Hierarchical Wireless Network Design for Synchrophasor Communication in Distributed Generation Grid

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Abstract—There has been a growing interest in the deployment of Phasor Measurement Units (PMUs) in a Distributed Generation (DG) grid system. A major obstacle is the lack of a communication network infrastructure that can support phasor measurements for distribution area monitoring as well as providing sensing capabilities for protection against undesirable grid dynamics. In the absence of such a network, the most cost-effective solution would be to consider a wireless network to support centralized control for situational awareness in a DG environment. Therefore, the main objective in this paper is to design and implement a synchrophasor network testbed using Wireless LAN (WLAN) technology. Based on a hierarchical network architecture, we propose an efficient method to reduce the synchrophasor data bandwidth, as well as provide capabilities for control and management at each hierarchical level. This testbed is then used to evaluate different network configurations under various test conditions.

Keywords-Smart Grid, synchrophasors, micro PMU, hierarchical networks, distributed generation grid, wireless mesh networks, WLAN

I. INTRODUCTION

The Phasor Measurement Unit (PMU) is becoming one of the most important measurement devices for power system monitoring and control. This is mainly due to its unique ability to sample analog voltage and current waveforms in synchronization with a GPS-clock. For a wide area monitoring and control system it is imperative to implement a network infrastructure capable of handling a large amount of real-time synchrophasor data arriving at the Phasor Data Concentrators (PDCs). Currently, PMUs are mainly considered for high voltage power transmission and their deployment for lower voltage distribution systems, referred to as micro PMUs (µPMUs), and are gaining momentum [1]. This is a consequence of the advances in sensor networks, anticipated low cost PMUs, and control technologies, which have made it possible to monitor power flows and voltage levels in distribution systems [2]-[4]. The main challenge is how to mitigate voltage fluctuations and keep the presence of the reactive power under tight control. Voltage regulators are normally placed along the distribution feeder so that they can adjust the voltage to a desirable level (e.g., + or - 5% of the nominal voltage). For example, in a passive network capacitors are normally used to compensate for the reactive power caused by the inductive load [5]. However, this would be at the expense of generating load, which could make it difficult to estimate the line frequency as well as measuring the phase angle between voltage and current in order to calculate the power factor (PF).

Normally, power system operators apply frequency and voltage regulation with a centralized control approach where synchronous generators equipped with speed governors and automatic voltage regulators operate. With a centralized control operation of the energy resources can be coordinated with the available voltage and reactive power throughout the distribution grid in order to minimize the power losses [6]-[8]. Currently, many energy resources have the capability of injecting or absorbing reactive power to achieve efficient energy distribution. Examples include advanced inverters (also referred to as smart inverters) that are capable of delivering real and reactive power [9], [10]. As penetration of the low power renewable energy, such as Photo-Voltaic (PV) inverters, is growing rapidly, dynamically controlling active and reactive power by means of power factor correction is becoming increasingly important [11], [12]. To ensure that the distribution system will maintain the voltage at the required level, a need for injecting the reactive (either capacitive or inductive) and/or active power has to be assessed on a regular basis so that it can then be adequately compensated by generators and inverters. With the help of a synchrophasor network this can be achieved in real-time by measuring the PF in the vicinity of the installed generator with respect to the load impedance. For instance, the control management in the PF mode may require injecting reactive power in order to maintain the power factor close to unity or to keep the ratio of real power P to reactive power Q (i.e., P/Q) constant.

In a centralized control management system without the support of a communication network, this cannot be done efficiently, especially in the presence of a large number of micro-generators and inverters. Therefore, as the DG installation continues to increase and more utility customers generate their own power, distribution system dependencies on communication for centralized control is becoming vitally important. Indeed, despite a tremendous number of published reports in the open literature about distributed generation systems, to the best of our knowledge there is no cost-effective communication networking scheme for a centralized control system. Therefore, in this paper we present a design framework...
of a hierarchical wireless network architecture where PDCs at each hierarchical level collect phasor information. The aggregated data is then forwarded to the next hierarchical PDC level, hence requiring a higher data transmission. In order to reduce the amount of data, we propose a data reduction scheme that removes redundant phasor information before transmission to the next PDC level. The scheme also includes a synchrophasor data classification methodology that would allow each PDC to identify faulted areas at the local level, thus reducing the computational and monitoring complexities at the control center. We use an Emulab [13], [14] platform to build a flexible testbed to access various wireless network configurations under real world conditions. For packet exchanges at the application layer, synchrophasor communication is based on the C37.118 [15], [16] standard, which is built on top of the UDP/IP layers. In addition, we have included Power Factor (PF) as an integral part of the synchrophasor measurements to evaluate the presence of reactive power in the system. For wireless Physical (PHY) and Medium Access Control (MAC) we use Extendable Mobile Ad-hoc Network Emulator (EMANE) [17] to implement the testbed. As an example, we use the IEEE 802.11b standard [18] for communication between PMU and PMU/PDC. We also present a routing scheme suitable for radial and closed loop distributed feeder systems. The testbed is then used to measure packet loss, latency, and bandwidth for wide ranging scenarios.

The paper is organized as follows. Section II describes our network strategy for designing the hierarchical synchrophasor network followed by the Emulab-based implementation of the testbed that includes the WLAN design architecture and some of its inherent capabilities in Section III. Section IV describes test scenarios in distributed generation environments. Finally, Section V presents the results in terms of throughput and delay performances. This is then followed by final remarks and the conclusion.

II. HIERARCHICAL SYNCHROPHASOR NETWORK ARCHITECTURE

Fig. 1 shows an example of a hierarchical synchrophasor network architecture, which has been developed for our testbed. As can be observed, PMUs in each region communicate with their local PDC. At the local PDC the aggregated data is then forwarded to the next PDC level and this process continues until all data reaches the final PDC at the control center or DNO (Distribution Network Operator). The data collected at the control center can then be archived for further processing, such as visualization and possible control/alarm actions for situational awareness.

To establish an end-to-end communication link between PMU/PDC and PDC, the first step would be to set up message communication at the application layer. The IEEE C37.118 standard provides specifications for synchrophasor measurement (Part-I) [15] and data formats for real-time communications (Part-II) [16]. Part-I specifies synchrophasors, frequency, rate of change of frequency (ROCOF) measurement and the evaluation methods, while Part-II provides a method to exchange synchrophasor data between power system equipment and defines message types, contents, and use. In addition, PDC requirements for power system protection, control, and monitoring are specified in [19], which includes requirements for synchronization, synchrophasor data processing, and real-time access.

The command frame is used to turn the transmission on or off. There are three configuration frame types; namely CFG-1, CFG-2, and CFG-3. CFG-1 provides information about the full capabilities of a PMU (i.e., reporting rates, frequency range, noise suppression, etc.). CFG-2 denotes the currently reported measurements. CFG-3 is optional and has a flexible frame format. Through the data frame, as shown in Fig. 2, a PMU transmits current and voltage amplitudes, their synchronized phasor angles, an estimated frequency, as well as a ROCOF. The message also includes SYNC, frame size, identification code (i.e., ID Code), a time stamp, which is specified as a Second of Century (SOC) and fraction of Second (FRACSEC) of the received data frame, and CTC check bits (CHK).

When a PDC receives data from its multiple PMUs or lower level PDCs, it should first align the frame according to their time stamps. The time alignment is arranged in accordance with the SOC and FRACSEC. Note that the SOC count starts at midnight 01 Jan-1970. A PDC has at least two sets of buffers for storing two consecutive data frames with two time slots.

The first set of buffers stores the incoming data information as it arrives and then sorts it according to their PMU/PDC ID [20]. It is possible that data frames from different PMUs may not arrive in the same order and therefore the received data has to be reordered in the buffer accordingly. The second set of buffers corresponds to the data from preceding time slot.
contains the data that is transferred from the first set of buffers as soon all the data frames reach the PDC within a pre-defined time period. The second set of buffers also includes data information that did not arrive on time (or lost) during the transmission of the previous time frame. As soon as a PDC receives data information from its multiple PMU’s, it will then forward it to the next level. To achieve this, the PDC will first construct a combined data frame that was received from its PMUs/PDCs with the same time-stamp. The format of the combined frame is shown in Fig. 3. Packets arriving late or lost at the PDC are not included in the combined frame. The status of these packets is marked as “0F” (see Fig. 3).

We should point out that the size of the combined frame increases at the next PDC level and continues to grow until it reaches the final PDC. Consequently, a higher level PDC would require more bandwidth for transmitting a combined frame to the next level. The synchrophasor data is reported on an N frames per second basis, where N can be selected between 1-120. Obviously, a higher frame rate would further accelerate a demand for more bandwidth. In addition, with deployment of a large number of PMUs in the serving area, analyzing the aggregated data at the final PDC located at the control center can become an enormous task.

A. Proposed Data Reduction and Control Strategy

In order to mitigate the computational burden at the control center, as well as reduce the transmission bandwidth at higher PDC levels, we propose a new scheme to overcome these shortcomings. The main objective is to remove redundant phasor information from the combined data frame before transmission to the next PDC level. As a result, the reduction of data rate would allow more PMUs to report to the local PDC and/or increase the number of hierarchical levels as long as the aggregated data rate at the highest PDC level remains within the bandwidth capacity of the Wireless LAN device.

According to the C37-118-2011-2 [16], a PDC generates a combined frame as soon as the pre-defined time period is reached. These data frames are collected in the PDC buffer and then rearranged in an order based on the previously received configuration frames. Our objective is to eliminate the redundant data received from the lower level through some additional processing at the local PDC. Therefore, in the proposed distributed-monitor-control scheme, that uses PMU classification at the PDC level, the combined frame will only include data for those nodes that undergo transitional changes. To accomplish this, a local PDC checks and compares its synchrophasor data with the measurements in the previous report (note that this information is readily available as it is stored in the PDC buffers) to assess the conditions of the nodes in its region. The assessment can be based on certain criteria such as frequency, ROCOF, power factor, etc. For instance, if PMU frequencies are stable and the phase difference remains the same as the previous measurements, the local PDC modifies the corresponding PMUs STAT from (00) to (90) without having to include the measured data (e.g., phasors, freq, dFreq, analog and digital) when generating its combined data frame for transmission to next PDC level. As shown in Fig. 4, the combined frame will include only the synchrophasors data of the nodes that are classified as abnormal with STAT: 80.

Obviously, in a situation where a data frame is lost or did not arrive on time, such a classification cannot take place. Under these conditions, the status of the node can be classified as unknown (STAT: A0) until two consecutive data frames become readily available in the PDC buffers. Alternatively, with adding more sets of buffers, the classification can be done using data from the two nearest time slots stored in the PDC buffers. In our implementation we increased the number of buffer sets up to 5 in order to reduce the number of nodes with unknown status. Once the next level PDC (above the local PDCs) receives the new combined frame from its regional PDCs, it can then identify the locations of the abnormal nodes and subsequently the lines or feeders that connect them. As a result, the regional PDC can have the capability to initiate any necessary action such as islanding, injecting reactive/real power, or some other protective actions. Estimating the PF at the local PDC can also contribute to controlling the power.

Currently, the PF calculation is not a part of IEEE C37.118 measurements, but in a distributed generation network PF can play a crucial role in controlling the reactive power by keeping, for instance, the power factor close to unity. In the vector diagram, PF is defined as: \( F_P = \cos \varphi_{v_j} \), where \( \varphi_{v_j} \) is the phase angle difference between voltage and current and can be measured using the synchrophasor data. For instance, the phase difference can be calculated at each measurement site, which could then be assessed at the local PDC or control center for possible PF correction. For inductive loads, PF correction can be achieved using capacitors to compensate for the inductive component of the current. As mentioned earlier, the capacitive and inductive loads create harmonic currents. In addition, calculation of the PF using the cosine of the angle difference between the voltage and current is based on the assumption that both waveforms have only fundamental frequency components. In the presence of harmonics the calculation for a single phase can be done by measuring what is called True Power Factor...
III. TESTBED IMPLEMENTATION

For an end-to-end transmission of synchrophasor data over wireless LAN, it is very important to select an appropriate set of tools for performance testing. Bear in mind that using hardware to implement a testbed for wireless applications imposes a significant challenge in terms of cost, effort, time consumption, and more importantly, a lack of flexibility for modifying network configurations, as well their evaluations under various test conditions. On the other hand, a combination of simulation and emulation leverages a common platform for real-time experimentation. Indeed, emulators can be effective tools to design a network at the implementation stage. Such a testbed would allow us to assess the suitability of different network configurations for local and wide area measurement systems. Our primary goal is to implement the hierarchical network described in the previous Section. To accomplish this, we use Emulab [13], [14] and EMANE [17] to construct PHY and MAC layers to emulate a wireless connection between PMUs and a PDC.

Our testbed comprises 29 Emulab nodes where each can be configured to represent either a PMU or a PDC. This provides a great deal of flexibility to construct different network configurations of PMUs and PDCs. Every node (PDC or PMU) is accessed via a 100 Mb/s Ethernet link as shown in Fig. 5. In order for each node to function as a WLAN device, such as IEEE 802.11, we use EMANE [17]. EMANE is an open source framework with a set of Application Program Interfaces (APIs) and supports creating MAC and PHY layers to function in emulation environments. A logical component of EMANE is the Network Emulation Module (NEM) that establishes MAC and PHY for wireless LAN experiments. The complete set up and the role of EMANE in setting up the interfaces for a wireless connection between PDC and PMU are shown in Fig. 5. As shown in Fig. 5, the NEM provides a virtual interface to the OTA (Over the Air) channel, which is part of the EMANE domain. A NEM is also responsible for transferring data between the emulation and application domains. This is done by creating a virtual interface to the transport layer that can route traffic within the emulation domains. Fig. 5 also shows the structure of communication link and the role of EMANE in setting up the interfaces for wireless connections between PDCs and PMUs.

It should be noted that the EMANE runs on each PC with its own IP address to represent an IEEE 802.11b-based WLAN device. To establish a peer-to-peer multihop communication between a PMU/PDC and a PDC, the IEEE 802.11b is set to operate in a Distributed Coordination Function (DCF) mode [18]. It should be noted that the IEEE 802.11 family standards (e.g., 802.11 a/b/g) uses a carrier sense multiple access with collision avoidance (CSMA/CA) access protocol. The protocol controls access to the shared wireless medium [18], which makes it very sensitive to the interference caused by real-time data transmission [25] as well as by other active nodes [26], [27]. In addition, the collision avoidance method operates in half-duplex to prevent interference by simultaneous transmission and reception by the same node.

IV. NETWORK DEPLOYMENT IN DISTRIBUTED GENERATION

The PMUs collect measurement data throughout the power system, which may include generation, transmission and distribution. The synchrophasor data consist of amplitudes of voltage and current and their respective phase angles and are time stamped using a GPS signal that is the same at every location. Based on these measurements the phase difference between the current and the voltage can then be used to calculate PF (or TPF with harmonics). From the synchronized measurements between two locations at the same time instant, it is possible to assess the system stress conditions in the presence of loads and inverters. Bear in mind that in DG environments the PF can be regulated by injecting active and reactive powers in order to maintain the voltage level within an acceptable range. Unlike the transmission grid, which has a meshed structure, the distribution system generally has a radial or, in some rare cases, a loop structure (note that in a loop structure a node can be fed from two directions). In the
presence of the generators, the injected power can cause severe problems, such as voltage rise. For voltage control over the radial feeder, the OLTC (On-Load Tap-Changer) at the transformer is normally considered. In the absence of any communication infrastructure using OLTC may not be sufficient to control the voltage level and reactive power [28]. With the support of communication networks, reactive power can be controlled remotely using a capacitor bank at the local control center [7]-[10]. Within the centralized scenario, if the synchrophasor information throughout the distributed feeder is made available at the DNO, the controller would then be able to instruct power injection from generators/inverters that are nearest to the loads with high demand by analyzing the data in each local area. Fig. 6 shows an example of two radial feeders with μPMUs placed at such sensitive locations. We assume the final PDC at the DNO (DNO-PDC) is connected to both feeder PDCs via the substation backbone network. In this figure we presume the measurement devices (e.g., μPMUs) are placed in the vicinity of the generators/inverters, as well as nearby loads and/or secondary transformers.

To provide a wireless communication link throughout the feeder, we are considering the Optimized Link State Routing Protocol (OLSR) [29] for multihop communication. The OLSR is a proactive routing protocol developed for mobile wireless networks. This protocol maintains a routing table by periodically exchanging topology information in the network. For our application, however, since all the PMUs are installed at fixed locations, the network topology does not need to be updated on a regular basis, but only in situations when the network topology undergoes some changes (e.g., new PMUs are added).

As can be observed from Fig. 6, the μPMUs are distributed along every sub-feeder, which may include a secondary transformer for volt/VAR assessment. These μPMUs report to their local PDC which will then generate a combined frame for transmission to the feeder PDC by hopping through other local PDCs along its way. Finally, we point out that both radial feeders, as shown in Fig. 6 with dashed lines, can be tied together to form a closed loop [30], [31].

As mentioned earlier, the loop system can add to the flexibility in a distributed generation system. While existing feeders are predominantly radial in most countries, utility companies are under growing pressure to upgrade the distribution feeders to a closed loop, especially for customers with critical needs, such as hospitals or factories for improved reliability. Looping the radial feeders through a tie breaker switch would allow the utilities to take advantage of closed loop by turning the tie breaker switch on when needed. This is considered the most cost effective solution for future upgrades [30]. For example, under normal conditions the two feeders from the same transformer can form a closed loop. In abnormal situations the tie breaker can be switched off so that feeders can operate in radial fashion until the abnormal areas where the fault occurred have been cleared. Although we have made no attempt to investigate the effect of a tie breaker in the loop, our network can be easily modified to include a sensor that can provide a wireless link for any control action to open and close the tie breaker switch.

Fig. 6: An example of Loop-Radial for wireless network structures consisting of local μPMUs communicating to the DNO PDC through their local PDC.

V. SIMULATION RESULTS

Having completed the implementation of a real-time testbed using the emulation platform, we present the performance of hierarchical PMU networks. The Emulab system, operating at 100Mb/s is employed. To implement a wireless LAN, we use the EMANE to set up links between PMUs and PDCs. The IEEE 802.11b wireless link is considered for the testbed and is set to operate in a Distribution Coordination Function (DCF) mode. While there are many on-demand and proactive routing protocols that can be selected, OLSR is invoked for our experiments. OLSR is a proactive routing protocol and is capable of reducing delay in our application, where all the PMU’s and PDC’s are installed at fixed locations. The wireless link’s bandwidth is set to operate at 2Mb/s.

The message exchanges at the application layer are based on the C37.118 standard. By comparing the data stored in multiple buffer sets the PDC can then detect PMUs with abnormal data. Currently, we use a change of frequency (within a certain range) as a criterion for a PMU classification. For distributed generation systems, we also include the power factor measurement at each PDC level in order to assess the amount of reactive and active power that is needed to be injected or absorbed by local inverters and generators.

For the sake of archiving, good PMU data is transmitted at a longer interval period (e.g., every one second). A set of data frame rates, namely 15, 30 and 60 frames per second, is used as input load of each PMU/PDC in our evaluations (i.e., 15 frames/s is around 9.6kb/s).

Two hierarchical network configurations are exploited, namely Config.-1 and Config.-2. In Config.-1 (refer to Fig. 1),
there is one central PDC in level 1, 3 regional PDCs in level 2, and 6 local PDCs in level 3. Altogether, there are 19 PMUs, which are controlled by 6 local PDCs. Two scenarios are considered for physical layer communication between PDCs at the last stage. In scenario A, communication between PDCs is through wired LAN, while in scenario B the connection is done via 802.11b WLAN with 2Mb/s bandwidth.

Config.-2 is specifically designed to implement network deployment in a distributed generation scenario (see Fig. 6). As opposed to Config.-1 where communication between PMUs and PDCs is operated in single hop mode, Config.-2 communications are in multihop mode. Specifically, in Config.-2, PMUs report to their local PDC by hopping through other PMUs while local PDCs forward combined frames to the central PDC by hopping through local PDCs. We have one central PDC in level 1, 6 local PDCs in level 2, and 22 PMUs controlled by local PDCs.

In Figs. 7 and 8, we assess the throughput and delay performances for the proposed distributed-monitor-control scheme using the PMU classification at each PDC and the IEEE C37.118 standard in Config.-1. It can be seen from Figs. 7 and 8 that the proposed PMU node classification scheme shows superior performance when compared with the IEEE C37.118 standard, both in terms of throughput and delay. This is particularly true for scenario B where the IEEE 802.11b wireless link is employed for communication between PMUs and PDCs. This is mainly because of the greatly reduced packet size of the combined data frame. This has also contributed to mitigating the co-channel interference as a higher data rate contributes to the effect of co-channel interference. Please note that throughput represents the reliability/success rate. It can also be easily deduced from Figs. 7 and 8 that both schemes perform better in scenario A than the scenario B. This is due to the fact that at the final stage, the wired LAN is used for scenario A to transmit the aggregated data.

We should point out that the main feature of the hierarchical structure is to allow the PDC to provide an assessment of the grid at a local level rather than at the control center. Consequently, this reduces not only the computation, but also decision making complexities at the main control center. The reduction of data rate would allow, for instance, more PMU to report to the local PDC and/or increase the number of hierarchical levels as long as the aggregated data rate at the highest PDC level remains within the bandwidth capacity of the Wireless LAN device. As shown in Fig. 7 and 8, the date rate remains within the IEEE 802.11b capacity even at the highest PDC level.

In Figs. 9 and 10, a multihop scenario of Config.-2 is investigated, where the OLSR protocol is employed as a proactive routing protocol for multihop communication. Different from the single hop communications in Config.-1, multihop communications generates more co-channel interference when a similar number of PMUs and PDCs are deployed. Therefore, both schemes’ performances degrade correspondingly in Config.-2. However, compared to the IEEE C37.118 standard, the proposed scheme demonstrates its robustness with much less degradation in this configuration, due to the benefit of less overhead. Obviously, the proposed distributed-monitor-control scheme is indispensable when implementing network deployment in distributed generation.

I. CONCLUSION

Our objectives in this paper were to design a hierarchical synchrophasor network for distributed grid systems and then
implement a testbed using an emulation platform to assess the network under a real world experimentation environment. The network has a hierarchical structure and the number of hierarchical levels depends on the control strategy and the placement of the synchrophasor devices throughout the distribution feeder. The main problem with the hierarchical network is that the size of the data can grow rapidly at each higher level PDC. A data reduction method was then proposed. The new scheme would allow the PDC at each level not only act as a local controller, but also considerably reduce the information that is needed to be transported to the next level.

We used Emulab to implement the testbed. The testbed is then used to assess different network configurations under various test scenarios. This also included a scenario for radial and closed-loop feeders in a distributed generation environment. A tree based routing has then been proposed for the distributed generation system. The results indicate that the PDC data classification method can not only mitigate redundant data, but can also assist the PDC at each level to monitor and control the grid locally.

REFERENCES


