The Impact of Wireless Communication Networks to Wide Area Monitoring and Protection Applications

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***Abstract*—The fast deployment of the Phasor Measurement Units (PMUs), especially in the transmission level of the power systems enables the development of wide area monitoring and protection and control (WAMPC) applications that enhance the situational awareness of the power system operator as well as the stability of the power system. Such applications are dependent on the communication network that supports the transfer of the PMU measurements to a central monitoring application or to a local protection application (situated in a substation). It is therefore of paramount importance to ensure the transfer of measurements with the least minimum delay, while at the same time to ensure the integrity of the PMU measurements. In this paper, the impact of using wireless communication network as a mean for transfer the PMU measurements to the WAMPC applications is examined and the advantage of the 5G communication network over the 4G and 3G network in such real time monitoring and control applications is demonstrated.**

Keywords—PMUs, System stability, wide area monitoring and protection system, Wireless communication network

I. INTRODUCTION

Power system operators today experience unprecedented challenges in maintaining the power system in admissible limits. The decarbonization of the energy sector with the massive penetration of renewable energy sources results to the decrease of power system inertia [1]. Low inertia power systems are prone to faults that compromise the stability, efficiency, and reliability of the system. On the other hand, the challenges brought by the penetration of renewable energy sources has forced the electric utilities to perform a lot of structural changes in order to transform the bulk power system as well as the distribution grid according to the smart grid concept. These changes include the digitalization of the power system substations, the introduction of smart schemes for taking advantage of the distributed resources that can provide ancillary services to the grid, and the monitoring and control of power grid in quasi real time [2].

Regarding the latter, the advent of synchronized measurement technology in the early 1990s has certainly bring an evolution to the monitoring and control of power systems. The key element of the synchronized measurement technology is the Phasor Measurement Unit (PMU), which is considered the most advanced measurement device that is currently installed in the power system substations today. PMU is a GPS synchronized equipment, which can provide with a great accuracy, synchronized voltage and current phasor measurements, frequency and rate of change of frequency. In addition, the latest models of the PMUs can provide a phasor measurement every 5 ms that corresponds to a reporting rate of 200 phasors per second (in a 50 Hz power system) [3]. Considering that the conventional measurement devices (power meters) provide measurements to the Supervisory Control and Data Acquisition (SCADA) system every 2-5 seconds in an asynchronous way; the key features of the PMUs enable the implementation of wide area monitoring, protection and control (WAMPC) solutions that offers the capabilities to the power system operators to monitor and control power system in near real time [4].

More specifically, the real time PMU measurements that are received to the control center are processed by a PMU-based state estimator that can provide in milliseconds range the wide area picture of the whole power system (considering a power system fully observable by PMUs). The PMU-based state estimator can increase the situational awareness of the operators by tracking the power system transients in case of faults or disturbance in the system. In addition, PMUs can be used in tie-lines between two areas in order to monitor in real time the power exchange between the areas as well as the loading of the transmission line. Such information is critical for the operators of the two areas to realize in quasi real time the actual available power margin in the tie-line in case of a power loss in one of the two areas [6]. Regarding the wide area control applications, the PMU measurements provided by the generation substation can be used in a wide area controller for damping inter area frequency and voltage oscillations in the power system. It should be noted that the damping of inter-area oscillations is not possible by the local controllers of the generators [7]. PMU measurement can also be used in wide area protection systems such as in differential protection schemes of transmission lines. Such schemes protect the transmission lines in case of a fault that occurs within the transmission line and requires the presence of two PMUs at the ends of the transmission line [8].

A crucial aspect for the designated performance of the aforementioned WAMPC applications is the transfer of the PMU measurements to the application in near real time. Thus, the communication network in a WAMPC system plays a crucial in its performance and reliability. Data loss due to

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communication network congestion compromise the integrity of the PMU measurements and essentially affects the accuracy of the WAMPC applications. Further to that, large delays that might be imposed to the transfer of PMU measurements (depending on the communication network) affect the real time responsiveness of the applications [4]. For instance, the data loss or the large measurement delays will affect the accurate tracking of transients by a PMU-based estimator in case of a fault, while it could also affect the timely detection of a loading increase in a tie-line. A large measurement delay can also compromise the operation of a wide area differential protection scheme that should trip immediately in case of a fault that might occur within the range of the transmission line. Therefore, the communication network should not be a preventive factor for the actual implementation of wide area monitoring, protection, and control applications.

The current practice of the electric utilities regarding the communication network is to have in some of the substations dedicated fiber optic communication network while some other substations are connected to the control center through existing internet network due to the lack of communication infrastructure [10]. According to [5], the delays that is imposed by a fiber network is around 100-150 ms, while delays of around 700 ms can be imposed by a satellite link. Although, fiber optic communication network seems the ideal solution for a WAMPC system, the civil works needed for implementing a fiber optic network as well as the increased cost associated with the wired communication network is sometime a preventive factor for the electric utilities to have their dedicated fiber optic network. On the other hand, one should also consider that PMUs are recently started to being deployed in power system substations thus several substations might not be connected with a fiber optic communication network. In this sense, a good solution for the actual implementation of a WAMPC system is the consideration of wireless communication network for the transfer of PMU measurements.

Over the last decade, wireless communication network gains a lot of attention providing the flexibility for easy and fast deployment of measurement devices in the field. Starting from 3G wireless communication, the wireless technology has advanced in the last years reaching to 5G communication network. Actually, 5G communication network has several advancements over its ancestors (i.e. 3G and 4G) that can play a crucial role for the transformation of the conventional power system into smart grid. This is more evident by the characteristic of a 5G network in terms of reliability of the data and delay of the measurements. The 5G network has a packet loss rate in the range of 10^{-5} and latency in the range of 1-3 ms [6], [13]. Such features can certainly support the safe transfer of PMU measurements in a WAMPC system without compromising the data integrity and the real time responsiveness of the applications.

In this work, the impact of using wireless communication networks in a wide area monitoring application that observe the line loading of a tie line is examined, comparing the performance of the application in case of 3G, 4G and 5G wireless networks. Further to that, the performance of a wide area differential protection system using PMU measurements that are transferred through 3G, 4G and 5G communication network is also investigated. The main contribution of this paper is the use of wireless communication technology in WAMPC applications, examining the feasibility of such case in terms of the performance of the considered applications. The results in this paper have been extracted by a realistic laboratory setup, incorporating actual PMUs as well as a communication network emulator in a hardware in the loop framework.

The paper is organized as follows: A general communication architecture that is used for transferring the PMU measurements in a central WAMPC system is discussed in Section II, while the wide area monitoring application as well as the wide area protection application that are used in this work are shown in Section III. Section IV includes the results from the application of wireless communication network to WAMPC system and the paper concludes in Section V.

II. COMMUNICATION ARCHITECTURE FOR TRANSFERRING PMU MEASUREMENTS

The PMUs are considered the most advanced measurement device in the power system measuring infrastructure and since it provides synchronized voltage and current phasor measurements, frequency and rate of change frequency. A general multi-layered architecture that is used for transferring the PMU measurements to the control center is shown in Fig. 1. The first layer mainly consists of PMUs installed in power system substations. The PMU measurements from the first layer are concentrated and time-aligned by regional Phasor Data Concentrators (PDCs) that are situated in the second layer of the architecture. It should be noted that PDCs are valuable components in a WAMPC system since they are responsible for collecting the PMU measurements. In addition, among other functionalities, PDC time aligns the PMU measurements according to their timestamp and forward a time aligned phasor measurement set to the higher layer.

A critical parameter that should be defined in the PDC is the waiting time, which denotes the time that the PDC waits the phasor measurements to arrive to the PDC before forwarding or storing PMU measurements with the same time stamp. Any PMU measurements that arrive after the waiting time elapse are discarded by the PDC. It should be noted that the PDC starts the countdown for waiting the PMU measurements with the same time stamp after the arrival of the first PMU measurement with the corresponding time stamp.

The waiting time is a means for compensating delays imposed during the transfer of the PMU measurements by the communication network [8]. By considering the communication network delays in the alignment procedure of the PDC, the integrity of the PMU measurement set is ensured. However, the waiting time is a tradeoff between data integrity and real time responsiveness. A large waiting time will ensure the completeness of the phasor measurements set for a specific time stamp, but at the same time it will compromise the fast reporting rate of the PMU measurements (since the forward of the PMU measurements to the next layer will be delayed considerably).

In the multi-layered architecture of Fig. 1, when the regional PDCs successfully time aligns the measurements of a specific region, they forward the measurements to a central PDC situated in the control center of the power system. The central PDC collects of the measurements of the system from the regional PDCs considering again a certain waiting time according to the communication network delay between the regional PDCs and the control center. It should be noted that in some WAMPAC communication architectures only a central PDC exists that is responsible for collecting and time align all the measurements from the individual PMUs. This however reduces the redundancy of the PMU measurements.

Based on the architecture of Fig. 1, the two main sources that introduce delay to the measurement transfer process are the communication infrastructure and the PDCs. The delay due to the communication infrastructure results from the transfer medium, the Wide Area Network (WAN) components (i.e., routers), and the communication protocols. In this sense, different medium in case of wired communication network can result in different delays and different waiting times in the PDC. The same is valid for the wireless communication network (3G, 4G, and 5G) whose delays should be known for setting the maximum delay in the PDC. In this work in order to show the impact of the wireless communication networks in the WAMPC architecture, it is implicitly assumed that the transfer of measurements is supported only by wireless communication networks.

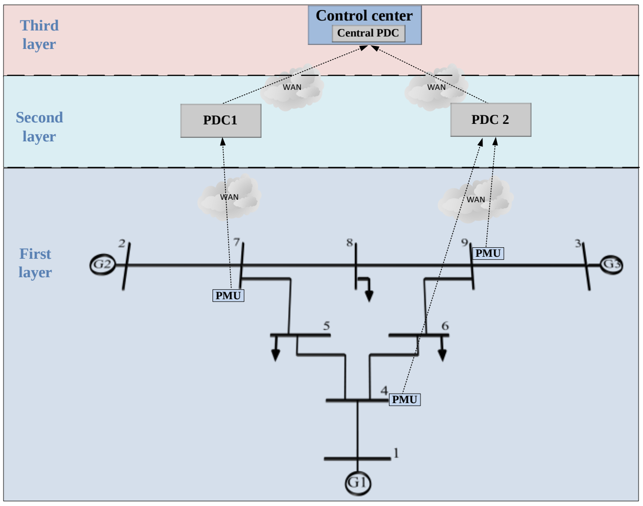


Fig. 1. Communication architecture of a WAMPC system

III. Wide Area Monitoring and Protection Applications

The PMU measurements that arrive to the control center are being processed by dedicated applications that run periodically in the control center for monitoring the operating condition of the whole power system. One of the most natural applications of the PMU measurements is the state estimation which provides in quasi real time the states of the power system [9]. Such application can run every few milliseconds considering the availability of measurements from different substations and given that the power system is fully observable by PMU measurements.

Another important routine that runs to the control center in case of interconnected power systems is a monitoring application for providing the loading condition of tie lines. It should be noted that tie lines are the lines that connect two individual systems together. Thus this application runs in real time by receiving measurements from the two PMUs that are installed at the two ends of the tie line. The real time knowledge of the loading of the tie line enhances the situational awareness of the transmission system operators, while ensures the reliability of the power system. Regarding the latter, the knowledge of the available transmission line margin from the tie line facilitates the better planning of the generation resources in case of a contingency, while the real time information enhances the accuracy of the system stability and contingency analysis that run routinely in the control center.

In the case of the wide area control applications, wide area controller for damping inter area oscillations is one of the applications that are enabled through the PMU measurements [10], while PMU measurements can be also used in local differential protection schemes for transmission line. Unlike the monitoring applications, the differential protection scheme can run locally to the substation level receiving measurements from the two PMUs installed at the two ends of a transmission line. Such schemes are intended to suppress the spread of a fault that occurs in any point of the line by disconnecting the line from the system.

In this paper, the monitoring application that deals with the loading condition of a tie transmission line as well as the differential protection system based on PMU measurements will be considered while the theory regarding the implementation of such applications is described below.

A. *Monitoring of tie line loading conditions*

The tie lines between interconnected power systems can enhance the reliability of each individual power system. Especially in the modern power systems that the penetration of renewable energy sources is high, tie lines can be used efficiently for exporting any excess power from renewable energy sources to neighboring systems and importing power in case of abrupt power deviation for balancing the generation with the demand. Considering that the changes in the generation of renewable energy sources can happen in millisecond range, the real time information of the available power margin of the tie line is therefore necessary.

In this framework, considering that the tie transmission line that is shown in Fig. 2 is monitored by two PMUs, the voltage and current phasor measurements from the two ends of the line are available to the control center after being concentrated and time aligned by the PDC. It should be noted that in this case a two layer architecture is considered, which means that only a central PDC exists in the WAMPC architecture. Denoting the two ends of the line as *i* and *j*, the voltage and current phasor measurements from the two ends (buses) $\overline{V}_i, \overline{V}_j, \overline{I}_{ij}, \overline{I}_{ji}$ can be used for calculating the real and reactive power that flows from the two ends of the line as,

$$P_{ij} = \Re\left\{\overline{V}_i\left(\overline{I}_{ij}\right)^*\right\} \tag{1}$$

$$Q_{ij} = \Im\left\{\overline{V}_i\left(\overline{I}_{ij}\right)^*\right\} \tag{2}$$

where, P_{ij} and Q_{ij} is the real and reactive power that flows through from bus *i* of the transmission line respectively, $\Re$ and $\Im$ denote the real and imaginary part of the complex number respectively, and $(*)$ denotes the conjugate of the phasor. Similarly, the real and reactive power that flows from bus *j* can be calculated as,

$$P_{ji} = \Re\left\{\overline{V}_i\left(\overline{I}_{ij}\right)^*\right\} \tag{3}$$

$$Q_{ji} = \Im\left\{\overline{V}_j\left(\overline{I}_{ji}\right)^*\right\} \tag{4}$$

where, P_{ji} and Q_{ji} is the real and reactive power that flows through from bus *j* respectively.

The application that is responsible for the monitoring of the tie transmission line receives the PMU voltage and current phasor measurements after being aligned by the PDC. Essentially, the PDC waits one of the two PMU measurements to arrive to the PDC and then the countdown for the waiting time starts in order to wait the measurement from the second PMU. If the measurement from the second PMU arrives within the waiting time range, the PDC forwards a complete phasor dataset to the monitoring application, while if the waiting time elapses before the arrival of the measurement, the PDC discards the delayed measurement and forwards to the monitoring application only the measurement from the one PMU.

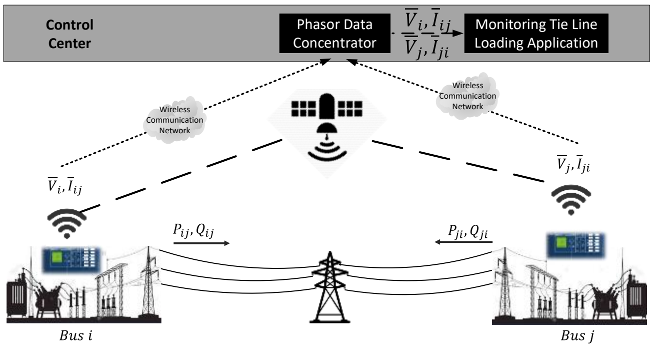


Fig. 2. Tie transmission line monitored by PMUs

The algorithm of the monitoring application for the tie lines in this work is based on the integrity of the PMU data set as its algorithm is shown in Fig. 3. The concept in this algorithm is to provide in real time the loading condition of the tie line while in case that there are some data losses due to discarded PMU measurements to replace these measurements with the most recent available measurement.

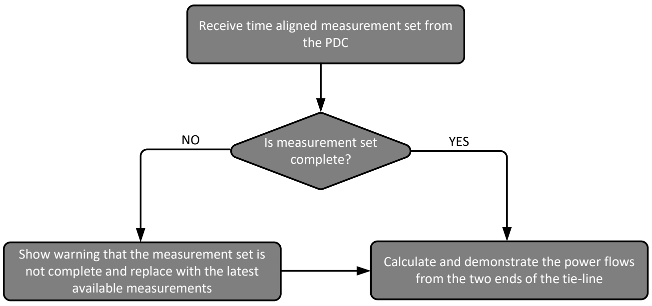


Fig. 3. Monitoring algorithm flowchart

B. *Differential Wide Area Protection application*

The second application in this paper deals with the wide area protection concept. In this case, again the PMU measurements from both ends of the transmission line are used, however the protection application processes the PMU measurements in the substation level using a local controller. Therefore, unlike the monitoring application outlined above, in the PMU-based differential protection application no PDC is involved.

The concept of the PMU-based differential application is to detect any faults that happen within the range of the transmission line and trip the breakers of the line in order to isolate the fault in the system. In order to achieve this, the line currents magnitudes from the two ends of the line are compared. As it is shown in Fig. 4, without loss of generality it is assumed that the PMU-based differential protection application is installed at bus *i* and receive local measurements from the PMU at bus *i*, while the remote measurements from the PMU at bus *j* are transferred through wireless communication network.

The PMU-based differential application compares the current magnitudes (from the PMU current phasors) with the same time stamp and if their difference is larger than a certain threshold (in this work 20 A) then a trip signal is sent to the breakers of the two substations (*i* and *j*) to trip. In principal, if there is no fault within the line that connects bus *i* and bus *j*, the current magnitudes from the two ends of the line will be almost equal, with some losses at the shunt admittances of the transmission line (assuming a pi model). However in case of a fault within the line, the difference between the two currents will be more than 100 A, due to the fault current that flows from the two ends of the line.

It is therefore of paramount importance the fault within the transmission line to be detected as fast as possible in order to isolate the transmission line and prevent any instability issues in the rest of the power system.

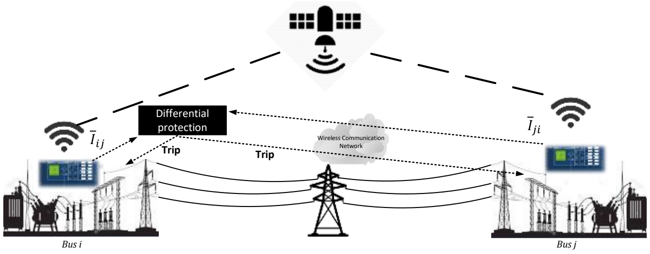


Fig. 4. PMU-based differential protection application

IV. SIMULATION RESULTS

The aim of this paper is to investigate whether the presence of a wireless communication network for transferring the PMU measurements benefits the accuracy and real time responsiveness of the two applications considered in this work. In this sense, in both applications it is assumed that three wireless communication networks exist for transferring the measurements namely, 3G network, 4G network, and 5G network.

In order to create a realistic environment to extract the simulation results, a real time hardware in the loop setup was developed as shown in Fig. 5 that includes, the dynamic IEEE 9 bus system [11] simulated in the OPAL-RT real time simulator, two Arbiter Sentinel PMUs [12] that are assumed to be installed in the line that connects bus 4 and bus 6, a SEL 5073 PDC [13], and a network emulator that emulates the delays imposed by the three wireless networks.

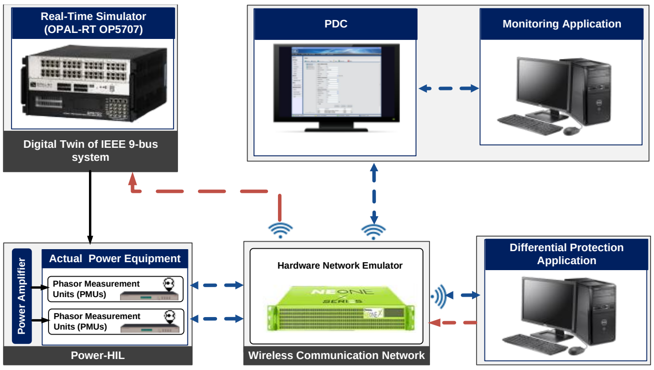


Fig. 5: Real time hardware in the loop framework

As illustrated in Fig. 5, the monitoring application communicates directly with the PDC to receive the measurements, while the differential protection application receives measurements from the two PMUs locally and sends back to the IEEE 9-bus system (OPAL-RT) a signal (red line) for tripping the breakers of the transmission line in case of a fault.

As it is aforementioned, the investigation of the impact of the wireless communication network to the responsiveness and accuracy of the two wide area applications (monitoring and differential protection) is main objective of this work. In order to simulate the characteristics of the wireless networks and especially the delay that is imposed to the transfer of the PMU measurements to the two applications, the network emulator is configured accordingly to simulate the 3G, 4G, and 5G delays. More specifically, the delays for the three networks are assumed to follow a uniform distribution with limits as shown in Table I [14]. Having simulated realistic conditions for the communication networks the two applications were executed to realize their performance when the PMU measurements are transferred from the 3 types of wireless networks.

TABLE I.
DELAY MEAN VALUE FOR COMMUNICATION NETWORK

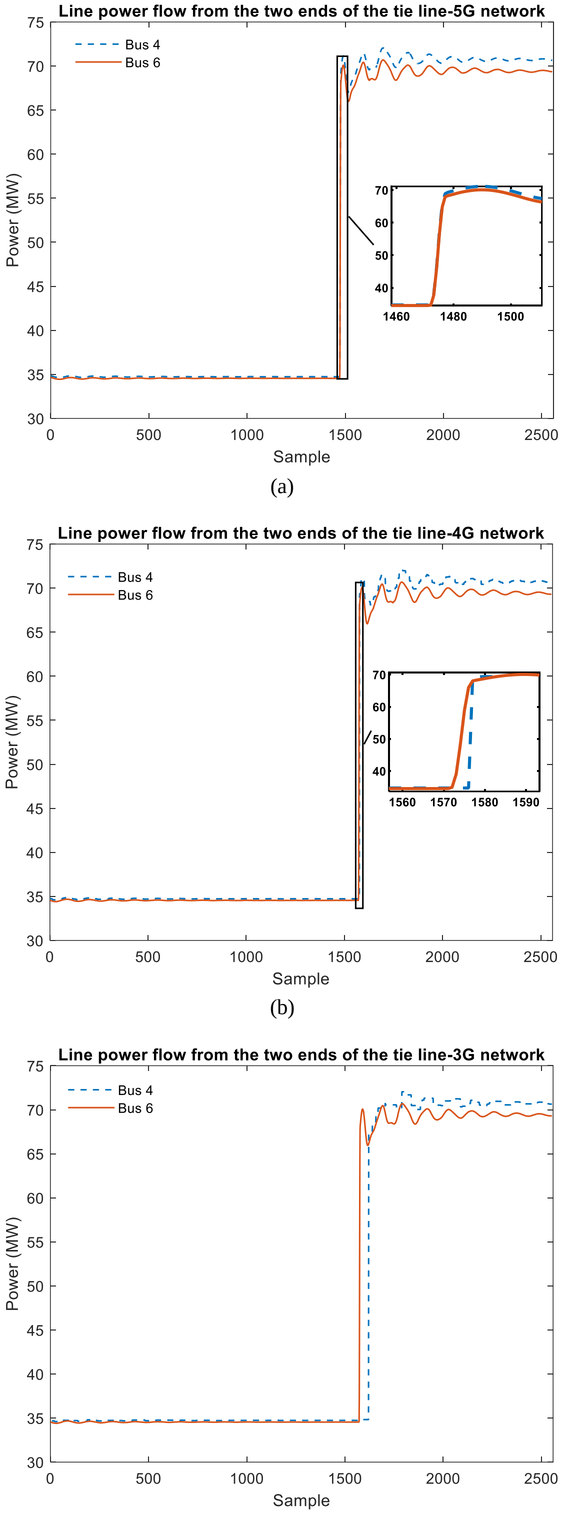
Communication Network	**Uniform distribution limits**	
	Minimum (ms)	Maximum (ms)
5G	3	10
4G	20	60
3G	20	150

A. *Results of the application for monitoring the tie line loading*

In this case study the accuracy of the tie line loading application was tested under the delay imposed by the three wireless communication networks. As shown in Fig. 5, the monitoring application receives measurements from the PDC which has waiting time 60 ms in order to ensure the fast reporting of the loading condition of the transmission line. The measurements of the PMUs are transferred with 3G, 4G, and 5G communication networks with the delays characteristics shown in Table I.

Since the tie line connects two independent systems, the measurements received by the two PMUs should be synchronized and time aligned in order to reflect the same operating conditions. Therefore, any change in the power flow of the tie transmission line should be visible to the operators of the two systems in real time. In other words, at each end of the line the same power flow change should be reflected in real time. In this case study, it is assumed that the initial power flow of the line is around 35 MW and suddenly a load increase of 35 MW occurs in the system of bus 6, increasing the line loading of the transmission line by 100%.

The monitoring application that runs in real time in the control center should detect this tie-line loading change immediately and make available (by demonstrating) this change to the two operators of the interconnected system. In Fig. 6, the results of the tie line monitoring application are shown when the PMU measurements from the two systems are transferred with 5G (Fig. 6a), 4G (Fig. 6b), and 3G (Fig. 6c). Based on the simulation results, it is evident that the 5G network ensures the timely arrival of the PMU measurements to the control center before the waiting time of the PDC elapses, and the monitoring application successfully captures the line loading change instantaneously for both systems. On the other hand, 4G communication imposes larger delays to the PMU measurement transfer (than the 5G) and therefore the line loading change is detected in bus 6 instantaneously and with a slide delay for the system that bus 4 belongs to. The impact of the delays is more obvious in the case of 3G network, where the line loading change in bus 4 is shown with a considerable delay in comparison to the other two networks.



(a)

(b)

(c)

Fig. 6. Line power flow from the two ends of the tie line using (a) 5G network, (b) 4G network, (c) 3G network

Table II tabulates the PMU measurements that were delayed more than the waiting time of the PDC (60 ms) and therefore they were discarded by the PDC. In the case of the 5G network, all the PMU measurements manage to arrive on time and therefore no data loss occurred due to measurement delays. In contrary in the other two wireless communication network data loss occurs. In particular, in the case of the 4G, 68.6% of the PMU measurements were discarded due to their late arrival to the PDC, while in the case of the 3G, 87.7% of the PMU measurement were discarded. It should be noted that the monitoring application as outlined in Fig. 3, in case of measurement loss, the previously available measurement is used. That's why at some point the loading change of the tie line is captured, because in the case of 3G and 4G networks at some point a PMU measurement delayed less than the waiting time of the PDC. In the case that multiple changes happen in the loading of the tie-line in small time intervals it is possible that some of the changes will not be captured in one of the two interconnected systems.

TABLE II.
DATA LOSS FOR THE TIE LINE LOADING MONITORING APPLICATION

Communication Network	Data Loss (%)
5G	0
4G	68.6
3G	87.7

B. *Results of the PMU-based differential protection application*

In the line protection application, its real time responsiveness is essential for clearing timely any fault that occurs within the transmission line. As it is outlined in Fig. 5, the PMU-based differential application is executed in the substation level, excluding the involvement of the PDC in the loop. In this case study, it is assumed that the application runs at bus 4 of the IEEE 9-bus system and receives measurements coming from bus 6 of the transmission line. The application compares the current magnitudes of the two ends with the same time stamp. This means that the application waits until two measurements (from the two ends) with the same time stamp are available to be compared.

In this case study, the three wireless networks (5G, 4G, and 3G) are assumed to transfer the measurements from PMU at bus 6 to the differential monitoring application. The network emulator emulates the three networks, while a uniform delay is assumed with characteristics that are shown in Table I. In order to indicate the impact of the delays to the real time responsiveness of the PMU-based differential protection, a three-phase fault with 60 Ω fault resistance was applied to the middle of the line that connects buses 4 and 6. Fig. 7, indicates the positive sequence voltage of bus 4 before, during and after the fault when the communication network used for transfer the PMU measurements is 5G, 4G, and 3G.

In the case of the 5G communication network the voltage is decreased during the fault, while after the clearing of the fault by the PMU-based differential protection application the voltage is restored quickly to the pre-fault values. The 4G communication network inserts larger delays to the transfer of the PMU measurements from bus 6 and as a result the fault stays longer to the system than in the case of the 5G communication network. In the case of the 3G communication network, the differential protection application fails to clear the fault timely and therefore the system is led to instability. This is evident by the high frequency oscillations that occurs in the last samples of the voltage (third subfigure of Fig. 7).

In order to better illustrate the responsiveness of the application in case of a three-phase fault in the line (considering the three communication networks), the positive sequence line current (that flows from bus 4 to bus 6) before, during and after the fault is shown in Fig. 8. It should be noted that the fault current is much larger than the pre-fault current and therefore an increase in the current flowing from bus 4 to bus 6 is observed during the fault. Further to that, in case the differential application detects the fault, a trip signal is sent to the breakers of the line to open and thus the line current is zero after the clearing of the fault.

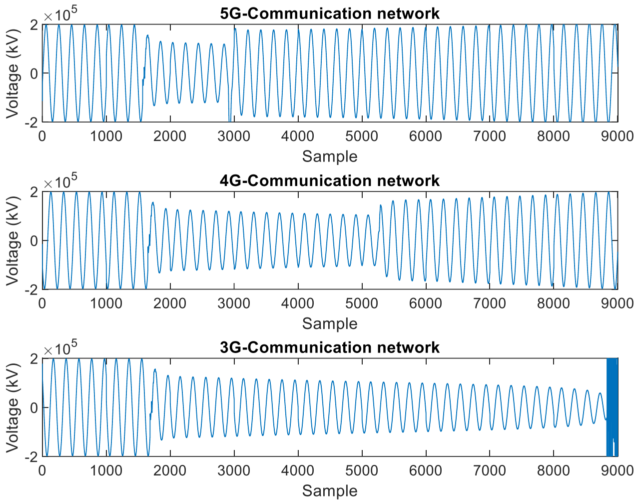


Fig. 7. Pre fault and post-fault positive sequence voltage of bus 4

From Fig. 8, it is obvious that the fault current stays the less time to the system when the 5G communication network is used for transferring the PMU measurements, while with 4G network the faults stays longer to the system before opening the line breakers. In the case of the 3G communication network, the fault stays enough time to the system in order to lead the system to instability.

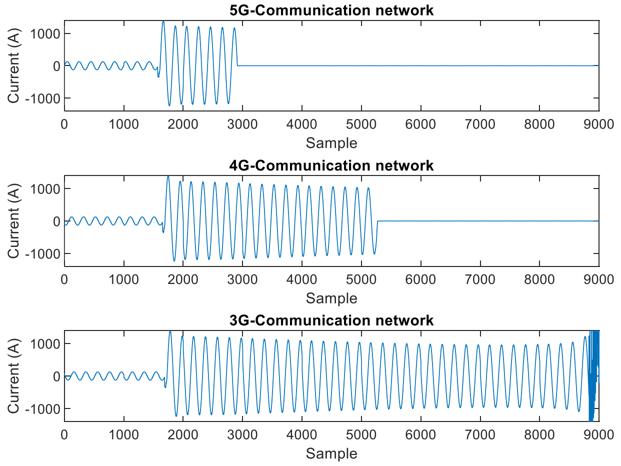


Fig. 8. Pre fault and post-fault positive sequence current flowing from bus 4 to bus 6

V. CONCLUSIONS

With the vast deployment of the PMUs in the transmission level of the power systems, the use of wireless communication networks for supporting the transfer of the PMU measurements to wide area monitoring, protection and control applications is a flexible solution for the operators. Considering the three available wireless communication networks in the field today, 3G, 4G, and 5G, this paper investigates how these networks impact the accuracy and real time responsiveness of two wide area applications namely (1) the monitoring of the tie line loading application and (2) the PMU-based differential protection application.

As it is evident from both investigations that are performed in this work, the type of the wireless communication network that will be used for transferring the measurements certainly affect the performance of the examined applications. More specifically, 3G network impacts negatively the wide area monitoring and protection applications which makes it inappropriate for being used in a WAMPC system. In the case of 4G wireless network, it is shown that it imposes delays to the transfer of the PMU measurements that affect the performance of the applications but certainly with the 4G wireless network the accuracy and real time responsiveness of the applications is improved (in comparison to the 3G). However, the two considered applications achieve the best performance when 5G communication network is used for transferring the PMU measurements. In the case of the 5G communication network, no data loss occurs, while the applications perform as expected. Considering the many capabilities that are provided by the 5G network, it seems that can be a reliable solution in future WAMPC systems.

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