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A cloud-based smart metering infrastructure for distribution grid services and automation

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A B S T R A C T

The evolution of the power systems towards the smart grid paradigm is strictly dependent on the modernization of distribution grids. To achieve this target, new infrastructures, technologies and applications are increasingly required. This paper presents a smart metering infrastructure that unlocks a large set of possible services aimed at the automation and management of distribution grids. The proposed architecture is based on a cloud solution, which allows the communication with the smart meters from one side and provides the needed interfaces to the distribution grid services on the other one. While a large number of applications can be designed on top of the cloud, in this paper the focus will be on a real-time distributed state estimation algorithm that enables the automatic reconfiguration of the grid. The paper will present the key role of the cloud solution for obtaining scalability, interoperability and flexibility, and for enabling the integration of different services for the automation of the distribution system. The distributed state estimation algorithm and the automatic network reconfiguration will be presented as an example of coordinated operation of different distribution grid services through the cloud.

1. Introduction

Over the last two decades significant changes have been affecting the power system. The deregulation of the energy market, the increasing penetration of Distributed Generation (DG), the availability of Distributed Energy Resources (DERs), like electric vehicles or storage systems, are only some of the most important changes that are reshaping the electric system scenario. While all these changes open new opportunities for a more sustainable and environmentally friendly operation of the electric grids, they also create new challenges for the safe management and control of the system [1]. The largest impact is at the distribution level, where the grids, which were previously intended to operate in a passive way and with very simple control logics, are now becoming an active complex system with bi-directional flows and the presence of heterogeneous components connected to it.

To deal with the increasing complexity of the electric system, and in particular of the distribution grids, it is evident that new solutions and technologies are thus needed [2,3]. This should be supported by the deployment of a suitable measurement infrastructure, which is the basis for enabling complex management and control schemes. At the same time, because of the large scale of the distribution networks, the proposed solutions also need to be highly scalable, distributed and possibly low cost.

An option to deal with these issues is to fully exploit end-user smart meters. During the recent years, a lot of countries started deploying Advanced Metering Infrastructures (AMI) and using emerging smart meters to improve the energy sector efficiency in the distribution domain. In Europe, 16 countries agreed to invest in a large roll-out of smart meters (up to 200 million devices by 2020 [4]) and several projects have been funded, aiming at realizing advanced smart metering infrastructures with innovative services for both Distribution System Operators (DSOs) and customers.

Recent development of IoT technologies can also help in creating fully operated Smart Grids, where new IoT devices will cooperate to better manage the status of the distribution network. In this scenario, a key challenge is developing a cloud-based software platform to manage such IoT devices and foster novel services to manage the grid. Middleware technologies can help to achieve this purpose and can be useful for developing Smart Grid solutions that exploit new data sources [5,6]. Different IoT solutions, offering

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different features, can be found in the literature. *CoSGrid* [7] is an example of middleware devised to monitor and control the electrical power of Smart Grid infrastructures. The communication across the entities in the grid is achieved exploiting both remote method invocation and event notification approaches. In [8], Kim et al. present a data-centric software solution to allow decentralized monitoring and control. Their solution exploits a publish/subscribe model [9], which is appropriate for delivering information but is not yet sufficient to have data access that is independent of this model. Indeed, also the request/response communication model is needed to provide new Smart Grid services that can easily retrieve information without having to wait for new events. An example of request/response is given by REST [10] Web Services. *GridStat* [11–13] is another software solution for Smart Grids. It exploits an event-based communication approach to propagate the information among the actors in the system. It provides support to its application for Quality of Service (QoS). In the communication, QoS provides different priority to different data flows. However, this solution works with its own closed and dedicated network infrastructure [14], which is incompatible with the Internet, so new routers and devices must be deployed.

In this paper, a cloud-based smart metering infrastructure is presented, which allows handling smart meters measurements and supporting the automation of future distribution grids and its smart management and control. With respect to literature solutions, the proposed cloud-based software infrastructure for Smart Metering (aka Flexmeter) aims at fostering novel services for Smart Grid management. It enables true interoperability between heterogeneous IoT devices and systems, providing hardware abstraction. It exploits both request/response and publish/subscribe communication paradigms. Indeed, it implements the MQTT protocol [15] and provides REST [10] Web Services to access information. In this platform, publish/subscribe is mainly used to exchange data among different entities in (near-) real-time. Finally, Flexmeter also includes scalable software components for data storage, assets and device management, and cyber-security functionalities.

The following Section shortly presents the general requirements for a smart metering architecture. The proposed infrastructure, the role and benefits provided by the cloud and the set of applications potentially enabled by the presented solution will be briefly introduced afterwards. As an example of possible services, in Section 4, the mapping of a distributed state estimator to the smart metering architecture is presented. In Section 5, an automatic network reconfiguration algorithm for losses minimization will be also presented, which uses the results of the state estimator as input. The goal is to show how the proposed cloud infrastructure is multi-service oriented and can enable the coordinated operation of different management and automation schemes.

2. Requirements for smart metering architecture

In the context of Smart City, both ICT (Information and Communications Technology) and IoT (Internet-of-Things) are fundamental to enhance energy management [16]. In particular, it is expected that future Smart Grids will be equipped with pervasive IoT devices (e.g., internet connected smart meters and smart appliances) to foster innovative services. These IoT devices, fully merged with traditional and industrial technologies, will improve monitoring and management of power systems. In this regard, novel distributed software infrastructures are needed and have to be developed [17–20]. Such infrastructures, also known as *Smart Metering architectures*, have to facilitate the access of new multiple actors (e.g., energy aggregators, virtual power plants and energy service companies) to both control technologies and relevant data. This fosters competition in a fast-evolving distributed marketplace by providing new services for energy distribution grid management that will increase its security and reliability [21]. In this scenario, emerging IoT technologies together with Smart Metering architectures can enable services such as: (i) User Awareness, (ii) State Estimation [22–25] and (iii) Demand Response [17,26]. Other examples of services include: (i) fast fault-detection, (ii) fault-tolerance, (iii) power quality monitoring, iv) detection of unauthorized power usage and (v) Non-Intrusive Load Monitoring (NILM) [17,18,26–31]. In this section, before presenting our proposed Smart Metering architecture (see Section 3), the main requirements to be addressed in order to design such kind of software platforms are discussed.

Hardware-independent interoperability among heterogeneous devices is a key requirement to enable communication and data transmission of devices [19,21]. Indeed, Smart Metering architectures need to integrate in the same environment different systems, technologies and low-level protocols that must interoperate to retrieve energy information. For this reason, middleware is a valuable software instrument to establish this interoperability between heterogeneous devices. This can be achieved by abstracting hardware functionalities from different low-level technologies through uniform interfaces.

A Smart Metering architecture has to implement features for *real-time data collection* from large number of different meters and sensors to provide actual information about events or behaviors in the energy distribution network. Thus, the platform has to include scalable storage systems and data-bases that should scale horizontally to better address the data storing and access.

(Near-) Real-time data transmission is another fundamental requirement that implies an asynchronous communication. This can be implemented by exploiting publish/subscribe approach [9], which is complementary to request/response. Publish/subscribe communication paradigm removes the interdependencies between producer and consumer of information. This allows developers in creating distributed software components that are independent from data-sources and can react in (near-) real-time to certain events. Furthermore, publish/subscribe enables a unified access to information sent by different entities, either hardware or software, in the system.

Fast bidirectional communication is needed to send/retrieve information to/from the entities, either hardware or software, in the distribution network. This can be implemented by exploiting request/response communication paradigm, again exploiting uniform interfaces like REST Web Services [10].

The *microservices approach* [32] is an emerging practice for developing distributed software platform and services. This designing pattern can be defined as *an approach to develop a single application as a suite of small services, each running in its own process and communicating with lightweight mechanisms* [32]. These services are *small, highly decoupled and focus on doing a small task* [33]. Hence, a Smart Metering architecture should be designed following the *microservices* approach to increase flexibility, maintainability and scalability.

Finally, a Smart Metering architecture has to expose *Web Services* and *APIs* (Application Programming Interface) to access data using open and web-oriented *standard data-formats*. This is needed to foster the design and development of novel services. Following this requirement, REST architectural principles can help in providing easy-to-use interfaces that are loose-coupled of individual (low level) components. Thus, a Smart Metering architecture should be designed coupling REST principles with *microservices* approach to foster development of novel services and distributed applications.

3. Flexmeter infrastructure

This section presents Flexmeter, our proposed Smart Metering architecture to foster general purpose services in the smart grid scenario. In particular, in this paper, two services aimed at improving the performances of the distribution network are presented:

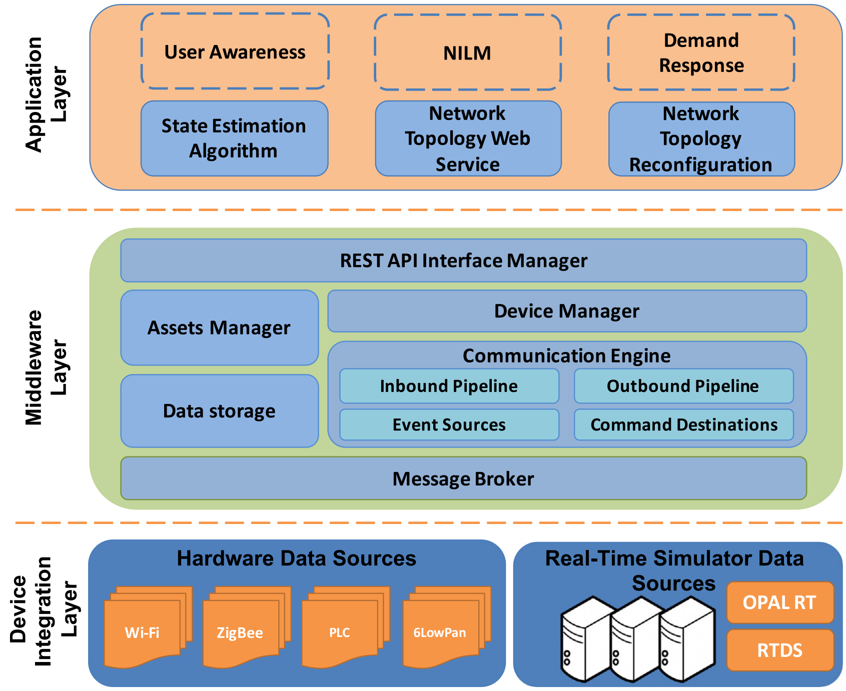

Fig. 1. Architectural schema of Flexmeter platform.

(i) the State Estimation service (see Section 4) and (ii) the Network Reconfiguration service (see Section 5). In addition, the Flexmeter platform also provides further services, such as User Awareness, NILM, Demand Response, etc., whose in-depth description is out of the scope of this paper. For this purpose, the proposed platform integrates heterogeneous technologies and devices to enable a fine-grained monitoring and management of the overall energy distribution network. Flexmeter has been designed following the requirements discussed in Section 2. As shown in Fig. 1, Flexmeter is a three-layered cloud architecture with: (i) a *Device Integration Layer*, (ii) a *Middleware Layer* and (iii) an *Application Layer*. In the next sections, the layers of the proposed infrastructure are described in more detail.

3.1. Device integration layer

The Flexmeter platform is capable of retrieving measurements from heterogeneous devices, either wired and wireless, that exploit different communication protocols (e.g., IEEE 802.11, ZigBee, PLC or 6LowPan). The lower layer in Fig. 1 enables the interoperability among these technologies through *Device Integration Adapters* (DIA). Thus, this layer integrates novel IoT devices with traditional and industrial technologies. DIAs are software modules able to convert measurements coming from devices and meters to the Flexmeter Data Format, transcending all the hardware technologies, protocols and data-sources. They have been developed following a methodology described in [34]. Then measurements are sent to the cloud infrastructure exploiting MQTT (Message Queuing Telemetry Transport) protocol [15]. Specific DIAs permit integrating also Real-Time Digital Simulators (like RTDS and Opal RT) into the Flexmeter infrastructure to achieve complex simulations of future Smart Grid system.

3.2. Middleware layer

The *Middleware Layer* consists of different software modules performing together to: (i) allow bidirectional communication with DIAs, thus with devices; (ii) receive, control and store measurements; (iii) provide REST web services to access data, devices, assets and maintenance operations; (iv) send commands to devices.

The *Message Broker*, shown in Fig. 1, enables an asynchronous bidirectional communication with devices through MQTT, which is a publish/subscribe protocol [9] to send data in (near-) real-time. This paradigm avoids interdependencies between information producer and consumer.

The *Message Broker* routes all events to and from the *Communication Engine* module that is in charge of managing a bidirectional interaction with DIAs collecting measurements into the *Data Storage* and sending commands to devices. The *Communication Engine* consists of two sub-components: (i) *Event Sources* and (ii) *Command Destinations*. The *Event Sources* are MQTT subscribers that sign up to input topics used by DIAs to publish measurements. *Event Sources* check the integrity of the incoming message payload and push it into the *Inbound Pipeline*. *Inbound Pipeline* is an intelligent buffer that manages network traffic spikes to relieve the database interface from congestion and to ensure the measurements storage. Flexmeter also allows receiving command requests to target devices. Command requests are managed by the *Command Destinations*. They are MQTT publishers that route command requests to the right devices. *Outbound Pipeline*, designed as the *Inbound Pipeline*, prevent spikes in command requests and send the payload content to *Command Destinations* and then to the target device.

The *Data Storage* module permits to manage the connection with different time-series databases and non-relational databases which are specifically developed for Big Data management. The *Assets Manager* is a software module that manages different information regarding people, places and things that are called *assets* in the Flexmeter platform.

Finally, the *Device Manager* handles the communication between the *Asset Manager*, the *Communication Engine* and applications that interact with the Flexmeter platform through the *REST API Interface Manager*. The *REST API Interface Manager* defines and provides REST web services that are designed to permit the access to information regarding devices, assets and measurements, and manages these entities in the infrastructure. An authentication is required to request REST web services. Hence, only allowed applications and services can operate with the Flexmeter platform. Through these software components, the abstraction from device communication, data and information storage management and from different low-level hardware functionalities is achieved.

3.3. Application layer

The highest layer in the Flexmeter platform is the *Application Layer*, as shown in Fig. 1. This layer offers tools and APIs to design and develop distributed applications and services provided by different stakeholders playing in a smart grid scenario to address the needs of different end-users. Thus, they are deployed across the Internet and exploit either REST or MQTT to exchange relevant information with the rest of the platform. In particular, this paper focuses on two services for managing and reconfiguring the network. The *Network Topology Reconfiguration* (Section 5) is a service that provides features for automatic grid topology reconfiguration. It works together with a *Network Topology Web Service* that makes available in the system the configured topology for the energy distribution network. The smart reconfiguration of the grid is enabled by the *State Estimation (SE) Service* (Section 4), which monitors the operating conditions of the grid with a low latency (in order of few seconds). These services, by cooperating together, enhance security, reliability and efficiency of the grid.

3.4. Cyber-security and scalability of the Flexmeter platform

Smart Metering architectures are decentralized systems where intelligence is distributed across several devices and/or actors in the system [35]. This introduces significant issues related to cyber-security. For this reason, Flexmeter platform has been designed to enable a secure and trusted communication among the different components in the system exploiting Transport Layer Security (TLS) to establish a secure communication channel where all the data are ciphered. TLS is a cryptographic protocol to provide communications security over a network of computers, thus the Internet, ensuring privacy and data integrity [36]. Moreover, identity of the communicating parties is authenticated using public-key cryptography. This implies that malicious cyber-attacker cannot send and/or retrieve any kind of data without an authorization. In particular, Flexmeter platform uses both MQTT over TLS and HTTPS (Hypertext Transfer Protocol over TLS) for REST web services. Moreover, Flexmeter web services exploit an authentication mechanism to validate the credentials of clients accessing the resources.

From a scalability perspective, the use of a publish/subscribe communication paradigm allows rising the whole infrastructure scalability in data transmission, as pointed out in [21]. Furthermore, the proposed platform has been designed to be a multi-tenant architecture that can run in a cluster of servers. A tenant refers to a group of users with shared common access and privileges to software instance. Multi-tenancy software infrastructure is a single instance of software that serves various tenants by providing to each of them a dedicated share of the same software instance. Flexmeter multi-tenancy allows (i) separating processing pipelines and (ii) separating data storage in different database instances. This avoids intermingling data between different tenants.

Finally, Flexmeter integrates different time-series and non-relational databases (e.g., InfluxDB [37] and MongoDB [38] respectively). These databases have been designed to deal with Big Data, providing features for clustering, replication and load balancing. Thus, they are highly scalable, extremely available and very fast in storing and accessing information.

4. State Estimation service

State Estimation (SE) is a well-known application that allows estimating the most likely state of a grid given a redundant set of input measurements [39]. With the transition towards active distribution grids, SE is becoming essential at distribution level for providing to Distribution System Operators (DSOs) the needed awareness about the network operating conditions. Several techniques have been proposed to perform SE, but most of the approaches are usually based on the Weighted Least Squares (WLS) method [40]. In this paper, the WLS formulation proposed in [41] has been used as basis for the developed SE service. Besides the estimation of the electric quantities of the grid, WLS estimators provide the possibility to compute the uncertainty associated to the estimated states. In fact, the inverse of the so-called Gain matrix used in the estimation process gives the covariance matrix of the estimated state vector (see [42] for details). For all the quantities computed indirectly starting from the estimated state vector, the law of propagation of the uncertainties can be applied to obtain the corresponding variances and covariances (see [43] for more details). The knowledge of the uncertainties associated to the estimated electrical quantities is important for two reasons: (1) the uncertainty affecting the estimated states can be duly taken into account to support the grid management [44] or to avoid the use of unnecessary too large safety margins; (2) the estimated values together with their uncertainty can be used to enable WLS-based multi-area or multi-level SE architectures (see for example [42,45]). In the latter case, SE results are used as equivalent input measurements for a subsequent SE process.

In the Flexmeter SE service, the features of WLS formulation have been exploited to design a bottom-up estimator that allows monitoring both LV and MV networks starting from the smart meter measurements at the end-user premises. The DSSE architecture here considered consists of three different levels: *concentrator level SE*, *LV grid level SE* and *MV grid level SE*. The different hierarchical levels, which can potentially belong to different DSOs, are coordinated by means of the presented cloud-based smart metering infrastructure. The use of this platform allows fully distributing (vertically among the hierarchical levels and horizontally among different LV grids or concentrators) the task of DSSE for the monitoring of the whole distribution grid.

4.1. Concentrator level SE

The concentrators are the devices used in the Flexmeter platform to talk with the smart meters and to retrieve their measurements. They are the units where the smartness of the measurement infrastructure resides, since they are responsible for collecting and aggregating the incoming amount of data, translating this into the Flexmeter data format (through the DIA), and sending the packed measurements to the central cloud system by means of the MQTT protocol. Given that concentrators need suitable processing capabilities to perform their tasks, the idea presented in [43] was to distribute the LV SE efforts among these devices in order to reduce the overall computational burden required for performing LV grid SE. Here the same concept is retaken, and concentrators are thus in charge to run a local area SE for all the customer nodes downstream a given feeder bus, to which they are associated.

From a SE perspective, concentrators collect voltage magnitude and active and reactive power measurements for each of their associated end-users downstream a LV grid node. This information is provided as input to the local concentrator SE, from which the voltage magnitude and the resulting overall power consumption at the LV feeder bus are taken as result. These data, together with the corresponding uncertainties, are then published through MQTT using a topic associated to the portion of LV grid where the concentrator is. Each concentrator thus works as an MQTT publisher and sends periodically (for example every minute) the information about its estimation results to the Flexmeter platform (Fig. 2).

4.2. Low Voltage level SE

The LV grid SE is in charge to estimate the operating conditions of the LV grid downstream an MV/LV substation. To perform this task, the LV estimator works as an MQTT publisher and subscriber (Fig. 2). First, thanks to the Message Broker, it receives the estimation results from all the concentrators that it serves. These estimates are provided together with their uncertainties and thus they enable the use of an upper level WLS estimator. As soon as the data arrive, the LV estimator post-processes this information and estimates the status of the LV grid. Then, these results are sent to the Flexmeter platform again exploiting the MQTT publishing mechanism.

4.3. Medium Voltage level SE

Similarly to the previous step, the MV estimator is in charge to estimate the operating conditions of the MV grid subtended to an HV/MV substation and it works as an MQTT publisher and subscriber. Assuming to have a reconfigurable MV grid, the MV estimator needs every time the updated information about the grid topology. For this reason, the MV estimator receives alerts through the Flexmeter platform every time there is a network topology change and then it uses the request/response paradigm to retrieve the updated topology information from a *Network Topology Web Service* via REST (see Fig. 2).

To perform SE, the MV estimator subscribes to receive the results of voltage magnitude and total active and reactive power consumption or injection (with their uncertainties) from the LV estimators in the MV/LV substations. In addition, it also receives the measurements from possible other smart meters deployed in the MV grid (for instance, industrial loads or DG directly connected to the MV level). Through the post-processing of these incoming data, the MV estimator is able to estimate the MV grid status and then it sends back the results to the Flexmeter cloud, where they are made available for other possible applications, like the *Network Topology Reconfiguration* service.

4.4. Requirements for the SE service

As it can be observed, the proposed *Smart Metering architecture* enables a multi-level SE approach, which allows running SE also at the MV level without using forecast measurements, regardless of the number of measurements available in the MV grid. Moreover, the whole picture of the distribution network operating conditions (both MV and LV grid) can be achieved distributing the computational burden among different hierarchical SE levels and among different processing units working in parallel within the same SE level. The SE results in the monitored areas can then be used as input for any other service or grid management application that needs the knowledge of the operating conditions, like the network reconfiguration algorithm presented in the next Section.

For the operation of the proposed multi-level SE, of course, some specific requirements exist. First, the information about topology and line characteristics of the grid is essential in order to enable WLS-based SE. To achieve the benefits previously indicated, the knowledge of the grid data at both MV and LV level is thus needed. In some cases, however, LV network data are not known or cannot be easily retrieved by the DSOs. In this scenario, the detailed monitoring of the LV grid (down to the single LV nodes) cannot be achieved, but other approaches (see for example [46]) can be used to forecast the power consumption at the MV/LV substation. This would allow performing MV grid SE, while the proposed *Smart Metering architecture* would serve to couple the MV grid SE results with other services like network topology reconfiguration.

In a similar way, the proposed approach fully relies on the use of smart meters and on the availability of voltage and power measurements at the different nodes to obtain the LV grid monitoring. In the case of partial deployment of smart meters in the considered LV network, an accurate monitoring of the grid cannot be easily obtained. Available measurements could be in any case used to infer the overall consumption at MV/LV substation level, thus leading to a scenario where MV grid SE is enabled by pseudo measurements at the substation nodes. Again, in this case, the proposed architecture would permit coordinating these steps and enabling network topology reconfiguration or other services.

5. Network reconfiguration

Distribution Networks (DN) are normally divided in Medium and Low Voltage levels. The LV portion of DN is usually radial and does not provide possibilities for reconfiguration. The MV part, instead, usually has a weakly meshed network structure, but is radially operated. This means that a certain number of lines, called *tie-lines*, are kept open. This type of operation is usually chosen by DSOs because it makes easier and cheaper to design and operate the network protections [47]. Network reconfiguration is therefore usually performed on the MV level and consists in modifying the DN topology by operating remotely controlled sectionalizing switches, closing normally open and opening normally closed lines, but keeping the radial operation of the network.

Focusing on the MV grid, this is composed of: N nodes or busbars (having identified with 0 the HV/MV substation); a total number of lines N_l. Based on these quantities, the minimum number of lines required to connect every node in a radial configuration is N, while the number of lines that must be left open, or tie-lines, is $N_t = N_l - N$. The DN reconfiguration is a combinatorial problem as the degrees of freedom are the open/closed states of the N_l switches, provided that, in each configuration, N switches must be closed and N_t switches must be open.

The reconfiguration of the DN can be done for different purposes, like to redirect the power flows or for improving some other DN performance indexes. Different optimization objectives have been proposed and pursued in literature, like: reducing network losses, improving the voltage profiles, load balancing, reducing service interruptions, minimizing fault currents, maximizing local consumption of renewable energy, etc. [48,49]. Here three main objectives are taken into account, namely reducing the network losses, enhancing the voltage profiles and fostering the local consumption of renewable energy. These objectives can be pursued if the accurate monitoring of the grid is available, and, to this purpose, the results of the SE service are used as input. Different objectives, like fault currents and service interruptions minimization, instead, rely on additional safety/reliability considerations associated to the network configuration but not directly on the monitored load/generation profiles and for this reason they are not considered here.

Network losses P^L are defined as the sum of all the active power losses on the DN lines (Eq. (1)).

$$P^L = \sum_{j=1}^{N_l} 3 \cdot R_j \cdot I_j^2. \quad (1)$$

The line current I_j in the jth line (characterized by series resistance R_j) can be calculated by a load flow computation on the DN, taking as known the operating points of the loads and generators connected to the buses. One objective of the network reconfiguration can be to minimize such losses. If HV/MV and MV/LV

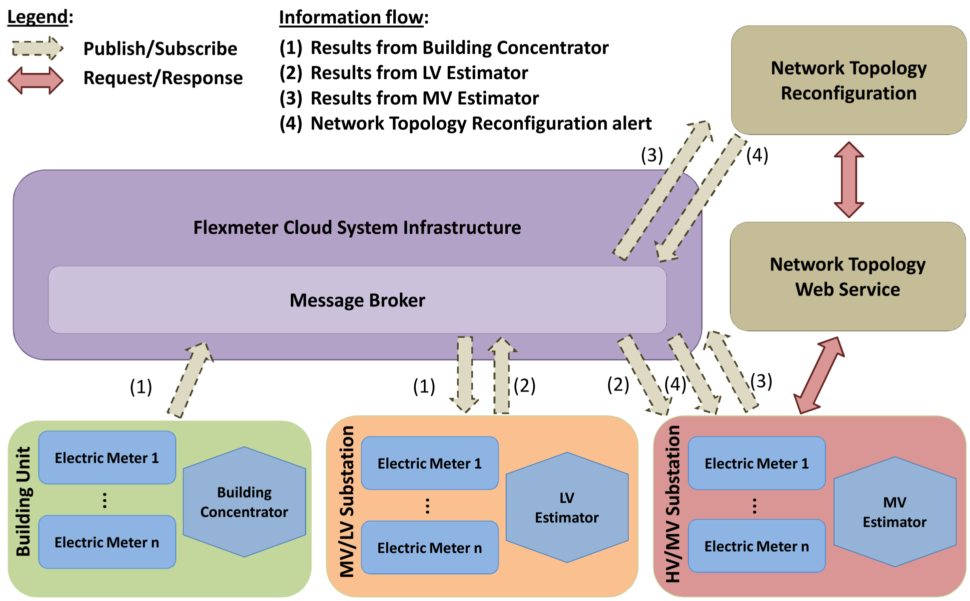

Fig. 2. Communication flows among different Services in the Flexmeter platform.

transformers are included in the network model, their losses could be also taken into account by the optimization algorithm, together with line losses.

Because of current loading on the lines, the voltage values V_k at the buses are generally different from the rated voltage V^r. Voltage deviations can be positive close to the buses with prevailing DG, or negative in case of load buses. In general, voltage deviations should be also minimized. An alternative objective can be thus the minimization of the maximum voltage deviation observed in the network (Eq. (2)):

$$\Delta V_{\max} = \max|\{V_k\} - V^r|, \quad k = 1 \div N. \tag{2}$$

In many cases a single DSO manages large DNs, fed by different HV/MV transformers. The portion of DN under a single HV/MV transformer is kept isolated from the other portions in order to enforce the radiality constraints. If a DN portion has prevailing load, while a neighboring portion has prevailing generation, the same DSO can face a reverse power flow in a HV/MV transformer, while the other is absorbing power from the transmission network. This situation should be avoided and the problem can be solved by re-configuring the two network portions, balancing load and generation. In this case the quantities considered in the optimization are the power flows through HV/MV transformers. The maximization of DG which is locally consumed, can be formulated as Wald's maximin optimization (Eq. (3)) [49,50]:

$$\max_x \left\{ f(x) = \min_{i=1}^{N_T} P_{HV}^{(i)}(x) \right\} \tag{3}$$

where $P_{HV}^{(i)}$ is the power flowing from the HV network to the DN through the ith HV/MV transformer, x is the id of the network configuration and N_T is the number of HV/MV transformers feeding the DN.

In the literature, different methodologies have been proposed to search the feasible spanning trees to optimize the network configuration, starting from the basic *branch exchange* procedure [51], up to sophisticated multiobjective stochastic combinatorial optimization procedures [52,53]. In this paper the focus is on the use of the results of the SE for on-line real-time automatic grid reconfiguration, for losses minimization. However, as it will be shown in the simulation results, this objective also allows achieving improvements on the voltage profiles since the two objectives are not contrasting.

The Flexmeter infrastructure enables the possibility of performing grid reconfiguration based on real-time data coming from the grid. For this purpose a fast reconfiguration algorithm should be used, which also minimizes the switching operations that need to be performed to change the grid topology. For the above mentioned reasons, a *Greedy* algorithm has been chosen [54], which not necessarily leads to the global optimum of the objective function, but usually provides a good solution in a very small amount of time.

The general formulation of the optimization problem can be stated as:

$$\begin{aligned} \min_x \;\; & f(x) = P^L(x) \\ \text{s.t.} \;\; & \\ & g(u) = 0 \\ & V_{\min} \le V_k \le V_{\max} \\ & S_j \le S_{j\max} \end{aligned} \tag{4}$$

where x is the id of the alternative network configuration. The constraints are the power flow equations $g(u)$, the voltage limits $V_{\min}$ and $V_{\max}$ and the line capacities $S_{j\max}$ respectively on every node k and every line j of the DN.

As described in Section 3, the grid reconfiguration algorithm is subscribed to the Message Broker and receives from the cloud the results of the *MV grid level SE*; it retrieves also the actual network topology from the *Network Topology Web Service*, where the switches status is represented by a boolean vector. At this point the power injections and consumptions calculated by the SE algorithm are applied to the MV buses and a load flow is calculated for the meshed network configuration, where all tie-lines are closed. Thanks to the load flow results, it is possible to know the magnitude of the currents flowing in the MV lines $|I_j|$. The current magnitudes are then normalized:

$$I_j^{norm} = \frac{|I_j|}{Max(|I_j|)}. \tag{5}$$

It is then possible to build a vector of line weights w, that are inversely proportional to the current flowing in the lines:

$$w_j = 1 - I_j^{norm}. \tag{6}$$

By starting from the full edge-to-node connectivity matrix and from the edges weights w, it is then possible to build, using the

Kruskal's algorithm, the spanning tree that minimizes the total weight [55]. This minimum spanning tree constitutes a radial distribution network whose operation is close to the operation of the meshed network, as preferably the lines with smaller currents are opened.

A new vector for the switches status can be produced based on the minimum spanning tree. Two load flow calculations can be performed now, one on the original radial network configuration and a second one on the new topology. The total network losses P_1^L and P_2^L are calculated for the original topology and for the proposed new topology and the losses percent reduction is calculated:

$$\Delta P^L = \frac{P_1^L - P_2^L}{P_1^L} \cdot 100. \tag{7}$$

If the performance of the new topology, in terms of power losses, is improved more than a certain threshold with respect to the previous one ($\Delta P^L > \varepsilon^L$), and the situation is stable for a certain time interval ε^t, a change of topology is activated. In this case, as shown in Fig. 2, the *Network Topology Reconfiguration* service first uploads the new topology (exploiting REST) into the *Network Topology Web Service*, then, it publishes a *reconfiguration alert* exploiting MQTT. This alert is received by the *MV Estimator* that can download the updated grid topology from the *Network Topology Web Service*. In this way, the *MV Estimator* is always in sync with the new grid topology needed for its computations.

6. Tests and results

The proposed *Smart Metering* infrastructure and the presented distribution grid services have been tested in a real-time simulation environment interfaced to the described Flexmeter cloud platform. In this Section, first the test setup and the real-time simulation platform built to emulate the distribution grid will be presented. Then, obtained results will be provided to show the proper coordination and operation of the implemented services through the cloud.

6.1. Tests setup

To test the proposed services, a sample distribution grid, composed of a 15 kV MV grid and 400 V LV grids, has been emulated in simulation environment. As shown in Fig. 3, the used grid is composed of 13 buses on the MV side, of which one is the primary HV/MV substation, nine are nodes connected to MV/LV substations supplying residential loads, two are industrial loads connected to the MV level and one is a generation plant, also directly connected to MV. In the following tests, a constraint on the radial operation of the grid is considered. One of the branches (between nodes *MV*_007 and *MV*_008) is considered as normally open and this represents a reference scenario for the tests. To assess the *Network Topology Reconfiguration* service, however, the possibility to open/close any of the MV lines is considered (always keeping the mentioned constraint on radial operation).

As for the LV side, each MV/LV substation subtends a LV grid composed of different feeders and a different number of buses in each feeder. Fig. 4 shows as an example the topology of the LV grid downstream node *MV*_002. The figure also shows (between parenthesis) the number of residential customers connected to each feeder bus, for phase *a*, *b* and *c*, respectively. Each residential customer is directly connected to the feeder bus through a LV line, thus creating a sort of star connection departing from the feeder node. The considered test network is thus emulated down to the single-phase connection of each residential customer to the main grid.

To create a test scenario, power profiles for the different nodes have been also created. The tool presented in [56] has been used to create random daily profiles for the residential users, compliant with the aggregated power consumption profile shown in Fig. 5a (which refers to the average profile of a family with consumption equal to 3000 kWh/year). Fig. 5b and 5c show instead the exact consumption and injection pattern assumed for the industrial and generation nodes, respectively.

Starting from this test scenario, the simulation of a whole day has been carried out with a time resolution of one minute. In the simulation, for each instant of time, a power flow of the whole network is performed to obtain the reference "true" values of the different electrical quantities of the grid. Given these reference values, voltage magnitude and active and reactive power measurements are extracted for each residential user by adding random noise (with normal distribution), in order to emulate the smart meters with their uncertainty. In order to represent realistic uncertainty values, common technical specifications of commercial smart meters have been taken into account. In the following simulations, the considered accuracy performance of the smart meters are class 1 and 2, according to the standards IEC 62053-21 and 62053-23, for active and reactive energy, respectively. Thus, uncertainties of 1% and 2% have been chosen for the active and reactive power (this level of accuracy is prescribed by the standard for currents larger than 20% of the basic current of the smart meter [57,58]). For the voltage measurements, since smart meter manufacturers usually do not provide specific information on this measurement, an accuracy equal to 1% has been chosen, which is the worst accuracy that can be considered to fulfill the 1% accuracy requirement for the active power. It is worth also noting that, for an accurate representation of the uncertainties, correlations arising among voltage and powers should be also taken into account. However, [59] proved that the effects brought by these correlations are almost negligible, thus these correlations have not been considered here in the modeling. Power measurements are also extracted for the industrial and the generation plant connected to the MV grid (with same uncertainties as before), in order to emulate also their own smart meter. While the residential customer measurements will be used as input to the *Concentrator level SEs*, the industrial and generation node measurements will be instead taken into account directly in the *MV estimator*.

Relying on this set-up configuration, the simulation is performed running in different machines the *Concentrator level SE*, the *LV level SE*, the *MV level SE* and the *Network Topology Reconfiguration*. All the algorithms are implemented in Matlab and each one is connected to an MQTT publisher/subscriber that runs on Node.js. The MQTT publisher/subscriber allows the communication with the Flexmeter cloud, which is in a different location with respect to all the various algorithms, and enables the reception/sending of the inputs/outputs of the algorithms. When necessary (namely when a change in the network topology is alerted), the algorithms also access the designed *Network Topology Web service* (through REST) to modify accordingly the considered grid topologies in the simulation.

6.2. Communication and computation performance

To assess transmission performances of the proposed infrastructure, communication tests have been carried out to estimate the time needed by the different actors in the system to send and receive data through the MQTT protocol. As shown in Fig. 2, *State Estimators* and *Network Topology Reconfiguration* work both as publishers and subscribers, while *Building Concentrators* act just as publishers. From here onwards in this section, we will refer to all these actors as either publishers or subscribers, depending on their current role. Tests have been performed in a Wide Area Network (WAN) environment. Thus, publishers, subscribers and message broker are in different locations and communicate across

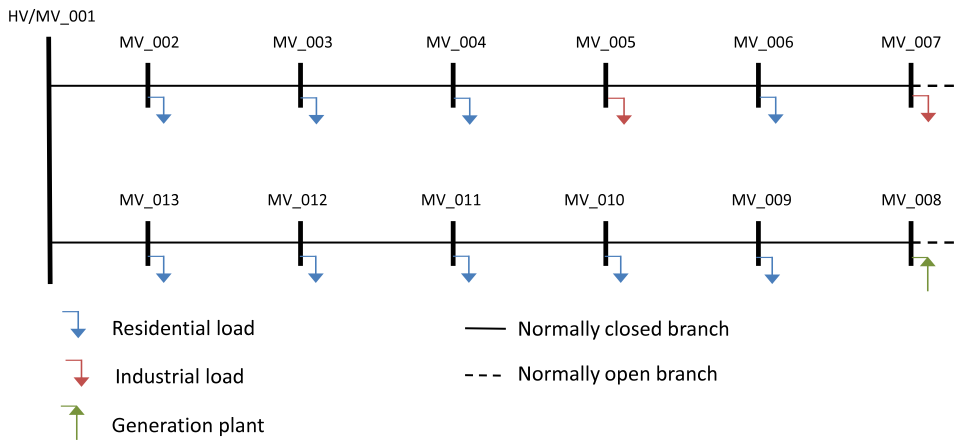

Fig. 3. MV side of the test network.

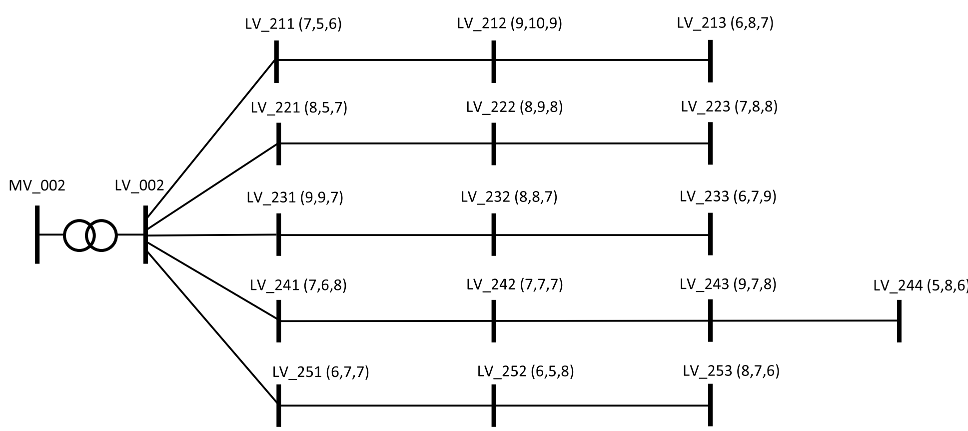

Fig. 4. LV grid downstream one of the nodes of the test network.

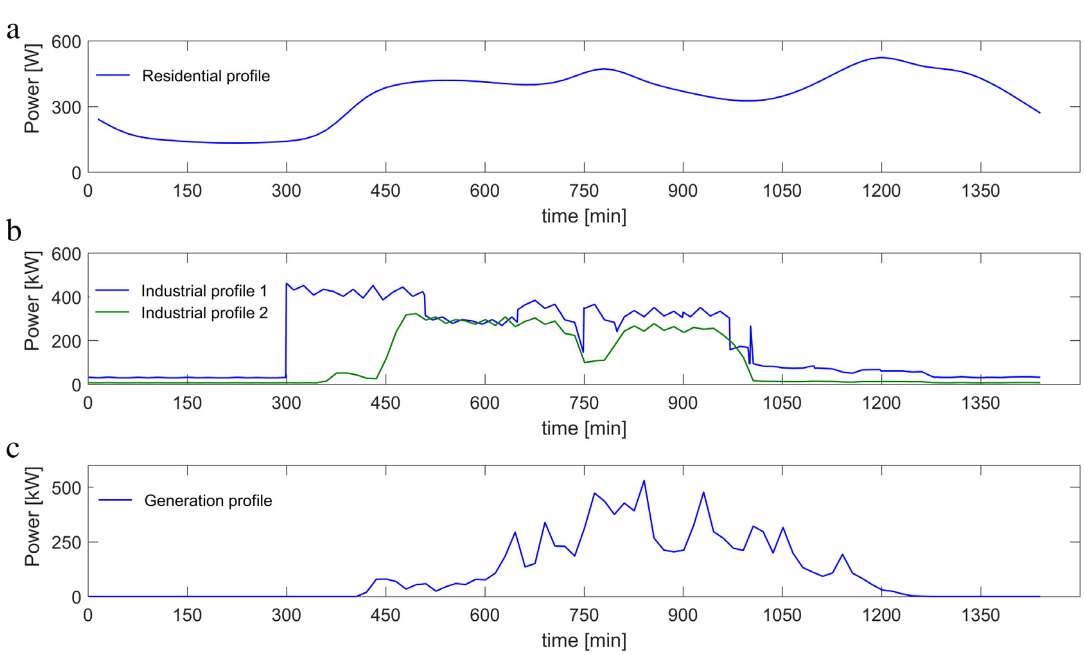

Fig. 5. Reference power profiles used for the grid: (a) residential customers; (b) industrial loads; (c) PV generation plant.

the Internet. Tests have been performed sending a data payload of about 1.3 Kbyte every 500 ms.

Fig. 6 reports the transmission latency for almost thirty thousand packets sent. This latency coincides with the *round-trip-time*

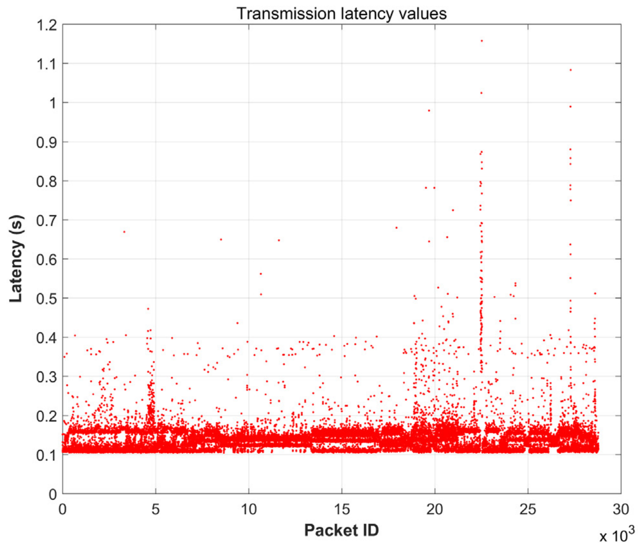

Fig. 6. Transmission latency: Experimental results.

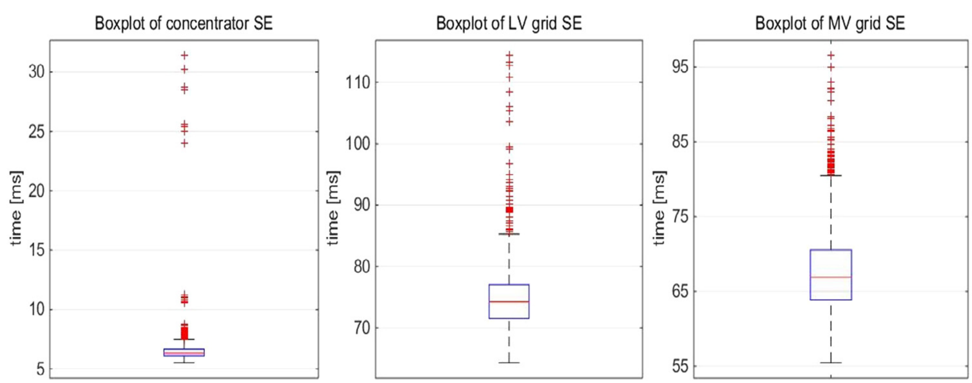

Fig. 7. SE time performance: Experimental results.

on the WAN, that is the elapsing time between sending and receiving a packet from the publisher to the subscriber respectively. In particular, the plot on the left side in Fig. 6 reports all packets sent and their transmission latencies. This plot highlights that most of the packets are delivered in less than 0.2s. On the right side of Fig. 6, we also show the box-plot of the transmission latency distribution, with outliers (values that lie more than one and a half times the length of the box from either end [59,60]) reported in black. The obtained median value is 0.14s, while Q_1 and Q_3 are 0.11s and 0.15s respectively. The bottom and top whiskers, W_1 and W_2 in the figure, are 0.1s and 0.21s: thus, almost 97% of the packets are delivered in less than 0.21s.

Similarly to the previous analysis, tests have been performed also to evaluate the computation times of the different SE algorithms. Fig. 7 shows the boxplot results for the different hierarchical levels of SE. The presented values are obtained checking the computation times of the Matlab SE algorithms during one of the simulations and include: the time needed for importing the data arriving through the MQTT subscriber and for translating them into the format used into the SE algorithm; the processing time required by the associated SE algorithm; the time for preparing and sending the SE results through the MQTT publisher. The median values obtained are 6, 74 and 67 ms for concentrator, LV grid and MV grid SE, while the top whiskers are at 7.5, 85 and 80 ms, respectively.

From the combination of the communication and processing results, it is possible to observe that, also taking into account possible outliers, this infrastructure is in general able to perform all the steps of the multi-level DSSE within few seconds. Referring to the performance classes defined by the *IEC 61850* standard [60] (see Table 1), the experimental results obtained for the communication through the MQTT protocol satisfy the requirements of classes *TT0*, *TT1* and *TT2* (note that [60] defines the communication requirements). When considering the whole chain of the multi-level DSSE, the overall times are beyond one second (also considering the additional latency given by the access network that connects the smart meters to the concentrators), but this is still compliant with this type of application, since SE can be included among the SCADA services that require a *TT0* performance class.

6.3. Simulation results

The accurate operation of the SE service is essential to provide reliable information to DSOs and to properly trigger the other services relying on the knowledge of the status of the grid. Fig. 8 shows, as an example, the results obtained for the voltage magnitude profile of phase a of node *MV_007* (identical considerations also hold for the other phases of the system). It is possible to observe that the designed multi-level SE approach allows tracking with high accuracy the dynamic changes of the network status. During the 24 h simulation, the obtained maximum error is 0.14% of the reference voltage value.

Table 1
Communication requirements and performance classes for power systems defined by *IEC61850* [60].

Performance requirements	Performance classes	Values	Example of services
Transfer time	TT0	> 1000 ms	Files, events, log contents, SCADA
	TT1	1000 ms	Events, alarms
	TT2	500 ms	Operator commands
	TT3	100 ms	Slow automation interactions
	TT4	20 ms	Fast automation interactions
	TT5	10 ms	Releases, status changes
	TT6	3 ms	Trips, blockings

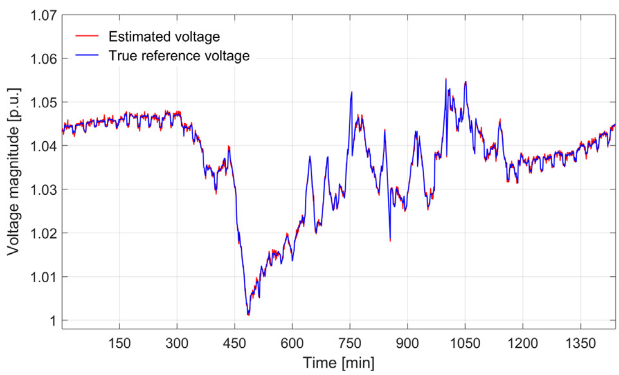

Fig. 8. Voltage magnitude profile over the day at bus *MV*_007.

Table 2
Changes of topology.

Time step [min]	Switches status vector
1 ÷ 163	[1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1]
164 ÷ 317	[1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1]
318 ÷ 515	[1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 1]
516 ÷ 693	[1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1]
694 ÷ 755	[1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 1]
756 ÷ 855	[1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1]
856 ÷ 925	[1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 1]
926 ÷ 1000	[1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1]
1001 ÷ 1032	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1]
1033 ÷ 1053	[1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1]
1054 ÷ 1065	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1]
1066 ÷ 1075	[1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1]
1076 ÷ 1187	[1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 1]
1188 ÷ 1440	[1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1]

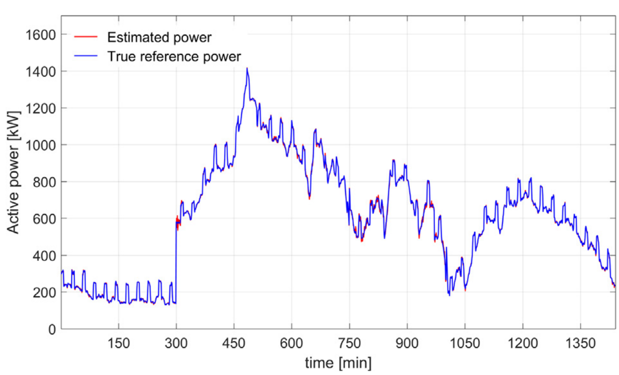

Fig. 9. Active power consumption profile over the day at the HV/MV substation.

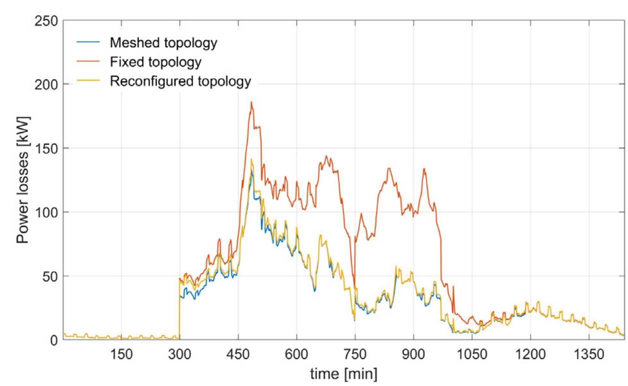

Fig. 10. MV network total power losses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Similar considerations are also valid when looking at the other electrical quantities of both the MV and LV grid. Fig. 9 provides the profile of the power consumption always at phase a for the HV/MV substation: even in this case the estimator tracks very well the dynamic variations of the power profile.

As for the configuration of the network topology, the operating condition of the MV network at $t = 0$ is the standard operating condition showed in Fig. 3, where, to keep the radial configuration, the line that connects buses *MV*_007 and *MV*_008 is open. Then, during the daily operation of the system, thirteen changes of topology were triggered by the network reconfiguration service, as showed in Table 2. For the tests, the threshold discussed in Section 5 are set as follows: $\varepsilon^L = 5\%$ and $\varepsilon^t = 5$ min.

The total network power losses during the day are showed in Fig. 10. In the figure, as a reference, the losses of the network operating in a meshed configuration (blue line) are plotted. This reference represents the minimum losses which could be reached only in an ideal situation, as the network is operating in a radial configuration. The red and orange lines show instead the losses of the network which operates with a fixed standard topology and those of the network which operates with the variable topology, reconfigured by the network reconfiguration service, respectively. The red and orange curves are very close during the first and final part of the day, when the loading conditions of the grid are low and the losses are relatively small. During the central hours of the day, instead, the orange curve is well below the red one: the change of topology provides evident savings in the power losses.

At the end of the simulation, it is possible to evaluate the total energy savings due to the network reconfiguration. The total losses over the simulated day are 716 kWh for the ideal meshed operation, 1283 kWh for the fixed standard topology operation and 749 kWh for the variable topology operation. By adopting the topology reconfiguration more than 40% of the energy losses are saved. This value obviously refers to the particular scenario and network configuration used for these simulations, but highlights the potential value of smart automation functions built on top of the smart metering infrastructure.

As further result, Fig. 11 shows the improvement achievable in terms of voltage profile. In particular, the graph shows the maximum bus voltage drop in the MV grid with respect to the nominal value. The results related to the meshed grid serve again as a reference for an ideal optimum case. As it is possible to note, even if the voltage optimization is not directly used as objective

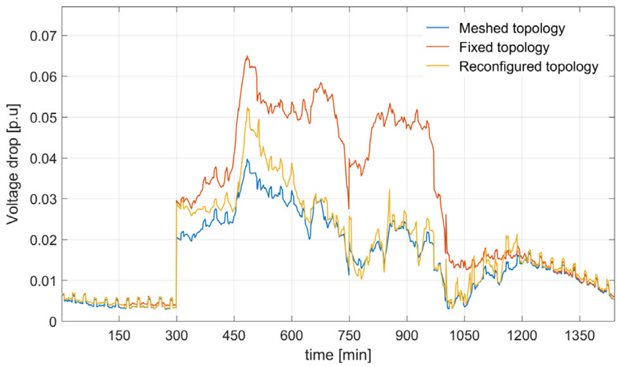

Fig. 11. MV network voltage deviation from the nominal value.

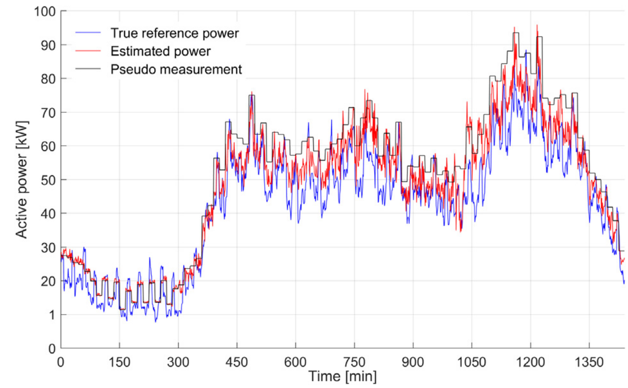

Fig. 12. Active power injection profile over the day at bus *MV*_011.

function in the topology reconfiguration algorithm, the used reconfiguration approach leads to clear enhancements also from this perspective, thanks to the minimization of the flowing currents and the consequent reduction of the voltage drops. In a similar way, the used algorithm also brings some benefits in terms of more efficient use of the locally generated energy. Simulation results show in fact that, when the default topology is used, the power generated by node *MV*_008 arrives till the HV/MV substation in 252 min out of 1440 (the active power flow is directed from node *MV*_013 to node *HV*/*MV*_001). This means that the generated power is more than the demand of the loads present in the same feeder, and the exceeding power has thus to be re-directed through the HV/MV substation to the other feeder. Through the reconfiguration of the network this situation can be avoided and when high generation is present, this can be directly linked to the industrial loads, which are the most demanding loads in the simulated grid, in order to have a better balance between generated and demanded power in the same feeder.

As additional test case, a scenario with partial deployment of smart meters (or lack of LV network data) has been also considered. In particular, in this scenario, it is assumed that the LV grids subtended by nodes *MV*_004, *MV*_009 and *MV*_011 cannot be monitored. As usually done in DSSE, pseudo measurements are used in this case to describe the forecast power consumption at the unmonitored MV nodes. In the presented simulation, pseudo measurements are created considering an average value of the true power consumption over 15 min and increasing this value of 20% to emulate a bias on the a priori knowledge; such pseudo measurements are then integrated into the MV estimator by assigning them an uncertainty equal to 50%. In such a scenario, the *MV grid SE* gets via MQTT the results from the monitored LV grids, while forecast measurements are taken from an internal database. It is worth noting that, in the proposed architecture, the pseudo measurements provisioning could be also conceived as an additional microservice interfaced to the cloud that updates periodically the pseudo measurement information on the cloud databases. In this hypothesis, the MV grid SE could, for example, access this information via REST and download every day the daily forecast profiles.

Fig. 12 shows the results of the estimated power injection at node *MV*_011 versus the true reference values and the starting pseudo measurements. In this case, differently from the buses subtending monitored LV grids, the estimation does not perfectly match the true values. However, it is possible to observe that the accurate information present in the monitored nodes allows enhancing the information given by the pseudo measurements.

The estimation errors brought by the use of inaccurate pseudo measurements obviously could potentially affect the results of the network topology reconfiguration service. In the presented scenario, however, very small changes have been obtained with respect to the outcome shown in Table 2. In particular, 13 topology changes have been triggered also in this case, which only slightly differ from the results in Table 2 for the activation time. Power losses are almost the same as the previous scenario and again they guarantee an energy saving larger than 40%. This small difference in the results is partially due to the prevalent demand of the industrial loads, but also thanks to the really accurate information achieved at the monitored MV/LV substations, which allows refining the power consumption estimation at the unmonitored nodes.

7. Conclusions

In this paper a smart metering architecture based on a cloud platform has been presented to enable different services for the management and the automation of future distribution grids. The proposed IoT platform allows achieving several benefits among which: interoperability, by abstracting from the particular hardware, devices and low-level protocols used in the measurement infrastructure; (near-) real time capabilities, thanks to the use of MQTT as event oriented publish/subscribe protocol; flexibility towards different requirements associated to different services, due to the simultaneous presence of both publish/subscribe and request/response mechanisms to access needed data; easy deployment of additional or updated services, given by the use of standard interfaces for the communication with the cloud; scalability, thanks to the clusterizable and big data oriented software modules used for the data management in the cloud. Two applications, namely a distributed state estimation and a network topology reconfiguration algorithm, are presented here showing also the possible interactions and coordinated operation unlocked by the proposed cloud-based smart metering infrastructure.

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