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A Review on Intelligent Synchrophasor Technology for Upgrading Microgrid to Smartgrid

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Abstract: With the improvement in technology and with the consideration of today's need, we need to upgrade our traditional electric grid to smart grid. We have to build microgrid more intelligent, automated and smart with advanced features. The advanced computer based synchrophasor technology is used for real time monitoring and control of all the parameters of microgrid with more accuracy and precision than traditional real time monitoring and control system i.e. SCADA (supervisory control and data acquisition) by measuring grid conditions at a rate of more than 30 times per second as compared with SCADA every 2 to 4 times per second. Synchrophasor technology uses high-resolution phasor measurement units (PMUs) along with fast communication network that provide time-synchronized data more precisely to detect disturbances that is difficult to be monitored with SCADA systems. The different applications of synchrophasor technology with PMU measuring devices, summarized in this review paper, updates microgrid as intelligent smart grid.

Keywords: Microgrid, Real Time monitoring, SCADA, Synchrophasor, PMU (Phasor Measurement Unit), Smart Grid (SG).

1. INTRODUCTION

In today's era of smart appliances (like smart phone, smart TV etc.) our microgrid also needs smart upgrade. Synchrophasor technology can be used to monitor on line and off-line data, corrective action and decision making support tools, avoids events, blackouts and other unwanted conditions, actions to improve the reliable and secure operation of microgrid and to upgrade it as smartgrid. A synchrophasor technology is along with the placement of phasor measurement units (PMU) and high-speed communications network to collect and transfer synchronized high-speed grid condition data, with advanced on-line dynamic security assessment is implemented in smart grid.

An advanced and improved technique that synchronizes the calculation of a phasor quantity to absolute time has been developed, known as "synchronized phasor based measurement" or "synchrophasors." The backbone of a successful smart grid operation is a reliable and secure operation, controllable and manageable standards, rapid communication network. Which makes intelligent link between the components of the grid which are involving in the decision making that delivers power to the utility, supply and load demand which are connected to it.

2. MICROGRID

A microgrid is a small or local power grid that can operate independently or in connection with the part of main electrical grid. [2]

A Microgrid can connect and disconnect from the grid to enable it to operate in either grid connected or islanded-mode.

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The main characristics of a Microgrid are:

- Can operate in both island mode or grid-connected mode.
- can present to the Macro grid as a single controlled unit.
- Can combine interconnected loads and near by located power generation sources
- Can provide different levels of power quality and reliable supply to the consumers, and
- Designed to accommodate total system energy requirements.

A simple diagram, Figure 1, showing the concept of a Microgrid along with the ability to separate from the maingrid or "Macrogrid" at a single point.

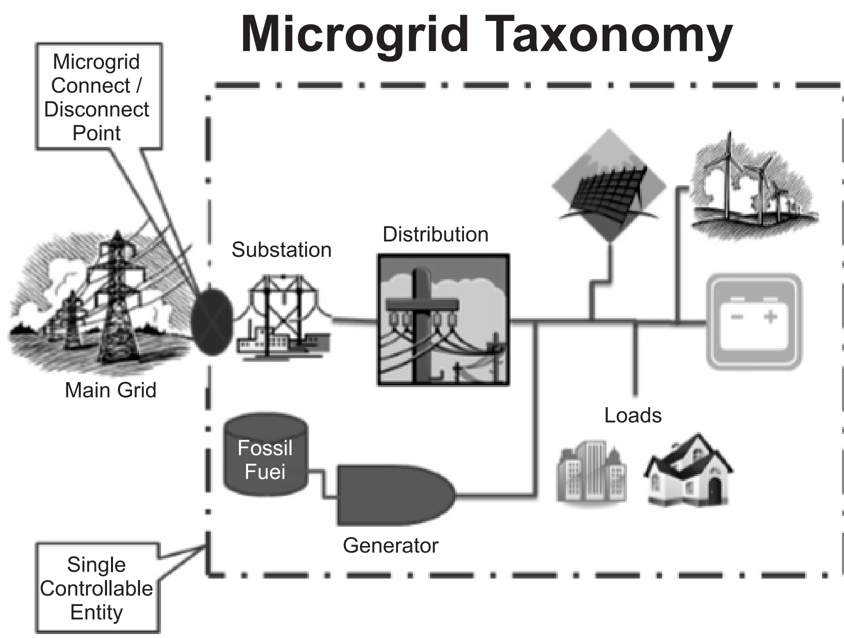

Figure 1: Microgrid components

The main microgrid components as shown in figure includes different loads, Distribution Energy Resources (DERs), master controller, smart switches, protective devices, controlling devices, communication network and automation systems.[2]

Microgrid loads aer either fixed or flexible (also known as adjustable). Fixed loads are cannot be changed while flexible loads can be changed and responds to controlling signals. DERs consist of distributed generation units (DG) and distributed energy storage systems (DESS) which could be installed at electric utility facilities and/or electricity consumer's premises.

Microgrid Distribution generators are either dispatchable (controlled by the microgrid master controller) or nondispatchable(cannot be controlled by the microgrid mastercontroller). Non dispatchable units are mainly renewable DGs(generally solar and wind) that produces a volatile, fluctuating and irregular output power. At the point of common coupling (PCC), a switch performs microgrid islanding operation by disconnecting the microgrid from the main grid. The master controller shown in Figure (2) determines the microgrid communication with the main grid, and take action to switch between interconnected and islanded modes.

A powerful controller is the Intelligent Centre of the microgrid and is able to responds to external data, like real-time signals and rapidly changing system loads.

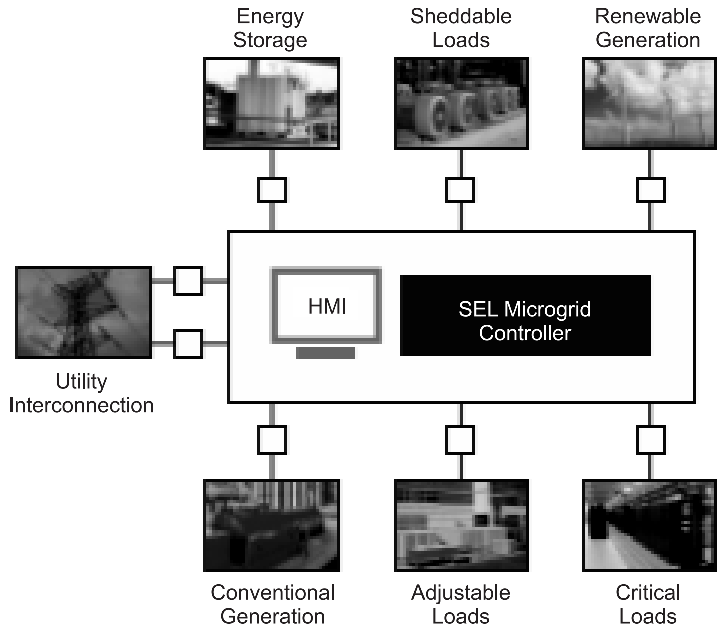

Figure 2: Microgrid Controller

3. SMARTGRID

When smart technology is implemented to grid it becomes a smart grid (SG), also called smart power grid. Smart grid is intelligent grid and to be future grid, that is an improvement of the 20^{th} century power grid. The traditional power grids are generally used to carry power from a few central generators to a large number of users or consumers. In contrast, the SG uses two-way flow of electricity and information to create an automated and distributed advanced energy delivery network.

The table shows comparison between the existing grid and the future Smartgrid. [10]

Table 1
Comparison between the existing grid and the smart grid

Existing Grid	*Smart Grid*
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

The smartgrid can be considered as an electric system that uses information, for two-way communication and intelligent computations in an integrated manner across electricity generation, transmission, substations, distribution and consumption for maintaining an efficient, intelligent, safe, secure, reliable, resilient, and sustainable system operation.

Smartgrid system is divided in three major systems as:

- **Smart infrastructure system:** The smart infrastructure system gives the overall structural idea about power, information or data, and communication network.

The smart infrastructure system as shown in Figure (3) supports two way flow of electricity and information. For example, in a smart Grid, power can transmitted and delivererd to consumers and also be given back to the grid by consumers or users. For example, users may be able to generate electricity using renewable energy sources like solar panels or biogas at homes and put that energy back into the grid.

The smart infrastructure can be subcategorised into three subsystems: smart energy subsystem, smart information subsystem, and the smart communication subsystem.

- The smart energy subsystem is responsible for advanced electricity generation, transmission, distribution, and consumption.
- The smart information subsystem is responsible for advanced information metering, monitoring, control and management in the smartgrid.
- The smart communication subsystem is responsible for communication, connectivity and information transmission among systems, devices, and different applications in the smartgrid.

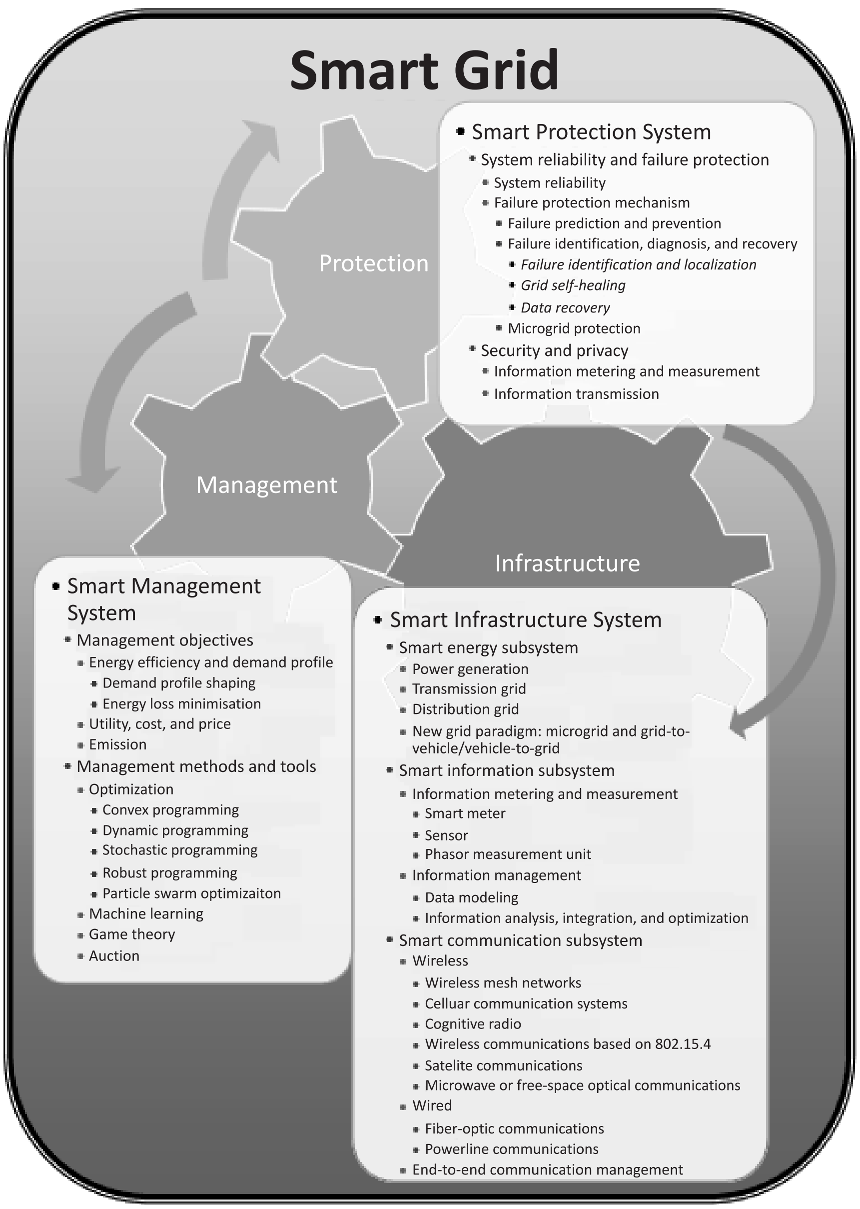

Figure 3: Smartgrid Infrastructure

- **Smart management system:** The smart management system is the system in smartgrid which provides advanced management and control services and various functions. Due to advancement of the new management applications and services, improves the technology and capability which upgrades the existing infrastructure and becomes "smarter." The various advanced management objectives like energy efficiency improvement, managing supply and demand side balance, operation cost reduction, and utility maximization can be achieved through smart magement system with the help of smart infrastructure.
- **Smart protection system:** The smart protection system is the system in smartgrid that provides advanced grid reliability and stability analysis, fault and failure protection, corrective actions, privacy and security protection services. The smarter protection system supports failure protection techniques, solve security problems, and preserve privacy of system.[10]

Benefits of Smartgrid:

1. Improving power system reliability, stability and power quality;
2. Increasing capacity and efficiency of existing networks;
3. Facilitating increased development of renewable energy sources;
4. Automatic maintenance, self healing capability against unpredictive outages, events, blackouts and natural disasters and less damage of equipments;
5. Reducing greenhouse gas emissions by enabling electric vehicles and new power sources;
6. Reducing the need for inefficient generation during peak usage periods, reducing oil consumption.
7. Improving grid security with advanced warning about possible faults and events and preventive action before fault;
8. Improving of demand-side management, energy efficiency.

4. SYNCHROPHASOR TECHNOLOGY

A phasor is a complex number that represents the magnitude and phase angle of the sinusoidal waveforms of voltage or current at a specific point in time.

An AC waveform can be mathematically represented as

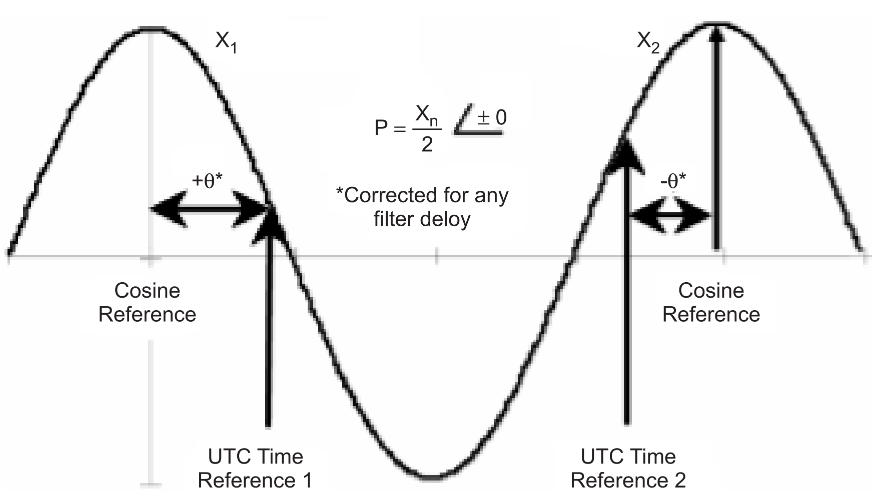

Figure 5: Synchrophasor Waveform

$$X(t) = X_m \cos(wt + \Phi)$$

Where, X_m – magnitude of the sinusoidal waveform.

$W = 2\Pi f$, f-instantaneous frequency.

Φ – Angular phase displacement.

A synchrophasor waveform shown in Figure 5 represents sinusoidal quantity with magnitude and angle.

Synchrophasor technology is a real time monitoring technology and more advantageous and faster than traditional real time monitoring system i.e. SCADA.

5. PHASOR MEASUREMENT UNIT

Phasor Measurement Unit: Phasor measurements that occur at the same time for magnitude and angle are called synchrophasor, and the devices used for measurement of synchrophasor is called PMU devices. PMU readings are obtained from widely dispersed locations in a power system network and synchronized using the global positioning system (GPS) radio signal that responds to system conditions in a fast and dynamic fashion.

PMUs sample power grid conditions at a rate of several hundred times per second and convert the measured parameters into phasor values, typically 30 or more values per second, compared to conventional monitoring technology (such as SCADA) that measure once every two to four seconds.

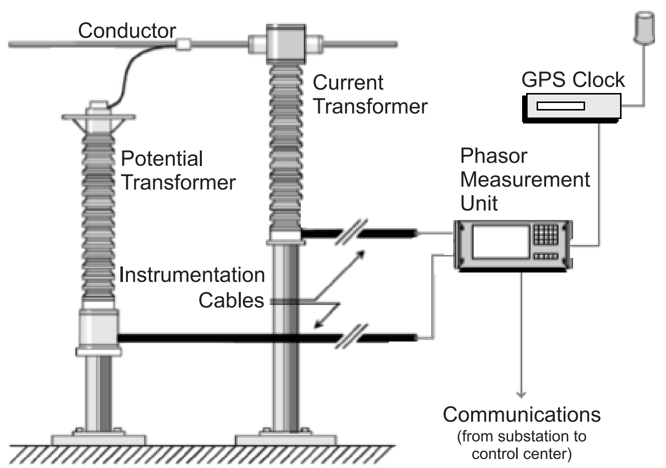

Figure 6: PMU Installation within a Substation

PMU installation within a substation is shown in figure (6).The PMUs phasors based on the Global Positioning System (GPS) time signal which turns phasor values into synchrophasor. The PMU values at different locations and across different power industry organizations are sent through communications networks to phasor data concentrators (PDCs) which collect and time-align the data. The resulting PMU data provides conditions throughout the grid to transmission grid planners, operators, and engineers with a high-resolution for different applications of grid. [18]

Applications of PMU:

1. Phase angle monitoring
2. Oscillation detection and monitoring
3. Voltage stability monitoring
4. Event detection, management & restoration

5. Islanding detection, management & restoration
6. Equipment problem detection
7. Wide-area situational awareness
8. Model validation and calibration
9. Post-event analysis
10. State estimation
11. Renewable resource integration
12. Operator training.

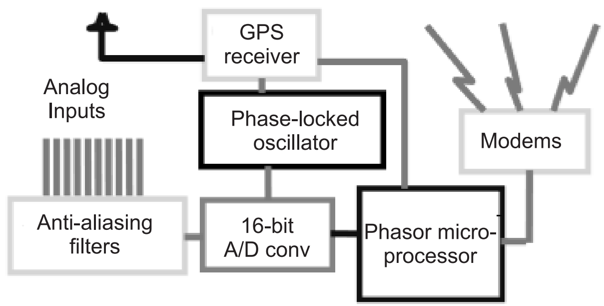

Figure 7: Block diagram of PMU components

Figure 7 shows a block diagram of PMU components. The analog input signals are obtained from the secondaries of the voltage and current transformers. The analog input signals are filtered by anti-aliasing filter to avoid aliasing errors. Then the signals will be sampled by the A/D converter. The sampling clock is phase-locked to the GPS time signal. The GPS receivers can provide uniform time stamps for PMUs at different locations. The phasor microprocessor calculates the values of phasor. The calculated phasors and other information are transmitted to appropriate remote locations over the modems. [11]

6. APPLICATIONS OF PMU TO UPGRADE MICROGRID AS SMARTGRID

Phase angle monitoring: The phase angle differences in voltages between two locations on a transmission grid is the deciding factor for power system stress, stability and reliability. The grid is said to be “stressed” when power transfer is high and phase angle between the ends of the line increases with loading of the line.

System stability is the ability of the system to run in a secure and steady operating condition following a disturbance like equipment outage or other failure. [18].

Traditionally, phase angles are calculated off-line with simulations and state estimation. Now PMUs can measure phase angles directly, and immediately available for system operators to monitor and to take action on stressed power system.

The examples who takes the benefits of using synchrophasors to monitor phase angles are:

- Florida Power and Light Company (FPL) uses PMUs to monitor phase angles directly when switching in transmission lines. PMUs, along with other monitoring devices improves the reliability and security of the FPL transmission system by detecting incipient failures and avoiding outages and equipment damage.
- WECC (Western Electricity Coordinating Council) uses PMU data to monitor phase angle differences between the ends of four major transmission paths.

Oscillation detection and monitoring: The rapid changes in voltages, currents, frequencies, etc. tend to (analogous to physical vibrations), the disturbances are referred to as "oscillations." Oscillations become a serious when they increase over time instead of decreasing. PMU data provides a way to detect the presence of oscillations, determine the extent to which an oscillation creats a threat to the electric grid, and monitor the oscillation to determine if conditions worst.

Implementation of PMU in the power system is a great advantage for oscillation monitoring and control. Based on the oscillation observed, immediate action is taken by system operators and prevented the oscillation to spread into whole system[20].

Frequency monitoring: The concept of building an real-time GPS-synchronized wide-area frequency monitoring network (FNET) was proposed in 2000.The FNET system consists of two components: FDR and IMS

(a) Frequency Disturbance Recorders (FDRs), which perform local GPS-synchronized frequency measurements and send data to a FDR structure and FDR server through the Internet.

(b) Information Management System (IMS), which includes data collection, data communication service, database operation service, and web service[19].

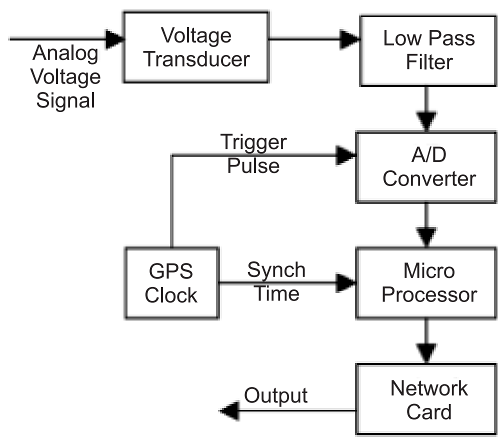

Figure 8: FDR Structure

A FDR unit is as shown in figure (8), consists of a voltage transducer, a low pass filter, an analog to digital (A/D) converter, a GPS receiver, a microprocessor, and the network communication modules.

The voltage transducer takes an analog voltage signal from an 110-V input and converts it to acceptable A/D levels, after filtering the high-frequency components using low pass filter, and the A/D converter converts the analog signal into digital data. A microprocessor is used to generate the sampling pulses synchronized to the 1 pps from the GPS receiver integrated into the FDR

Voltage stability monitoring: The important factor of power system is maintaining the voltage at permissible levels that keeps system stable, even after load demand changes and outages occurs. PMU-based devices provides an advantage to the system to keep its voltage stability limit,has ability to rapidly detect and diagnose voltage problems and develop remedial actions.

The electrical system is disturbed when there is a sudden loss of one or more generators, transmission lines, or loads. The voltage stability limit is the lowest voltage at which the power system will operate without blacking out loads. Steady state stability limit with power transfer curve is shown in Figure 9. [29].

Voltage stability assessment (VSA) program is a computer simulation tool to monitor and control voltage stability. Accurate voltage stability analysis results using VSA program depends on the accuracy of modeling the generation, load, and transmission facilities. Inaccurate VSA results may lead operators to make incorrect decisions, and increase the risk of voltage collapse. VSA program also depends on the state estimator to provide steady-state solution for further analysis.

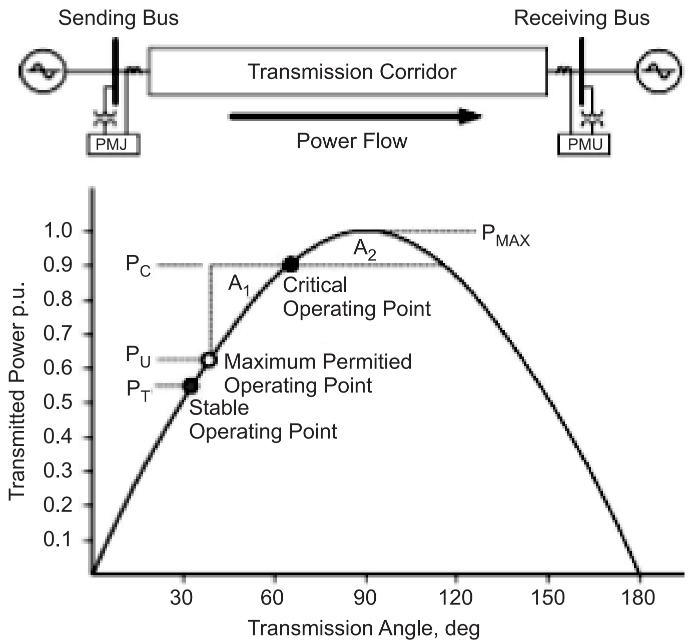

Figure 9: Steady state stability limit with power transfer curve

As the integration of renewable energy sources is increasing, the long-term voltage stability (LTVS) of fixed-speed induction generators (FSIGs) has become a major concern for distribution power networks as they will always consume reactive power. The loss of the stable equilibrium point will result in long-term voltage instability problems

Event detection, management, and restoration: An event is the condition that disturbs the normal operation of the power system like a tripping transmission line or tripping of generator occurs. Good event detection, management, and restoration allows system operators to understand the event, mitigate its effect, and restore service as quickly as possible. PMU data provide early indications of grid stress, including abnormal voltages, phase angles, frequencies, and power flows. PMU data provides high-resolution graphic displays which shows the operator how the system is reacting as the event occurs. As earlier operator understands the event, the more options are available for mitigating the event [21].

Event detection is performed with principal component analysis and a second order difference method with a hierarchical framework for the event notification strategy on a small-scale microgrid

There are various methods introduced in previous research work for event detection. The event detection algorithms classified as (1) the statistical algorithms; and (2) the signal processing algorithms.

The flowchart for real time event detection is shown in figure (10) which shows the steps to be followed for event detection using PMU data.

Islanding detection, management, and restoration: Islanding means separating a part of the power system from the larger power grid. Islands can occur when multiple lines are forced out of service thus isolating part of the grid. When islanding occurs data obtained from PMU helps to detect, monitor, and better management. Synchrophasor technology can quickly identify an island, allowing operators to synchronize the island to the larger power grid and restore connection to the rest of the grid.

Traditional methods used for islanding detection, when the installed capacity of distribution generations (DGs) had a negligible impact on system operation, were rate-of-change-of-frequency and vector shift that

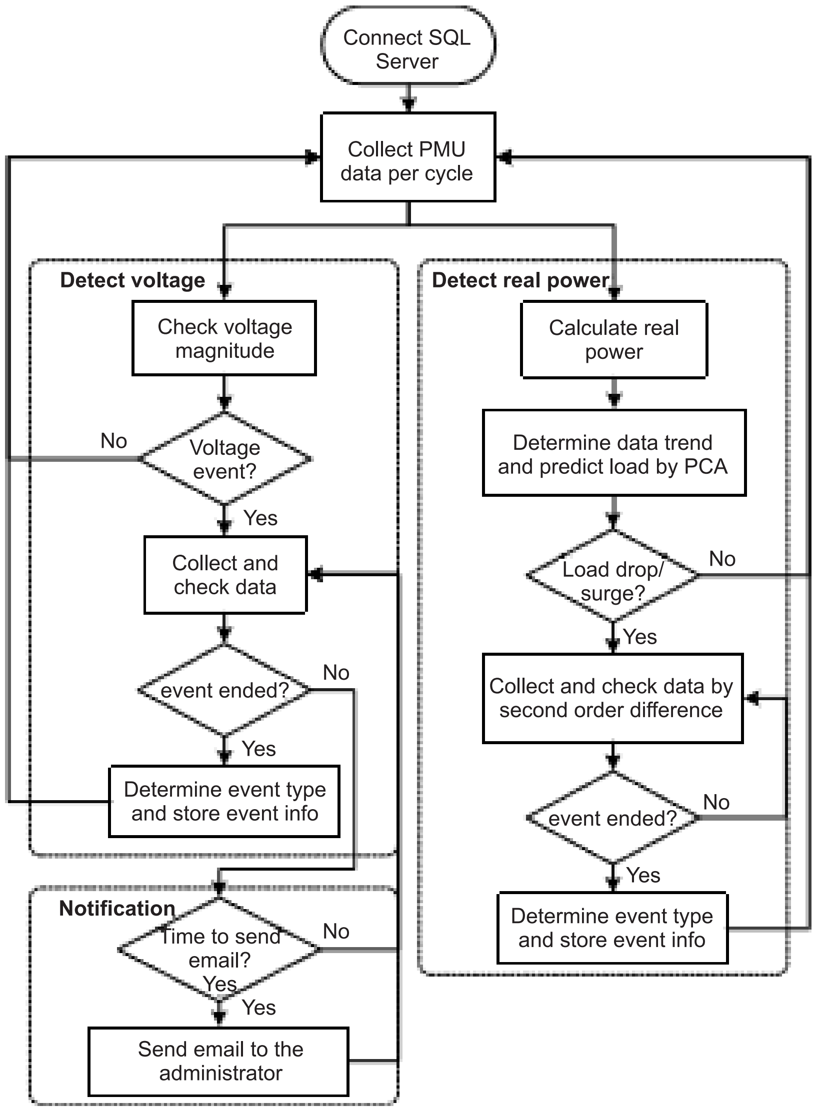

Figure 10: Flowchart for Real time Event Detection

were capable for processing local information; but as installed capacity of DGs are increasd, the distribution network starts to show some features similar to the transmission network, like bidirectional power flow within the distribution and upstream network, and back-synchronization after islanding, etc. Therefore, islanding detection for such a distribution network is no longer remains a local issue, and in that case conventional methods gives unreliable results for power systems .

So Systematic Principal Component Analysis (PCA) method is implemented for reliable islanding detection of power systems. To reduce the false alarms for time-varying process and for reliable result a Recursive PCA scheme is proposed. The PCA and RPCA [27] methods can be verified by detecting abnormal transients occurring in the utility network.

The flowchart for RPCA method is shown in Figure 11.

Wide area situational awareness: With the rapid development of PMUs from last few years it is attractive choice for wide-area monitoring.Wide area situational awareness is the capability for grid operators to detect and moitor parameters of the bulk electric power system beyond their service territory – across an entire interconnection with widely shared data. Wide area data allows all operators in an interconnection to have a common understanding of the problem of the overall electric grid, resulting in better solutions to emerging problems.

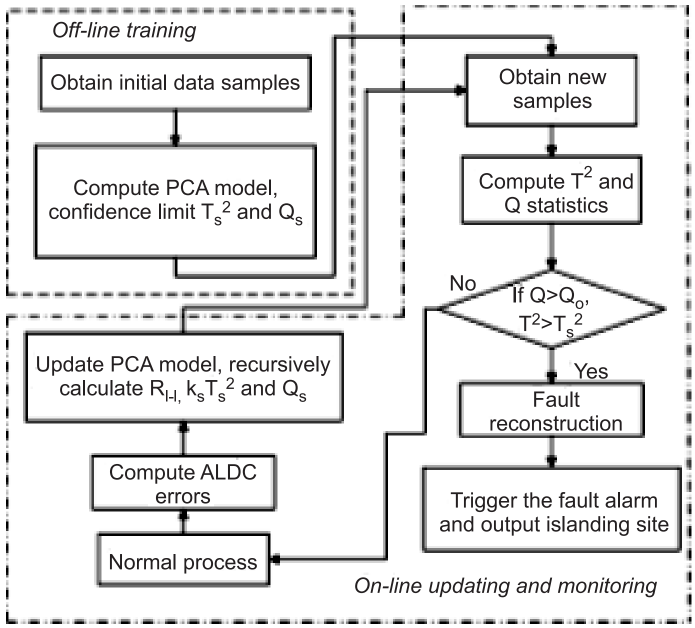

Figure 11: Flowchart of systematic RPCA monitoring

Wide area monitoring involves

i) Monitoring Distribution Operations

ii) Transmission and Distribution Grid Management

iii) Grid monitoring and control.

Current differential protection relays are widely used for the protection of power plant due to its different advantages like simplicity, sensitivity and stability for internal and external faults. This scheme has the feature of unit protection relays to protect large power transmission grids based on phasor measurement units. The principle of the protection scheme depends on comparison of positive sequence voltage magnitudes at each bus during fault conditions inside a system protection center to detect the nearest bus to the fault. Then the absolute differences of positive sequence current angles are compared for all lines connecting to this bus to detect the faulted line.

The new technique depends on synchronized phasor measurement technology with high speed communication system and time transfer GPS system. The simulation of the interconnecting system is applied on 500kV Egyptian network using Matlab Simulink. This technique can successfully distinguish between internal and external faults for interconnected lines. This protection scheme works as unit protection system for long transmission lines. The time of fault detection is estimated by 5 msec for all fault conditions and the relay is evaluated as a back up relay based on the communication speed for data transferring [29]

State estimation: State estimation plays a very important role in the real-time monitoring and control of the power system. State estimation processes redundant measurements and provides steady-state operating state for advanced Energy Management System (EMS) application programs (e.g. security analysis, economic dispatch, etc.[20]

The PMU measurements do not need a common reference: power system active power, reactive power flow measurements, voltage magnitude, etc., collected over a fairly long interval, to estimate the power system state. The process combines the measurements with the network model to find the variables of interest by solving nonlinear equations by numerical iterations. State estimation helps to observe the operation conditions of power system.

Traditional state estimation only uses measured voltage, current, real power and reactive power to understand the operating condition of the electric network. But it suffers from certain drawbacks such as it is technically more difficult and computationally more expensive to estimate the state of the system based on measured data and is slow solved at intervals of minutes.

Synchronized phasor measurement units (PMUs) which provide globally time synchronized phasor measurements with accuracy of one microsecond for bus voltages and line currents, also along with the improvement of computer computation ability, PMU overcome those technical difficulties. The use of PMUs improve state estimation in the following areas: bad data processing, state estimation accuracy, dynamic state estimation, and research requirement in state estimation.

Consider the placement of PMUs at buses G, J and S on the power system shown in Figure (12). The PMU at bus S measures the voltage phasor (amplitude and angle) and current phasors.[29]

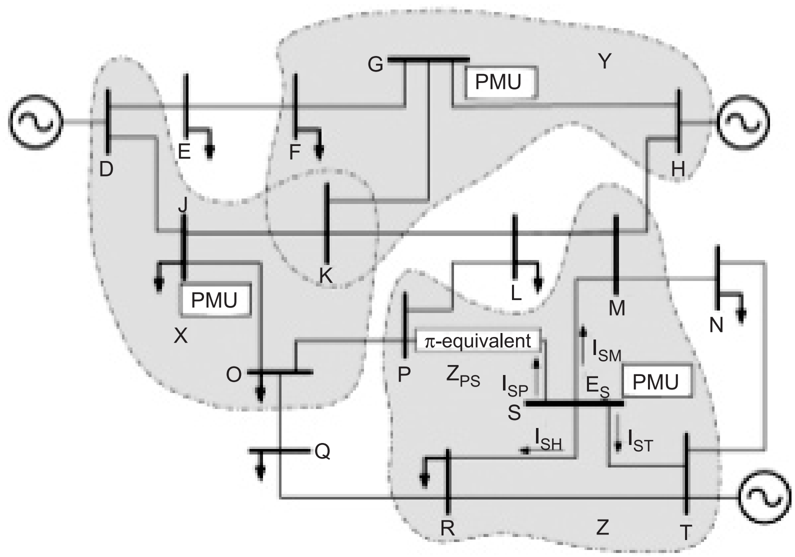

Figure 12: PMU coverage of the power system network.

With these phasor quantities and an accurate system model, the voltage phasors at the remote buses M, P, R, and T can be directly calculated with linear equations ("indirectly measured"). These buses are therefore referred as "observable" to bus S, the PMU location. Similarly the placement of PMUs at buses J and G define regions X and Y where the state is accurately measured either directly or indirectly. The remaining buses E, N, L and Q are not considered "measurable" with the current PMU placement. The number of adjacent buses that are not measurable (directly or via calculations with linear equations) defines the "depth of nonobservability" for a system with partial PMU coverage. It is optimum to place the PMUs in such a way to maintain a uniform depth of "non-observability." Power system state-vector determination from PMU measurements is the most precise method for obtaining real time static and dynamic information about the condition of the network

Renewable resource integration: Due to limitations of conventional sources renewable energy resources are being more aggressively developed at various distant locations on the grid. They are not only necessary near to load centers, but also at locations that are available optimally for the renewable energy resource—for example, where wind is more plentiful. These resources cannot be controlled by the grid operator and are not easily predictable or reliable. They may introduce new harmonics, which affect power quality. They may be located far from load centers, and may need long transmission systems [24].

Large-scale renewable generation plants are relatively new to the bulk electric system, so their plant characteristics and control algorithms need to be better understood in the context of the operation of the grid . Renewables can be challenging to manage in the grid due to the unpredictable and unreliable nature of their production. Synchrophasor systems are particularly useful for monitoring, modelling, managing, and integrating distributed generation and renewable energy into the bulk power system. PMU data show in high resolution how the renewable generation facilities affect the grid and respond to changes in grid conditions [11].

7. CONCLUSION

To meet the increasing demand of power, generating more power is not only the solution but the effective and efficient use of available power is necessary. So if we take precautions of grid health its efficiency can be increased with advanced monitoring and control using synchrophasor technology. PMU devices continuously monitoring all grid parameters not only locally but also centrally leads to take precautionary measures before any fault, damage and breakdown of supply.

This new efficient and intelligent technology can be implemented to improve many power quality issues We can use this technology for enhancing the real time voltage stability monitoring capability and many more issues to solve using PMU-based approach. Applications of synchrophasor technology for future smart and intelligent grid we dicussed here. This real time monitoring synchrophasor technology can easily solve the power quality problems and makes better tomorrow.

It is a bright future of power system that connects all supply, grid, and demand elements through an intelligent and fast communication network. Though PMU technology was limited to transmission system applications due to its high initial cost, but, recent developments in the electronics field have decreased the cost of PMU components and now it is used in distribution sector as microsynchrophasor technology.

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