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1. Executive summary

The aim of this report is to provide a holistic overview of the Active Network Management (ANM) concept which is based on hierarchical decentralized distribution automation and flexibility services of commercial aggregators. Interactions and roles of commercial aggregators, Distribution System Operator (DSO) and different markets has been defined and developed. Descriptions of the real-time medium and low voltage grid monitoring and control use cases that characterize the proposed approach are provided. The proposed concepts and distribution automation lead to improvement of the network efficiency and to the increase of network hosting capacity.

The ANM concept and solution has been designed for future distribution systems which have very different characteristics from the existing system. In the future a high share of Renewable Energy Sources (RESs) will be connected to all voltage levels in the distribution grid. Other Distributed Energy Resources (DERs) will be similarly common and their flexibility will be available for control and scheduling realized by commercial aggregators or DSO. The IDE4L ANM has been developed to enable this scenario and ensure reliable and efficient operation of the distribution grids.

IDE4L project has posed and achieved three main objectives: 1) Definition of concepts for active network, distribution automation system, and commercial aggregators, 2) Development and implementation of planning methods and automation functionality, and 3) Building and running of demonstrations in three field sites in Denmark (Østkraft Holding A/S), in Italy (Unareti SpA) and in Spain (Unión Fenosa Distribución, S.A.) and six laboratory sites.

All main outcomes and findings are merged and interpreted here, whereas detailed results are presented in the various deliverables of the project. First of the all, the demonstrations have shown the applicability of the proposed concepts and functionalities and have provided values of key performance indices. Second, the project has produced several breakthroughs for real-time monitoring of the complete distribution network, establishing the basis for the ANM. Third, the project has developed the control and flexibility service solutions to realize the active management of the distribution grid, thus enhancing grid reliability, hosting capacity for RESs and DERs, and power quality.

The IDE4L active distribution network controls DERs in addition to grid assets. Enhanced controllability is achieved by several complementary control methods of increasing complexity: grid codes, dynamic grid tariffs, direct control of grid assets and DERs, and flexibility services of aggregators. The operation is supported by a well-defined hierarchical and distributed automation architecture for distribution. Monitoring and control use cases utilizing the proposed automation architecture are defined and demonstrated, yielding the results summarized here.

Full exploitation of proposed ideas requires radical changes in distribution network design. However, this will lead to significant improvement of distribution network efficiency in terms of network capital and operational costs, and will provide a remarkable increase in network hosting capacity for RESs and DERs. The integration of controllable DERs is based on market approach where DERs are controlled indirectly via commercial aggregators. Distribution system operator has a role to validate flexibility service requests and to purchase flexibility services like scheduled and conditional re-profiling products from commercial aggregators to solve congestion in the distribution network.

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The proposed automation system is based on standards, it is scalable to monitor and control of whole distribution grid, and it may be implemented utilizing off-the-self products. The hierarchical and distributed automation architecture is based on existing devices, international standards (IEC61850, DLMS/COSEM and CIM), protocols and interfaces, which will allow DSOs to gradually deploy the new solutions. Monitoring, control and protection functions can be deployed locally in the substations, and can operate in a coordinated manner. Vertical and horizontal integration provides a complete view of the distribution network status. This yields business benefits in the short run, without demanding a total replacement of the existing infrastructure, which would not be feasible. Automation system enable ANM by creating a platform for information exchange and functionalities within distribution domain and between domains affecting on it. This comes at the cost of a notable increment in complexity of distribution network design and operation.

The IDE4L project has designed, implemented and demonstrated concepts of active network management, hierarchical and distributed automation architecture and commercial aggregator to provide flexibility services for grid management. Implementations of concepts have been validated by successful demonstrations in integration laboratories and field. Concepts and technical solutions extend the monitoring and control of the distribution grid to all voltage levels, increase the distribution grid hosting capacity for RESs and DERs, and enhance the reliability of power supply.

The solutions of IDE4L empower the DSOs to undertake the modernization of distribution grids based on proven technologies. They don’t have to devise themselves the right framework for initial small scale deployment and future expansions. IDE4L provides this framework, and the means to implement it, down to the individual algorithms and communications. In particular, IDE4L’s benefits include:

- Reference, validated concepts, architecture and functionalities to realize the automation and modernization of distribution grids
- The support to realize the automation and modernization of distribution grids, thanks to a reference, validated concepts, architecture and functionalities
- A solid base of critical monitoring and control algorithms, readily available and validated to work with the architecture, on top of which more can be built
- Planning tools that include the automation as an asset and a way to evaluate technical and economic benefits of proposed automation solutions in addition to traditional grid reinforcement actions
- The detailed schema to interface the commercial aggregator to validate market based flexibility services and to purchase flexibility services for active network management

The overview of project outcomes and findings is presented in the form of final report [1].

2. Project context and main objectives

Context

The main aim of the IDE4L project is to define, design and demonstrate the “ideal grid for all”, an active distribution network which integrates Renewable Energy Sources (RESs) and new loads, and guarantees the reliability of classical distribution networks. The active distribution network consists of the infrastructure of power delivery, active resources and Active Network Management (ANM). It combines passive infrastructure with active resources, ANM functionalities and Distribution Automation ICT infrastructure. Active resources are e.g. Distributed Energy Resources (DERs) like Distributed Generation (DG), demand

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response and storage, Micro-grids, flexibility services from Aggregator, STATCOMs, etc. Secondly the concept of commercial aggregator offering flexibility services is integrated with ANM.

The boundary of the project comprises medium voltage (MV) and low voltage (LV) networks. The clean and reliable energy of the future requires a new kind of electric infrastructure that is capable of integrating and exploiting DERs. Large scale penetration of renewable energy sources in MV and increasingly in LV networks, new type of loads such as heat pumps and, more pervasively in future, Electric Vehicles (EVs) are expected to adversely affect the operation of existing distribution networks. The power distribution grids are undergoing fundamental changes towards more dynamic and complex structures, due to the integration of DERs.

Motivation

- RES, active consumers, prosumers and commercial third parties increase the complexity of network planning and operation. Real time monitoring needs to be improved to supervise fast changing conditions and to be aware of new phenomena in complete system.
- Advanced distribution automation and flexible DERs like distributed generation and demand response enable active network management to integrate more RES and new loads into distribution grids, i.e. increase the hosting capacity. Improved controllability of distribution grid enables completely new ways to design and operate distribution grids.
- Existing and new networks and resources should be fully utilized to avoid over-dimensioning of grids due to quality of supply obligations and missing possibility to control DERs.
- Guaranteeing continuity and quality of electricity supply by distributed real time fault location, isolation and supply restoration solution cooperating with microgrids.

Enhanced solutions to be applied therein are distribution automation and planning of active network. Active distribution network will offer significant opportunities for the integration of DERs into ANM. ANM is based on distribution network automation and aggregated flexibility services of DERs. Active networks apply a design principle where network scaling is based on network loading conditions but also availability of DERs for network management. Intelligent DERs control can prevent extreme loading conditions that are posing tough challenges to electricity networks.

Main objectives

The main objective of IDE4L project was to develop and demonstrate the next generation of active distribution networks which will fully comply with the new sustainable energy and efficient use of electricity frameworks. Future distribution grid enables the integration of wind and solar power plants, heat pumps and electric vehicles to ANM and fulfils the reliability requirements of distribution networks. To this aim, project partners are designing and developing the next generation distribution automation architecture that enables flexibility services from DERs and aggregators. ANM is based on new monitoring, control, and network planning functionalities, which were also developed and demonstrated in the laboratories and real distribution networks.

The idea of IDE4L is to develop a concept of distribution network automation exploiting existing automation systems in order to monitor the whole distribution network and to control DERs. Distribution network automation includes the whole chain of electricity network management starting from control

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centre information systems, substation automation, secondary substation automation and ending with customer interface (smart meters and home energy management systems). Small scale DERs do not fall under direct supervision and control of DSO's. DSO's usually acquire services from aggregators to monitor and control DERs. IDE4L automation concept dynamically integrates end-use energy services with real time network operations. The automation concept revolves around three design points: i) Hierarchical control architecture in distribution network automation, ii) Virtualization and aggregation of DERs via aggregator and iii) Large scale utilization of DERs in network management.

To realize the project, project partners have designed, developed and field-tested the next generation hierarchical and distributed architecture for distribution automation, based on international standards, in particular IEC 61850, DLMS/COSEM (IEC 62056) and CIM (IEC 61970, IEC 61968). This automation enables real time monitoring and control of the medium and low voltage grids, and trading of flexibility services offered by DERs through aggregators. Aggregators will offer flexibility services for a flexibility market and grid companies may validate submitted offers and purchase flexibility services to avoid network constraints.

The overall aim of development and demonstration is to develop advanced distribution network automation systems including utilization of flexibility services of DER, and to develop advanced applications that enable the monitoring and control of whole network and embedded DERs. Therefore, a common architecture for distributed network automation and management needs to be developed based on standards and formal methodologies to design the architecture and to guarantee its replicability at a European level.

Working methodologies

Defining

The IDE4L project has defined three concepts:

- **The ANM concept** to design and operate future distribution grids and to define roles and responsibilities of stakeholders,
- **The distributed automation concept** for ANM, and
- **The aggregator concept** for validating and purchasing flexibility services for ANM from DERs and offered to flexibility service market.

Developing

The architecture has been designed based on the Smart Grid Architecture Model (SGAM) and semantic models of the components. About 30 use cases of active network management have been utilized to define it. As a result, the description of architecture is reusable to include additional use cases for the model or to implement it in the form of alternative components, communication media or protocols, and information exchange methods and protocols. The proposed architecture also reuses existing automation solutions by integrating them like control centre IT systems (SCADA, Distribution Management System (DMS), etc.) into proposed architecture. Therefore, the proposed solution may easily be expanded from the existing systems when needed.

New functionalities for the active grid, fit for the automation solution, have been developed. The complete system including functionalities, database and standard based interfaces in the form of Substation Automation Unit (SAU) has also been implemented. Following functionalities have been developed in the project.

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- Real-time monitoring and state estimation of complete MV and LV grids
- Decentralized Fault Location, Isolation and Supply Restoration (FLISR)
- Congestion management: Tertiary and secondary controllers for voltage control, network reconfiguration, and market validation, bidding and activation of flexibility services from commercial aggregator
- Microgrid supporting ANM: interconnection switch and island operation with RESs connected through power electronics
- Optimal scheduling of flexibility services of commercial aggregator
- Distribution network dynamics monitoring facilitating DSO/TSO interactions

Testing of complex automation system utilizing the test platform (hardware- and software-in-the-loop simulations by utilizing digital real-time simulators for power system, commercial and prototype Intelligent Electronic Devices (IEDs), and SAUs) will shorten the initialization time of field installations. The use of the testing platform in a real world scenario provides validation of functionalities, interfaces and components in scenarios which are difficult or unsafe to realize in field demonstration and post-validate the performance of the complete automation system against real world data from field demos. [3]

Demonstrating

Installing a complex automation system in a real operating environment is a non-trivial task, especially if the target environment provides a public service as the electricity distribution grid. The leap from design and development stage of single “bricks” of the architecture to the real testing of subset of the overall system, needed to run a use case is quite big. For this reason, WP7 responsible of demonstrations, proposes an intermediate step where couples of components of the system are tested together to validate their interaction, before stacking many of them together. This intermediate step is called Integration Lab, because it’s main focus is on the integration. The result of adding the integration lab is the testing approach of the WP7 became a three-steps procedure, as depicted in Figure 1.

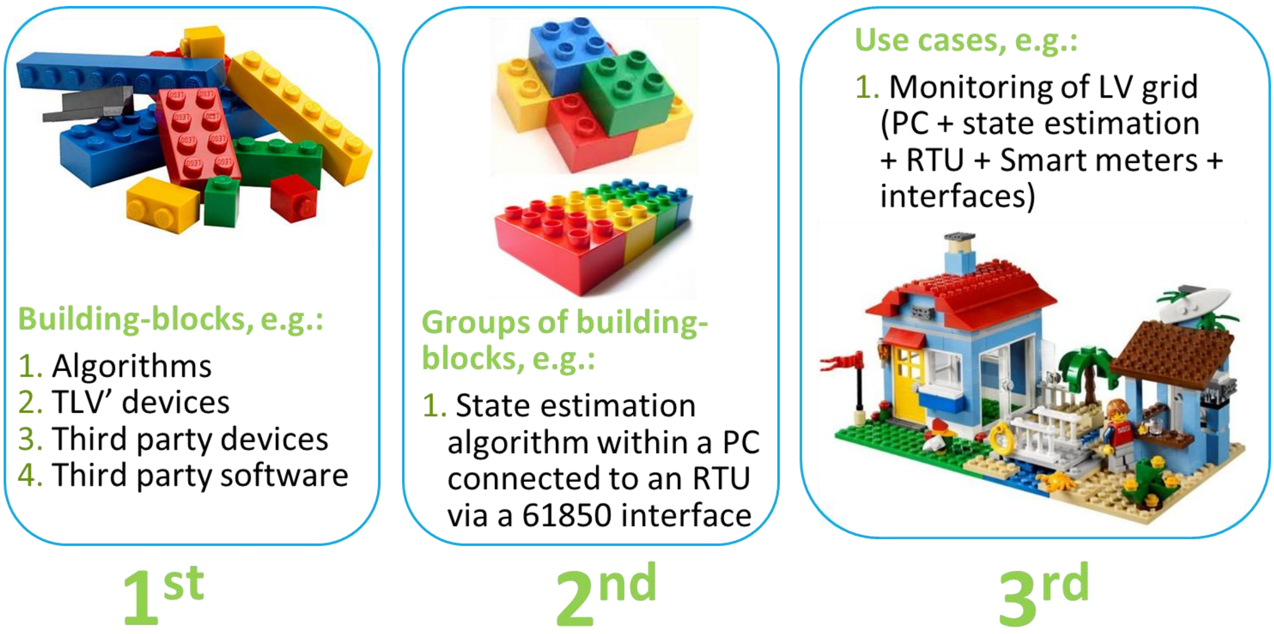

Figure 1. The testing approach.

The first step is the testing of single components of the overall architecture. The place where this testing take place is called "Development Laboratory" and is carried out by each WP work group. These tests should be executed in simulated environments for each module. **GOAL**: Validate and test each module and algorithm before the integration phase.

The second step is the integration step, carried out during the Integration phase of the WP7. These tests should be executed in simulated/prototype environments integrating architectures, algorithms and tools provided by development laboratories. **GOAL**: Validate and test the overall integrated IDE4L architecture and technologies solutions that will be applied on real demonstration scenarios.

The demonstration phase is the final assessment phase, which is carried out by demonstrator owners and supported by integration laboratory group. These tests must be executed in simulated/real scenarios. **GOAL**: Validate and test the IDE4L architecture with a set of real applications. Prototyping state to generate a set of recommendations.

According to the classification reported in Figure 1, Figure 2 reports the list of Development sites, Integration labs, laboratory and field demonstrators.

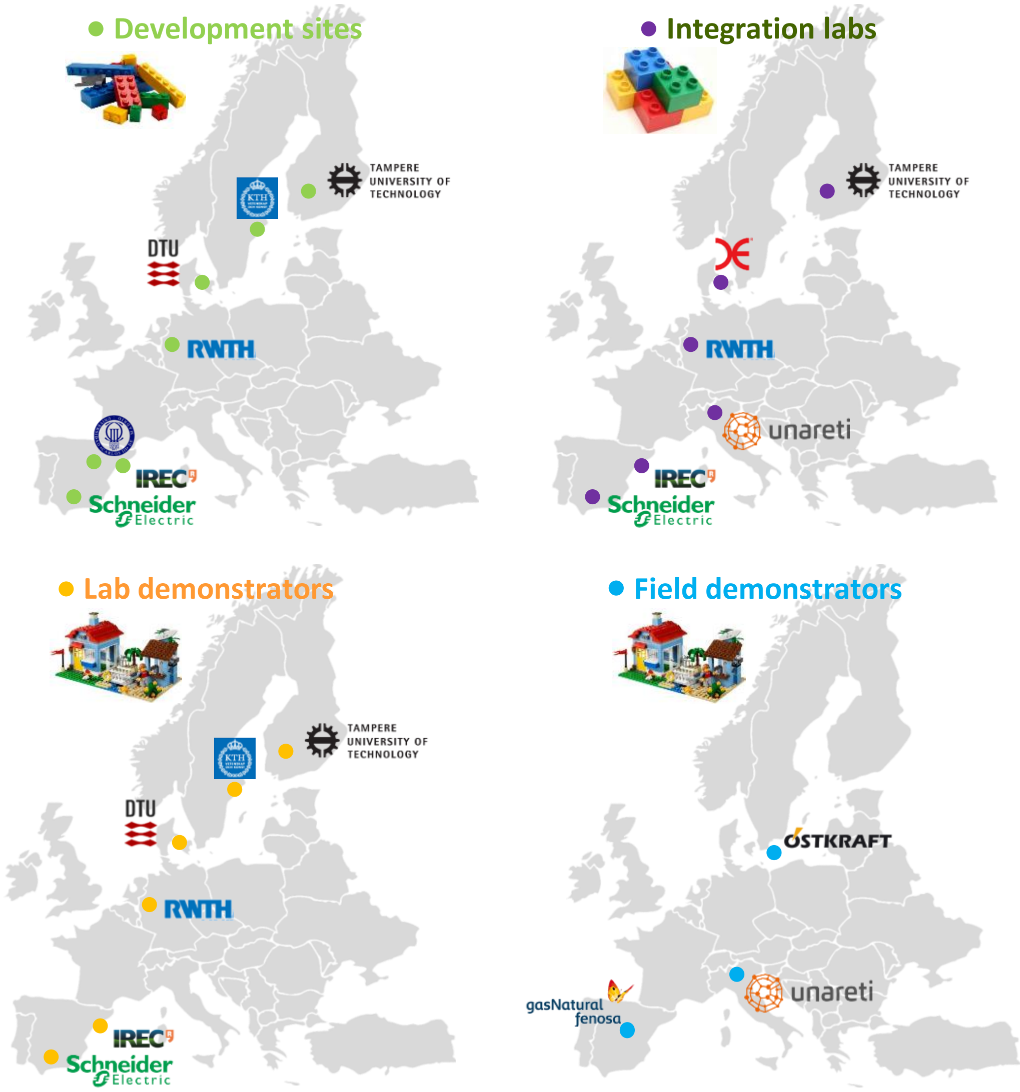

Figure 2. Development, integration and demonstration sites.

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The demonstrations show the applicability of proposed concepts and functionalities, and the performance of implemented algorithms, architecture, interfaces, etc. in field conditions or in real-time simulator environment [3]. The results of demonstration provide very valuable information about the value of complete system.

3. Main scientific and technical results

IDE4L concepts

Electricity distribution networks have so far been designed and operated as passive networks according to a design point that requires them to handle all probable loading conditions. Distribution networks are over-dimensioned today due to quality of supply obligations and missing possibility to control DERs. This results into sub-optimizing the network efficiency by over-dimensioning the network capacity which is being fully utilized only a small percentage of time. With that design point, the only way to increase the number of serviced users is adding network infrastructure assets in proportion. [12]

The management of power delivery infrastructure is enhanced by utilizing active resources in the ANM and specially by coordinating the operation of DERs from the whole system viewpoint to achieve synergy benefits instead of optimizing their operation individually from a single party’s viewpoint. In order to realize this vision, it is very essential to integrate active resources as part of an active network instead of just connecting them to the network with the “fit and forget” principle. Perhaps the most fundamental difference between passive and active networks is that not only do active networks connect DERs, but they also exploit them to the end of optimizing network asset investments and operational costs. Active networks indeed will have substantial impact on both network planning and the operation. [14]

Control methods of active distribution network

Active distribution network utilizes controllability of DERs in addition to grid assets. Enhanced controllability will be achieved by several control methods which complement each other. The control methods described in coming paragraphs in increasing complexity are: grid codes, dynamic grid tariffs, direct control of grid assets and DERs, and flexibility services. [14]

Connection requirements (grid codes) are an efficient method to establish technical capabilities for the control of DERs. The challenge in establishing connection requirements consists of foreseeing all necessary technical capabilities many years before they are actually applied to network management. However, unnecessary connection costs should be avoided. An example in the opposite direction is the so-called 50.2 Hz problem in Germany where previous rules required PV units connected to the LV network to disconnect when frequency exceeds 50.2 Hz to avoid unintended islanding in the distribution network. Addressing the impact of large-scale PV disconnection on system stability however necessitates increasing the frequency setting which will be costly for units already installed. When the power system stability challenges have been resolved by introducing several requirements for inverters like low voltage fault ride through, voltage support and increment of over-frequency protection setting, an additional challenge for unintended island detection has been created which will increase costs at DSO and customer levels while the savings go to transmission system level. Therefore, the conflict-of-interests between stakeholders should be equally treated. Examples of connection requirements applicable in ANM of distribution grids are:

- Production curtailment by remote control (DSO requires capability to allocate curtailment to a specific congestion area, i.e. broadcast based control method (e.g. ripple control) is not efficient enough for congestion problems)
- Voltage or reactive power control of DG unit (requirement for a power factor of DG unit and DSO's right to determine control mode and settings)

Dynamic or power based grid tariff provides customers with incentives to shift load demand to network off-peak hours. Several European counties apply day/night time tariffs to shift large electric heating loads to night time. In the future, more dynamic grid tariffs are expected to be needed because peak demand will not be as predictable as before, thus each network section will have its own peak hours and network loading will vary more due to self-generation and price based control of load demand. Notice in fact that, for example, time-of-use tariffs applied to full storage electric heating customers in Finland efficiently shift load demand to night hours but creates a system level peak during cold days in the beginning of night time.

Distribution grid may also be controlled directly by DSO. Direct control is applied when fast and precise control actions are needed for example to maintain required voltage quality in the grid. Naturally DSO may control its' own resources directly. Traditionally European distribution grids have included very few control elements like on-load tap changer (OLTC) of primary transformer and reactive power compensation units at primary substation. Remote control of MV grid switches may also be utilized for congestion management by changing the location of normally open switch along MV feeders. Recently OLTC for secondary transformers has been introduced to mitigate voltage problems in LV grids. Secondary transformer OLTC is very effective method, if the voltage profile of all LV feeders are always same kind. FACTS devices like dSTATCOM and dynamic voltage restorer may be applied to guarantee voltage quality for sensitive customers, but today these devices are too expensive to replace traditional grid asset investments in case of congested grid. In future energy storage like batteries may also provide very interesting resource also for grid management (e.g. power quality enhancement, congestion management and outage management) in addition to transmission system ancillary services, and balancing at system and customer level.

The continuity of electricity supply to customers is one of the main concerns of DSOs today. Although the reliability of distribution grid is mainly effected by passive grid investments, the continuously tightening requirements, ageing grid infrastructure and protection impacts of DG units require more active and faster protection system and outage management (manual or remote controlled Fault Location Isolation and Supply Restoration (FLISR)) than applied today. Distribution automation reduces mainly outage duration while additional reclosers or circuit breakers along MV feeders will reduce the spread of outage area i.e. will have impact on interruption frequency. Automated FLISR solutions may combine both of these enhancements by FLISR logic in distributed IEDs or centralized DMS, and by direct control of circuit breakers and switches. Next step of reliability enhancement may be provided by microgrids capable of island operation, by microgrids supporting supply restoration of congested backup connection, and by microgrids automatically isolating in fault conditions and resynchronizing after restoration phase.

Some DSOs are already forced to utilize production curtailment to manage their networks due to high penetration of RES. This may result from very rapid growth of RES and delays in grid asset investments, or from extremely costly grid investments in case of occasional curtailment and therefore the socio-economic optimum is to replace grid asset investments with production curtailment. DSO's chance to realize production curtailment may be mandated by grid code like in Germany, or it may require a special contract between DSO and customer. Similarly, the voltage control of DG units may be mandated by grid code or a

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special contract would be needed to allow DSO control the voltage or reactive power of a DG unit. Grid code and special contract should be applied only to non-market based control resources like reactive power, or emergency control actions like production curtailment before over-voltage tripping of DG unit. Therefore, the demand response should be allocated to flexibility services mainly. Meanwhile the market place and products for distribution level flexibility services are missing, DSO may utilize direct control of demand via ripple control, smart metering system or dedicated automation solution like home energy management systems.

In addition to previous more traditional control methods, DSO may utilize flexibility services from Commercial Aggregators in future. Two type of flexibility services called scheduled and conditional re-profiling of flexible DERs have been proposed by Address project [15] and those have also been utilized in IDE4L project. Scheduled re-profiling is an indirect control method to prevent forecast congestion day-before for example in case of maintenance work in the distribution grid. Conditional re-profiling is a real option type product which is traded day-before but requires activation before operation in real-time. Therefore, it is more suitable for occasional and more uncertain congestion cases in the grid for example due to unexpected high or low demand and correspondingly low or high production.

From distribution grid design viewpoint, the utilization of flexibility services requires building trust on stakeholders of flexibility market capable of providing requested services when and where needed, and transparent and competitive enough market where pricing may not be manipulated by market stakeholders. From aggregators viewpoint, the distribution level flexibility market should be attractive enough, i.e. include continuous earning possibilities. The very local characteristics of distribution level flexibility market is a challenge due to previous reasons. Therefore, one possible solution is not to create dedicated distribution level flexibility markets, but bring the ideas of distribution level flexibility market for example to balancing market utilized only by TSOs today.

Active network management

The ANM integrates DERs into the grid management instead of connecting them to the network with the “fit and forget” principle. Controllability and flexibility of DERs is exploited to optimize network investments and operational costs. Synergy benefits may be achieved by coordinating the operation of DERs from the whole system viewpoint instead of optimizing their operation individually from a single party’s, like retailer, viewpoint. Retailer and DSO must be separate companies in European regulatory context.

Essential part of the implementation of ANM is distribution automation and integration of it to other parties of electricity market and power system management. Figure 3 presents the vision of complete automation solution for ANM based on previously described control methods.

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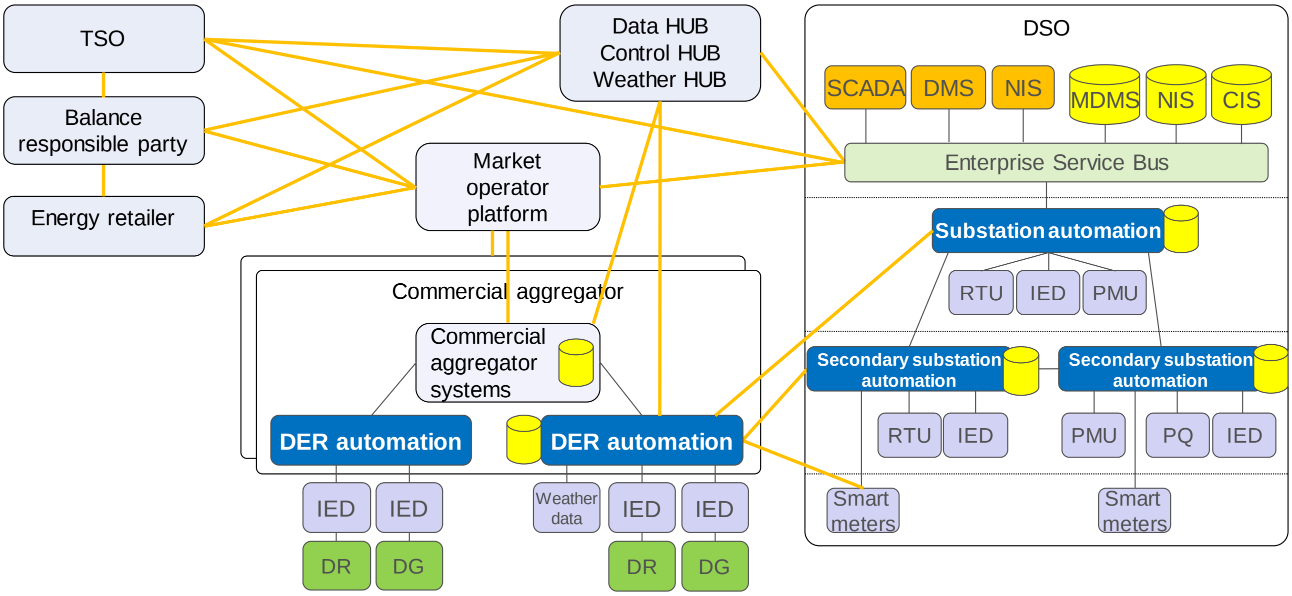

Figure 3. Overview of IDE4L automation solution.

Distribution automation (entity inside a box called DSO in Figure 3) includes control centre information systems, substation automation, secondary substation automation and IEDs including multiple type of devices like smart meters in customer interface. It realizes the real-time monitoring and controlling of the whole medium and low voltage networks, and direct control of DERs. Traditional distribution automation solutions (e.g. centralized SCADA/DMS (Distribution Management System)) are not rapid and scalable enough to monitor and control large-scale DERs in real-time both medium and low voltage networks.

Therefore, a novel hierarchical decentralized automation architecture is proposed for ANM. The hierarchy is implemented by three actors: IED, SAU and DMS. Central elements of the hierarchical automation architecture are the primary and secondary substations (see Chapter 3.1 about details of substation automation). The SAU manages monitoring and control within the substation, stores the collected data and takes independent decisions, e.g. for local control and restoration. Externally, the SAU sends alarms and reports to the control centre (and possibly to other substations). This way, the majority of real-time data is seen by the SAU only, although if needed it can be retrieved by the control centre. The SAU data are received and sent from/to the IEDs, which are heterogeneous devices, not limited to the typical substation IEDs. In fact, the measurement IEDs are measurement units, including strategically selected smart meters, RTUs, phasor measurement units and power quality meters. and the control IEDs are DG units, controlled for production curtailment or as voltage regulators, and OLTC voltage controllers.

The substation automation has external links (DSO's communication infrastructure) to DER automation, which is part of commercial aggregator's automation system. This link is utilized to send, in emergency, the direct control commands to DERs, which in the architecture are considered as a particular type of IED. The same link may be leased to market participants to access DER automation. Similarly, the link between smart meter and DER automation is utilized to provide real-time metering data to customer (customer and commercial aggregator has to agree about metering data sharing).

The control centre information systems consist of several IT systems used for operational and planning purposes. The integration of the control centre IT systems is necessary to get the best out of the available data. For example, the smart metering data is primarily used for billing, but it may be utilized for planning to create enhanced customer load profiling and clustering [16], which is becoming more challenging due to

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prosumers. Similarly, the smart metering data may be utilized for operational purposes like alarming of outages and voltage deviations. Efficient integration requires utilization of modern integration technologies (e.g. Enterprise Service Bus (ESB)) together with a common language (CIM) within the bus. Field data flows through ESB to systems subscribing the data, for example in case of smart metering data alarms go directly to SCADA/DMS, and everything else is stored to Meter Data Management System (MDMS). MDMS is further integrated with Customer Information System (CIS) for billing purposes and with Network Information System (NIS) for customer profiling and clustering purposes. Control centre IT systems also support SAUs in field by providing necessary network information (e.g. impedances, etc.) and updating the status of manually controlled switches.

The second major automation system is owned and operated by the commercial aggregator, which is assumed to sell flexibility services to the DSO to prevent or resolve congestions, besides its other market operations. This automation system is also hierarchical and distributed. The first central layer of the aggregator system includes IT systems to collect and store DER data, schedule DERs to maximize the profit and communicate with market operator platform for bidding and flexibility validation purposes. The second layer is DER automation, (possibly including building or home energy management systems monitoring DERs), which coordinates local DERs and realizes the activation of DER scheduling. The lowest level of hierarchy consists of the IEDs themselves, which are for example programmable logic controllers or advanced thermostats of DER units. The development of the automation system for the commercial aggregator is not in the focus of IDE4L project and therefore further details of implementations are missing. Coordination of control actions of commercial aggregators and DSO/TSO are essential for management of complete power system. IDE4L project has defined the main principles of how to realize validation and flexibility service purchase for congestion management.

The complete automation solution of IDE4L includes also two neural platforms (HUBs and market) in order to simplify the interaction between electricity market stakeholders. The basic idea is very simple: each market stakeholder communicates and exchanges information only with these platforms and not directly between stakeholders. Platforms are not developed in the IDE4L project and therefore these should be understood as logical diagrams instead of physical data flows which are implementation dependent.

Grid design principles and methods

Previous control methods (grid code, dynamic tariff, direct control and flexibility services) provide many novel possibilities to design distribution grids in a new way. Non-firm connection of DG unit, electric vehicle charging station, and other DERs allow the DSO to influence occasional production and consumption peaks, provide great saving for DSO and customers if the hosting capacity of distribution grid would otherwise be exceeded. Intelligent DERs' control can prevent extreme loading conditions that are posing tough challenges on electricity networks. This drives the improved quality of electricity supply; reduced capital investments in the capacity of electricity networks – often required to manage grid anomalies and peaks.

Traditionally all network customers have had firm network capacity available. However, grid may reach its constraints in extreme combined operating conditions of distribution grid and DERs, which are not considered in the rating of grid. The extreme conditions may be e.g. exceptional switching states of network or variety of intermittent DG units producing maximum power during very low demand. The probability of extreme conditions should be low enough in order to have an economically attractive solution. If DER units are used as a means to increase the network hosting capacity, active resources should be controlled almost in real-time (direct control) or extreme conditions should be predicted (indirect control via dynamic tariff or flexibility services) to reduce power transfer at the overloaded part of the network. [14]

The design of firm grid capacity may be based on the so-called worst case planning principle. For example, in radial distribution networks, where no DG is present, the limiting worst case parameter is the voltage drop at the end of the feeder, which occurs during maximum loading of the feeder, and the thermal limits of the conductors. When DGs are connected to this radial feeder, the worst case may occur in a combinations of minimum DG production together with maximum load (voltage drop and thermal limits) and maximum DG production together with minimum load (voltage rise and thermal limits). The worst case principle utilizes fairly conservative assumptions of DG output, load demand and controllability of those and therefore underestimate grid hosting capacity for DERs, but may guarantee the good quality distribution grid operation by passive network assets. [14]

The design of non-firm grid capacity requires utilization of more complex design principles and methods than those applied for firm capacity. Stochastic network analysis offers more information e.g. for assessing the network hosting capacity for DG. With this method, the load and production profiles (time-series based on clustered smart metering data) are used in the load flow calculations. The load flow simulations are used to analyse what kind of network conditions might appear and to find out the limiting network constraints and their duration. They can also be utilized for the comparison between network reinforcement and ANM strategies. Another advantage of stochastic load flow simulation is the possibility to model time dependencies of the components like controllable loads and storages in the planning process. [12]

Active network may become alternative for network reinforcement by postponing investments of physical infrastructure by ANM or by replacing network reinforcement with smart functionalities. The investment planning of distribution grid is a complex dynamic optimization problem including many uncertainties which become more complex to model and solve while ANM and smart functionalities are considered in the planning.

Commercial aggregator

As defined in [17] flexibility can be described as the modification of consumption patterns and generation injection in reaction to a price signal or activation request in order to provide a service within the energy system. The sole source of flexibility are assumed to be prosumers – meaning consumers capable of producing their own energy – in the form of industrial, commercial and domestic providers [18].

Potential services to be provided by means of flexibility within the power system are traded in electricity markets. Given that most consumers and prosumers do not have nor the means nor the size to trade directly into wholesale electricity markets, they require the services of a commercial aggregator to access for them [19]. The main role of the commercial aggregator will be therefore to gather flexibility from its consumers/prosumers portfolio and to optimize its trading in electricity markets to maximize profits.

In order to ensure a transparent and equitable market design for flexibility aggregation, the role of commercial aggregator towards other market parties (i.e. customers, balance responsible parties/suppliers and TSOs/DSOs) should be clarified. Commercial aggregators are entering several European electricity markets, some of them acting as third parties, contacting directly customers for flexibility services and selling them in an aggregated manner on wholesale electricity or TSO's ancillary service markets [20]. In this context it should be ensured that balance responsible parties/suppliers are compensated for the energy they inject and that is re-routed by these commercial aggregators acting as third parties – as it is already done in Switzerland, where clear rules on imbalances management have been recently settled [19]. For the future, the simplest scheme – as it is proposed here – is the one where balance responsible parties /suppliers act as commercial aggregators, making the chain of balance responsibility remain intact and delivers simple arrangements such as one main contact point for the customer [21].

To ensure safe, secure and cost-efficient distribution and transmission network operation and development, commercial aggregators will have to coordinate with DSOs and TSOs, that must also coordinate to each other and have access to flexibility services and all technical relevant data needed to perform their activities both at pre-qualification and operation stages.

From DSO perspective, flexibility should be integrated as part of ANM where new functionalities should be integrated aiming to realize the new roles of DSO: (i) flexibility procurer to feed DMS and its functions to hinder network congestion; and (ii) responsible for technical validation of distribution network located flexibility products coming from day-ahead and intra-day markets and technical validation before its activation when requested by third parties (TSOs, balance responsible parties, etc.).

In relation to role (i), as described below the ANM will include a market agent functionality in charge of flexibility procurement on a day-ahead and intra-day basis, and activation of already procured conditional re-profiling products from commercial aggregators for addressing short-term grid contingencies when they become the most cost-effective measure. Flexibility services offered by commercial aggregator to DSO could be for example active power flexibility for power flow management (by means of production curtailment, load shedding or demand shifting). Proper principles of coordination between DSOs and TSOs should be defined for validation of conditional re-profiling products when its activation could potentially affect the TSO network.

Regarding role (ii), in order to ensure DSOs having visibility of the planned aggregation actions connected to their networks, and ensuring that market schedules are not in conflict with network operation, the ANM will use its tertiary control system as described below for validation purposes both during the off-line time frame (at day-ahead and intra-day markets), and during real-time periods. In Figure 4 the interaction among actors and its functionalities is depicted. As shown in the figure, a flexibility market where TSOs and DSOs can access to is proposed to avoid fragmentation of markets and ensuring effectiveness of system operation [22].

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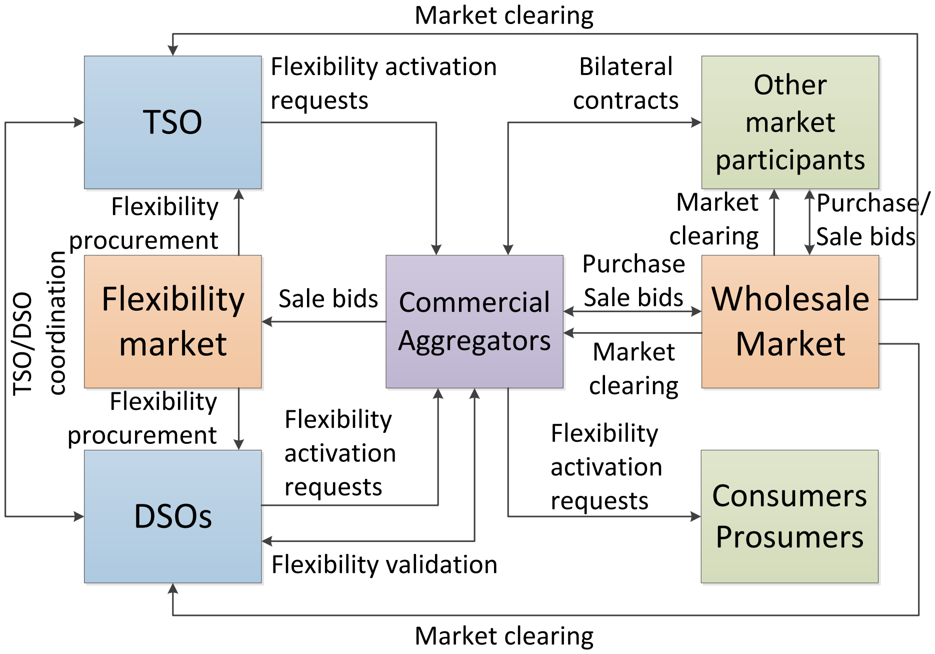

Figure 4. Commercial aggregator market setup.

Roles and responsibilities

The primary role of DSO is to own, maintain and operate the infrastructure for power delivery. DSO has natural monopoly to deliver electricity in its service areas and therefore network business is strongly regulated by energy regulator. The power delivery infrastructure is also a key component of the critical infrastructures of modern society, therefore DSO's responsibility is to guarantee the reliability, safety and quality of power supply by passive grid asset investments complemented with ANM, by necessary asset maintenance programs, and by sufficient operation capabilities.

Electricity distribution network is a delivery infrastructure that connects the customers of this network to the transmission network and therefore enables participation of customers into the electricity market to buy or sell electrical energy and to provide flexible DERs to Aggregators. Therefore, DSOs enable electricity and flexibility markets by providing physical access for power delivery to every customer with equal terms.

Although DSO may not participate in electricity market by selling energy, it may buy network losses from electricity markets and interact with distribution grid flexibility market to validate and purchase flexibility services if needed. As described before, the most likely scenario of distribution grid flexibility market is to merge it with TSO level flexibility market. In order to have transparent enough market place, the market place should be operated by a service company and not by one of the market stakeholders. The role of DSO on this market is to calculate and provide necessary market information (available capacity for each load area), to validate all market transactions belonging to his service area (off-line validation before market closing and real-time validation to activate purchased flexibility services), and to purchase flexibility services in case of forecast congestion.

Additional role and responsibility of DSO in the future will be the enabling of new product and service concepts based on information collected from distribution grid and customers, and based on ANM infrastructure. For example, the smart metering data collected by DSO will be further delivered to Data HUB to simplify metering data exchange between DSOs, retailers, balance responsible parties and TSO, and to enable new data analytic services combining metering data and open source data. Similarly, the access

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to control loads for example via control HUB and DSO's ICT and automation system (e.g. smart metering system), would be provided to all electricity market stakeholders within equal terms. Data analytics service providers may also utilize other measurement data collected by DSO like fault recordings for example to detect coming component failures, estimate remaining lifetime of critical components, or estimate the location of intermittent earth faults.

Commercial aggregators operate in competitive market where several aggregators trade for the same electricity and flexibility markets and compete about the same contracts of prosumers. The role of aggregator is to contract with prosumers about flexible DERs and conditions how to utilize flexibility, and to maximize its profit by utilizing flexible DERs within conditions of contracts and taking advantages of different markets based on capabilities of portfolio. Aggregators utilize technology vendors and service providers to realize necessary automation solution. Most likely the intelligent part of aggregator automation system (tertiary and secondary controllers) is owned by aggregator itself, because the business logic of aggregator will be included in those.

Aggregator has responsibility to meet the conditions set in prosumer contract and to provide the electrical energy and flexibility services accepted at different markets. Aggregator has also responsibility to provide information for DSO's validation process. When the aggregator is a role of retailer and all customers providing flexible DERs for aggregator have also retail contract with the retailer, the retail balance management may be considered internally. If the aggregator has flexible DERs from customers with several different retailers, the aggregator needs to inform retailers about flexibility schedules and activations in order to keep retailers' balance management in control. Otherwise retailers balancing costs would increase remarkably.

The customer of the DSO may be consumer, producer or prosumer of electricity. Prosumer combines consumer and producer roles and may also have electricity storage to be used as consumption or production (charging/discharging). Essentially prosumer is an active customer which actively participates in electricity market by tendering retailers, utilizes dynamic retail and grid tariffs, and/or tenders and contracts with an aggregator to provide flexible DERs to be traded for electricity and flexibility markets. Active customer needs to be active only occasionally and day-to-day activity is realized by DSO, retailer and aggregator.

Business ecosystem needed for future ANM includes several service providers. The outsourcing of DSO's business functions is not considered here. Market operator may be understood as a service provider because he is a neutral party in the market and provides the trading platform to run the information exchange and to track market transactions. Similarly, the different kind of HUBs are essentially information exchange platforms which simplify the integration of information and automation systems and provide data produced by other systems.

Solution for hierarchical and distributed distribution automation

Hierarchical and decentralized automation architecture is the basis of the whole project. The architecture has been designed for complete distribution grid management including high-share of DERs, and it is based on real-time, scalable, decentralized and interoperable (standard based and modular) field automation and control centre IT systems. The architecture is capable of realizing the management of DERs in several different ways including market based flexibility services from commercial aggregators. This type of automation system should be cheaper in the long run and easier to adapt for the specific needs of DSO. [3,4,7]

Real-time monitoring must be extended from primary substations only, to secondary substations down to final customers, where the Advanced Metering Infrastructure is present or underway in many countries. Power quality meters, fault recorders and Phasor Measurement Units are examples of new sources of measurements that are integrated in the distribution automation.

The control of the distribution grid, which is active at all voltage levels and equipped with pervasive monitoring, should be designed coherently: distributed, in order to use locally the measurements and estimates available locally, and coordinated, in order to smoothly control over different time horizons and vertical positions within the distribution network, and to harmonize commercial and technical decisions. From the actuation standpoint, this requires IEDs as control units and SAUs to decentralize decision making and shift it from control centre to primary substations, secondary substations and DERs. [4]

The IDE4L project has designed an architecture based on monitoring, control and business use cases, which effectively coordinates DER and power and voltage control actuators to resolve congestions and power quality issues. The SGAM formulation of this architecture is derived and explained in details in [4,7,25]. Selected implementation instances are presented, and the performance of the architecture is assessed based on indexes such as communication traffic and level of distribution of automation functions.

The IDE4L architecture is technology neutral as far as standards are used; hence, it can be implemented with heterogeneous types of measurement devices, controllers and computation units. All data exchange and data modelling are based on international standards IEC 61850, DLMS/COSEM and CIM to enable interoperability, modularity, reuse of existing automation components and faster integration and configuration of new automation components.

The development methodology is complete: it starts with use case definition (monitoring, control and business), followed by SGAM layers definition and eventually implementation of software and hardware in the field. Operatively, we have proceeded systematically, specifying the requirements for information exchange following the parameters of IEC 61850-5 standard; the actors have been defined in terms of interfaces, databases and functions, and the information exchanges have been clustered in data objects of IEC 61850 and CIM data models.

Schematic Model

The high level, semantic model of the architecture and its domain (rectangles with solid line) is represented in Figure 5 together with external parties (dashed boxes). Within the ANM, the DMS is the central control and monitoring arm of the DSO, realizing centralized and grid wide control decisions and interfacing with the commercial aggregator via market operator. Other centralized systems like Automatic Metering Management (AMM), Customer Information System (CIS), Geographic Information System (GIS) and Network Information System (NIS) are integrated with DMS. Commercial aggregator interacts directly with the IEDs of the resources that the commercial aggregator manages. DSO owned IEDs are installed in the substations and along MV feeders, and interact with the Substation Automation Unit (SAU), which is the brain and communication/data hub of the monitoring and control area. The Microgrid Central Controller, which is itself a specialized instance of SAU, interacts with commercial aggregator for commercial purposes and with DSO’s SAUs for technical purposes. SAU represents a general concept, where Primary and Secondary SAUs are instances of the same SAU concept. Also each block is represented by data (that it

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owns, and stores), interfaces (through which it interacts to get data or provide services through its functions; all this defined according to the standards), and functions they can host. [4,25].

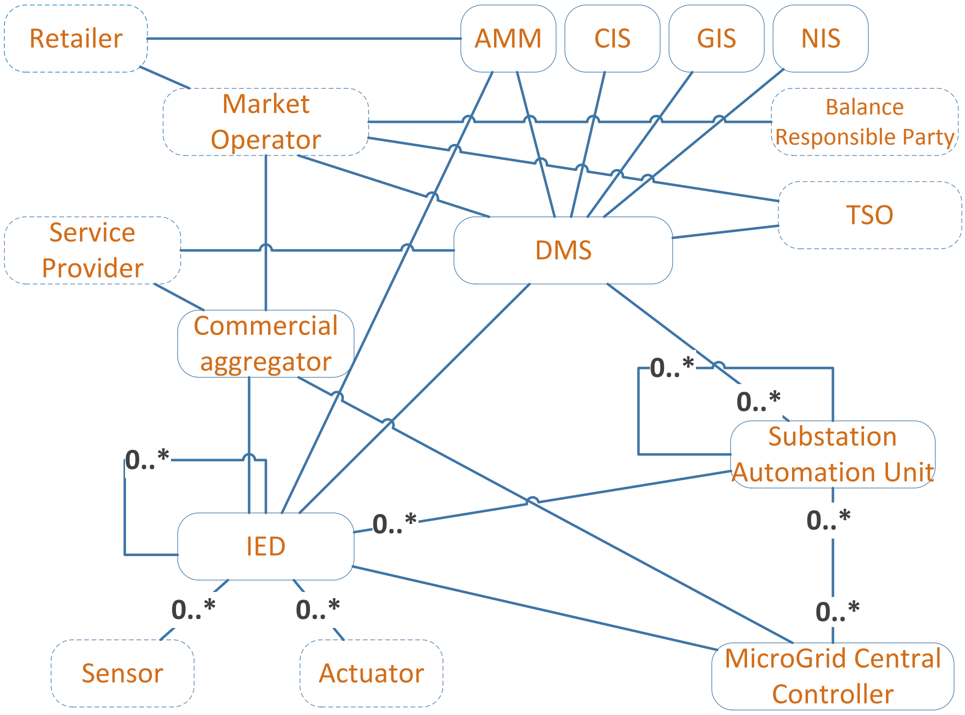

Figure 5. Semantic model of automation system.

Substation Automation Unit

SAU is the core of the hierarchical/distributed IDE4L architecture. The SAU realizes the local and remote monitoring and coordination of resources. Its definition in terms of interfaces, functions and database makes the SAU adaptable, it can be implemented with a subset of features, which are easy to extract from the general model, and as such it can be supported by hardware with very different performance characteristics. The SAU can be exploited for measurement and control devices that are already installed in the field, thus reducing the investment for automation upgrade.

The SAU may reduce the burden for computation, data storage and information exchange of the Distribution Management System (DMS), thanks to the local data processing and control. It may also speed up coordination/optimization of control actions and extend the monitoring and control of distribution network to every corner of medium and low voltage networks when compared to traditional control centre solutions.

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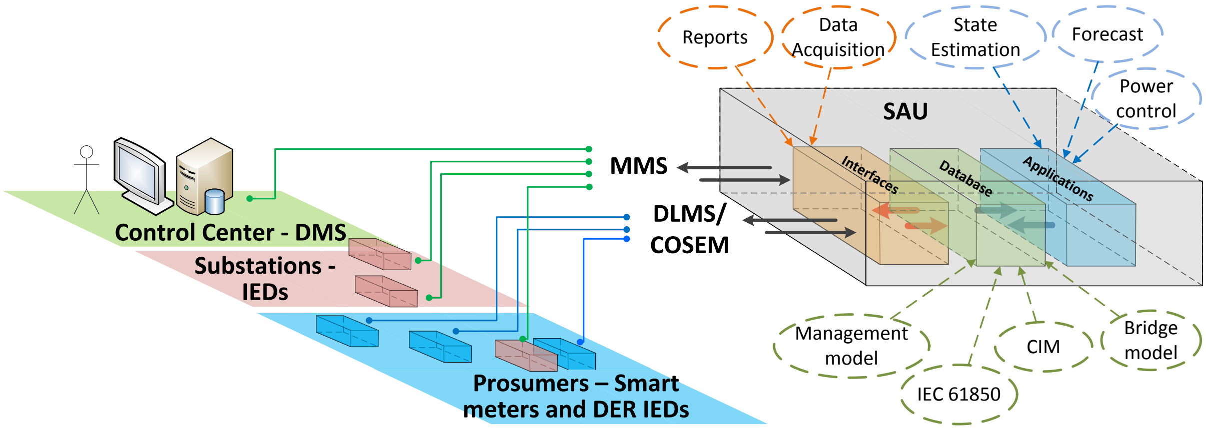

Figure 6. Substation Automation Unit.

The database component of the SAU is the core of the data storage related to the field measurements, network models, business models and SAU algorithms execution. The same database is used to exchange information among algorithms and interfaces implemented in the SAU and used for the state estimation/forecast, for the control and monitoring of the grid connected to the SAU.

The two most important schemas of the database are the Measures and Commands and the Network Models, designed to be compliant with the main standards of the automation area: the IEC 61850 and the CIM.

- The Measure & Control schema has been defined starting from IEC 61850 data model. The model, structured in physical device, logical device, logical node, data object and data attribute, has been expanded with a set of entities used to collect real time and historical data retrieved from the field and with a set of information to parameterize the communications interface to any other physical device (such as IP addresses, TCP ports, users and passwords, etc.). A group of tables has been defined specifically to model forecast profiles.
- The Network Model schema has been designed starting from the Common Information Model (CIM). It contains a set of table per each of the most relevant CIM classes. For example, the 'ConductingEquipment' table is used to model the parts of the AC power system that are designed to carry current or that are conductively connected through terminals.

Requirements for Automation System

Scalability is a critical feature in distribution automation, because of the large number of nodes, substations and DERs. Therefore, the proposed architecture is distributed and modular. The monitoring system that supports this automation architecture is expected, within the next decade, to be able to handle millions of measurement points and a large volume of data. Therefore, the architecture is based on a hierarchical structure where on-line and automatic handling and analysis of data is performed to reduce the amount of data transfer to control centre. Distributed data storage allows tracking every detail without real-time communication to control centre [26]. Same can be said for the functionalities like distributed Fault Location Isolation and Supply Restoration (FLISR) and power control, which are carried out in IEDs and SAUs, without resuming to the control centre.

The automation system should also be based on standards. From a design standpoint, this is needed to enhance and simplify the integration of subsystems, which is an essential requirement of DSOs. The IEC 61850 has been adopted for the distribution automation. Data acquisition and the interfaces between the

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SAU and the peripheral devices has been implemented using standard protocol such as DLMS/COSEM for smart meters and IEC 61850 MMS messages for IEDs. Quasi-static information such as the network topologies and network asset information is however encompassed by the CIM standard. [26,27]

Use cases

Monitoring

The optimal control and high performance management of a grid requires knowledge of all network levels. For this reason, the monitoring encompasses all network levels, aggregating and processing the collected information in a hierarchical and distributed structure with the aim to manage the complexity and the big amount of data.

In the monitoring system, SAU is in charge of collecting values, events and signals from its subnet to monitor the grid and reporting an aggregated view of network, after an internal elaboration phase, to the upper level. Measurement and static network data are stored in a local database with an increased granularity from the underlying grid to the control centre and it is maintained only where it is needed to perform forecasting, estimation and control algorithms locally. State estimation provides system quantities which are not directly measured and because real implementations of monitoring system are subject to errors in measurements, due to communication failures, corruption of the data or temporal unavailability of a meter. Load and production forecasting algorithms are needed to predict the state of the network few hours and day-ahead.

Despite of smart metering deployment in some EU countries, LV networks cannot be neither monitored or controlled by DSO to manage DERs in real-time. The breakthrough of IDE4L project was to integrate smart meters as a sensor for real-time monitoring and control of LV grids which will significantly enhance the visibility of LV grids for a DSO to maximize the hosting capacity of DERs and to utilize already available meters for grid monitoring and control. [3,4]

State estimation and forecasting are two advanced functionalities to provide information about complete network using incomplete and uncertain information. Distribution of these functionalities to Substation Automation Units (SAUs) is a completely novel idea. Decentralized advanced functionalities enable real-time scalability of monitoring system, may also reduce investment and operational costs of monitoring system, and provide a tool to detect broken or unreliable measurement unit. [3,5]

Decentralized IEC 61850 FLISR Solution

Fault Location, Isolation and Service Restoration (FLISR) is the application that can reduce outage duration and have therefore considerable impact in the profit of DSO. Distributed FLISR scheme with peer to peer communication proposed in the project is based on logic selectivity and IEC61850. In addition to alternative network reconfigurations, it may consider DERs and microgrids to manage service restoration to minimize outage duration and the number of affected customers. [3,8]

Automated protection reconfiguration is needed to optimize protection system performance independently from grid or DER configuration. Adaptive protection schemes enhance the coordination of IEDs and therefore the availability of protection system in complex scenarios. IEDs operation parameters will respond to changeable operation situations avoiding technical crew to be dispatched to the installation point and protection system to be interrupted. The use of the IEC61850 configuration language and the

IEC61850-MMS Service for configuration update makes this feature easily exploitable to the EU market and reduces integration efforts. [3,8]

Interconnection switch of microgrid provides protection and islanding capabilities for the microgrid and possibility to support distribution grid. For the stable operation of microgrid, interconnection switch includes protection capabilities to isolate microgrid from faulted grid. However, the islanding of microgrid should not happen to fulfil DERs grid support (connection) requirements, if the grid fault does not cause an outage for a microgrid. Therefore, the integration of decentralized FLISR with microgrid interconnection switch by utilizing FLISR IEC61850 communication, provides great advantage for coordination purposes to ensure the selectivity of interconnection switch protection. [8]

The FLISR solution designed for the IDE4L project is based on the principle that in future secondary substations will be also provided with circuit breakers. This fact will require logic selectivity to be deployed not only between Fault Passage Indicators, but also among Circuit Breaker controllers. Considering this, a decentralized approach to be performed by distributed IEDs has been deployed based on the use of IEC 61850 and the GOOSE communication service, which is indicated for this kind of applications. The application divides the operations in the network in three different steps:

- 1st Isolation step to be performed between distributed IED controlling circuit breakers. This IED will be provided with protection functions ANSI 67N, ANSI 50, ANSI 51 and ANSI 79 as minimum in order to fulfil the requirements imposed by the decentralized logic that has been designed.
- 2nd Isolation step to be performed between distributed IED controlling switches once the 1st isolation step is finished. This IED will be provided with Fault Passage Indicators based on ANSI 50/51, ANSI 67N, ANSI 27 and ANSI 59 functions.
- Restoration Algorithms: This restoration algorithm will be run at SAU level to consider DER capacity and alternative branches for mesh networks, thus obtaining a more efficient restoration.
- Both 1st and 2nd Isolation steps integrate also a backup chronometric selectivity that allows for the provision of backup operations in case the logic selectivity fails. This way the reliability indexes are even better.
- In addition, DER coordination commands are included in order to command disconnections of DER when it is required to avoid islanding situations or unnecessary reclosings. Blocking commands to avoid unnecessary disconnections are also sent from FLISR IEDs in order to avoid unnecessary disconnections form the distribution grids.
- The improvement of reliability indexes relies mainly on the fact that the 1st isolation step reduces the number of customers that are affected at the first instant. In traditional approaches all the users connected to the same line were affected.
- The second isolation step allows restoring the service to part of the affected customers in less than 1 second, so customers affected by service interruptions computing on quality indexes are only the ones connected downstream the fault location.

Congestion management

The main aim of tertiary controller is to enhance the hosting capacity for DERs. [9,10]. Hence, the tertiary control for distribution grid congestion management may reconfigure MV network topology to reduce losses or solving congestion situations. Also, it may validate and purchase flexibility services (i.e. change the scheduling of DER units) for congestion management purposes.

The secondary control for distribution grid congestion management optimizes (by coordinating) the settings of primary controllers to enhance the hosting capacity for DERs and to solve occasional congestion problems. Secondary controller benefits most the cases in which congestion occurs occasionally, network reinforcement costs are high, and control area includes several controllable DERs and DSO's controllers. In weak distribution network the hosting capacity provided by secondary controller is typically three to four times higher than the hosting capacity of passive network, and two to three times higher than the hosting capacity of active network utilizing only primary controllers. [3,9]

Dynamic grid tariff is an indirect control method of DSO to influence on DER scheduling realized by commercial aggregators before day-ahead market closing. Dynamic grid tariffs are locational price signals to prevent the occurrence of congestion in distribution grid and thus they motivate commercial aggregators to consider grid condition in flexibility scheduling. [10,11]

Figure 7 illustrates the hierarchy of the controllers and their interactions. Primary controllers (IEDs) operate autonomously with fast response and the set points may be adjusted remotely. Secondary controller coordinates (optimizes) the operation of primary controllers (IEDs) within a control area. Secondary controllers are located at primary or secondary SAUs depending on which network, medium or low voltage grid, they are managing or on customer premises in case of commercial aggregator. Tertiary controller (DMS) manages the whole system. It is located in DMS and it communicates with commercial aggregators via market operator to validate and to request flexibility services, and it adjusts network topology remotely via SCADA and workforce management system. It may also advise secondary controllers from system and day-ahead viewpoints.

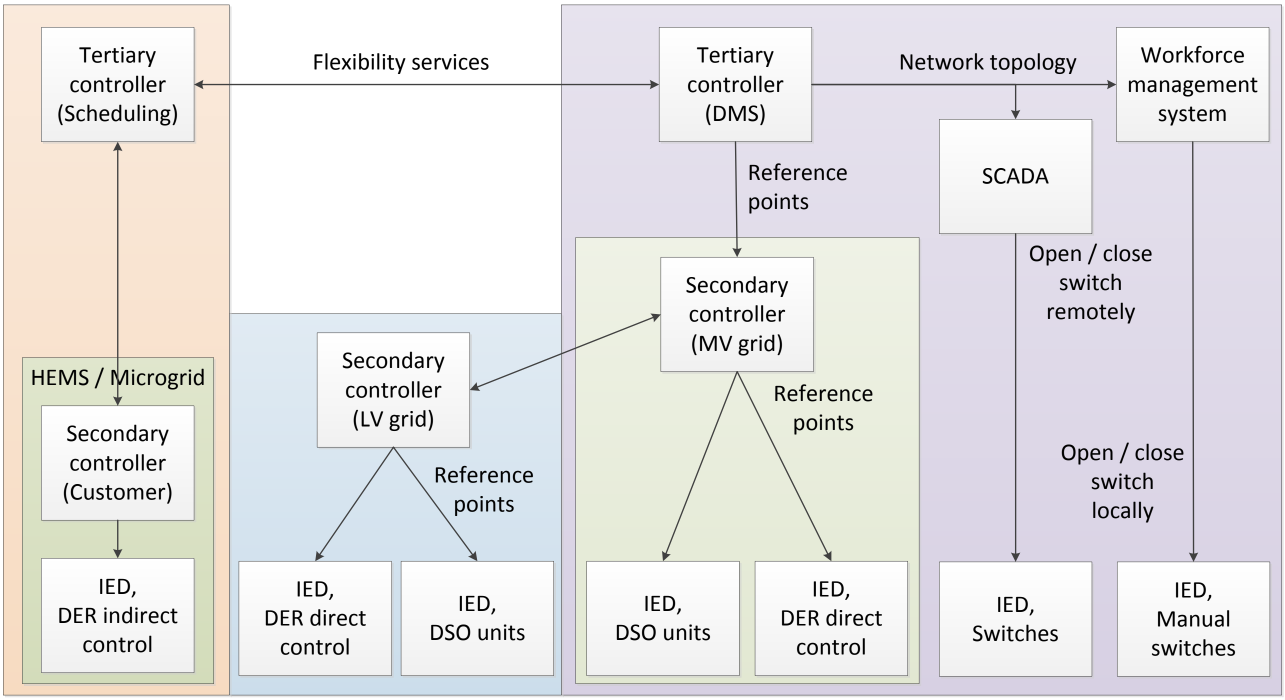

Figure 7. Hierarchy of controllers. (colours indicate control areas)

Secondary controller addressing power flow and voltage control may enhance the network hosting capacity for DERs compared to primary voltage control schemes [28]. Secondary controller is running in real-time and it is based on optimal power flow to define set points for primary controllers to minimize operational

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costs like losses, production curtailment and demand response. As an input it needs the state estimation of the control area.

Tertiary controller manages the TSO-DSO interface and medium voltage grid and it is running both day-ahead and real-time. First of all, the tertiary controller calculates dynamic grid tariffs to be introduced for commercial aggregators and retailers to prevent congestion conditions before day-ahead market closing. If dynamic grid tariffs are now allowed by regulator, this step may be left out from tertiary controller. Secondly, the tertiary controller takes responsibility to validate network acceptance for flexibility service actions of commercial aggregators within DSO's network, and to purchase flexibility services if needed to solve congestion (market agent algorithm). Tertiary controller is also planning the optimal network topology (network reconfiguration) for the next day while considering boundary conditions between control areas and forecasted states of the network to prevent congestion (network reconfiguration algorithm). In real-time mode the network reconfiguration algorithm is supporting FLISR functionality by acting as slow restoration functionality after fast FLISR in order to enlarge the restoration area. In addition to the main algorithms mentioned above, the tertiary controller, also contain a state estimator and a forecaster to provide states and forecasts as inputs for the other algorithms.

The main duties of the tertiary controller are as mentioned below:

1. Calculating a new dynamic tariff based on day ahead forecasts and sending it to all retailors in the network (Dynamic grid tariff algorithm)
2. Solving congestions by purchasing flexibility products through the flexibility market and aggregators (Market agent algorithm)
3. Finding the optimal configuration of the medium voltage network (network reconfiguration algorithm)
4. Operating as a slow restoration functionality which operates as a backup for the FLISR system that performs fast restoration actions (network reconfiguration algorithm)
5. Solving real time congestions at the medium voltage networks by reconfiguring the network (network reconfiguration algorithm)

Details and thorough explanations of the secondary and tertiary controllers and the operation of all of their functionalities are given in [9].

Commercial aggregator scheduling

Optimal scheduling of flexibility is a tool utilized by commercial aggregator. The aim of the tool is to maximize the profit of aggregator and to determine market bids within given constraints like customer comfort limits and available capacity of distribution grid. The implementation of the aggregator concept and optimal scheduling will lead to an increased percentage utilization of electricity network components, a substantial reduction in CO2 emissions, a reduction of RES curtailment, a reduction of technical network losses together with a peak demand reduction ratio. [10,13]

The two main features of the aggregator have been developed within IDE4L project:

- Day ahead scheduling and operation tools
- Real time algorithms

For the day ahead operation of the aggregator, several modules have been developed that work as one business tool.

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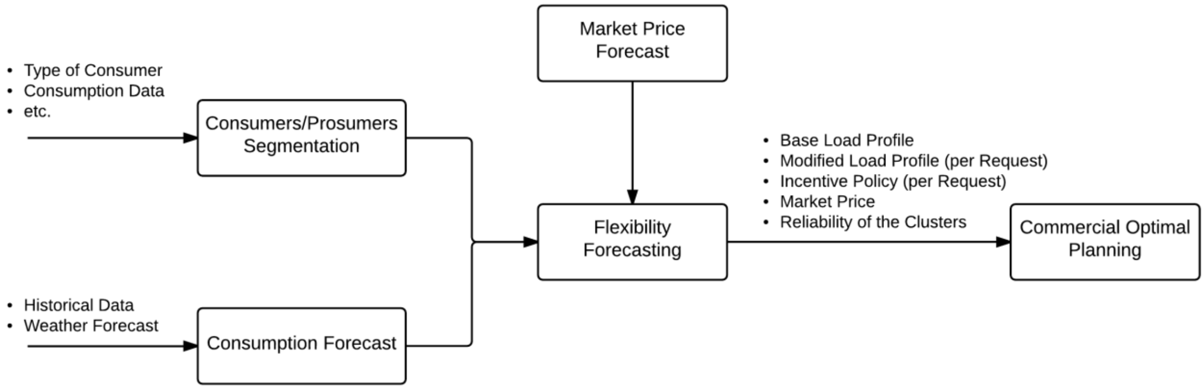

Figure 8. The different modules of the Commercial Aggregators.

The Commercial Aggregator Architecture consists of the following modules:

- Consumption Forecasting
- Consumer Segmentation (Clustering)
- The Flexibility Forecast Tool
- Market Forecasting
- The Commercial Optimal Planning Tool

Within the scope of this project, Flexibility Forecast Tool and the Commercial Optimal Planning Tool have been further developed. Main reasoning behind is the high impact they have in relation to the rest of the project, as well as the fact that they have been identified as key further research topics in previous EC founded projects. The other functions (Consumption Forecasting, Consumer Segmentation and Market Forecasting) have been implemented following the algorithms proposed in ADDRESS Project.

The Flexibility Forecast Tool: main objective of the flexibility forecast module is to estimate the available flexibility of every cluster, upon the different price signals. This is achieved by forecasting the response of the consumers to these price signals. The following steps are followed:

1. The EMS calculates the load profile of the prosumer when no incentives are applied.
2. Sensitivity analysis procedure is included in order to investigate prosumer's responses to several price incentives, improving commercial aggregator's portfolio optimization.
3. Afterwards, every load profile (corresponding to a price signal) is compared to the base load profile, i.e. to the initial load profile, where no incentive is sent by the CA. This comparison gives an estimation of the achieved re-profiling of the average prosumer, which is in fact the available flexibility.

The Commercial Optimal Planning: decision making module of the Commercial Aggregator when dealing with wholesale markets participation.

In the Real Time tools, the algorithms run by aggregator to activate and validate flexibility of DERs have been developed. The schema for the aggregator prosumer's flexibility activation algorithm is:

1. Order of flexibility activation
2. Status request (baseline + available flexibility) and operational status return
3. Allocation of flexibility volume among DERs proportional to their available amounts
4. DERs' activation

5. Activation confirmation
6. Energy measurements (request and return)
7. Modification of flexibility volume target for remaining activation period and re-allocation of set points among DERs
8. Sending of modified control set points

Each of these steps have been developed, programmed and tested within IDE4L lab testing.

Interference of use cases

The use cases are interdependent, in that they exchange data and take actions that other use cases have to cope with. As a consequence, use case “interfere”. The coordination of control use cases, from a conceptual viewpoint, is realized through a primary-secondary-tertiary scheme and control areas. The monitoring use cases interfere with control use cases by providing current and forecasted data. The way of interfere of these two groups of use cases defines most of the data exchange requirements in the architecture design.

Figure 9 presents the detailed description of interferences between hierarchical levels of the control system and functioning of grid management in different time frames (day-ahead, intra-hour, and real-time). Tertiary controller is indicated by dark blue colour and consists of dynamic grid tariff calculation, off-line validation (network reconfiguration and market agent), slow restoration (real-time implementation of network reconfiguration), and real-time validation. Secondary control is indicated by light blue colour and consists of secondary power control, Block OLTC of Transformers and power control parameter update. Primary controllers are indicated by white colour. Figure includes also supporting functionalities like forecasting (orange), monitoring/estimation (green) and market functionalities (purple).

Day-ahead hourly forecasts of load demand and production are fed in tariff calculation and off-line validation. Dynamic grid tariffs are published for all commercial aggregators to intensifying for load shifting from network peak to off-peak hours [9]. After the day-ahead market bidding process, DSO will validate if proposed schedules of all market parties for load demand and production will fit in local distribution network constraints. If congestion does not exist then market may be closed, otherwise the tertiary controller will try to mitigate congestion by reconfiguring the network or requesting help from market agent to seek for the cheapest solution by means of rejecting/activating Scheduled ReProfilings (SRPs) and/or Conditional ReProfilings (CRPs) from the market and/or from bilateral contracts (direct control of DERs). SRP services may be purchased from day-ahead energy market but also from other markets like intra-day or intra-hour markets. CRP is purchased from flexibility market.

Intra-hour time frame links day-ahead decisions to real-time frame. Power control parameter update functionality modifies the cost parameters of optimal power flow within real-time secondary controllers in order to adapt them to changes in forecasted network state and in MV network topology.

Real-time follows similar structure as previous time frames except real-time monitoring is utilized instead of forecasting. State estimation provides necessary inputs for the real-time secondary controller. The State estimation utilizes in addition to real-time measurements customer specific load and production forecasts and customer group based load profiles as pseudo measurements to enhance the observability of the network.

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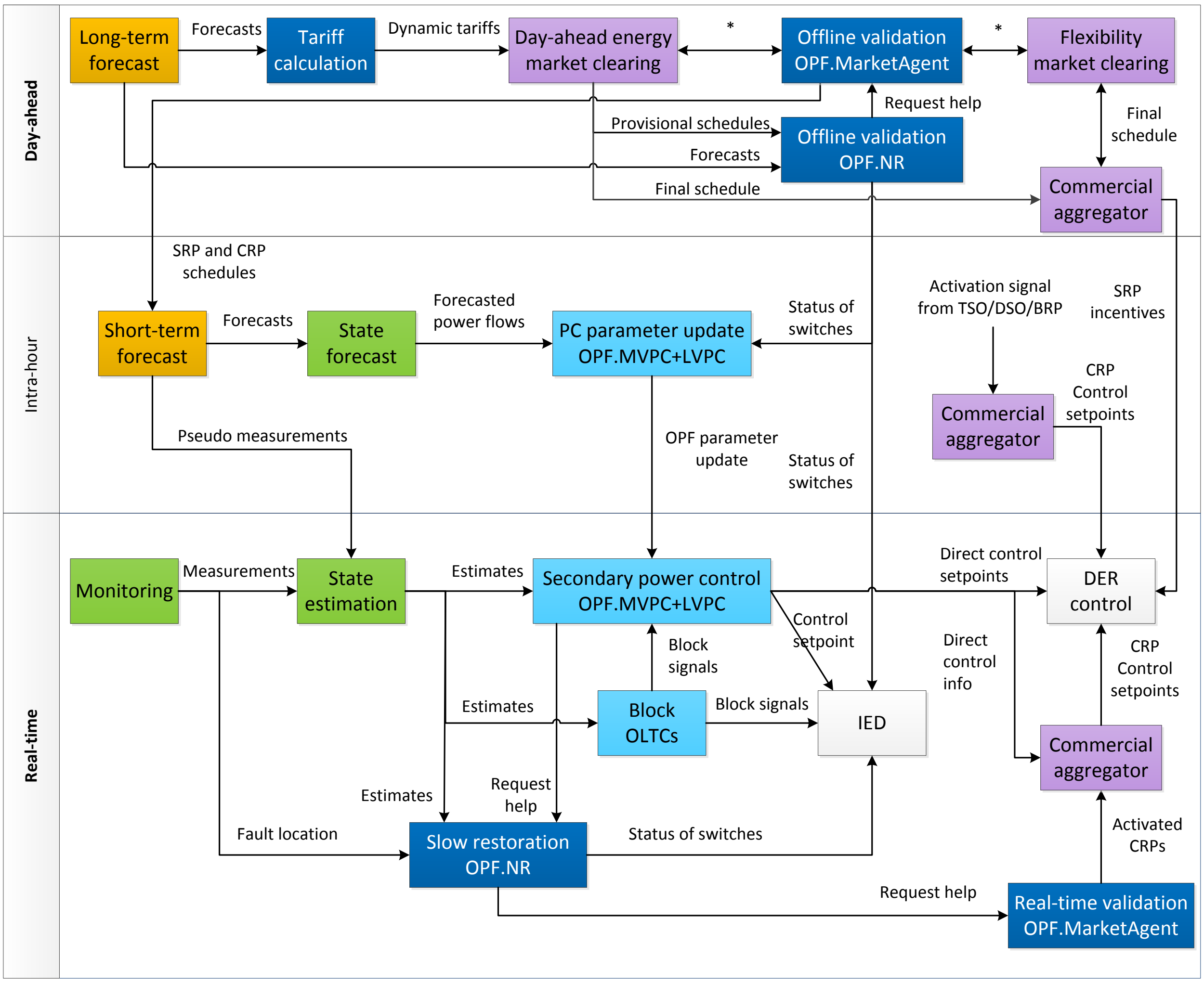

Figure 9. Interferences of congestion management.

The secondary control is focusing on coordination of voltage controllers which are under direct control of DSO and to minimize the amount of production curtailment or load control needed in the control area. Therefore, the secondary controller is adjusting settings of two different kinds of primary controllers: IED and DER control. IED includes e.g. Automatic Voltage Controller (AVC) of OLTC and Automatic Voltage Regulator (AVR) of dSTATCOM both owned by DSO. DER control includes both the contracted control and the emergency control of DERs. Contracted control includes e.g. AVR of DG or production curtailment in case of non-firm connection contract. Secondary controller will also inform commercial aggregator in case of emergency control of DERs. Block OLTC is coordinating the functioning of real-time secondary controllers and AVC of OLTCs when two or more OLTCs are operated in cascade and AVC delay grading is not efficient enough method from voltage quality viewpoint. [9]

Real-time secondary controllers may also request help from the tertiary controller to solve the congestion. Slow restoration will reconfigure the network and if this is not enough, then the real-time validation is requested. Optimal power flow of market agent is activated to activate already procured CRPs, and to refuse/curtail new CRPs requested to be activated by third parties. If a fault has occurred, then the slow restoration is activated to isolate fault and restore supply.

The benefit of integrating day-ahead, intra-hour and real-time scales consists of minimizing the unanticipated interventions on the more demanding real-time scale, exploiting at best all available

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knowledge of the system state and evolution, being able to accommodate business and technical interactions on very different time scales.

Power quality enhancement

Improved microgrid operation is performed by active filter including storage element and by improved droop control. Active filter aims to improve power quality (harmonics, flicker, etc.) to facilitate increased hosting capacity for DERs, to prevent the lifetime reduction of sensible equipment, and to ensure the constancy of the voltage and frequency. The storage element of active filter permits to perform an excellent filtering of both active and reactive fluctuating power components from RES. The developed droop control enables microgrid island operation with only RESs connected through power electronics. [7]

Distribution network design

Target network and expansion planning is the processes to plan grid infrastructure and ANM investments for forecasted needs of customers in the long run. The target network is the optimal grid designed for green field condition i.e. for long term scenario where complete network has to be replaced. Expansion planning decides the optimal path from the existing grid to the target network. The aim of both planning tasks is to minimize the costs of network infrastructure and ANM investments without compromising service level. The novelty of the methods is the inclusion of smart functionalities of ANM (congestion management and flexibility scheduling) as part of network planning. The benefits of smart functionalities are to replace or postpone some passive network investments with smart functionalities. [12]

Operational planning includes the design of congestion management methods aimed at optimizing the use of the existing grid and reducing the need for grid reinforcements, and making use of the flexibility services provided by DERs. These congestion management tools will be used by the DSO. The contribution in this point will be centred on the optimal scheduling of flexible DERs (RES but also other generation technologies, demand response and storage devices) taking into account the uncertainties of different forecasts. [12]

DSO/TSO information exchange

Phasor measurement units located in distribution grids provide valuable information for a TSO to determine real-time and adaptive reduced models of active distribution networks for transmission system management. This helps TSO determine reduced models more accurately and to include complexities and interdependences between transmission and distribution systems. [6]

To facilitate adequate technical functioning of the overall electrical system, the interactions between the technical operation of distribution networks and the main transmission network requires to “exchange information” that can help in the technical functions that are the responsibility of the operators of each of these networks. As of today, there it is challenging for DSOs to provide and maintain a network model of their electrical grid, which if constantly updated, could help in extracting key information about the network’s operation. In addition, DSOs currently do not have access to nor exchange (between DSOs and with TSOs) much measurement data, and if they do, very little (or non) of these measurements are shared in hard real-time, high sampling resolution and time-synchronization. This means that the measurement data available is too limited in quantity (i.e. locations and signals), and also in “observability” (i.e. the content of the frequency spectrum available, sampling resolution).

Therefore, in the current situation, a short-term solution to enhance "information exchange" would be to make new measurement devices that provide real-time, high-sampled data across operational boundaries from which information can be extracted. To this end, the work within the IDE4L project considered the utilization of synchronized phasor measurements with millisecond resolution, that is, real-time data from PMUs (Phasor Measurement Units). The choice of PMUs is only because they have recently seen an explosion in adoption in transmission networks, although, mainly in North America [29].

IDE4L answers the following questions, for which, methods were formulated and their associated prototype implementations were tested in the laboratory:

- How should PMU data from the DSO be treated to be used in "steady-state" computations (e.g. such as fault studies)?
  - By extracting the different time-scale behaviour from the measurement data, see our results in [30].
- How to improve the representation "modelling" of the distribution network for monitoring and "steady-state" computations by a TSO?
  - By obtaining an equivalent model of the distribution network, see our results in [31].
- How to perform real-time monitoring of DSO feeders and exploit Dynamic Line Rating at the distribution level for both TSO and DSO operations?
  - By developing a Dynamic Line Rating method for distribution feeders, see [32].
- How to extract information about the "dynamics" of the distribution network that allow both TSO and DSOs gain real-time awareness of the stability of the distribution network?
  - By developing a method and tools for centralized and de-centralized small-signal oscillation detection, see [33].
  - By developing a method for voltage stability assessment that allows to quantitatively determine how voltage-stable the DSO or TSO network are, individually, and how each contribute to the stability of the whole system together [34].

In addition, the work carried out in IDE4L shows that accurate time-synchronization is paramount for the use of PMU data in the different applications discussed above, which use PMU measurements as input. Hence, one key recommendation from IDE4L is to support work to move forward to the adoption of the IEEE 1588 standard for time-synchronization in embedded devices (i.e. PMUs, and other control and protection equipment); to directly support the development, implementation and the use of the IEEE/IEC 61850-90-5 for both data and time synchronization data transfer.

PMUs are not yet readily available in most distribution networks, however this trend will change with recent demonstration advances in Europe [35] and North America [36]. In this context, IDE4L makes two major contributions in this field that will help in PMU adoption and utilization in MV & LV networks:

- Highlight the added value of the use of PMUs for TSO/DSO and inter-TSO-DSO operations by proposing several PMU applications (to be used as the basis for Use Cases and Business Cases by DSOs).
- Proposing an implementation of the latest IEC 61850-90-5 protocol for synchrophasor data transfer, that will be released as open source software, that can be used to support interoperability and facilitating market access to new integrators or hardware providers [37].

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Demonstrations

IDE4L demonstration has been achieved through a set of demonstrators: 6 lab demonstrators and 3 field demonstrators (Figure 2). The following three subsection report further details about the three field demos.

Oestkraft demo site

Oestkraft (OST) demo site is located on the Northern part of Bornholm Island, Denmark, in a residential area in the village Tejn. It consists of two secondary 10/0.4 kV substations (namely no. 29 and no. 370) and a Low Voltage (LV) network. The network consists of four LV lines with 126 customers. This area has been selected because of the relatively high percentage of customers with heat pumps and PV panels.

In this area, 12 smart meters have been connected using a GPRS communication technology and transmit data every 15 minutes with a resolution of 5 minutes. Additionally, the remaining 114 smart meters use a Power Line Communication (PLC) technology and transmit data every 2 hours with a 5-minute resolution. The data from the meters are collected once a day.

The Medium Voltage (MV) network is composed of one MV/MV (60/10 kV) substation, one MV line (No. 7) and 18 MV/LV (10/0.4) kV substations. Two MV/LV substations (namely no. 29 and no. 122) have been fully automated with IED for monitoring, control, and protection. To enable MV automation, an Ethernet/IP network has been implemented by using optical fibres.

Unareti demo site

Unareti's (UNR) field demonstrator is located in the city of Brescia, Italy, in a district called "*Il Violino*". This district was recently designed to promote an eco-compatible life-style: it is characterized by a high percentage of customers equipped with PV panels, which is about 40 % of the total peak power demand, and using a district heating system.

The LV field demonstrator consists of the whole LV network of a MV/LV substation, which has – in total – 10 LV lines and feeds 294 customers, mainly residential ones. Out of all the nodes of the network, 45 (belonging to six out of the ten LV lines) have been equipped with a new generation of smart meters, for a total of 60 meters that are able to monitor in real-time a wide set of electric parameters of customers and PV units. Moreover, also six new PV inverters have been installed for voltage and power regulations. For communication purposes, a Broadband Power Line (BPL) over LV cables communication system has been used.

The MV network demonstrator consists in 1 MV/MV substation, 3 MV lines, 40 MV/LV substations and 9 MV customers. Out of the three MV lines, two have been fully automated with monitoring, control, and protection systems, while the third one has been mainly involved in simulations and for the LV field trial. To enable the MV automation services, a proper communication network has been implemented by using a mix of technologies, specifically optical fibres, broadband power line over MV cables and Wi-Fi.

Unión Fenosa Distribución demo site

Unión Fenosa Distribución (UFD) demo site is located in the headquarters of Antonio Lopez Street in Madrid, Spain. It consists of a LV network connected to a MV line fed by the primary substation 'Puente Princesa'. The substation is located on the southern edge of Manzanares River, close to the street, and it shares the facilities of the University Corporate Company and offices of the high-voltage network operation.

UFD low voltage demo site has different facilities connected (already existing before the project) such as amorphous photovoltaic installation (10 kW), monocrystalline photovoltaic installation (20 kW), polycrystalline photovoltaic installation (20 kW), gas generator (5.5 kW), wind turbine (3.5 kW), two 3-phase

EV chargers and a meteorological station. Most of these installations have a smart meter connected, and all PV generators have controllable inverters.

What was realized and why was realized

In the three field demos, only some use cases have been tested. Figure 10 depicts – through a simplified version of the control hierarchy defined by IDE4L – the components include in the demonstrations. The reason why those components have been selected is they constitute together two very important business cases:

- Congestion management business case, where:
  - a portion of the network is monitored by collecting data from IEDs (monitoring use case),
  - its status is determined through a state estimation algorithm (state estimation use case),
  - pseudo-measurements are sent to the state estimator based on a forecast of load and production profiles (load and production forecast use case),
  - in case that forecast is missing, fixed profiles are used as a back-up input (not a use case),
  - eventually, the network performance is optimized by the secondary (power) controller, issuing set point to IEDs.
- The Fault Location Isolation and Service Restoration, where IEDs are communicating based on a peer-to-peer paradigm in order to solve clear faults on the network.

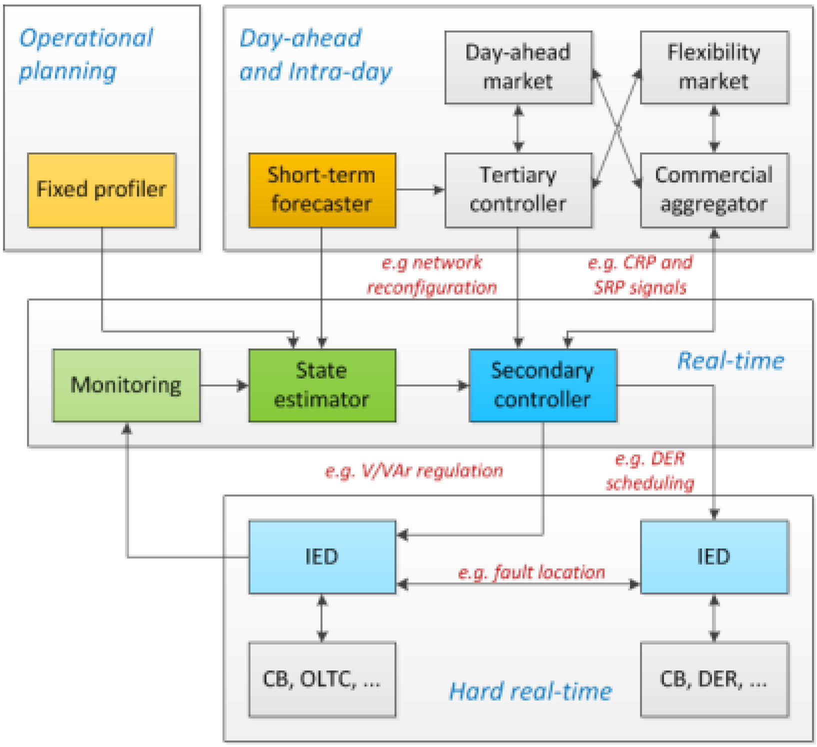

Figure 10: Simplified control hierarchy, with the emphasis on the components tested in field demonstrators.

For the sake of simplicity, Table 1 reports the mapping between the use cases tested in the project and the demo\lab site where the test has been performed. Laboratory demonstration sites are Tampere University of Technology (TUT), RWTH Aachen University (RWTH), and Schneider Electrics Electrics (SCH).

Table 1: Use cases vs. demonstrators mapping.

Use Case	TUT	RWTH	SCH	UFD	OST	UNR

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MV Load and Production Forecast		x				
MV power control in Real Time operation	x	x				
Decentralized FLISR	x		x		x	x
LV Load and Production Forecast	x	x		x	x	x
LV State Estimation	x	x		x	x	x
LV power control in Real Time operation	x	x				x

Conclusions of demonstration use cases

The low voltage load and production forecast demonstrations were successfully finalized in the IDE4L experimental campaigns, as well as in lab sites, that proved that the proposed algorithm works even if its performance may differ depending on the conditions of use. On one hand, the load forecast turned out to be quite accurate and consistent across demo sites. On the other hand, the generation forecast showed less accurate and consistent solutions, due to the volatility of renewable generation plants and to their dependency on weather forecast, thus emphasizing the need for a more advanced and customized algorithm to predict the production of these kinds of sources. Finally, demonstration results showed that for both loads and generations, the algorithm is very consistent in predicting power\energy data over a one day-horizon since no major degradation was found in increasing the forecast horizon.

The demonstration of low voltage network state estimation proved to be more difficult than expected. Problems in monitoring were frequent and since the state estimator relies heavily on input measurements, the state estimator performance was often affected by issues in the monitoring systems. As learned from demonstrations, a bombproof backup solution should always be available to overcome potential problems coming from missing measurements. In UNR site, fixed load profiles were indeed available for all individual load and generation points through an algorithm specifically designed and developed for this site. Despite several challenges, the low voltage network state estimation demonstrations were finalized and it was proven that the developed state estimation algorithm works quite properly and provides an improved view to the state of the network.

The demonstration results confirm that the proposed and implemented secondary controller for congestion management operates in all the demonstration cases as expected and that no adverse time domain operation occurs. The same controller is able to operate for medium and low voltage grids. Also, the results show that the algorithm is able to improve the defined KPIs in all the demo cases. In general terms, it can be said that the weaker the network and the larger the amount of generation connected to it, the larger the benefits of the secondary controller. The annual benefits of secondary controller have been evaluated in [7,38] which show that the secondary controller is able to both prevent voltage and current congestions and to decrease the annual network losses. The integration of medium voltage secondary controller and low voltage secondary controller was also effective and resulted as correct operation interactions of medium voltage and low voltage secondary controllers. Graded time delays of the AVC relays seem to be an adequate measure to prevent back-and-worth operations of control in most of the cases.

The FLISR solution proposed in IDE4L is a distributed solution based on IEC 61850 GOOSE communication between IEDs deployed along the distribution network, on processed local measurements and on a logic selectivity that depends also on the switching technology available at each secondary substation. This kind of implementation has shown to be able to completely isolate faults in less than 2 seconds (with time settings selected for SCH demo site) at the same time that the number of customers that are affected by momentary interruptions are reduced. The deployment of circuit breakers along the medium voltage feeders allows reducing considerably the average interruption duration experienced by customers. Each circuit breaker will further reduce the average interruption duration when decentralized FLISR ensures selectivity. SAIFI and Breaker Energized Operations also show better results for IDE4L solution, being even more effective in those cases where second isolation step is also performed for those secondary substation that have not been provided with circuit breakers.

Final conclusions

Based on three successful field and six laboratory demonstrations we may conclude that the proposed concepts, automation architecture and functionalities work as expected. The following paragraphs highlight the general conclusions of IDE4L project demonstrations.

Basis for distributed grid management and interaction of business players

The IDE4L project has successfully designed, implemented and demonstrated concepts of active network management, hierarchical and distributed automation architecture and commercial aggregator to provide flexibility services for grid management. Implementations of concepts have been validated by successful demonstrations in integration laboratories and field.

Efficient utilization of grid assets

The IDE4L concepts and technical solutions extend the monitoring and control of the distribution grid to all voltage levels, increase the distribution grid hosting capacity for RESs and DERs, and enhance the reliability of power supply. The improvement of the quality of supply and the management of network outages are based on decentralized FLISR, which significantly reduces the number of customers experiencing an outage and speed up supply restoration to other customers compared to traditional manual or partly automated solutions. Both the hosting capacity increment and the quality of supply enhancement will have a positive effect on social acceptance of the network infrastructure and the RESs.

More hosting capacity will help the integration of a larger share of RESs into medium and low voltage distribution grids, thus supporting Europe’s 20-20-20 targets. Also, it may enable postponing new network reinforcements. Secondary and tertiary controllers of congestion management are the key components for the increment of distribution grid hosting capacity. The increment depends on the grid itself and the control possibilities of DERs and flexibility services. Planning tools developed in the project are able to estimate the hosting capacity increment in different conditions.

Scalability of automation solution

The hierarchical and distributed automation architecture designed and validated in the IDE4L project is based on existing devices, protocols and interfaces, which will allow DSOs to gradually deploy the new solutions. Furthermore, the same architecture and cores of the automation are suitable for both primary and secondary substations. Monitoring, control and protection functions can be deployed locally in the substations, and can operate in a coordinated manner thanks to the IDE4L architecture. This fine granularity makes the individual local functions light, and the design of the architecture makes their integration highly scalable. Vertical and horizontal integration provides a complete view of the distribution network status. This yields business benefits in the short run, without demanding a total replacement of the existing infrastructure, which would not be feasible.

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Data exchange between DSO and aggregator, merging information about DERs (validating flexibility actions) and controlling them (purchasing and activating flexibilities), will further extend ANM capabilities of DSO from distribution network to DERs and flexibility services provided by aggregators.

Replicability of solutions in other EU member states

The three DSOs partners of IDE4L represent urban and rural networks in different parts and countries of Europe. Demonstration grids also include relatively high penetration of RESs connected to low voltage grid. The same IDE4L automation system was implemented in all field demonstration sites. Results prove it effective in the different configurations (functionalities chosen by the DSO) and hardware implementations that were tested. Because the IDE4L solutions work in this variety of conditions, they are expected to be suitable for most of the EU.

However, network regulation and energy market rules are also different in each country. Whereas not all the developments may currently be deployed everywhere, the IDE4L demonstrations are not tailored to individual DSOs but rather represent general solutions, i.e. replication is already considered in the solutions.

Finally, the IDE4L concepts of active network management, automation and commercial aggregator have been influenced by all project partners and members of the advisory board, spanning all in all 12 EU member countries.

Benefits of proposed solutions

The solutions of IDE4L empower the DSOs to undertake the modernization of distribution grids based on proven technologies. They don't have to devise themselves the right framework that is suitable for initial small scale deployment and that supports future expansions. IDE4L provides this framework, and the means to implement it, down to the individual algorithms and communications. In particular, IDE4L's benefits include:

- The support to realizing the automation and modernization of distribution grids, thanks to a reference, validated concepts, architecture and functionalities
- The availability of a solid base of critical monitoring and control algorithms, readily available and validated to work with the architecture, on top of which more can be built
- Planning tools that include the automation as an asset and a way to evaluate technical and economic benefits of proposed automation solutions in addition to traditional grid reinforcement actions
- The detailed schema to interface the commercial aggregator to validate market based flexibility services and to purchase flexibility services for active network management

Utilization and development of standards

The IDE4L project has utilized international information model and interface standards (IEC61850, DLMS/COSEM (IEC 62056) and CIM (IEC 61970/61968)) for the design of the automation architecture and the implementation of devices and interfaces (FLISR IED, SAU and PMU) and all demonstrations. Most of the implementations are based on existing standards, only the implementation of decentralized FLISR have required utilization of draft standards and have also provided feedback for the standardization working group. Concepts and implementations have been proved to be interoperable and scalable.

The interoperability has been achieved in IDE4L through:

1. Identification of interfaces and information exchange synthesized from the IDE4L use cases of advanced distribution automation concept for active distribution networks. The automation architecture was hence derived and defined based on the SGAM framework.
2. Implementation of interfaces and messaging has been realized based on above standards and off-the-shelf products. Pre-deployment interoperability of the automation system has been validated with hardware- and software-in-the-loop simulations and integration laboratory tests. Different installations of real time simulator RTDS, grid and DER emulators, real and emulated IEDs, prototype implementations of the IDE4L SAU have been used for the purpose. The same testing set ups, augmented to integrate full IDE4L functionalities, have been used to investigate scenarios which cannot be realize in the demonstrations.

The applications of active network management and the implementations of the IDE4L automation system have been demonstrated in three demonstration sites in Denmark (Ostkraft), Italy (Unareti) and Spain (Unión Fenosa Distribución). The automation system in the field demonstrations has been exactly the same as the one validated in the interoperability testing.

4. Potential impact and main dissemination activities and exploitation results

Potential impact

Extended real time monitoring

IDE4L automation system extents real-time monitoring deep into MV and LV networks and enable DER control directly or indirectly via aggregator for distribution network management. Therefore, the automation system is the backbone of all technical solutions and they enable supervision and management of active distribution network to enable reverse power flows and utilization of DERs in network management.

The Substation Automation Unit (SAU) is the core of the hierarchical/distributed IDE4L architecture. The SAU, installed in the substations, conceptually identical in primary and secondary substations, realizes the local and remote monitoring and coordination of resources. Its definition in terms of interfaces, functions and database makes the SAU adaptable, it can be implemented with a subset of features, which are easy to extract from the general model, and as such it can be supported by hardware with very different performance characteristics. The SAU was designed for substation automation for distribution, and was not adapted from hardware and software solutions developed for the much more automated transmission networks. As such it is naturally slim, and scalable. Its computation and communication requirements can be modulated to meet specific needs, thus avoiding over-design. The SAU can be exploited for measurement and control devices that are already installed in the field, thus reducing the investment for automation upgrade.

The SAU may reduce the burden for computation, data storage and information exchange of the Distribution Management System (DMS), thanks to the local data processing and control. It may also speed up coordination/optimization of control actions and extend the monitoring and control of distribution network to every corner of medium and low voltage networks when compared to traditional control centre solutions.

The decentralized applications are executed in the SAU device. The Real time monitoring application collects data from IEDs in the monitoring and control zone of SAU, stores the data in a local database for further use and for reporting of data, events and alarms to higher layers of distribution automation architecture. IEDs are all kind of available measurement units and sensors like protection relays, controllers, RTUs, PMUs, power quality monitoring units, smart meters, etc.

The load and production forecasting utilizing real time monitoring and weather data, provides a short-term view of loading and production condition for state estimation. State estimation computes the grid quantities based on monitoring and forecasted data and grid model. State estimation provide system wide view without requirement of real-time measurements every corner of the system. It may also reduce the communication requirements by detecting bad monitoring data and estimating missing data. Smart meter off-line data is also essential to compute accurate enough load profiles for prosumers to be used as pseudo measurements in state estimation.

IDE4L has delivered feasible and proven technical solutions for real time congestion management in medium and low voltage grids. It is realized by primary and secondary control schemes. Primary control like voltage control of tap changer is based on local measurements and may operate extremely fast, but it is lacking information about the complete system. The objective of secondary control is to coordinate primary controllers (including DER controls like load shedding, production curtailment or utilization of energy storage) in the network area to minimize operational costs within technical constraints. The secondary controller is located in SAU.

The distribution of applications to primary and secondary SAUs allows utilization of real time data from a complete grid. This will enhance distribution grid observability and controllability compared to existing centralized systems. Scalability of applications is also enhanced because single application is responsible for a rather small grid area and therefore the computation performance of algorithms is not a limiting factor. Applications may also be re-used in all layers: DMS, primary SAU and secondary SAU. The modular structure of SAU allows replacing applications when needed because they are completely independent of the implementation of SAU interfaces.

Real time monitoring is a basis for the rest of applications and it extends real time monitoring to the complete grid without overloading centralized SCADA/DMS systems. It does not need to have IEDs in all grid nodes because state estimation is able to provide accurate enough data when real time measurements are correctly selected and reading frequency and data resolution are high enough. State estimation is also enhancing the accuracy of monitoring by correcting erroneous and missing data.

Increment of hosting capacity for RESs

Coordination of controllers provides significant enhancement for distribution network hosting capacity compared to passive network and primary control and operates in different time frames. Passive approaches can lead to high connection cost of DERs.

Congestion management scheme developed in the IDE4L project will allow the DSO to manage congestion and control voltage at minimum costs (reduced losses, production curtailment and outage times) by allowing a higher penetration of distributed generation with less network investments. Moreover, using system flexibility services for voltage control and congestion management could further enhance the benefits for the DSOs.

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New regulatory frameworks should include mechanisms that both allow DSOs to procure system flexibility services and to recover their cost. European Network Codes, such as Demand Connection, Operational Security and Electricity Balancing should not hinder the use of system flexibility services at distribution level.

One major result of IDE4L is the improved network management through the use of control system designed to operate with high penetration of DER and capable of using market based flexibility services. Tertiary control of congestion management is located in the control centre (DMS) and its main tasks are to verify the state of the medium voltage network, set the topology of the entire network, coordinate secondary controllers and order flexibility services from Aggregator to minimize operational costs within a given voltage range and component ratings. The tertiary control will evaluate the current and future states of the network by using the data series provided by the state estimator/forecaster. Day-ahead rescheduling of controllable loads (demand response), production units and storage devices by technical aggregator may be realized by utilizing smart metering infrastructure, home and building automation systems or micro-grid management system. The aim of the secondary controller is to enhance the hosting capacity of distribution grid for DERs in real-time by optimizing the setting points of primary controllers (DSO's resources and DERs under direct control of DSO) within a control area. Case studies have shown that the hosting capacity for distributed generation connected into a weak medium voltage grid may increase three times compared to a passive network solution and more than two times compared to a primary control scheme. The following figure indicates clearly how much the total annual operation costs of producer and DSO will reduce by applying secondary control compared to decentralized voltage control (primary control) and reference cases having a fixed DG unit power factors. The major cost components realizing the reduction of total operation cost is the DG unit lost revenue due to production curtailment when distribution network hosting capacity is not high enough.

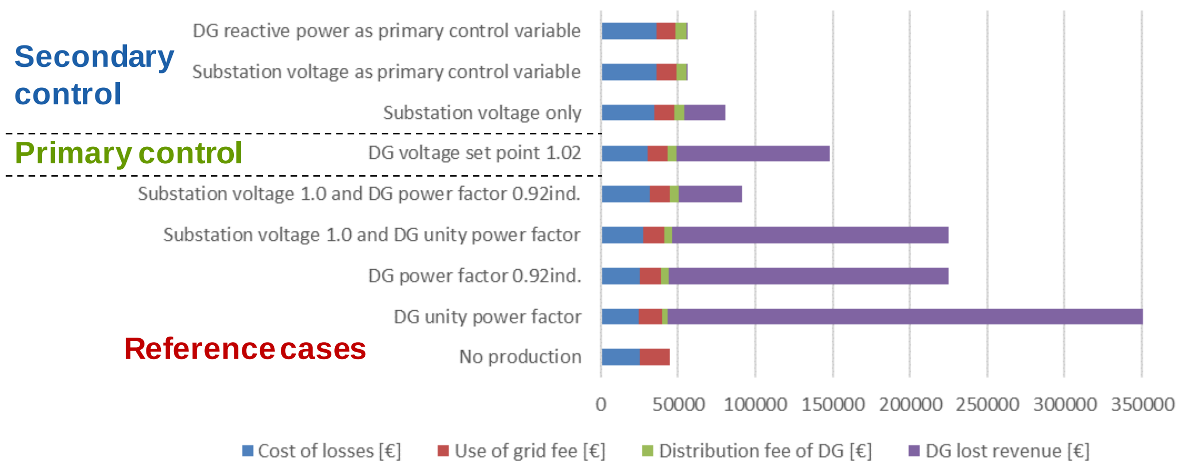

Figure 11. Costs comparison of congestion management in weak medium voltage grid [38].

The proposed solution will not be implemented as a standard or an alternative solution to passive network reinforcement unless grid regulation allows DSOs to include congestion management investments as part of grid assets or service quality which define how much profit the DSO may make. The value of congestion management from the grid regulation perspective should be somehow comparable to passive network reinforcement, or otherwise profit maximizing DSOs will always invest in passive solutions. Similarly, the increased operational cost of congestion management compared to passive solution should not penalize

DSOs in grid regulation if the lifecycle costs of congestion management are cheaper than the total costs of the passive solution.

Continuity of service

Design and proof of concept of a decentralized Fault Location Isolation and Supply Restoration (FLISR) solution fully based on the IEC 61850 standard that allow very fast responses of the automation system to fault events. Additionally, a mechanism to change remotely GOOSE communication schema and protection settings has been developed, what makes possible to continue operating after network reconfiguration as the result of the restoration or congestion algorithms.

IDE4L FLISR solution relies on GOOSE interlocking messages that are used for the implementation of the two-step logic and chronometric selectivity schemas, and for the integration of the control functions for DER or microgrid connected to the medium voltage grid.

GOOSE interaction with FLISR IEDsalong MV lines allows the DER or microgrid controllers to manage connection or disconnection from the grid. Interlocking messages to be exchanged with DER or microgrid controllers depends on fault locations and actions being performed on circuit breakers or switches under control. Microgrids with DER are integrated with remote or local control based on interconnection switch, with appropriate fast and soft switching conditions according to interconnection switch requirements and, providing IEC 61850 connectivity with SAU. Local monitoring is included at the point of common coupling. In such points, power quality issues have been also implemented (power smoothing by storage elements due to i.e. flicker noise).

The use of IEC 61850, the global standard for communication in substations, applied to protection functions in medium voltage networks together with logic selectivity functionalities are far from a real deployment. Unareti’s medium voltage demonstration site is one of the first operating environment where the concept is tested. Real demonstration has allowed us to corroborate that the adoption of the IEC 61850 for IDE4L FLISR makes it easy to integrate into existing solutions in EU networks and to operate together with other third-parties IEC 61850 IEDs and functionalities.

The main limitation of FLISR solutions is that every time the grid changes, protection settings and logics are no longer valid. IDE4L proposes an adaptive FLISR solution where settings and GOOSE communication schemas can be adjusted to the network configuration and load currents, without interrupting operation. Solution is based on MMS communication with an IEC 61850 client.

IDE4L FLISR solution allows reducing the number of customers that experience power outages in the event of a fault and the isolation of the outage area in few seconds, thus reducing the duration of loss of load in comparison with traditional schemas where protection functions are only applied at primary substation and with logic selectivity where decisions are taken at control centre level.

Feeder automation functionalities are not currently included in the approved parts of the IEC 61850 standard, although some efforts are being performed. Missing functionalities have been identified and proposed through the National Standardization Committee for IEC TR 62689-100: *Requirements and proposals for IEC 61850 data model extensions to support Fault Passage Indicators applications*.

Grid planning and optimization

All demonstrated solutions have been evaluated by utilizing KPIs for business as usual solution and smart grid solution proposed by IDE4L project. KPIs indicate that distribution network technical performance may be enhanced by proposed solutions in the demonstration cases.

Smart grid technologies typically enhance distribution network operational performance like indicated by KPI evaluation. In order to understand if such technologies are also viable from network investment planning viewpoint, distribution network planning principles and algorithms were also developed and demonstrated by a case study. Target network and distribution network expansion planning algorithms are evaluating distribution network long-term investment strategies by considering capital and operational costs and comparing different investment options like passive and active network solutions, while defining the optimal target network and required investment steps towards that from existing network. These algorithms may be applied to study how much benefit smart grid solutions potentially could provide by postponing or replacing grid investments. Single and small-scale case study realized within the project is now enough to draw general conclusions about developed solutions from grid long-term development viewpoint. Case studies of FLISR, congestion management and aggregator scheduling however indicate that in proper conditions, the developed solutions may provide major technical and economic benefit for a DSO.

Major changes in distribution network design and regulation are however needed in order to realize the benefits of developed solutions. The worst case design principles used for passive distribution network to design firm network capacity for all customers, needs to be replaced with principles which consider stochastic behaviour of DERs and customers, and controllability of DERs. The utilization of non-firm network capacity will increase the hosting capacity of distribution network for RES and DER remarkably. However, DSOs do not have economic incentive to do that because network regulation typically favour capital investments instead of increment of operational costs. Shift from passive to active distribution network evidently decrease necessary capital costs but will increase operational costs while the utilization rate of grid assets is enhanced. Distribution network operational planning algorithm developed in the project help DSOs to analyse and schedule the utilization of flexibility from aggregated flexibility services.

In order to see remarkably higher utilization of smart grid solutions in distribution network domain, the network regulation needs to changed first. Motivation to enhance distribution network reliability already exists in several European countries through power quality regulation which allows making higher profit if reliability is enhanced or avoids penalties by exceeding reliability level defined by a network regulator.

Improvement of power quality

The automation architecture developed in the project allows also collection and analysis of real-time power quality data from all voltages levels of distribution grid by adding power quality monitoring units as part of automation system. This will further expand the real-time monitoring of power quality from primary substations to secondary substations or even beyond. With extended power quality monitoring DSO may detect power quality challenges before customer complains.

Improved microgrid operation may mitigate adverse impacts of RES and load demand for power quality. A power smoothing system composed of a storage device (supercapacitors) with a voltage control scheme has been tested to smoothen RES generation profile to smooth short-term power fluctuations of RES and to reduce flicker in the voltage supply of a weak grid. These power quality mitigation methods enhance voltage quality and therefore enable to increase hosting capacity for DERs.

Asset management and asset capital investment ramp down

Automation system and all congestion management functionalities developed in the project aims for postponing distribution grid reinforcement. Therefore, the aim is to utilize the existing grid assets more efficiently. In that kind of case, the monitoring and control functionalities are required to ensure secure operation of grid assets.

Demand side management and demand response

IDE4L automation system is able to utilize demand response in multiple ways. Direct load control may be applied for example is real-time secondary control of congestion management. However, the direct load control should not be utilized if other solution preferably market based solutions exists. Direct load control may be used as a backup emergency action if other solutions fail to solve the problem.

Commercial aggregator and flexibility market provide new opportunities for prosumers and DSO to benefit from demand response. Prosumers may benefit because an introduction of flexibility market to be utilized by DSO increase the demand response volumes (income of prosumers) and market actions are validated by DSO (distribution grid costs are not increased due to demand response). DSO may similarly benefit by validating market actions and purchasing flexibility services for network management, i.e. avoid network reinforcement or decreased quality of service. Commercial aggregator and flexibility market enable fully market based solution for the utilization of demand response for distribution network management. At the same time the same resources may be utilized for all other markets where demand response may participate. Comparing this solution to bilateral load control contract between DSO and prosumer, the proposed solution is much more efficient in economic terms. From DSO's technical perspective the capability of market based solution to provide necessary flexibility services where and when needed in practical cases requires further investigation.

DSOs will have to modify the way they operate by becoming more proactive. However, the implementation of technical solutions that permit this way of operation is limited by the lack of technical, economical and regulatory framework in several aspects, such as:

- Rules forbidding RES energy curtailment except for security issues so that the flexibility that these kinds of assets can provide is not utilized. DSOs should be capable of controlling the production, either by themselves or through third entities such as aggregators.
- Little/no incentives for smart grid solutions: DSOs are currently remunerated for reinforcing the network, so there is no immediate need for finding different solutions apart from reinforcements (i.e., smart grid solutions). In this sense, regulation linked to performance is a key element for the evolution of the smart grids.

Monitoring of distribution network dynamics

The increase of renewable generation sources in distribution grids creates more interactions between TSOs and DSOs. These interactions need to be monitored with measurement-based applications, and analyzed with models of the joint transmission and distribution system model.

The use of dynamic measurements (time series) from PMUs can be applied systematically to extract key information to be used in DMS functions and also to be sent to TSOs to be used in their operational functions. One crucial piece of information, which can be of immediate interest to exchange between DSOs and TSOs, is the equivalents of distribution network models. Using time-series from PMUs, equivalent models can be computed in near-real time which helps in understanding the strength and state of the distribution grid and consider the impact of these changes at TSO level.

Comparison to state-of-the-art

Today all automation systems like SCADA/DMS, monitoring solutions for secondary substations and automatic meter management (smart metering system) work as vertical solutions – each silo's to deal with a specific purpose - but they do not interoperate with one another to manage the overall complexity and the new tasks of future distribution networks.

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If commercial aggregators exist on electricity and flexibility market, they are taking care of the responsibilities of those markets. Because distribution level flexibility market is completely missing, there is no need and possibility to exchange information between aggregator and DSO. Although the congestion challenges in distribution grids originated due to aggregator intervention are extremely rare or completely non-existing. Similarly, the first data exchange platforms (data HUBs) for smart metering data has been build up, and therefore they don't represent the state-of-the-art.

ANM as a concept is a research or a demonstration topic at the moment. Close to 100 % distribution networks are designed and operated as passive networks. Several active network trials and demonstrations exists, but those are typically build due to research and development needs [23,24]. IDE4L field demonstrations belong to this category. Demonstrations are extremely important, but the roadmap from first demonstrations to business-as-usual solution may take several years or even decades due to very long lifetime of grid assets.

Similarly, the IDE4L automation solution is rather far ahead of the state-of-the-art solutions of distribution automation. First of all, majority of existing automation solutions are centralized and decisions are made in control centre in SCADA/DMS systems operated by human operators. These systems are designed to supervise and manage the distribution system from global perspective and to control primary substations and large-scale DERs. Therefore, the scalability of such system is not a big issue. Distribution grid management has two-level hierarchy: IEDs (protection and control units) and control centre systems, which makes the centralized management functionalities very dependent on communication. Key issues for such systems to enhance novel management functionalities are the software integration to merge information from SCADA/DMS and back-end systems like network information system, customer information system and meter data management system, and the quality of service of communication system.

Hierarchical and distributed automation solution proposed by the project consists of centralized and distributed elements. Centralized control centre system may continue operating like today even if large-scale and real-time management of LV grids are attached to automation solution. Three-level hierarchy allows to do automated decisions for dedicated grid area without interaction with control centre. Therefore, the proposed automation concept may solve global and local challenges simultaneously, and monitor, communicate and manage small-scale DERs and other resources without compromising the scalability of automation system in real-time. The system is dependent on communication, but it has been designed to tolerate reasonable disturbances in the communication system, i.e. communication requirements are less-demanding than in centralized solution. The automation system has especially been designed for novel concepts like active distribution network and microgrids. Management of information exchange and coordination of application performance between several hierarchical levels are the key issues for the proposed automation solution.

Although, from technical perspective the hierarchical and distributed automation solution would sound very natural choice for future active distribution network, the complexity increment of automation system would at least slow down the adaptation of existing system towards proposed solution. However, the modularity of proposed system in many levels allows utilization of specific elements and ideas where needed, and the complete system must not be built at once. All existing automation components may be re-used in the proposed solution and new components even with high frequency measurements may be included in the solution.

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Connections to national and European projects

SDG: used the LV monitoring use cases as starting point for IDE4L developments. SDG results and lessons learnt have been used as guidelines for the definition of IDE4L automation architecture (D3.1, D3.2) and the substation automation unit internal architecture. The Unareti LV demo site in IDE4L shares a section with SDG demonstrator, in particular the communication infrastructure and metering infrastructure in the residential area installed in SDG has been enlarged with new installations in IDE4L.

Integris : used the use cases and automation architecture as starting point (D3.1, D3.2) to develop the IDE4L use cases and architecture. Also the above used as reference to quantify the advancement of the IDE4L architecture with respect to state of the art solutions (D3.3)

EcoGrid EU: used the locational marginal pricing (LMP) based grid tariff concept for congestion management in real time market as the starting point. A quadratic formuation of determinging the LMP based grid was developed in the IDE4L project which can solve the multiple solution issue at the aggregators' decentralized optimization. It ensures that the centralized DSO optimization and the decentralized aggregator optimizations converge.

EDISON: used the driving pattern analysis results as the inputs for the aggregator based DER scheduling. It was incorporated in the quadratic programing based dynamic tariff algorithm.

National smart energy system programs Smart Grid and Energy Market (SGEM) and Flexible Energy systems (FLEXe) have utilized knowledge and implementations realized within IDE4L project and provided inputs for IDE4L project as well. Active network management using DERs and microgrids developed within SGEM program and INTEGRIS FP7 project was the starting point for ANM concept of the IDE4L project. Also the coordinated voltage control method developed within SGEM was extended to congestion management during IDE4L project. Off-line and real-time functional testing of congestion management algorithm (coordinated voltage control) was realized within SGEM. The role of FLEXe program was to cofinance the development of integration laboratory testing environment for non-functional testing of congestion management. Secondly the initial cyber security development and real-time testing of FLISR solution developed in IDE4L project has been realized by FLEXe program.

DISCERN we adopted the "mixed" approach for mapping the use cases onto the SGAM reference architecture and the approach to the definition of KPIs; (DISCERN D2-2.3)

The FP7 iTesla project was concerned with the development of a set of tools for power system dynamic security assessment considering uncertainties rising from renewable energy sources. Within iTesla, several algorithms to identify stability conditions from simulation time-series data and model-synthesis methods where developed in WP3 and WP4. Some of these results were utilized in IDE4L. In general, the challenges identified by iTesla that highlighted the need for coordination between TSOs and with RES were the initial point of study to develop TSO/DSO requirements for dynamic information exchange. In addition, and more specifically, the methods for stability identification served as a basis for the design and implementation of the algorithms for real-time PMU-based stability monitoring of oscillations and voltage stability in WP6.

The project was financed by the Nordic Energy Research agency, and aimed to set a foundation for synchrophasor research and technology development in the Nordic and Baltic region. Several results from STRONgrid where exploited in IDE4L. (1) The SmarTS Lab hardware-in-the-loop real-time simulation platform was utilized for development and demonstration of PMU-applications for TSO/DSO interactions of

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WP6, (2) the open source software developed in STRONgrid, SmartGrid Synchrophasor Development Kit (S3DK, https://github.com/SmarTS-Lab-Parapluie/S3DK), was utilized to implement the real-time prototype PMU applications; and (3) the design of the IEEE C37.118.2-compliant real-time data mediation software from STRONgrid was used as a starting point for the work in the development of the new IEC 61850-90-5 gateway (Khorjin).

Main dissemination activities

IDE4L project organized three public events to disseminate project results. The main target audience of these events were DSOs.

- Future role of DSO with large-scale DERs, The Co-operation projects workshop, March 2015, Germany
- Future flexible distribution system seminar, December 2015, Finland
- IDE4L Symposium, May 2016, Italy

For scientific audience three events were also organized.

- Tutorial “Distributed and hierarchical congestion management in distribution network containing distributed energy resources” in ISGT 2016 Europe, October 9-12, 2016
- A special session named “monitoring platforms for distribution system” in AMPS 2014 conference in Aachen, Germany
- Workshop on Resiliency for Power Networks of the future 8th May 2015 in Stockholm, Sweden

The IDE4L reference active distribution system is already published and is publically accessible under the terms of the GNU Public License version 3 (GPLv3) on a designated github repository at https://github.com/SmarTS-Lab. In addition, all advanced PMU-based applications, developed in order to extract key dynamic information of distribution networks for TSO/DSO information exchange, will be accessible publicly under the terms of the GPLv3 license on the same repository within 5 years of the end of the project. Substation Automation Unit database schema will be published under the GPLv3 license.

IDE4L FLISR Use cases were also presented by Schneider-Electric in the International Standardization Committee (SC) meeting in China, in June 2016. The feedback provided was very positive. SC will introduce in the coming IEC 61850-90-6 what is needed to support IDE4L Use Case. IEC 61850-90-6 is currently in draft status and will suppose the first part of the IEC 61850 standard covering feeder automation functionalities. Presentation for the Spanish National Standardization Committee for IEC TR 62689-100: Requirements and proposals for IEC 61850 data model extensions to support Fault Passage Indicators applications, was also given to propose additions to IEC 61850.

Exploitation roadmap

The roadmap to exploit IDE4L project outcomes has been divided into five viewpoints named knowledge and attitudes, grid codes and standards, market and grid regulation, flexibility market, and technology. Figure 18 represents how these viewpoints have been scheduled for design, development, demonstration and commercialization phases.

The IDE4L project has a strong focus on technology development and therefore this aspect is probably the most advanced one of the selected viewpoints. However, the experiences collected from demonstrations should be utilized to further improve and extend the technology and therefore the second technology development and demonstration phases are required before commercializing the developed technology. Also the design and development of other viewpoints are also required before a market for all technologies developed in IDE4L project really exists.

Flexibility market for flexibility services, which are validated and purchased by DSOs, does not exists yet anywhere in Europe. Therefore, the flexibility market has to be designed first in EU member countries and harmonized on the European level, which might in practice take much more time than the scheduled two years. In addition to market design common agreement on transactions and contracts are needed to really create a well-functioning flexibility market, which should be followed by a demonstration phase of several commercial aggregators operating at DSO domain. The most important issue is to create continuity for profitable business and trust between market players, as otherwise the flexibility market will not have enough players.

Very important aspect for the success of active network management in distribution grids is the modification of grid regulation to allow efficient utilization of DERs for grid management and to enable existence of flexibility market for DSO use. Otherwise DSOs continue developing their grids as passive infrastructure. The design, development and demonstration of regulation goes hand in hand with the schedule of flexibility market.

Modification of grid codes and standards is a long process. Therefore, the objective of grid code and standard development should also focus on the future requirements of active network management in addition to the urgent needs of existing systems. The IDE4L project has utilized SGAM for automation architecture development and also provided the description of use cases to be used in the standardization work. Active participation of research and demonstration projects is required to understand future needs for the development of grid codes and standards, and to create a European vision of future active distribution grid.

Probably the most challenging aspect of the viewpoints is the knowledge and attitude. The research and development persons of DSOs are very enthusiastic to develop and demonstrate new solutions, but the challenge is to implement the new ideas as a standard practice in a DSO. For this effort it is proposed that more information about real knowledge gaps in business and engineering tasks while DSOs are making investment decisions needs to be collected. In addition to this, sharing IDE4L outcomes and collecting the best practices from other demonstration projects is needed before utilizing new ideas as the best practice in a DSO.

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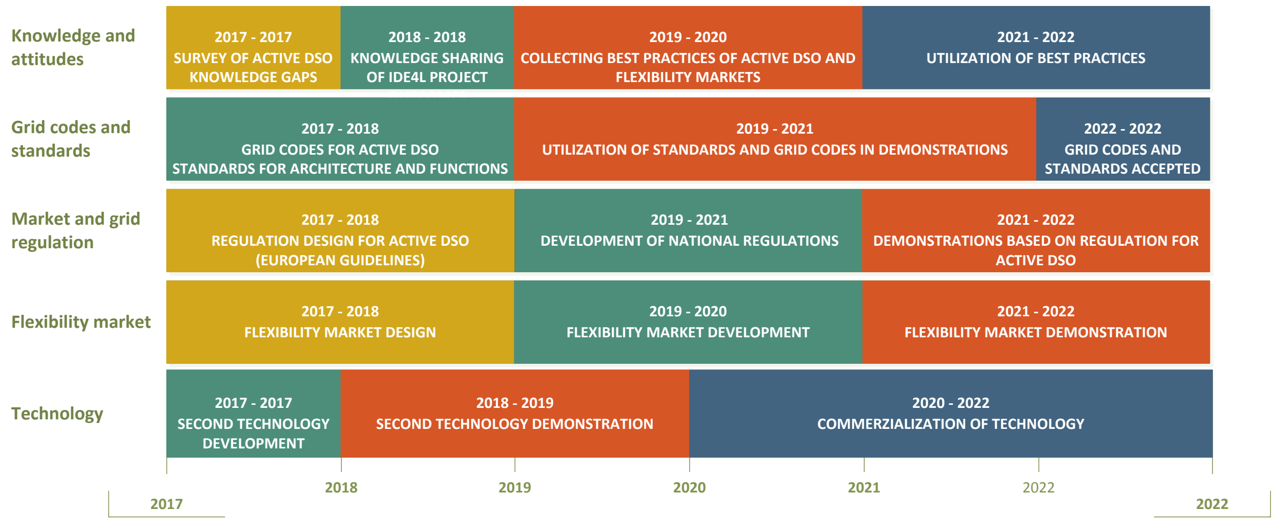

Figure 12. Roadmap to exploit IDE4L outcomes.

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