5G for the Support of Smart Power Grids: Millisecond Level Precise Distributed Generation Monitoring and Real-Time Wide Area Monitoring

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Abstract. Smart grid deployment can strongly be supported and enhanced by the expansion of 5G infrastructures as the latter can offer immense opportunities to enable better efficiency, observability and controllability of the power systems, especially at the distribution side where the numbers of monitoring devices and automation equipment exponentially increase. Among the fundamental context of the original Smart5Grid EU-funded project, we focus upon two selected use cases of significant interest for the corresponding energy vertical sector. These are the millisecond level precise distributed generation monitoring and the real-time wide area monitoring. Both use cases are described, conceptually assessed and evaluated as of their proposed services, their main business goals and their benefits in various sections, with specific emphasis given on the need for the inclusion of 5G facilities.

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1 Introduction

Large and interconnected power systems are seen as the backbone of the critical infrastructures in any society. They are complex cyber-physical systems for which the communication layer plays an important role in monitoring, control and automation of the grid. So far, the communication networks dedicated to power systems' control and automation were hosted and managed by the electric utility itself. At the same time, telecom providers played little or no role in the communication infrastructure of the power grids, especially upstream the meter of the electricity consumers. However, this status quo is expected to drastically change in the smart grid era, a phase which has already started [1]. The smart grid concept and its deployment environment(s) are aiming to increase efficiency, resilience, reliability and security of the evolved and greener power grids, by means of increased digital automation and control [2]. In this respect, the traditional power grids need to be complemented with advanced communication and information technologies [3, 4], targeting to achieve efficiency and security, in a way that will "reshape" the modern landscape in the energy vertical. With the development of smart grids [5, 6], existing power networks fell short of the demanding requirements of industrial applications, especially with respect to bandwidth, end-to-end latency and reliability. Combining with vertical industry is a major development direction of 5G mobile communication technology, while its communication capacity of large bandwidth, low latency, high reliability as well as massive connection is matched with the service requirements of smart grid service.

The Fifth Generation (5G) of communication networks appears to possess the right features to allow the power grid to tackle the above-mentioned challenges [7, 8]. It is envisioned that 5G networks will play a significant role in the power grid transformation [9] to enable better efficiency, observability, and controllability of the power system, especially at the distribution side [10], where the number of monitoring devices and remote automation equipment is expected to dramatically increase [11, 12]. The vision for 5G is to not only provide better broadband with higher capacity and higher data rates at much lower cost, but also to address entirely new challenges, to enable new services, empower new types of user experiences, and connect new industries. With the continuous development of power grid information construction, 5G network is gradually applied to all aspects of power generation, transmission, transformation, distribution and use [13].

Specifications, such as high data rates and low latency across wide areas of coverage, flexible massive Machine Type Communication (mMTC) specific for dense urban areas, and Ultra-Reliable and Low Latency (URLL) communication are those which could enable a significant shift for the smart grid's communication layer. The flexibility of the 5G technology is the most valuable feature along with modularity and full programmability, allowing fast deployment of services to be tailored to the unique requirements of the energy vertical. This transition from a "horizontal" service model, specific for past mobile network versions such as 3G, 4G and LTE, towards a "vertical" dedicated service model opens the path for a plethora of innovative applications across a variety of industry- or community-related verticals, including the energy vertical [14, 15].

The present paper is composed by several distinct sections: Sect. 1 delineates the necessary introductory framework where the strong innovative correlation between smart grids and 5G is outlined. Section 2 serves as a brief overview of the full scope introduced by the ongoing Smart5Grid EU-funded project, practically structured around four selected use cases of practical market interest. Sections 3 and 4 discuss, in more detail, the corresponding use cases 3 (UC#3) and 4 (UC#4), by focusing on their conceptual descriptions, their proposed services that are related to UC-specific NetApps, their main business goals and services objectives, the need for involving 5G technology and their expected benefits. Section 5 provides some concluding remarks.

2 The Smart5Grid Concept

Taking into account the above concerns, the Smart5Grid EU-funded project [16] is focused on boosting innovation for the highly critical and challenging energy vertical, by providing an open 5G enabled experimentation platform customized to support the much promising smart grid vision for the benefit of the related market sector(s). The Open Smart5Grid experimental platform aims to be an ecosystem where stakeholders in the energy vertical, ICT integrators, Network Applications (NetApps) developers, actors in the telecom industry and/or network service providers in general, could "come together" fostering collaboration and innovation in a fully interactive way. The core goal of the project effort is to validate, both at the technical and business levels, the opportunities offered by the 5G technology [17], to be demonstrated in four meaningful use-cases, relevant to real scenarios of use [18], specifically targeting to the Renewable Energy Sources (RES) production and distribution of energy vertical ecosystem(s).

The proposed four use-cases (UCs) cover a broad range of operations for the power grids and a very diverse set of applications such as: (i) advanced fault-detection, isolation, and self-healing for the power distribution grids (UC#1, in Italy); (ii) enhanced safety tools for maintenance workers in high-voltage power substations (UC#2, in Spain); (iii) advanced and remote monitoring with millisecond precision for dispersed renewable-based power generation units (UC#3, in Bulgaria); and (iv) wide area monitoring of cross-border transmission power grids (UC#4, in Greece and Bulgaria). The UCs addressed by the Smart5Grid project are focused upstream the electricity meter, and more specifically at the power distribution and transmission system operators' sides, as well as at the power generation side, specifically multi-unit renewable generation owners.

These use-cases were specifically chosen in order to "capture" a wide range of operation scenarios for the power systems as well as to "reflect" scalable business needs at the European level for all stakeholders operating in the power distribution grids (e.g., electricity suppliers and Distribution System Operators (DSOs)), European Transmission System Operators (TSOs), owners, aggregators or operators of distributed, renewable-based power generation. The main outcomes from the use-cases analysis are a set of technical, business, and regulatory related requirements which are specific for the highly regulated and standardised energy vertical; and, a set of 5G network requirements which are particular to the Smart5Grid use cases. The requirements of these use cases also addressed the scope of the dedicated NetApps and their service objectives, the sequence diagrams of these services, as well as conditions and technologies involved, *per case*.

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. DSOs and 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.

The emerging 5G mobile cellular network, along with the celebrated new features introduced with it, (i.e.: URLLC, mMTC and enhanced Mobile Broadband (eMBB)) together with the innovative concept of MEC (Multi-Access Edge Computing) which extends the capabilities of cloud computing by bringing it to the edge of the network, provides a competent environment for the case of smart grids [19].

The Smart5Grid architecture which will accommodate and mediate the validation process of the demonstrators revolves around the Network Function Virtualisation (NFV) concept. The design targets an open experimentation facility for 3rd party NetApps developers, fully softwarised, and which integrates an Open Service Repository (OSR), a framework for Validation and Verification (V&V), and a flexible and modularized Management and Orchestration (M&O) framework.

The open testing platform built in the context of Smart5Grid will allow the implementation and experimentation with appropriate VNFs (Virtual Network Functions) [20] 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 UC#3: Millisecond Level Precise Distributed Generation Monitoring

The scope of **UC#3** is the millisecond level precise distributed generation monitoring which addresses the domain of the distributed energy operation and maintenance with a specific focus on renewables [21]. Specifically, in the context of this UC, the real-time (RT) monitoring of a wind farm is to be performed, by using the emerging capabilities of 5G telecommunication networks. RT monitoring is vital for the proper operation of the wind farms, mainly for two reasons: (i) The owner, being aware of the RT condition of the farm, can predict and prevent on time potential future malfunctions that will cause significant financial losses, and; (ii) the wind farm owners, acting both as a BRP

(Balancing Responsible Party[1]) and BSP (Balancing Service Provider[2]), are accountable for the potential imbalances and for the provision of the committed services in the real-time market, respectively [22]. Hence, high granularity precise monitoring of the RT power production will offer the capability to wind farm owners to minimize their cost and, simultaneously, being eligible for provision of ancillary and innovative flexibility services (voltage regulation, congestion management, etc.) through flexible plant management. In addition, UC#3 intends to demonstrate a working solution of a distributed Renewable Energy Sources (RES) generator/producer, which could be adopted and implemented on a bigger scale for other RES producers during the post project market exploitation stage [23]. The strict requirements set by power system operators for the service provision by RES, render essential the utilization of a highly reliable and secure telecommunication connection between the physical asset (wind farm) and the dispatch centre of the operator.

In the context of UC#3, the goal is to facilitate energy generation forecast for balancing purposes and to enable energy cost optimization as well as visualization of end-users' behaviour to optimally manage their energy profile for operational availability, and provision of flexibility services through respective electricity markets (intraday and balancing markets), in millisecond-level information exchange. Regarding operational availability, an illustrative example showing the benefits is the following one: it is important the wind farm owner, or aggregator or DSO to be confident if the power plant is currently in operation. Sometimes due to maintenance, inspection, or unforeseen circumstances, the power plant may not be in operation. In such a case, the power plant manager may forget to notify the aggregator/DSO which can result in heavy balancing costs (unbalance penalties occur). In case of RT monitoring such mistake can be found in time, allowing cost optimization. Regarding the provision of flexibility services, the wind farm can provide all its RT operational information to the system operators, allowing flexible plant management for procuring accurate and secure frequency and voltage control services [24] by the DSOs/TSOs.

Thus, ***two services are targeted as part of UC#3*** *which are related to two distinct and UC-specific NetApps.* These are briefly described as follows:

- *Predictive maintenance:* gathering measurements from sensors capturing the performance of key components of the wind turbines, and thus offering to the wind farm owner information regarding the asset performance of the wind farm, and to the power system operator (i.e., TSO) information about operational availability of the asset.
- *Real-time energy production monitoring:* The wind farm owner and the power system operator (i.e., TSO) monitor RT energy production of the wind farm in a millisecond basis. On the one side, wind farm owner can increase efficiency and accuracy of both

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[1] A BRP in the EU internal electricity market is a market participant or its chosen representative responsible for its "imbalances" (i.e., deviations between generation, consumption and commercial transactions).

[2] A BSP in the EU internal electricity market is a market participant providing balancing services (here the term "balancing" stands for either or both balancing capacity and balancing energy) to its connecting TSO (Transmission System Operator) or in case of the TSO-BSP Model to its contracting TSO.

production control and forecasting, using also other information, such as weather data. On the other side, TSO can enhance power system stability through the supervision of RES production in hard-real-time.

From the vertical application point of view, there are three ***main business goals or level objectives*** about: (i) Offering predictive maintenance recommendation services in the wind farm (located in a rural area), by receiving RT measurements from multiple sensors; (ii) providing RT monitoring services of the energy generation of the controlled wind farm in hard RT conditions, and; (iii) providing the wind farm owner live monitoring features through a web-based dashboard and/or an application upon a smartphone device.

In order to accomplish the previous defined business level objectives, the following ***technical objectives*** are defined: (i) Collecting RT measurements from the sensors existing at different locations of the wind farm; (ii) forecasting the energy production of the wind farm in order to participate in the day-ahead, intra-day and balancing electricity markets; (iii) collecting RT measurements of the energy production in order to conduct RT control, and; (iv) analyzing data to offer data analytics services regarding predictive maintenance and RT operation of the wind farm.

The ***need for 5G technology*** for the development of this use case is based on the following reasons: (i) Previous generations of wireless technology do not fulfil the criteria for low-latency and high reliability in millisecond basis, as imposed by the UC3#'specifications; (ii) anticipating and foreseeing the massive deployment of Distributed Energy Resources (DERs) that are going to enter the grid, there is a need for new technology that could assist the transformation the grid is going to experience as well as the issues that will arise from that. The envision that more and more Internet of Things- (IoT-) enabled energy devices will be connected and also controlled by aggregators or system operators render necessary the investigation of robust solutions that consider the scalability aspect. In this case, we are talking about a widespread IoT ecosystem that includes millions or even billions of devices that operate on a range speed, have different bandwidth as well as a variety of quality and service (QoS) requirements. To achieve that, technologies before 5G cannot provide the needed coverage, latency, security, and cost optimization. Hence, scalability can be achieved through the utilization of 5G infrastructure, where more RES and IoT devices can be connected to the NetApp without deteriorating the performance of the services; (iii) compared to the optical fibre, 5G offers a more flexible and cost-efficient way of communication, with similar values of the above-mentioned metrics, and; (iv) the rural location of the RES significantly increases the capex in new projects, due to the high cost for dedicated investments in fibre infrastructure. Hence, the utilization of 5G can provide incentives to RES owners to further invest in new installations, by utilizing 5G networks even for the last mile network connection.

The ***benefits*** coming from UC#3 can be classified in several categories such as:

Business: Increased visibility in wind farm operation, not only from an energy production point of view but also from a multi-parameter wind turbine life cycle perspective provides the owners fertile ground to better manage their assets and offer innovative flexibility services. This is important as a well-functioning internal market in electricity should provide producers with appropriate incentives for investing in new power generation, including in electricity from renewable energy sources, while it should also provide consumers with adequate measures to promote more efficient use of energy, which presupposes a secure supply of energy.

Economic: Replacing parts of the wind turbines on time before the complete performance degradation of the wind farm, leads to continuous uninterruptible production, minimizing, at the same time, the maintenance cost. Having knowledge of the RT production in a millisecond basis, the system operator can minimize the overall system cost and the owner can benefit financially by providing innovative services to the operator, such as voltage regulation. In addition to that, better portfolio management of the BRPs can lead to lower deviations from the committed program and thus to lower needs and cost for balancing services.

Social: Secure and uninterruptible energy provision to the end-user.

Environmental: High visibility in RES production leads to better management of the power system and thus reducing the need for RES curtailment in order to alleviate congestion issues and imbalances. Higher participation rate of RES in the energy mix leads to cleaner energy production and lower levels of CO_2 emissions.

Technological: 5G is a relatively new technology and researching, testing and validating IoT devices to work over 5G in a real use case will pave the way for further adoption of IoT devices over 5G into energy sector and other industry verticals.

4 UC#4: Real-Time Wide Area Monitoring

The scope of **UC#4** is the real-time monitoring of a geographical wide area where cross-border power exchanges take place. UC#4 addresses the energy reliability and security domain of the broad energy vertical. Specifically, in the context of this UC, the interconnection flow between Greece and Bulgaria is monitored leveraging the advantages that the 5G telecommunication infrastructure provides. This function will be executed from the newly established Regional Security Coordinator (RSC) in Thessaloniki, Greece. The role of the RSC is to promote regional cooperation and to support the strengthening of the neighbouring power systems and market operations in the region. To achieve the enhancement of the interconnected power system operation, live monitoring of the power flows between the countries under its area of interest is of vital importance. Hence, this UC can be considered as the development of an additional element that increases the live monitoring capability of the RSC. Phasor Measurements Units (PMUs) located at the High Voltage network of Northern Greece, monitoring the interconnection area with Bulgaria, will be used as the input in the monitoring process of the RSC. By incorporating time-stamped synchronized PMU measurements high data granularity can be achieved (receiving the requested data 50 to 60 times per second, including positive, negative and zero sequence phasors of voltage and currents) [25–27]. A virtual Phasor Data Concentrator (vPDC) will be developed for the data gathering process. The utilization of 5G in UC#4 contributes to the connectivity between the PMUs and the vPDC, offering its low latency and high reliability needed, due to the criticality of the UC.

To give a broader perspective, it is worth mentioning that the continuous expansion of of the European high penetration rate of the Distributed Energy Resources (DERs) significantly increases the complexity of the power system making its RT operation and control functions demanding and difficult to handle. As the DER penetration rate increases, inverter-connected devices dominate, leading to the lack of physical inertia. The lack of inertia results in significant variations in the Rate of Change of Frequency (RoCoF), thus subsequently resulting in fundamental changes in the dynamic behaviour of the power system. Therefore, for the proper RT operation of the power system, the existence of a Wide Area Monitoring (WAM) system is essential [28, 29], that is capable of capturing and alleviating dynamic phenomena that create hazardous conditions for the stability of the entire interconnected European power system. Occurrences taking place at a specific location of the power system are able to create instability in the entire power system. WAM systems mainly leverage the high accuracy of PMUs and the low latency of the new era telecommunication networks [30]. Multiple control areas exist in the European power system, where each Transmission System Operator is responsible for the control of its system. For the proper coordination between neighbouring control areas, RSCs owned by adjacent TSOs were established. One of the RSC's goals is the coordinated security analysis in multiple timeframes (day-ahead, intraday and real-time). Regarding the RT monitoring of their area (including areas controlled by multiple TSOs), the RSCs provide advice to the TSOs for the proper operation of the power system. In addition, an RSC contributes by offering post-event feedback (in case of a major grid disturbance or frequency deviations) to the concerned TSOs in order to develop and improve guidelines for this kind of problematic situation. In the context of this UC, the RT monitoring function of the respective RSC from PMU measurements from Northern Greece monitoring the interconnection area is demonstrated. Afterwards, TSOs can leverage the information of their connected assets and the recommendations arriving from the RSC in order to perform better control actions and alleviate occurrences that threaten system stability.

Interconnected power systems often face frequency oscillations that tend to challenge their proper way of operation, even leading to instability of the system. A very effective way to monitor those events is the use of the synchronized measurements provided by the PMUs, which are placed near the borders of the connected power systems. These measurements are gathered by the PDCs in order to be sorted accordingly and get forwarded to the WAM service [31]. However, due to the vast amount of data provided by the PMUs and their criticality, a highly reliable means of communications is needed to ensure the flawless monitoring of the power system. This is where the 5G infrastructure can be utilized, offering that high reliability and low latency needed, as well as the flexibility to add more measurement units, without high cost and hard to move installations (e.g., optical fibre).

The UC#4 specific NetApps aim to cover ***three types of services:***

- *vPDC Service:* The first service that this use case addresses is the vPDC that is responsible for data gathering from the PMUs placed in the broader interconnection area of Greece and Bulgaria. In that way, they are going to be comparable to each other. The vPDC receives and time-synchronizes phasor data from multiple PMUs to produce a RT, time-aligned output data stream. Virtualization of the PDC significantly minimizes communication and transfer delays in the network as it is closer to the PMUs. It also minimizes the implementation cost.

- *WAM Service:* Afterwards, the WAM service will present several status indicators and visualization features of the PMUs. Some of those features may be: (i) A map indicating the device's current location; (ii) the device's name, address, model, serial number and firmware version; (iii) the nominal grid frequency [Hz] and the current reporting speed [fps]; (iv) the phase diagram with voltage and current vectors displayed (updated in near-RT), and; (v) voltage magnitude and angle difference monitoring, derived from historical data of both sites.
- *Advisory Service:* The third service will provide advisory indications for RT operation to both TSOs, and ex-post analysis provision in case of severe event occurrence in the grid.

Business Goals: The Primary Actor of this use case can be considered the entity that monitors both concerned transmission grids. The RSC may be responsible for this task. Both TSOs (i.e., Greek and Bulgarian) involved in the use case can be considered as facilitators providing access to the measurement infrastructure (i.e., the PMUs). The business goal of the RSC is the RT monitoring of the supervision area and the provision to the TSOs of the information and strategies for the proper coordinated security analysis and operation of the system in RT conditions. By doing so, the power system in the greater region operates under secure conditions and is robust towards abnormal dynamic contingencies that threaten the overall system balance.

Service objectives: In terms of services, the goal is the monitoring of the PMUs' status and the visualisation of their features in such a way that efficient suggestions regarding power system control will be offered to the TSOs. Such indicators may be the voltage and current values as well as the angle between them, and, of course, the RoCoF value in both sides of the area to be monitored. The combination of different features and the comparison of each one with its symmetrical could also reveal hidden but useful results and deductions.

The ***need for 5G technology*** for the development of UC#4 is based on the following reasons: (i) Previous generations of wireless networks do not fulfil the latency, bandwidth, and reliability requirements imposed by the criticality of the application; (ii) compared to the optical fibre, 5G offers a more flexible and cost-efficient way of communication, with similar values for the aforementioned metrics.

Expected benefits are briefly discussed covering the following distinct categories:

Business: Better monitoring of the power system for the RSC leads both of the operators to have an enhanced monitoring ability and supervision of their area by being aware of the adjacent energy network condition.

Economic: By establishing an adequate level of coordination, faults leading to severe conditions in the transmission system such as outages can be captured and handled in time, saving TSOs from costs due to the energy not being provided to the customers. In addition to that, better network observability in the critical elements connecting Greece and Bulgaria can increase the energy transfer between the two countries, leading to stronger electricity market coupling between the countries and thus potential financial benefits for both.

Social: Secure and uninterruptible energy provision to the participating end-users.

Environmental: Higher share of renewable energy sources in the energy production mix significantly reduces the usage of fossil-dependent conventional power plants, thus leading to CO_2 emissions' reduction. However, the high penetration of RES increases security issues due to their intermittent stochastic nature and the inverter-based grid connection. This use case can be seen as a step to increase coordination security, an essential element for the further increase in the penetration rate of RES. Therefore, we can consider that this use case has indirect environmental benefits.

5 Concluding Remarks

A smart grid is a modernized power grid which uses information and communication technologies to collect information from the power grid. This information is used to adjust the production and distribution of electricity or to adjust power consumption in order to save energy, reduce losses and enhance the reliability of the power grid. In a normal power grid, devices are monitored manually onsite. With smart grids, these devices can be monitored and measured remotely and can automatically determine, adjust, and control power usage. Therefore, connecting these devices to the communications network is fundamental to smart grid construction and efficient operation.

As a representative example of the vertical industry, smart grid implicates for new and very important challenges to modern communications networks. In particular, the diversity of power grid services requires a flexible and orchestrated network, high reliability requires isolated networks and millisecond-level ultra-low latency requires networks with optimal capabilities. 5G networks constitute an ideal choice to enable smart grid services. 5G network slicing allows the power grid to flexibly customize specific slices with different network functions and different SLA (Service Level Agreement) assurances according to the needs, to meet different network requirements of various services. 5G also contributes to the effective integration of a multiplicity of devices to smart grids, it allows handling of immense data sets and permits for exact monitoring and management of energy needs of various underlying systems, thus providing benefits in a variety of applications and related services.

Being within this scope, the Smart5Grid project is a modern EU-funded research oriented initiative, around four distinct operational use cases scheduled to be implemented in four European countries. The core aim of the effort is to structure a modern platform able to serve high performance smart grids, especially with the implementation/experimentation of appropriate VNFs and corresponding NetApps.

In the present work we discuss, in more detail, two of the proposed uses cases, dealing with millisecond level precise distributed generation monitoring and RT wide area monitoring, correspondingly. The aim has been about explaining the relevant conceptual background as well as about discussing their proposed services related to UC-specific NetApps, their main business goals and the expected benefits in various categories, in parallel with support provided by the inclusion of 5G technology.

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