# Final report

## 1.1 Project details

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| **Project title** | `ELECTRA top up` |
| **Project identification (program abbrev. and file)** | `64014-0163` |
| **Name of the programme which has funded the project** | EUDP |
| **Project managing company/institution (name and address)** | Technical University of Denmark, Department of Electrical Engineering, Center for Electric Power and Energy (CEE)<br>Frederiksborgvej 399, 4000 Roskilde |
| **Project partners** | - |
| **CVR** (central business register) | 30 06 09 46 |
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## 1.2 Short description of project objective and results

This project is a top up financing project aiming at strengthening the effort of CEE in the EU project "ELECTRA" initiated by EERA Joint programme on Smart Grids.
The project aimed at investigating the various challenges that the transmission system operators and distribution system operators are facing today due to the high share of distributed and inertia less resources replacing conventional power plants. The project has, in the frame of Web-of-Cells concept, developed a method for stability assessment, analysis of control approaches in low inertia systems and decisions support in control rooms in view of an anticipated transition from centralized control approaches into distributed ones.

- **Dansk *version.***

Dette projekt er et "top up" finansierings-projekt med det formål at styrke bidraget fra CEE I det EU-støttede project "ELECTRA" som blev gennemført af EERA joint programme for Smart Grids.

Projektet har som formål at undersøge nogle af de forskellige udfordringer som systemansvarlige og distributionsselskaber står overfor pga. den øgede mængde af distribuerede ressourcer der erstatter eller vil erstatte konventionelle kraftværker. Projektet har med udgangspunkt i Web-of-Cells konceptet, udviklet løsninger til stabilitetsundersøgelse, analyse af styringsmetoder i systemer med lav inerti og beslutningsstøttesystemer til kontrolrum i lyset af den forventede overgang fra centraliseret kontrol til en udbredt, decentraliseret kontrol.

## 1.3 Executive summary

The need for a transition towards a new functional architecture is based on a number of scenario assumptions regarding the 2030+ power system. It is assumed that in the future power system, generation will shift from classical dispatchable units to intermittent renewables and combined heat and power plants. Therefore, a great part of the generation will shift from few large units to many smaller units. It is also assumed that electricity consumption and therefore system loads will increase significantly. Electrical energy storage is expected to be a cost-effective solution for offering ancillary services that stabilise the system and fill the momentarily gap between system generation and system load. Next to this, it is presumed that the power system observability will increase due to more ubiquitous sensors. Moreover, the large amounts of fast reacting distributed resources will be able to offer reserves capacity.
In the ELECTRA Integrated Research Program proposal, the EU power grid is decomposed into a Web-of-Cells (WoC) structure, where the cells are defined as a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate the cell generation and load uncertainties in normal operation. Cells have adequate monitoring infrastructure installed, as well as local reserves capacity enabling them to resolve (even partially) voltage and cell balancing problems locally. Each cell is managed by a cell system operator, relying on a cell controller, who takes responsibility for the real-time reserves activation and dispatching in his cell(s). Inter-cell reserve exchanges and coordination is included in order to benefit from imbalance netting. In each cell, the Cell system operator maintains an accurate view on the overall cell state, and consequently dispatches reserves located in the cell in a secure manner based on his knowledge of the cell state. In principle, no global system state information is required for this. In this way, a 'divide and conquer' way of tackling voltage and balancing issues is

implemented, and local problems are re-solved locally in the cell in a fast and secure manner, limiting complexity and communication overhead. There is no need to expose local problems at global system level. In the proposed WoC-based architecture, Cell System Operators are responsible to contribute to containing and restoring system frequency, as well as containing local voltage within secure and stable limits. For this purpose, proposals for frequency and voltage control within a Web-of-Cells system were developed.

Different Frequency control approach were developed and investigated within Electra top-up namely Synthetic Inertia Control (SIC), Fast Frequency Control (FFC) and Load Frequency Control (LFC). The proposed SIC imitates the effects of the currently available system inertia limiting the faster rate of change of frequency due to the high share of inertia-less resources. It ensures that additional synthetic inertia is supplied (by managing suitable flexible resources), to complement the physical inertia of the system. The proposed FFC shows resemblance to the present frequency containment reserves or the so-called primary frequency control. However, FFC is characterized by using fast acting reserves such as energy storages and electric vehicles, which improves the overall frequency dynamics in terms of RoCoF, frequency nadir and steady stare value.

Moreover, a LFC was developed which resemble to the present frequency restoration reserve or the so-called secondary frequency control. However, the presented LFC approach uses direct state observations to determine area imbalances, and actively involves primary devices in frequency control to achieve tuning-free secondary control.

## 1.4 Project objectives

The Joint Research Activity of ELECTRA investigated and demonstrated new concepts for control strategies for the power system of 2030, regard given to the efficiency, flexibility, safety, reliability and quality of the European electricity systems within the context of a more integrated European energy market.

With this goal in mind, the following technical and scientific objectives were achieved throughout the project:

### O1: To design the information flows and control mechanisms required to synchronize the activities of the different stakeholders for managing the system frequency in 2030 power system

To operate the network of the future it will be necessary to understand and design the detailed interplay between all the participants (including new actors foreseen in the evolving market such as aggregators) at different levels and in a distributed way. TSOs operate the network at Pan-European level but using distributed resources, which may be located in the distribution network. DSOs will assume roles, currently fulfilled by TSOs, using distributed resources.

TSOs operate the network at Pan-European level but using distributed resources, negotiated in the market, which may be located in the distribution network. DSOs will assume roles, currently fulfilled by TSOs, using distributed resources negotiated in the market whose behaviour may have an impact on the work performed by the TSOs. Therefore, multiples control functions for system balancing are designed and investigated within the project. This objective can be summarized as: Design of the 2030 power system functional architecture for frequency control.

### O2: To develop concepts and methods for increasing network observability as a vital basis for novel controls.

Along with the enhancement of existing tools, complementary monitoring methods must be developed for increased observability and situation awareness. To facilitate the decision process, tools that provide specific operational information, based on the current grid condition, need to be developed.

This objective covers three areas in which specific challenges for improved observability and decision support in future control rooms are addressed: Classical large power system stability issues, innovative data-driven techniques for voltage estimation at the distribution level, and aggregation functions for geographically dispersed time-dependent distributed energy resources are investigated.

**O3: To conduct experimental testing of ELECTRA controllable flexibility solutions in a lab environment**

The objective is to conduct experimental testing for proof of concept evaluation of ELECTRA controllable flexibility solutions, incorporating system modelling and simulation tools in order to prove the system performance across numerous devices distributed across the power system. Different experimental testing were conducted during the project to prove the feasibility of the proposed controllers. Moreover, simulation analysis were carried out to investigate the feasibility and limitations of the proposed control schemes on a large power system scale using validated data and models from stakeholders, e.g. the power system model and simulated dispatches of the Island of Ireland power system obtained form the transmission system operator of Ireland (EirGrid).

## 1.5 Project results and dissemination of results

### 1.5.1 Information flow and control mechanism

Power system operators need to maintain the power system in a secure state under increasingly complex conditions. The increasing share of renewable energy sources (RES) over the distribution and transmission grid, and the introduction of new components and services, such as energy storage, electric vehicles (EVs) and demand side management (DSM), introduce further complexity and challenges to the system's operation. The current monitoring, analysis and control room functionalities of transmission system operators (TSOs) and distribution system operators (DSOs) are unable to meet these increasingly diverse challenges. Consequently, it is necessary to enhance these functionalities to maintain and operate the power system in a secure and reliable manner. The future power system, which is usually addressed as the smart grid, will accommodate a large share of weather dependent RES, such as wind and solar energy sources, which will be both centralized and distributed [19]. At the moment, one of the main challenges is the shift from centralized conventional power plants that are connected to the transmission grid, to distributed converter-based resources that are connected to the distribution grid. This paradigm shift imposes considerable challenges for today's control centers, where the TSOs is no longer able to monitor the total power generation through the energy management system (EMS) because a large share of the generation is connected to the distribution grid. Meanwhile, the DSOs are required to introduce new functionalities into the DMS to observe and control these units. Therefore, throughout the project new control room functionalities are designed as well as DMS future requirements. A detailed focus was given to the frequency control functions in general and to the emulated inertia control (EIC) in particular that is required due to the high share of converter-based resources. This function can be included in future DMS and/or EMS platforms.

#### 1.5.1.1 Future control room functionality and requirements

The control centre has been described as the "central nervous system" of a power system [1]. It supervises, controls, optimizes and manages generation to balance electricity demand, and to ensure the system's security and reliability. Due to the increased flexibility within the power system, the increased market influence and automation, among others, significantly improved information and visualization techniques are essential for future control rooms [2].

The ELECTRA IRP EU FP7 project has investigated several innovative approaches for real-time operation to accommodate a higher share of DER [3]. One entire work package, namely WP8, focused on the development of the functionalities and requirements for future control rooms. The full results of the work package are presented in [2] and [4]. This package aims to derive new metrics and associated visualizations for future control rooms. The existing trends from vendors were examined by focusing on the experience in updating an actual DMS and in understanding the current landscape. Simultaneously, support for the final set of requirements for future control centres has been received from various European DSOs, who answered the questionnaire that was developed within WP8 and which described the experiences they are having with smart grid demo projects.

Controlling many small and distributed generation units instead of controlling few large generation units is a considerable challenge. The system has to be kept stable and balanced using a centralized control action, as it is currently from TSOs. In this case, an advanced ICT infrastructure with a huge amount of data to be centrally transmitted to the TSO will be needed. An alternative solution is the transition towards distributed and decentralized control actions where distributed units could be locally or remotely controlled. System operators need to address these challenges. Meanwhile, increased collaboration between TSO and the various DSOs needs to be established because many of the DER units are connected to the distribution grid but are not sufficiently observed. When implementing a distributed architecture, it is expected that the DSOs will also be responsible for local active power balancing and voltage control, and will share some of the TSOs's roles. Therefore, it is expected that there will be a core change in the TSOs and DSOs control rooms, in general, and in the EMS and DMS, in particular, to better serve the new requirements. Figure 1 presents a graphical representation of how the DMS and EMS are expected to change. In the following, some of the current DMS's functionalities are presented, including some of the future requirements that could also be included in the EMS.
Based on di different EU projects, it is expected that by 2030 between 52% and 89% of electricity production will be generated by renewable energy resources, mainly connected to the distribution grid [5][6]. To provide solutions for the different challenges that DSOs are facing today, advanced DMS functions are needed. Figure 2 presents some of the current and future requirements to be integrated into the DMS. Among the different needed functions to be integrated into the DMS are:

1- Emulated inertia control
2- Energy storage monitoring
3- Load estimation
4- Load geographical location

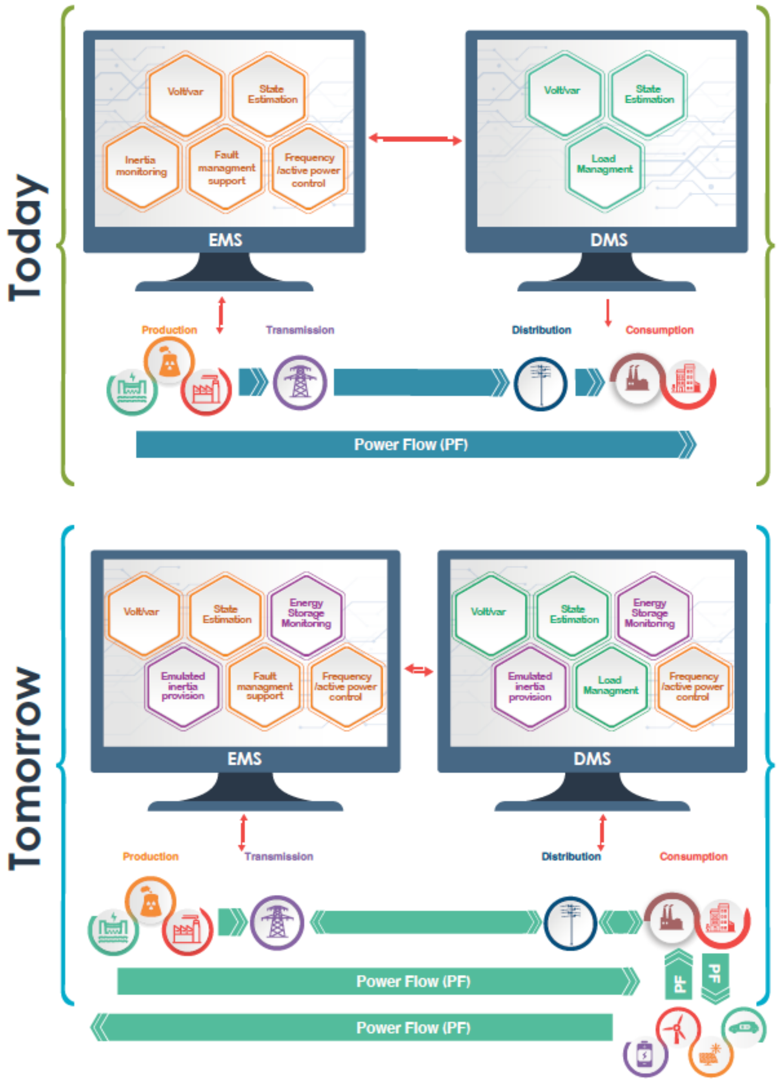

Figure 1: DMS and EMS's current and future requirements

### 1.5.1.2 Electric power system inertia and grid requirements

Traditionally, inertia response has not been considered to be an ancillary service but has instead been considered as a natural characteristic of the power system. Due to the high integration of converter connected resources, which replace SGs, several TSOs in different countries have begun to recognize the value of the inertia response that can be provided by wind power plants, synchronous condensers, and emulated inertia [7]–[10].

To maintain and operate the power system in a secure state, the following three parameters: 1) RoCoF, 2) frequency nadir, and 3) steady state frequency, that characterize the system frequency, should be constrained to avoid further implications, such as load shedding, cascade tripping, and, in the worst case, system collapse. The secure operation area for a given operating point can be represented by considering the previously mentioned frequency constraints as shown In Figure 3.

As previously mentioned two control schemes were designed and investigated to improve the frequency dynamics in terms of RoCoF, frequency nadir and steady state value, namely FFC and SIC. However, energy storages can play a crucial role in delivering such services due to their fast response. Similarly, EVs could play a significant role in the ancillary services market due to their high degree of flexibility. EVs could adapt their active power consumption to improve the grid conditions and support further integration of RES. They are a quick-response unit with an attached storage and potentially bi-directional power flow capabilities [11].

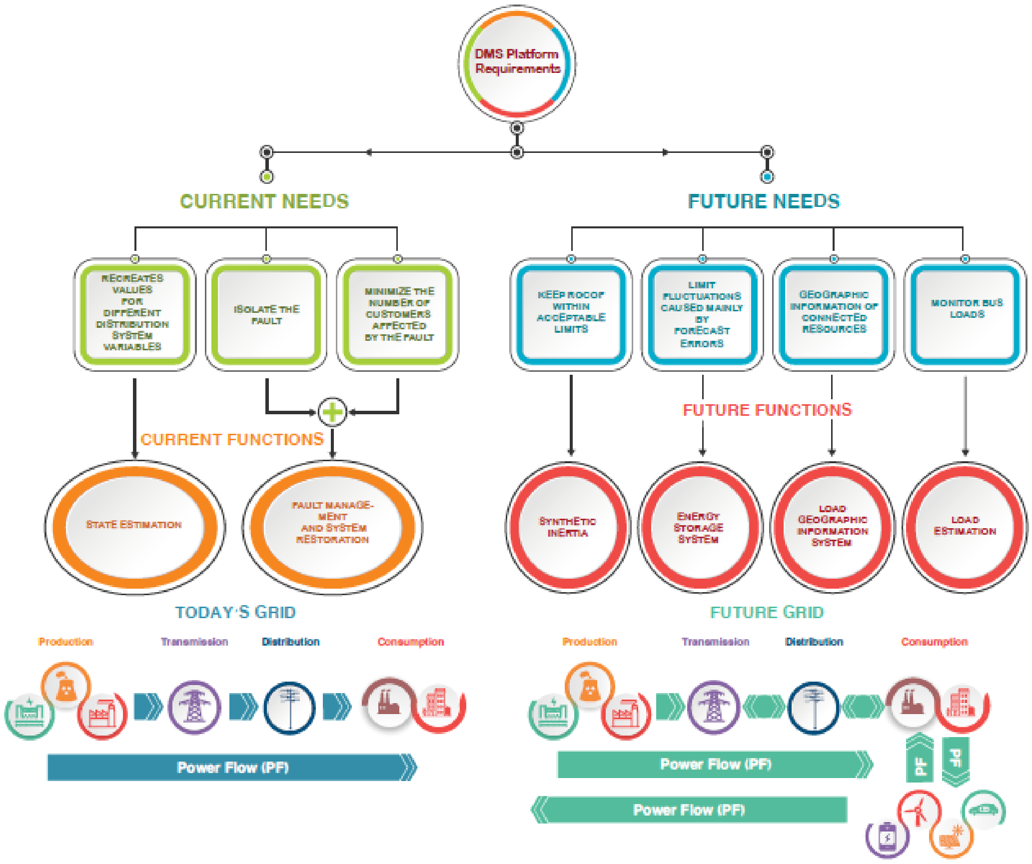

Figure 2: DMS current and future requirements.

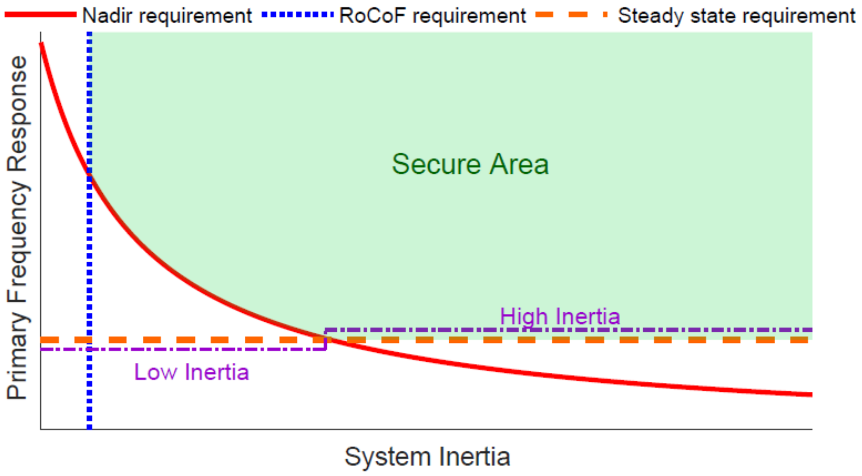

Figure 3: Frequency response requirements

Essentially, EVs are energy storage devices and most of the time they are plugged into a charging spot. Therefore, a transmission system operator (TSO) can greatly benefit from EVs' participation in frequency services provision. In principle, EVs are capable of providing fast regulating power in both directions in case of Vehicle-to-Grid (V2G) or they can simply modulate the charging power [11]. The majority of EVs that are present in the market comply with the IEC 61851 and SAE J1772 standards [12], according to which, the EV charging current should be limited between the minimum charging current of 6 A and the maximum value, which is the electric vehicle supply equipment (EVSE)'s rated current (10 A, 16 A, 32 A, etc.).

The previously mentioned controllers FFC and SIC we designed and implemented in simulations analysis and validated by experimental analysis using series produces EVs. The experiments were executed in the experimental infrastructure SYSLAB, which is part of the PowerLabDK platform. One Nissan leaf and two Nissan e-NV200 were used to provide those services. The results of the experiment are presented in Figure 4.

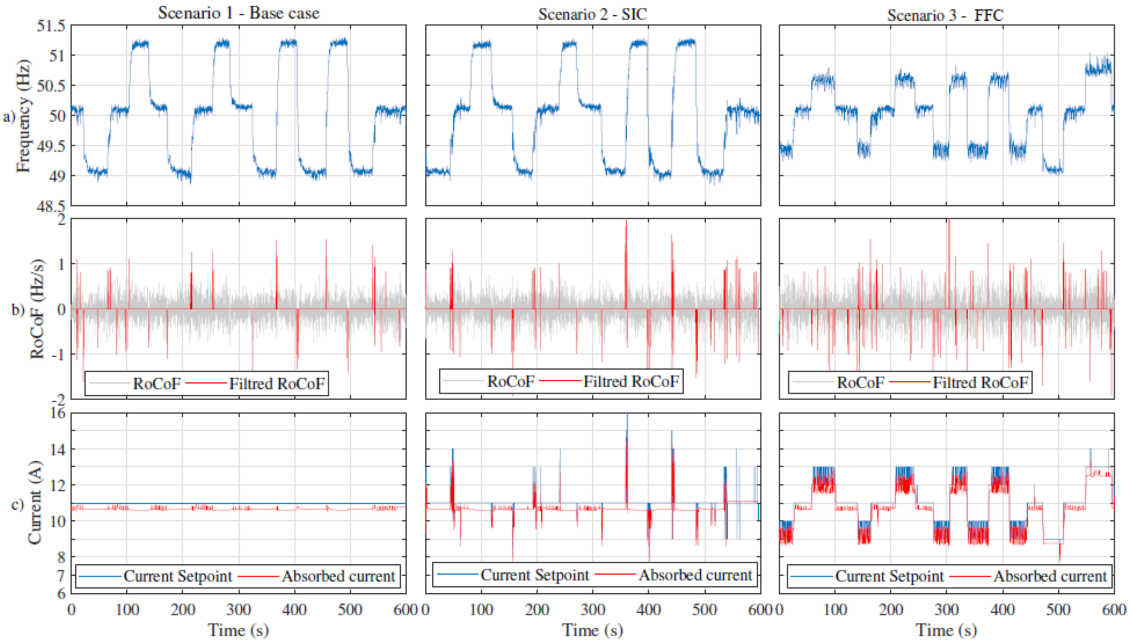

Figure 4: a) Frequency, b) RoCoF measured over 200 ms in grey and the filtered signal after applying the deadband in red (±0.8 Hz/s deadband is considered), and c) EV1's set-point vs absorbed current.

The simulation analysis showed the better performance of FFC compared to SIC, mainly in terms frequency nadir and steady state value, while the two controllers were similar in terms RoCoF. However, for SIC, a deadband of ±0.8 mHz/s was needed to avoid frequency oscillation, which limited the controller's participation. A sensitivity analysis was carried out to better understand the effects of the 1 A granularity imposed by the IEC 61851 and SAE J1772 standards on the two controllers. It was shown that the granularity did not influence the results in the tested islanded microgrid. However, it should be noted that under a certain combination of system attributes (i.e. system inertia and stiffness of the power system) and control units parameters (i.e. amount of power involved in the regulation, droop and response time of the control actions), the granularity might lead to system instability or oscillation between two consequent set-points; as was experienced during the validation phase. The experimental validation showed the ability of series produced EVs to participate in frequency services. It was shown that FFC had a very noticeable effect in improving the frequency dynamics in terms of frequency nadir and steady-state value. However, due to the 1 A granularity and certain combination of system attributes, the FFC implied that the EV's absorbed current to oscillate between two set-points, which led to a worse RoCoF compared to the base case. In contrast, SIC did not have any noticeable effect in terms of frequency nadir, steady-state value or RoCoF. It should be noted the SIC had a negligible effect on the RoCoF due to the applied deadband, as was experienced in the simulation. To better investigate the two controllers and the EVs capability under more challenging circumstances, a wind turbine was connected by imposing a continuous power fluctuation. Similarly to the previous study case, the FFC did have a particularly noticeable effect in mitigating the frequency fluctuation. However, it did lead to slightly worse behavior in terms of RoCoF. In contrast, the SIC did not show an improvement in terms of frequency performance and it had a noticeable negative effect in terms of RoCoF. All in all, it should be noted that for such a small system with low inertia, the actual series produced EVs are capable of improving the frequency performance when FFC is applied. However, with the actual EV's response time, the

FFC had only marginal effects in terms of RoCoF. With the actual EV's response time, a large deadband was needed for the SIC, which limited its contribution. Nevertheless, one should consider that, in principle, EVs were not intended to provide frequency services and, therefore, new requirements in terms of the EV's response time need to be set to achieve better performance.

### 1.5.2 Network observability and decision support

In order to cope with the growing complexity of power system operation, the control room operator must be provided with adequate tools with respect to both, observability of the power system and decision support tools that analyze the grid data and deliver compact and precise information for specific operational aspects. Monitoring tools need to deliver information of various types that allow the control room operator to derive the current state of the power system under complex conditions. Monitoring must include conventional information such as bus voltages and line flows, and newly available data such as EV demand of a grid area. In addition, dedicated decision support tools need to be developed analyzing the already existing and newly available data to provide the control room operator with tailored information about specific operational aspects. Decision support tools aim at making power system operation more reliable, efficient and secure by increasing the control room operator's situation awareness (SA) and, therefore, reducing the space for human error [13].

A high level of SA is fundamental for effective decision-making. In order to maintain and increase the SA of operators to facilitate their decision process, dedicated observability and decision support tools that provide the suitable information are needed. However, the massive amount of available information must be presented in an organized and integrated way to avoid overloading of the control room operator. The focus is on particular aspects for increasing the observability and delivering decision support.

To clarify the role of observability and decision support tools, the structure of a control room and its components must be discussed. Depending on the implementation of a specific control room, the integration of components can vary, thus, a high-level view of the most important components of a control room and their interactions are shown in Figure 5. The control room comprises the visualization and decision support tools, the SCADA or energy management system (EMS), and an information and communication (ICT) system. The information and communication (ICT) layer gains more importance for two reasons. First, it is the enabler for implementation of future smart grid concepts and, second, future power system operation requires a higher level of coordination, e.g. more data exchange between neighboring TSOs [14, 15].

The ELECTRA project investigated innovative approaches for real-time operation to accommodate the coordinated control of distributed resources accross all voltage levels including requirements and concepts for increased observability. One entire work package focused, on basis of these control and observability concepts, on the development of functionalities and requirements for future control rooms in terms of decision support. A condensed form of the lessons learned from the work related to increased observability and decision support is presented here.

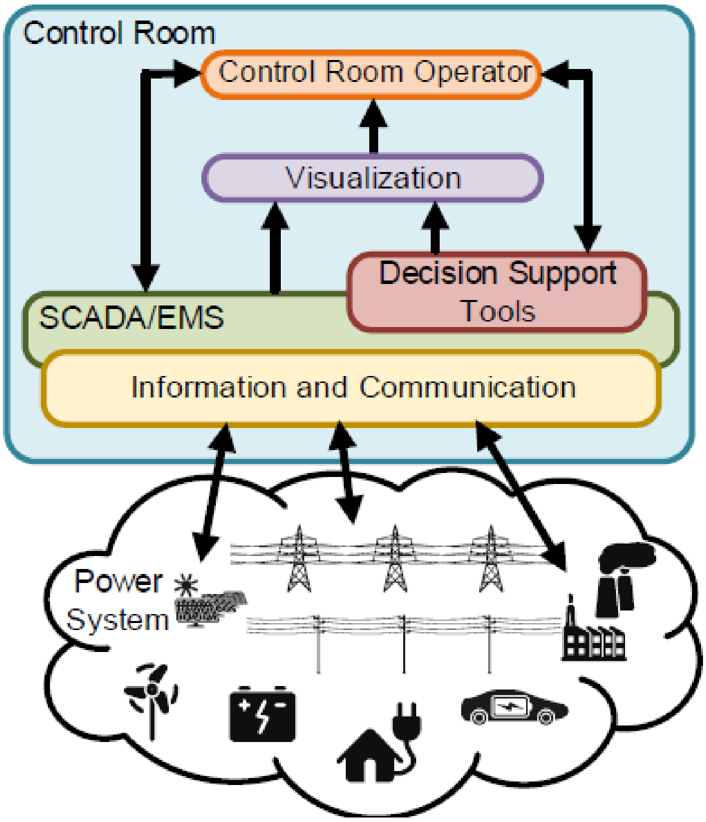

Figure 5: Control room structure in the power system environment

A survey among six DSOs from four different countries consolidates the view on a changing role of control room operators in the future. The increased automation of distribution grids will essentially lead to more interaction of the operator with decision support systems which suggest operational actions to be taken. The surveyed DSOs also agree that monitoring and control concepts need to be taken even to the lowest voltage levels focusing on power quality and load flow management. The survey participants foresee that DSOs will get additional responsibilities, e.g. in terms of maintaining active power balance in their area using regulation of distributed generation and demand response mechanisms. Generally speaking, local issues should be solved more locally. In ELECTRA, a new tuningless load frequency control scheme that actively engages distributed resources was proposed in [16]. These new controllers and activities require also new tools for decision support of the operator in an environment with an enormous amount of available data and tremendous complexity. However, the most important overall requirement is that all new types of activities and decision support systems, which interpret the data, contribute to guarantee the continuity and quality of service. Great potential for improving the observability in control rooms is seen in the data from smart meters, which can benefit state estimation, localization of faults, network reconfigurations after a fault, minimization of losses and voltage control. However, the most relevant observability needs were found to be state estimation and availability of reserves. An increased need for sharing of grid information with neighboring operators was determined. In particular, operational information about actions that influence also the neighboring grids should be shared. Additionally, information about the general state of the grid in terms of normal, alert or emergency operation could be shared to improve inter-area observability. In ELECTRA, the Pan-European reference grid was developed to derive novel observability concepts of large interconnected grids [17]. Concerning the area-wide observability of synchronously interconnected AC grids, monitoring of inertia was determined crucial to allow the shift to a converter-dominated future grid.

Another important factor that was highlighted is that control room operators should be notified and presented the necessary information to understand the situation only when an issue is detected and its intervention is needed. If the system is operating in a normal state without any issues, the operator should have access to in-depth information at various levels. Future control rooms should shift to a modular architecture which allows integration of various new applications and visualization modules, and also replacement of existing modules. In addition, each operator should be able to customize its modules. Geographical location of distributed resources was identified to become more important in order to allow to solve local problems efficiently. For example voltage control is a local problem and, therefore, it is important to have accurate locational information of the resources to make more optimal decisions. Enhanced forecasting of numerous electric and non-electric variables was found extremely important to ensure the secure and efficient power system operation in the future. More frequently updated load and generation forecasts are necessary for the operator to foresee possible critical situations, which allows proactive activation of preventive actions. Real-time weather and forecasting information possibly represented in geographic displays would further enhance observability. Another important aspect is the forecast of available flexibility. This is a challenging task as the flexibility is time-dependent and affected by specific resource characteristics. On top of that, a number of small resources should be aggregated to achieve a workable resource capacity. In summary, due to the fact that observability decreases as the voltage level decreases, monitoring and control concepts are/should be taken down even to the lowest voltage level. This, in turn, produces tremendous amounts of newly available data, which must be interpreted by decision support tools, which present the operator prioritized actions for specific operational aspects. The overarching goal is to develop an integrated solution for all existing and new observability/decision support tools to enable seamless co-operation of them.

As previously pointed out, it is crucial to increase the observability of distribution grids to enable high penetration of renewable energy sources (RES). A large portion of RES is being connected at the distribution level, e.g. photovoltaics (PV) on residential rooftops [18]. Distribution feeders are transitioning to host both, energy consumers and producers, hence, the power flow of distribution grids changes significantly in the presence of dispersed generation units [19]. Under certain circumstances, even reverse power flows can occur, e.g. when low demand and high PV generation coincide [20, 21]. In addition to that, voltage becomes more volatile due to the fluctuating power output of renewable generation and the charging of single-phase electric vehicles at the lowest voltage level [22, 23]. Previous research has focused on the application and adaptation of conventional state estimation methods for distribution grids which are widely used and well understood for transmission grids. However conventional state estimation approaches, such as [24, 25], suffer from the assumption that the network topology and accurate line parameters are given. The accuracy strongly depends on accurate line parameters and actual topology, and seriously degrades in presence of inaccurate parameters [26, 27]. To overcome these drawbacks of conventional state estimation, a novel voltage estimation approach using Neural Networks (NN) in active distribution grids with high RES penetration is proposed within ELECTRA. The approach utilizes data from already existing measurement sensors in today's distribution grids, e.g. substation measurements and smart meter data. Two different phases of the voltage estimator are distinguished, namely training phase and real-time estimation phase.

**Training phase:** The estimator is established in the training process by use of an suitable training algorithm. The choice of training algorithm depends on the problem type and complexity of the NN. Here, the well known Levenberg-Marquardt algorithm is used to train the NNs because it is usually the fastest training method for function approximation up to a few hundred weights and biases, it is very accurate and it shows superior convergence behavior over other algorithms [28, 29].

**Real-time estimation:** After the training process, the voltage estimator can be used for real-time voltage estimation at the specific bus, i.e. substation measurements are fed into the estimator and the voltages of the downstream bus are calculated in the order of milliseconds on a standard laptop due to the direct calculation without further iterations. It is crucial for real-time applications that the computation time is deterministic, since it has to be accounted for the worst case.

The method has been implemented and tested in Matlab and PowerFactory DIgSILENT simulation environments.

A comparison between the estimated and actual phase-ground voltages at the two downstream buses on Feeder 1 and 3 from the tested grid in PowerFactory is shown in Figure 6. The two upper plots show the results for the downstream bus of Feeder 1 including the absolute error of the estimation and the two lower plots for the downstream bus of Feeder 3. The estimated and actual voltages are shown as dashed and solid lines, respectively. The difference between the estimated and actual values are small and can hardly be noticed but the plots of the absolute error reveal that there is a difference between the real and actual voltages. It can be seen that the absolute error reaches its maximum at around midday, coinciding with the PV generation peak. Before and after this period the error is smaller. As the voltage estimator has been established with five scenarios which differ primarily in terms of load distribution, this is expected. The voltage estimator had not been trained with a high PV penetration scenario, therefore its ability to estimate the voltages under high PV production is limited. However, when analyzing the results in Figure 6, it can be seen that the absolute error is still small compared to the nominal voltage, as its max deviation is less than 1.5 V for the downstream bus at Feeder 3 despite the presence of complex load and generation patterns within the feeders.

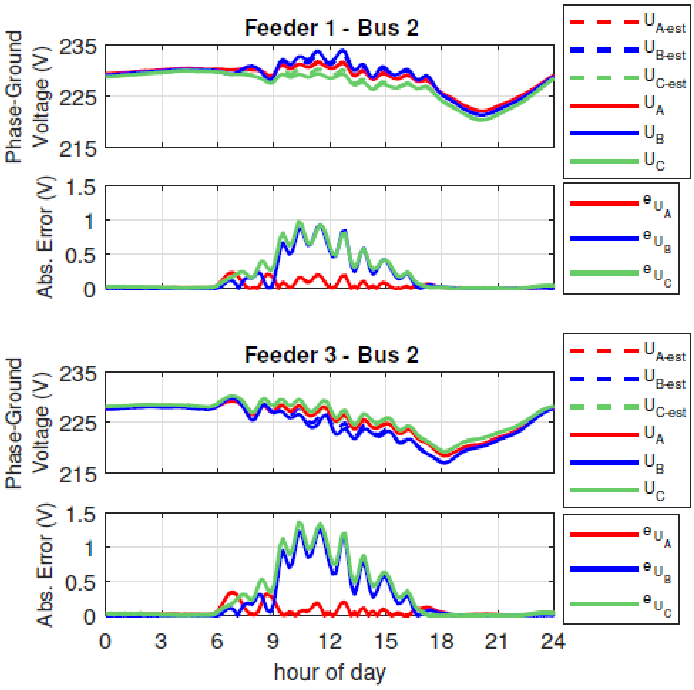

Figure 6: Estimated voltage compared with actual voltage of the buses including the absolute errors of the estimation. Top plots

The results indicate that NNs are suitable for accurate voltage estimation in active distribution grids with high distributed generation using data from currently available real-time and non-real-time measurements. As seen in the results, the error of the estimation increases when the PV generation reaches the highest level at around midday due to the fact that no such scenario was considered in the training process of the NN. This could be improved when such scenarios are considered in the training process. However, the estimator was also validated against real data.

The validation of the approach was carried out on field data from a real Danish LV distribution grid with PV generation.

exclusively trained on simulated data and, therefore, the method needs to be validated on data from a real distribution grid in order to allow application in practice.

The validation showed that the number of neurons in the hidden layer is not of great importance as long as the model is not underdetermined because the validation checks during the training procedure prevent overfitting. However, it is suggested not to use an unnecessary large number of neurons to keep the model complexity as low as possible. The data quantity analysis showed that about 30 days of historical data, given a granularity of 1 min average, is enough to establish an accurate estimator whereas the performance of the estimator varies for different feeders due to their different characteristics. The retrain analysis showed that the performance of the estimator declines with longer retrain intervals. Additionally, the estimator was found not to be sensitive to high PV in-feed and reverse power flows. The errors during periods of high load, and periods of high PV generation do not show noticeable differences.

### 1.5.3 Experimental testing of ELECTRA controllable flexibility solutions in a lab environment

Electric power grids face massive changes with the crumbling top-down generation scheme, where a few generators inject power into the transmission grid towards consumers deep down in the distribution grid [11]. Inverter-coupled DERs deployed throughout the low and medium voltage levels are gradually replacing synchronous generators, reducing the inertia of the system. This is being further promoted by the expansion of HVDC infrastructure that decouples the inertial response between interconnected areas [4]. Consequently, the system’s ability to withstand frequency changes by compensating transient load events with the energy stored in rotating masses is significantly reduced. The highly volatile nature of renewable energy sources, such as wind and solar energy, additionally increases the uncertainty in the planning, and contributes to stability problems [98]. Established LFC schemes, notably AGC [5], have difficulty coping with the entailed changing dynamics because of their rigid tuning requirements [99], [100]. A direct consequence is the rising number of frequency violations as reported by the ENTSO-E [12]. However, the blurring line between TSOs and DSOs [101], the expanding monitoring infrastructure [102], and the availability of new flexibility resources [103], [104] opens new possibilities for LFC. Present-day LFC as described in Section 4.1.2 uses operating principles from earlier times when grid state awareness was very limited. Measurement devices would typically be found on tie-lines crossing control area boundaries, which led to the formulation of the ACE in (4.2). While the ACE can perfectly determine imbalances in steady-state, its dynamic behavior is limited by the system dynamics and the AGC tuning (4.3). Modern power grids see a significant decrease of inertia and stronger fluctuations of power production, resulting in rising numbers of frequency violations because AGC is inept to cope with changing system dynamics for its rigid tuning. Harnessing directly the DSOs’ situational awareness, however, provides new solutions to LFC.

Therefore a novel LFC was designed and implemented in the simulation environment Matlab-Simulink and validated the experiment facility SYSLAB. The implemented The LFC approach called Direct Load Frequency Control (DLFC) is tuning-free and adaptive to the capabilities of its controlled area, rendering it suitable for dynamically changing power grids. The DLFC is simple, consisting only of two algebraic equations and first-order low-pass filters describing two concurrent processes. First, area imbalances are obtained through direct observation of production and consumption, which enables the fast activation of secondary resources. Second, primary resources are actively involved in frequency restoration by systematically adjusting their frequency references. The frequency is effectively treated as a local quantity in the method, as it is inferred over the primary resources' output state with regard to their nominal set points. The resulting control loop is largely decoupled from the non-linearity of the actuators, secondary power is only activated in response to local events; and no integrators are required to mitigate steady-state errors if the primary droop capabilities are well-known. Active state data exchange between neighboring areas enables load sharing, and the only free parameter is the control interval. The signal flows of the DLFC and the AGC are shown side-by-side in Figure 7.

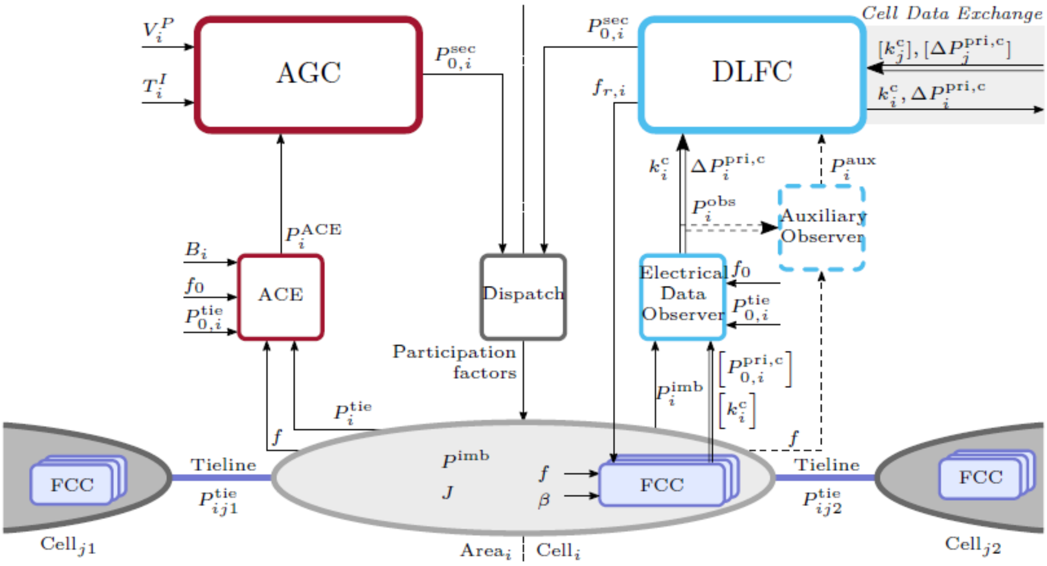

Figure 7: Structural overview of AGC versus DLFC signal flows.

On the DLFC side, the EDO acquires state information from the Cell, and the auxiliary block allows for incorporating additional corrective powers. The primary devices perform Frequency Containment Control (FCC) and actively participate in secondary control as part of the method. The FCCs report their droop gains and output powers to the EDO, which forwards the aggregate values to the DLFC, and takes the reference frequency signal in return. Neighboring Cells appear as atomic devices with droop capabilities, and as such they exchange state information, similarly to the FCCs. Both LFCs feed their power regulation signal into a dispatcher that evaluates the participation factors for all plants bidding into secondary control. Experimental verification of the DLFC's practical applicability was conducted in the SYSLAB experimental facility and on the setup described in Figure 8.

The DLFC was implemented in Java and executed on SYSLAB's headless computer nodes, which provide access to the devices via Java RMI calls. Inter-Cell communication was realized with JeroMQ, an open-source library of the ZeroMQ (ØMQ) protocol stack. Wind turbines, solar panels, and the EV were randomly plugged in and out of the charging station, creating additional disturbances on the islanded system. Cloudy and gusty weather during the experiment caused low PV output and highly fluctuating power production on the part of the wind turbines.

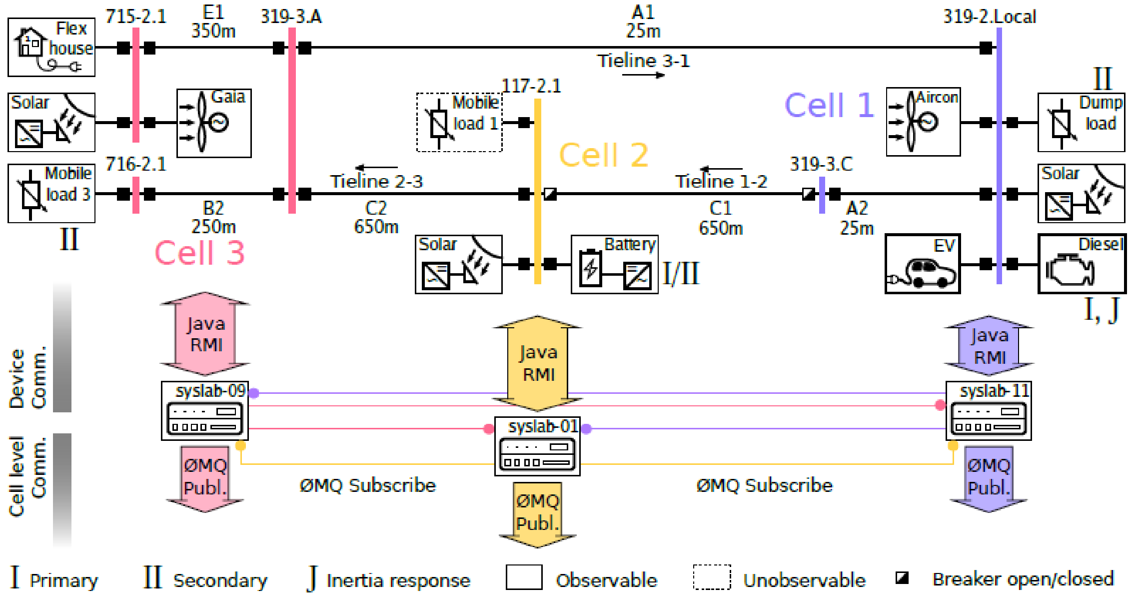

Figure 8: Single line diagram of the setup used during the experiments together with the communication infrastructure

Throughout the simulation and the experiment validation the DLFC approach proved its applicability for highly dynamic power systems in analytical and experimental assessments. Its main characteristic, the absence of power system-dependent parameters that would require tuning, is rendered possible through high observability in the distribution grid. As only power balances are considered, hierarchical structures involving TSOs, DSOs, and aggregators (whose resources may be obfuscated for regulatory or privacy reasons) can be maintained. Given the inexorable advancements in monitoring and communication infrastructure, using primary resources for secondary control is both feasible and reasonable for managing low-inertia systems. Direct secondary power regulation allows for harnessing the benefits of fast-acting flexibility resources while reducing the number of activations. Consideration of the resources' capabilities in real-time promotes the notion of "plug-and-play", while scalability is ensured by the neighborhood interaction scheme that is independent of the network's total extent.

Considering the possibility of DSOs participating in secondary control, power balancing control schemes need to account for the fact that these smaller areas are not necessarily self-sufficient. In this case, an online power interchange approach was implemented throughout the ELECTRA project and also validated through experimental analysis in SYSLAB. The online power interchange approach distributes the load across the neighborhood. Global active power balance is thereby maintained as demonstrated in the laboratory experiment, where the net power exchange with the external grid was maintained around zero. The power set points transmitted between the areas are added to their respective imbalance set points, rendering the method compatible with traditional AGC. This mechanism could also be adapted for TSOs to deal with unforeseen outages of bulk generators or related events.

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### 1.5.5 Dissemination

The project results have been published in various conferences and journal articles, project deliverables as well as in three PhD thesis:

#### 1.5.5.1 Journal articles:

[1] M. Rezkalla, M. Pertl, and M. Marinelli, "Electric Power System Inertia: Requirements, Challenges and Solutions," Springer Electr. Eng., 2018.

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### 1.5.5.2 Conference articles:

[1] M. Rezkalla, K. Heussen, M. Marinelli, J. Hu and H.W. Bindner, "Identification of Requirements for Distribution Management Systems in the Smart Grid Context", in Power Engineering Conference (UPEC), International Universities. Stoke on Trent, United Kingdom, Sep. 2015.

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### 1.6 Utilization of project results

The project results have been a core part of three PhD thesis and the results have been published and discussed in high ranked journals and conferences. The dissemination of the results inspired different researchers to look into the same challenges and use the results of the project as a starting point for their research.

Moreover, some of the results have been used in some courses as teaching material as the case with the Integration of wind power in the power system course.

## 1.7 Project conclusion and perspective

The project aimed at investigating the various challenges that the transmission system operators (TSOs) and distribution system operators (DSOs) are facing today due to the high integration of distributed and converter connected resources replacing conventional power plants. The project aimed at supporting the transition towards a higher share of renewable energy sources (RES) by investigating different challenges such as: the reduction of system inertia, low observability and decisions support in currently present control rooms as well as the needed transition from centralized control approaches into distributed ones. The project focused on the challenges that are imposed by the high integration of converter connected resources and the consequent reduction in system inertia on the system frequency. It also focused on selected aspects aimed at increasing the situation awareness of control room operators by developing innovative monitoring and decision support tools. The presented work covered classical power system issues such as transient stability, innovative data-driven approaches for voltage estimation, and aggregation functions for harnessing time-dependent flexibility from geographically distributed EVs. Moreover, the project addressed supervision and control of horizontally integrated electric power systems, in which Distribution System Operators (DSOs) assume an active role. Focus lies on the technical possibilities emerging from the expanding Information and Communication Technology (ICT) and monitoring infrastructure in distribution grids. Strong emphasis is placed on experimental verifications of the investigated concepts wherever applicable. Around these major areas, different research question have been outlined and addressed such as: What are the capabilities and limitations of series-produced EVs in providing frequency services in terms of synthetic inertia and fast frequency control? And through simulation and experimental analysis it was shown that Electric vehicles can represent an effective solution to enhance frequency stability thanks to their property of being quick-response units.

## Annex

Add links to relevant documents, publications, home pages etc.