An Introduction to Synchrophasors

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***Abstract*—The awareness of the state of the power grid, such as voltage magnitude, frequency and phasor angle is critical to maintain reliable and stable operations of the power grid. Synchronized by a common timing source, synchrophasors measure the electrical waves on power grids. The collected data are transmitted to the central server for further data processing and analysis, such as abnormal event detection and location, power flow analysis. However, the high installation fees and large form factors prevent the large-scale deployment of the synchrophasors. In this paper, a brief history and the basic principles of synchrophasors are introduced. The state-of-the-art synchrophasor technologies and the smart grid protection method using Phasor Measurement Units (PMU) - a member of the synchrophasor family, are presented. The application and the challenges of synchrophasor technologies are also discussed.**

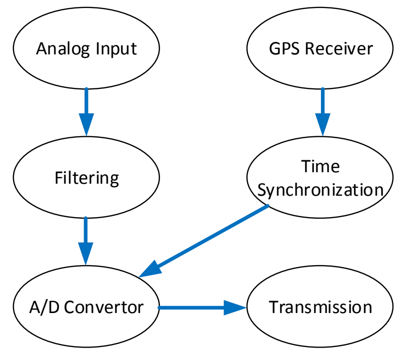


Fig. 1: Synchrophasor components and processes

I. Introduction

Power grid is a critical infrastructure of the modern society, but is susceptible to various types of disturbances. When a significant disturbance occurs, the frequency and the phase angle of the power grid vary in both time and space, and, in many ways, exhibit the characteristics of electromechanical wave propagation phenomenon [1]. Therefore, the real-time awareness of phasor state could serve as a significant indicator of the power grid stability [2], and is indispensable for cyber-controlled smart grid construction.

How to obtain the phasor state more accurately and efficiently has been an active research topic for decades. Current power grid monitoring systems allow direct measurement of frequency and voltage phase angle by installing synchrophasors at either high-voltage transmission level such as PMU [3] or low-voltage distribution level, such as Frequency Disturbance Recorders(FDRs) [4].

The synchrophasor is a vital component of power grid research and development. Its role in the construction of smart grid technologies has become apparent as engineers within the field of power systems continue to work towards a more unified vision of future electrical grids. Synchrophasor development began at Virginia Polytechnic Institute and State University with initial funding provided by the Department of Energy, the National Science Foundation, and the Electric Power Research Institute [5]. There are three important milestones that led to the invention of the synchrophasor, the first of which occurred in 1893.

Charles Steinmetz, a mathematician and electrical engineer at General Electric, presented a paper titled Complex Quantities and Their Use in Electrical Engineering in 1893 [6]. This paper outlines a simple mathematical description of alternating current (AC) waveforms known today as phasors. The principle theory behind this representation of AC waveforms originates with Eulers formula, which states that a sinusoidal wave can be represented by the sum of two complex functions. Phasor notation is only concerned with the complex constant portion of this sum, $Ae^{i\theta}$. Here, A is the magnitude of the waveform, i is the imaginary unit $\sqrt{-1}$, and θ is the phase of the waveform. Phasor notation greatly simplifies calculations involving AC waveforms.

The second important milestone in the development of the synchrophasor was the invention of the Global Positioning System (GPS) in 1973 [7]. GPS enabled the synchronization of measurement devices and as a result the data collected from said devices would be comparable. Although the appearance of GPS occurred in 1973 it was not until later that GPS technology was advanced and accurate enough to be useful in synchrophasor development.

Perhaps the most important milestone leading to the invention of the synchrophasor was the creation of the Symmetrical Component Distance Relay (SCDR) by A. G. Phadke in 1979. The SCDR was an essential aspect of synchrophasor development in that it relied on an a single relaying algorithm based on the measurement of positive, negative, and zero sequence voltage and current signals that could determine all types of faults [5]. This was significant because the computational power required for the single algorithm was much lower than previous methods that relied on multiple algorithms. The development of the SCDR also led to the Symmetrical Component Discrete Fourier Transform (SCDFT), which was used to measure the aforementioned voltage and current signals with a high degree of accuracy [5]. With this final development all of the pieces required for the construction of a synchronized measurement system were realized. In 1988 the first synchrophasor prototype was constructed and in 1992 Macrodyne built the first commercial synchrophasor unit.

Now that the important milestones in the history of synchrophasor development have been addressed an overview

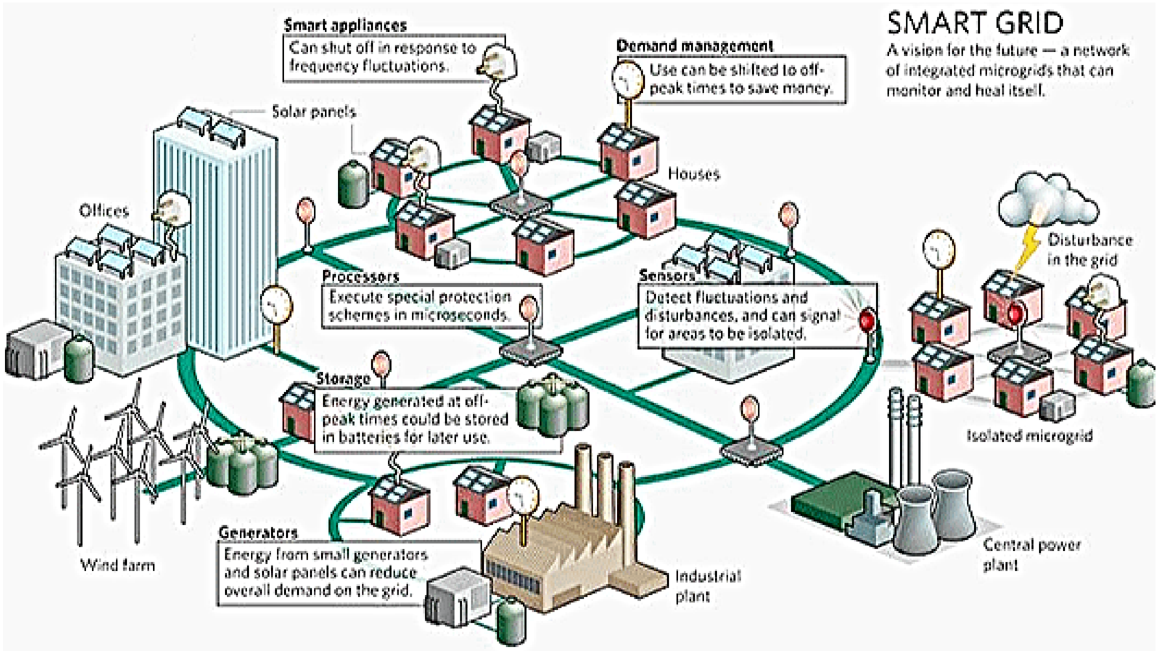


Fig. 2: Smart grid - A vision for the future[8]

of the basic theory behind the systems operation will be put forth. Figure 1 outlines the basic components and actions that take place in a typical synchrophasor unit. The process begins with the measurement of voltage and current signals via an analog input. Typical sample rates are on the order of 48 samples per cycle (2880 samples per second) [9]. These signals are then passed through an anti-aliasing filter to circumvent aliasing errors. Next the signals are converted to digital signals by an analog-to-digital (A/D)converter. It is at this point that a phase-lock oscillator, in conjunction with GPS time reference (obtained from the GPS receiver) stamps the digital signals. Once this process is completed the time stamped phasors are either stored or are transmitted for processing and evaluation.

The rest of this paper is organized as follows. Section II discusses the benefits and the applications of synchrophasors. Section III discusses the challenge to develop the synchrophasors and the Research and Development (R&D) focus of synchrophasor technology. Section IV discusses the state of the art designs. Section V presents the concerns and problems to deploy the synchrophasors. Section VII concludes the paper.

II. Benefits and Application

Synchrophasors can be used for a wide variety of applications that help maintain power grid reliability. These applications include wide-area monitoring, real-time operations, forensic analysis, and smart grid operations.

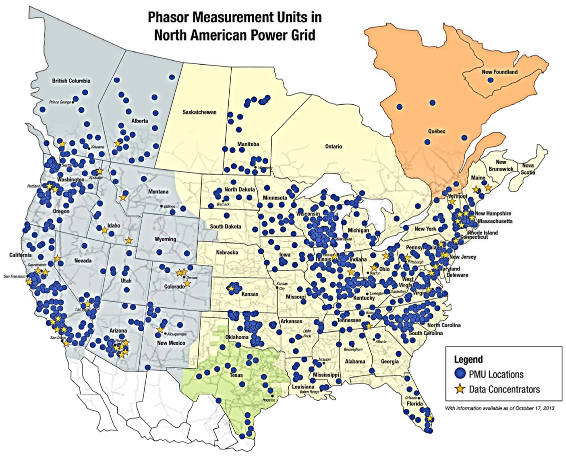
As a member of the synchrophasor family, the Frequency Disturbance Recorders (FDRs) have been deployed at the low-voltage distribution level such as 120V wall outlet with significantly reduced costs. Based on these FDRs, a worldwide Frequency Monitoring Network (FNET) has been designed, implemented, and deployed [10], enabling many applications of power system monitoring, control, and management. It is expected that 2,000 FDR units will be deployed worldwide in the next few years. The deployment map of PMUs and FDRs in the north America are shown in Figure 3

Synchronization among different synchrophasors is important for wide-area power system frequency measurement. Each measurement must be assigned a timestamp for lateral comparison with measurements retrieved from other devices. To enable the global synchronization and timing accuracy, the Pulse-Per-Second (PPS) signal retrieved from GPS receivers are usually used as the timing signal by synchrophasors [11]. The PPS signal is an analog output signal with a rising edge at each one second boundary of the Universal Coordinated Time (UTC). Since the precision of PPS signal is in nanoseconds with non-accumulative time drift [12], synchrophasors at dispersed locations can measure local system frequency synchronously using the integrated GPS clock.

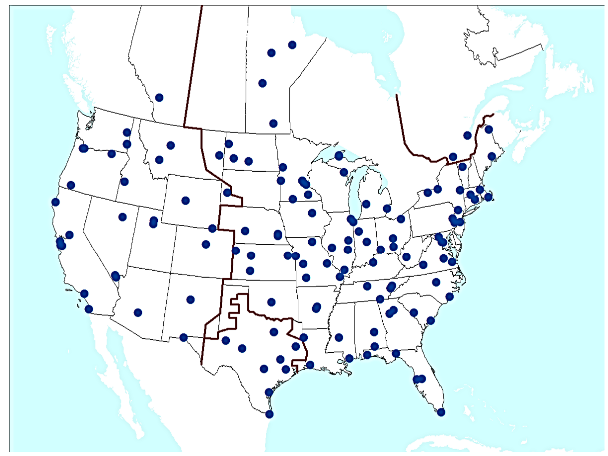
With wide-area monitoring, synchrophasors can provide high-speed, real-time data analysis across the entire power system, including all interconnections. This data is "...collected and fed into processing applications that allow grid operators to understand real-time grid conditions, see early evidence of changing conditions and emerging grid problems..." [13]. The grid operators are then able to evaluate, diagnose, and implement techniques that protect system reliability based on the phasor data. These wide-area monitoring systems are being used "...in the Eastern and Western interconnections of North America and in China, Quebec, Brazil, Iceland, and elsewhere" [13] to help monitor multiple power grids and prepare for impending problems. Real-time operations are

(a) PMU

(b) FDR



(c) PMU deployment map



(d) FDR deployment map

Fig. 3: PMU and FDR and their deployment maps

closely related to wide-area monitoring systems in that both provide real-time data. This data is being used increasingly by individual utilities to manage grid operations, as well as being incorporated into their estimation tools to get more accurate and higher sampling rates. These higher sampling rates help grid operators in damping and stabilizing frequency operations. Synchrophasors also help with forensic (or failure) analysis. "Because PMUs collect and store high volumes of high-speed, time-synchronized data about conditions across an interconnection, those data can be compiled quickly and analyzed to determine the sequence of events and what caused the disturbance" [13]. This feature was particularly useful during the 2003 Northeast coast blackout. "On August 14, 2003, shortly after 2 P.M. Eastern Daylight Time, a high-voltage power line in northern Ohio brushed against some overgrown trees and shut down..." [14]. The current was so high in the line that it had softened. This problem would have normally tripped an alarm in the control room of FirstEnergy Corporation, but the alarm failed. "Over the next hour and a half, as system operators tried to understand what was happening, three other lines sagged into trees and switched off, forcing other power lines to should an extra burden" [14]. The burden was so immense that it tripped a cascade of failures in eight northeastern states and even into southeastern Canada. For almost two days, 50 million people were without power in the biggest blackout in North American history. The data from the synchrophasors was studied after the blackout to analyze what had happened, which led to many new regulations that will prevent another such catastrophe.

One final benefit of synchrophasors is that they can be implemented in smart grid technologies [8]. A schematic of smart grid is shown in Figure 2. Synchrophasor systems are the most effective technology to realize and implement the smart grid "because synchrophasor systems collect, distribute, and analyze critical data and convert it in real-time into information and insights that improve grid automation and operation" [13]. This can help manage grid operations by improving transmission efficiency and utilization.

III. Challenge and R&D Focus

Although the synchrophasor technology faces many challenges, three main challenges are most prominent which focuses on product improvement, infrastructure development, and education in the synchrophasor technology for end users.

Product improvement is directly related to research in the PMU field. The technology has been around for more than a decade, but is steadily improving. A major concern with product improvement is accuracy and reliability of the synchrophasor equipment. Leading companies such as Schweitzer Engineering Laboratories and General Electric have devoted funds for research and development of their synchrophasor equipment. This is key to continued improvement across the utility industry. Related to this is the price range of available equipment. A single unit is in the area of $3,000 per unit. With a price this steep, it is difficult to spread synchrophasor technology. Driving the price down to a more affordable range must be a requirement in equipment producers' scope of work.

Infrastructure development is the leading challenge for synchrophasor technology across the United States. An activity area named the North American Synchrophasor Initiative (NASPI) has been created to focus on infrastructure development. NASPI is collation between the electric industry, the North American Electric Reliability Corporation (NERC), and the U.S. Department of Energy (DOE). These are the three main contributors for development and deployment. The collaboration from experts from the industry, NERC, and DOE provides the most informed panel for increasing synchrophasor use across the nation. NASPI is funded by many groups, but receives a large amount from the Transmission Reliability and Renewables Integration Program. Another large funding contributor is the American Recovery and Reinvestment Act (ARRA). The NASPI states, "By 2014, this ARRA investment will help bring the total of installed PMUs to more than 1,100, offering nearly 100 percent coverage of the transmission system." [15]. Field deployment is the first challenge to overcome, but introduces a new challenge for PMU users. This is related to secure communications and data concentrators. Transmission measurements on the nations system is a highly sensitive area. This data must be protected and be able to be transmitted securely. This is not a new challenge for the industry as it has been apparent with the SCADA technology which preceded synchrophasor technology. Related to solving the secure communications challenge is the amount of data that must be protected. PMU technology is outstanding because of the amount of data that can be obtained. Once real-time data has been delivered there is the issue of how to store the mass amount of data, along with the decision regarding data archiving.

Synchrophasor technology in the field is a relatively new product. This introduces the challenge of having field experts and engineers educated in the PMU field. Synchrophasor technology has not always been included in the electrical engineering curriculum which results in many current utility operators not understanding the technology, and furthermore not knowing what to do with the data that is obtained from the equipment. As funding from corporations is provided for PMU development, there has also been a rise in funding provided for education in the PMU field. DOE has been a major contributor over the past year for education. There are two key areas, the first being educating engineers that are currently in the electric industry, and the second being educating at the collegiate level. Examples of such include DOEs funding opportunity of up to $9 million dollars for utilities and software developers in the field [16] and also DOEs $1.4 million funding for colleges to provide synchrophasor curriculum [17]. As more and more people become educated in the PMU field, there will be a more efficient use of the available technology and greater deployment.

IV. State of the Art Design

Phasor measurement unit, or synchrophasor, technology is designed to provide phasor information, both magnitude and phase angle, in real time. Phasor data concentrators are used to collect the real time phasor data streams for use in synchrophasor applications. Next, the data is transmitted to a regional monitoring system which is usually maintained by a local ISO, independent system operator. The independent system operator will monitor the phasor data from individual synchrophasors. This monitoring system is designed to provide accurate means of establishing controls for power flow from energy generation sources. This is why synchrophasor technologies are on the uptick right now because saving energy is of the upmost importance to the majority of companies.

- **Schweitzer Engineering Laboratories (SEL).** SEL offers many different PMU products for a variety of purposes. Schweitzer claims on their website that whether or not their customer are working with individual units or a complete system, that SELs products can help design, install, and commission the system. Their products consist of relays with PMU capability as well as standalone phasor measurement units. SEL has very competitive prices and flexible communications and designs, which makes them a viable competitor in the synchrophasor market. Their PMU's are high speed, and have a secure line current differential protection system which isn't offered everywhere. SEL uses IEEE C37.118 format, which is essential to be competitive in the synchrophasor market, with one to sixty messages per second for interleaved communications. They also apply direct relay-to-relay synchrophasors for wide area based control without having to add additional devices.
- **Relab Software.** The drivers that Relab offers provide a high performance conduit from the PMU or the PDC to the OPC, object linking and embedding for process control. These drivers are fully compliant with IEEE C37.118. The drivers were developed using sophisticated optimization technologies. They can support up to 16 PMU's or PDC's per one instance of the driver. The phasor data processing solution allows easy monitoring, analysis, and storage of PMU and PDC data at a rate of one hundred frames per second, which is exceptional. These Relab products will work with any compliant PMU or PDC including Areva, ABB, GE, Schneider Electric, SEL, and Siemens. This is a very important selling point for Relab because their drivers are not brand specific. They developed the first and unique synchrophasor OPC drivers on the market.
- **GE Multilin.** GE offers synchrophasor measurement in two ways. The first one is synchrophasor measurement integrated with your protection relay. This way offers transmission line protection and synchrophasor measurement in one device. This also exceeds the IEEE C37.118 synchrophasor standard with a total vector error under one percent. It allows direct Ethernet synchrophasor communications and multiple record triggering modes. The second way is a stand-alone synchrophasor measurement unit. This allows synchrophasor measurement of up to four PMUs per device. It has extended on board memory for record based data collection. Also, this way provides enhanced mathematical logic operations for automated system control as well as phase and ground protection. GE offers reliable and secure protection on lines equipped with series compensation which is not offered too many other places.

V. Concerns and Problems

Even though there are benefits for the use of synchrophasors, there are a few issues with the implementation of these devices. A few of the larger challenges include the scale of the technology, which sub include network capability and security, and cost of implementation. Project scaling is an extremely difficult aspect of the synchrophasors considering there is such a large network of distribution lines, generators, loads, etc. Implementing at such a large scale causes two problems:

- **The difficulty of setting up such a complex communication network.** There are a few issues within this topic. With networking there are problems with power consumption, security concerns and bandwidth requirements. Comparing the SCADA system with the Synchrophasors "it can be seen that the first major difference is that synchrophasors data is acquired at high speed typically 50 samples per second while data in SCADA is acquired once in 4 to 10 second" [18]. With this characteristic of synchrophasors comes higher power consumptions due to the more data points per cycle. Secondly, using a network for this technology cause security issues. Having someone manipulate the information could cause problems for utilities. Lastly, this network is going to have a standard bandwidth to transmit the information to the utility companies in which limits other industries in bandwidth capabilities.
- **The cost of implementation on such a scale that the grid, as a whole will benefit.** The cost of "the average price of a synchrophasor unit amounted to $3,000 per unit in 2013". This does not even include the cost of the network, the labor to install and maintain the technology, or the operations power cost of the device. When looking at this technology the cost can be a huge benefactor to the choice of to do or not to do considering this could add up to hundreds of millions of dollars.

VI. Related Work

With the development of smart grid, researchers paid more attention to synchrophasors which will facilitate the control of smart grids. Papers in the last five years mainly focused on the algorithm of synchrophasors and their applications on smart grid. The paper we chose here is titled as 'A novel back up wide area protection technique for power transmission grids using phasor measurement unit' [19], published on IEEE Transactions on Power Delivery, Jan. 2010. In this paper, the authors reported their research on how to apply PMU on wide area protection of power transmission grids.

A. Problems of the Conventional Technologies

The distance relays nowadays are widely used for power grid protections. A distance relay is designed to operate only when faults occurring between relay and the selected reach point, therefore will state stable if the fault is outside this region. One example is fault arc takes outside the relay's tripping characteristic [20].

A vast of unwanted trip or fail-to trip of protection is one of the origins to the raises and propagates of major power system

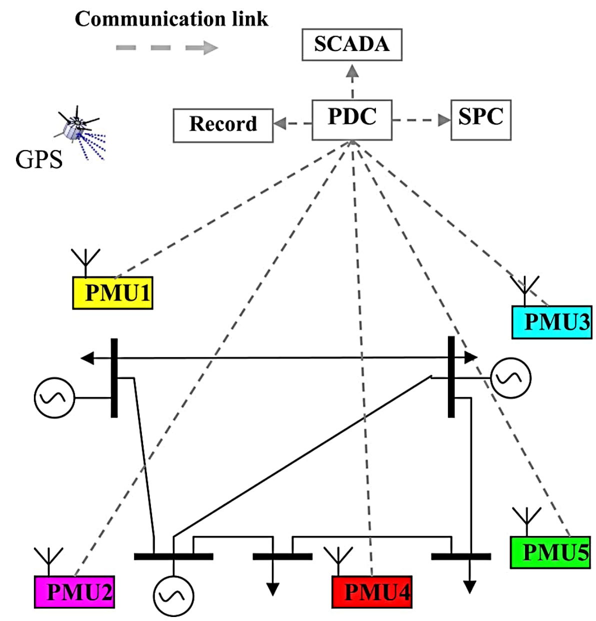


Fig. 4: The PMUs arrangement with phasor data concentration and system protection center

disturbances [21]. Backup protections are designed by keep the system free of fault. However the recent complexity and enlargement of power systems makes it difficult to coordinate operation times and reaches among relays.

Furthermore, the individual relays work alone and can hardly coordinate with each other, which restrains the wide-area based protection to be implemented.

B. Proposal of the PMU-based technology

The PMU-based technology is raised to solve the problems of the conventional technology. The PMUs are installed in the substations and acted as the distributed backup protection system. The network ensured them to share data and decisions rather than stand alone, providing the situation of all the power system area to the protection algorithm. The optic-fiber network ensures the fast responsibility of this system. The computation and communication capabilities of PMU allow the implementation and concentration of novel sophisticated protection principles. One example of this technology is shown in Figure 4.

The transmission network is divided into 5 areas, and 500 kV lines area are selected. PMUs are installed at substations and send real-time data to a Phasor Data Concentrator (PDC). The measurements are correlated and exported to System protection center (SPC) for protection as well as Supervisory Control and Data Acquisition (SCADA) for system analysis and monitor. Data of PMUs are synchronized by GPS and time stamped.

The main idea of this technique is to identify the fault area on the transmission lines. Two components, voltage reduction and power flow direction are utilized to identify the fault area. For a fault occurred on the grid, the minimum positive sequence voltage magnitude indicates the nearest area to the fault. Therefore, it could be determined by equation

$$\min(|V_1|, |V_2|, ...|V_m|, ...|V_n|) \tag{1}$$

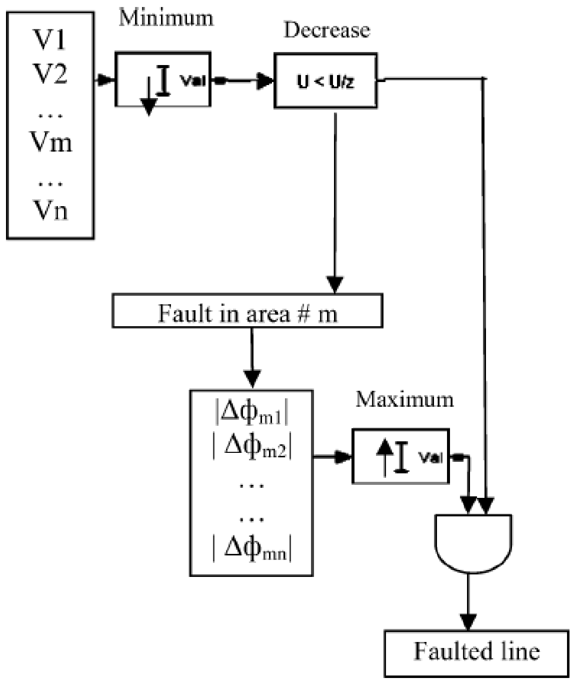


Fig. 5: The logic implementation of the technique

Where $|V_n|$ is the positive sequence voltage magnitude measured by PMU and located at area ”1”, ”2”,...”m” to ”n”. The direction of the power flow indicates the fault direction among the lines connected to the area obtained from 2. The fault caused the reverse of power flow and eventually the phase angle between voltage and current. Taking voltage as the reference, the phase angle of the fault will change from its power factor angle $\pm\phi$ to $(180° \pm \phi)$. Then the absolute difference of positive sequence current angle for a transmission line connecting area ”m” with ”n”, denoted by $|\Delta\phi_{mn}| = |\phi_{mn} - \phi_{nm}|$, will be the larger than all other absolute angle differences between the fault area and all other neighboring areas. Therefore, by comparing and selecting the max angle difference of all the transmission lines connecting to area ”m” will obtain the faulted line. Thus

$$\max(\Delta\phi_{m1}, \Delta\phi_{m2}, ...|\Delta\phi_{mn}|) \qquad (2)$$

In case of mal-operation caused by disturbance, thresholds are set. The voltage magnitude should go lower than 0.95 of the operation voltage and the absolute difference of current angle above $100^{c}irc$ before they can be considered as a fault character on the line respectively. Only both conditions are met will a trip output be produced. The whole process can be implemented logically in Figure 5.

C. Case Study

One example of the proposed technique is given in the power system given in Figure 4. Three phase to ground fault are located on line 1 which connecting area ”1” to area ”2”.

Figure 6 shows the output of the positive sequence voltage magnitudes of the five different areas, measured by the five PMUs. The minimum value is selected, indicating the nearest area to the fault is area ”2”.

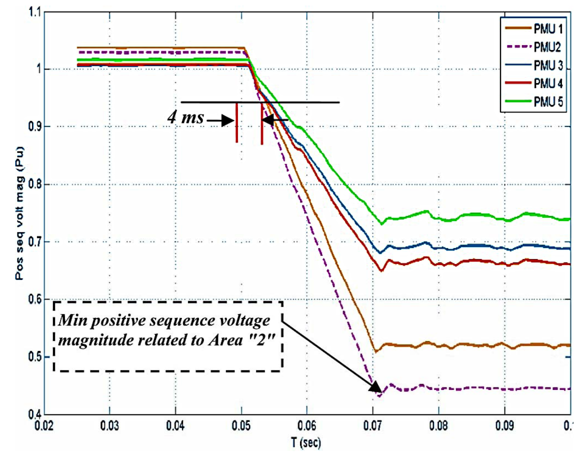


Fig. 6: Positive sequence voltage magnitudes

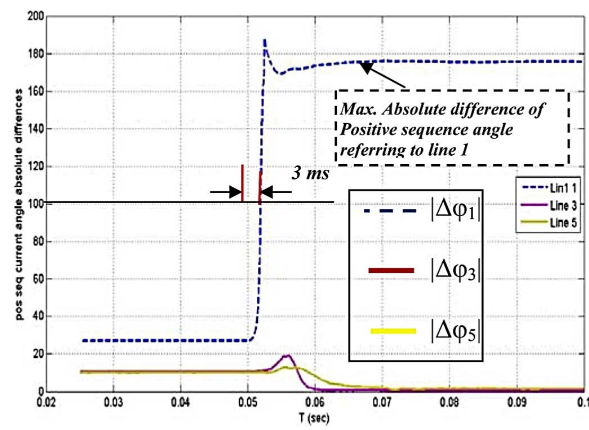


Fig. 7: Positive sequance current angle absolute differences for all lines connected to the faulted area (area ’2’)

The absolute differences of positive sequence current angles for all lines connecting the faulted area (area ”2”) with all other neighboring areas (areas ”1”, ”3” and ”4”) are shown in Figure 7. According to the graph, the maximum absolute difference of positive sequence current angle (about 175°) refers to line 1.The fault line is correctly detected in about 4 ms.

D. Summary of the Paper

The paper presents a new protection technique for transmission grids using PMU in a wide area system. The protection scheme successfully identified the faulted line over the interconnect system. Compared to the conventional technologies, this new relay is based on sharing data from all areas, and one relay is now used instead of many standalone ones with different complexity coordination. Under this condition, the relay has the feature of unit protection in identifying the faulted zone, and only one trip decision is issued from the protection center. The fast detection time estimated by 5 ms for all fault cases. It has the potential to become the main relay on the interconnected grids in the future.

VII. Conclusion

In this paper, the basic principle of synchrophasors are introduced. As a main member of synchrophasor family, PMUs which are deployed in the transmission line level, are discussed. The benefit and the application of PMUs are described, and the limitations of the PMU techniques are addressed. The state-of-the-art PMU techniques as well as the R&D focus of future development is discussed. Finally a related work about PMU-based protection is given.

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