PHASOR MEASUREMENT UNIT FOR POWER SYSTEM OBSERVABILITY: A REVIEW

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Abstract—Many countries around the world are affected by power failures, which are caused by factors such as lack of investment into power system infrastructure, inadequate asset maintenance, and continuous increase in electricity consumption that overstresses the power transmission and distribution system. Consequently, power companies suffer from losses of billions of dollars, and inconvenience to private and business customers. In order to prevent the prevalent blackouts, implementation of state-of-the-art technologies, such as a state estimation of the transmission network, is required to achieve better controllability, higher reliability and stability of the power system. The Phasor Measurement Unit (PMU) is a device that is employed to detect the voltage and current waveform that is synchronized with a clocking signal obtained continuously from the global positioning system (GPS). Integrating with the GPS receiver, the base station is able to receive the synchronous data from each PMU in real time.

Keywords— *Power system, phasor measurement unit, pmu, scada, transmission grid.*

I. INTRODUCTION

Current Electric Grid was conceived more than a hundred years ago, when electricity needs were simple, power generation was localized and built around the communities. Most houses had small energy demands such as a few light bulbs or a radio. In previously designed Grid, the limited one-way interaction makes it difficult to the ever-changing and rising energy demand of twenty-first century. The Smart Grid introduces two-way dialogs, where electricity and information were exchanged to the utility and their customers. That's where the system monitoring comes into play. Synchrophasor Smart Grid technology can contribute to overcome several currently prevailing problems of power system e.g. blackouts, low reporting rate, unavailability of universally synchronized and time stamped data. The technology aims to improve existing supervisory control and data acquisition system (SCADA). The prime differentiator between conventional and smart grid is the use of synchrophasor data [1].

The power systems mean, it is the interconnection of more than one control areas through tie lines. The generators in a control area always vary their speed together (speed up or slow down) for maintenance of frequency and the relative power angles to the predefined values in both static and dynamic conditions. If there is any sudden load change occurs in a control area of an interconnected power system then there will be frequency deviation as well as tie line power deviation. If there is a small change in load power in a single area power system operating at set value of frequency then it creates mismatch in power both for generation and demand. This mismatch problem is initially solved by kinetic energy extraction from the system, as a result declining of system frequency occurs. As the frequency gradually decreases, power consumed by the old load also decreases [1] [2]. In case of large power systems, the equilibrium can be obtained by them at a single point when the newly added load is distracted by reducing the power consumed by the old load and power related to kinetic energy removed from the system. Definitely at a cost of frequency reduction we are getting this equilibrium. The system creates some control action to maintain this equilibrium and no governor action is required for this. The reduction in frequency under such condition is very large. However, governor is introduced into action and generator output is increased for larger mismatch. Now here the equilibrium point is obtained when the newly added load is distracted by reducing the power consumed by the old load and the increased generation by the governor action. Thus, there is a reduction in amount of kinetic energy which is extracted from the system to a large extent, but not totally. So the frequency decline still exists for this category of equilibrium. Whereas for this case it is much smaller than the previous one mentioned above. This type of equilibrium is generally obtained within 10 to 12 seconds just after the load addition. And this governor action is called primary control. When there is a fault in one part of system or if any major generating unit is cut off from the national grid, then the remaining generators also begin to trip one by one due to excessive load stresses [1]. This catastrophic failure results in a Science after the introduction of governors action the system frequency is still different its predefined value, by another different control strategies it is needed the frequency to bring back to its predefined value. Conventionally Integral Controllers are used for this purpose. This control is called a secondary control (which is operating after the primary control operation) which brings the system frequency to its predefined value or close to it. Whereas, integral controllers are generally slow in operation. In a two-area interconnected power system, where the two areas are connected through tie lines, the control area are supplied by each area and the power flow is allowed by the tie lines among the areas [3]. Whereas, the output frequencies of all the areas are affected due to a small change in load in any of the areas so as the tie line power flow are affected. So, the transient situation information's of all other areas are needed by the control system of each area to restore the pre-defined values of tie line powers and area frequency. Each output frequency finds the information about its own area and the tie line power deviation finds the information about the other areas.

II. SMART GRIDS

With the growing ultimatum of electrical power, Quality of Service (QoS) and continuity of supply has been the utmost primacy for all major power utility sectors across the world, prior to the global market strategy. Smart Grid is predominantly proposed as the quantum leap in harnessing communication and information technologies to enhance grid reliability, and to enable integration of various smart grid resources such as renewable energy, demand response, electric storage and electric transportation. It allows greater competition between the providers, enabling greater use of intermittent power resources, establishing the wide area automation and monitoring capabilities needed for both bulk transmission over wide distances and distributed power generation, empowering more efficient outage management, streamline back office operations, aiding the use of market forces to drive retail demand response and energy conservation [4]. Smart Grid technology underscores factors like policies, regulation, and efficiency of market, costs and benefits, and services that normalizes the marketing strategy, by restructuring the global power scenario in a very dynamic approach. In addition to this, the concerns like secure communication, standard protocols, advance database management and efficient architecture with ethical data exchange, adds to its requisites. The development of Information and Communication Technology (ICT) has updated the technology by supporting dynamic real-time two-way energy and information flow, facilitating the integration of renewable energy sources into the grid, empowering the consumer with tools for optimizing their energy consumption, by introducing Advance Metering Infrastructures (AMI), Virtual Power Plant (VPP) and other such incipient implements. In addition, it helps grid to continuously self-monitor and self-adjust to achieve self-healing function, so as to monitor all kinds of turbulences, carry on compensations, redeploy the power flow, avoid the intensification of accident and make each kind of different intelligent devices to realize the network communication topologies. Phasor measurement units (PMUs) are power system devices that use common time reference from global position satellite (GPS) to provide synchronized ac measurements converted to phasors of voltages and currents in a power system [2]. The ability to calculate synchronized phasors Power engineers across the rondure have developed a curiosity in decarbonizing the electrical power while minimizing the dependency of the fossils. Such interest has fortified the growth of renewable energy by ensuing the efficiency and economy of the power grids. Integrated distributed power sources, includes renewable energy such as Fuel cells, Photovoltaic cells, Wind turbine, Micro hydro generators etc. could prolific the needs like power stability, improve grid efficiency, recruit use of the Plug-in EVs, support customer in changing their energy usage patterns, by reduction in power consumption and saving money [5]. High power electronics is also a key technology to build the smart grid technology in an eventual way by adding new DC grids and AC Var sources at the T&D level, serving as backbones and additional stability pillars to existing grids.

III. CONVENTIONAL METHOD OF NETWORK MONITORING

The state estimator block diagram shown in the fig 1.1. Monitoring and control of power system is conducted by the Supervisory Control and Data Acquisition (SCADA) system, which collected the measurement data in real time from the Remote Terminal Units (RTU) installed at the substations across the power system network. The term SCADA consists of two parts.

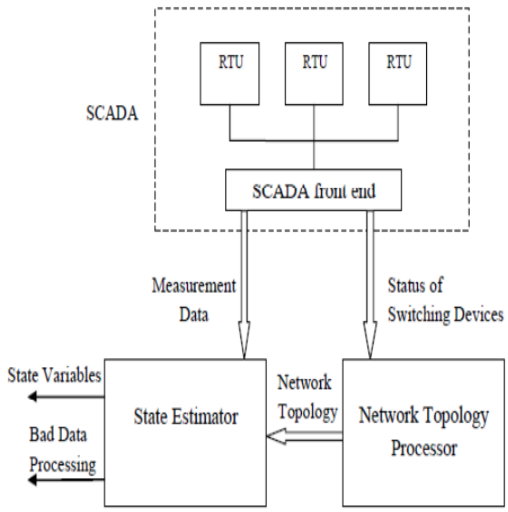

Figure 1. State Estimation Block Diagram.

Supervisory Control indicates that the operators in Energy Control Center (ECC) have ability to control the RTUs. Data Acquisition indicates that the data gathered by the RTUs are sent to the operator for monitoring purpose. Typical RTU measurements include bus voltage magnitudes, power injection and flows (both real and reactive). In addition to those measurements, RTU also record the on/off status of the switching devices, such as circuit breakers and transformer taps. This set of the measurement and status information is telemetered to the energy control center through a periodic scan of all RTUs. A typical scan cycle is usually 2 or 4 seconds. The traditional types of SCADA telemetry includes telephone wire and microwave radio [2] [6]. A more recent development in communication technologies has taken advantages of fiber optic cable, satellites, spread spectrum radio, and internet/intranet systems, which have improved communication reliability and speed, although the cost is still higher than the conventional mediums. By processing RTU status information of switching devices, the network topology processor in Energy Management System (EMS) determines the topology of the network, which characterizes the connectivity between busses (nodes), the shunt elements at each bus, and which generators and loads are connected to those busses by using one-line diagram. The status information of switching devices coming to topology processor is referred to as the bus section-breaker-switch data. It provides the on/off information at each substation and how they are connected. Different bus sections connected with closed breakers and switches can be recognized as an electric bus. The topology processor converts the bus section-breaker-switch data into so called bus-branch in one-line diagram.

The network topology processor must reflect the actual network condition in order for the state estimator to determine the optimal operating state of the current system. Unfortunately, an accurate network topology processor is not always available. Many current topology processors are not capable of acquiring the status change of circuit breakers automatically due to destruction of communication mediums. Besides, equipment status of remote substations is usually managed running manually through telephone call to report to the ECC. Hence it is common to have topology errors occurred in the network models.

IV. INTRODUCTION TO PMU

In contemporary society, many countries around the world are affected by power failures, which are caused by factors such as lack of investment into power system infrastructure, inadequate asset maintenance, and continuous increase in electricity consumption that overstresses the power transmission and distribution system. Consequently, power companies suffer from losses of billions of dollars, and inconvenience to private and business customers. In order to prevent the prevalent blackouts, implementation of state-of-the-art technologies, such as a state estimation of the transmission network, is required to achieve better controllability, higher reliability and stability of the power system [3] [5]. The Phasor Measurement Unit (PMU) is a device that is employed to detect the voltage and current waveform that is synchronized with a clocking signal obtained continuously from the global positioning system (GPS). Integrating with the GPS receiver, the base station is able to receive the synchronous data from each PMU in real time. The location of malfunction circuits or transmission lines can be immediately identified if phase differences between different PMUs are detected [8]. Phase angle between the voltage phase and current phase as the basic measuring function of PMU has been utilized to monitor the condition of power networks. Theoretically, the active (real) power flow in a distribution line is proportional to the sine of the angle difference between voltages at the two terminals of the line. In which case, the angle difference was deemed as a special consideration to manage and operate the power network [9]. In the early 1980s, novel phase angle measurement equipment was introduced. The communication channel, which was based on LORAN-C, GOES satellite transmissions and the HBG radio transmissions in Europe was utilized to maintain the reference signal in synchronization. Researchers established the local phase angle with respect to the time reference for resolving zero crossing of the phase voltage. The phase voltage was referred to the common reference signal and the phase angle difference between two sets of phasor measurements was computed. However, the best-achieved time reference from the communication channels mentioned above only provided measurement accuracy in the order of 40 microseconds. As a consequence of this, these devices could not offer high precision to realize power network measurements in time synchronization [2].

The global positioning system (GPS), which was invented and deployed by the U.S. Department of Defense in 1993, was introduced to the next generation of phase measurement devices called the Phasor Measurement Unit (PMU). The GPS consists of space satellites, control stations and user equipment. A total of twenty-four satellites orbit at a height of a million miles from the earth, and transmit the high frequency signals to the control stations to provide the precise message of the time and orbital information. As a result, the users can achieve 24-hour continuous real-time information-processing that is synchronized to the international standard time. In addition, the GPS provides high precision timing, ranging from 1 nanosecond to 10 nanoseconds. At the same time, the GPS receiver can supply a unique pulse signal in one second intervals, which is known as 1 pulse per second (PPS). Therefore, the issue of unsynchronized standard time in the power grid was solved by installing or embedding the GPS receivers into various devices in arbitrary positions, such as in the high voltage sub-station and transmission towers [5].

Apparently, the implementation of the GPS technology into the power network is a perfect idea as it allows for accuracy and reliability of clock synchronization. For instance, the accuracy of the GPS timing pulse is better than 1 microsecond, which for a 50 Hz system corresponds to about 0.02 degrees. In comparison with the previous methods, it offers several advantages, such as clock synchronization with high Accuracy in the nanoseconds range, extensional usage range, and no special demand for a communication channel; there is also less chance of the device being influenced by weather conditions and/or geography.

The ever-growing global population, as well as the consumption of electricity, has triggered the increasing demand for reliable electricity. The transmission and distribution network plays an essential role in power systems to transmit power from the generators to the customers. To prevent events such as loss of electricity, power network providers must recognize the quality and stability of various parts of the power transmission network through monitoring and measuring equipment. Based on the GPS synchronized clock, the phasor measurement unit can measure a vast amount of critical power network information, which includes bus voltage, bus current, generator speed and power angle.

V. RELATED WORK

Anamitra Pal et al. (2015) presents an integer linear programming (ILP) methodology for such a placement scheme while considering realistic costs and practical constraints. The IEEE 30 bus system is used to illustrate the proposed concept while the IEEE 118, IEEE 300, and Polish 2383 bus systems are used to show the performance of the method under different test environments. Heloisa H. Müller et al. (2015) States that the phasor measurement technology has made it possible the monitoring and control of wide-area power systems. In this study, a new genetic algorithm based method for optimal placement of phasor measurement units (PMUs) considering observability and security issues is proposed. The idea is to allocate the least number of PMUs while providing the most redundant set of measurements. Kiarash Gharani Khajeh et al. (2015) states that the main requirements of the wide-area monitoring system is to acquire the real-time measurement of state variables that can be provided by phasor measurement units (PMUs). Miles H. F. Wenetal. (2015) defines that phasor measurement units (PMUs) are time synchronous measuring devices that acquire highly accurate phasor data at high frequency. They are the core components in wide-area measurement systems for smart grid monitoring, protection, and control. V. Seshadri Sravan Kumar et al. (2015) discusses that the Identification of optimal locations to deploy the phasor measurement units (PMUs) is a preliminary task in wide area monitoring and control of power systems. Given the cost and other associated restrictions, it is highly unlikely for any utility to install all the required number of PMUs to ensure the complet eobservability of the network. Abdishakur Mohamed Mohamud et al. (2016) presents partial observability techniques for calculating the minimum number of Phasor measurement units (PMUs) required in a power system. Abdul Aziz G. Mabaning et al. (2016) presents an optimized version of exhaustive search (ES) algorithm for OPP. The proposed algorithm reduces the search space and the number of computations compared to the traditional ES thus it is named as reduced exhaustive search (RES). Ahmed Hamdy Ghazy Ibrahim et al. (2016) presents a two-stage method for the placement of Phasor Measurement Units (PMUs) to achieve a fully observable power system while considering the PMUs channel limitation. The first stage uses the Binary Integer Linear Programming (BILP) to find the initial optimum locations of PMUs which ensure full system observability under normal conditions. Bulut Ertürk et al. (2016) proposes an optimal Phasor Measurement Unit (PMU) placement method based on a modified version of the well-known binary integer linear programming formulation, which will utilize the installed PMUs and conventional measurements, i.e. active and reactive power flow and power injection measurements, to reduce the number of PMUs to be placed required for system observability. The proposed method applies conventional observability analysis to evaluate the system of concern and to reduce the size of the PMU placement problem. Buyung Sofiarto Munir et al. (2016) discusses that the existence of the phasor measurement units (PMU) technology provides new approach in understanding the condition of power system compared to the old technology. However, the parameters recorded by the PMU still rely on traditional installed measuring equipment. The measuring equipment has its own level of accuracy which will affect the data credibility for further analysis. Eugene Y. Song et al. (2016) States that Phasor measurement units (PMUs) provide real-time synchrophasor data and good situational awareness of power grid, and could be used to take corrective actions to maintain grid reliability. Thousands of PMUs deployed in the North American power grid are supplied by a number of different PMU vendors. Hari Prasanna Das et al. (2016) extends the concept of Synchrophasor Technology, currently in use for transmission system, to provide synchronized measurements at distribution level by designing an instrument specifically for the purpose, called Micro-PMU. It investigates the properties of a Micro PMU, taking distribution system constraints and the possible sources of measurement errors into account and then presents the hardware implementation of a prototype of Micro-PMU Commercial importance and suitability for installation in actual distribution system of the product i.e. Micro-PMU has also been discussed. Md Shafiullah et al (2016) illustrates that the phasor Measurement Unit (PMU) provides both magnitude and phase information of current and voltage signal swith appropriate time stamp which is very useful in controlling power system networks in real time. Consequently, PMU is considered as one of the most significant measurement devices for complete observability of the future electricity grids. But placing PMU in every bus of the network is not economically viable. Milad Dalali et al. (2016) Illustrates a new evolutionary algorithm named as modified binary cuckoo optimization algorithm (MBCOA)is presented to solve optimal phasor measurement unit (PMU) placement (OPP) problem. The proposed method is classified as topological approaches. The basis of the method is in the lifestyle of the brood parasite bird named cuckoo that immigrates to the best habitat to obtain sufficient food and suitable nests for egg laying.. Naqui Anwer et al. (2016) discusses the application of Phasor Measurement Unit (PMU) which provides advance monitoring and recording of any faults or disturbances on any grid. It also presents the idea of PMU as essential component for the Smart Grid to be a reality. Shahrokh Akhlaghi et al. (2016) proposes a two-step optimization approach for optimal placement of phasor measurement unit (PMU) to obtain complete observability of power system in the case of pre installedPMUs. The complete observability of the system in the case of normal operation and pre-installed PMUs is formulated and then, different contingency conditions in the system are considered, i.e. single line outage and single bus outage. Shalini Karn et al. (2016) deals with the development of a laboratory prototype of PMU. Synchrophasor estimation algorithms are modelled using Lab VIEW. The model is burned into FPGA based controller to achieve an online Phasor measurement system. Songhao Yang et al. (2016) Proposes a novel method for optimization of Phasor Measurement unit (PMU) placements. The method aims to reduce the number of PMUs on generators and still well represent the transient stability of power system.

VI. RESEARCH MOTIVATION

By installing a PMU at a bus, gives the bus voltage magnitude and phase angle. For n-bus system, it is needed to install n PMUs to get accurate voltage magnitude and angle at each bus. Knowing network information correctly, a full picture of the n-bus network can be generated. To have the minimum number of PMUs, which can give all the bus voltage magnitudes and phase angles optimal PMU placement is very essential. In the previous sections, the traditional formulation and the variations of the PMU placement problems were discussed which aimed at minimizing the number of devices deployed in the network with various constraints. One of the common assumption taken in the previous works is that each substation is treated as a single bus when doing data preprocessing which is not a valid assumption since in a practical system, the busses at various voltage levels in the same substation may not be necessarily coupled through a transformer or even if they are coupled, the tap settings may not always be known or a utility my plan to estimate those too through phasor measurements and so treating each substation as a single bus won't be the correct approach. In simple words, observability of one voltage level won't translate to observability of the whole substation. The emphasis of the proposed PMU installation problem is not to minimize the number of devices/busses but to minimize the substations/locations covered in the network for the installation which accounts for the real cost as seen by utilities while writing the observability rules bus wise rather than substation wise. Now again, the basic difference between a substation and a bus should be kept in mind- A substation is a collection of busses of one or multiple voltage levels. This chapter will deal with the various facts used in formulating and developing the problem mathematically. Computationally, the OPP problem is highly nonlinear, discontinuous and multi-modal, having a nonconvex, nonsmooth, and no differentiable objective function. Phasor networks are seeing increased world-wide deployment, in order to improve stability, state estimation, monitoring and protection, and control and operation in power systems. Phasor Measurement Units (PMUs) are a keystone technology in phasor networks, and their deployment and maintenance costs are a major driver in phasor network design. Consequently, the problem of minimizing the cost of PMU placements in phasor network design is of significant practical interest, and as a result has seen widespread attention from the research community. Phasor measurement units (PMUs) provide time-synchronized (real-time) phasor measurements in power systems. This is available with the Global Positioning System (GPS). In addition, the PMUs are accurate devices for state estimation. Using PMUs results in linear state-estimation equations, and this makes them easier to solve than general nonlinear-state estimation equations. However, PMUs are expensive devices. Therefore, a suitable methodology is necessary to minimize the number of PMUs while maintaining complete observability of the power system. A power system is considered completely observable when all of its states can be uniquely determined. After establishing complete system observability, it is necessary to determine the optimal places of the PMUs to maximize measurement redundancy. A power system has measurement redundancy when its buses are observed by more than one PMU or the number of observable buses is maximized. In other words, some of the PMUs can be removed from the measurement system while all of the buses remain observable.

System topology affects the minimize number of PMUs. For example, zero injection measurements (Zero IMs) reduce the number of PMUs. On the other hand, the conventional state estimators cannot provide a real-time picture of the power system. Therefore, it is necessary to consider zero injection. However, consideration of conventional measurements is optional in the optimal determination of the number and location of PMUs.

Therefore, an effective PMU placement algorithm has to consider the following additional items:

1. Keeping complete system observability.
2. Maximizing measurement redundancy.
3. Modeling of zero injection buses to consider the topology conditions.

VII. CONCLUSIONS

For the power system to operate securely, reliable and accurate monitoring is necessary. This is done by making a variety of measurements throughout the network. The traditional measurements originated from the supervisory control and data acquisition (SCADA) system. Since the power system is spread over a large geographical area, time synchronised monitoring of the power system using only SCADA measurements was not possible. With the proliferation of phasor measurement unit (PMU) technology that provides highly accurate GPS synchronized phasor measurements, synchronised monitoring of the power grid's bulk transmission network is now possible. Unlike traditional meters the PMU has advantage of providing voltage phasors and current phasors of all branches incident to the installed bus. Since PMU can measure branch current phasors, using branch parameters voltage phasors at the other end busses of all incident branches can be obtained by employing less number of PMUs than total number of buses.We have reviewed the main contribution of phasor measurement unit in power system We will study the existing PMU (Phasor Measurement Unit) placement mechanisms and will design a new Optimized PMU placement mechanism using IEEE 39 bus system keeping system completely observable.

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