A Cloud-Based Platform for Service Restoration in Active Distribution Grids

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Abstract—In modern distribution grids, the access to the growing amount of data from various sources, the execution of complex algorithms on-demand, and the control of sparse actuators require on-demand scalability to support fluctuating workloads. Cloud computing technologies represent a viable solution for these requirements. To ensure that data can be exchanged and shared efficiently, as well as the full achievement of the cloud computing benefits to support the advanced analytic and mining required in smart grids, applications can be empowered with semantic information integration. This article adopts the semantic web into a cloud-based platform to analyze power distribution grids data and apply a service restoration application to re-energize loads after an electrical fault. The exemplary implementation of the demo is powered by FIWARE, which is based on open-source and customizable building blocks for future internet applications and services, and the SARGON ontology for the energy domain. The tests are deployed by integrating the semantic information, based on the IEC 61850 data model, in the cloud-based service restoration application and interfacing the field devices of the distribution grids. The platform performances, measured as network latency and computation time, ensure the feasibility of the proposed solution, constituting a reference for the next deployments of smart energy platforms.

Index Terms—Cloud-based platform, FIWARE, middleware, semantic web, service-oriented, service restoration, smart energy platform.

ACRONYMS

API	APPLICATION programmable interface.
CAIDI	Customer average interruption duration index.
CB	Context broker.
CDC	Common data class.
CIM	Common information model.
CT	Current transformer.
DER	Distributed energy resources.
DMS	Distribution management systems.
DO	Data object.
FLISR	Fault location isolation and service restoration.
GTNET	Gigabit transceiver network.
HILP	High-impact low probability.
IED	Intelligent electronic device.
LD	Logical device.
LN	Logical node.
NGSI-LD	NGSI-linked data.
OMA	Open mobile alliance.
RESTful	Representational state transfer.
RTDS	Real-time digital simulator.
RTU	Remote terminal unit.
SAIDI	System average interruption duration index.
SAREF	Smart appliance reference.
SCADA	Supervisory control and data acquisition.
SOA	Service-oriented architecture.
SOAP	Simple object access protocol.
SR	Service restoration.

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I. STATE-OF-THE-ART

THE electrical grid network must be continuously monitored through data gathered from measurement instruments, to guarantee the prompt intervention of protection components in case of fault, minimize the consequences of outages on the power delivery, and recover to healthy conditions in minimum time [1]. The occurrence of electricity interruptions causes several economic and social impacts on the network and worsens the reliability indices such as Average Interruption Duration Index (SAIDI) or Customer Average Interruption Duration Index (CAIDI), which represent the quality of power delivery [2]. The utilities aim at improving these performance indicators to avoid sanctions and increase the end-users satisfaction, by equipping the distribution grid with smart automation solution [3]. Currently, many electrical networks are not fully automated, and corrective actions for the fault management are performed by human operators. This process introduces delays and criticalities, which reduce the reliability of the system, depending upon the size of the outage [4].

Fault Location Isolation and Service Restoration (FLISR) is a key enabler of the self-healing of Distribution Management Systems (DMS) in automated electrical grids [5], [6]. FLISR consists of two parts: At first, the faulted area is isolated by tripping the nearest upstream circuit breaker and opening the downstream switches. Then, the network is reconfigured to energize the restorable loads, which had been disconnected being

downstream the isolated faulted area. This article focuses on the Service Restoration (SR) functionality, on which the duration of the service interruption and therefore the reliability indices depend upon.

The automated SR requires a vast amount of data (switching devices statuses, measurements from metering devices, load and generation profiles, as well as network parameters) that need to be analyzed, requiring high computing power and time-consuming algorithms. Consequently, different solutions have been suggested by researchers based on cloud computing to provide scalability on-demand, at fault occurrence. Previous research activities investigated distributed and parallel computing in future power systems. A grid computing method is proposed in Ref. [7], a fast parallel processing of mass data in cloud computing is given in Ref. [8], and a study of running a smart grid control software in cloud computing is presented in Ref. [9], to identify and examine technical needs for building the smart grid automation and the computing infrastructure.

Furthermore, to ease and improve the development of distributed architectures, cloud vendors are offering distributed system services, called middleware, which have standard Application Programming Interface (API) and protocols. Several studies focus on middleware, in the frame of projects or research, as compared and classified in Refs. [10], [11]. Recently, middleware development is central importance to the concept and design of a Service Oriented Architecture (SOA). In SOA, application components provide services to other components via a communication protocol and web standards such as Simple Object Access Protocol (SOAP) and Representational State Transfer (RESTful) [12], [13]. SOA enables SR application development through discrete units of functionality, which are self-contained interoperable and technology neutral.

Hence, the traditional cloud computing paradigm like data center and cloud services must be extended to address cross-domain requirements and include a diverse type of data sources. Indeed, such a system requires to address the challenges regarding the access to the different resources.

Accordingly, one of the primary requirements of such infrastructure is the provisioning and discovery of various data sources, including registration, removal, querying, etc. Therefore, a semantic-based approach has been taken, which is introduced at early stages of cross-domain information access and tackles discovery of various data sources [14].

Moreover, smart grid is known as a complex cyber-physical system due its decentralized infrastructure. To address challenges introduced in smart grid on substation automation level, IEC 61850 and IEC 61499 are taken into consideration as reference industrial standards. There have been several researches that applied ontology modeling of these two standards. To harmonize the industrial standards IEC 61850 and the Common Information Model (CIM), Refs. [15], [16] use ontologies which consist of the industrial standards IEC 61970 and IEC 61968. Yang *et al.* [17] have developed a requirement-modeling framework that automated the process of translation from requirements to ontology-based on IEC standards. Nevertheless, the main contribution of mentioned researches was on modeling the smart grid rather than demonstrating the usage of semantic information model in the system. In Ref. [18], semantic information model has been employed to provide sufficient
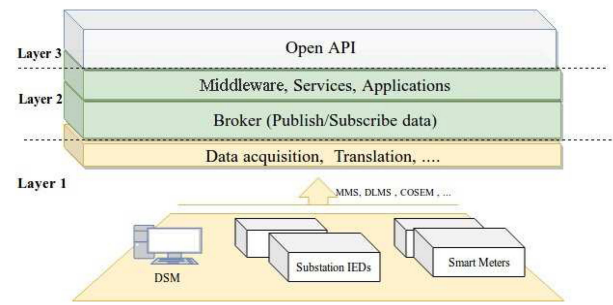

Fig. 1. Three main layers in cloud-based platform.

interoperability and reduce cost associated with implementing advanced controls, fault detection, and diagnostics. Although they have investigated effort in developing information model, their work is limited to the smart building technologies and use cases.

According to the aforementioned studies, in this article, cloud-based platform for SR in active distribution grid has been extended with a semantic information model based on IEC 61850 standard. The features of semantic model ease the future graph analysis in support of network reconfiguration. Furthermore, advanced analytic can be established with engaging semantic model of smart grid system.

To accelerate the implementation process, FIWARE [19] has been used. FIWARE is an example of SOA and open-source architecture platform that extended its powerful interface with NGSI Linked Data (NGSI-LD) [20], to include semantic web into its core model. NGSI-LD model helps to cross-cut context information and precisely communicate the nature of context information for a given service, such as its period of validity, its geographical constraints, and each relevant semantic information.

II. ARCHITECTURE OVERVIEW

This work presents a cloud-based SR according to the SOA. This goal is achieved via combination of a multilayered architecture and SOA based on three main layers: data acquisition and translation related middleware, generic and specific domain middleware, and an open API, as shown in Fig. 1.

Layer 1 is responsible of data acquisition, collection, translation, and transmission to layer 2. It accommodates several standard protocols (such as IEC 61850 MMS, GOOSE, DNP3) and data translation. This layer supports the mapping of raw data coming from Intelligent Electronic Device (IED) to a standardized data representation in the cloud.

Layer 2 is a combination of generic and specific domain middleware that are loosely coupled to perform a distributed SR in cloud. The scenario of this work uses services to manage, analyze time-series, and visualize information. The services in this layer are taken from FIWARE catalogue and presented in the following. Layer 3 is a publicly available API that provides developers with open access to the back-end data.

Fig. 2 represents the detailed mapping of middleware with respect to the layered architecture explained before and presented in Fig. 1. The yellow and green boxes in Fig. 2 present the first and second layer middlewares, respectively. The IoT agent, which is shown in yellow, is located in layer 1 of the architecture and used to collect and translate the data from the field. CrateDB,
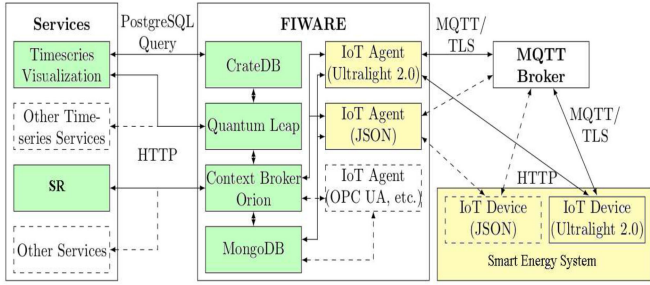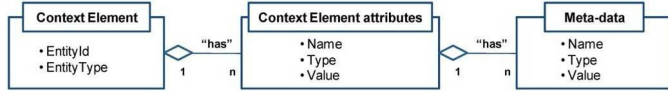
Fig. 2.   Architecture mapped to the services.

Fig. 3.   Context element conceptual diagram [19].

Fig. 4.   NGSI-LD information model [20].

Quantum Leap, Context Broker (CB), MangoDB, time-series visualization, and FLISR are a list of generic and specific services that are located in layer 2 of the architecture and shown in green.

In the following, the platform services are explained. Furthermore, SR is a domain-specific service implemented by composing FIWARE services. In particular, the embedding of SR into FIWARE services and the feasibility of the presented cloud-based platform for SR are analyzed in Sections III and IV, respectively.

A. FIWARE Services

FIWARE framework is used as a central system to manage and store the data; moreover, this framework contains a list of open-source services to facilitate and accelerate development of smart Internet-related application in various domains [19]. In the following, a brief overview of the services powered by FIWARE that are used in the SR platform is given.

The CB is a key service in the FIWARE catalogue. It eases the development and provisioning of innovative applications that require management, processing, and exploitation of context information as well as data streams, in real time and at massive scale and distributed format. This broker is used to develop applications dealing with publish/subscribe data through NGSI, which is currently a *de facto* standard that has been released by the Open Mobile Alliance (OMA) [21]. Contextual elements that are defined based on NGSI are referred to as entities. Entities are physical objects (i.e., sensors or actuators), hardware, and software as presented by generic data structure in Fig. 3.

Based on this conceptual definition, entities are uniquely identified by an ID. Each entity can have attributes which are related to its characteristics. These attributes have static or dynamic values and are represented by the triplets <name, type, value>. NSGI-LD includes semantic data representation within entities and their attributes and is published as a standard by ETSI [20]. NGSI-LD is expressive enough to connect and federate other existing information models, using JSON-LD. It is also compatible with RDF so that triple stores and application logic, e.g., in SPARQL or DataCube software, can be applied. The NGSI-LD information model is defined at two levels, consisting of the core meta-model, i.e., the cross-domain ontology and the domain-specific ontologies, as shown in Fig. 4. Based on
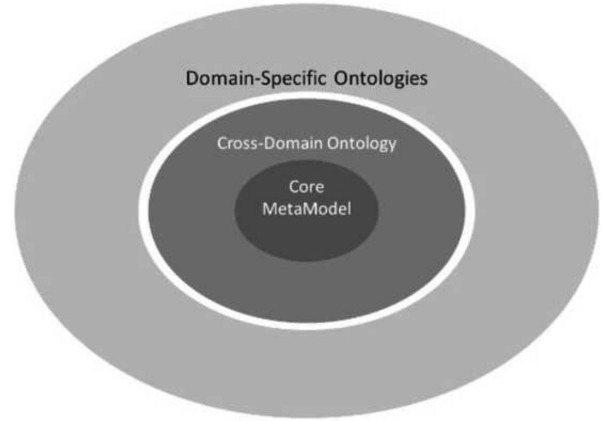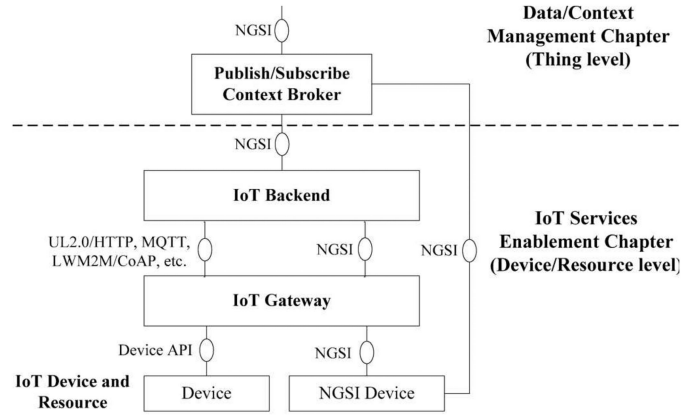

Fig. 5.   FIWARE IoT platform architecture [19].

different studies in the agricultural domain with several sensors [22], this conceptual definition of context information is compatible with IoT infrastructure and easily extendable. In order to publish data of physical devices called "IoT devices through cloud," NGSI-LD interfaces IoT devices and context management services. To accomplish this transaction of information, NGSI-LD uses RESTful API via HTTP. The data itself is stored in an underlying MongoDB, which refers to CB. CB provides data like as a storage; therefore, to make this service more powerful, other building blocks are considered. Each block has its own technological focus, which is dealing, for example, with storing time-series data like Quantum-Leap and CrateDB, Big data processing, or visualization.

IoT agents establish communication of devices or smart resources with the cloud platform based on defined standard protocols. The FIWARE IoT platform contains the two blocks that are IoT backend and IoT edge. The IoT backend focuses on the management of IoT devices by providing a list of functions and services in the cloud. It connects the physical objects with the platform. The IoT edge is a protocol or standard adapter to all on-field IoT physical objects connecting them with IoT backend. The IoT edge offers the communication layer to the host environment. The overall view of FIWARE IoT is presented in Fig. 5.
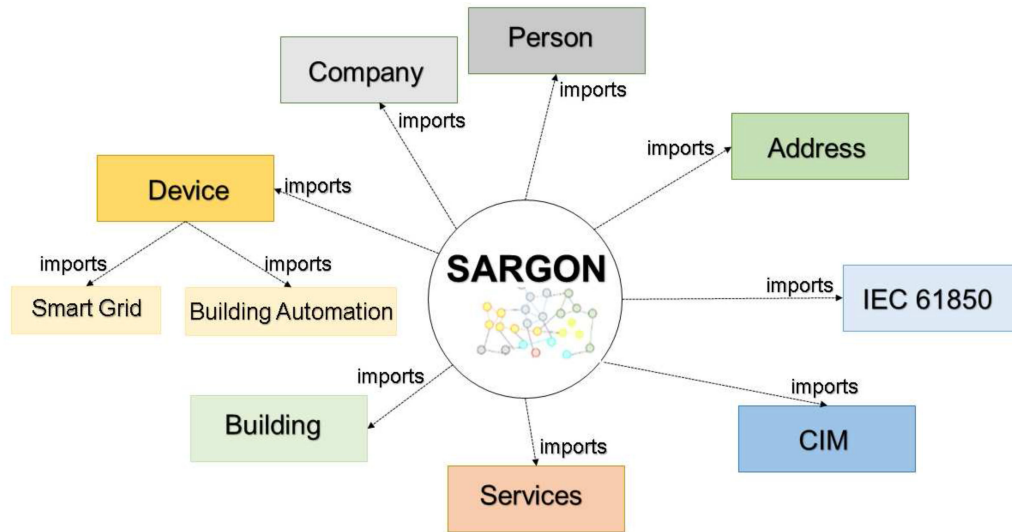
Fig. 6.   SARGON ontology network structure [24].

B. Domain-Specific Ontology

The previous work regarding cloud-based platform for SR in active distribution grids is described in Ref. [23] and it assesses the SR as a cloud-based service. To integrate the semantic web into the implemented SR cloud-based platform, this article proposes the developed SARGON [24] ontology, which extends Smart Appliance Reference (SAREF) ontology [25] to cross-cut domain-specific information, representing the smart energy domain, and includes joint management of building and electrical grid automation. SARGON ontology is based on IEC 61850 and CIM standards and is developed for the real use cases like monitoring and control of electrical grids via IEDs, automation of medium voltage distribution grids, controlling of the energy demand in buildings, energy management with residential/nonresidential involvement, etc.

Additionally, in the smart energy domain, the role of CIM and IEC standards is undeniable. Therefore, reference to these two standards as a pattern is useful to extract the domain model and components to monitor and protect the smart grids. Indeed, it improves the interoperability in the information layer.

By considering the aforementioned concept, SARGON ontology is made of several interconnected domain ontologies that are linked into the core SARGON ontology. Fig. 6 presents an overview of SARGON ontology. In the core of SARGON ontology, different types of devices in the smart energy domain are defined, which are either grid- or building-related, to extend SAREF ontology. Smart energy devices are the main building blocks in SARGON ontology and add several properties and classes into SAREF, based on the mentioned standards CIM and IEC 61850.

Concerning NGSI-LD information model as presented in Fig. 4, the SARGON ontology, which is developed for the smart energy domain, is taken as a domain-specific ontology. Furthermore, it is mapped into the cross-domain ontology of the NGSI-LD information model.

For feasibility check, the assessment cases adopt the SAR-GON ontology to provision, govern, discover, and query the data of smart grid network.

C. SR as a Domain-Specific Service

To perform the SR functionality, this article uses an innovative implementation of a rule-based optimization algorithm, specifically adapted for the cloud-based platform presented in this article, and that has been developed as first reaction in critical situations [26]. This algorithm was proved to be fast, simple, and, thanks to its adaptability to unstable grid conditions, suitable for High Impact Low Probability (HILP) events as cascade faults, which cause multiple de-energized sections in the electrical network [1].

In this study, the RBO algorithm for service restoration of active distribution grids has been implemented as a service. It is applied to radial electrical grids that host Distributed Energy Resources (DER) along the feeders and are fed through several primary substations, assumed to behave as power sources, energizing the loads connected along their own feeders. The feeders of different primary substations are connected via normally open switches, called bus-tie units. As soon as an electrical fault (e.g., a short circuit) occurs in the grid, the nearest switching devices, upstream and downstream, open to isolate the fault area. After the fault is cleared, the service restoration is activated to re-energize the loads downstream the fault area, which were disconnected due to the actuation of the protection schema.

The RBO algorithm analyzes the priority factors of the de-energized loads, from the grid parameters data set, to select the node of most crucial customer (e.g., hospitals, gas network pumps, critical infrastructures), which becomes the objective of the iterative restoration process. The type of demand in the network determines the criticality of the corresponding network node and, hence, the priority factor. Considering the grid topology based on the actual statuses of the switches, the algorithm identifies which is the most suitable primary substation to re-energize the selected node with an alternative path, by closing a normally open bus-tie unit. Each network topology, obtained by closing a different bus-tie unit for each substation in the network that can reconnect the target node, is evaluated with a state estimation approach, which considers as measurements the

voltage at the slack bus and the power injections (active and reactive) at each other bus of the feeder [27], [28]. These measurements are ordinarily available for medium-voltage distribution grids, whose nodes are associated with secondary substations. If the technical constraints are verified (voltage, thermal, and network radiality), the restoration scheme having the minimum total power losses is implemented. Sections of the feeders that include DERs assume a particular priority because they reduce the power requested from the primary substation and facilitate compliance with the technical constraints. After the selected tie unit successfully closes, the process restarts and continues until all the de-energized loads are reconnected or the constraints are violated. The algorithm can manage whichever network change that could occur during the restoration process and considers real-time measurements from field devices or forecast data, together with their accuracy, in the computation process. The algorithm is developed in the programming language Python, suitable for the integration in the cloud-based architecture with the presented FIWARE services: It has been adapted to retrieve necessary data from CB and provide the computed solution, according to a common data structure. As a specific service in the platform, it is completely independent of grid topology and electrical parameters.

III. CLOUD-BASED PLATFORM FOR SERVICE RESTORATION

The presented architecture is used to implement an automated cloud-based SR. The services introduced in the last section are assembled in OpenStack, which is a free and open-source software platform for cloud infrastructure management. With respect to Section II, the data from measuring devices are sent to the platform via communication protocols such as MQTT and CoAp. Since CB supports HTTP and RESTful API, data from measuring devices can be sent directly to CB based on SARGON ontology. The FIWARE IoT enabler, as an interface to the field, supports data stream to the platform by translating and transferring the data of measuring devices to the CB with different communication protocols.

In the test setup, the main focus is on cloud-based SR; therefore, the given architecture is validated in the simplest possible case. In this case, measurement values are provided according to the SARGON ontology to the cloud platform via Ethernet using HTTP protocol. Since all interactions between the services are initiated by HTTP, IoT enabler is omitted in this setup. Additionally, FIWARE includes many services for context data process, analysis, and visualization, which are however not used in the SR platform configuration. The proposed platform aims to enhance the data management and the associated services for real distribution grids. Its application consists of the integration within the existing DMS: The deployed software components make use of a semantic information model to efficiently integrate the field devices and manage their data in a scalable, cloud-based platform that supports on-demand workloads. This approach is particularly relevant due to the increasing amount of data to be managed by the Supervisory Control And Data Acquisition (SCADA) systems of the grid operators. Several services to operate the distribution grids can be further integrated into the platform: Our application focuses on the automated service restoration component, to efficiently re-energize the disconnected MV nodes due to fault occurrences.
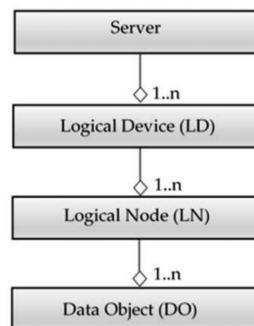

Fig. 7. IEC 61850 information model [31].

A. IEC 61850 Object Model in SARGON

IEC 61850 is the leading standard for substation automation, whose information can be found in Ref. [29]. IEC 61850 defines an object-oriented modeling of data process required for the system automation and has been primarily defined for exchange of information within substations in the part IEC 61850-7-4 [30]. Fig. 7 presents the main structure of the IEC 61850 information model. The main class is the server, hosted by physical devices, corresponding to the controller part of IEDs. The server can host one or more Logical Device (LD), which are virtual representation of devices designed for supervision, protection, or control of automation systems. LDs are the combination of several Logical Node (LN) which define device functionality interfaces. Data Object (DO) are known as a Common Data Class (CDC) from IEC 61850-7-3 or IEC 61850-7-2 [30]. Furthermore, type and structure of the data for each CDC are described within the LN.

According to aforementioned description of IEC 61850, logical device class has been defined in SARGON ontology to represent the subclass of devices for grid-related domain. Furthermore, the hierarchical data model according to developed IEC 61850-7 in SARGON is shown in Fig. 8, which represents various developed IEC 61850 elements. To adopt SARGON into the platform, a serialization into NGSI-LD is required, which has been performed manually and accurately described. For instance, *"Relay1.XCBR1.ST.Pos.stVal"* is sent to CB, representing the status of the circuit-breaker switches. It is constituted by the specific components described here: *Relay1:* logical device, protection relay related to the circuit breaker; *XCBR1:* logical node "circuit breaker" of instance "1"; *ST:* functional constraint for "status information"; *Pos:* data object "position," accessed to verify the switch position; *stVal:* data attribute to indicate the status value of the data.

B. Service Restoration Middleware Control Flow

Fig. 9 shows the overall control flow of SR: Detecting the fault via CB, performing the service restoration process, and sending the command to actuate the computed solution. In this setup, both the CB and the SR services run in the same network. Data are provided from the smart devices in the electrical network to the platform via HTTP and are formulated based on the data structure of CB.

The grid data include the switches information (status and tripped condition) and the real-time measurements necessary for the state estimation. The switches statuses are provided to CB as changes occur, whereas the field measurements are updated
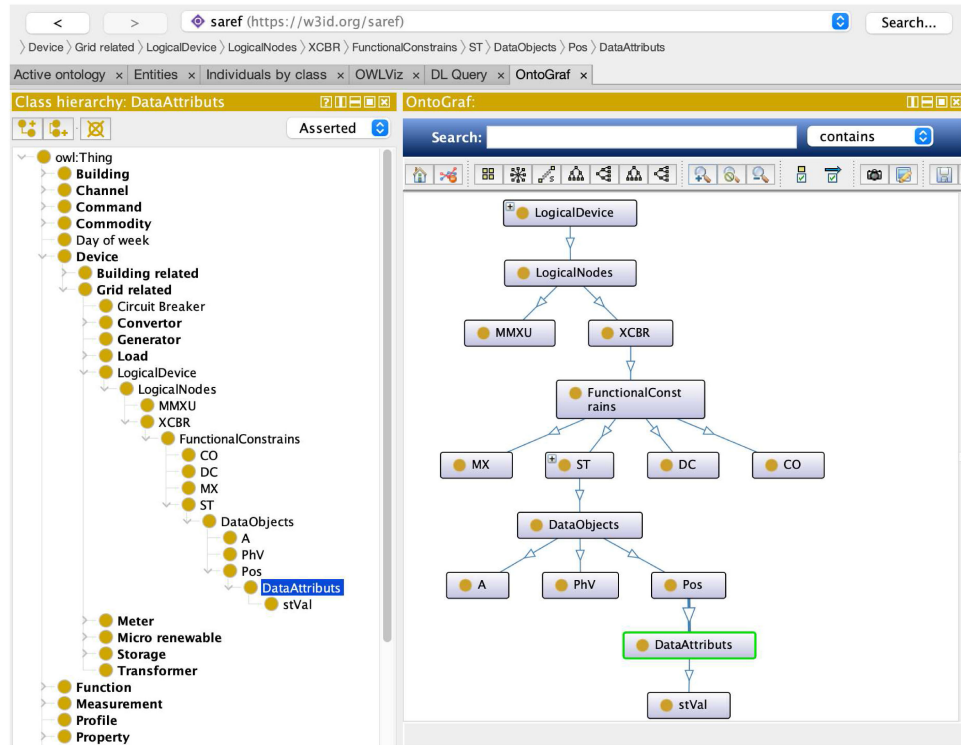
Fig. 8.   Data representation based on IEC standard presented in Protege.
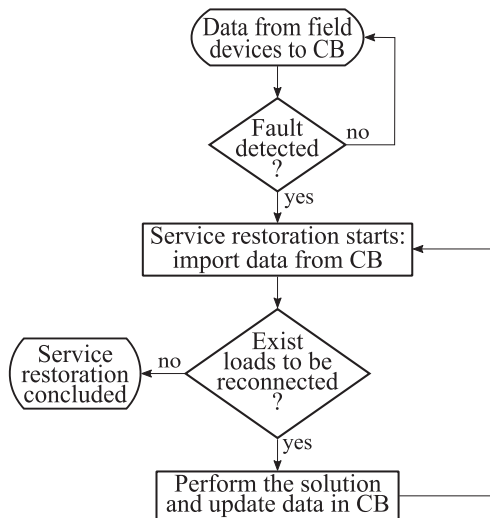

Fig. 9.   Control flow of the service restoration process.

every 2 s, in line with the cycling polling rate from Remote Terminal Unit (RTU) to SCADA systems in distribution networks [32]. In order to execute the state estimation, static data are stored and accessible in the CB: Network model (topology and parameters of the lines) as well as configuration and accuracies of measurement devices.

The CB is capable of receiving data and notifying an event, in case of correspondence of the acquired value to a specific entity. In this specific implementation, the condition of tripped circuit breakers due to a fault in the grid is monitored to activate the SR. If network data that indicate the presence of a fault are updated

in CB, these values satisfy the notification condition: The CB sends a message to SR service, which starts to process the information and retrieves the data related to the network from the CB. The SR algorithm continuously iterates to re-energize each disconnected load, until all possible loads are reconnected or the safety electrical constraints are violated, and provide the solution to the CB. Then, the CB issues the network reconfiguration commands, i.e., closing of specific switches, to the devices in the grid network. Once the closing operation is successfully performed, data are updated in the CB.

C. Electrical Grid Emulation

The electrical network is emulated through the Real Time Digital Simulator (RTDS) with its NovaCor hardware platform. The dedicated hardware components guarantee the accurate simulation of grid behavior, i.e., the measurements of electrical quantities that are exchanged with the implemented software platform. Grid modeling is carried out via the dedicated software RSCAD: in addition to the power systems components (as electrical loads, distributed generators, switches, etc.), the IEDs and RTUs are emulated. These devices publish the grid measurements (node voltages and power injections) and switches information (tripping condition and position status) into the communication network, reaching the interface layer of the platform. In particular, the Gigabit Transceiver Network (GTNET) card of RTDS provides a real-time communication link to and from the simulator via Ethernet. Similarly, the network reconfiguration commands (as outcomes of the performed SR algorithm) are issued to the emulated RTUs/IEDs and, consequently, to the modeled switching devices.
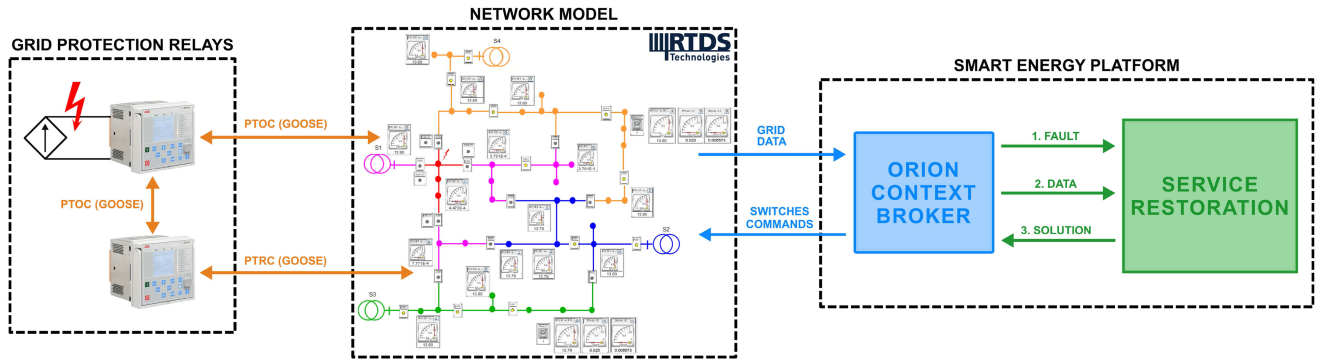
Fig. 10.   Setup of the implemented platform with the emulated electrical grid.

The setup includes also industrial protection relays for detection of electrical fault and, consequently, the coordination to isolate the fault area through the tripping of nearby (upstream and downstream) switches. Particularly, the tests are conducted by integrating two ABB REF615 feeder protection and control relays, equipped with IEC 61850 communication feature. The grid measurement is emulated by injecting current, from a controlled source, in the Current Transformer (CT) terminals of one relay: As the value overcomes the predefined threshold, the overcurrent protection is triggered and the IEC 61850 GOOSE message is published, via the logical node PTOC (time overcurrent). The message is subscribed by the GTNET card of RTDS, issuing a tripping command for the circuit breaker associated to the relay (upstream the fault). Additionally, the same GOOSE message is subscribed by the second relay, which publishes its own GOOSE message via the logical node PTRC (protection trip conditioning), in order to accomplish the fault zone isolation and similarly open the associated (downstream the fault) switch in the grid model. The complete setup of the implemented hardware and software component, together with the exchanged data flows, is represented in Fig. 10.

The setup has been implemented in order to replicate the operational behavior toward the DMS in the real electrical grid. Particular focus has been placed on the deployment of standard communication protocols for the automation of electrical grids, specifically the IEC 61850 and CIM: The use of these data models allows to interface realistic gateway from the implemented platform. This aspect is also ensured by the integration of industrial protection relays for the coordination of fault management actions. The accuracy of the measured quantities, to reflect the network behavior in real time, is guaranteed by the high quality of professional RTDS system. This described setup allows to obtain precise and reliable statistical information related to fault occurrences and the consequent responses for each feature of the deployed platform.

IV. ASSESSMENT CASES

The analysis aims at evaluating the latency of the cloud-based platform to handle SR in case of fault occurrence in the grid network, in which different communications networks of the grid are not considered and just latency of FIWARE services to support SR is tested. All tests were performed 50 times to statistically identify the latency between services to activate
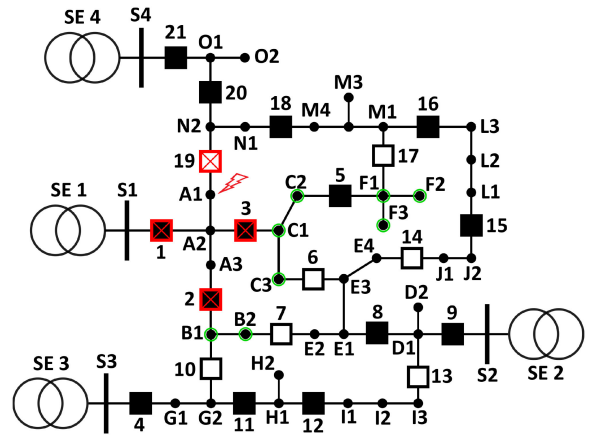

Fig. 11.   Network model for the first test case.

SR. CB performs not only the data publishing but also context information management to handle SR. Therefore, the reported time to activate SR depends on the grid size and pattern. In the following, a description of grids used in this evaluation is presented.

A. First Case: 40-Nodes Network

Each node of the electrical grid includes a primary substation, a passive load, or a DER, whereas the electrical lines, which connect two nodes, can host switching devices.

Fig. 11 shows the single line diagram of the electrical grid used to perform the test [33]. It represents a medium voltage distribution grid at 13.8 kV, with four primary substations whose feeders are connected by normally open tie units, indicated with white squares in the figure. The black squares indicate the normally closed switches. Each node hosts a load, in the range from 100 kW to 1 MW, with the exception of nodes I2 and L1 to which DERs of 200 and 250 kW, respectively, are connected. The overall data of the network are reported in Ref. [26]; they are mapped according to the contextual information model of the CB as described in Section II.

Tripped condition of the circuit breakers is the monitored attribute which, eventually, indicates the presence of a fault and determines the activation of the SR with a notification by CB. Once the SR middleware is initiated, the algorithm retrieves from CB information regarding the topology of the network, statuses (open/close) of the switching devices, parameters of electrical

lines, power consumption/generation, and priority indexes of the loads.

In the test case, a fault is assumed to occur at node A1. Hence, the protection system opens the switches indicated by numbers 1, 2, 3, and 19, as is shown in Fig. 11, to isolate the fault area. The switch statuses are updated in the CB; among them, the information about tripped breakers satisfies CB subscription for fault occurrence and the SR is activated. The SR retrieves all the network data from CB; then, the algorithm determines the loads that became de-energized (indicated by green circles in Fig. 11). Considering loads criticality, B2 is the one with the highest priority, then it is considered as target node for the restoration. There are two feasible restoration paths which preserve the radiality of the network: from substation SE 2, by closing switch 7, or from substation SE 3, by closing switch 10. Since the latter option guarantees lower power losses, this restoration topology is implemented: The SR provides the closing command, related to switch 10, to CB via HTTP protocol. This command is sent to the switch in the grid by CB, which in the successive collection of measurements verifies that the closing operation has been successfully performed and updates the CB table. It is worth mentioning that, since nodes B1 and B2 are electrically connected, the closing of switch 10 re-energizes both of them.

Then, the algorithm retrieves the network data from CB and repeats the analysis of the disconnected loads, for which C2 becomes the target node. Its restoration can be performed by substation SE4, by closing switch 17, or by substation SE 2, by closing switch 6. In this case, the restoration topology from SE 2 is the most convenient. Once the closed status of switch 6 is updated in the CB, the RBO algorithm terminates because all the possible loads have been reconnected. The reconnection of loads inside the fault area (A1, A2, and A3) involves inspection/reparation of the fault and it is beyond the scope of the service restoration.

B. Second Case: 400-Nodes Network

This scenario considers a larger network model, which is composed by 400 nodes. Fig. 12 represents this model, in which the basic network model refers to the grid reported in Fig. 11 and used for the first test case: Starting from its nodes S3 and I3, nine subgrid blocks are connected to each other in series.

Each subgrid block is composed by one substation, 39 passive loads in the same range from 100 kW to 1 MW, and 21 switches. As in the first test case, also in this scenario, the fault occurs at node A1; the restoration from any of the primary substations in the added subgrid blocks is not possible, since the radiality of the network would be lost. Hence, the restoration proceeds as explained in the previous paragraph. This larger grid model has been introduced to test the feasibility of the algorithm to manage a network having greater dimensions and to evaluate the communication latency.

V. SERVICE RESTORATION PLATFORM EVALUATION

To investigate the validity of the proposed setup, the communication network latency is recorded: It corresponds to the time that elapses between sending data to CB and the detection of the fault occurred in the electrical network, the consequent
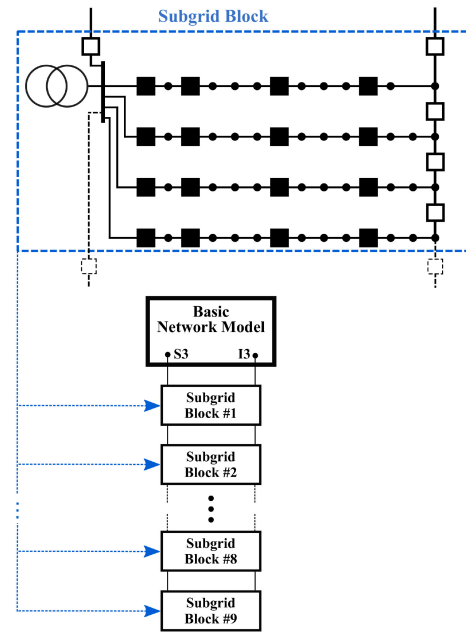

Fig. 12. Expanded network model for the second test case.

TABLE I
NETWORK LATENCY TO ACTIVATE SR

Number of Nodes	Min	Max	Average	STDEV
40	0.136s	0.192s	0.157s	0.015s
400	1.145s	1.481s	1.319s	0.101s

activation of the SR middleware, the computation of the restoration solution, provided to CB, and the implementation of closing commands in the field devices. Table I reports the time between the data transmission to CB and the initiation of the SR, due to a fault condition in the grid; it presents detailed measurements of an average communication network latency variation between the two grid networks.

With respect to an implementation on the field, the communication latency to receive data from meters, relays, and IEDs is not included; this latency is anyway negligible with respect to the presented results. Internal network latency of the cloud infrastructure is reduced by running the CB and SR at the same network. Therefore, the major latency is the time to publish data into CB and the event detection.

The fourth column shows a difference of over 1 s between the two grid networks; the comparison between the two test cases demonstrates a relation between communication time of services and grid network size. As indicated in Ref. [32], the central control system receives data from remote terminal units, typically, every 2–4 s for high-priority data. This is in line with the proposed SR platform, confirming its feasibility.

According to the test setup, the effect of grid network size into computation latency is evident. In the future, to reduce computation time of SR in the large grid network, several SRs can be deployed with a load balancer to distribute the workload in the platform.

Moreover, the processing time of SR algorithm is measured: Starting from the activation of the SR algorithm, it includes the provision of computed solution to CB and the verification

TABLE II
COMPUTATION TIME OF SR IN DIFFERENT TEST CASES

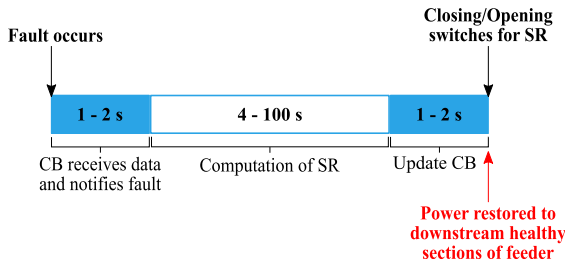| Number of Nodes	Min	Max	Average	STDEV
40	4.846s	5.574s	5.21s	0.013s
400	84.121s	88.78s	86.45s	0.123s

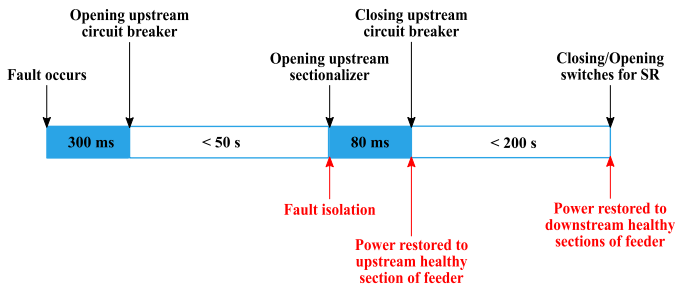Fig. 13.   Time chart of SR process.

Fig. 14.   Postfault timing diagram in automated SR.

that the specific switches successfully implemented the received closing commands. The computation time needed for applying SR in the faulty grid network is reported in Table II.

The computation time of SR depends on the size of the grid and varies between 4 and 100 s in the test setup with the networks having 40 and 400 nodes, respectively. Fig. 13 represents the timing of cloud-based SR integrated into FIWARE services, for which, according to the results of time measurements, CB needs around 1–2 s to notice the fault presence from the data collected in the electrical grid.

Fig. 14 presents the result of time measured in smart grids that deploy advanced distribution automation, as reported in Ref. [34]. According to the given information, the duration of the entire FLISR process is estimated at 5 min. Since the initial step of the presented test is the acquisition of grid data for which fault location is already performed by opening the nearest switches, only the SR operation should be considered, whose duration is evaluated at 3 min [34]. Hence, with respect to this time range, the computation time results for the proposed implementation confirm the suitability for a field implementation. Moreover, Council of European Energy Regulators[35] reports the values of reliability indices of European networks in 2016; for German electrical grid the CAIDI value, indicating the average time required to restore service in case of interruption, corresponds to 40 min. The shorter computation time obtained in the conducted test confirms the feasibility of deploying the service restoration to reduce the duration of power outages, decrease CAIDI, and consequently SAIDI indices, improving reliability of utilities in automated grids.

VI. CONCLUSION

This article presents a cloud-based platform powered by FI-WARE and based on SOA for the re-energization of loads after the occurrence of electrical faults in active distribution grids. Embedding required FIWARE services with the implemented SR as a specific domain service leads to an easy setup and benefit of the cloud-based solution properties such as computation power on-demand. Furthermore, the platform integrates the semantic information model and the functional requirements from the SARGON ontology for semantic provision, governing, discovering, and querying smart grid network based on IEC 61850 standard for substation automation. The conducted tests and the obtained results on different grid sizes confirm the viability of integrating the proposed platform with the DMS of distribution grids, to efficiently manage the continuously increasing amount of data by SCADA systems. In fact, the recorded communication network latency and the SR computation time are in line with standard values of smart automated systems, for which FLISR contributes considerably to increasing grid reliability.

In further developments, in addition to the SR, different services for the smart energy system can be included. Particularly, new services for network operations may pose additional requirements on computation time and data availability, for which additional features of the platform within the DMS (as load balancers or distributed approaches) are needed. Moreover, the coupling with cross-sectorial activities by the system operators will introduce the necessity to integrate new communication standards and data models within the architecture components.

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