CHAPTER II

THEORETICAL BACKGROUND OF PMU AND VOLTAGE STABILITY

2.1. INTRODUCTION

The fast growth of power networks in order to fulfil the ever increasing load demands has led to requirement of robust, reliable and safe monitoring along with control techniques based on the concept of WAMS. PMU is the key element in WAMS which provides positive sequence voltage and current measurements across the network within a microsecond. It has been made possible by the accessibility of GPS and the sampled data processing techniques established for the computer relaying applications. The positive sequence measurements provide the most direct access to the state of power network at any given instant. There are many applications of this device which has been discussed in the literature.

This chapter contributes the basic background theory of the PMU such as the PMU technology, fundamentals of PMU, synchrophasor definition and measurement. The comparison between PMU and SCADA is also discussed to show the advantages of the PMU over the SCADA system. Besides, the various applications of PMU discussed in this chapter shows its real time applications for safe, stable and reliable operation of the power system. This chapter also discusses the basic concept of voltage stability which has been proposed in this work as a voltage stability predictor index (VSPI).

2.2. PHASOR MEASUREMENT UNIT TECHNOLOGY

PMU was developed in 1980s and the first product appeared in the market in the early 1990s, shown in Figure 2.1. PMU is the time synchronized tool used by power engineers and system operators for the WAMS applications. PMU measures the time synchronized voltage and current phasors in real time with the high precision. It helps to provide the wide area snapshot of the power system. PMUs are equipped with GPS system that allow for synchronization of many readings taken at distant points. Synchrophasor based measurements support the real time measurements of the voltage and the current phasors at

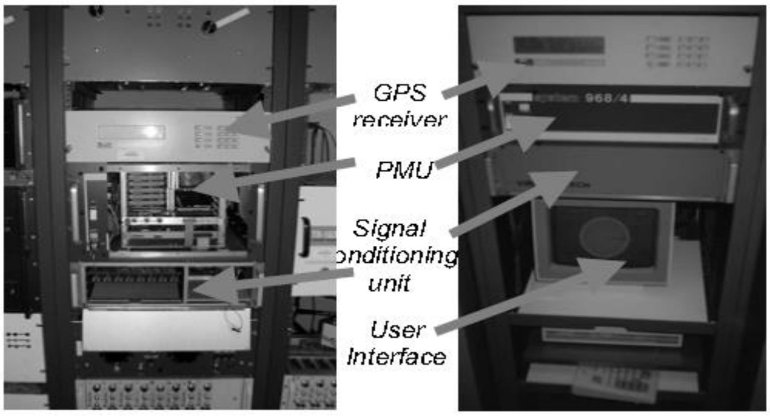


Figure 2.1 First PMU developed at Virginia Tech in 1980s

observable system buses. The voltage phasor contain sufficient information to detect the voltage stability margin directly from their measurements. It also calculates power from the measurements (MW/MVAR) and frequency. The measurements are reported at a rate of 20-60 times a second. The effective application of this technology is very useful in mitigating blackouts and learning the real time behavior of the power network.

The PMU architecture is shown in Figure 2.2, which is based on the configuration of first PMUs built at Virginia Tech. Here, the voltage or current in analog form is given to A/D converter followed by anti-aliasing filter, these digital values are then given to phasor micro-processor for calculation of voltage or current phasors. The analog inputs (voltages and currents) are obtained from secondary windings of the voltage and current transformers. GPS receiver sends signal to phasor micro-processor so that synchronized phasors are the output of Modem. Phase-Locked Oscillator is used here to check the frequency of voltage or current phasor and lock the frequency for Discrete Fourier Transform (DFT) calculation. Finally, the PMU output is the time stamped measurement to be transferred over the communication links through the modem to a higher level in the measurement hierarchy.

2.3. FUNDAMENTALS OF PMUs

2.3.1. Phasor representation of a sinusoidal signal

A pure sinusoidal waveform can be represented by a unique complex number known as a phasor. Consider a pure sinusoidal quantity

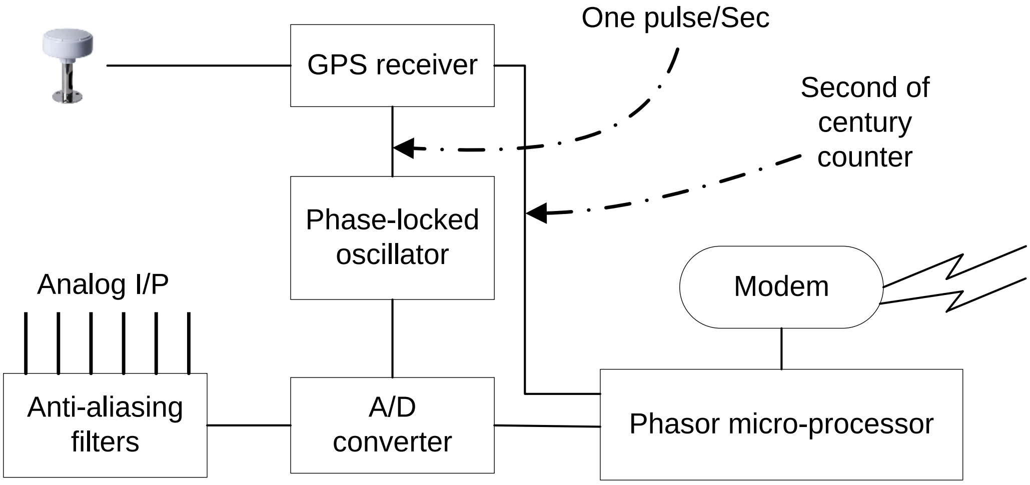


Figure 2.2 Architecture of PMU

$$\psi(t) = \Psi_m \cos(\omega_s t + \phi) \tag{2.1}$$

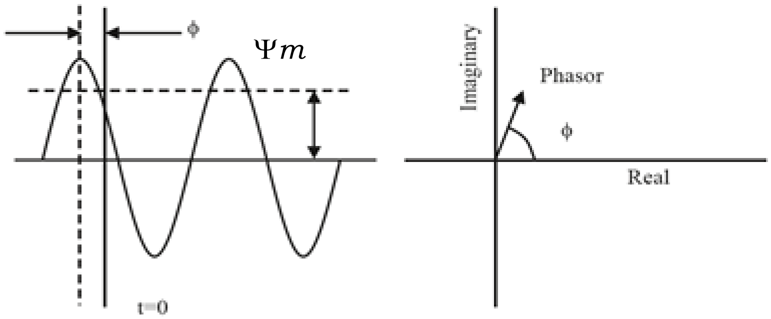
where, ω_s is the signal frequency in radians per second, ϕ is the phase angle in radians. The phasor representation of this sinusoidal is given by

$$\psi(t) = \frac{\Psi_m}{\sqrt{2}} e^{j\phi} = \frac{\Psi_m}{\sqrt{2}} (\cos\phi + j\sin\phi) \tag{2.2}$$

The magnitude of the phasor is the root mean square (rms) value of the sinusoid ($\Psi_m/\sqrt{2}$). The sinusoidal signal and its phasor representation given by Equations (2.1) and (2.2) are shown in Figure 2.3. As the frequency of the sinusoidal is implicit in the phasor definition, the positive phase angles are measured in a counter clockwise direction from the real axis. Therefore, all the 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.

2.3.2. Phasor Measurement Concepts

While a constant phasor indicates a stationary sinusoidal waveform, in practice it is necessary to deal with phasor measurements which consider the input signal over a finite data window. In many PMUs the data window in use is one period of the fundamental frequency of the input signal. If power system



(a) (b)

Figure 2.3 Phasor representation of a sinusoidal signal (a) Sinusoidal signal (b) Phasor representation.

frequency is not equal to its nominal value (it is seldom), the PMU uses a frequency tracking step and thus estimates the period of the fundamental frequency component before the phasor is estimated. It is clear that the input signal may have harmonic or non-harmonic components. The task of the PMU is to separate the fundamental frequency component and find its phasor representation. The most common technique for determining the phasor representation of an input signal is to use data samples taken from the waveform, and apply the Discrete Fourier Transform (DFT) to compute the phasor. Since sampled data are used to represent the input signal, it is essential that antialiasing filters be applied to the signal before data samples are taken. The antialiasing filters are analog devices which limit the bandwidth of the pass band to less than half the data sampling frequency.

If ψ_i (i=0, 1, 2, 3,...., N-1) is the N samples of the input signal taken over one period, then the phasor representation is given by [86]

$$\Psi = \frac{\sqrt{2}}{N}\sum_{i=0}^{N-1}\psi_i e^{-ji\frac{2\pi}{N}} \tag{2.3}$$

Note that for real input signals, the components of the signal at a frequency w_s, appear in the DFT at $\pm w_s$ and are complex conjugates of each other. They can be combined, giving a factor of 2 in front of the summation sign in Equation (2.3). The peak value of the fundamental frequency thus obtained is then converted to rms value by dividing by √2. The DFT calculation eliminates the harmonics of the input signal. However, the non-harmonic signals and any other random noise present in the input signal leads to an error in estimation of the phasor.

2.3.3. Synchrophasor Definition and Measurements

'Synchrophasor' is a term used to describe a phasor which has been estimated at an instant known as the time tag of the synchrophasor. In order to obtain simultaneous measurement of phasors across a wide area of the power system, it is necessary to synchronize these time tags, so that all phasor measurements belonging to the same time tag are truly simultaneous. Consider the marker $t = 0$ in Figure 2.3 is the time tag of the measurement. The PMU must then provide the phasor given by Equation 2.2 using the sampled data of the input signal.

There are antialiasing filters present in the input to the PMU, which produce a phase delay depending upon the filter characteristic. Furthermore, this delay will be a function of the signal frequency. The task of the PMU is to compensate for this delay because the sampled data are taken after the antialiasing delay is introduced by the filter. The synchronization is achieved by using a sampling clock which is phase-locked to the one-pulse-per-second signal provided by a GPS receiver. The receiver may be built in the PMU, or may be installed in the substation and the synchronizing pulse distributed to the PMU and to any other device which requires it. The time tags are at intervals that are multiples of a period of the nominal power system frequency. It should also be noted that the normal output of the PMU is the positive sequence voltage and current phasors. In many instances the PMUs are also able to provide phasors for individual phase voltages and currents.

A by-product of the GPS navigation signals is a high precision synchronized one second pulse available worldwide. The GPS timing pulse keeps accuracy better than 250 nanoseconds and allows, in the case of PMUs, for the synchronization of local sampling pulses to precisions better than one microsecond. One microsecond in a 60 Hz system corresponds to an angle error in the measured phasor of less than 0.02 degrees [87], which is more precise than what is required by most advanced power system applications.

2.3.4. PMU Standards

The standards form the fundamental structure blocks for product development by starting constant protocols that can be universally understood and accepted. In order to interchange synchrophasor measurements between different devices with different communication protocol, it is essential that all the synchrophasor devices implement to a common standards. Whereas, synchrophasors may be made by different manufacturers. The standard for phasor network messaging is known as "synchrophasor standards for power system".

The first synchrophasor standard is "IEEE Standard 1344-1995" [88] and its revision as the second synchrophasor standard is "C37.118" [89]. In next synchrophasor standard, C37.118 split into two standards, C37.118.1-2011 [90] for measurement and C37.118.2-2011 [91] for communication. Standard C37.118.1-2011 defines synchrophasors, frequency and rate of change of frequency measurement under all the operating conditions and an amendment [92] for same standard is presents in this work. Standard C37.118.2-2011 specifies messaging that can be used with any appropriate communication protocol for the real-time communication between PMU, PDC and other applications. It also defines message types, contents, and use.

2.3.5. Comparisons between SCADA system and PMUs System

Automation of power system monitoring and control to some extent has been initiated by the integration of SCADA system but owing to advanced features with enhanced capabilities the Phasor Measurement Unit based monitoring and control with existing SCADA system as a secondary/supporting system would become a viable option. In terms of resolution the SCADA sends one signal every 2 to 4 seconds which is appropriate for steady state observability whereas PMU is capable of sending 10 to 60 samples per seconds which can be used for dynamic observability. SCADA system is capable of providing only the magnitude of the measured signals/variables on the other hand the PMU can provide both magnitude and phase of the measured signals. The measurements obtained by the PMU are time synchronized and hence can be considered as a snapshot of the measured grid at the instant for which the measurements are taken. SCADA with more than 100 digital/analog input/output channels is most suitable for local monitoring and control but PMU's with approximately 16+ analog and 16+ digital input output channels is suitable for wide area monitoring and control of the power system. Comparison between SCADA and PMU is given in Table 2.1. From this table, it is concluded that the PMU gives more accurate and efficient results as comparisons of SCADA systems and it tends the system toward more real-time applications.

Table 2.1. Difference between SCADA and PMU

Attribute	SCADA	PMU
Resolution	1 sample every 2-4 Seconds (steady State Observability)	10-60 samples per second (Dynamic Observability)
Measured Quantities	Magnitude only	Magnitude and phase
Time Synchronization	No	Yes
Total Input/output Channels	100+ Analog & Digital	~10 Phasors, 16+ digital, 16+ analog
Focus	Local monitoring and control	Wide area monitoring and control

2.4. APPLICATIONS OF PMU IN POWER SYSTEM

The synchrophasor technology is relatively new, therefore, several research groups around the world are actively developing applications of this technology. It seems clear that many of these applications can be conveniently grouped as follows:

- Advanced network protection
- Power System Real Time Monitoring
- Advanced control schemes

The applications of PMUs such as monitoring, control and protection in power system networks are as follows:

2.4.1. Application of PMUs for state estimation of power system

Current state estimation (SE) techniques were developed in 1970s. The approaches that evolved depended upon the measuring active and reactive power flows and voltage magnitudes at substations, and communicating them to a control center for further processing. This is still the technology which is used in most of the power systems. The fact that the data is scanned over a considerable period means that the calculated state is at best an approximation to averaged system state. Therefore, the estimates that are produced are referred to as "Static State Estimates".

Phasor measurements of positive sequence bus voltages (and currents) directly are a natural vehicle for state estimation or state measurement applications. If there were no existing state estimation software in an EMS center, a PMU only system would be a logical choice. The positive sequence voltage and currents lead to a linear state estimator [87]. PMUs are considered as a promising tool for the future monitoring, protection and control of the power networks [93]. State Estimation is widely used in transmission control centers and ISO operations today to supplement directly telemetered real time measurements in monitoring the grid; to provide a means of monitoring network conditions which are not directly telemetered; and to provide a valid best estimate of a consistent network model which can be used as a starting point for real time applications such as contingency analysis, constrained re-dispatch, Volt- VAR optimization, and congestion management. State estimation has a number of applications with varying degrees of successful utilization in the industry such as bad data detection, parameter estimation, status estimation, and external model.

In [94], a SE problem in multi area has been developed. In this, a central entity coordinator accesses the solution of the area state estimation, the data from PMUs from each bus and raw measurements only from the area boundaries. The techniques for solving the SE problem based on the PMUs have been given in [95], [96] and [97]. Static SE algorithm is iterative and initialized as flat start. It uses the heavy computations and cannot be executed in the small intervals. A methodology to include the measurements from phasor measurements as well as conventional measurements in a state estimator has been proposed in [98] and [99]. A comprehensive approach to combine the conventional measurements, such as power flow and power injection measurements with the direct and pseudo voltage measurements by the PMUs in a weighted least square (WLS) formulation of the SE problem is demonstrated in this work. *Chakhchoukh et al.* [100] has been proposed a novel approach for hybrid static state estimation based on PMUs, which is improved one and provides the accurate confidence intervals.

2.4.2. Application of PMUs for protection of power system from faults

A time-frequency-based method for contingency severity ranking and fast stability assessment has been described in [101] in order to classify correctly all single or multiple contingencies that may result in loss of voltage or frequency stability in the first 20 s following the last disturbing action. By selecting a number of strategic monitoring buses where the PMUs are located to capture representative voltage magnitudes and angles during detailed time-domain simulations, which cover special protection systems and on-load tap-changers. In [69], two solutions, able to face stability and security problems in the transmission grid are proposed. Both need real-time effective risk indicators whose timely computing is a crucial issue.

The expansion of synchrophasor systems by *Phadke et al.* [13] permits the use of new input signals, local and remote for power network control. A synchrophasor system comprehends a set of PMUs, which use a GPS signal to improve the time label for measurements and PDC, which processes the data sent by the PMUs, originating the synchrophasors. This system allows the measurement of system variables that can provide further information on the non-measurable system states, and can be used as input variables for the controllers. A current differential protection relays are broadly applied to the protection of the electric plant due to their simplicity, sensitivity and stability for internal and external faults [102]. The given idea has the feature of unit protection relays to protect large power grids based on PMUs. The principle of the protection scheme depends on comparing positive sequence voltage magnitudes at each bus during fault conditions inside a system protection center to detect the nearest bus to the fault.

For local monitoring of the voltage collapse, and protective, and emergency control in the presence of voltage-sensitive loads, the voltage and current phasors measurements are used. The onset of voltage collapse point is calculated based on the load characteristics and simulated voltage and current phasors, which are provided by a network of PMUs. If the stability margin is small and the reactive-power reserves are nearly exhausted, then controls to steer the power system away from the critical point will be activated. Jiang et al. [103] proposed an adaptive PMU based approach for the detection and location of faults on an EHV/UHV transmission line accurately. Proposed algorithm is recursive, fast and suitable, therefore it can be applied in the field of computer relaying.

In [104], a novel fault location algorithm has been proposed which is based on the phasor measurements for series compensated lines. This method used two step algorithms viz., pre-located step and corrected step, in order to calculate the location of fault and voltage drop in the system. It can be easily applied to any series FACTS compensated line. *Eissa et al.* [102], *Jiang et al.* [105] and *Liu et al.* [106] proposed a wide area protection for power grids and fault location for two terminal multi-section compound transmission lines using synchrophasor measurements. The suggested algorithm may fail when the fault resistance is very high because the voltage may change during fault.

2.4.3. Power system operation, control and planning

The voltage and current phasors measured by the PMUs at widely dispersed locations are time-stamped with respect to a GPS clock. To determine the confidence levels associated with the state variables obtained by using the PMUs, it is needed to evaluate the corresponding uncertainties. The main sources of measurement uncertainties are [107]: 1) the instrument transformers; 2) the analog interfaces, including cables, connecting the instrument transformer and the digital equipment; and 3) the analog to- digital converters (ADCs) and the associated computational algorithm. The uncertainty associated with the voltage magnitudes and phase angles at the buses, as determined by the PMUs, is evaluated using three different approaches: the classical uncertainty propagation theory, the Monte Carlo method and the use of random fuzzy variables (RFVs). Precise time-synchronized phasor measurements are available to us today from the PMUs. One of the most promising uses of the PMU is during transient control applications. The ability of synchronized Phase Angle Measurements is to identify impending instabilities through real time measurements and to trigger remedial actions in time to prevent major power system outages. The capability of the emerging synchronized phasor measurement technology is to improve the overall stability of the transmission system through supplementary modulation of voltage regulators.

A technique of monitoring the power system stability by PMUs has been developed in [108]. The Fourier spectrum to estimate the eigenvalue, which changes with total generation and power flow in the areas has been discussed. By the monitoring of inter area oscillation mode, stability limits and Available Transfer Capability have been calculated. The design of wide area damping controller for inter area oscillations has been proposed by *Zhang et al.* [109]. This work presents a systematic design scheme of wide area damping control systems by combining linear matrix inequality based robust control design and stabilizing signal selection. While the use of linear, continuous approaches to design the controller is very powerful, it requires considerable testing and tuning.

2.4.4. Application of PMUs for power system Oscillations

In [110], a direct method to compute the generators' internal dynamical states from the terminal measurements of the voltage, power and field current of a generator has been suggested. This method is fast, whereas, the estimated rotor angle may not be quite exact as it neglects the system dynamics. In order to calculate the correct estimation of phasors by PMUs, during power system oscillations under disturbance, some techniques have been proposed in the literature [111] and [112].

Synchrophasors and frequency estimations play an progressively important role in the power networks [113]. Discrete Fourier Transform (DFT) may introduce errors into the phasor and frequency estimations under dynamic conditions, such as power oscillation. A dynamic phasor and frequency estimator for PMUs has been proposed in this work to improve the accuracy by considering dynamic characteristics of power network expressed as Taylor derivatives. *Brian et al.* [114] proposed the use of regression analysis in the study of small signal stability in large interconnected power networks. In [115], an application of non-stationary time-frequency analysis techniques has been proposed to identify the nonlinear trends and filtering frequency components of the dynamics of large and interconnected power networks. Two different analytical approaches to examine non stationary features have been investigated. The first method is based on the selective empirical mode decomposition of the measured data. And the second is based on the wavelet shrinkage analysis.

Mai et al. [116] proposed a novel algorithm for the synchrophasor estimation to improve the estimation accuracy under dynamic conditions. The real component of a constantly rotating vector and a low-frequency band-limited vector, which is linearized by Taylor series, has been employed to model supplied signals in power networks. Using the present technology, latency associated with remote feedback signals can be determined from the time stamp information at both the PMUs location and the control center. Mostly, existing literature for power network oscillations using Prony method report implementing fixed sampling window that has been obtained following a systematic iterative approach taking into account potential disturbances [117].

2.4.5. Application of PMUs in power systems with FACTS controllers

The application of PMU with FACTS controller is a very important application in power system. Some works from the literature have been discussed below;

In [118], a concept using remote signals acquired through PMU has been proposed to damp out the sub-synchronous resonance (SSR). After the advent of WAMS technology, it is possible to measure the states of a wide interconnected power system with synchronized phasor measurement units (PMU). *Choudhuri et al.* [119] presented a latency associated with remote feedback signals which determine time stamp information at both PMU location and control center. From this, a phasor power oscillation damping (POD) has given to continuously adapt to the real latency and maintain the desired dynamic performance over a range of different operating conditions. *Choudhuri et al.* [120] presented a study on POD control using wide area measurement system applied to a single Static VAR Compensator (SVC). An equivalent power network model representing key characteristics of the Nordic power system has been used. A feedback signals from the remote PMUs in Norway and Finland have been incorporated to damp out the critical inter area modes through a large SVC unit located in south-east Norway.

A series compensated power network may lead to a very uncommon problem known as SSR. The Static Synchronous Compensator (STATCOM) is a shunt device of the FACTS family. In [121], the concept of using remote signals acquired through PMU has been proposed to damp SSR. An auxiliary sub-synchronous damping controller (SSDC) for a STATCOM using the remote accelerating power of generator signal as the stabilizing signal has been designed to damp sub-synchronous oscillations. *Yu et al.* [104] presented a new fault location algorithm based on the PMUs for series compensated lines. The voltage drop of series device has computed by the device model in the fault locator of series compensated lines traditionally, whereas, using this approach errors have been induced by the inaccuracy of the series device model or the uncertainty operation mode of the series device. The proposed technique can be easily applied to any series FACTS compensated line. This study also considers the effect of various operation modes of the compensated device during the fault period.

2.5. POWER SYSTEM STABILITY

"*Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.*"

The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs and key operating parameters change continually. When subjected to a disturbance, the stability of the system depends on the initial operating condition as well as the nature of the disturbance. Stability of an electric power system is thus a property of the system motion around an equilibrium set, i.e., the initial operating condition.

Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load changes occur continually; the system must be able to adjust to the changing conditions and operate satisfactorily. It must also be able to survive numerous disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator. A large disturbance may lead to structural changes due to the isolation of the faulted elements. At an equilibrium set, a power system may be stable for a given (large) physical disturbance, and unstable for another. It is impractical and uneconomical to design power systems to be stable for every possible disturbance. The design contingencies are selected on the basis they have a reasonably high probability of occurrence. Hence, large-disturbance stability always refers to a specified disturbance scenario. A stable equilibrium set thus has a finite region of attraction; the larger the region, the more robust the system concerning large disturbances.

The response of the power system to a disturbance may involve much of the equipment. For instance, a fault on a critical element followed by its isolation by protective relays will cause variations in power flows, network bus voltages, and machine rotor speeds; the voltage variations will actuate both generator and transmission network voltage regulators; the generator speed variations will actuate prime mover governors; and the voltage and frequency variations will affect the system loads to varying degrees depending on their individual characteristics. Further, devices used to protect individual equipment may respond to variations in system variables and cause tripping of the equipment, thereby weakening the system and possibly leading to system instability.

If following a disturbance the power system is stable, it will reach a new equilibrium state with the system integrity preserved i.e., with practically all generators and loads connected through a single contiguous transmission system. Some generators and loads may be disconnected by the isolation of faulted elements or intentional tripping to preserve the continuity of operation of bulk of the system. Interconnected systems, for certain severe disturbances, may also be intentionally split into two or more "islands" to preserve as much of the generation and load as possible. The actions of automatic controls and possibly human operators will eventually restore the system to normal state. On the other hand, if the system is unstable, it will result in a run-away or run-down situation; for example, a progressive increase in angular separation of generator rotors, or a progressive decrease in bus voltages. An unstable system condition could lead to cascading outages and a shutdown of a major portion of the power system. Power system stability is divided into 3 categories and that are

i) Rotor angle stability
ii) Frequency stability
iii) Voltage stability

The classification of power system stability shown below is based on the following considerations:

- The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.
- The size of the disturbance considered which influences the method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to assess stability.

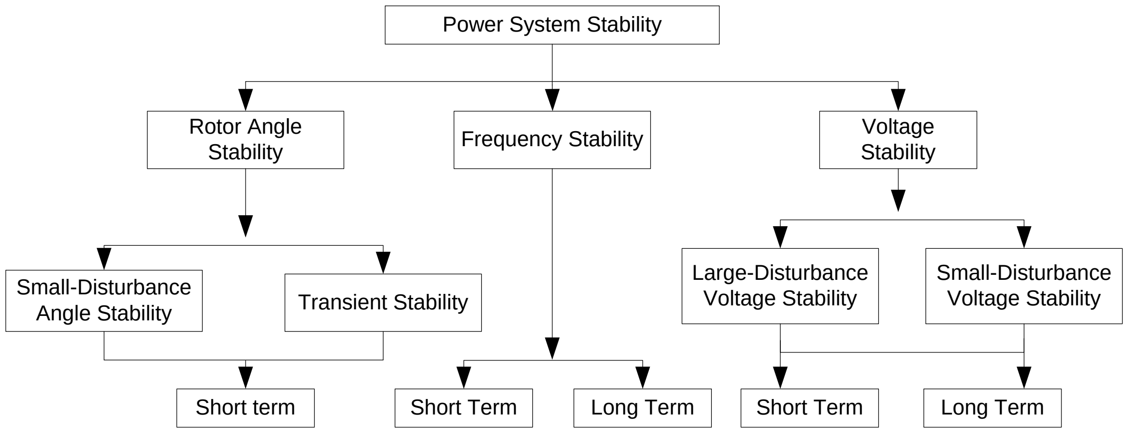


Figure 2.4 Classification of power system stability [122]

The Figure 2.4 clearly shows the classification of power system stability according to [122]. The overall picture of the power system stability problem, identifying its categories and subcategories is given in Figure 2.4.

Power system stability is essentially a single problem; however, the various forms of instabilities that a power system may undergo cannot be properly understood and effectively dealt with by treating it as such. Because of high dimensionality and complexity of stability problems, it helps to make simplifying assumptions to analyze specific types of problems using an appropriate degree of detail of system representation and appropriate analytical techniques. Analysis of stability, including identifying key factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories as shown above.

2.6. VOLTAGE STABILITY

Voltage stability is concerned with the ability of power system to maintain acceptable voltage at all buses in the system under normal conditions and after being subjected to a disturbance from a given initial operating condition. A system enters a state of voltage instability when a disturbance, such as increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power. A possible outcome of voltage instability is loss of load in an area or tripping of transmission lines and the other elements by their protection leading to cascading outages that in turn may lead to loss of synchronism of some generators.

Continuous increase in power demand, with limited expansion of transmission systems, modern power system networks are being operated under highly stressed conditions. This has imposed a threat to maintenance of the required voltage profile, and thus the systems have been facing voltage instability problem. If these instabilities are not detected within time then the system operator is not able to take any appropriate control action against that instability then progressive voltage instability further degraded the system condition, and may cause the voltage collapse. Voltage collapse is the process by which the sequence of events, accompanying voltage instability, leads to a blackout or abnormally low voltages in significant part of a power system.

2.6.1. Principal causes of voltage stability problems

Some of the causes for occurrence of voltage instability are:

-Difference in Transmission of Reactive Power under Heavy Loads.
-High Reactive Power Consumption at Heavy Loads.
-Occurrence of Contingencies.
-Voltage sources are too far from load centers.
-Due to unsuitable locations of FACTS controllers.
-Poor coordination between multiple FACTS controllers.
-Presence of Constant Power Loads.
-Reverse Operation of ON Load Tap- Changer (OLTC).

2.6.2. Classification of voltage stability

As discussed in [122], the voltage stability is further classified into four categories: large disturbance voltage stability, small disturbance voltage stability, short-term voltage stability and long-term voltage stability. These subcategories of voltage stability are classified according to the time span of a disturbance in a power system and are summarized below.

- Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections. Determination of large-disturbance voltage stability requires the examination of the nonlinear response of the power system over a period of time sufficient to capture the performance and interactions of such devices as motors, under load transformer tap changers, and generator field-current limiters. The study period of interest may extend from a few seconds to tens of minutes.

- Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining, at any instant, how the system voltages will respond to small system changes. With appropriate assumptions, system equations can be linearized for analysis. This linearization, however, cannot account for nonlinear effects such as tap changer controls (dead bands, discrete tap steps, and time delays). Therefore, a combination of linear and nonlinear analyzes is used in a complementary manner.

As noted above, the time frame of interest for voltage stability problems may vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short-term or a long-term phenomenon as identified in Figure 2.4.

- Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations.
- Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance. Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance. Instability is due to the loss of long-term equilibrium (e.g., when loads try to restore their power beyond the capability of the transmission network and connected generation), post-disturbance steady-state operating point being small-disturbance unstable, or a lack of attraction toward the stable post-disturbance equilibrium (e.g., when a remedial action is applied too late). The

disturbance could also be a sustained load build-up (e.g., morning load increase). In many cases, static analysis can be used to estimate stability margins, identify factors influencing stability, and screen a wide range of system conditions and a large number of scenarios [123].

2.7. CONCLUSION

This chapter provided a detailed introduction of the PMU and its basic background theory. The importance of PMU as compared to SCADA system has discussed in this chapter. Besides, various applications of PMU have deliberated. A brief introduction of voltage stability has also been discussed in this chapter.