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5G Communications as “Enabler” for Smart Power Grids: The Case of the Smart5Grid Project

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Abstract. The fast 5G deployment at global level influences a variety of vertical sectors and offers many opportunities for growth and innovation, drastically affecting modern economies. Among the major sectors where significant benefits are expected is the case of smart grid, where the management of energy demand is expected to become more efficient, leading to less investments. 5G inclusion and adaptation in smart grid will allow easier balance of energy load and reduction of electricity peaks, together with savings of energy cost. In the present work we introduce the innovative scope proposed by the Smart5Grid research project, aiming to complement contemporary energy distribution grids with access to 5G network resources through an open experimentation 5G platform and innovative Network Applications (NetApps). Smart5Grid administers four meaningful use cases for the energy vertical ecosystem, in order to demonstrate efficiency, resilience and elasticity provided by the 5G networks. In particular, each one among these use cases is presented and assessed as of its expected benefits and proposed novelties, based on the corresponding demonstration actions.

Keywords: 5G, energy management, energy vertical ecosystem, grid fault detection, inter-area oscillations, latency, Network Applications (NetApps), power network remote inspection and maintenance, smart-grid.

1 Introduction

Today, the immense multiplicity of interconnected networks of power plants, energy transmission towers, substations, poles and wires that make up the power grid, can be considered as “the largest machine” in the world. This is not a surprise, considering that electricity is the most versatile controlled form of energy. What is more, to transfer electrical power efficiently nowadays, “smart grids” [1-2] combine traditional grids with communication and information control technologies, targeting to achieve efficiency, cleanliness and security, in a way that will “reshape” the modern landscape in energy transportation [3-5].

The Fifth Generation (5G) networks [6-8] will be an important ingredient for the development of smart grid technologies, especially allowing the grid to adapt better to the dynamics of renewable energy and distributed generation. As renewable resources – such as solar and wind power – are gaining pace with dynamic trends to become prevalent in a few years from now [9-10], the power grid will require integrated and more enhanced monitoring and control, as well as integration with substation automation in order to control differing power flows and to plan for stand-by capacity that supplements energy generation. Smart grid capabilities promise to control easier bi-directional power flows and to monitor, control and support distributed energy resources. This, in fact, implicates for more challenges as well as for more opportunities in the related market domain.

Furthermore, the 5G mobile networks will help to integrate previously unconnected devices to smart grids for accurate monitoring and improved forecasting of their energy needs [11-12]. Consequently, the managing of energy demand will become more efficient and will implicate for less investments, as the smart grid will allow for easier balance of the energy loads, for reduction of electricity peaks and, ultimately, for reduction of energy costs [13]. In this modern scope, large cities will be able to plan their energy infrastructure based on collected data, spending less resources and reducing the “downtime”. Likewise, from the perspective of power supply, 5G is expected to enable better efficiency, observability and controllability of the power system, especially at the distribution side [14]. Energy suppliers will be able to collect and store power grid related data at much faster rates, ensuring secure and stable power supply, while risk mitigation and fault management will become simpler and more straightforward.

Up-to-now, the power distribution grids have only seen very little application of mobile-network technology and, consequently, the coverage of the current communication networks remains practically low [15]. Most of the applied efforts practically focus on the three following pillars to achieve efficient communication at the power distribution level, that is: (i) Power Line Communications (PLC) that use the distribution lines and cables as a transmission channel; (ii) Wireless or Radio Communications (WLC) that use the radio technologies for transferring the information between two or more points, and; (iii) Fibre Optical Communications (FOC) that use pulses of light through an optical fibre for transmitting information. Utility companies may use communication networks based on a combination of two or more of these technologies for grid access, backhaul and backbone communications, based on specific applications. On the other hand, network operators have not participated actively and widely in providing communication services for the

transmission and distribution grid operation, due to the variety of network technologies being used by the power grid operators [16]. Another important reason is that traditional 3G/4G public network is a large all-in-one channel / single shared network, where operators cannot provide different network slices to preferred customers. Lastly, using FOC to build communication networks on the distribution level has difficulties in the deployment due to the massive-connections and the wide areas where coverage is required [17]. Such concerns have resulted to a sort of “inactive” involvement of telecom operators in the highly demanding energy vertical.

Clearly, the “smart grid transformation” must rely on existing electrical infrastructures of the generation, transmission, distribution and consumption levels of a power grid and, as such, to connect energy metering and measuring devices through a communication network that enables real-time information flow and control among power devices. Because it consists of a unified network that fulfils all the key communication requirements of smart distribution grids (including flexibility, reliability, coverage throughput, latency and massive device support), 5G is the first communication technology expected to address the plethora of current and future challenges of the energy sector [18-20].

Our work is organised as follows: Section 1 serves as an introduction, identifying the important role that 5G is to perform in order to support the operation of power transmission and distribution grids. Section 2 briefly focuses on the specific context proposed by the ongoing Smart5Grid project which is among the few research initiatives for applying 5G in the energy vertical sector. Section 3 introduces four distinct use cases that are to be deployed during the project’s life-time. Each one is presented and assessed, as of its intended beneficial use and in parallel with the corresponding demonstration scenario. Section 4 provides some concluding overview and remarks.

2 Smart5Grid: An Innovative Context for the Energy Ecosystem

Following to the above challenges and taking into account the enormous potential introduced by the intended 5G applicability in the market sector, the ongoing Smart5Grid project [21] aims to complement contemporary energy distribution grids with access to 5G network resources through an open experimentation 5G platform and innovative Network Applications (NetApps). Towards achieving this target, Smart5Grid administers four meaningful use cases for the energy vertical ecosystem, in order to demonstrate efficiency, resilience and elasticity provided by the 5G networks. On top, Smart5Grid provides an open environment to third parties for experimentation, which will be able to support development, testing and validation of 5G Network Applications specialised for the Energy Vertical [22].

The smart grid paradigm poses new challenges to communication networks requiring a flexible and orchestrated network, slicing and millisecond-level latency [23]. In order for today’s power distribution grids to be transformed into “evolved” smart grids to enable efficient, fast and secure operation, power distribution companies need new tools allowing them to monitor/operate the distribution network and to maintain/increase reliability and Quality of Service (QoS). To efficiently deal

with these issues, Smart5Grid's effort identifies the following high-level requirements for the communication network that will allow building innovative and high performance smart grids: (i) Very high device density for connecting thousands of energy metering and power electronic devices, in one location; (ii) very high bandwidth to allow massive data flows from multiple devices simultaneously, allowing remote maintenance and substation monitoring, and; (iii) ultra-low latency for fault detection, network isolation and operation of recovery devices within one power cycle (i.e. 20ms for the 50Hz frequency used in electric current).

Through the effective adoption of 5G networks and the expected assistance of the respective NetApps that will be developed and validated on real power grid facilities, Smart5Grid facilitates the current energy sector stakeholders (i.e. Distribution System Operators (DSOs) and Transmission System Operators (TSOs)) as well as future smart grid shareholders (i.e.: Smart Grid Operators, Independent System Operators, Energy Aggregators, Regional Distribution Organisations and Energy Service Providers (ESPs), etc.) to: (i) Easily and effectively create and offer advanced energy services; (ii) interact in a dynamic and efficient way, with their surrounding environment (by assessing and considering multiple options), and; (iii) automate and optimise the planning and operation of their power and energy services, thus enhancing their market activity. In this way, Smart5Grid envisages towards providing a more secure, reliable, efficient and real-time communication framework for the modern smart grids. In particular, Smart5Grid leverages on resilience and elasticity (i.e. network slicing [24]) provided by the 5G technology in order to contribute to an open and flexible platform for secure testing, validation and operation of NetApps, specifically targeting to the Renewable Energy Sources (RES) production and distribution of vertical ecosystem(s). The emerging 5G mobile cellular network, along with the celebrated new features introduced with it, (i.e., Ultra-reliable Low Latency Communication (URLLC), massive Machine Type Communications (mMTC) and enhanced Mobile Broadband (eMBB)) and the concept of MEC (Multi-Access Edge Computing) which extends the capabilities of cloud computing by bringing it to the edge of the network [25-26], provides a competent environment for smart grids.

Notably, the Smart5Grid architectural framework aims to enable efficient and cost-effective distributed State Estimation (SE) algorithms based on more sophisticated optimisation techniques [27]. This will allow smart grid voltage and phase measurements to occur at a much greater frequency than it has been possible by using the legacy measurement infrastructure. SE is a key functionality of electric power grid's energy management systems and it aims to provide an estimate of the system state variables (i.e. voltage magnitude and angles) at all the buses of the electrical network from a set of remotely acquired measurements. Indeed, for URLLC, the generic radio interface latency target is about 0.5ms, while reliability targets Packet Loss Rate of 10^{-5} for 32-byte packets and 1ms latency [28]. The open testing platform built in the context of Smart5Grid will allow the implementation and experimentation with appropriate VNFs (Virtual Network Functions) [29] and NetApps, not only to Smart5Grid partners but also to third parties (i.e. entities outside the contractual Smart5Grid consortium). This will support and "give rise" to an experimental execution environment that increases reliability, availability and maintainability in smart grid energy networks, through application of specialised 5G solutions.

3 Smart5Grid Use Cases

The Smart5Grid project is focusing towards developing network applications specifically tailored to the requirements of existing real operational issues faced by the modern smart energy grids and, thereby, it will heavily contribute to the energy vertical ecosystem. NetApps will be consisted of appropriately chained VNFs that will be developed on the Smart5Grid platform and then tested and validated on real power grid infrastructures, under true operational conditions. Following to these actions, the successful and wide adoption of the Smart5Grid NetApps will allow the smooth penetration of (mobile) network operators, telecoms and ICT industries and SMEs (Small and Medium-sized Enterprises) into the energy sector for the provisioning of novel network services; in addition, it will offer automation and real-time inspection and control to the existing energy stakeholders. The real-life validation of the Smart5Grid NetApps has been planned to take place in four countries (Italy, Spain, Greece and Bulgaria). The intended, for demonstration, scenario and setup for each use case is described below.

3.1 Use Case 1: Automatic Power Distribution Grid Fault Detection

A fault in a distribution grid is an abnormal condition that can be caused by equipment (i.e. transformers and rotating machines) failure, human errors and/or various environmental conditions. Such an error consists of a stressful situation for the DSOs, since it can have a great impact on the supplied power quality; thus it can create equipment damages and, also, it may reduce the electrical system reliability and stability resulting to power interruptions. To maintain a reliable and high-quality power supply to consumers without any interruptions, smart grids and distribution networks require real-time self-healing (i.e. the identification and isolation of faults in the backbone network and automatic recovery in less than 1 sec [30]). As manual outage handling in a control centre fails to achieve such short restoration time (manual switching takes on average 120 minutes [31]), automated fault detection solutions are widely used to restore the power supply within a few hundred milliseconds [32]). To do so, modern communication systems primarily use the international IEC 61850 standard [33] to support self-healing distributed functions, as it provides the required flexibility and interactivity for the implementation of such applications, while peer-to-peer communication via IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages provides analogue and binary data at low latency among the system components [34]. Typically, the controllers conduct self-healing of the distribution line in approximately 500msec by isolating the fault, but the tremendous social and economic consequences of a potential fault have pushed the DSOs to constantly search for mobile communication network configurations that allow even shorter restoration times, with the ultimate challenge, the peer-to-peer, Layer-2, multicast IEC 61850 GOOSE communication to become less than 5msec (i.e., less by two orders of magnitude) [15].

Smart5Grid added value: The inherent characteristics of the proposed MEC platform will contribute to the millisecond level precise discrimination of a line fault which is helpful to the immediate isolation and the rapid self-healing of the regional

power supply. A dedicated monitoring feature will facilitate the communication troubleshooting at MEC level, discriminating if the eventual issue or quality degradation is either in RAN (radio access network) or IP network, increasing the system reliability. Coupling of the URLLC and mMTC 5G network services will allow the effective operation of grid control and protection devices, enabling the ultra-fast fault detection and isolation while, at the same time, the platform will support the big in number (thousands) of grid control and protection devices.

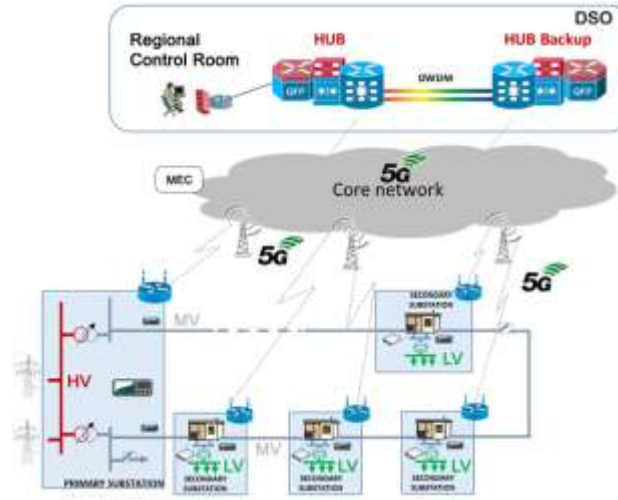


Fig. 1. Smart-grid automatic power distribution grid fault detection.

Scenario to be demonstrated: Smart5Grid will demonstrate the capabilities of the developed NetApps to extract valuable information for the DSO by constantly monitoring the communication between the protection and fault detection devices on real power distribution infrastructures over a public 5G network, as illustrated in Fig.1. As soon as a failure is detected and isolated in milliseconds using the Smart5Grid communication platform between the peripheral nodes, the central system and the communication among the Intelligent Electronic Devices (IEDs), the rest of the network shall continue its normal function whereas the goal of the demonstrated scenario will be the capability to minimise the SAIDI (System Average Interruption Duration Index) and CAIDI (Customer Average Interruption Duration Index), which are important indices for benchmarking by DSOs internationally [35].

3.2 Use Case 2: Remote Inspection of Automatically Delimited Working Areas at Distribution Level

Currently, DSOs are incurring high operational expenditures for inspecting and maintaining their infrastructures, as the inspection and the maintenance of the energy distribution grid assets is a very demanding and essential task [36]. Up-to-now, such actions are undertaken by human maintenance crews through visual examination. As

a result, dedicated personnel are often exposed to dangerous working conditions, such as high heights for tower/pylon climbing inspections, difficult ground patrols and often exposures to electrical risks (e.g. electric arcs that can cause an electrocution) during substations' visits [37-38]. For personnel safety precautions, planned power disruptions are scheduled during the inspection and maintenance procedures and so the capacity and availability of the distribution network is reduced periodically. Additionally, when maintenance works are performed in the vicinity of critical equipment of the distribution grid (e.g., transformers, circuit breakers, switchgears, etc.) the working areas are restricted and only authorised personnel can access them. As evident, it is critical for DSOs to obtain efficient and short-duration inspection and maintenance procedures from central offices to support the risk prevention and help field operators. This is done through the provision of advanced information/data, with remote inspection and maintenance procedures, without compromising quality.

Smart5Grid added value: The capabilities of the proposed Smart5Grid 5G platform will offer a solution for the improvement of working conditions for the power grid maintenance crews and inspection personnel, through remote inspection and control of the automatically delimited working areas. The 5G eMBB features will permit high-bandwidth communication between the power grid monitoring equipment (i.e. existing permanent and manual sensors and high-resolution cameras of various types) and the cloud-based inspection platform, in order to be processed with artificial intelligence (AI) and machine learning (ML) based algorithms and inference models; the latter will help to achieve automated evaluation of equipment condition and also automated delimitation of working areas at the period of their remote inspection. The Smart5Grid project aims to enable remote inspections in high risk areas and real time execution, by serving a variety of distribution network applications and by providing accurate results and information on the operational condition of the power grid assets through augmented reality. For maintenance works real-time control will be enabled, to assist the working procedures remotely and automatically without exposing the supervisor personnel to dangerous conditions.

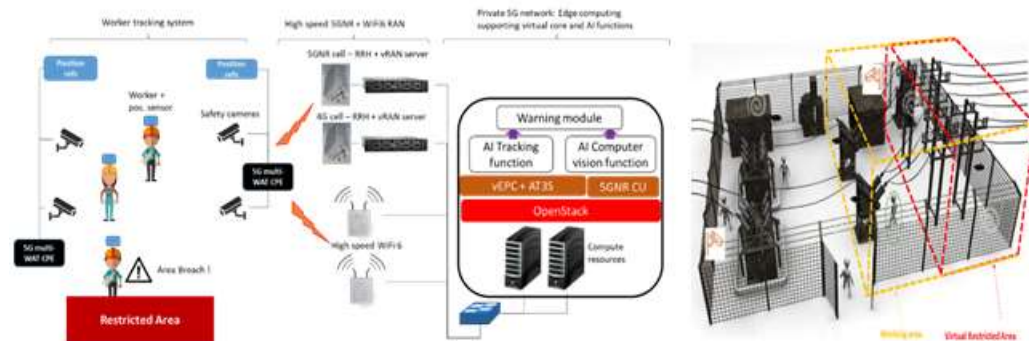


Fig. 2. 5G communication infrastructure in the substation (left) and 3D model of primary substation with open air busbars.

Scenario to be demonstrated: Smart5Grid will demonstrate the capabilities of the developed 5G platform and of the NetApp for the remote inspection of automatically

delimited working areas at distribution level through the deployment of a private 5G network (see Fig.2). The developed NetApp will: (i) Generate a detailed 3D volumetric model of the configuration of the power grid assets where the work will be carried out; (ii) automatically delimitate the working areas and the authorised personnel; (iii) permit the real-time communication of big data generated from the existing permanent and manual sensors and cameras within the working area; (iv) allow the real-time remote control of the work and capture the movements of the different operators (authorised and non-authorised), and; (v) provide instant warning signals and alerts. It is expected that the developed 5G private network shall support peak data rate of 10 Gbps.

3.3 Use Case 3: Millisecond Level Precise Distribution Generation Control

Due to the climate change, the finite reservoirs of fossil fuels and the constantly reducing cost of RESs technologies, it is expected that by 2050 most of the worldwide electricity will be produced by renewable sources ([10, 39]). This unprecedented high percentage creates new challenges for the power grid stability, as most of the RESs produce extremely volatile energy and have extreme power variations in short amounts of time. Additionally, the most widely used RESs (i.e., solar and wind energy) cannot reliably inject mechanical inertia into the local power grid, which creates reliability issues for keeping the frequency at the desirable level constant [40-41]. As the RES deployment is essential, DSOs/TSOs need to deploy new techniques for keeping the power grid performance on high levels. Control of voltage and frequency in distribution and transmission grids are the key challenges of the future 100% renewable smart grids [10]. These new procedures are still under development, and they require many economic, legal, and technological changes (apart from the modifications in the electric grid). A major enabler is the inter-connected communication systems and computing infrastructure, which interconnects control centres, substation automation units, energy storage systems and power plants of all sizes in a flexible, secure and consistent manner.

Today, the vast majority of the communication technologies used for the communication between the RES assets and the power grid are still wire-bound, including a variety of dedicated Industrial Ethernet and power line solutions, as there was no need for wireless connectivity in the past, due to the relatively static and long-lasting installation of the power grid equipment [42-43]. With the advent of future Smart Grids and 5G, however, this will change fundamentally, since wireless connectivity can increase the degree of flexibility, mobility, versatility, and ergonomics required for the energy networks of the future. It is evident that the modern smart grid era will depend on devices that can monitor the various assets and manage big data, through ultrafast communications and cloud-based apps for efficient processing and decision-making [44-45].

Smart5Grid added value: Smart5Grid will enable the connection of thousands of Medium Voltage (MV) and High Voltage (HV) level decentralised RESs units and their inverters, to a platform with installed 5G communication protocols, which will allow their aggregation and control by the DSOs/TSOs in millisecond rates. Through

the developed platform, the electricity producers owning renewable generation assets can use fast real-time cloud-based tools to formulate optimal energy scheduling according to the power system needs. Additionally, they will be able to monitor and rebalance the network by managing the distributed flexibilities provided by their decentralised energy resources (i.e., Wind Plants, Hydro Plants, Storage and Dispatchable Loads), according to the incentives provided by the grid services markets and business models (e.g., aggregators, suppliers, storage owners). All exchanged messages will be secured (especially in terms of data integrity and authenticity) so that the probability of two consecutive packet errors to be negligible.

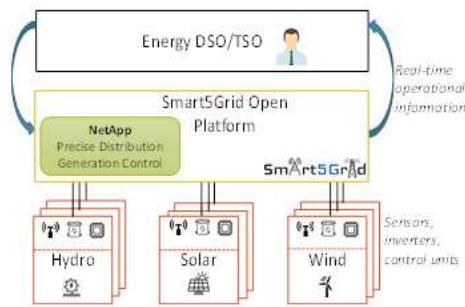


Fig. 3. Smart5Grid low latency distribution generation control of energy units.

Scenario to be demonstrated: Various power electronic devices of grid-connected, decentralised renewable power plants will be used to demonstrate the capabilities of the developed monitoring platform on real operational conditions. The application will facilitate energy generation/consumption forecast for balancing purposes, enable energy cost optimising and visualisation of end-user behaviour, to optimally manage the energy profile, operational availability and flexibility services, through respective markets (intraday and balancing markets) in millisecond-level information exchange. The platform (cf. Fig.3) will be designed for Hydro, Solar and Wind Power Plants, providing all the real-time operational information of the RES plants to the system operators and plant owners, allowing flexible plant management for procuring accurate and secure frequency and voltage control services by the DSOs/TSOs as well as visibility to plant owners for optimal plant management. Requirements on the communication service availability and reliability will be achieved by appropriate resilience and redundancy measures of the available generated power and accurate weather forecasts.

3.4 Use Case 4: Real-time wide Area Millisecond Level Precise Distribution Generation Control

Inter-area frequency oscillations represent one of the major challenges that face modern power systems, since their appearance is increasing due to the vast changes (i.e. increased penetration of renewable sources, growing energy demand, etc.) and

constant expansion [46]. The appearance of inter-area oscillations creates many issues such as power quality degradation, limitation of transmission system capacity and, on several occasions, it can even lead to system instability. The detection and observation of inter-area oscillations is possible only with the use of synchronized measurements provided by the Phasor Measurement Units (PMUs) [47]. Exploiting PMU inputs for a robust, decentralised and real-time operational solution calls for novel communication infrastructure that will support the Wide Area Measurement Systems (WAMSs) of each smart grid, with aim to detect and counteract power grid disturbances in real time, while providing the observability needed.

Currently, the time-stamped phasor from each PMU is sent either through public Internet or serial cable to the Phasor Data Concentrator (PDC). The PDC receives data from all the PMU locations and, after sorting them accordingly, it transfers them to the WAMS [48]. For the WAMS to be able to obtain timely synchronized measurements from PMUs installed in all over the power system, the communication networks play an essential and crucial role. However, communication networks impose latency and errors, and these are the main obstacles towards the implementation of real-time applications. These are found to be the most known factors responsible for the degradation of the Wide Area Control damping capability which can even lead the system to instability, since the wide area controller is a near real-time application (operation rate of $\sim 40\text{msec}$ [49]).

Communication delays take place during data exchange between devices (e.g. PMUs and PDC) in a shared medium and they are mainly introduced by the long distance transportation of feedback signals, the medium type, the data buffering and the time required to send each bit. This kind of delay has the most variability mainly due to the conditions of the communication network (e.g. traffic, medium length, routers, switches, etc.). According to the IEEE Synchrophasor Standard C37.118.2-2011, typical delays from a PMU to the PDC are between 20-50msec and each level above adds additional delays in the range of 30-80msec [50], as illustrated in Fig.4. Therefore, for a two-level communication infrastructure, the overall delays are in the range of 50-130msec.

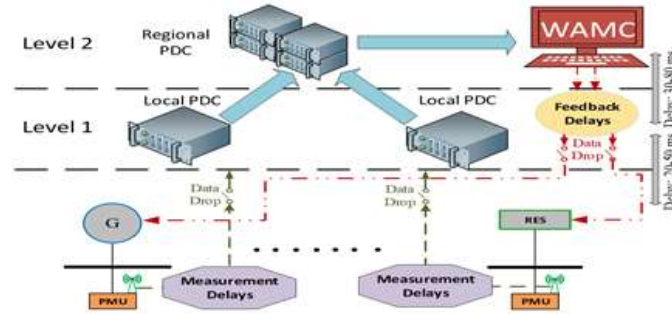


Fig. 4. Measurement infrastructure delays included for the data transfer between the PMUs, the local PDCs (Level 1) the regional PDC/WAMC (Level 2) and feedback delays from the WAMC to the local controllers.

Smart5Grid added value: With the proposed network configuration and applications for the real-time communication of the time-stamped phasor from each

PMU station to the developed virtual PDC (vPDC), Smart5Grid is expected to significantly minimise the communication and transfer delays of the current WAMSs. It is also expected that Smart5Grid communication platform will minimise the transfer delays of the PMU measurements and the feedback control signals, while it will also minimise the data dropouts – such events are experienced using the contemporary communication infrastructure that often compromise the WAMS operation. Message loss and corruption and interference with other, lower priority traffic will be avoided as much as possible. In this sense, Smart5Grid is envisioned to improve WAMS' reliability and performance, thus contributing to the effective maintenance of the transmission and distribution power grid stability and reliability.

Scenario to be demonstrated: Smart5Grid aims to demonstrate the 5G virtual PDC capabilities for serving the Wide Area Monitoring of end-to-end electricity networks, that is: from Distributed Energy Resources at Medium Voltage level operated by DSOs to High Voltage level operated by TSOs, as well as inter-TSO cross border Regional Security Coordination, aggregating the data from the PMU devices installed, enabling precise state measurements and processing to be made across grid segments. To do so, the four main functionalities of the developed Smart5Grid virtual 5G PDC NetApp will enable: (i) The comparison of different measured variables from various monitoring PMU devices for both real-time and historical data; (ii) the real-time monitoring of triggered events detected by PMU devices, as well as snapshots of the events in various levels of detail; (iii) the real-time displacement of the rate of change of frequency across the entire monitored network, and; (iv) configuration of the voltage magnitude and angle difference state measurements across the distribution and transmission grid segments in real-time. The developed 5G virtual PDC will be also applicable for TSO-DSO PMU configurations to maintain the stability of the overall power grid at national level.

4 Concluding Remarks

In the scope of the present work we have discussed the important role of modern 5G communications as a real “enabler” of the power grid domain, thus promoting significant opportunities for growth in the energy vertical sector. In particular, the deployment of 5G infrastructures and of all potential related facilities allows for the support of smart grid technologies within a fully converged environment, enhancing adaptation to the dynamics of renewable energy and distributed generation. 5G also contributes to the efficient integration of numerous devices to smart grids, allows handling of immense data sets and permits for exact monitoring and management of energy needs of various underlying systems, offering significant benefits in a variety of activities and services.

Smart5Grid is among the on-going research initiatives supporting transformation of the power distribution grids towards smarter entities via the beneficial incorporation of innovative 5G features. The project aims to identify high-level requirements for the communication network, allowing the structuring of innovative and high performance smart grids. Via the adoption of 5G network infrastructure and the effective inclusion of suitable Network Applications consisted of chained VNFs,

an innovative platform shall be deployed. This will allow offering of multiple benefits to the corresponding market actors, coming from both energy and ICT sectors.

Smart5Grid has identified several operational use cases that will take place in 4 European countries. Each one has been assessed as of its specific framework of reference and about the expected positive impact. In particular, we have discussed options for the added value that shall be provided by the Smart5Grid intended approach and details about the scheduled demonstrations have also been presented. All use cases are about real scenarios of use and “face” direct challenges identified by the energy vertical sector, thus their further treatment is expected to be both innovative and purely beneficial.

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