GRID CONTROLLER OF INDIA LIMITED

Formerly known as Power System Operation Corporation Limited (POSOCO)

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EASTERN REGIONAL LOAD DESPATCH CENTRE

A Report On

"SYNCHROPHASOR TECHNOLOGY"

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1.Introduction

The modern power system is a complex interconnected network which can generally be split into four important parts: generation, transmission, sub-transmission, distribution and loads. Due to the complex nature of PS, it is necessary to continuously monitor and protect its elements in order to avoid major contingencies. As a result of different power system contingencies that have occurred in the past, the concept of monitoring the PS network in real-timehas become very important today.

Conventional Supervisory Control and Data Acquisition (SCADA) systems provide steady, non-synchronous information of the power system with time resolution between 1 and 10 s. Conventional SCADA systems are limited to steady-state measurements and cannot be used for observing the system dynamics. Various cascaded outages occurred in the U.S. in the last two decades were a result of deviation in power flow, frequency, and voltage. These outages made it necessary to monitor power system parameters such as frequency, phase angle, and amplitude to ensure those system parameters are always within the limits. Synchrophasor technology has many applications in electric power system which can be primarily grouped into three categories: *real-time grid operations; system planning and analysis; response-based control applications.*

Synchro-phasor Technique - A synchro phasor is a ‘phasor measurement unit’ (PMU) that measures the electrical waves on an electricity grid to determine the magnitude and phase angle of the sinusoidal waveforms at specific locations in the grid.

The key feature of synchro phasors is their ability to synchronize measurements from multiple locations using a common time source, typically GPS. This enables real-time monitoring of the grid with precise time-stamped data.

2. Synchrophasor Overview

- **Phasor representation of sinusoids**

Consider a pure sinusoidal quantity given by ,…

$$x(t) = X_m \cos(\omega t + \phi) \qquad (1.1)$$

ω being the frequency of the signal in radians per second, and ϕ being the phase angle in radians. X_m is the peak amplitude of the signal. The root mean square (RMS) value of the input signal is ($X_m/\sqrt{2}$). Recall that RMS quantities are particularly useful in calculating active and reactive power in an AC circuit. Equation (1.1) can also be written as

$$x(t) = Re\{X_m e^{j(\omega t + \phi)}\} = Re[\{e^{j(\omega t)}\} X_m e^{j\phi}].$$

It is customary to suppress the term $e^{j(\omega t)}$ in the expression above, with the understanding that the frequency is ω. The sinusoid of Eq. (1.1) is represented by a complex number X known as its phasor representation:

$$x(t) \leftrightarrow X = (X_m/\sqrt{2})\, e^{j\phi} = (X_m/\sqrt{2})\, [\cos\phi + j \sin\phi]. \qquad (1.2)$$

A sinusoid and its phasor representation are illustrated in Figure 1.1

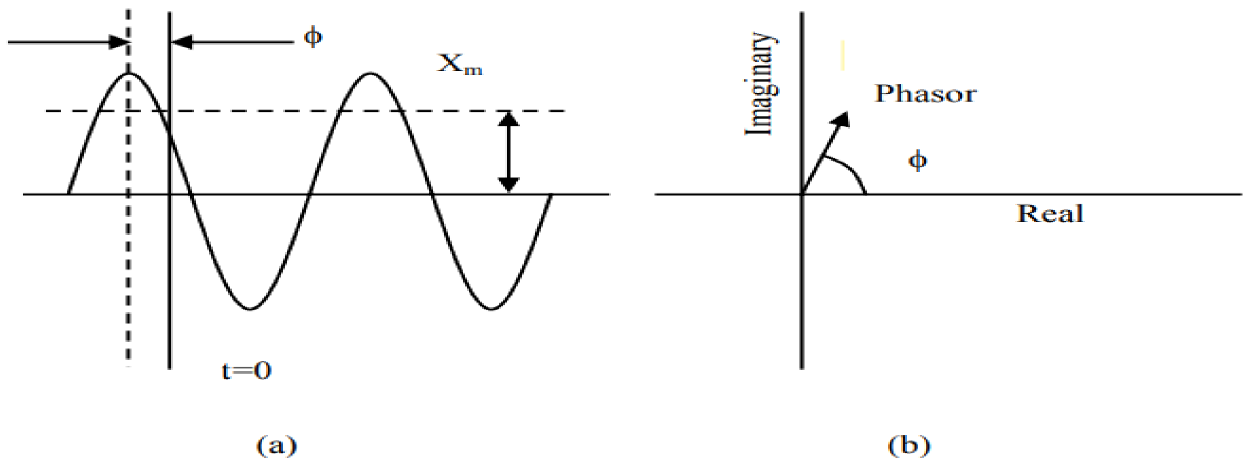


Fig. 1.1 - A sinusoid (a) and its representation as a phasor (b). The phase angle of the phasor is arbitrary, as it depends upon the choice of the axis t = 0. Note that the length of the phasor is equal to the RMS value of the sinusoid.

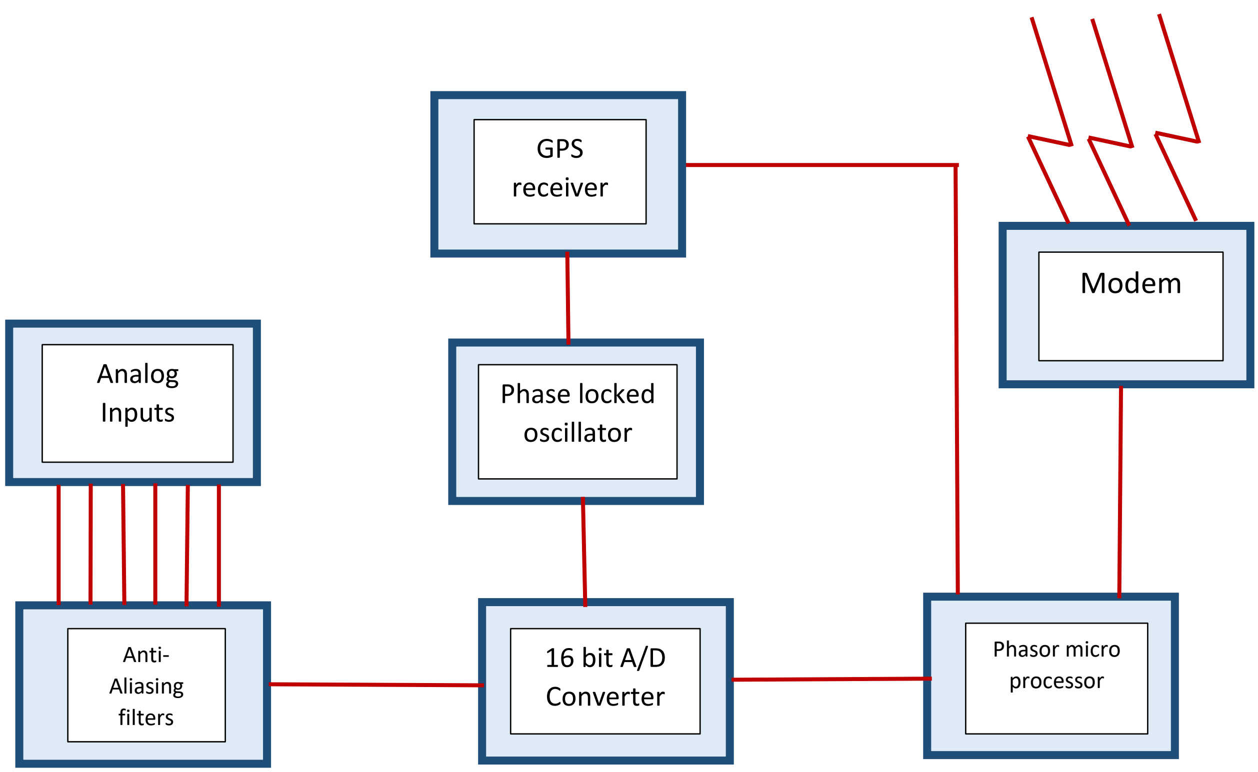


Fig. 2- Block diagram of PMU

2.1 Phasor Measurement Units(PMU)

A phasor measurement unit (PMU) is a device which measures the voltages and currents on an electric power system, using a common time source for synchronization. Time stamping of each measurement to a common time reference allows synchronized real-time measurements from different locations in the power system to be synchronised.

The PMU is a function or logical device that provides synchrophasor and system frequency, as well as other optional information such as calculated active power (MW) and reactive power (MVAR), sampled measurements, and Boolean status words. The PMU may provide synchrophasors from one or more voltage or current waveforms. The PMU can be realized as a stand-alone physical device or as a part of a multifunction device such as a protective relay, fault recorder, or meter. This information may be recorded locally or transmitted in real time to a substation or central location.

Phasors measured throughout an interconnected grid require a common timing reference provided by a synchronizing source. The signal provided by the synchronizing source shall be referenced to Coordinated Universal Time (UTC). The signal shall be accurate enough to allow the phasor measurement equipment to maintain synchronism within 1 microsecond of UTC including both synchronizing source and local receiving equipment error.

The Global Positioning System (GPS), which is a satellite-based system, is the main synchronizing source that is used to provide a time reference on the communication networks, and its widespread availability makes it possible at each point of the system to obtain a 6-clock signal that is synchronized with the one generated in other remote places.

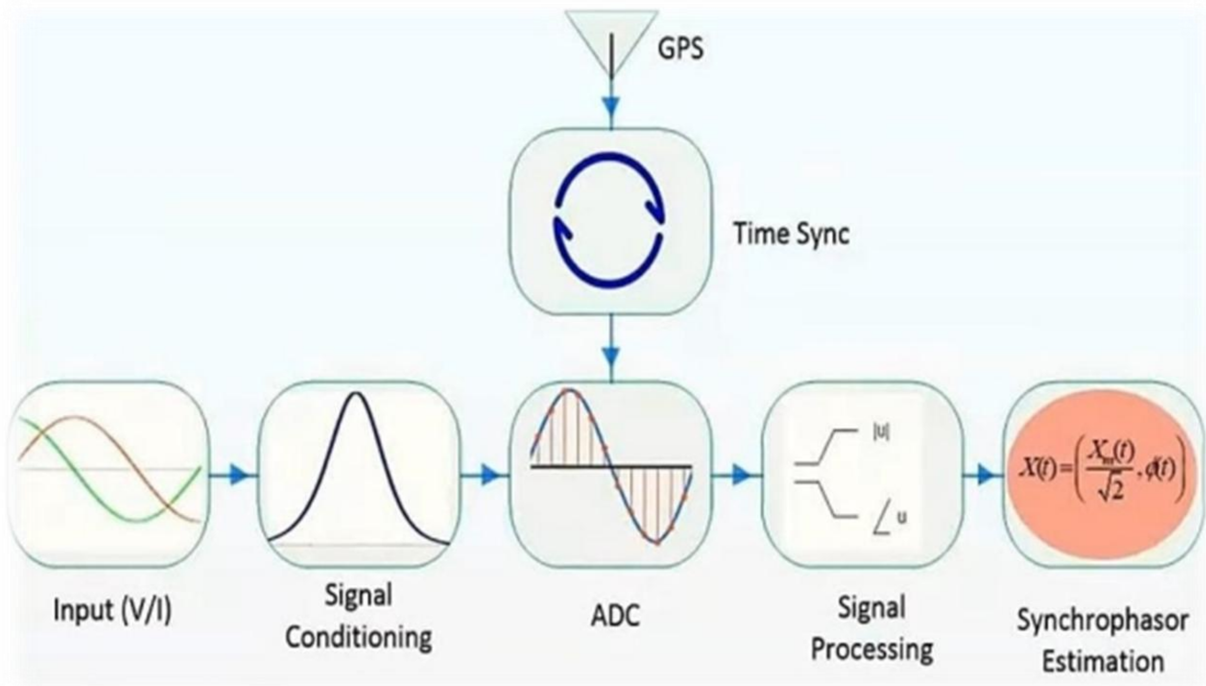


Figure 1: The block diagram of a PMU

2.2 Phasor data concentrators (PDC)

A phasor data concentrator (PDC) is a core component of the WAMS. A PDC can be implemented as a stand-alone unit that collects data and re-distributes it to other applications. PDC functions can also be integrated into other systems, for example monitoring/control platforms. In the following the PDC is described from the following aspects:

- Real-time data exchange
- Real-time data processing—detection functions 7
- Data storage
- Data visualization.

2.2.1 Data Acquisition from PMU Devices

A PDC must support the following standard communication protocols for connection with PMU devices:

- IEEE C37.118.2 (2011) client driver
- IEEE C37.118 (2005) client driver
- IEEE 1344 (1995) client driver.

The PDC must be able to simultaneously acquire data from at least 100 PMUs with full resolution of 50 samples per second for 50 Hz power system.

2.2.2 Data Exchange with Other PDCs

A PDC must support the following standard communication protocols for data exchange with other PDCs:

- IEEE c37.118.2 (2011) server driver
- IEEE c37.118 (2005) server driver
- IEEE 1344 (1995) server driver.

The PDC as a server driver must fulfil the following requirements:

- Simultaneously send data to several (at least 10) clients with full resolution of 50 samples per second for 50 Hz power systems.
- Optionally the data transfer resolution can be lower e.g. 10 samples per second depending on the client and transfer capacities.
- Filtering functionality for restricted signals (selection of which data will be exchanged).
- Protecting the PDC from unauthorized access.

2.2.3 Data Exchange with SCADA/EMS System

A PDC must have the ability to exchange data by standard protocols like IEC 60870-5-101/104, DNP3, etc. The purpose of this connectivity is to send data to a control center (SCADA/EMS systems) and to get commands from a control center.

2.2.4 Data Exchange with Real-Time Visualization

A PDC must have the ability to send data to a system (software) for visualization. The visualization system must acquire data with a maximal delay of 3 s. This way monitoring of the trend through visualization is assured.

3.Application of Synchrophasor Technology

3.1 Applications of PMUs in power transmission systems

RT grid applications require RT data collection and processing with immediate analysis and visualization. Due to the very high sampling speed, granularity into phase angles and time synchronization, many RT operations are possible using PMUs.

PMU data enable excellent visualization, analytics and alarming which can improve operators' ability to see and understand the dynamics of bulk PS. It can also help to anticipate or identify potential problems, and evaluate, implement and assessremedial measures. This section reviewsRT applicationsof PMUs in transmission systems.

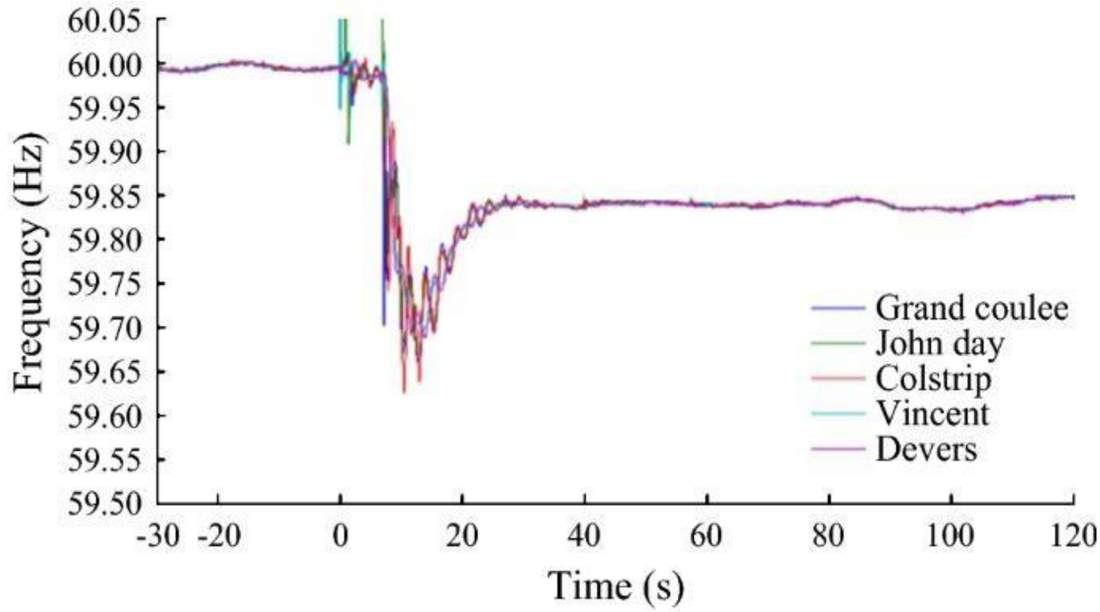
3.1.1 Wide area situational awareness and monitoring

One of the major online applications of PMU data is wide area situational awareness and monitoring. After several cascading outages in the U.S easternand western interconnection, many utilities developed in-house tools to provide wide-area visualization in order to monitor the dynamics of the grid in real time . These tools provide RT monitoring of grid and also trigger alarms predicting abnormal system conditions. One such example is phasor RT dynamics monitoring system (RTDMS) by Electric Power Group which is a synchrophasor software application for providing RT wide-area situational awareness to operators. It can provide small signal stability monitoring, voltage and frequency stability monitoring, phase angle differences and can also trigger alarms on abnormal system conditions.

- **Wide area frequency monitoring**

PS frequency is the key indicator of the load-resource balance. For example, the size of a generation loss can be correlated with the size of frequency deviation. Figure 4showsanexampleoffrequencyresponse to a generation outage at WECC. PMU frequency plot is a good indicator of the lost generation. PMU based wide area frequency monitoring readings can also be used in the post-disturbance analysis. A very good example of wide area frequency monitoring is wide-area frequency monitoring network (FNET) constructed in Virginia tech by utilizing the frequency disturbance recorder (FDR) data coming from the three interconnections in North America

Fig.4

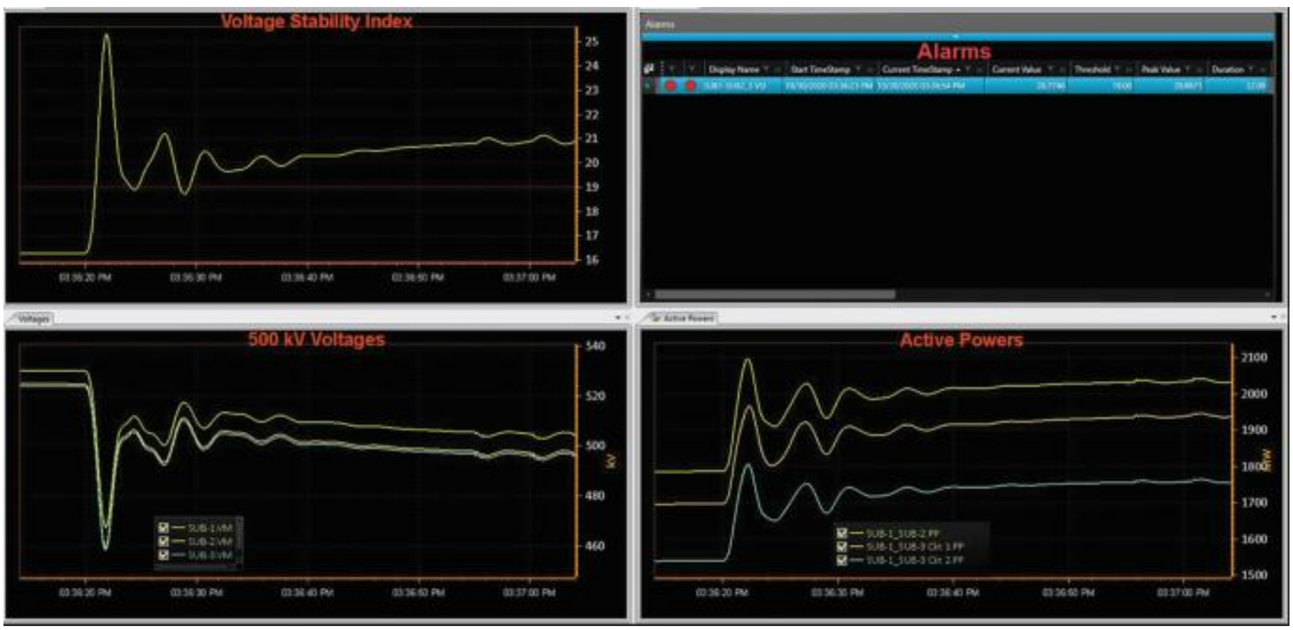


Westernsystemfrequencyduringalargegenerationoutageon July17, 2002

- **Voltage stability monitoring**

  Voltage stability is the ability of a PS to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. Different types of voltage stability can be found. Voltage stability indices(VSI) are used by the operators to know howclosethesystemistovoltagecollapse,orhowmuchpower canbesupplied to loads. PMU data helps to predict voltage instability in real time to perform better control actions in order to avoid cascading outages. Algorithms to perform voltage stability can be classified into two broader categories: Jacobian matrix based VSI and system variable based VSI.

VSI developed is based on PMU measurements available in WAMSs. This VSI determines the voltage stability margins of all system load buses and correctly predicts voltage collapse as it approaches zero. This approach assumes that synchronized voltage and current phasors are coming from PMUs located on different buses in the PS. A singular valued composition(SVD)metric to indicate grid vulnerability against voltage instability is proposed. The presented method for long-term voltage stability requires no information of system parameters or topology information. PMUs are used to get the voltage and current measurements from different buses for approximating a voltage stability indicator in near real time.

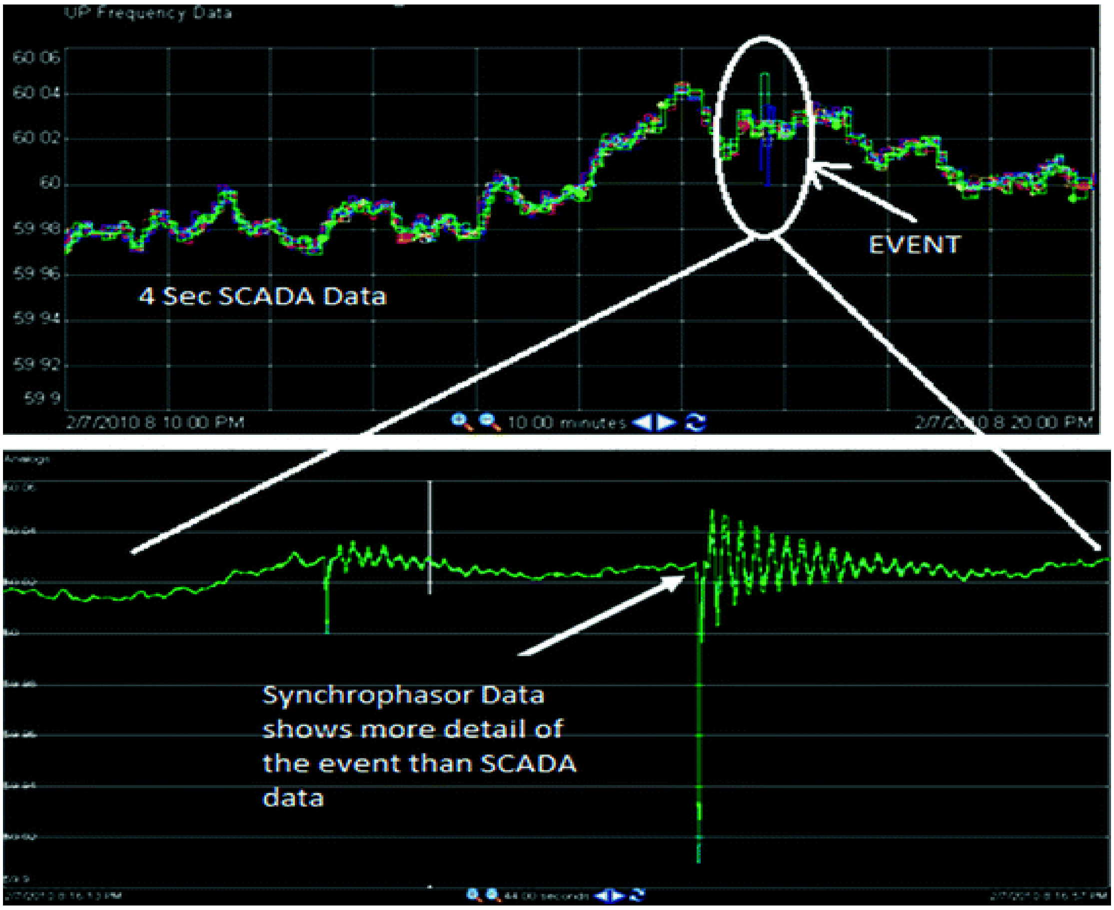


- ## Oscillation monitoring and detection

Oscillations occur in PS primarily due to rotor angle disturbances. Poorly damped or unstable oscillations can lead to undesirable system conditions such as instabilities and cascading outages which can ultimately lead to catastrophic blackouts such as 1996 blackout of the western U.S./Canada interconnected PS. Oscillations in the power grid can be divided into two categories i.e., forced oscillations and electromechanical oscillations.

Forced oscillations are usually caused by some rogue input driving the system, rather than a property of the system itself. Whereas, intra- plant mode oscillations, local plant mode oscillations, inter-area mode oscillations, control mode oscillations are all types of electromechanical mode oscillations. PMU data is very helpful to detect undamped electromechanical oscillations due to its high sampling rate.

Such type of oscillations can lead up to generator failure. So, asset management can also be performed by implementing control using PS stabilizers and flexible AC transmission system (FACTS) devices using local control modes. A self-coherence method for detecting sustained oscillations by using PMU data has been presented. Similarly, across- coherence method using multiple-channel PMU data is presented. Event location such as generator tripping is presented by triangulating frequency responses. Moreover, a model validation approach to locating the source of oscillation based on post-fault analysis is presented. An algorithm for the detection and frequency estimation of periodic forced oscillations is proposed.



- **State Estimation**

State estimation(SE)is a process of estimating the state of the network based on the available measurements. It is not feasible having measurements at every node of the system; therefore, SE is being widely used to estimate the value of state variables where measurement devices are not available. This is an imperative tool for on-line monitoring, analysis, and control of PS. Traditionally ,entire PS measurements are obtained through remote terminal units(RTU)of SCADA systems which have both analog and logical measurements. State estimator uses a set of analog measurements such as bus V, I, P and Q for estimating the unknown variables.

PMU based SE was first proposed in 1985 which took the advantage of linear state estimation(LSE).In LSE, voltage variables are expressed in rectangular form and the least squares problem to reduce measurement noise is solved in one step. Applications of LSE using PMU data further extended by to correct for: phase biases in PMU channels; current scaling errors; transformer tap ratios. SE can be categorized into the following three classes: static SE (SSE); tracking SE (TSE); dynamic SE (DSE).

SSE estimates the PS state associated with a given time and based on the measurement set corresponding to that moment of time. The SSE algorithm uses a flat start for initialization and it is iterative in nature. Therefore, it is computationally heavy and cannot be executed in small intervals. To overcome this problem, TSE was introduced where the estimation starts from the last calculated state variables instead of a flat point. In both types, the PS state is estimated based on a single set of measurements. However, in the DSE, the system states are continuously monitored at the regular interval. It is becoming more prevalent in the modern energy management systems due to its ability to predict the PS state progressively in short time steps. Each timestep of DSE, both measurement and prediction data sets are used. A comprehensive survey of DSE techniques and model implementation using PMU data are presented.

4. Working Principle of Synchrophasor Technology

Synchrophasor technology, also known as phasor measurement technology, is a sophisticated method used in modern power systems for real-time monitoring and control. The fundamental principle of synchrophasor technology revolves around the precise measurement of electrical waves, known as phasors, across different points in the power grid. This technology provides critical data on the amplitude, frequency, and phase angle of these electrical waves, enabling enhanced situational awareness and grid stability. Here is a detailed breakdown of its working principle:

1. Phasor Measurement Units (PMUs)

At the core of synchrophasor technology are Phasor Measurement Units (PMUs). These devices are strategically placed at various points in the power grid, such as substations and key transmission points. PMUs measure the electrical waves (voltage and current) at their location. The measurements are taken multiple times per second, providing a high-resolution view of the electrical system's behavior.

2. Time Synchronization

A critical aspect of synchrophasor technology is the synchronization of measurements from different PMUs. This synchronization is achieved using Global Positioning System (GPS) signals. Each PMU is equipped with a GPS receiver that provides a precise time reference. The measurements taken by the PMUs are time-stamped with this GPS time, ensuring that all data points across the grid are synchronized to the same temporal reference. This synchronization allows for accurate comparison and analysis of phasor data from different locations.

3. Phasor Data Calculation

The PMUs process the measured electrical waveforms to calculate the phasors. A phasor is a complex number representing the magnitude and phase angle of a sinusoidal function (such as a voltage or current wave). The magnitude indicates the strength of the wave, while the phase angle indicates the position of the wave relative to a reference point in time. By continuously calculating these phasors, PMUs provide real-time data on the dynamic state of the power grid.

4. Data Communication

The calculated phasor data is transmitted from the PMUs to central processing systems called Phasor Data Concentrators (PDCs). The communication network used for this transmission must be fast and reliable to ensure real-time data flow. Common communication protocols used include IEEE C37.118, which is specifically designed for synchrophasor data.

5. Phasor Data Concentrators (PDCs)

PDCs aggregate the data received from multiple PMUs. They align the data based on the time stamps, ensuring that all measurements are synchronized and can be accurately compared. PDCs can operate at various levels, from local to regional and central levels, providing a hierarchical structure for data aggregation and analysis.

6. Data Analysis and Applications

The synchronized phasor data collected by PDCs is used for various applications, including:

- **Real-Time Grid Monitoring:** Operators can monitor the real-time state of the grid, identifying issues such as voltage instability, frequency deviations, and oscillations.
- **Fault Detection and Localization:** Synchrophasor data helps in quickly detecting and locating faults, enabling faster restoration of services.
- **Grid Stability Analysis:** By analysing phasor data, operators can assess the stability of the grid and take proactive measures to prevent blackouts.
- **Integration of Renewable Energy:** The precise measurements provided by synchrophasors facilitate the integration of renewable energy sources, which can be variable and intermittent.
- **Post-Event Analysis:** Detailed phasor data is invaluable for investigating grid disturbances and improving future grid operations.

5. International usage of Synchrophasor Technology

This document explores the **current** status of synchrophasor technology adoption in several countries to enhance their power grid operations. It highlights the specific purposes, deployment efforts and key players involved in each nation's implementation.We are giving statuses continents wise.

THE RISE OF SYNCHROPHASORS IN DIFFERENT CONTINENTS:

ASIA:

Across Asia, a growing number of countries continue to embrace synchrophasor technology as a critical tool for modernizing and strengthening their power grids. **Advanced capabilities** offered by this innovative technology provide real-time, high-fidelity data on grid conditions, enabling operators to make informed decisions that improve grid stability, reliability, and efficiency.

NATIONAL CASE STUDIES

- **China:** A leader in synchrophasor deployment, China leverages this technology to manage the integration of large-scale renewable energy sources, enhance grid stability, and improve real-time monitoring and control. Key players include the China Electric Power Research Institute (CEPRI) and the State Grid Corporation of China (SGCC). Their efforts are likely **expanding further** to accommodate China's growing energy demands.
- **India:** As part of its ongoing grid modernization efforts, India is actively deploying synchrophasor technology. This initiative aims to improve operational efficiency, manage the ever-increasing demand for electricity, and facilitate the integration of renewable energy sources. The Power Grid Corporation of India Limited (PGCIL) is spearheading this nationwide deployment. We can expect to see **significant progress** in India's synchrophasor implementation.
- **Japan:** Japan prioritizes using synchrophasor technology to enhance grid reliability and stability. Their implementation focuses on improving fault detection, real-time monitoring capabilities, and response times.

Key players involved include the Japan Electric Power Information Center (JEPIC) and various utility companies. It's likely that **advancements in synchrophasor data analysis** are being incorporated into Japan's grid management strategies.

- **South Korea:** South Korea has integrated synchrophasor technology into its grid infrastructure to achieve several objectives, including enhancing grid stability, improving fault detection and response capabilities, and supporting the integration of renewable energy sources. The Korea Electric Power Corporation (KEPCO) is responsible for deploying and managing this technology. We can expect to see **continued refinement and optimization** of South Korea's synchrophasor use.
- **Singapore:** As part of its smart grid initiatives, Singapore is incorporating synchrophasor technology. The primary goals are to enhance grid reliability, improve real-time monitoring capabilities, and facilitate the integration of renewable energy sources. Singapore Power (SP Group) plays a key role in the deployment and management of this technology. With Singapore's focus on smart city development, we can expect to see **deeper integration** of synchrophasor data into their overall grid management strategy.

EUROPE:

Across Europe, countries are continuously modernizing and strengthening their power grids with synchrophasor technology. This innovative technology provides real-time, high-fidelity data on grid conditions, empowering operators to make informed decisions that ensure a more:

- **Efficient Grid:** Improved situational awareness and control capabilities lead to a more optimized and reliable power grid.
- **Stable Grid:** Real-time monitoring allows for proactive measures to prevent grid instability caused by fluctuations in power generation or demand.
- **Sustainable Grid:** Synchrophasors facilitate the seamless integration of renewable energy sources like wind and solar power into the grid, paving the way for a more sustainable energy future.

NATIONAL CASE STUDIES

- **United Kingdom:** The UK continues to be a leader in synchrophasor deployment, spearheaded by National Grid ESO (Electricity System Operator). They utilize PMUs (Phasor Measurement Units) for real-time monitoring and advanced grid management. This approach remains focused on improving grid stability and integrating renewable energy sources like wind and solar.
- **Germany:** As Germany progresses with its ambitious Energiewende (energy transition) strategy, synchrophasor technology remains a critical tool. Utilities like TenneT and 50Hertz play a crucial role in deploying and using PMUs across the transmission network, ensuring grid stability and a reliable power supply for continued integration of renewable energy.
- **France:** France's extensive power grid continues to benefit from synchrophasor technology for monitoring and management. Réseau de Transport d'Électricité (RTE), the primary operator, is responsible for deploying PMUs across the national grid. This approach remains focused on enhancing grid reliability, stability, and the integration of renewable energy sources.
- **Italy:** Italy continues to utilize synchrophasor technology to support its electricity grid operations. Terna, the Italian electricity transmission system operator, oversees PMU deployment. This initiative remains focused on improving grid stability, real-time monitoring capabilities, and the seamless integration of renewable energy sources.
- **Spain:** Spain's power grid continues to be enhanced by synchrophasor technology, particularly in managing the integration of a substantial amount of renewable energy resources. Red Eléctrica de España (REE), the main operator, plays a key role in deploying PMUs. This approach remains focused on improving grid stability and enhancing real-time monitoring capabilities.
- **Nordic Countries:** Several Nordic countries, including Norway, Sweden, and Denmark, have embraced synchrophasor technology. Norway's Statnett, Sweden's Svenska kraftnät, and Denmark's Energinet, the respective transmission system operators in each country, are responsible for deploying and utilizing PMUs. These implementations share common goals: enhancing grid reliability and stability, and integrating renewable energy sources like wind and hydro power into

the grid, with a specific focus on real-time monitoring and control for Denmark in the case of wind energy.

NORTH AMERICA:

The landscape of North American power grids is undergoing a significant transformation driven by synchrophasor technology. This document delves into the implementation and utilization of this innovative technology in the United States and Canada, the two leading forces in its adoption.

NATIONAL CASE STUDIES:

- **United States:** The United States leads North America in synchrophasor adoption with a mature and extensive infrastructure. This translates to real-time data for grid operators, enabling them to identify and prevent issues, optimize grid management, and seamlessly integrate renewable energy sources like wind and solar. The deployment is overseen by a diverse group including ISOs, RTOs, and utilities. Key initiatives like NASPI and the Grid Modernization Initiative further propel synchrophasor use, with a unique focus on broad adoption across regions, maintaining grid reliability with high renewable energy penetration, and continuous innovation through advanced research and development.
- **Canada:** Canada's synchrophasor adoption is strategic and targeted, focusing on integrating renewables like hydro and wind power into the grid for a sustainable future. Utilities and transmission system operators lead deployment, with key players like Hydro-Québec, IESO, and BC Hydro leveraging PMUs to enhance grid stability, optimize management, and improve fault detection. This targeted approach, along with collaboration between stakeholders, fosters continuous improvement in synchrophasor applications and paves the way for a more reliable and sustainable Canadian power grid.

SOUTH AMERICA:

Several South American countries are embracing synchrophasor technology to transform their power grids. This innovative technology provides real-time data for enhanced monitoring, control, and integration of renewable energy sources.

NATIONAL CASE STUDIES:

- **Brazil:** Brazil stands out as a leader in synchrophasor adoption within South America. Their vast power grid, heavily reliant on hydroelectric plants, necessitates advanced monitoring and control systems. Synchrophasors perfectly address this need by providing real-time data for grid operators. This allows for improved decision-making, leading to enhanced grid stability and a more robust electricity supply. Additionally, Brazil prioritizes using synchrophasors to seamlessly integrate hydroelectric power, a cornerstone of their energy mix.
- **Chile:** Chile is taking a strategic approach to synchrophasor technology, utilizing it to propel their renewable energy goals. By strategically deploying PMUs across the grid, they aim to enhance overall reliability and ensure a secure power supply. This focus on reliability is crucial as Chile integrates more solar and wind power into their energy mix. Synchrophasors provide the advanced monitoring capabilities needed to manage the inherent variability of these renewable sources, ensuring a smooth transition towards a cleaner energy future.
- **Argentina, Colombia and Peru**: These countries are emerging as synchrophasor adopters in South America. While all three aim to improve grid stability and integrate renewable energy, their unique approaches highlight their specific needs. Argentina tackles regional grid challenges strategically with synchrophasors, while Colombia leverages them for real-time monitoring and fault detection to enhance reliability, particularly for hydroelectric power integration. Peru focuses on strategic deployment to integrate renewable energy sources and achieve overall grid reliability improvements. These targeted approaches position each country to build more robust and sustainable power grids for the future.

AFRICA:

Synchrophasor technology adoption may be in its early stages across Africa compared to other regions, but several countries are emerging as pioneers, paving the way for a more robust and sustainable future for their power grids. This document explores the current landscape and unique approaches employed by leading African nations in this technological shift.

NATIONAL CASE STUDIES:

- **South Africa:** South Africa emerges as a frontrunner in synchrophasor technology adoption across Africa. Eskom, the state-owned utility, spearheads this initiative with a multi-pronged approach. First and foremost, real-time data from PMUs (Phasor Measurement Units) empowers grid operators to proactively identify and prevent potential issues. This translates to a more robust and dependable electricity supply for the entire nation. Secondly, South Africa recognizes the potential of renewable energy sources like wind and solar power. Synchrophasors play a vital role in seamlessly integrating these variable resources into the grid. This fosters a cleaner energy future by facilitating the transition away from traditional fossil fuels. Finally, Eskom leverages real-time data to closely monitor grid performance. This enables informed decision-making for optimized load management and efficient grid operations, ensuring a reliable and sustainable power supply for South Africa.
- **Egypt:** Recognizing the need for grid modernization, Egypt is actively exploring the use of synchrophasor technology. The Egyptian Electricity Holding Company (EEHC) is at the forefront of these efforts, aiming to improve grid stability and reliability while facilitating the integration of renewable energy sources like solar and wind power.
- **Kenya:** In the early stages of deployment, Kenya recognizes the value of synchrophasors for integrating geothermal and wind power, key renewable resources in the country's energy mix. Additionally, the technology will enhance grid monitoring and stability. This initiative is being led by the Kenya Electricity Transmission Company (KETRACO) in collaboration with other major utilities.
- **Nigeria:** Nigeria is taking its initial steps towards synchrophasor adoption to address its grid challenges, particularly instability and reliability issues. The Transmission Company of Nigeria (TCN) is leading this effort, leveraging real-time data from PMUs to effectively monitor and manage the grid.

OCEANIA:

Synchrophasor technology is transforming power grids across the globe, and Oceania is no exception. This document explores the implementation of this innovative technology in Australia and New Zealand, two leading countries in the region with developed electricity grids and a strong focus on integrating renewable energy sources.

NATIONAL CASE STUDIES:

- **Australia:** Australia stands out as a leader in adopting synchrophasor technology across Oceania. The Australian Energy Market Operator (AEMO) and various utilities spearhead this initiative with a multi-pronged approach. Firstly, real-time data from PMUs empowers grid operators to proactively address potential issues, enhancing overall grid stability and reliability. Secondly, Australia, a leader in renewable energy integration, leverages synchrophasors to manage the variability of solar and wind power, ensuring a smooth transition towards a cleaner energy future. Finally, Australia remains at the forefront of research and development in this field, focusing on advanced grid analytics and predictive maintenance to further optimize grid operations and ensure long-term sustainability.
- **New Zeeland:** Inspired by Australia's success, New Zealand is actively modernizing its power grid with synchrophasor technology. Led by Transpower, the national grid operator, this initiative prioritizes two key areas. Firstly, real-time data from PMUs empowers grid operators to make informed decisions, enhancing overall grid reliability and stability. This translates to a more secure and dependable electricity supply for the nation. Secondly, synchrophasors play a crucial role in integrating New Zealand's growing wind and geothermal energy sectors alongside their existing hydroelectric base. This ensures seamless integration of renewable sources while maintaining grid stability, paving the way for a more sustainable energy future.

• Conclusion:

This paper provides an in-depth literature review of ST, its architecture, placement techniques and applications in power transmission and distribution systems. The review also presents potential research areas for OPP techniques and ST applications in transmission and distribution systems. PMUs are deployed in large number in transmission networks but with the addition of more DG resources and the advent of PMUs, they are becoming popular in the distribution system. Most of the applications presented in this paper are currently in practice in the electric power industry. Some evolving applications also exist in academic publications and will be part of the electric power industry in the near future. These applications use data analytics and machine learning algorithms for power systems security and resilience. With ST, the benefits gained in terms of reliability, resiliency and operational efficiency of the grid justifies its installment.