JAIPUR ENGINEERING COLLEGE AND RESEARCH CENTRE	Jaipur Engineering college and research centre, Shri Ram ki Nangal, via Sitapura RIICO Jaipur- 302 022.	Academic year- 2020-21

DEPARTMENT OF ELECTRICAL ENGINEERING

Syllabus
Power System Protection

III Year - VI Semester: B. Tech. (Electrical Engineering)

1. Introduction: Objective, scope and outcome of the course.

2. Introduction and Components of a Protection System: Principles of Power System Protection, Relays, Instrument transformers, Circuit Breakers.

3. Faults and Over-Current Protection: Review of Fault Analysis, Sequence Networks. Introduction to over current Protection and over current relay co-ordination.

4. Equipment Protection Schemes: Directional, Distance, Differential protection. Transformer and Generator protection. Bus bar Protection, Bus Bar arrangement schemes.

5. Digital Protection: Computer-aided protection, Fourier analysis and estimation of Phasors from DFT. Sampling, aliasing issues.

6. Modeling and Simulation of Protection Schemes: CT/PT modeling and standards, Simulation of transients using Electro-Magnetic Transients (EMT) programs. Relay Testing.

7. System Protection: Effect of Power Swings on Distance Relaying. System Protection Schemes. Under-frequency, under-voltage and df/dt relays, Out-of- step protection, Synchro-phasors, Phasor Measurement Units and Wide-Area Measurement Systems (WAMS). Application of WAMS for improving protection systems.

Unit-VII

System protection:

Effect of Power Swings on Distance Relay.

The concept of power swings that the post fault power swings may approach the relay characteristics. This can lead to nuisance tripping of distance relays which can sacrifice the system security.

Analysis of Two Area System:

Power swings refer to oscillation in active and reactive power flows on a transmission line consequent to a large disturbance like a fault. The oscillation in the apparent power and bus voltages is seen by the relay as an impedance swing on the R-X plane. If the impedance trajectory enters a relay zone and if stays there for sufficiently long time, then the relay will issue a trip decision on power swing. Tripping on power swings is not desirable. We now investigate this phenomenon and then discuss remedial measures.

Let us consider a simple two machines system connected by a transmission line of impedance Z_L as shown in fig 1. E_S and E_R are the generator voltages at two ends and we assume that the system is purely reactive.

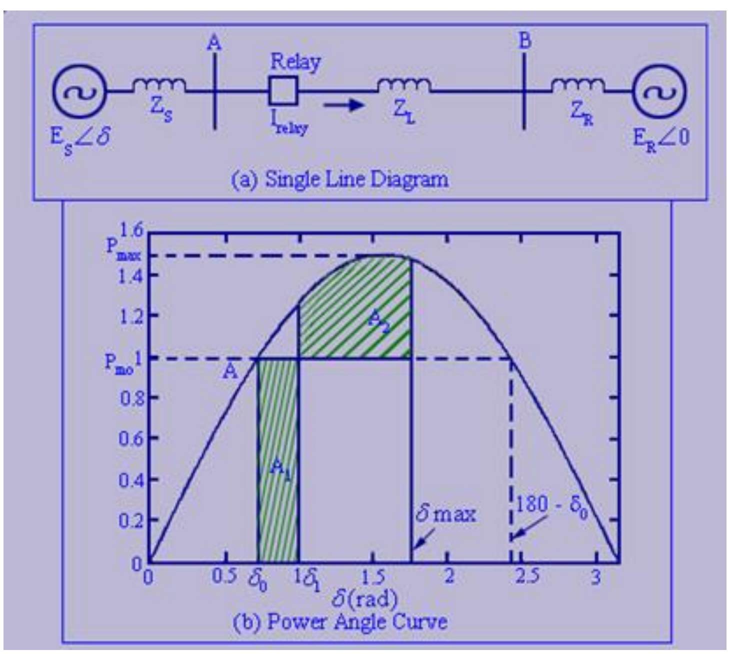

Fig.1: Two Machine System

The voltage E_S leads E_R by an angle δ so that power flows from A to B during steady state. The relay under consideration is located at bus A end. The power angle curve is shown in fig. 1. The system is operating at initial steady operating point A with P_{mo} as output power and δ_0 as initial rotor angle.

From the power angle curve, initial rotor angle, δ_0 is given by:

$$\delta_0 = \sin^{-1}\left(\frac{P_{m0}}{P_{max}}\right) \quad (1)$$

Now, suppose, that a self clearing transient three phase short circuit fault occurs on the line. During the fault, the electrical output power P_e drops to zero. The resulting rotor acceleration advances rotor angle to δ_1. After a time interval t_{cr}, corresponding to angle δ_1, the fault is cleared and the operating point jumps back to the sinusoidal curve. As per equal area criteria, the rotor will swing up to maximum rotor angle δ_{max}, such that,

Accelerating Area (A_1) = Decelerating Area (A_2)

Rotor angle δ_1 corresponding to fault clearing time t_{cr} can be computed by swing equation,

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{mo} - P_e = P_a \quad (2)$$

where H is the equivalent rotor angle inertia. During fault, P_e = 0, hence,

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{mo} \quad (3)$$

On integrating both the sides with respect to variable t,

$$\frac{d\delta}{dt} = \frac{\omega_s P_{mo}}{2H}(t - t_0) \quad (4)$$

Recall that prior to fault, δ_0 is a stationary point. Hence, the initial condition of $\frac{d\delta}{dt}$ is specified as follows:

$$\left.\frac{d\delta}{dt}\right|_{t=t_0} = 0$$

Analysis of Two Area System (contd..)

Integrating equation (4).,

$$\delta_1 = \frac{\omega_s P_{mo}}{4H}(t_{cr}^2) + \delta_0 \qquad (5)$$

Thus, accelerating area A_1 is given by,

$$A_1 = \int_{\delta 0}^{\delta 1} P_{mo} d\delta = P_{mo}(\delta_1 - \delta_0) \qquad (6)$$

Substituting equation (5) in equation (6),

$$A_1 = \frac{\omega_s P_{m0}^2 (t_{cr}^2)}{4H} \qquad (7)$$

Similarly, decelerating area, A_2, can be calculated as follows.

$$A_2 = \int_{\delta 1}^{\delta \max} P_{\max} \sin\delta . d\delta - P_{m0}(\delta_{\max} - \delta_1) = P_{\max}(\cos\delta_1 - \cos\delta_{\max}) - P_{mo}(\delta_{\max} - \delta_1) \qquad (8)$$

Since for a stable swing, $A_1 = A_2$

$$P_{mo}(\delta_1-\delta_0)=P_{\max}(\cos\delta_1-\cos\delta_{\max})-P_{mo}(\delta_{\max}-\delta_1) \quad (9)$$

i.e. $$\cos\delta_{\max}=\cos\delta_1-\frac{P_{m0}}{P_{\max}}(\delta_{\max}-\delta_0) \quad (10)$$

Since, δ_0 is a function of P_{mo} from equation (1) and δ_1 is function of P_{mo} as well as t_{cr} from equation (5), it follows from equation (10) that $\delta_{\max}$ depends on P_{mo} and t_{cr}.

i.e.

$$\delta_{\max}=f(P_{m0},t_{cr}) \quad (11)$$

Analysis of Two Area System (contd..)
The variation of $\delta_{\max}$ versus P_{mo} for different values of t_{cr} is shown in fig.2.

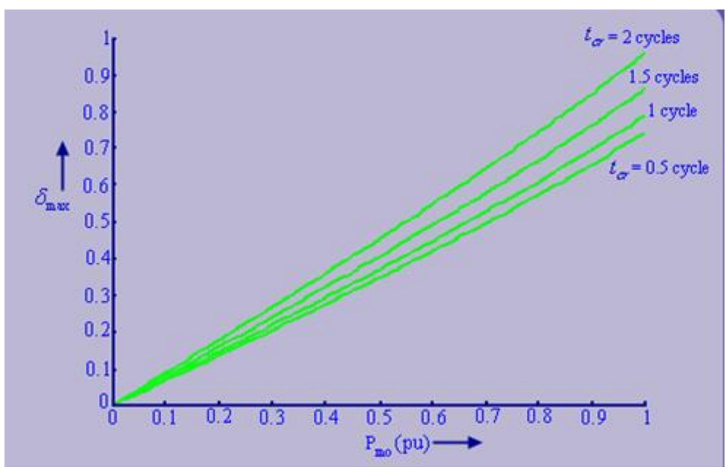

Fig.2: plot of $\delta_{\max}$ versus P_{mo} for different value of t_{cr}

Now that we have reviewed, the rotor angle dynamics, we proceed to discuss the relay's perception of dynamical system.

Determination of power swing locus

A distance relay may classify power swing as a phase fault if the impedance trajectory enters operating characteristic of the relay. We will now derive the apparent impedance seen by the relay R on the R-X plane. Again consider simple two machine system connected by a transmission line of impedance Z_L as shown in fig 24.1(a). For the sake of convenience machine B is treated as a reference and it's angle is set to zero.

$$I_{relay} = \frac{E_S\angle\delta - E_R}{Z_T} \qquad (12)$$

Where, $Z_T = Z_S + Z_L + Z_R$ (13)

Determination of power swing locus (contd..)

$$Z_{seen}(relay) = \frac{V_{relay}}{I_{relay}} = \frac{E_S\angle\delta - I_{relay}Z_S}{I_{relay}}$$

Now, the impedance seen by relay is given by the following equation,

$$= -Z_S + \left(\frac{E_S\angle\delta}{E_S\angle\delta - E_R}\right)Z_T \qquad (14)$$

$$= -Z_S + Z_T\left(\frac{1}{1-\frac{E_R}{E_S}\angle -\delta}\right)$$

Let us define $k = \left|\frac{E_S}{E_R}\right|$. Assuming for simplicity, both the voltages as equal to 1pu, i.e. k = 1. Then,

$$Z_{seen}(relay) = -Z_S + Z_T\left(\frac{1}{1-\cos\delta + j\sin\delta}\right) = -Z_S + \frac{Z_T}{2}\left(\frac{1}{\sin^2\frac{\delta}{2} + j\sin\frac{\delta}{2}\cos\frac{\delta}{2}}\right)$$

$$= -Z_S + \frac{Z_T}{2\sin\frac{\delta}{2}}(\sin\frac{\delta}{2} - j\cos\frac{\delta}{2})$$

$$= \underbrace{-Z_S + \frac{Z_T}{2}}_{\text{a constant offset}} - \underbrace{j\frac{Z_T}{2}\cot\frac{\delta}{2}}_{\text{perpendicular line segment}}$$

We have discussed power swings for a 2-machine system. Evaluation of power swings on a multi machine system requires usage of transient stability program. By using transient stability program, during post fault the relay end node voltage and line currents can be monitored.

Under Voltage Protection Working Principle:

Under voltage fault protection is used to protect the alternator/generator/transformer winding from low voltage operation. Under voltage protection sense the phase to phase voltage of the generator/transformer using instrument transformer (Potential transformer). When the voltage drops below the rated voltage typically 85% (stage 2)-90% (stage 1) the under voltage protection will be activated.

Principle of Under voltage protection:

Three number of potential transformer normally installed in the generator LAVT panel (lighting arrester voltage transformer). They detect the voltage across the generator in real time. When the voltage across the generator winding drops the simultaneous voltage drop occurs in the PT output also. The reduced or dropped voltage activates the power system alarm or trip circuit.

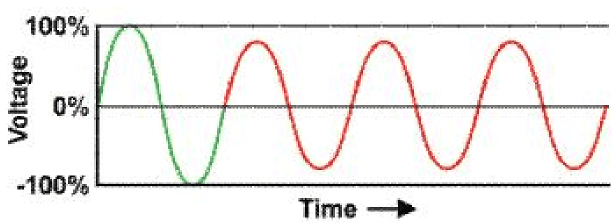

Fig.3: Under Voltage wave form

The output from the generator's LAVT potential transformer will be given to the under voltage coil typically 110 Volts relay coil. In principle of U/V coil, which do not trip the circuit breaker when the voltage across the PT is high. When the voltage drops the preset value, the voltage coil operates the circuit breaker.

The generator under voltage protection consists of two stage tripping. Stage 1 trip command is given to grid circuit breaker and stage 2 trip command is given to generator circuit breaker. Most of the time in synchronous generator, the under voltage fault occurs from the grid due to earth fault and line short circuit. That's why, the first stage will be given to grid circuit breaker.

At that same time, the under voltage fault occurs due to failed excitation, diode failure, under frequency or turbine low speed, failed PT fuse etc.

Under voltage relay setting:

Stage1: 90% of the rated voltage trip command to grid circuit breaker.

Stage2: 85% of the rated voltage, trip command to Generator circuit breaker.

Protection df/dt working Principle:

Rate of Change of Protection is used for load shedding in situations where sudden loss of generating capacity on a system will be accompanied by a decrease in system frequency. In such a situation of load Generation mismatch, the system frequency tends to fall. The df/dt relay can control the circuit breakers and allow feeders to be disconnected from the network, one by one. As a defense mechanism, df/dt relays are particularly effective in arresting the frequency collapse of a grid in the event of sudden loss of major generation. This is because by measuring the frequency decay rate, the corrective action can be initiated much ahead of the time when frequency of the synchronous interconnection would have actually dipped to a point at which generator under-frequency relays or unit auxiliaries would trip / operate leading to a complete system shutdown.

Principle of rate of change of frequency relay:

Whenever the load increases in the generator the frequency falls down. Consider two parallel generators (example 1MW, 1.5MW), both is running with the grid and the auxiliary load of the two generator is 1.1 MW. Here, if the grid also failed and 1.5 MW generator also tripped. Therefore, all the auxiliary loads will fall on the single generator and the generator frequency drops as the load increases. Here, the auxiliary loads should to be properly shaded to avoid the tripping of the remaining generator. This action will be done by df/dt relays.

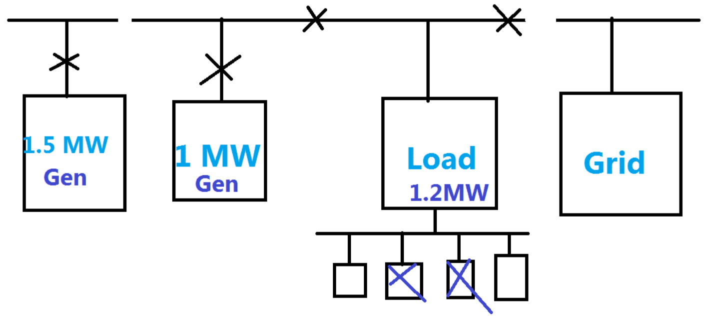

Fig.4: Rate of change of frequency protection for alternator.

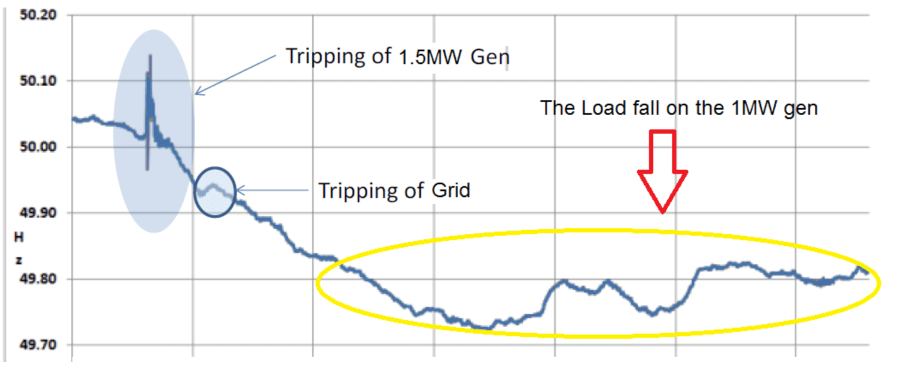

Fig.5: Rate of Change of Frequency (ROCOF) Protection

The rate of change of frequency measurement is based on two successive frequency measurements and the time difference between the frequency measurements. The measured frequency value for df/dt calculation is averaged over three cycles. The accuracy of df/dt measurement depends on the accuracy of frequency measurements. This frequency measurement is carried out through time measurement of a cycle (time between two zero crossing).

Under Frequency Protection Working Principle:

Under Frequency Protection is used to protect the transformer/generator/alternator when the frequency drops below the operating frequency. It is a backup protection for over fluxing (V/F) protection. Under frequency occurs due to turbine low speed, AVR failure, diode failure, grid frequency fluctuation etc. The generator can tolerate moderate under frequency operation provided voltage is within an acceptable limit. Under frequency causes over fluxing in the generator/transformer, speed drops in the motors, output voltage dropping etc. The abnormal under frequency on the machine may be due to improper speed control adjustment or disoperation of the speed controller.

The generator under frequency protection consists of two stage tripping. Stage 1 trip command is given to grid circuit breaker and stage 2 trip command is given to generator circuit breaker.

Fig.6: Under frequency protection Relay

Under Frequency relay setting:

Stage1: 48.5 % of the rated frequency & trip command to grid circuit breaker.

Stage2: 47.5 % of the rated frequency, trip command to Generator circuit breaker.

Out-of-step protection philosophy:

The philosophy of out-of-step relaying is simple and straightforward avoid tripping of any power system element during stable swings. Protect the power system during unstable or out-of-step conditions. When two areas of a power system, or two interconnected systems, lose synchronism, the areas must be separated from each other quickly and automatically in order to avoid equipment damage and shutdown of major portions of the power system. Uncontrolled tripping of circuit breakers during an OOS (Out-of-Step) condition could cause equipment damage and pose a safety concern for utility personnel. Therefore, a controlled tripping of certain power system elements is necessary in order to prevent equipment damage, and widespread power outages, and minimize the effects of the disturbance.

Out-of-Step Detection Methods and Types of Schemes Out-of-step protection functions detect stable power swings and out-of-step conditions by using the fact that the voltage/current variation during a power swing is gradual while it is virtually a step change during a fault. Both faults and power swings may cause the measured apparent positive-sequence impedance to enter into the operating characteristic of a distance relay element. A short circuit is an electromagnetic transient process with a short time constant. The apparent impedance moves from the pre fault value to a fault value in a very short time, a few milliseconds.

On the other hand, a power swing is an electromechanical transient process with a time constant much longer than that of a fault. The rate of change of the positive-sequence impedance is much slower during a power swing or OOS condition than during a fault and it depends on the slip frequency of the OOS.

For example, if the frequency of the electromechanical oscillation is about 1 Hz and the impedance excursion required to penetrate the relay characteristic takes about half a period (a change in δ of 180°), the impedance change occurs in about 0.5 seconds. When δ approaches 180° during an OOS, the measured impedance falls into the operating characteristic of a distance relay for a particular transmission line. The impedance measurement by itself cannot be used to distinguish an OOS condition from a phase fault.

The fundamental method for discriminating between faults and power swings is to track the rate of change of measured apparent impedance. The difference in the rate of change of the impedance has been traditionally used to detect an OOS condition and then block the operation of distance protection elements before the impedance enters the protective relay operating characteristics.

Actual implementation of measuring the impedance rate of change is normally performed though the use of two impedance measurement elements together with a timing device. If the measured impedance stays between the two impedance measurement elements for a predetermined time, then an OOS is declared and an out of-step blocking signal is issued to block the distance relay element operation. Impedance measurement elements with different shapes have been used over the time.

Phasor Measurement Units for Power Systems

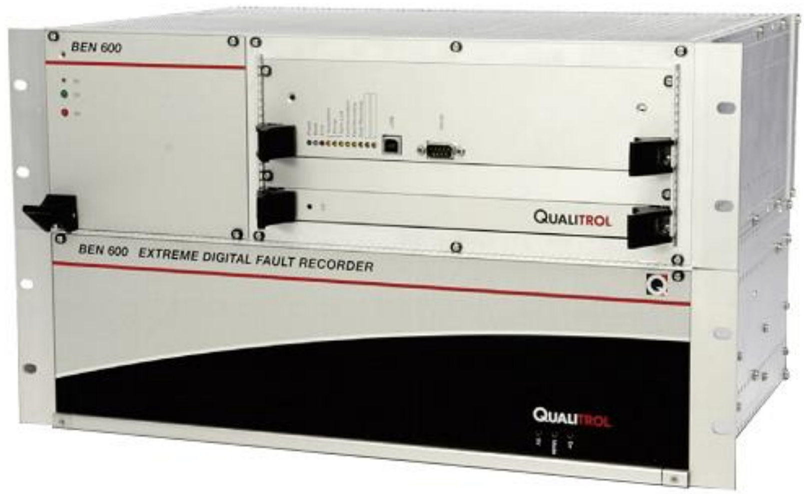

Fig.7: Phasor Measurement Units for Power Systems.

Phasor Measurement Units for Power Systems

Existing systems in power grid such as Energy Management System (EMS) and Supervisory Control and Data Acquisition system (SCADA) have the capability to provide only steady state view of power system with high data flow latency. In Supervisory Control and Data Acquisition system (SCADA) it was not possible to measure the phase angles of bus voltages of power system network in real time, due to technical difficulties in synchronizing measurements from distant locations.

Measurements were obtained at slower rates; it was not possible to get dynamic behavior of power system as well as limited situational awareness was conveyed to the operator. Advent of Phasor Measurement Units (PMUs) alleviated this problem by synchronizing voltage and current waveforms at widely dispersed locations with respect to global positioning system. PMU is superior to SCADA with respect to speed, performance and reliability.

As per definition of IEEE, PMU is defined as device that produces synchronized phasor, frequency and rate of change of frequency estimates from voltage and/or current signals and time synchronizing signal. PMUs provide real time synchronized measurements in power system with better than one microsecond synchronization accuracy, which is obtained by Global Positioning System (GPS) signals. PMUs are situated in power system substations, and provide measurement of time stamped positive sequence voltages and currents of all monitored buses and feeders. Data from various substations are collected at suitable site, and by aligning time stamps of measurements a coherent picture of the state power system is created. PMUs are time synchronized, high speed measurement units that monitor current and voltage waveforms (sinusoids) in the grid, convert them into a phasor representation through high end computation and securely transmit the same to centralized server.

PMU technology is well suited to track grid dynamics in real time, the data obtained can be used for wide area monitoring, stability monitoring, dynamic system ratings and improvement in state estimation, protection and control. It enables utilities to proactively plan energy delivery and prevent failures.

Fundamentals of PMU's

PMU technology provides phasor information (both magnitude and phase angle) in real time.

Advantage of referring phase angle to global reference time is helpful in capturing wide area snapshot of power system. Effective utilization of this technology is useful in mitigating blackouts and learning real time behavior of power system.

A phasor is a complex number that represents both the magnitude and phase angle of the sine waves found in AC system. The waveform can be represented by:

Where ω is the frequency of the signal in radians per second, and φ is the phase angle in radians. xm is the peak amplitude of the signal. The Root Mean Square (RMS) value of the input signal is (xm /√2).

Positive phase angles are measured in a counter clockwise direction from the real axis. Since the frequency of the sinusoidal is implicit in the phasor definition, it is clear that all phasors which are included in a single phasor diagram must have the same frequency. Phasor representation of the sinusoidal implies that the signal remains stationary at all times, leading to a constant phasor representation. These concepts must be modified when practical phasor measurements are to be carried out when the input signals are not constant, and their frequency may be a variable.

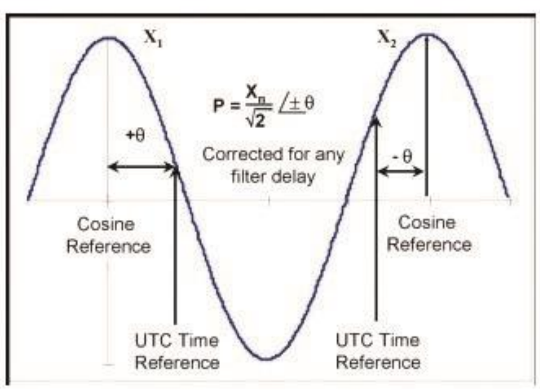

Figure 8: Phasor representation.

Wide Area Measurement Systems

PMU installation is a part of wide area monitoring system network consisting of locating of PMUs throughout the electricity grid at strategic locations in order to cover the entire grid. A Phasor data concentrator at central location collects information from PMUs, and passes that to supervisory control and data acquisition system after time aligning the same.

A complete WAMS network needs rapid data transfer within frequency of sampling of phasor data samples of phasor measurements at PMU are time stamped at each location. GPS installed at PMU location provide accurate time along with time synchronization among different PMUs. PMU components: The main components of a PMU are data acquisition module, communication module and GPS signal receiver.

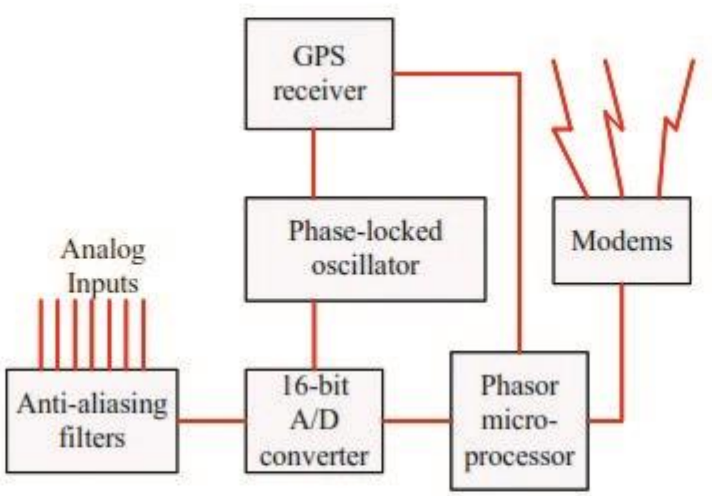

Figure 9: Block diagram representation of PMU.

The analog inputs to device are currents and voltages obtained from the secondary windings of the current and voltage transformers located in substation. All three phase currents and voltages are used so that positive-sequence measurement can be carried out. The current and voltage signals are converted to voltages with appropriate shunts or instrument transformers to match with the requirements of the analog to digital converters.

The sampling rate chosen for the sampling process dictates the frequency response of the anti-aliasing filters. Anti aliasing filters ensure that all the analog signals have the same phase shift and attenuation, thus assuring that the phase angle differences and relative magnitudes of the different signals are unchanged.

The GPS system is used in determining the coordinates of the receiver, although for the PMUs the signal, which is most important is the one pulse per-second. This pulse as received by any receiver on earth is coincident with all other received pulses to within 1 microsecond.

Architecture of Wide Area Measurement Systems

In power grid, the phasor data is used from PMUs placed at different locations. WAMSs are advanced measurement technology to collect information. WAMS perform the function of obtaining data and extracting value from that data.

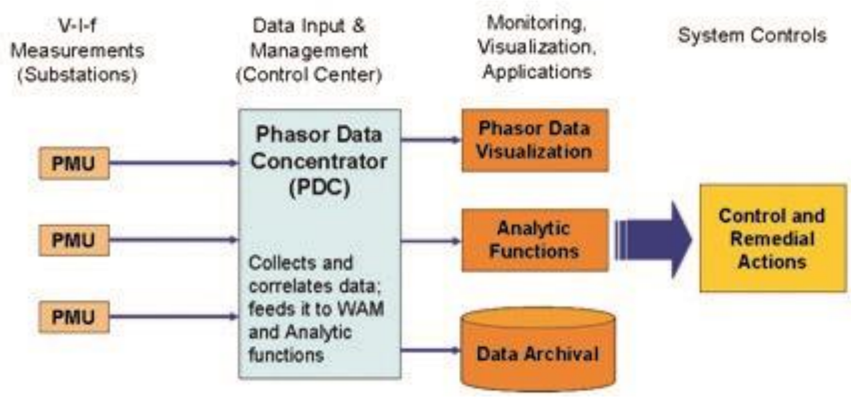

Figure 10: Integration of PMU data.

PMUs are located at substations, and provide measurements of time-stamped positive-sequence voltages and currents of all monitored buses and feeders (as well as frequency and rate of change of frequency). The measurements are stored in local data storage devices, which can be accessed from remote locations for diagnostic purposes.

The local storage capacity is necessarily limited, and the stored data belonging to an interesting power system event must be flagged for permanent storage – so that it is not overwritten when the local storage capacity is exhausted. The phasor data is also available for real time applications in a steady stream as soon as the measurements are made.

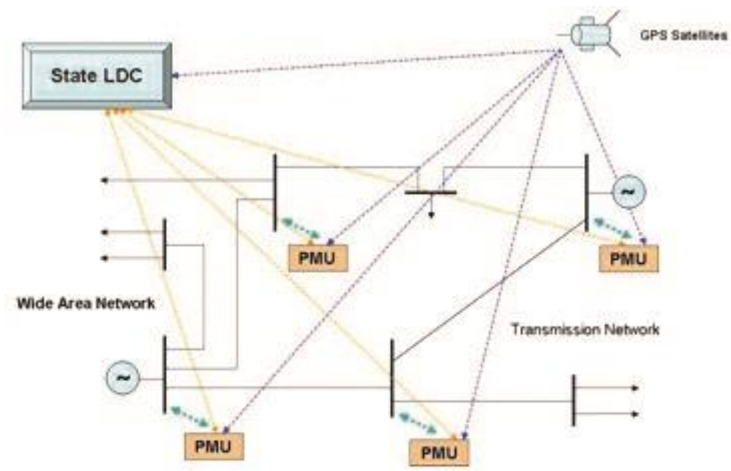

Figure 11 : WAMS architecture.

The devices at next level of the hierarchy are commonly known as Phasor Data Concentrators. Typical function of a PDC is to gather data from several PMUs, reject bad data, align the time-stamps and create a coherent record of simultaneously recorded data from a wider part of the power system.

There are local storage facilities in the PDCs, as well as application functions, which need the PMU data available at the PDC. This can be made available by the PDCs to the local applications in real time.

Motivation for Synchronized Measurements (Synchrophasors)

When a Phasor measurement is time stamped against GPS universal time it is called synchrophasor. This allows measurements taken by PMUs in different locations or by different owners to be synchronized and time aligned, then combined to provide a precise, comprehensive view of an entire region or interconnection. A synchrophasor system is wide deployment of PMUs and dedicated high speed communication to collect and deliver synchronized high speed grid condition data –along with analytics and other advanced online dynamic security assessment and control application. Synchrophasors enable much better indication of grid state, and are used to trigger corrective actions to maintain reliability of the network.

Need of Synchrophasor : – i) To obtain high resolution data ii) The data from different locations are not captured at precisely the same time, iii) Voltage, active power and reactive power normally do not change abruptly, unless there is a large disturbance nearby, iv) System monitoring is crucial during disturbance and transients, v) To capture dynamics of the system faster synchronized data is required.

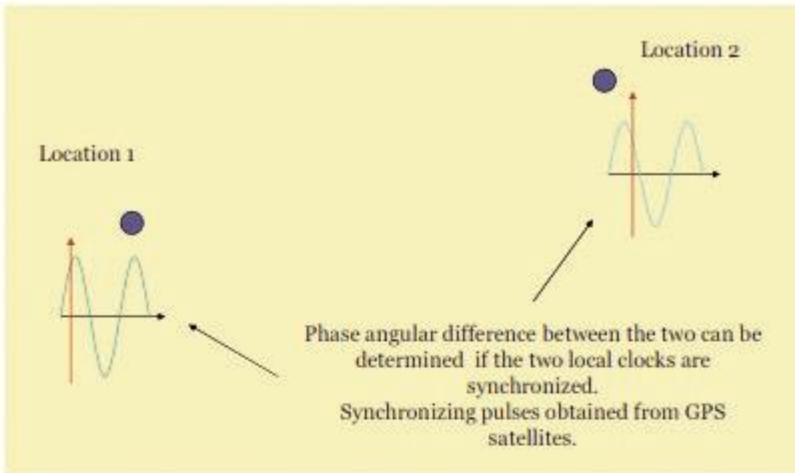

Figure 12 : Synchronization of sample at different locations

Synchrophasors in Indian Power Grid

Indian power grid is one of the largest power grids in the world. Operation of Indian power grid is monitored and co-ordinate through national load dispatch centre and five regional load dispatch centres and state load dispatch centres. To complement visualization and enhance the situational awareness of large Indian power network to grid operators in control centre synchrophasor projects are deployed. Synchrophasors enable superior indication of grid stress and are often used to trigger corrective actions to maintain reliability.

The first PMU pilot project was set up in northern region in the year 2010, which consists of PMUs along with GPS installed at selected 9 substations in the grid. A Phasor Data Concentrator and other associated equipment are placed at Northern Regional Load Dispatch Centre (NRLDC) located at New Delhi.

Considering the need for wide area measurement for Indian power grid ,installation of PMUs on substations at 400kV level and above in the State & Central grids, all generating stations at 220kV level and above HVDC terminals, important inter-regional connection points, inter-national connection points etc. are being taken up. This will facilitate a Unified Real-time Dynamic State Measurements (URTDSM) towards improved system operation.

PMU application

- Post disturbance analysis
- Stability monitoring
- Thermal overload monitoring
- Power system restoration

- State estimation
- Real time control
- Adaptive protection

All the regional grids in India are interconnected, to assess the power system the angular separations over wide area are one of the key indicators. The larger the phase angle, difference between source and sink, greater is power flow between those points. Greater phase angle differences imply large stress across the interface and large stress could move the grid closer to instability. Angular separation provides insights into the healthiness of synchronous interconnection. Relative phase angles across the system at the starting time of disturbance provide information about initial system loading conditions. It also provides indication of how system reacted to disturbance. In case of oscillations, relative phase angles can be analyzed to understand the nature and shape of oscillations – and to know how different parts of system oscillate relative to each other.

Challenges in PMU implementation

- Selecting suitable location for PMU placement
- Integration of synchrophasor technology with SCADA
- Communication delays
- Low frequency oscillation monitoring
- Distorted power system waveforms makes prediction difficult
- High computational requirement
- Developing tools for in depth post facto analysis.

PMU provide innovative solution to traditional utility problems. It also facilitates improved protection and effective control of power system network.