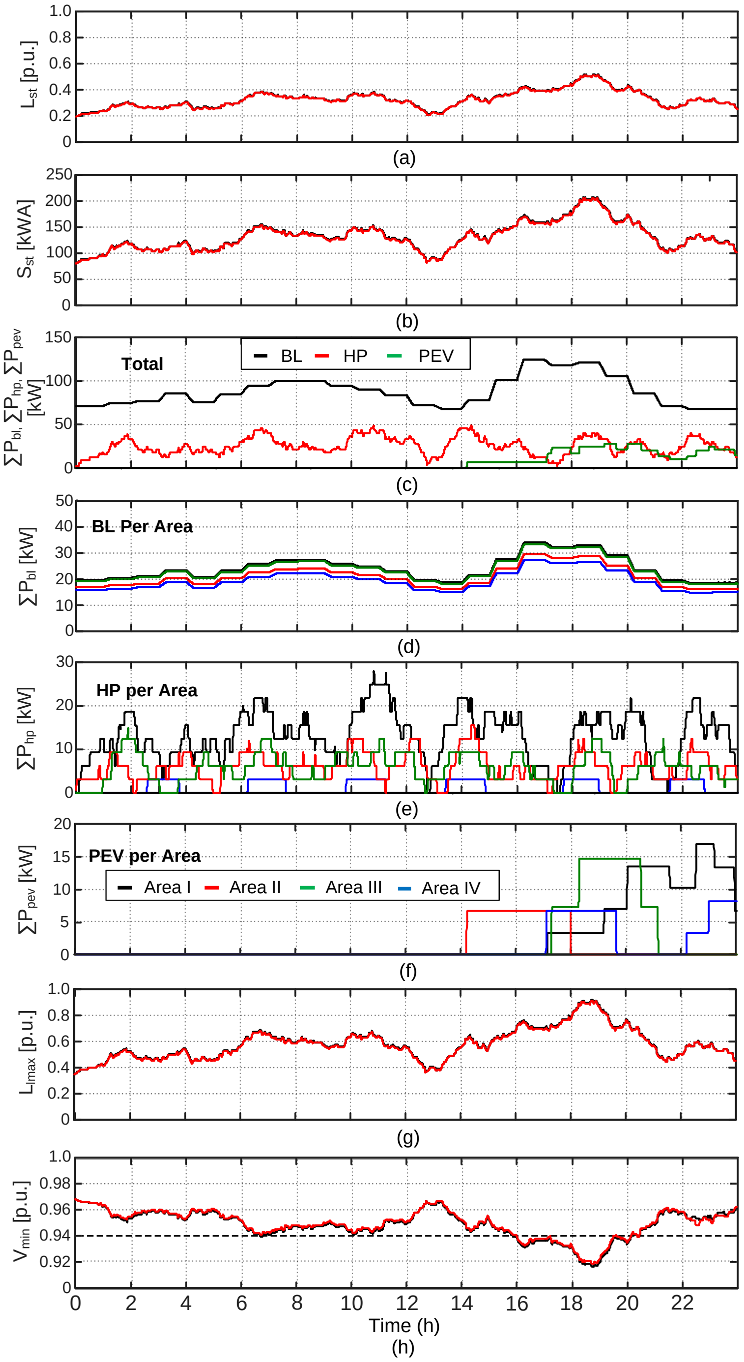


Fig. 40. Results for case II: (a) Loading of the ST (b) Apparent power at the ST level, (c) Aggregated active power consumption for all the BL, HP and PEV across the LV grid, (d) Aggregated active power consumption of BL per area, (e) Aggregated active power consumption of HPs per area, (f) Aggregated active power consumption of PEVs per area, (g) Loading of maximum loaded line in the LV grid, (h) minimum voltage in the LV grid.

Fig. 41 shows the results obtained for cas III when it is intended to solve a local voltage constrain produced during the peak moments of the day. Fig. 41d, e and f is related to the controlled scenario. In an controlled scenario, when the under-voltage situation occurs at bus N7, the DC of that area (area 3) modifies the power consumption of HPs and EVs unders its domain in the proportion showed in fig. 41i. How this is reflected to each of the aggregated loads is depicted in fig. 41e and fig. 41f. Additionally, it is interesting to see how the DC of area 2 is also participating in this regulation. This reason is that voltage threshold at which this is responding has been toned differently – slightly higher- in order to share the voltage regulation responsibility among the DCs in different areas in order not to penalize always the same DC. Finally, as shown in fig. 41j no request is made from the CC to respond according to its interest.

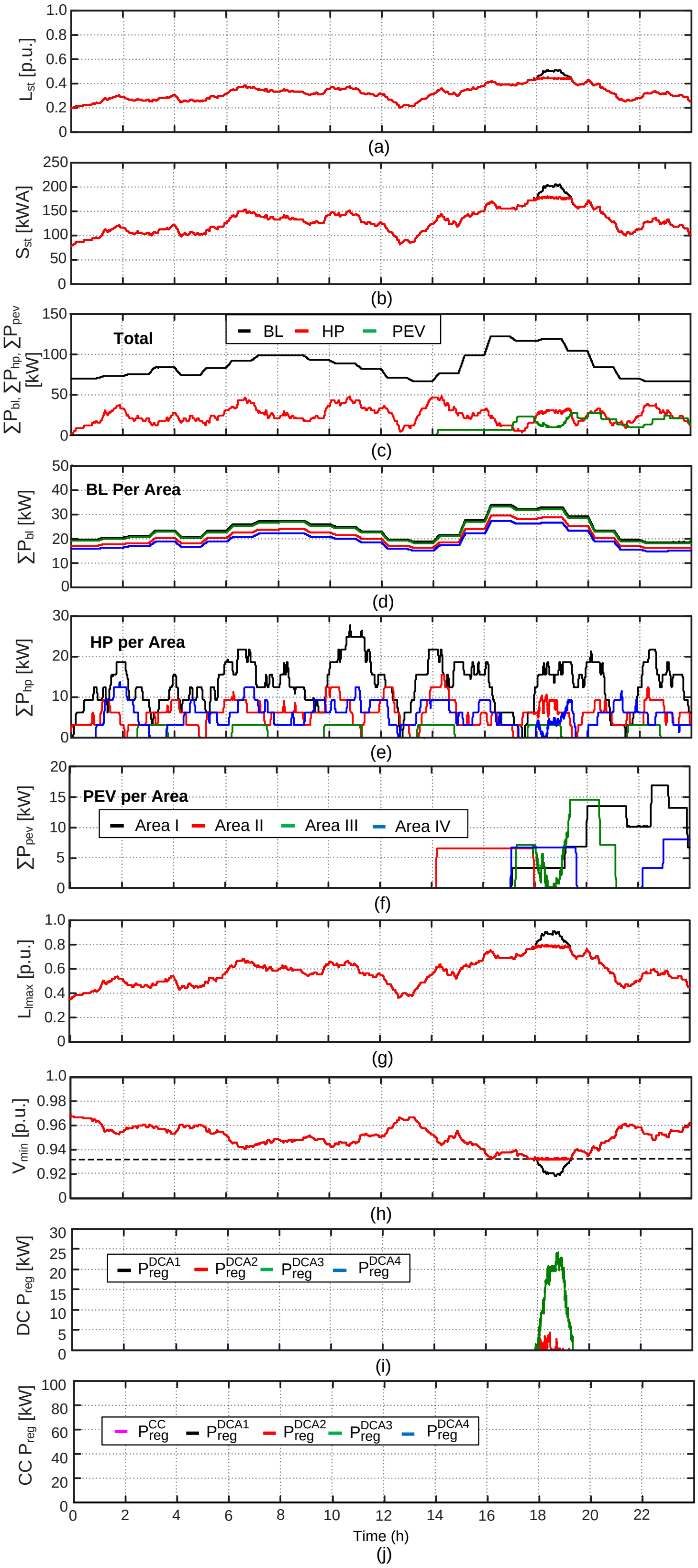


Fig. 41. Results for case III: (a) Loading of the ST (b) Apparent power at the ST level, (c) Aggregated active power consumption for all the BL, HP and PEV across the LV grid, (d) Aggregated active power consumption of BL per area, (e) Aggregated active power consumption of HPs per area, (f) Aggregated active power consumption of PEVs per area, (g) loading of maximum loaded line in the LV grid, (h) minimum voltage in the LV grid, (i) regulation power required from each distributed controller, (j) Regulation power required from the central controller to each distributed controller.

Finally, the obtained results for case IV are depicted in fig.42 where once again fig. 42.d, e and f have to be related with the controlled scenario. In this case, the DSO is interested in having 70 % as the maximum loading of line 1. Therefore, since there is no existing voltage violation the DC do not respond to any local needs, see fig. 42i. However, it is clear that in those moments where the maximum loading limit is crossed in line 1, the CC sense it and accordingly request for regulating power from the DC across the LV system. As it is illustrated in fig.42j, the amount of regulating power is different for the different DCs due to their differences in the power consumption capacity of HPs and EVs. The peak of regulation power which is requested by the CC is given between the 18 and 20 hours and is about 45 kW.

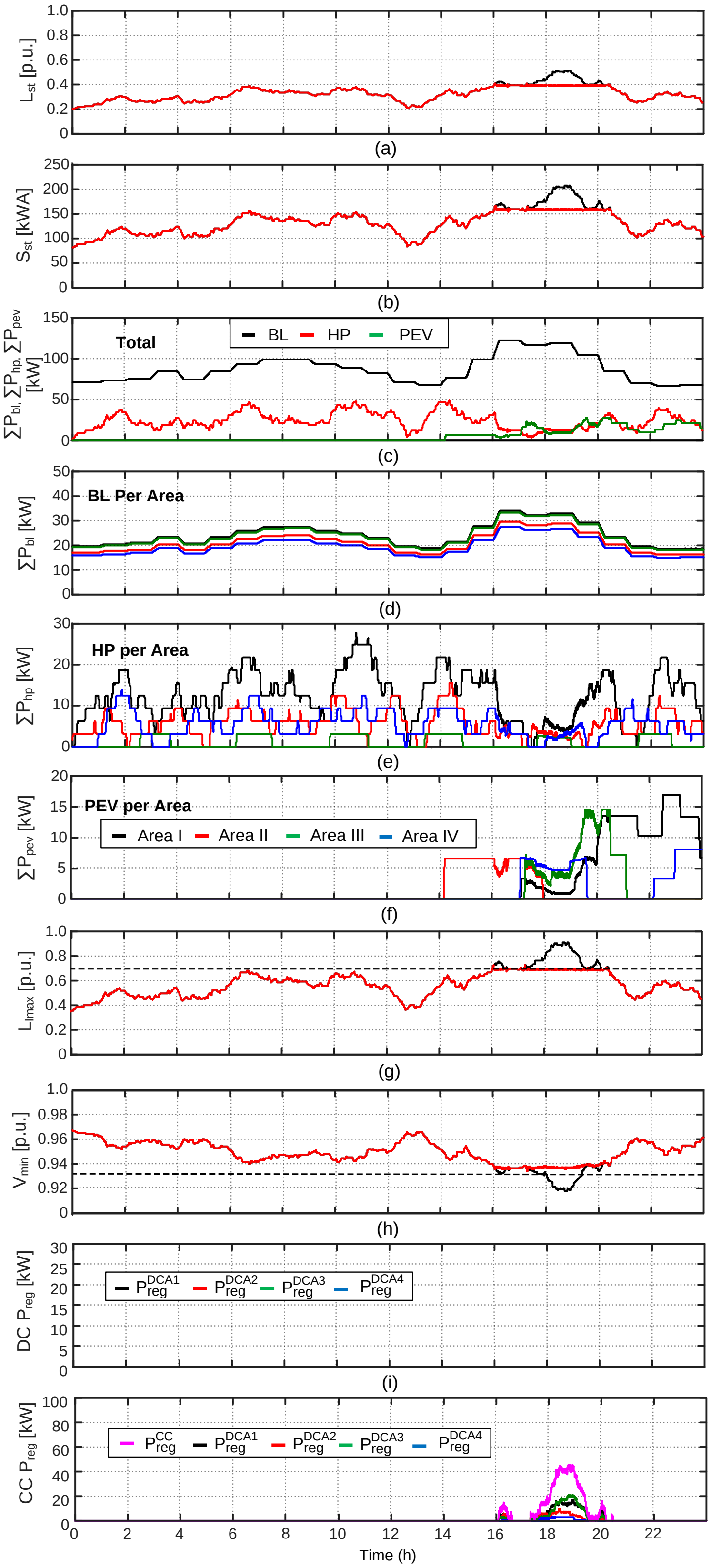


Fig. 42 Results for case IV: (a) Loading of the ST (b) Apparent power at the ST level, (c) Agregated active power consumption for all the BL, HP and PEV across the LV grid, (d) Aggregated active power consumption of BL per area, (e) Aggregated active power consumption of HPs per area, (f) Aggregated active power consumption of PEVs per area, (g) loading of maximum loaded line in the LV grid, (h) min-

imum voltage in the LV grid, (i) regulation power required from each distributed controller, (j) Regulation power required from the central controller to each distributed controller.

In this way it is shown that use of aggregated models can be effectively used by the DSO for control purposes, and also aggregators can benefit from aggregated values when bidding at the market.

1.5.9 Management of the project

In relation to the original application we have more or less fulfilled all objectives except for having direct access to control functions at the costumers via their smart meters. Therefore, instead the hierarchical control methods for controlling heat-pumps and electrical vehicles is only done in the laboratory, however using real-time testing facilities and using smart meters in the loop and based on real measurements and data for the case study. On the other hand an extension of the project was also made, where aggregation issues are seen both from an aggregator and a DSO point of view. So extra results were gained compared to the original application.

The project was as such not a commercial project but a research project which focus on demand response and protection focus, and the hierarchical control and protection methods established are still on a research level. Therefore, there are still work to do before they are fully commercial ready.

The dissemination is done via one Ph.d thesis and 9 international journal and conference papers. Further, the project results are disseminated to the partners at our regular meetings. Further, the results are used in different Ph.D courses and summer schools running at Aalborg University, and some of the results have also been used for making new national and international applications.

1.6 Utilization of project results

The project provides a good method to ensure demand flexibility from controllable loads and establish integrated ANM and protection methods to ensure an effective control and protection of the future distribution grids, given that new legislation allows the set up method. If so, the end consumers will get reliable and cheap electricity and the utility can prevent or delay huge investment in network grid reinforcement. The DSO can implement the aggregation and control methods in their planning and operational stages to avoid grid bottlenecks and the aggregators can use the results when bidding in the market. The project results are also used to form the background for the new Forskel project “Determination of Automation Demands for Improved Controllability and Observability in Distribution Networks (DECODE)”, where especially how to roll out the control and protection issues dealt with in the project are to be focused but with as less measurement devices as possibly. The ideas can also be used as basis for future projects in for instance relation to smart cities and demonstration project for smart grid activities under for instance Horizon 2020.
As mentioned above the results are also used in Ph.D courses held at Aalborg University related to smart grids such as Smart Distribution Systems, Dispersed Generation of Electricity, and Building the Bridge between Electrical Grid Control and Communication in Smart Grids, which has been held annually or bi-annually. But also the course in Dispersed generation has been held in Tallinn twice during the period as well. Further, some of the ideas has been introduces at summer-schools in Aalborg, held every summer.

1.7 Project conclusion and perspective

In this project intelligent control architectures and an adaptive protection method for the future distribution system has been developed. The methods coordinates the interaction between the elements of the smart grid and uses data from smart meters, controllable loads (electrical vehicles (EV), heat pumps (HP) and electrical water heaters (EWH)), the network grid layout, the power generation data (here photovoltaic system (PV)) for performing the control and protection of the network. Also information and communication technology (ICT) characteristics are taken into account. The results from the projects are demonstrated mostly by simulations and partly by laboratory setups with real-time assessment.

The major contributions of this work are described in the following five stages:

- Development of an intelligent Demand Response (DR) control architecture coordinating the key SG actors. Here a Hierarchical Control Architecture (HCA) with primary, secondary, and tertiary control loops is developed together with a heterogeneous communication network to establish coordinated control of widely distributed loads and generations. The control loops in the HCA are designed with specific control latency and time to establish coordination between the loops. The structure is demonstrated with a power and communication co-simulation.
- Development of detailed models of controllable loads such as EVs, HPs and EWHs, local generation in the form of PVs, and the distribution network. Different control strategies are developed to realize various DR techniques, such as autonomous, voltage, incentive based, and price based control. By use of the HCA developed in stage 1 and the set up models and control strategies, the performance of the method is demonstrated for a case study with a low voltage distribution network from Zealand. These models and control methods are generic and can be applied to any network. The outcome from this part exploits the demand flexibility and the technic support from the consumers/prosumers as well as their possibility to trade the flexibility in electricity markets.
- Development and implementation of a scaled down SG testbed including communication system for physical demonstration of the developed DR models and control strategies. Both a centralized and decentralized control approach is implemented in the testbed for optimized EV charging coordination. As practical demonstration of SG control and communication behaviour is lagging, the developed scaled down testbed provides a novel economic and riskless approach for practical demonstration of the SG control and is a new research area in the SG field.
- Development of an adaptive overcurrent protection for the future distribution system. This protection should be able to take bidirectional power flow and ANM activities such as demand response, network reconfigurations into account. A two-stage protection strategy with an offline proactive stage combined with an online adaptive stage is designed. The method is demonstrated with good results for a medium voltage distribution network using a real time digital simulator in the laboratory.
- Development of an aggregated model and control structure for distribution systems. Aggregated models for HP and EV demands are created and a control-architecture is developed for activating the aggregated flexible demands and comparing the results with the results from situations where individual loads are simulated. The aggregation models can be used by the DSOs to assess the network conditions and the aggregators could use the aggregated values when bidding in the market.

Future work based on this project could be related to the following issues:

- Analysis of power quality issues in relation to the new control structure and the additions of new loads and power generation units at the LV grid. Frequent control of inverter interfaced EV and PV might inject harmonics, whereas the high starting currents of the HPs might contribute to the voltage flicker.
- Implement probabilistic models to quantify the flexibility and impacts from the stochastic behaviour of heavy loads and generation to the grids.
- Investigate the application of the developed architecture and DR control methodologies for frequency support, since the focus in this project has mainly been on the voltage and capacity support on the LV grid.
- Detailed investigation of the communication performance including latency, delay, through-put, jitter, and error rates would be interesting to better access the practical viability of the developed DR control methods.
- Development of a hybrid control algorithm considering DR and storage technologies.
- Integration of a LV network protection with the ANM activities would be an interesting study that could support the DR deployment better. Detailed investigation on the

need of actual control instrumentation to realize the proposed control strategies as well as observability and controllability of the grid would also be of interest for future studies.

In summary, the outcomes from this research provide a framework for exploiting demand flexibility from widely distributed consumers/prosumers, which in turn are potential solutions for DSOs to deal with network technical issues such as voltage and current capacity limitation and the protection of the future network grid where the power generation at local level fluctuates and give different fault currents which demands for adaptive protections. In addition, the outcomes provide economic incentives to the consumers to trade their flexibility to electricity markets. Therefore, this study provides a framework to integrate heating, gas, and transportation sectors into the electrical system, thereby supporting Danish government's 100% renewable energy goal by 2050.

The research can serve as a reference for new research projects in this direction and can also if new legislation regarding costumer payments allows it, be used by the distribution companies and aggregators to solve voltage, capacity and protection issues along the radials when integration a huge amount of renewable energy and/or due to the electrification of the heating and transport sector. The DSOs can thereby avoid or delay investment in new lines with higher capacity. Finally, also aggregators can use the results in market relations having knowledge about different price or incentive methods and aggregation methods for making bid at the market.

Annex

Relevant links

1. Bishnu Prasad Bhattarai, Intelligent control and operation of distribution system, Ph.D thesis, Aalborg University 2015.
2. Bhattarai, B.P.; Levesque, M.; Maier, M.; Bak-Jensen, B.; and Pillai, J. R., "Optimizing electric vehicle coordination over a heterogeneous mesh network in a scaled-down smart grid testbed," IEEE Transactions on Smart Grid, vol. 6, no. 2, pp. 784-794, Jan. 2015. https://www.academia.edu/10098948/Optimizing_Electric_Vehicle_Coordination_over_a_Heterogeneous_Mesh_Network_in_a_Scaled-down_Smart_Grid_Testbed
3. Bhattarai, B. P.; Bak-Jensen, B.; Mahat, P.; Pillai, J.R.; and Maier, M., "Hierarchical control architecture for demand response in smart grid scenario," in Proc. IEEE PES Asia Pacific Power and Energy Engineering Conference (APPEEC), pp. 1-6, Dec. 2013. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6837221
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5. Bhattarai, B. P.; Bak-Jensen, B.; Mahat, P.; and Pillai, J. R., "Two-stage electric vehicle charging coordination in low voltage distribution grids," in Proc. IEEE PES APPEEC, pp 1-5, Dec. 2014. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7066078
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8. Bhattarai, B. P.; Bak-Jensen, B.; Pillai, J. R.; Gentle, J. P.; and Myers, K. S., "Coordinated control of demand response and grid-tied rooftop photovoltaics for overvoltage mitigation," 3rd IEEE SusTech2015, Jul.–Aug. 2015. http://192.38.67.156/Search.external?operation=search&search-query=au:%22Pillai+Jayakrishnan%20Radhakrishna%22

9. Bhattarai, B.P.; Bak-Jensen, B.; Chaudhary, S. K.; and Pillai, J. R.; “An adaptive overcurrent protection in smart distribution grid,” in Proc. IEEE PES PowerTech, Jun.–Jul. 2015 http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7232310
10. Bhattarai, B. P.; Mendaza, I. D. D. C.; Bak-Jensen, B.; and Pillai, J. R., “A local adaptive control of solar photovoltaics and electric water heaters for real-time grid support,” To be submitted to CIGRE Session2016 (synopsis accepted).