On the Impact of Using Public Network Communication Infrastructure for Voltage Control Coordination in Smart Grid Scenario

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Abstract. This paper focuses on the impact of using the existing public network communication infrastructure for online voltage control support and coordination of renewable generation (ReGen) plants in medium voltage distribution systems. The communication network infrastructure and related communication protocols have introduced several test scenarios and cases that are evaluated with respect to the related latencies and validity of the signals being exchanged between a control center and the ReGen plants. An exemplary benchmark grid area in Denmark, including flexible ReGen plants, is used as a base case for evaluating the network performance in terms of latency. The main outcome of this study is to provide a generic overview of the aspects and their effects related to the use of existing public network communication infrastructure for online coordination of voltage control in a distributed system, considering the huge ReGen penetration, in order to ensure a resilient voltage controlled distributed systems.

Keywords: Communication · Public network · ReGen plants · Coordinated control

1 Introduction

The Danish Government has a target to use 50% of renewable energy by the end of 2020, while making this to be a 100% by 2050. This goal is anticipated to be accomplished by a large scale integration of wind power plants (WPPs) and solar photo-voltaic plants (PVPs) in the medium voltage (MV) distribution system. The high penetration of these ReGen plants into the distribution systems may cause a reverse power flow and depending on the amount of generation and consumption, this will lead to rise in voltage levels. In order to deal with such problems, there are several solutions proposed, for instance, reactive power control using capacitor banks and inductors [1], on-load tap changer (OLTC) transformers at substations [2] and advanced power electronic devices based solutions for voltage control [3]. These solutions either have issues with the power quality, cause a huge percentage of failures or are too expensive for a large scale deployment. However, a simple solution proposed in [4] is the provision of reactive power support from the existing ReGen plants in the distribution grid. This will not only make

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it possible to down-regulate the entire voltage profile in the distribution system, but also keep the voltage within the limits at the given nodes.

Grids connection requirements for ReGen plants also necessitate the provision of reactive power support, which is offered by today's ReGen plants. However, this capability is not utilized by Distribution System Operators (DSOs), mainly due to the lack of technical infrastructure to communicate and control these units. The DSOs in Denmark have already started to install and deploy SCADA systems [5], but, controlling the ReGen plants may not be feasible in long term due to lack of regulatory framework. It is foreseen that aggregators of these ReGen units may take the responsibility, in close cooperation with local DSOs, for hosting voltage control capabilities besides the energy trading. An ancillary market for the provision of voltage/reactive power provision is also expected in the near future [6]. Thus, the needs for coordination in providing reactive power support and hence controlling voltage locally on a distribution grid is required in respect of the increasing number of dispersed units. This service may be provided by the same aggregators which nowadays are trading renewable energy or may be in the responsibility of the DSOs. Therefore, at this stage, we consider that it is the Aggregator control unit that is responsible for providing reactive power support and controls the voltage locally on the distribution grid.

Nevertheless, the coordination between ReGen plants and the Aggregator imposes high responsibility on the ICT infrastructure. Although implementing a reliable, high speed connection, e.g. fiber optics, to all ReGen plants in the grid seems the best possible option, but this being very expensive considering the huge penetration of ReGen plants, is not feasible. There exist several other options too, as detailed in [7, 8], but the idea is to use an already existing infrastructure that offers low operating costs, faster deployment, high speeds, flexibility and provide full expertise and manning to operate the network. Nowadays, cellular networks (e.g. UMTS, LTE) are already widely deployed by the telecom operators in Europe with high coverage [9]. Therefore, this paper focuses on the use of the existing cellular network communication infrastructure, e.g. owned by Tele Denmark Communication (TDC), as a base case and outline its impact on the online voltage control and coordination functionalities for ReGen plants in distributed grids. The outcome of this study serves as a generic guidance on the use of existing public network infrastructure to coordinate the voltage-stability support capabilities of ReGen plants in a distribution system with large ReGen penetration in order to ensure a resilient voltage controlled distribution system.

The control of power systems over cellular networks has been addressed in several papers. In [10, 11], the authors focus on the latency requirements of delay-critical operations in medium voltage grid. They perform an assessment of latency and reliability for LTE technology under various load conditions. The work is based on conducted field trials using IEC-61850 standard. The authors conclude that LTE, in general, fulfills delay and reliability requirements of medium voltage grid applications. However, the authors in [10, 11] do not focus on the voltage control coordination in particular considering the high penetration of ReGen plants in the power grid. [12] provides a comprehensive survey investigating the challenges and propose architectural and protocol improvements of cellular technology to support NAN applications in a smart grid scenario. The authors propose a redesign of current LTE cellular networks to enable autonomous and automatic interactions for smart energy systems, with emphasis on enabling mission-critical applications.

The remainder of this paper is organized as follows: Sect. 2 explains the voltage control coordination scenario in power distribution systems, highlighting several ways and challenges to connect ReGen plants to the Aggregator control unit. The challenges related to the online voltage control coordination in the MV grid are outlined by exemplary test cases in Sect. 3. In Sect. 4, time domain analysis is performed to test the impact of using public network infrastructure for online voltage control coordination. The conclusion of this study and future work is given in Sect. 5.

2 Power System and ICT Challenges

2.1 Voltage Control Coordination in Power Distribution Systems

One of the challenges in power systems is to keep the voltage profile within the desired tolerance band margins, stipulated by the so-called Grid Code requirements that need to be fulfilled by any generation unit being connected to the power system. In MV distribution grids the voltage has to remain within ±10% of its nominal value [13]. If these limits are violated at certain points within the grid, affected generation and consumption units need to be disconnected, which can eventually lead to severe stability problems in the entire power system. One way for a single ReGen plant to contribute to voltage regulation is realized by a local voltage controller as shown in Fig. 1.

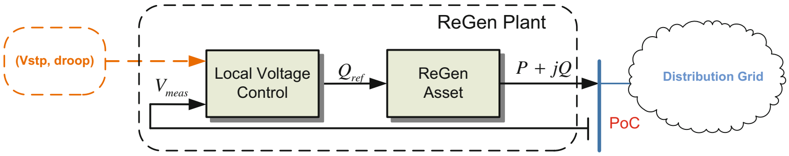

Fig. 1. Voltage control scheme of ReGen plant [4]

The ReGen plant has an inner control loop for regulating reactive power provision at the Point of Connection (PoC) and an outer voltage control loop for controlling the voltage in the PoC. A typical droop function is to be configured for the ReGen plant controller, i.e. a voltage reference point V_{stp} and a droop value needs to be specified. It has been ascertained in [4] that it is sufficient to introduce these settings once as an off-line initial system analysis in order to achieve satisfactory voltage regulation within the tolerance band margins.

However, there can be other control objectives imposed by the DSO, e.g. to reduce the grid power losses which are caused by reactive power provision. This can be achieved by optimizing the control settings in a so-called distributed on-line coordination scheme [14]. Since the power output of ReGen plants varies continuously and thereby the voltages in the distribution grid, an Aggregator of grid support services may take over the task to update the controller settings of the ReGen plants continuously in real-time according to the actual operating point.

The involved actors of such coordination scheme are illustrated by means of Fig. 2. The DSO needs to provide the system parameters of the distribution grid. The Aggregator receives measurement signals of voltage, active and reactive power ($V_{meas}, P_{meas}, Q_{meas}$)as well as the available reactive power $\left(Q_{ava}\right)$ from all ReGen plants (1…N) and dispatches the droop settings (V_{stp}, droop) for the voltage controllers.

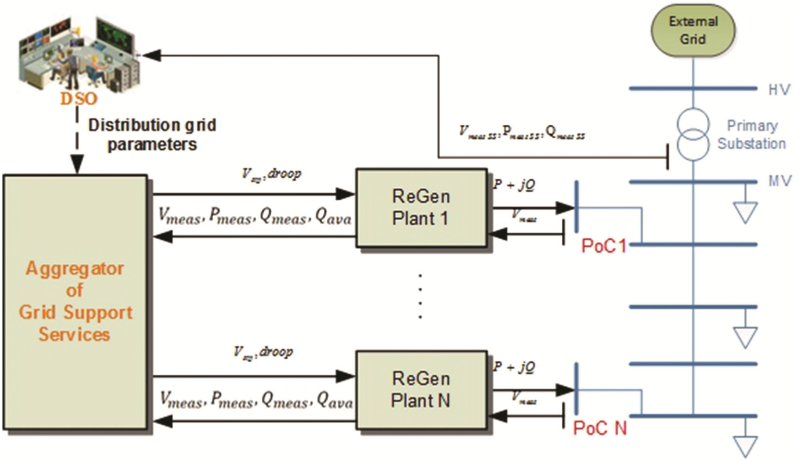

Fig. 2. Scheme for distributed on-line coordination of voltage control functionalities

In this study, an MV distribution grid in the Northern Denmark is used as benchmark test model. It represents a typical radial feeder topology with primary substation (60/20 kV) and four ReGen plants (WPP, PVP 1, PVP 2 and PVP 3), accounting for realistic penetration of renewables in Danish distribution grids in the future (see [4] for more details of the benchmark grid model).

2.2 Communication Network Infrastructure

In order for a ReGen plant to have online coordination with an Aggregator control unit, it should be connected to the Internet via some Internet Service Provider (ISP). This lets the ReGen plant to exchange information with all of the other accessible controllers/ReGen plants on the Internet. Since here as a base case we are considering the public mobile networks as ISPs, there are, therefore, a number of ISPs available. The ISP used by the ReGen plants can, thus, be different with that used by the Aggregator. The ISPs are usually distinguished by the amount of bandwidth they provide, the service cost and most importantly, the connectivity.

An ISP network consists of long distance transmission lines that interconnect routers at Point-of-Presence (POP) in different cities that the ISPs serve. This equipment is called the backbone of the ISP. If an information packet is destined for a device directly served by the ISP, it is routed over the backbone and delivered to that device. Otherwise, it must be handed over to another ISP [15]. The ISPs are connected to rest of the Internet through Internet eXchange Points (IXP) and exchange information [16]. Thus, for devices on different networks to communicate, the communication traffic needs to go through an IXP, even though the devices are physically right next to each other. These ISPs are said to peer with each other, having a bilateral agreement [16] for the provision of a certain service level. Therefore, in the existing implementation, this change of ISP networks will not have significant effect and the delay may increase up to a few tens of milli-seconds (ranging between 10–50 ms above the normal delay) [17].

Furthermore, in the given benchmark grid scenario (see Sect. 2.1), the Aggregator control unit can be placed at the local primary substation or anywhere else in Denmark. The distance between ReGen plants and the Aggregator, however, can be one of the external influences on latency as well as other communication properties described in [18]. The voltage control information being time critical can, therefore, be effected by the time the signal takes to go from a ReGen plant to the aggregator and a set-point/reference signal from Aggregator to the ReGen plant. Since the ISPs are deploying faster network technologies [17], e.g. 3G, LTE/4G and HSPA+ etc., this enables higher data transfer rates and quality of service for the network users, and makes the users accustomed to have high speed networks and capable devices. Still, for the heterogeneous networks that are usually shared by a large number of users and data exchange is exposed to stochastic non-controllable delays and packet drops, extra delays can be expected in long distance communication.

2.3 Communication Network Model

In order to get a realistic and accurate model of the network behavior within the benchmark grid area, a system called NetMap [17] is used. NetMap is a mobile-network performance measurement system based on crowd sourcing, which utilizes end user smart devices to automatically measure and gather network performance metrics on mobile networks. The measured metrics include throughput, round trip times, connectivity, and signal strength, accompanied by a wide range of context information about the device state [17]. It offers a Network Performance Map (NPM) based on actual measurements on existing networks using actual end user devices in real end user scenarios. The NPM shows what network performance to expect and provides a more realistic image of what the end system can expect as the measurements are performed with similar devices [17]. According to the NMP in [17], the throughput provided by the existing public network infrastructure is sufficient enough to support voltage control coordination in the said scenario. Therefore, in this paper we base our analysis on the latency a signal might incur while going from the ReGen plants to the aggregator controller (and vice versa) and other connectivity related issues to see the impact on the performance of voltage controller.

NetMap gives the measure of latency in the form of Round Trip Times (RTT) measured using a large number of end devices located at different distances from the Aggregator control unit. Figure 3 shows the real time RTT measurements based on around 3500 TCP-RTT measurement sequences at different distances/locations of the end devices from the Aggregator control unit using different ISPs. These measurements have been obtained over a period of one and a half year with varying number of end devices.

It can be observed in Fig. 3 that for the maximum cases, RTT lies within the range of 30 ms approximately, which means that a minimum of 15 ms delay (half of RTT – assuming the same route for request and reply to/from the server) in the transfer of information update can be expected for the maximum times in daily operations. We, therefore, take this as a normal base case for our future evaluation. However, this network being heterogeneous (and shared by a large number of users), the delay may increase depending on the network conditions. In the worst case, this delay may jump up to 500 ms (RTT), as seen in Fig. 3.

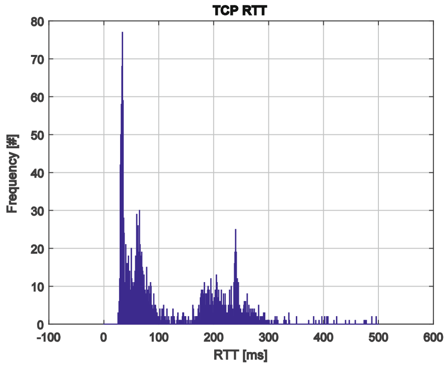

Fig. 3. Distribution of TCP RTT measured around the benchmark region

3 Link Layer Failure

In public wireless communication networks, despite of having several communication masts (base-station) nearby, the ReGen plant usually connects to the nearest communication mast having the strongest signals. While associated with a mast, a plant controller periodically measures the strength of a beacon signal from its nearest mast as well as beacon signals from nearby communication masts that it can hear. These measurements are reported once or twice a second to the controller's current mast [15]. A handoff occurs when an aggregator controller changes its association from one communication mast to another while communicating with any ReGen plant controller.

The handoff occurs due to several reasons, for instance: (a) current communication mast fails to operate, (b) the signal between current communication mast and the plant controller deteriorate to such an extent that the connection between a ReGen plant controller and the aggregator controller is in danger of being dropped or (c) cell becomes overloaded, handling a large number of users [19]. This situation can be dealt by handing off the connected stations to less congested nearby cells. It is worth mentioning that a handoff between masts results not only in the controller transmitting/receiving to/from a new mast, but also in the rerouting of the ongoing communication from a switching point within the network to the new mast. All this would ultimately add to the delays in sending update information from a ReGen plant controller to the aggregator control unit and set-points from Aggregator to ReGen plants.

Therefore, we consider here a test case where, for instance, the radio connection of a plant controller with its base station (cell) suddenly fails. This failure can be due to equipment failure, radio link failure or any other problem within the base station. During such failures, there exist two possibilities: (a) the area is covered by other cells or (b) the area is not covered by other cells.

3.1 The Area Is Covered by Other Cells

The end system detects that there is a problem at the physical layer, when it is out of synchronization for a certain number of consecutive times defined in a parameter set by ISP [20]. A common value of this parameter is 20 times [20]. After detecting a physical layer problem, the user equipment (UE) starts a timer configured by ISP (a typical value is 2 s. [20]). If it recovers synchronization with the serving cell, it resets the timer and everything continues as it was (the recovery was possible). However, if it does not succeed, UE initiates the whole process, look for a suitable cell, connection setup and so on. Putting in nutshell, the whole process may take few seconds to minutes, depending on the severity of the problem.

3.2 The Area Is not Covered by Other Cells

In such a case, the service remains disrupted until the same mast is fixed or communication link is recovered. The delay in service outages may vary from few minutes to hours depending upon the type of problem incurred.

While considering the worst cases, it is worth mentioning a problem seen a couple of years back in Norway at part state-owned telecoms firm Telenor that left around 3 million users without coverage for up to 18 h, caused by a signal storm [21]. Although rare, but such outages must also be considered when targeting to design resilient communication systems.

From the above discussion and the test-cases defined, it can be remarked that the network architecture/setup can introduce signal delays in the range of milli-second to seconds, while failures in communication may impose latencies in the range of minutes up to hours, depending on how severe the failure is. Table 1 summarizes the latencies in communication, resulting from all considered test cases.

Table 1. Resulting performance metrics for test cases

Test cases	Category	Latency (RTT)
Base case	Normal	30–50 ms
	Worst	500 ms
Link layer failure	Normal	Seconds to few minutes
	Worst	Minutes to several hours

4 Assessment of Voltage Control Coordination

As mentioned in Sect. 2, distributed voltage control can increase the power losses in the grid due to reactive power loadings of the lines. The total power losses occurring in the cables/lines are evaluated based on the total active power generation by the ReGen plants in a certain distribution grid, as given in 1:

$$P_{loss,tot,\%} = P_{loss,tot} \cdot 100\% = \frac{\sum P_{loss}}{\sum P_{gen}} \cdot 100\% \tag{1}$$

According to [14], continuously updating the voltage set-points (see Fig. 2) for the ReGen plants is the only effective option to improve the proposed distributed control concept with regard to the power losses within the grid. The idea behind this control concept is that nominal voltage with $V_{stp} = 1\,pu$ does not necessarily have to be targeted, as long as the voltage remains within the tolerance band margins of $\pm 10\%$. Thus, as long as the measured voltage does not exceed a certain critical point, the voltage set-point can be enhanced to avoid unnecessary reactive power support, hence avoiding additional power losses. In this context, the update rate of the voltage set-point will have an impact on the average power losses over a certain time period. A more detailed description of this control concept will be given in a separate publication.

4.1 Impact of Latency

The latencies introduced by the communication network lead to delays of measurement signals being sent from the ReGen plants to the Aggregator as well as delays of reference signals being set from the Aggregator to the ReGen plants. The results obtained in [10] show that, for adjusting the voltage set-point, various update rates in the range of seconds to minutes have a minor impact on the resulting power losses within the grid. Hence, with regard to the obtained latencies for the test cases in the communication network (Table 1), it can be remarked that RTTs in the time range of seconds to minutes would not affect the control performance significantly. As, for instance, if the maximum signal delay in worst case reaches to 500 ms (Fig. 3.) is negligible, assuming that the update rate of the voltage set-point is minimum 10 s.

4.2 Impact of Link Failures

Even if a communication failure in the network sustains for several minutes, the local voltage controller of the ReGen plant will apply the last sent set-point, which results in negligible deviations in the power losses in the distribution feeder. However, as revealed in Sect. 3, under certain circumstances connection failures up to several hours can occur which may affect the power losses more significantly. These communication problems can be due to a failing communication mast without having any available back-up cell. For this, taking into account different test cases, we evaluate the extent to which the latencies in communication up to several hours will affect the on-line coordination of voltage control functionalities in distribution grids.

Test Cases. For testing long-lasting communication failures, a benchmark test scenario with a time frame of 24 h is applied [14]. Four test cases are considered in terms of hours of delay caused due to communication failure i.e. 1 h, 6 h, 12 h and 24 h.

Test Results and Analysis. Figure 4 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of 24 h, with and without various communication failures. It can be observed in Fig. 4 that the power losses increase for longer communication failures. The blue-colored bars show the power losses without any voltage control. However, in this case the tolerance band margins of the voltage (±10%) are not fulfilled. Then, voltage regulation with maintained settings for the ReGen plant controllers (off-line, red-colored) leads to a considerable increase of the power losses. By introducing distributed on-line coordination (no fail., green-colored), the losses can be reduced to a significant extent. However, the power losses increase depending on the duration of the communication failure in the system.

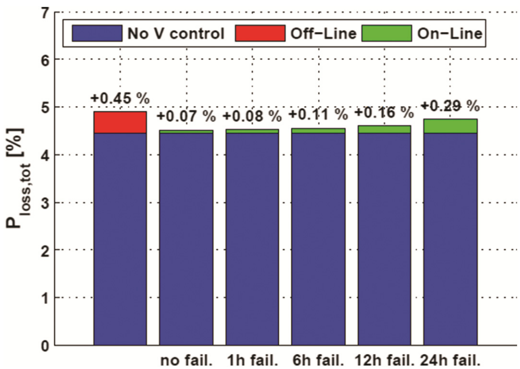

Fig. 4. Average power losses over the simulation period for various durations of communication failure for updating the voltage set-points (Color figure online)

An exemplary voltage profile for a communication failure persisting for 12 h is depicted in Fig. 5. The resulting depression of the voltage profile between 6 a.m. and 6 p.m. is not required as the voltages are sufficiently below the upper limit of 1.1 pu, implicating an undesirable rise in the power losses. After occurrence of the failure at 6:20 a.m., the last sent voltage set-point will be applied during the faulty period. This results in significant reactive power provision, since the voltage set-point is not anymore updated according to the voltage measurements, hence increasing the power losses in the system.

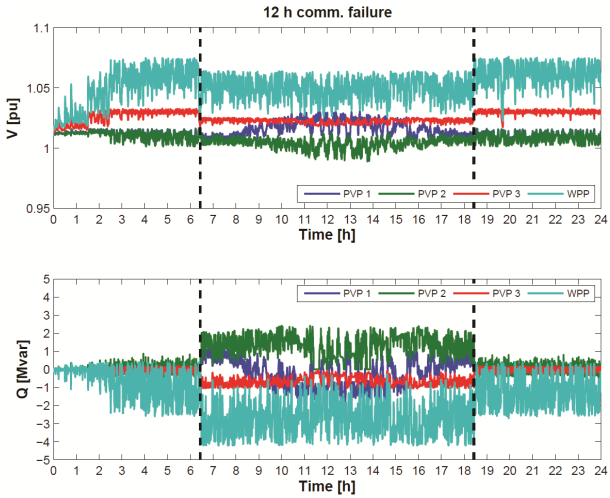

Fig. 5. Voltages of all ReGen plants over one day for a communication failure occurring between 6 a.m. and 6 p.m.

5 Conclusion and Future Work

This paper elaborates on the impact of communication on on-line voltage control coordination in distribution grids using existing public network communication infrastructure. The use of public network communication infrastructure has various aspects associated to it that may result in deviating voltage control performance in the distribution grid. Although, the throughput offered by these networks is suitable enough to support voltage control coordination; but, being used by a number of users at the same time, unexpected/unwanted delays in information exchange may incur. Therefore, several test cases are introduced and evaluated with respect to the related latencies and validity of the signals being exchanged between Aggregator and ReGen plants. According to the results, delays in communication in the range of seconds to minutes have a minor impact on the resulting power losses. However, the delays up to several hours may lead to higher power losses in the grid, increasing the cost of energy which is eventually recovered by the end-consumers of electricity.

In this paper, we only focus on the use of existing public network infrastructure, which leads to the direction of studies in future. For instance, cost estimation to employ these cellular networks for voltage control coordination and then comparing it to the cost of employing other communication networks, such as cable networks. Secondly, securing networks when used in critical infrastructures is crucial. Therefore, the impact of adding security to the information exchange on the controller's performance will also be explored as a next step.

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