Systematic Method for the Development of Future Active Distribution Network Automation Architectures

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***Abstract*—In response to the EU Mandate M/490, two crucial tools were developed for supporting the standardization of the Smart Grid: the Smart Architecture Model (SGAM) framework and the Use Case Methodology. This paper shows and exemplifies the use of these tools to incrementally develop the automation architecture for future active distribution power systems, by leveraging on existing automation architectures from literature and existing standards. This method for architecture development has been formalized and used in EU Project IDE4L, but it is generally applicable.**

***Index Terms*—Automation Architecture Development, Standards, Use Case Management, SGAM, Smart Grid**

I. INTRODUCTION

The power distribution grid is facing changes towards a more dynamic and complex infrastructure, due to the increasing integration of distributed energy resources (DERs), new equipment, such as Intelligent Electronic Devices (IEDs), smart meters, and new services, such as Demand-Response (DR). In this context, the traditional unidirectional, passive distribution network is being transformed into the next generation network, which is active and bi-directional. The operation of the active distribution network calls for a new concept of automation architecture that can accommodate present and future components, centralized and distributed functions, communication, information and new business models.

The challenge of defining a common architecture for the automation of the European distribution grid of the next 10-15 years is addressed (among others) by the European project "Ideal Grid for All" (IDE4L) [1], part of the European Seventh Framework Program (FP7). Within this project, the authors have followed a systematic method for designing the automation architecture of an advanced distribution network. This architecture accommodates the partial distribution of functions and services, i.e. the monitoring, protection and control applications, which are implemented at various points of the distribution infrastructure (e.g. Primary, Secondary Substations, Control Centers) and also among different interacting entities (DSO, TSO, Aggregator, other service providers). This feature challenges the development of the architecture because of the "across domain" and "across business" nature of the system; hence, the need to define and map the system functionalities onto a comprehensive framework, with partitioning fit for distributed systems. To this purpose, we adopted the Use Case Methodology [2] and the Smart Grid Architecture Model (SGAM) framework [3], developed by the CEN-CENELEC-ETSI Smart Grid Coordination Group to address the EU Commission mandate M/490 [4]. These tools are primarily intended to support the development of new standards. However, they can also be used for architecture development, as we show here. And even though this idea and the tools themselves are not new, their systematic application to the IDE4L architecture design can be considered valuable mainly because of its general applicability, reusability and extensibility. Moreover, the systematic application of the method allows tackling difficulties that stem from the complexity of the system avoiding oversimplification. Finally, it avoids redundancies and duplications, when information about the automation architecture is shared among similar projects, thus enhancing synergies and collaborations.

Other related work aimed at transitioning passive systems with centralized automation architecture to active systems with distributed automation architecture is presented in [5]-[7], where the focus is mostly on the ICT architecture. The concept of "Aggregator", developed for enabling the active participation of customers in the energy markets and in the provision of ancillary services is presented e.g. in [8], [9]. At the end, a very limited usage of tools in [2] and [3] was performed in both works. A deeper usage of those tools has instead been carried out in [12], [13], but for another purpose, i.e. to document, in a holistic way, the solutions adopted by different DSOs for determining the optimal cost-effectiveness of ICT in distribution.

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II. ACTIVE NETWORK MANAGEMENT REQUIREMENTS

The architecture to be developed in the IDE4L Project must address a set of functional and ICT requirements.

A. *Functional Requirements*

Figure 1 presents the distribution network management and its interface to external stakeholders (e.g. TSO, domestic customers). The concept of Active Network Management (ANM) is based on distribution automation and flexibility services of DERs, which include distributed generation (DG), demand response loads, and micro-grids. The distribution automation supervises network state, controllable devices, emergencies, and monitoring, control and protection of Primary and Secondary substations. Control of DERs may be direct or indirect, with the small-scale DERs aggregated by a technical Aggregator, which provides flexibility services. The architecture of ANM must support (i) Hierarchical and distributed control, (ii) Virtualization and aggregation of DERs and (iii) Large scale utilization of DERs in network management.

New functionalities for the operation of the distribution networks and supported here, are: distribution state estimation, automatic Fault Location, Identification and Service Restoration (FLISR), coordinated voltage control, power flow control, static and dynamic distribution model order reduction (to coordinate with TSOs). All these functions are based on new monitoring solutions, sensors, and opportunity to merge information.

Automation is structured in Primary, Secondary and Tertiary control, exemplified here by the Congestion Management use case, which may be realized via:

- active voltage control methods with DERs,
- power flow control via DG direct or indirect control, power flow control devices (e.g. OLTC transformer), load and DG scheduling.

Primary control (DG control) operates at device level, and operates with local measurements. Secondary control, located at Primary or Secondary substations, uses state estimate to coordinate with Primary controllers and DGs controls directly. Tertiary control, typically located in the control center, uses state estimates and forecasts to coordinate Secondary controllers and to purchase flexibility services from the Commercial Aggregator.

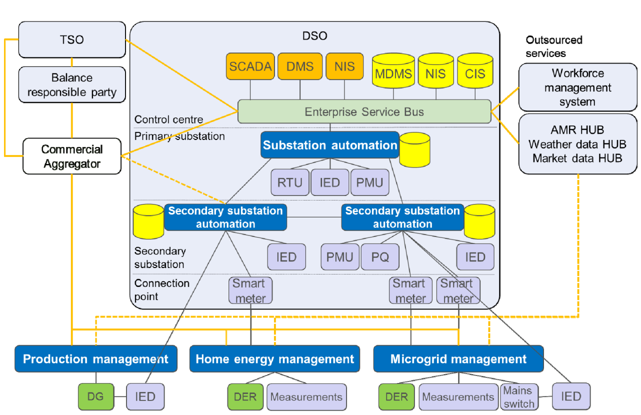

Figure 1: Automation architecture for active network management.

B. *ICT Requirements*

The communication infrastructure for an active network management has to satisfy several performance requirements. A reference is provided by the IEC 61850-5 [11].

The transfer time, i.e. the time a packet transmitted by a node takes to reach the destination, is a critical ICT requirement for the ANM. Different services defined by the IEC 61850 require different degrees of determinism to the communication infrastructures. For this reason they are grouped in Transfer Time Classes (TTC) [11]: from the less demanding TT0 (typically required by monitoring services), to the strictest TT6 (typically required by applications like protections). Some experimentation has been done by using different communication technologies to enable different services [14]. Experimental results proved that the most challenging TTC (3 ms) can be achieved only by using a fast Fiber Optic (FO) connection, while other technology e.g. wireless networks or Broadband Power Line (BPL) could be a viable solution in some conditions to enable less demanding TTC.

Time-synchronization is another relevant requirement for ANM. It consists of propagating an accurate time reference to correlate data from the distributed monitoring system. Different control and monitoring applications require different synchronization accuracy, as defined in [11], ranging typically from hundreds of milliseconds, like in SCADA monitoring applications, to few microseconds, as required by protection applications. The level of accuracy depends on the protocol adopted and the underlying communication media [15]. From a protocol standpoint, the de-facto time synchronization standard in computer network is the Network Time Protocol (NTP), even if, the more a more accurate time synchronization can be achieved by using the IEEE 1588.

III. THE IDE4L APPROACH

The "Use Case Methodology" [2], originally intended for supporting standardization bodies in identifying existing gaps, is adopted in the IDE4L Project to systematically derive the requirements for the architecture. This methodology is based on use case descriptions in a standardized template (the IEC Publicly Available (PAS) 62559 [10]) and the mapping of these use cases onto the layers of the SGAM framework [3]. This implies "filling" the SGAM framework with the details of the architecture, thus yielding the outcome of this process.

This section shows how the IDE4L automation architecture can be incrementally and iteratively developed by leveraging on existing automation architectures from literature (starting point architecture) and how the tools above are used for this purpose.

A. *Process for the development of the automation architecture*

The proposed methodology is summarized in Figure 2. The process of defining the automation architecture consists of the following steps:

- Development and collection of use cases (UCs) (sources are applications within IDE4L Project, other projects, and envisioned future use cases).
- Review for consistency; if consistent go ahead, if not harmonize; synthesis may be needed for UC refinement.
- UC analysis for the extraction of list of actors, list of functions, and links with the addition of the UC diagram for both the IDE4L automation architecture and the starting point architecture (from other EU projects, e.g. INTEGRIS+ADDRESS); synthesis and harmonization of UC descriptions according to final list of actors, functions and links.
- Mapping on the SGAM framework of the starting point architecture and of the new use cases.

The incremental approach consists of relating the output of the last two steps yielding what (services, applications) cannot be done with the starting point architecture and why (missing data, links, functions, actors, performance), and how these gaps are to be filled.

The outcome of these steps is the distribution automation architecture itself, formalized in UML by using the *SGAM-Toolbox* (http://www.en-trust.at/downloads/sgam-toolbox/), i.e. an extension for the modeling tool "Enterprise Architect" *from Sparx Systems*. While this constitutes a shared basis for developing demonstrations, the actual implementation of the architecture requires the application of the standards for the development of the automation software. The formal representation of the architecture also embeds the requirements for full testing features in demonstration.

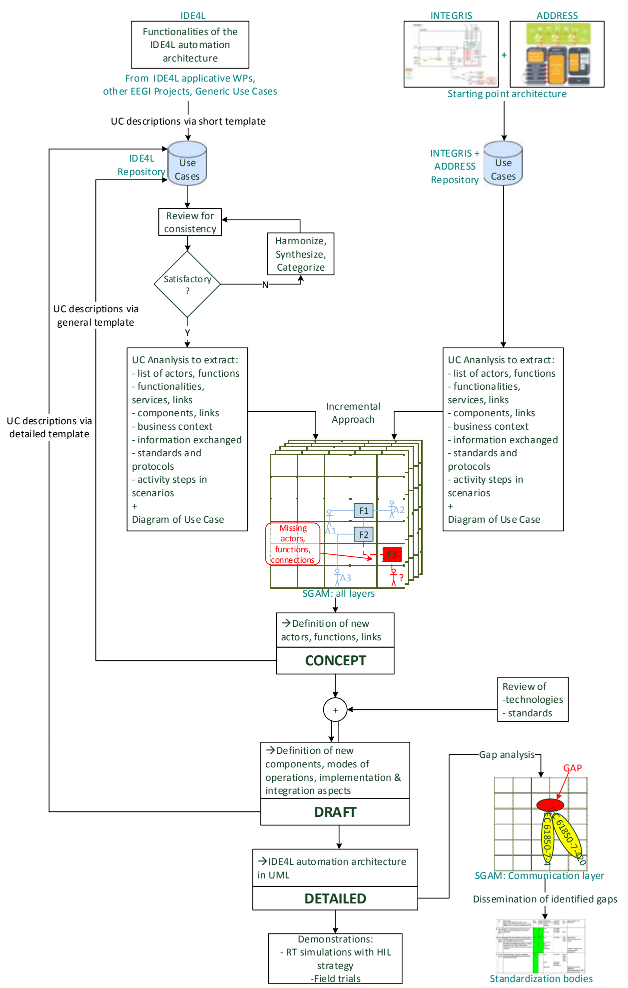

Figure 2: Conceptual process for the development the IDE4L automation architecture using the use case methodology.

The architectural gaps allow also for the evaluation of existing standards and technologies. IDE4L bases the architecture on existing standards (primarily IEC 61850 [11]) and off-the-shelf solutions. However, standardization gaps may be identified in the process, and disseminated among researchers and standardization bodies.

The starting point architecture inherits from [5]-[7] the distribution of functions and from [8], [9] the market orientation. Then, the starting point architecture is expanded with new use cases and advanced functionalities which include other stakeholders besides the DSO, namely TSO, Commercial Aggregator and service providers. Table I shows the Primary Use Cases used in this work, categorized by High-Level and Cluster Use Cases according to the convention adopted in [2]. The use cases from literature are underlined, while the dashed underlined use cases are expanded to include more flexibilities from DERs [1], [6]. The FLISR use case has been modified to a decentralized version. All the other use cases are the original contributions of IDE4L.

TABLE I: HIERARCHICAL STRUCTURE OF USE CASES IN IDE4L PROJECT [1]

Clusters	High Level Use Cases	Primary Use Cases
Monitoring	RT-Monitoring	• MV Real-Time Monitoring • LV Real-Time Monitoring • MV State Estimation • LV State Estimation • Dynamic Monitoring for TSO
	Forecasting	• MV Load and State Forecast • LV Load and State Forecast
	System Updating	• Network Description Update • Protection Configuration Update
Control	Power Control	• MV Network Power Control • LV Network Power Control • Control Center Network Power Control
	FLISR	• Decentralized FLISR • Microgrid FLISR
	Power Quality	• Power Quality Control
	Network Planning	• Target Network Planning • Expansion Planning • Commercial Aggregator Asset Planning
Business	Interaction among Commercial Aggregator, DSO and TSO – Operation Domain	• Load Area Configuration • Flexibility Table • Off-Line Validation • Real-Time Validation
	Interaction among Commercial Aggregator, DSO and TSO – Market Domain	• SRP and CRP Day-Ahead and Intra-Day Market Procurement • Conditional re-profiling activation (CRP Activation)
	Grid Tariffs	• Day-Ahead Dynamic Tariff • Day-Ahead Demand Response

B. *Role of templates in the UC description*

The iterative nature of the process for developing the architecture described in Subsection A, is depicted in Figure 3, where the increasing level of detail of the use case descriptions is provided through standard use case templates [10]. These templates are provided in three versions, i.e. short, general, and detailed, whose contents are summarized in Figure 4. The iterative process uses the three templates at different development stages, receiving the key inputs (orange boxes), producing the outputs (blue boxes). The advantage of this process is the following. Due to the "multi-resolution" structure of the templates (the detailed version contains all the info of both the general and the short versions, and the general template contains the info of the short version), a later inconsistency in the use case description, which might reflect in incorrect architectural features, does not require to step back to the beginning (note the retrofitting arrows in Figure 3). Moreover, it allows the development of the architecture in parallel with the increasing level of description detail of the use cases.

The described process enables crucial steps. First the *concept* of the architecture is derived from the use case short template. This concept defines functionalities and modes of operation that the architecture must enable. Then from the use case general template, the *draft* architecture is derived (with enough details for first steps in implementation integration, and demonstration set up). Finally, from the use case detailed template the complete, *detailed* architecture (in terms of infrastructure, information, communication, and functions) is derived, together with the full testing features of the demonstrations. The next step consists in implementing the architecture for deployment in non-technology neutral form.

IV. Example of Use Case

The goal of this section is to demonstrate the process for a sample case, the *LV network Power Control (LVPC)*. The steps described in Figure 2-Figure **3**, yielding the definition of the first *detailed* architecture, along with the requirements that will be used for the next steps in the process, are here shown.

First, the narrative of the chosen use case is formulated in terms of scope/objectives/description according to the IEC PAS 62559 template [12]. Then, the use case diagram, both for the starting point architecture (INTEGRIS only for space reasons) and IDE4L, is formulated. From this diagram, the layers of the SGAM are mapped. The comparison yields a list of requirements for the IDE4L architecture comprising missing actors, functions, components, information exchanged, standards/protocols that support the interconnections between *actor x* and *function y*. In this paper, for sake of example, we show the mapping of the communication layer only, and only the requirements in terms standards/protocols.

A. *LV network Power Control (LVPC)*

1) *INTEGRIS Case*

The INTEGRIS architecture [5]-[7] relative to the secondary substation is shown in Figure 5. The purpose of this use case is to manage power flows and voltage level in LV

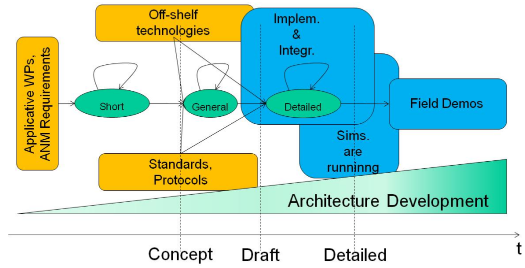

Figure 3: The iterative process for the development the IDE4L automation architecture using the use case templates spanned over the time length of the project.

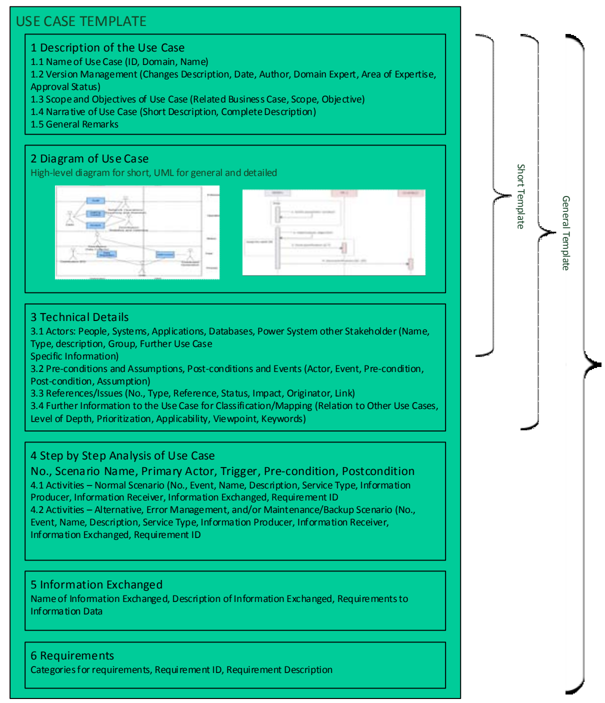

Figure 4: Overview of IEC 62559 Use Case Template.

network by controlling domestic consumption and PV generation by means of Smart Meters (SMs), Power Quality Meters (PQMs), and Home Energy Management System (HEMS). After collecting the measurements from the Remote Terminal Unit (RTU) Data Collector and Meter Data Collector (MDC), they will be stored in a dedicated Data Base (DB). If an alarm is detected, it will be sent to the SCADA/DMS. The steps in INTEGRIS are the followings:

1. The LVPC algorithm checks the state of the grid against a static network data.
2. If congestion (power or voltage violation) is detected in current state, the power control algorithm will act to solve the congestion. To find a solution, it will need to access to the following information: static network data, and PV generation availability (if it is connected, what the current state is).
3. After an iterative process where an acceptable solution to congestion is found, the algorithm outputs the appropriate control actions. The control actions include PV generation set points, and load disconnection commands.

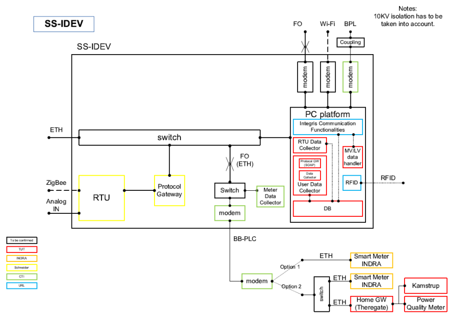

Figure 5: INTEGRIS architecture at the secondary substation [5]-[7].

2) IDE4L Case

In IDE4L, the LVPC optimizes the power and voltage of the LV feeders of the secondary substation where it is installed through changes of topology (switches, tap changer), DER utilization (both that one directly managed by the DSO and that one managed by the Aggregator, i.e. HEMS), and DR. To achieve this, the LVPC algorithm receives inputs from the DR model, state estimator, and state forecaster. The DR model produces a forecast for the flexible loads in the grid based on an energy price signal, weather data and grid model. The state forecaster produces forecasts for load and production based on events causing an increase in consumption, weather data, flexible load forecast, and measurements. The state estimator requires load and production forecasts, measurements, grid model and topology, from which it estimates voltages and currents in the grid in real-time. The business objective of the LVPC is to enhance the efficiency in day-to-day grid operation and to reduce the need for grid reinforcement. The steps in IDE4L case are similar to the INTEGRIS case, with some relevant difference:

1. The LVPC algorithm checks the state of the grid against the current grid model.
2. If congestion (power or voltage violation) is detected in current or future states, the power control algorithm will act to solve the congestion. To find a solution, it needs access to the following information: current grid topology, price of activating DER through the mediation of the Commercial Aggregator, boundary conditions (if there are any limits from the MV grid), DER availability (if the DER is connected, what the current state of the DER is), weather data, and FLISR (if there are any faulted components to take into account).
3. After an iterative process where an acceptable solution to congestion is found, the LVPC outputs the appropriate control actions. The control actions include the new topology (switches, tap changer settings), DER set points, and flexible load commands.

The data necessary for the operation of DR model, state estimator, state forecaster, and LVPC algorithm itself are stored in a Data eXchange Platform (DXP), which covers the same function of the DB in INTEGRIS. The Incremental Approach applied to the LVPC UC

The diagram of the LVPC use case for both INTEGRIS and IDE4L is given in Figure 6. This diagram is the result of the first iteration of the process depicted in Figure 2Figure **3** where the use case is described in the short template. In particular, the diagram is drawn a posteriori for INTEGRIS by performing the analysis of the use case steps and the "inverse synthesis" of the architecture, while the analogous diagram for IDE4L is drawn by extracting the functionalities of the use case in the short template. From this diagram, the system engineer can easily identify the first list of requirements for the new architecture in terms of actors, functions, and their interconnections to define the *concept* of the IDE4L architecture.

Next, the mapping of the use case onto the SGAM layers is performed from the description of the use case in the general and detailed templates and after a review of standards and technologies. This is the result of the second and third iterations of the process depicted in Figure 2Figure **3**. Only the communication layer is mapped here and the required standard protocols that support the interoperable exchange of information between physical components are shown. Figure 7 shows the communication layer for the starting point architecture (INTEGRIS) with the addiction of the new components in support of the new *detailed* architecture (IDE4L) functionalities.

Based on the analysis of Figure 7, the following communication requirements can be identified. All the acronyms used here can be found in [1], [5]-[7]. At the Operation and Station zones, the CIM standard (IEC 61970-301 and IEC 61968-11) is used for the network topology update to the primary and secondary substations computers (PS-IDEV PC and SS-IDEV PC, respectively). This represents a new functionality. The IEC 61850 is used for all communications, in particular MMS for substation automation, communication to the SCADA/DMS at the operation control center and for inter-substation communication. The DLMS/COSEM and the HTTP proprietary protocol are used for communication between the SM/PQM and the MDC, and the HEMS and the MDC,

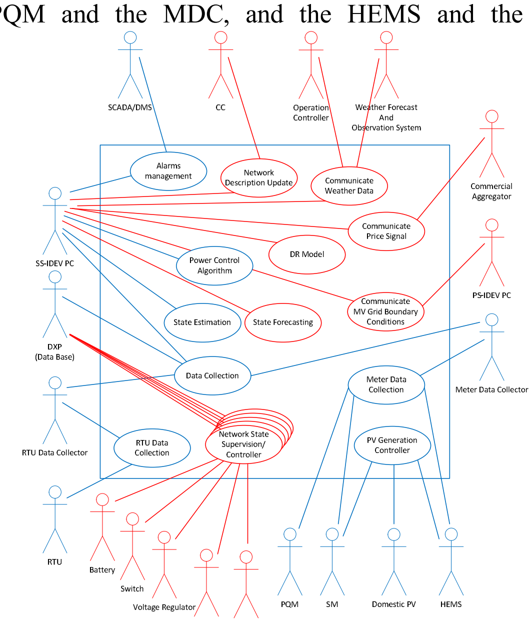

Figure 6: Diagram of the LV network Power Control use case for INTEGRIS case (in blue), and new actors, functions and interconnections introduced by IDE4L (in red).

respectively. The communication between MDC and SS-IDEV PC was previously done via SOAP, but DLMS/COSEM messages can be used for IDE4L. The DXP implemented in the SS-IDEV PC manages all the protocol-related issues. The communication with the Aggregator and the Weather Forecast and Observation System located at the Market and Enterprise zones, respectively, require to use the Internet. Demilitarized Zone (DMZ) concept is applied at the control center level to decouple the field communication network from the Internet, thus guaranteeing Cyber-Security requirements. In the starting point architecture, only the monitoring feature was supported by communication between RTU and SS-IDEV PC, and between the control center and the PS-IDEV PC. In the new architecture, the control feature is newly added, supported by MMS. The communication network architecture between the control center and primary substations is generally a routed network (Layer 3 network). Secondary and primary substations should be connected as if they are on the same "extended" local network (L2 network) if MV network automation schemes based on the IEC 61850 GOOSE have to be implemented.

V. CONCLUSIONS

The systematic method for developing the IDE4L automation architecture is presented in this paper. The method is based on the Use Case Methodology and the SGAM framework. The method is based on an incremental approach that expands a starting point architecture applying new requirements. The approach can also be used in other EU projects aiming at architecture development because is based on common tools. The use case example shows the application of the method, but not the validation of the architecture which is beyond of the scope of this paper.

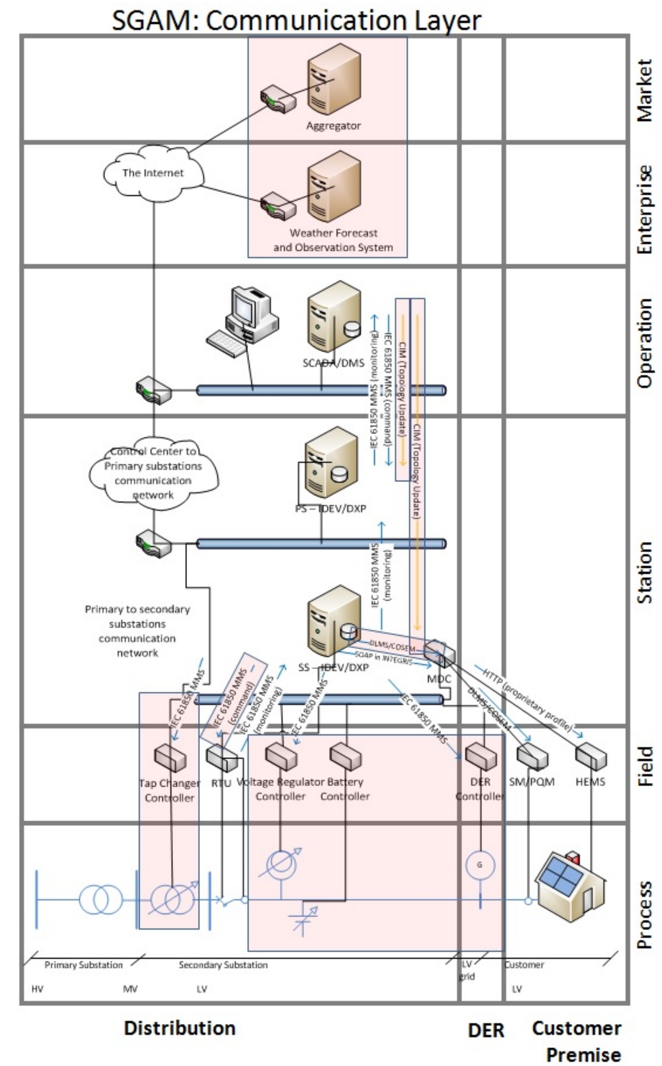

Figure 7: SGAM Communication layer for the IDE4L architecture which supports the LV network Power Control use case. The shadowed components are the new ones with respect to the starting point architecture.

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