Sustainable Energy, Grids and Networks 15 (2018) 3–13

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

journal homepage: www.elsevier.com/locate/segan

A distributed automation architecture for distribution networks, from design to implementation

Andrea Angioni [a,*], Shengye Lu [c], Hossein Hooshyar [f], Ignasi Cairo [e], Sami Repo [c], Ferdinanda Ponci [a], Davide Della Giustina [b], Anna Kulmala [d], Alessio Dedè [b], Antonello Monti [a], Gerard Del Rosario [e], Luigi Vanfretti [f], Cristina Corchero Garcia [e]

[a] *Institute for Automation of Complex Power Systems, Eon Energy Research Center of RWTH University of Aachen, Germany*
[b] *Unareti S.p.A., Milano, Italy*
[c] *Tampere University Of Technology, Tampere, Finland*
[d] *VTT Technical Research Centre, Tampere, Finland*
[e] *IREC Institute, Barcelona, Spain*
[f] *KTH Royal Institute of Technology, Stockholm, Sweden*

ARTICLE INFO

Article history:
Received 10 November 2016
Received in revised form
13 March 2017
Accepted 3 April 2017
Available online 27 April 2017

Keywords:
Architecture
Smart grid
Distribution system

ABSTRACT

With the current increase of distributed generation in distribution networks, line congestions and PQ issues are expected to increase. The smart grid may effectively coordinate DER, only when supported by a comprehensive architecture for automation. In IDE4L project such architecture is designed based on monitoring, control and business use cases. The IDE4L instance of SGAM architecture is derived and explained in details. The automation actor are specified in terms of interfaces, database and functions. The division in these three layers boosted the implementation phase as dedicated interfaces, databases or application has been developed in a modular way and can be installed in different HW/SW. Some implementation instances are presented and the main output of the architecture is discussed with regards to some indexes as communication traffic and level of distribution of automation functions.

1. Introduction

Today's power distribution systems are heading toward the concept of smart grids. This is occurring in response to the new types of devices injecting or absorbing active and reactive power. Distributed generation reaches significant penetration both in MV and LV grids and in it is expected to increase, together with local storage and electric vehicles. This combination may lead to line congestions and PQ issues when not effectively controlled [1]. When power resources (passive active and storage) may be locally controlled, they are named DERs. Smart grid is the grid where DERs may be coordinated in order to reduce line congestions, PQ issues and to reduces the losses of the network. Such coordination is possible only through an architecture that permits to monitor the status of the grid, as well as forecasting it for the next 24 h, and to control the DERs and the resources of the DSOs. Furthermore, such architectures define the actors responsible for buying/selling energy and flexibility services from/to the electrical market. In particular a link between operation and business/market, is needed as they are heavily interdependent, particularly in demand response schemes.

Literature already sees a large growth of research publications, on automation architectures [2]. With that, we mean publications discussing the automation actors, automation functionalities or showing how the actors should be interconnected. Regarding the networks of automation actors, the main schools of thoughts are based on completely centralized system, based on DMS [1] or completely distributed ones, based on multi agents [3,4]. Of course, also hybrid architectures, which combine concepts of hierarchical and horizontally distributed systems, are proposed [5,6]. The information flow, in terms of communication protocols and communication infrastructure, among actors has been also strengthening

* Corresponding author.
E-mail addresses: aangioni@eonerc.rwth-aachen.de (A. Angioni), shengye.lu@tut.fi (S. Lu), hosseinh@kth.se (H. Hooshyar), icairo@irec.cat (I. Cairo), sami.repo@tut.fi (S. Repo), fponci@eonerc.rwth-aachen.de (F. Ponci), davide.dellagiustina@unareti.it (D. Della Giustina), anna.kulmala@vtt.fi (A. Kulmala), alessio.dede@unareti.it (A. Dedè), amonti@eonerc.rwth-aachen.de (A. Monti), gdelrosario@irec.cat (G. Del Rosario), luigiv@kth.se (L. Vanfretti), ccorchero@irec.cat (C.C. Garcia).

http://dx.doi.org/10.1016/j.segan.2017.04.001
2352-4677/

List of Acronyms

AD: Amount of Data
ADMS: Advanced Distribution Management System
AMM: Automatic Meter Management
AVC: Automatic Voltage Control
BRP: Balance Responsible Party
CA: Commercial Aggregator
CAASs: Commercial Aggregator Automation Systems
CAEP: Commercial Aggregator Asset planning
CAPEX: CAPital EXpenditure
CCPC: Control Center Power Control
CIM: Common Information Model
CIS: Customer information service
CRP: Conditional Re-Profiling
DERs: Distributed Energy Resources
DG: Distributed Generation
DLMS/COSEM: Device Language Message Specification/ COmpanion Specification for Energy Metering
DM: Dynamic Monitoring
DMS: Distribution Management System
DR: Demand Response
DSO: Distribution System Operator
FLISR: Fault Location, Isolation and Service Restoration
FO: Fiber Optic
FP7: Seventh Framework Programme
GIS: Geographical information service
H2020: Horizon 20 20
HEMS: Home Energy Management System
ICT: Information and Communication Technologz
IDE4L Ideal Grid for All
IE: Information Exchange
IEDs Intelligent Electronic Devices
IP: Information Producer
IR: Information Receiver
KPIs: Key Performance Indexes
LAN: Local Area Network
LTE: Long Term Evolution
LV: Low Voltage
LVPC: Low Voltage Power Control
MGCC: MicroGrid Central Controllers
MMS: Manufacturing Message Specification
MO: Market Operator
MOP: Market Operator Platform
MTT: Maximum Transfer Time
MV: Medium Voltage
MVPC: Medium Voltage Power Control
NIS: Network information service
OLV: Off Line Validation
OPEX: OPerational EXpenditure
PC: Power Control
PLC: Power Line Communication
PMU: Phasor Measurement Unit
PQ: Power Quality
PSAU: Primary Substation Automation Unit
RP: Retailer Platform
RR: Reporting Rate
RTU: Remote Terminal Unit
RTV: Real-Time Validation
SAU: Substation Automation Unit
SCADA: Supervisory Control And Data Acquisition
SCL: Substation Configuration Language
SE: State Estimation
SF: State Forecast
SGAM: Smart Grid Architecture Model
SM: Smart Meter
SPP: Service Provider Platform
SSAU: Secondary Substation Automation Unit
TR: Transfer Rate
TSO: Transmission System Operator
TSOEMS: Transmission System Operator Energy Management System
TT: Transfer Time
UMTS: Universal Mobile Telecommunications System

in [6–8]. In [9] an IEC 61850 standard base communication scheme to perform control of DERs is proposed. Regarding the automation functionalities and actors, developed for smart grid architectures, a lot of research has been conducted in the area of micro-grids, which allow with islanding operation to maintain power supply during faults in the main grid. Moreover, in [10] micro-grids are also exploited for coordination of voltage control. In [11] some instances of monitoring and control use cases in LV grids are presented. Eventually, [12,13] developed the concept of aggregator and the framework of electrical market to purchase flexibility products.

In the same way, large and small companies, active in the area of grid automation are competing to offer complete automation solutions for distribution networks. ABB [14], Schneider electric [15] and Siemens [16] propose SCADA systems for monitoring and control of distribution grids. Such solutions suffer, however, from the great initial investment required and the need to maintain legacy hardware, both SCADA and RTUs, and software. GE [17], and Oracle [18], on the other way, propose an ADMS which perform automation in software environment installed in cloud type of hardware. Therefore, the generic DMS, can be easily updated/upgraded and can interact with heterogeneous IEDs. However, the proliferation of research and development activities in the area of architectures for automation did not yield to a straightforward integration of their contributions. This is because some implementation focus on particular actors (e.g. SCADA, IEDs, converters etc.) while other concentrate on systems' design (control and monitoring algorithm) and infrastructures. Therefore, it was necessary to define a common modelization standard for automation architectures.

The European Commission mandate M/490 [19] standardized the framework for definition of architectures for smart grids. This is the so-called SGAM [20], proposed by the CEN-CENELEC-ETSI Smart Grid Coordination Group. The SGAM model, require to specify the smart grid functionalities in the form of use case, later to be merged in the five automation layers of the SGAM. Many research projects as well as industrial users started exploiting the SGAM to define their particular instance of smart grid automation architecture [21].

The FP7 European projects ADDRESS [13] and INTEGRIS [22], developed several use cases respectively in the area of customer aggregation and electrical market and network monitoring and real time control, however the requirements are specified without developing a SGAM instance. The FP7project EvlovDSO exploit the use case methodology and define two of the layers of the SGAM, respectively the business and function layer [23]. The H2020 project SUCCESS [24], will implement several cyber security use cases to guarantee data robustness in smart grids.

In this paper, the architecture instance of IDE4L project, completely specified following the use case methodology and SGAM model, will be presented. Such architecture will permit to perform the main monitoring and control functionalities and will be detailed by the five fundamental layers of the SGAM. The compatibility with the requirements for automation of distribution grids, have been tested by means of the so-called KPIs. This architecture has been developed in the European project IDE4L [25], part of the

European FP7. The definition of the IDE4L instance of SGAM architecture starts from the use cases, like monitoring, state estimation, forecast, power control, grid protection, from where it is possible to infer the business actors, automation actors and information exchanges needed for the design of the five SGAM layers. The link between use cases' requirements and the design of the SGAM model is presented in Section 2. The SGAM IDE4L instance is afterwards fully detailed respectively as, business layer in Section 3, component and function layer in Section 4, communication and information layer respectively in Sections 5 and 6. The SGAM instance of IDE4L, is, at this point, a technology neutral architecture, that can be implemented with several technologies (e.g. measurement devices may be Smart Meters or Phasor Measurement Units). Some implementation instances, corresponding to the field demonstration sites, are thus, presented in Section 7. The performances and the key features of IDE4L architecture are finally qualitatively and quantitatively evaluated, in the form of KPIs in Section 8.

The proposed architecture is distributed, in the sense, that the automation burdens (monitoring, control and protection) are shared among three hierarchical levels, that are, starting from the lower level, IEDs SAUs, and DMS. IDE4L architecture is being designed for distribution networks, in the sense, that it supports the automation functionalities (monitoring, control and protection) designed to solve issues peculiar of distribution grids.

2. IDE4L architecture development

The process of development of the architecture is defined in the following steps: 1. Use case definition; 2. synthesis of use cases in SGAM five layers description; 3. Evaluation of architecture through KPIs. In paragraph 2.1, a summary of IDE4L use cases is presented (full detailed use cases are available in D3.2 [25]). The SGAM architecture model is a three dimension structure, where the x and y axis represent, respectively, the zones (Process, Field, Station, Operation, Enterprise, Market) and domains (Generation, Transmission, Distribution, DER, Customer Premises) of the smart grid plane, and the z axis represent the layer, respectively, business, function, information, communication and components.

2.1. IDE4L use cases

Monitoring use cases include the collection of measurements from IEDs in the substation and SMs located at prosumers connection point; the processing of measurements in SE and SF algorithms to obtain respectively the current and future state of MV and LV grid. In IDE4L a use case dedicated to DM of distribution grid based on PMUs is also defined [26]; some indexes on the dynamic behavior of the grid are calculated and then forwarded to the TSO. Primary control is executed at each local IED. Secondary control functionalities located at primary and secondary substations include Real time, based on current status, and off line, based on forecasted status, control of low voltage grid and medium voltage grid (respectively named MVPC and LVPC). The secondary control operates through changing the set points of primary controllers such as AVC, real and reactive power controllers of DG units, reactive power controllers of reactive power compensators and real power controllers of controllable loads in order to avoid network congestions (voltage level violations and overloading of components) and to optimize the network state. In the distributed IDE4L control architecture each SE and PC algorithm is responsible for estimating and controlling either one MV or one LV network, which makes the system scalable. Tertiary control functionalities at control center level (also called CCPC) are designed in order to optimize switch position, therefore avoiding congestions and reducing power losses. In case such control actions are not enough to solve line congestions, the tertiary control may purchase energy and flexibility services from the electrical MO. The FLISR is executed on a fast loop, through peer to peer communication involving only IEDs, then in a slow loop including centralized controllers in order to also optimize the power flow with the new configuration of switches and breakers. The business use case, describe how energy and flexibility products, named respectively CRPs and SRPs products are created and traded. DMS may demand CRPs and SRP and the CA may offer them. Therefore, the CA takes care of bi-directional communication with the customer and to sell/buy energy and flexibility services to/from the electrical market. The bids are collected and processed by the MO, that subsequently sends a request of the validation of electrical market results, both from the day-ahead market, named OLV and in the infra hour market named RTV to TSOs and DSOs. The figure of CA manages an energy portfolio of DERs (in the CAEP use case) in order to build SRPs and CRPs to offer to the MO.

2.2. SGAM layers' development

The process of SGAM layers definition architecture requires as input information the use cases and the business cases. The business case contains the business actors of the architecture, business goals and regulation for business transactions. Business actors are enterprises (e.g. DSO or TSO) or business individuals (e.g. customer) that have a business goal (e.g. the DSO may want to reduce PQ issues and line congestions in order to extend the life of network components). Thus, each business actor exploit some automation actors (actors present in use cases, e.g. IED or SM), following the steps described in use cases, in order to build products that can be exploited or purchased to reach its business goals. When any product (e.g. flexibility services) is traded, the regulation for such exchange has to be defined. The business cases are synthetized in the business layer, which also includes the link between them and the use cases, indicating, thus, how each business actor may realize the products that he needs to obtain its business goal. Consequently, the use cases are exploited in order to extract the "automation" actors, functions, information exchange and the communication requirements for each of the information exchanges. Each automation actor (e.g. IED) is linked to a business actor, in the sense that the business actor owns and exploits it to perform any automation tasks. Consequently, the automation actor is mapped onto hardware and software systems that are needed in the field. HW and SW required for each automation actor together with the communication technology needed to link them, compose, what is named, component layer. The functions are linked to actors, or group of actors, when they require the cooperation of more of them, in the function layer. The information that are required as input, or produced as output, by each function, go in the information layer; at first defined in term of content (e.g. power, voltage measurement) and then in standardized data model (e.g. IEC 61850 logical nodes, data object and data attribute). Eventually the requirements for information exchange (e.g. maximum delay, availability) are used to derive which communication technologies and protocols are needed to exchange that piece of information, in the communication layer.

3. SGAM business layer

A business layer has been defined showing interrelation and dependencies among business actors and their business goals through business use cases. The DSO monitors the distribution networks and can acquire flexibility products through the electrical markets to overcome network constraints. In IDE4L, DSOs extend his responsibility with the exchange of indexes on the dynamic behavior of the system with the TSO. The CA: participates in the DR scheme optimizing his profits by participating in the

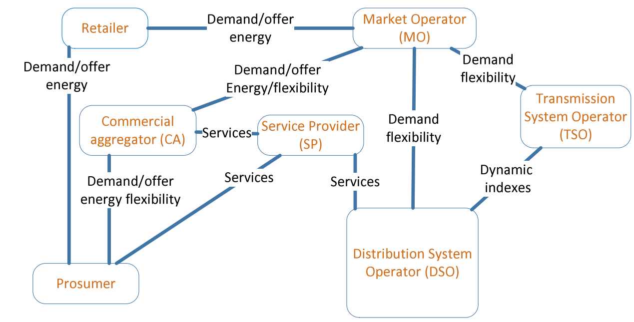

Fig. 1. Business actors in IDE4L architecture.

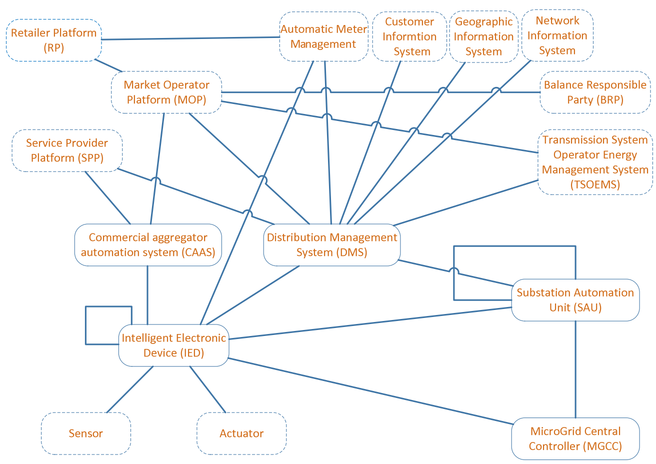

Fig. 2. Automation actors involved in IDE4L architecture.

energy market selling their flexibility products (SRPs and CRPs). Prosumers, intended as owner of adjustable power injection components, participates in the DR through CAs. The prosumers are MV or LV electricity users that can maximize their income of energy bought compared to energy and flexibility sold. The MO is responsible for ensuring market settlement; it receives the bids from DSOs, TSOs, retailers, commercial aggregators and Balance responsible parties. BRP is responsible for system's energy balance. Service Provider sell services such as price forecast, weather forecast or generation forecast to the DSO and CAs. Retailers may buy and sell energy from/to customers, but unlike CAs they do not trade flexibility products in distribution networks. The business actors and transactions are shown in Fig. 1.

4. SGAM component and function layer

The component layer is obtained through three steps. The first one is the mapping of the business actors, that are enterprises and persons, onto automation actors, that are computer or devices. For instance, being the DSO a business actor, the automation actors that allow him to perform automation are DMS, SAUs and IEDs. The second step is the mapping of such automation actors onto hardware and software components. Moreover, the main connections between automation actors are identified. The third step is the mapping of components in zones and domains. In the paragraph 4.1 a general overview of automation actors is given, afterwards a brief presentation of the functions performed by each of them is given in 4.2. Consequently the automation actors invoked by DSO, CA and prosumer are presented. Each of the automation actor is specified in terms of interfaces, database and functions required. The division in these three layers, simplified the organization of the implementation phase as dedicated interfaces, databases or application has been developed in a modular way and can be installed in different HW/SW in order to be reusable by several actors (e.g. the MMS interface can be exploited by both SAUs and IEDs). Some details on the implementation of the architecture are further discussed in Section 7.

4.1. Overview automation actors

Seen the functionalities in the use cases described in Section 2.1, it is derived that the following actors are needed PSAUs and SSAUs, IEDs (smart meters, RTUs and PMUs are here considered as particular instances of IEDs), MGCC, DMS and CAAS. Such actors are presented in Fig. 2 together with other actors, as the one to support MOP, TSOEMS, SPP and RP that have not been further developed in the IDE4L architecture, but still have some strong relations with it. The automation actors are shown in Fig. 2.

4.2. Summary of function layer

In this section the main functions are mapped to the automation actors. Monitoring and control functions are divided into hierarchical levels. Initially, measurement and control actions are performed locally at IED level. The measurements are forwarded to the so-called Substation Automation Unit (SAU), which also may modify the control set point of the IEDs. The SAUs may perform SE and SF and exchange such results with the bordering SAUs. The DMS, the third hierarchical level, receives regularly the results of SE and SF at MV level and may, in order, reconfigure the status of the switches to reconfigure the power flow, or buy and later activate flexibility services from the electrical market.

Such flexibility is offered by the CA, which based on forecast results, provided by service providers, such as power load and generation, market electricity price and weather forecast, may organize his energy portfolio in terms of energy and flexibility bills and offer them in the market. When the products are purchased, the CA should, in order, organize its resources in order to be able to furnish such product, Furthermore, the CA may be contacted by DMS in order to activate flexibility product, previously purchased; in such case, it should redirect the power to be activate among its customers. The customers or prosumers, manage either the power at the point of connection, through a dedicated IED (in this case also called HEMS) handling the power resources of the prosumer (load, generation and storage), or a micro grid, through the MGCC. The MGCC, differently from the case with the simple IEDs, is able to disconnect the microgrid in presence of electrical faults in the main grid, and manage optimally the power flow. When the fault is cleared it coordinates with the SAUs the phase of reconnection to the main grid.

4.3. Automation actors invoked by business actor DSO

The DSO is a fundamental figure in IDE4L architecture. It manages a set of computers in the control center, as the DMS for the optimal control and supervision of the system, the AMM for the collection of smart meter data, the Geographical, Customer, Network information services (GIS, CIS and NIS) to update periodically the models of topology, parameters and customer of the grid. Moreover, at substation level dedicated computers called SAUs realize automatically monitoring, SE and PC of their portion of grid. The SAU is able to communicate both with IEDs and control center. Finally the DSO exploits the IEDs in MV and LV networks. The DMS is the component owned by the DSO used to collect data from the field and to assist the control center operator in managing the overall distribution network. The DMS actor is represented in terms of interfaces, databases and functions in Fig. 3. In Fig. 3, as well as in Figs. 4–7, the interfaces are defined for the instance

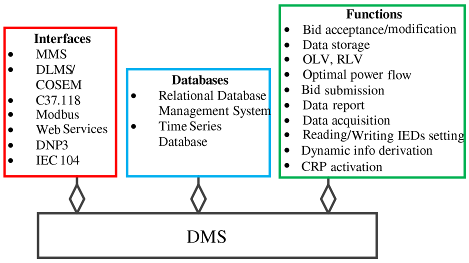

Fig. 3. DMS interfaces, databases and functions.

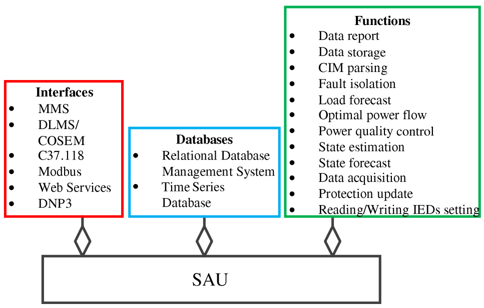

Fig. 4. SAU interfaces, databases and functions.

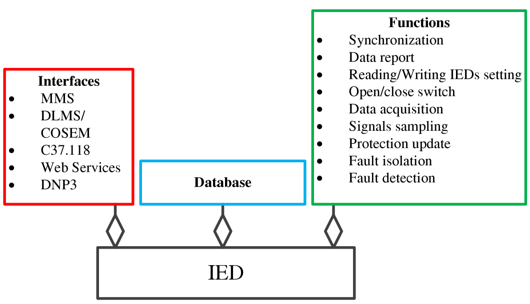

Fig. 5. IED interfaces, databases and functions.

of architecture implemented in IDE4L; more details on them are given in Section 7.

The SAU, in Fig. 4, is the device in charge of managing the distribution network fed by the substation where it is located, on behalf of the control center. SAU takes care of measurement collection, SE, SF and network control. It represents a level of automation between control center and IED, and allows the DSO to better distribute the burden of information and computation. The IED, presented in Fig. 5, is a generic electronic device used for monitoring, controlling or protecting the distribution grid and a microgrid. Falling into this category are RTUs, PMUs, Smart Meter and HEMSs. Furthermore also primary controllers such as substation ACV relay and real and reactive power controllers of DERs, as well as switches and breakers controllers are considered as IEDs.

4.4. Automation actors invoked by commercial aggregator

The commercial aggregator is a key business actor proposed in ADDRESS projects [12,13] and further developed in IDE4L. The automation actor exploited is the so-called "commercial aggregator system". It represents a generic hardware able to carry the optimization algorithm to manage the DERs and prepare SRPs and CRPs, the interfaces, mainly web services, to electrical markets, for selling SRPs and CRPs, to DSOs and TSOs to receive the response of validation procedures, and home energy management systems to activate the products sold in the market. This interface is also critical as it is important to activate the sold bids with sufficient time accuracy. Such computation effort is, in IDE4L, generically mapped in a computer. But it can be more efficiently performed on distributed clouds platforms, where the business actor commercial aggregator can access to set the main economic parameters. The automation actors invoked by commercial aggregator is depicted in Fig. 6.

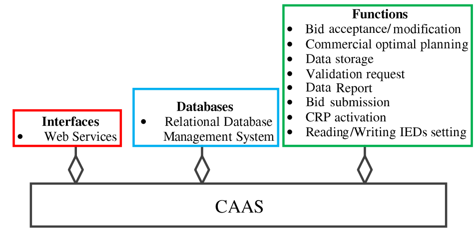

Fig. 6. CAAS interfaces, databases and functions.

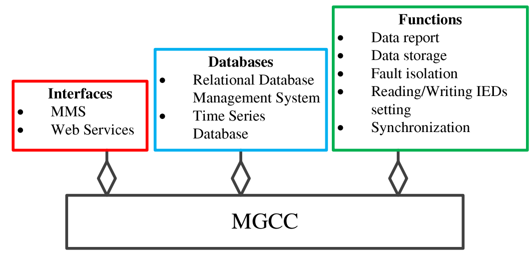

Fig. 7. MGCC interfaces, databases and functions.

4.5. Automation actors invoked by prosumer business actor

Prosumers can manage its own domestic private grid or a so called "micro-grid". In both the cases the prosumer is served by some optimal functions either in HEMS or in MGCC for the optimal management of the prosumer distributed energy resources, and sold to a commercial aggregator. The HEMS, is considered to be a particular instance of IED, already presented in Fig. 5, whereas the MGCC is presented in Fig. 7. The micro-grid can be disconnected in case of fault and its reconnection being coordinated by the primary substation automation unit. Consequently the micro-grid could be managed as a power island in case of faulty condition in the main grid. Prosumers that manage a micro-grid, not only have the right to control and sell energy and flexibility services from their owned DERs, but also the possibility to operate in island mode during faults or congestions in the main distribution grid. The micro-grid is involved during the FLISR phases by IEDs and SAUs, provoking isolation from the main grid; consequently the micro-grid is reconnected during the recovery phase through the isolation switch.

5. SGAM communication layer

This section introduces the communication layer of the IDE4L architecture in the SGAM framework in order to describe protocols and communication technologies utilized for the interoperable exchange of information between the use case actors. The protocols, utilized for each communication link, are determined by the actors which perform information exchange through it. Each information exchange sets specific requirements, as defined in the use cases, in terms of transfer time and transfer rate on the technology employed for the implementation of the communication link through which it is transmitted. The particular requirements defined in the use cases, have been defined following the indications of the standard IEC 61850-5 and the specification of the algorithm developers and DSOs present in

Table 1
Requirements on communication links.

Information producer	Information receiver	Most demanding information exchange	Transfer time (ms)	Transfer rate (kb/s)	Availability (%)
DMS	SAU	Switch control	500 (TT2)	1000 (TR4)	High (99.7)
DMS	CAAS	Grid tariff	500 (TT2)	10 000 (TR5)	High (99.7)
DMS	TSO	Key dynamic information	20 (TT4)	1000 (TR4)	Very high (99.85)
CAAS	HEMS	Energy plan, CRP activation	> 1000 (TT0)	1000 (TR4)	Medium (99.5)
CAAS	MGCC	Energy plan, CRP activation	> 1000 (TT0)	1000 (TR4)	Medium (99.5)

Table 2
Example technologies for communication links.

Actor	Actor	Protocol	Example technologies
DMS	SAU	MMS	BroadBand PLC on the MV grid, BB-PLC on the LV grid (cell with less than 20/30 of nodes), FO, LTE, HiperLAN/Wi-Fi (with a point-to-point link)
DMS	CAAS	WS	
DMS	TSOEMS	WS	FO, LTE (with no traffic), HiperLAN/Wi-Fi (with no traffic and with a point-to-point link)
CAAS	IED-HEMS	WS	UMTS, BroadBand PLC on the MV grid, BB-PLC on the LV grid (cell with less than 50/100 of nodes), HiperLAN/Wi-Fi, FO
CAAS	MGCC	WS	

Table 3
Information object flows between LV SE use case actors.

Information objects	Actors involved in the information exchange
Network topology	SAU database → SAU SE function
Switch status	IED → SAU interfaces → SAU database → SAU SE function
Current, voltage, power measurements	IED → SAU interfaces → SAU database ↔ SAU SE function
Energy measurement	IED → SAU interfaces → SAU database ↔ SAU SE function
Long term and short term power forecast	SAU SF function → SAU database → SAU SE function

Table 4
Information object flows between LV PC use case actors.

Information objects	Actors involved in the information exchange
Current, voltage, power, reactive power measurements; Total active power, reactive power; average phase to phase voltage	SAU SE function → SAU database → SAU PC function
Tap changer position	IED → SAU interfaces → SAU database → SAU PC function
Active, reactive power setpoints for distributed generation; band center voltage setpoint	SAU PC function → SAU database → SAU interfaces → IED
Estimated voltage	SAU SE algorithm → SAU database → SAU PC function

Table 5
The IEC 61850 data model used in LV SE, PC use cases, modeling all information objects except for network topology.

Information objects	IEC 61850 logical node type	IEC 61850 data object	IEC 61850 data attribute
Switch status	XCBR	Pos	stVal[ST]
Current, voltage, active/reactive power measurements	MMXU	A, PhV, W, VAr	phsA.cVal.mag.f[MX] phsB.cVal.mag.f[MX] phsC.cVal.mag.f[MX]
Total active/reactive power, average phase to phase voltage	MMXU	TotW, TotVAr, AvPPVPhs	mag.f[MX]
Tap changer position	ATCC	TapPos	valWTr.posVal[ST]
Energy measurement	MMTR	TotWh	actVal[ST]
Long term, short term power forecast	MMXU	W	phsA.cVal.mag.f[MX] phsB.cVal.mag.f[MX] phsC.cVal.mag.f[MX]
Active, reactive power setpoints for distributed generation	DRCC	OutWSet, OutVarSet	Oper.ctlVal.f[CO]
Band center voltage setpoint	ATCC	BndCtr	SetMag.f[SE]
Estimated voltage	MMXU	PhV	phsA.cVal.mag.f[MX] phsB.cVal.mag.f[MX] phsC.cVal.mag.f[MX]

the project consortium. As there might be various information exchanges through the same communication link, it is required to assess all of them to determine the demanded requirements on the links. The appropriate technology is then assigned to the communication links to satisfy the transfer time and transfer rate requirements imposed by the information exchanges. Table 1 lists the requirements imposed by the exchanged information on the communication links between the main actors of the IDE4L architecture. For example, the technology used to implement the communication link between DMS and SAU should be able to accommodate 1000 kb/s information exchange with transfer time of at least 500 ms.

Examples of technologies, satisfying the requirements listed in Table 1, are proposed in Table 2 for each communication link. It is worth noting that the example technologies are recommended by the IDE4L DSO partners who have experienced achieving the required transfer times and transfer rates by utilizing those technologies. Also note that, as indicated in Table 1, there are certain amounts of availability required from the underlying ICT connections. Such availability depends on the usage of the information in the use cases. For ICT connections with high (H, i.e. 99.7) or very high (VH, i.e. 99.85) availability requirements, it is important to consider some sort of redundancy for example by constructing ICT connections to implement a parallel communication path.

Table 6
Table regular information exchanges.

UC	IP	IR	IE	AD	AD DMS [-]	AD PSAU [-]	RR [frame/s]
Regular information exchange between DMS and PSAU and between DMS and MOP							
LV SF	DMS	PSAU	Weather forecast (temperature, irradiation, wind speed for 24 h)	72	18 000	72	0.001
MV SF	DMS	PSAU	Weather forecast (temperature, irradiation, wind speed for 24 h)	72	18 000	72	0.001
MV SE	PSAU	DMS	Result estimation Amount of	12 for each node	120	12	0.02
MV SF	PSAU	DMS	Result forecast (V.P.Q) for 24 h	216 for each node	540 000	54 000	0.001
DM	PSAU	DMS	3 indexes with dynamic status of the grid	3	120	6	0.02
OLV	DMS	MOP	Off line validation response	1 200 000 for each node	1 200 000	–	0.001
Regular information exchange between PSAU and SSAU							
MV SE	PSAU	SSAU	Estimation at point of connection (V.P.Q)	9	2 250	69	0.02
LV SF	PSAU	SSAU	Weather forecast (temperature, irradiation, wind speed for 24 h)	72	18 000	72	0.001
MV SF	PSAU	SSAU	Forecast point of connection for 24 h	216	54 000	216	0.001
LV SE	SSAU	PSAU	Estimation at point of connection (V.P.Q)	9	2 250	9	0.02
LV SF	SSAU	PSAU	State forecast at connection for 24 h	216	54 000	216	0.001
DM	SSAU	PSAU	3 indexes with dynamic status of the grid	3	6	3	0.02
Regular information exchange between PSAU and IED and between SSAU and IED							
LV Mon.	IED	SSAU	3ph V RMS. P. Q measurements and connection status	12 for each node	3 000	12	0.02
MV Mon.	IED	PSAU	3ph V RMS. P. Q measurements and connection status	12 for each node	3 000	12	0.02
DM	IED.PMU	SSAU	3ph V and I. phasor	12 for each node	24	12	50
DM	IED.PMU	PSAU	3ph V and I. phasor	12 for each node	48	12	50
Regular information exchange between CAAS and IED.HEMS							
CAEP	CAAS	IED.HEMS	Energy plan (P setpoint, time tag, flexibility range, with 15 min resolution for 24 h)	480 for each node	480	48 000	0.001

Note that the availability requirements, mentioned in Table 2, is aimed to be realized in future ICT infrastructure and might be difficult to achieve in the current ones.

6. Information layer

The purpose of SGAM Information Layer modeling is to model the information object flows between actors in terms of data content, and to identify proper data model standards that are suitable to reflect these information objects. In IDE4L architecture, automation actors exchange large volume of information. For instance, SAU collects multitudes of measurement from IEDs, and it also dispatches calculation results from its functions such as SE and SF, to control center, IEDs and/or other SAUs. Inside the SAU, there are also lot of information exchanges among its database, function and interface components. To reduce the integration costs, it is beneficial to present these information objects using standardized data model. The major data model standards used by IDE4L project are IEC 61850 and CIM model. IEC 61850 data model (IEC 61850 standards, section 7-4, 7-3 and 7-420) are used to model monitoring and control related data, mainly covering SGAM Station/Operation zones, and Distribution/DER domains. CIM model (IEC 61970-301, 61968-11 and 62325-301) has been chosen for describing the static feature of the network, as well as business operation and market process data. It lies in Distribution/DER domains, covering from Station zone up till Market zone. Besides, for conveying smart metering data from prosumers' premises, DLMS/COSEM model (IEC 62056-6) is also used. In paragraph 6.1 SE and real-time PC use cases are exploited as an example to illustrate how information layer analysis is applied in IDE4L project.

6.1. Example of information layer analysis

The information objects exchange between actors (or internal components of actors) in SE and PC use cases are summarized in Tables 3 and 4. The first column indicates the data content. The second column explains the sender and receiver of information objects flow, '→' meaning unidirectional, and '↔' for bidirectional exchange.

The data identified in Tables 3 and 4. are then mapped to data model standards. The network topology data is modeled by CIM model, using CIM classes including: AclineSegment, PerlengthSequenceImpedance—for describing MV or LV feeder, distribution line; EnergyConsumer—for consumers; PowerTransformer, PowerTransformerEnd—for transformer; RationTapChanger—for transformer tap changer; Switch—for circuit breaker, disconnector, etc.; SynchronousMachine, GenerationUnit—for modeling distributed energy resources such as PV generation and STATCOM; Measurement—for indicating measurement points; Terminal, ConnectivityNode—for presenting network topology. It is worth noticing that the choice of those CIM classes tries to balance the conformity of CIM standards and the simplicity of implementation. The rest of data listed in Tables 3 and 4 are mapped to IEC 61850 data model, as elaborated in Table 5.

7. Implementation of generic automation actor

In the following section some details are given on the implementation of a generic automation actor, composed of interfaces, database and algorithms, as described in Section 4. Many implementation details bring the architecture out of the technology neutral area that is considered in the SGAM architecture. In this case the authors want to present a method to implement the architecture, but other instances may be implemented starting from the same SGAM project [25].

7.1. Communication protocols

Many of the algorithms running in the SAU need real-time data as an input. Those data have to be collected by monitoring devices installed in the network e.g. smart meter, RTUs, etc. by using domain-specific protocols. Automation devices installed in the distribution grid are now converging on the use of the IEC 61850 standard, which suggests using the MMS as application protocol for monitoring and controlling application. In the smart metering domain, one of the most common standard is the DLMS/COSEM. Both the two protocols are client/server protocols, where the server is the unit producing information while the client is the unit consuming this information. IDE4L implemented two clients to enable the communication between the SAU and those monitoring devices. The MMS client is based on the libiec61850 libraries, an open source project including the MMS protocol stack, together with other protocols (GOOSE and sample values) proposed by the 61850 standard to implement automation services. The MMS client is configured by thought the database described in the next paragraphs. Briefly, a list of physical devices (IED) is specified together with its connection parameters (socket table). Per each of them, the client connects to the IED and start to retrieve its data model, exploring the entire hierarchy (Logical Device, Logical Node, Data Object, Data Attributes). A general interrogation is then performed to determine the starting status of the device. If properly configured, the client can subscribe data reports. The report service is reading service where the server spontaneously reports data to the client when a trigger condition is satisfied. This condition can be event-based *o* periodic. This approach is more band-efficient than a more traditional polling approach where the client have to ask every time to the server to send the data. Every time the client receives a new report the incoming data are stored in the real time reading table, where other algorithms can use it. At the same time, a new item is added in the historian table. The same approach is valid for the DLMS/COSEM client. The only differences are that the report service is not supported in the current version of the protocol, so the client has to poll the meter to get a new data; the database structure (described in the next paragraph) has been designed to be compliant with the 61850 data model. For this reason the client itself acts as a protocol gateway. The DLMS/COSEM client is based on the Gurux DLMS libraries. Since any SAU has to interact with other SAUs and the DMS, a server component is also required. This server is based on the IEC 61850 SISCO MMS-lite libraries. Its implementation supports both reading and report services. Its configuration is done by a configuration file (based on SCL) – as proposed by the standard – while data are retrieved by the same database hosting clients. From a practical implementation prospective it can be noticed that some DSOs may have a more traditional SCADA system without the MMS support. The most common standard protocol supported by electricity SCADAs in Europe is the IEC 60870-5-104. This protocol is the IP-based implementation of the serial protocol IEC 60870-5-101. It is based on a master–slave concept where the master is the entity starting the communication (equivalent to the client in the 61850) and the slave is the entity providing the information (equivalent to the server). Demo sites having just a SCADA with a 104 interface have needed an external application protocol gateway to perform the conversion to IEC 61850.

7.2. Database

The Database structure is based onto 4 set of tables, real-time type of tables that will be populated with measures and command data that followed IEC 61850 standard. The network model database that contains grid topology and parameters is defined following CIM standard. The management database contains the information required by algorithms, and therefore has been customized with respect to IDE4L ones. It is used to instantiate, parameterize and control the execution of any specific algorithm (SE, SF and PC). Eventually, there is a bridge database that permits to connect the previous three databases among each other's. Defining the data structure following the standard documents allowed to ease the exchange of information among algorithms that may use the database as a bridge.

8. Evaluation of IDE4L architecture

The quantitative analysis of the information exchange among the automation actors and on the distribution of monitoring and control tasks are presented, respectively, in paragraph 8.1 and Table 8. The aim of these paragraphs is to underline the advantages of IDE4L architecture with regards to completely centralized approaches as well as with completely distributed ones. The complete set of KPI results of IDE4L architecture is available in D3.3 [27].

8.1. Full mapping of information exchange onto automation actors

A key index in the definition of the performance of an automation architecture is the amount of data to be exchanged and the communication traffic generated. In particular, the automation actors exchange information on regular base or in case of events; these two cases lead different requirements on the HW and SW interfaces and on the communication infrastructure. Events, that trigger unexpected information exchange, may be due to electrical faults, line congestions and estimated or forecasted issues in the state of the grid.

In Tables 6 and 7 the amount of data to be exchanged, are valid considering the following assumptions on the feature of the distribution grid. The DSO, through its DMS manages a total of 10 primary substations, each one having MV grids with 250 buses. Each MV bus has a secondary substation with a LV grid of 250 buses. Such assumption is realistic for the field demo site, at "A2A Reti Elettriche SPA" DSO in Italy. Therefore, there will be a total of 250 primary and secondary SAUs. Moreover, it is assumed to have a generic measurement device (could be an IED or a SM) in each node of MV and LV. Furthermore, it is assumed that a PMU is installed at each substation, both primary and secondary, and in each feeder. Considering an average of three feeders, both in MV and LV grid, there will be totally 4 PMUs providing measurements to each PSAU and SSAU. The assumption on the number of IEDs and PMU does not represent a requirement for any of IDE4L functionalities but is intended to represent a worst case scenario from the point of view of communication burden. Then, it is assumed to have a controllable IED in each of the MV buses and in 25% of LV buses; again this does not represent a necessary requirement from the point of view of the control function but rather a communication test worst case. It was decided, that each commercial aggregator manages a portfolio of 100 customers and the microgrid central controller has a grid of 10 nodes. Eventually, it was considered that all the buses of the distribution grid are involved in case of events (even if it is very unlikely in real cases).

In Tables 6 and 7 the first column indicate the UC where the information exchange takes place, the 2nd and 3rd column indicate respectively the Information Producer and Receiver; the 4th column indicate the information exchange content; the 5th column indicates the amount of data for each of the information exchange; the 6th and 7th column indicate the AD sent or received by the IP and the IR; the 8th column indicates the reporting rate that is required by the UC, for the case of regular information exchange, whereas it indicates the maximum transfer time for the case of event information exchange. The RR and MTT have been defined in the use cases by algorithm developers, standard documents and DSOs, but may be customized depending on the features of the distribution grid where the architecture is installed. From Tables 6 and 7 it is possible to see that only a subset of SE and

Table 7
Table event information exchange.

UC	IP	IR	IE	AD	AD DMS [-]	AD PSAU [-]	RR [frame/s]
Event information exchange between DMS and PSAU and between DMS and MOP							
CCPC	DMS	PSAU	IED setting	1	2500	250	0.5
LV Mon.	DMS	PSAU	SWI-BRE status move to event	3	7500	187.5	300
MV Mon.	DMS	PSAU	SWI-BRE status	1	2500	62.5	300
LV Mon.	PSAU	DMS	SWI-BRE status	3	7500	187.5	300
MV Mon.	PSAU	DMS	SWI-BRE status	1	2500	62.5	300
CCPC	DMS	MOP	Flexibility demand bill day ahead market (power, flexibility band, time of activation, price)	1 200 000	3 000 000 000	–	86 400
CCPC	DMS	MOP	Flexibility demand bill infra day market (power, flexibility band, time of activation, price)	12 500	31 250 000	–	900
RTV	DMS	MOP	Real timevalidation response	12 500	31 250 000	–	900
RTV	MOP	DMS	Real time validation request	12 500	31 250 000	–	900
Event information exchange between PSAU and SSAU							
LV Mon.	PSAU	SSAU	SWI-BRE status	3	46 875	187.5	300
LV Mon.	SSAU	PSAU	SWI-BRE status	3	46 875	187.5	300
Event information exchange between PSAU and IED and between SSAU and IED							
FLISR	PSAU	IED	Switch-breaker control	1	250	1	0.1
FLISR	SSAU	IED	Switch-breaker control	3	187.5	3	0.1
FLISR	IED	PSAU	Switch-breaker status	1	250	1	0.1
FLISR	IED	SSAU	Switch-breaker status	3	187.5	3	0.1
MVPC	PSAU	IED	IED setting (single phase)	1	250	1	0.5
MVPC	IED	PSAU	IED status	1	250	1	0.5
LVPC	SSAU	IED	IED setting	3	187.5	3	0.5
LVPC	IED	SSAU	IED status	3	187.5	3	0.5
CCPC	PSAU	IED	IED setting	1	250	1	0.5
CCPC	IED	PSAU	IED status	1	250	1	0.5
Event information exchange between CAAS and IED							
CAEP	CAAS	IED.HEMS	Energy plan to be activated (power setpoint time tag, flexibility, for 15 min range for 24 h)	5	5	500	300
Event information exchange between PSAU and MGCC and between SSAU and MGCC							
FLISR	PSAU	MGCC	Switch-breaker control	1	10	1	0.1
FLISR	SSAU	MGCC	Switch-breaker control	3	30	3	0.1
FLISR	MGCC	PSAU	Switch-breaker status	1	10	1	0.1
FLISR	MGCC	SSAU	Switch-breaker status	3	30	3	0.1
Event information exchange between IED and MGCC and between IED and IED							
FLISR	IED	IED	Switch-breaker control	1	2	2	0.003
FLISR	IED	IED	Switch-breaker status	1	2	2	0.003
FLISR	IED	MGCC	Switch-breaker control	1	2	2	0.003
FLISR	MGCC	IED	Switch-breaker status	1	2	2	0.003

Table 8
Table number of nodes monitored by each actor in each use case in IDE4L architecture.

Use cases	DMS	PSAU	SAU	IED	MGCC	CAAS
Monitoring (Data concentration)						
LV Mon.	0	0	250	1	1	0
MV Mon.	0	250	0	1	1	0
LV SE	0	1	250	0	0	0
MV SE	0	250	1	0	0	0
LV SF	0	1	250	0	0	0
MV SF	0	250	1	0	0	0
DM	10	250	62.5	1	0	0
FLISR	0	250	250	1	10	0
CAEP	0	0	0	0	0	100
Control						
FLISR	0	250	250	1	10	0
MVPC	0	250	0	0	0	0
LVPC	0	0	250	0	0	0
CCPC	2500	0	0	0	0	100

SF results are forwarded from SSAU to PSAU and then to DMS. This reduces the amount of information to be exchanged in average. Furthermore, the measurements are collected locally by each SAU (having to deal with 250 nodes) and not by the DMS (which will have otherwise to concentrate information from 62 500 nodes). The same is true regarding power control set points, both at MV and LV level. In case of estimated or forecasted power congestions, a communication exchanged is initialized with MOP. The IED–IED, as well as, IED–MGCC information exchanges are triggered only in case of electrical fault and are stopped when the fault is located and isolated; consequently also the SAU participates to the restoration phase. Eventually, it is possible to verify how the amount of data to be exchanged between CAAS and customers is relatively low. Given the requirements on RR and MMT, it is possible to convert the amount of data to be exchanged by each actor into expected communication traffic. The result is presented graphically in Fig. 8, with blue and yellow connectors representing, respectively, regular and event information exchanges, assuming that each data is mapped onto float format, having therefore a size of 64 bits. However, it is worth noticing that the communication traffic, in the real implementation will strongly depend on the communication protocol used (i.e. the header frame and how the packets are built).

8.2. Distribution of control and monitoring tasks among automation actors

In Table 8 the nodes that are monitored and controlled by each actor for a network, with the same size as the one specified in

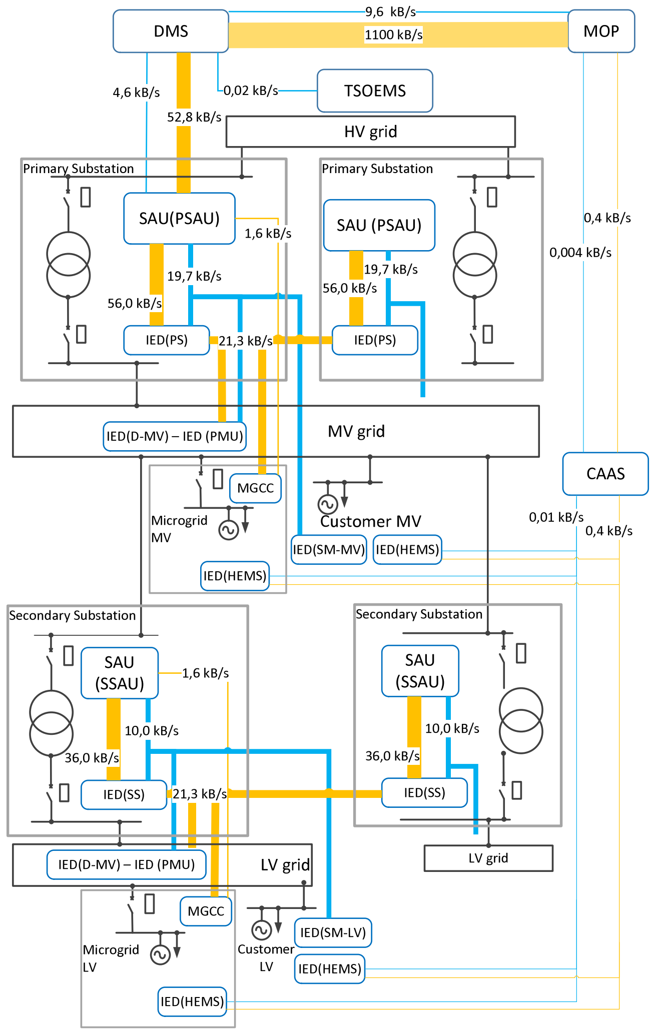

Fig. 8. IDE4L architecture, with expected communication traffic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Section 8.1, are shown. It can be noticed that even if the total size of the network is 62 500 nodes, each actor manages a maximum of some hundred nodes. Exception is made in the case of control center power control, when the DMS may directly coordinate IEDs at medium voltage level. The reduced number of nodes managed by each actor yields a low risk of communication congestions and relax the requirements for computation of each individual unit. This is a design specification expressively defined in use cases by, both, algorithm developers and DSOs. In fact, it was required to avoid situation of execution of heavy computation duties (as large power flow or state estimation calculations) in regular operation, in order to reduce the risk of error propagation and to reduce the average computation times. Similarly, the specifications for the individual units are relaxed for data acquisition and storing. This also permits to realize field implementations based on low cost automation units. At the same time, IDE4L architecture has the advantage of guaranteeing through the hierarchical distribution of monitoring and control function a certain robustness versus failure of single area with regards to fully distributed architecture. In fact, in case of failure of a certain SSAU, the portion of, e.g. 250 low voltage nodes will be temporarily monitored and controlled by the local IED controllers as well as the upper level PSAU, assuring for the time being, the necessary automation tasks and guaranteeing operation security. At the same time the other areas, not monitored/controlled by the failed SSAU, can continue the regular operation. On the other way, completely centralized systems, have to rely on the DMS operation, which in case of failure do not allow any backup monitoring or control solution.

9. Conclusion

The IDE4L architecture has been presented in terms of SGAM architecture and implementation instance and evaluated, with KPIs, to see how it addresses the main smart grid functionalities and how distributes the information exchanges and the automation tasks among actors. The automation actors have been defined in a similar three layer structure, based on interfaces, database and applications. In this way the scalability of the architecture is improved and there is also a positive impact on CAPEX by reusing of existing automation components (e.g. existing RTUs or SMs). The information exchange among layers and among actors is simplified by the use of standardized data models like the ones defined IEC 61850 and CIM standards. Moreover standard data models permits to limit the integration with existing automation units and devices and improves the interoperability of hardware and software provides positive impact on CAPEX and OPEX. The automation burden is distributed over three hierarchical levels, namely formed by IEDs, SAUs and DMS. They elaborate locally a limited amount of information and exchange with other level synthetized data. In this way the requirements for the computation units are released as well as the requirements for the communication exchanges.

The architecture and in particular the distribution in the power system of automation actors, as well as their interconnections, as presented in Fig. 8 shows to distribute effectively the amount of data to be handled. SE and PC algorithms may be performed in shorter times and with less expensive HW, reducing the CAPEX. Moreover, the actors at higher hierarchical levels need only compressed data or synthetic indexes from the lower levels, reducing the overall exchange of information.

References

[1] J. Northcote-Green, R. Williams, Control and Automation of Electrical Power Distribution System, Vol. I, Taylor and Francis Group, Boca Raton, 2007.
[2] Y.V. Pavan Kumar, Ravikumar Bhimasingu, Key aspects of smart grid design for distribution system automation: Architecture and responsibilities, Procedia Technol. (ISSN: 2212-0173) 21 (2015) 352–359. http://dx.doi.org/10.1016/j.protcy.2015.10.047.
[3] F. Perkonigg, D. Brujic, M. Ristic, Platform for multiagent application development incorporating accurate communications modeling, IEEE Trans. Ind. Inf. 11 (3) (2015) 728–736.
[4] P. Vrba, et al., A review of agent and service-oriented concepts applied to intelligent energy systems, IEEE Trans. Ind. Inf. 10 (3) (2014) 1890–1903.
[5] A. Vaccaro, V. Loia, G. Formato, P. Wall, V. Terzija, A self-organizing architecture for decentralized smart microgrids synchronization, control, and monitoring, IEEE Trans. Ind. Inf. 11 (1) (2015) 289–298.
[6] J. Navarro, A. Zaballos, A. Sancho-Asensio, G. Ravera, J.E. Armendariz-Inigo, The information system of INTEGRIS: INTelligent electrical GRId sensor communications, IEEE Trans. Ind. Inf. 9 (3) (2013) 1548–1560.
[7] A.I. Sabbah, A. El-Mougy, M. Ibnkahla, A survey of networking challenges and routing protocols in smart grids, IEEE Trans. Ind. Inf. 10 (1) (2014) 210–221.
[8] V.C. Gungor, et al., A survey on smart grid potential applications and communication requirements, IEEE Trans. Ind. Inf. 9 (1) (2013) 28–42.
[9] T. Strasser, F. Andrén, F. Lehfuss, M. Stifter, P. Palensky, Online reconfigurable control software for IEDs, IEEE Trans. Ind. Inf. 9 (3) (2013) 1455–1465.
[10] Fanghong Guo, Changyun Wen, Jianfeng Mao, Jiawei Chen, Yong-Duan Song, Distributed cooperative secondary control for voltage unbalance compensation in an islanded microgrid, IEEE Trans. Ind. Inf. 11 (5) (2015) 1078–1088.
[11] S. Repo, S. Lu, T. Poho, D. Della Giustina, G. Ravera, J.M. Selga, F. Alvarez-Cuevas Figuerola, Active distribution network concept for distributed management of low voltage network, in: Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES, vol., no., pp.1,5, 6–9 Oct. 2013.
[12] E. Peeters, D. Six, M. Hommelberg, R. Belhomme, F. Bouffard, The ADDRESS Project: An architecture and markets to enable active demand in: Energy Market, 2009. EEM 2009. 6th International Conference on the European, vol., no., pp.1,5, 27–29 May 2009.
[13] R. Belhomme, R. Cerero, Giovanni Valtorta, P. Eyrolles, The ADDRESS project: Developing Active Demand in smart power systems integrating renewables in: Power and Energy Society General Meeting, 2011 IEEE, vol., no., pp.1,8, 24–29 July 2011.

[14] ABB. Available online: abb.com.
[15] Schneider Electric. Available online: schneider-electric.com.
[16] Siemens. Available online: siemens.com.
[17] GE grid solutions. Available online: gegridsolutions.com.
[18] Oracle. Available online: oracle.com.
[19] European Commission, Smart Grid Mandate - Standardization Mandate to European Standardization Organizations (ESOs) to support European Smart Grid deployment, 2011.
[20] Smart Grid Coordination Group, Smart Grid Reference Architecture,CEN-CENELEC-ETSI, Tech. Rep., 2012.
[21] A. Riccobono, et al. Systematic method for the development of future active distribution network automation architectures, in: PowerTech, 2015 IEEE Eindhoven, Eindhoven, 2015, pp. 1–6.
[22] INTEGRIS FP7 project. Available online http://fp7integris.eu/.
[23] EvolvDSO FP7 project, deliverable 2.2. Available online http://www.evolvdso.eu/getattachment/cd99e181-f0b5-4d38-9663-e001377a2468/Deliverable-D2-2.aspx.
[24] SUCCESS H2020 project. Available online http://success-energy.eu/.
[25] IDE4L, Deliverable 3.2 Architecture design and implementation, http://webhotel2.tut.fi/units/set/ide4l/D3.2/ide4l-d3.2-final.pdf.
[26] Narender Singh, Hossein Hooshyar, Luigi Vanfretti, Feeder dynamic rating application for active distribution network using synchrophasors, Sustain. Energy, Grids Netw. (ISSN: 2352-4677) 10 (2017) 35–45. http://dx.doi.org/10.1016/j.segan.2017.02.004.
[27] IDE4L, Deliverable 3.3 Laboratory Test Report, https://webhotel2.tut.fi/units/set/ide4l/ide4l-D3.3-2016-final.pdf.