STUDY OF ESTIMATING DYNAMIC STATE JACOBIAN MATRIX AND DYNAMIC SYSTEM STATE MATRIX BASED ON PMU

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

POWER SYSTEM

SUBMITTED BY

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2k18/PSY/21

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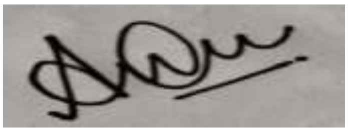
CANDIDATE'S DECLARATION

I, ANNU AHLAWAT, Roll No. 2K18/PSY/21 student of M.Tech. (Power System), hereby declare that the project Dissertation titled "**STUDY OF ESTIMATING DYNAMIC STATE JACOBIAN MATRIX AND DYNAMIC SYSTEM STATE MATRIX BASED ON PMU**" which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.



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CERTIFICATE

I hereby certify that the major project titled "**PMU-BASED ESTIMATION OF DYNAMIC STATE JACOBIAN MATRIX AND DYNAMIC SYSTEM STATE MATRIX**" which is submitted by ANNU AHLAWAT, Roll No-2K18/PSY/21 ELECTRICAL ENGINEERING DEPARTMENT, Delhi Technological University, Delhi, in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree to this University or elsewhere.

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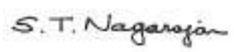
X 

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ABSTRACT

Large and extensive power system is dynamic in nature and changes occur very rapidly. Stability condition of power system need to be assessed continuously to prevent collapse of power grid. Stability of power system can be estimated with dynamic state Jacobian matrix and dynamic system state matrix. Conventionally, these matrices are estimated based on State Estimation and by assuming initial network parameter values. Also, there are possibilities of corrupted information of the assumed network model which may results in erroneous estimation of the Jacobian matrices and the state matrix.

In this work, a Synchrophasor measurement-based method has been studied to calculate the dynamic state Jacobian matrix and Dynamic system state matrix in varying load conditions. The advantages of these synchronized measurement based methods is high speed and completely model free. Therefore, there is no need of system model information such as network topology and parameters for calculation of Dynamic state Jacobian matrix and system state matrix.

A case study on WSCC 9-bus, 3-machine system has been performed in Digsilent Power factory Simulator Software for simulation of ambient conditions. For this purpose, we have developed a low cost laboratory scale setup of PMU architecture for development of PMU applications on MATLAB platform, based on an open source software developed by Grid Protection Alliance, Delft University of technology and Digsilent Power Factory Simulator software. The resultant matrices obtained using proposed method and model based method has been compared and error is estimated. The critical Eigen values are estimated of the System state matrix to show a good measure of proximity of instability by observing the right most points on the eigen value plots.

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LIST OF ABBREVIATIONS

PMU	Phasor Measurement Unit
WAMS	Wide Area Measurement Unit
WAMACS	Wide Area Monitoring And Control System
SCADA	Supervisory Control and Data Acquisition
PDC	Phasor Data Concentrator
GPS	Global Positioning System
UTC	Coordinated Universal Time
ROCOF	Rate Of Change Of Frequency
EMS	Energy Management System
SCDR	Symmetrical Component Distance Relay
RTU	Remote Terminal Unit
IEEE	Institute of Electrical and Electronics Engineering
URTDSM	Unified Real Time Dynamic State Measurement
PGCIL	Power Grid Corporation of India
CT	Current Transformer
PT	Potential Transformer
PLL	Phase Locked Loop
DFT	Discrete Fourier Transform
GPA	Grid Protection Alliance
PWS	PowerWorld Simulator
PWDS	PowerWorld Dynamic Studio
WSCC	Western System Coordinating Council
EHV	Extra High Voltage

LIST OF SYMBOLS

T_m	Mechanical torque applied by the prime mover – retarding torque due to mechanical losses, N-m
T_e	Electrical torque applied for the electrical power output + electrical losses, N-m
P_m	Mechanical power supplied by the prime mover –mechanical losses, Watts
P_e	Electrical power output supplied by the generators + electrical losses, Watts
θ_m	Rotor angle position w.r.t stationary axis, rad
$\boldsymbol{\delta}_m$	Rotor angle position w.r.t synchronously rotating reference axis, rad
ω_m	Angular velocity of rotor, rad/sec
ω_{sm}	Synchronous angular velocity of rotor, rad/sec
P	Number of poles in synchronous generator
M	Moment of Inertia
D	Damping factor of generator
V_t	Generator terminal voltage magnitude measured by PMU
I_a	Generator current magnitude measured by PMU
Φ	Phase angle of the generator current w.r.t its terminal voltage measured by PMU
$\boldsymbol{\delta}_i$	Generator i rotor angle w.r.t its terminal bus (i)
E_i	Emf magnitude behind the transient reactance
$Y_{ij}\angle\varphi_{ij}$	Reduced admittance matrix of the system
I_{bus}	Current injected in the bus
V_{bus}	Voltage of the bus with respect to ground
Y_{bus}	Bus admittance matrix
W	Standard Wiener process

σ_i^2 Variance of load variation

G Equivalent conductance

Σ Variance of load variation

Ɛ Standard Gaussian random variable

C_{XX} Stationary Covariance Matrix

A Dynamic System State Matrix

J Jacobian Matrix

N Sample size

Q_{XX} Sample Covariance Matrix

$\widetilde{\delta_i}$, $\widetilde{\omega_i}$ Center-of-inertia reference frame of the classical generator model

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Growing demands of electricity causes highly extensive and interconnected large electric power system, which mainly consist of wide generating system, large and extensive transmission network requires high level of power system security assurance. With large and complex power system it is difficult to detect any faults or unwanted activities which sometimes may cause serious system failure. The main objective of our power system is to supply reliable and continuous power to all the consumers without any interruption. To achieve this objective there is a requirement of advanced and intelligent power system which depends on the real time information.

Due to occurrence of Blackouts in power grid in the recent past, there is a renewed interest to make the power system resilient from external and internal disturbances. Phasor Measurement Unit is one such device developed (PMU) for deeper insight in the operation of power grid [1]. Phasor Measurement Unit is a high speed measuring device in power system that can provide the synchronized measurements of electrical quantities. Recently, Phasor measurement units are being deployed over power grids, popularly known as the wide area measurement system (WAMS) or wide area monitoring and control system (WAMACS). WAMS is an intelligent power system device setup, which are capable of providing highly precise and synchronized phasor data of the power grid in real time [2].

PMUs have high reporting rate in the order of 30-60 frames per seconds while traditional SCADA system provides one measurement in every 2-3 seconds. Therefore, due to high resolution of PMU, helps in analysing dynamic events occurred in power grid. PMUs have two major functions, first is to measure the Analog signal and sample into digital form to estimate the phasor quantity of the signal such as, phasors of voltage and current, frequency, rate of change of frequency (ROCOF), circuit breaker and switches status with a real time tag. Second, is to transmit the estimate quantity at a fixed reporting rate over a communication protocol to higher level device at local or remote location.

In WAMS there are two main components, first one is the Phasor Measurement Units (PMUs) and the other one, Phasor Data Concentrators (PDCs), which are interconnected with communication technologies and time synchronized with Global Positioning Systems (GPS) [3][4].

Time synchronization is achieved from a Global Positioning Systems (GPS) receivers which is based on Coordinated Universal Time (UTC). The estimation part is still evolving with research community and industry, whereas the transmission part has been standardized by IEEE standards.

The only disadvantage is shortcoming of the currently developed Phasor Measurement Units (PMU) as they require high installation cost and having very restricted copyright limitations. The detailed matter on Flaws of developed PMU is explained in chapter 2(refer 2.4).

1.2 MOTIVATION OF THE RESEARCH

The large and highly interconnected power system is dynamic in nature due to rapid variations in the system conditions which are sometimes undetectable and unidentified by conventional methods. To secure the electric system it is highly necessary to continuous monitoring the dynamic system stability conditions to maintain the system efficiency and reliability. To observe the power system dynamic stability, dynamic state Jacobian matrix and system state matrix plays very important role [5].

For estimation of these matrices it is assumed that system model is well known and system provides coherent set of measurements. As power system is a dynamic system, there are chances of erroneous calculation in the state estimation results, due to corrupted information of the system data, leading to erroneous calculation of Jacobian matrix and system state matrix. The deployment of Wide Area Measurement System (WAMS) advanced technologies gives opportunity to avoid these problems.

The Phasor Measurement Units (PMU) provides high speed, real time measurement-based approach for reliable and accurate monitoring, analysis and control of electric power system. The advantages of these synchronized measurement based methods are high speed and completely model free. Therefore, there is no need of system model information such as network topology and parameters for calculation of Dynamic state Jacobian matrix and system state matrix. These matrices are calculated by using real time synchronized information provided by the Phasor Measurement Unit (PMU) based measurements.

In recent years the selection of PMUs has made it conceivable to approve the expected network model and the estimations of system parameters. There are various methods to estimate the values of system parameters based on PMU measurements. One of the PMU based methodology is to build up a dynamic equivalent model of the dynamical system [6]-[9].

1.3 OBJECTIVE AND CONTRIBUTIONS OF THE THESIS

In this work, we study a different methodology to calculate the dynamic state Jacobian matrix and the dynamic system state matrix A without knowing the values of system parameters of the assumed system model which are important to estimate these matrices by utilizing statistical properties withdraw from the real- time series of PMU estimations of phasors of voltages and current.

In this work, we assumed that all the generator buses have available PMUs, by utilising the measurements extracted from these PMUs we can figure rotor angles and rotor speeds [10]-[15] and the designed power system dynamic are energized by stochastic load variations [15] [16]-[18]. This method uses the Lyapunov equation [19] [20] to linearized the system equations and then Covariance matrices is calculated but they depend on system parameter like Emf of the generating unit therefore sample covariance matrix is estimated using the real time data of rotor angle and rotor speed. By using Covariance matrix of PMU based measurements, the dynamic state Jacobian matrix is computed assuming that generator moment of inertia is known. This technique is not completely measurement based as we have to assume the knowledge of generator moment of inertia M which is generally known at the same time, above all, we need not require any data of the system model like system parameters and network topology. To estimate the entire dynamic system state matrix A requires the information of generator damping coefficients D.

If in any case, the damping D of generator is not known or unsure, then this proposed method also build up a methodology for calculation of damping D, but this requires information of the system model like variances of load variations and electromotive force of generator (emf), while all this information is not required for calculation of the Jacobian matrix.

The estimation of dynamic state Jacobian matrix using the proposed method which is based on PMU measurements have various applications. This matrix can be utilized for the purpose of model validation. By making comparison between the calculated dynamic state Jacobian matrix using assumed system model and the estimated dynamic state Jacobian matrix utilizing the PMU based proposed method, any undetected changes in the system model can be distinguished. Also, the approach of calculating damping D of generator using proposed method can be utilized to approve the assumed the Damping D values of the assumed system model connected generators. There are some different applications investigated by researchers in [21]-[23].

In this work, utilizing the estimated dynamic state system matrix the critical eigenvalues are evaluated that are the right most points of the eigenvalue plots which provides the good information of the proximity of instability of the designed system [24]. The estimated left and right eigenvectors of the critical eigenvalues may additionally be assessed to anticipate the response of the system and accordingly design the emergency control actions [22] [25]. Fig.1.1 shows the complete architecture of the thesis work.

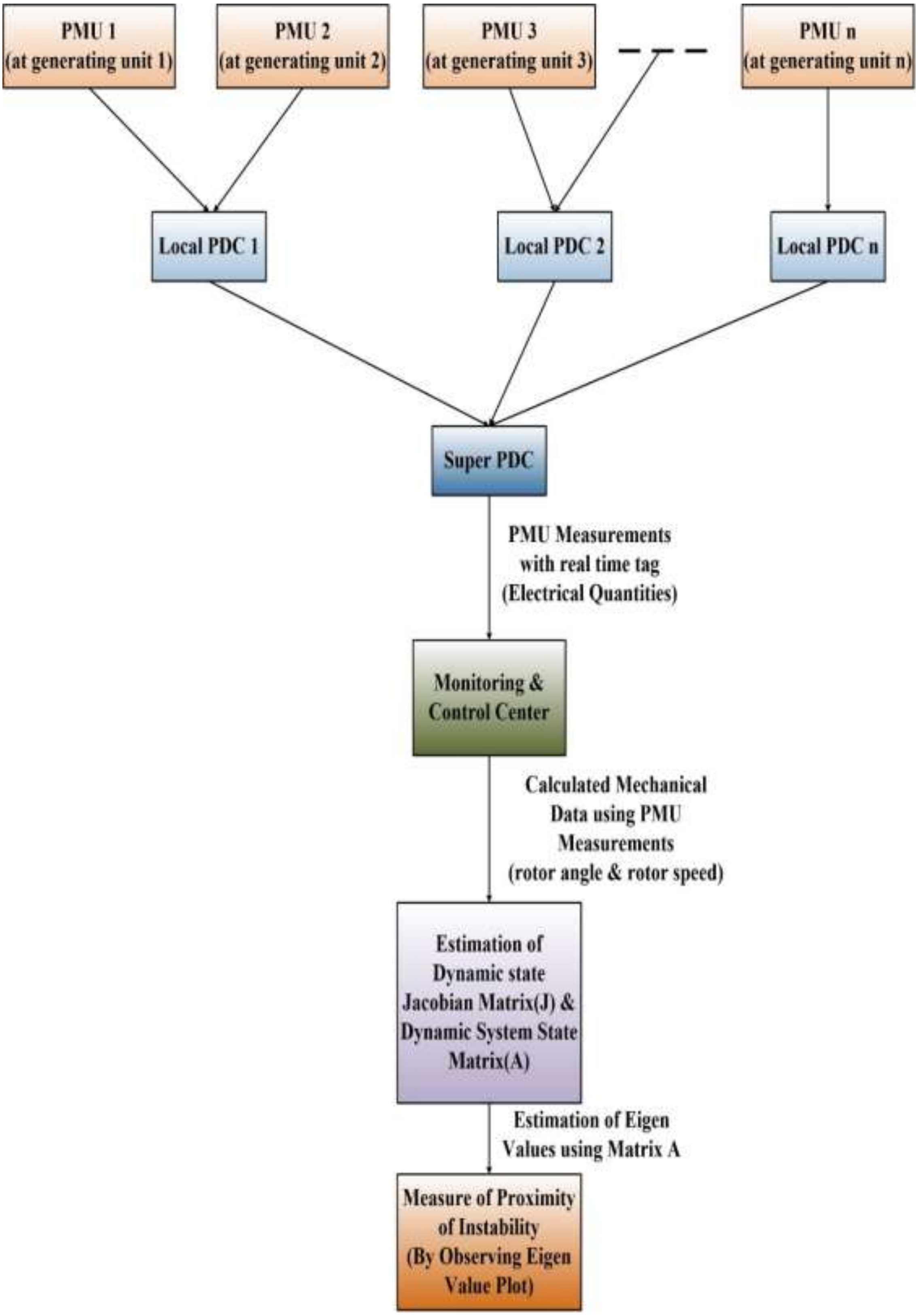

Fig.1.1 Architecture of Proposed methodology

1.4 THESIS ORGANIZATION

In view of the increased deployment of PMUs across the globe in power grids, it is necessary for introduction of PMU topics in power engineering education at graduate level itself. Most of the educational institutions imparting power education do not have a PMU laboratory setup at this point of time. Further, setting up a laboratory for study involving a PMU shall be expensive for graduate level programs in educational institutions which do not have access to real time simulators.

The outlines of this thesis are as follows:

Chapter1: The basic introduction of Study of proposed method based on PMU measurements for estimation of Dynamic state Jacobian Matrix and Dynamic system state matrix.

Chapter 2: The basic introduction of PMU in smart power system, a historical overview of PMU, comparison between PMU and SCADA, the applications of the PMU, Shortcomings of PMU and present work in PMU field is discussed in detail.

Chapter 3: The development of low cost laboratory setup of PMU architecture on MATLAB platform is explained with complete details of open source softwares such as OpenPDC, PMU connection tester and power world simulator.

Chapter 4: The dynamic stability of the system based on PMU measurements is described in this chapter, along with basics of stability and swing equation. How to estimate rotor angle or rotor speed from PMU information.

Chapter 5: The estimation of dynamic state Jacobian matrix and dynamic system state matrix based on PMU measurements using system model and proposed techniques.

Chapter 6: In this chapter, the results and plots are obtained using proposed method and system based method, using that errors are estimated and plot of proximity of instability is shown. The simulation of WSCC 9bus, 3 machine system is done in this chapter using PowerWorld Simulator and Digsilent Power factory software.

Chapter 7: This chapter includes the conclusion and the future work on this work

CHAPTER 2

PHASOR MEASUREMENT UNIT

2.1 INTRODUCTION

Increasing demand of electricity causes increase in size of power grid. The wide generating system, large and extensive transmission network requires high level of power system security assurance. With large and complex power system it is difficult to detect any faults or unwanted activities which sometimes may cause serious system failure. The main objective of our power system is to supply reliable and continuous power to all the consumers without any interruption. To achieve this objective there is a requirement of advanced and intelligent power system which depends on the real time information.

Traditionally, the measuring units installed at substations provides both analog and digital information which includes information of power flow, frequency and circuit breaker status and then send to load center using control and analyzing units such as Supervisory Control And Data Acquisition System (SCADA) or Energy Management System (EMS). The limitation of EMS and SCADA is the estimation of phase angle difference between two substations is done using the available data and many times also calculated offline which leads to inaccuracies. The deployment of Wide Area Measurement System (WAMS) advanced technologies gives opportunity to avoid these problems [1].

Phasor Measurement Units are high speed power system devices that can provide the synchronized measurements of electrical quantities. Recently, Phasor measurement units are being deployed over power grids, popularly known as the wide area measurement system (WAMS) or wide area monitoring and control system (WAMPCS).

WAMS is an intelligent power system device setup, which are capable of providing highly precise and synchronized phasor data of the power grid in real time [2]. PMUs have high reporting rate in the order of 30-60 frames per seconds while traditional SCADA system provides one measurement in every 2-3 seconds. Therefore, due to high resolution of PMU, helps in analyzing dynamic events occurred in power grid [3].

The Phasor measurement units (PMUs) measures both magnitude and phase angle of the current and voltage, this information has been analysed to monitor the power network conditions. The active power flow in the transmission lines is directly proportional to sine of angle difference between voltages at the two terminals of the line. Hence, the information of angle difference of voltage between two terminals is very important factor to monitor and control purposes in power system [4].

The expanding development of distributed energy resources in the power system requires highly intelligent systems for accurately monitoring and control of power flow purposed. Before, these resources power is flowing uni-directional manner from generating station to consumers, but now by using renewable sources which can install anywhere easily such as solar PV, customers can generate their own power. This causes change into distribution, the system now becomes bidirectional i.e, generated power can flow in both directions. With this change in the power system, transmission and distribution systems are need to be continuously monitored by utilizing advanced technologies, for example, – PMUs and μPMUs.

Initially, the operating company generates the electrical power and feed it to power grid, from where it is transferred to consumers simply i.e, there is only one side power source. Presently, Consumers are generating their won power using solar PV panels, wind turbines etc, and to earn money they sell the power to the electric grid or feeding electric power to the grid back. Due to this procedure, voltage and current must be estimated and managed so as to guarantee the quality and standard of the power feeding to grid by customers through meters, for example, phase synchronicity, frequency and voltage.

Fig.2.1 Station Phasor Measurement Unit

2.2 HISTORICAL OVERVIEW

The beginning of the advanced EMS system dependent on state estimators have been started with the consequence of the 1965 electric failure (blackout) of the NorthEastern power grid in North America. At Virginia Tech, the development of Phasor Measurement Unit (PMU) device was supported by different financing organizations throughout the years. The early development funding was funded by US Department of Energy, US Electric Power Research Institute and the US National Science Foundation [40].

The significant steps in the development of Phasor Measurement Units are as followings below:

1) Development of Symmetrical Component Distance Relay (SCDR)
2) Synchronization of sampling clocks (GPS)
3) Invention of the prototype PMU
4) Commercial PMU development
5) Installation in power system
6) Applications Research

In the early1970s, the Symmetrical Component Distance Relay (SCDR) was developed. The microcomputers available that time were not equipped for taking care of the necessities of a distance relay algorithm, which utilized symmetrical components of voltages and currents to obtained a single equation to solve 6 fault equations using symmetrical components of a three phase transmission lines [41].

In mid 1980s GPS satellites were being deployed in several numbers, and it turned out to be evident that by utilizing GPS time flags as inputs to the sampling clocks in the measurement system of digital relays, developed an extremely amazing estimation device, which would have the option to give image of the condition of the power system at any instant of time [42].

The synchronised PMUs with GPS were first introduced in 1988 by Dr. Arun G. Phadke and Dr. James S.Thorp at the Power System Research Laboratory of Virginia Tech. This advanced measuring device provides measurements of phasors with absolute real time reference synchronised with Global Positioning System (GPS). The initial PMU prototypes were built at Virginia Tech and the first PMU model 1690 was assembled in 1992 by Macrodyne (New York Independent System operator).

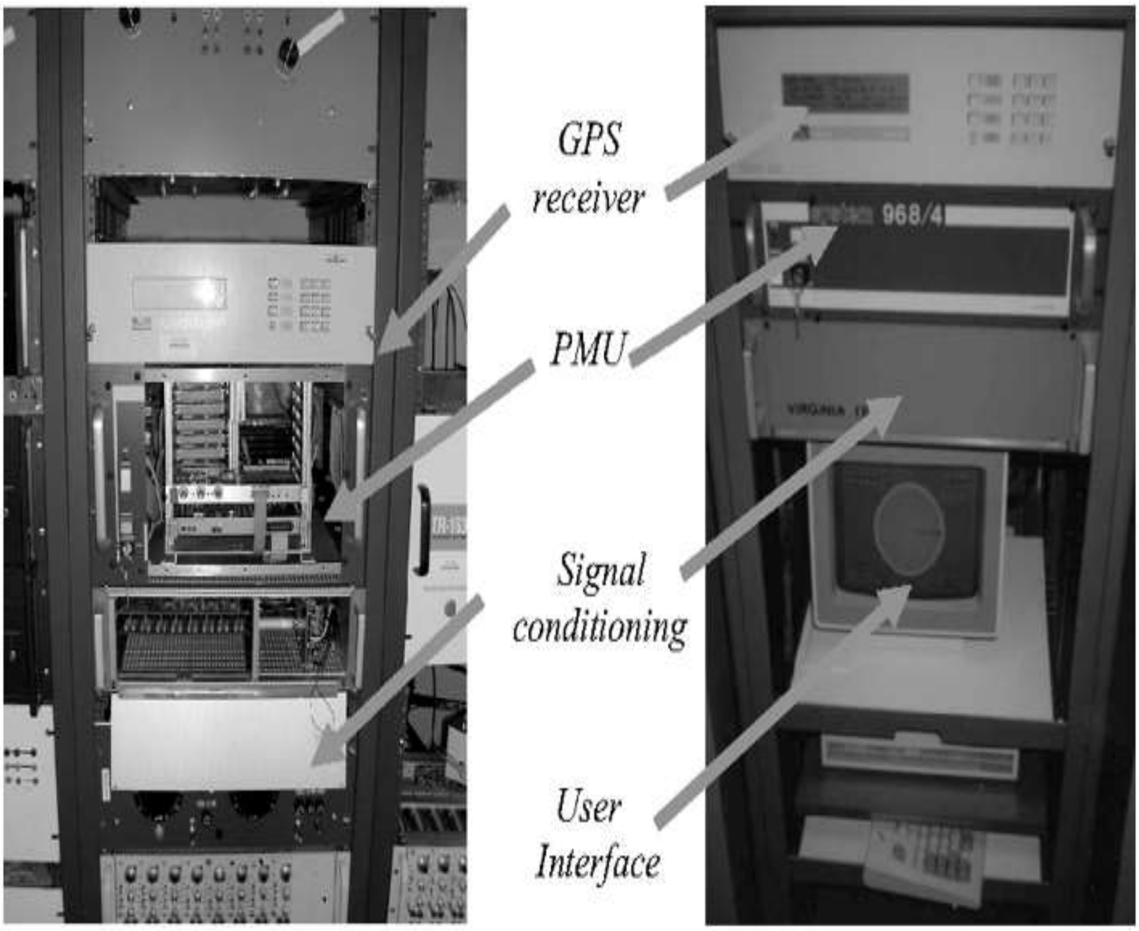

Fig.2.2. First PMUs developed at Virginia Tech [41]

Initially GPS receivers were very expensive because they required very precise internal crystal clocks to keep time precisely until the following GPS satellite came into use. Therefore, limited number of satellites were deployed. Today, the complete chip set of GPS receiver could be easily obtained in less amount as compared to early cost.

2.3 COMPARISON BETWEEN PMU AND SCADA

The advantages of Phasor Measurement Unit (PMU) over Supervisory Control And Data Acquisition System (SCADA) is shown in Table 1.1 as followings,

PMU	**SCADA**
Fast sampling: 30 samples a second or higher (Both for steady state and disturbances)	Slow sampling: Every 1 second to every 10 seconds (OK for steady state. Limited use during disturbances)
Synchronized sampling: All measurements synchronized by GPS signals	Asynchronous sampling: Times could be off by 1 to 10 seconds
Phase angles can be measured (GPS UTC common time/phase reference) (Better Monitoring of States)	Phase angles cannot be measured (No common reference. Magnitudes provide "half" the information)
Measurement error typically less than 1% IEEE C37.118 standard: 1% Total Vector Error	Measurement error typically less than 2%

Table 2.1 Comparison between PMU and SCADA

2.4 PHASOR MEASUREMENT UNIT APPLICATIONS

Synchrophasor technology and the PMU device is introduced in the structure of modern electric power system, due to which the system major achievement like reliability, stability and controllability of power networks has arrived at a greater improved level. In the accompanying sections, different applications and the fundamental advantages of enforcing PMUs in power systems will be spoken to.

2.4.1. Wide Area Monitoring System (WAMS)

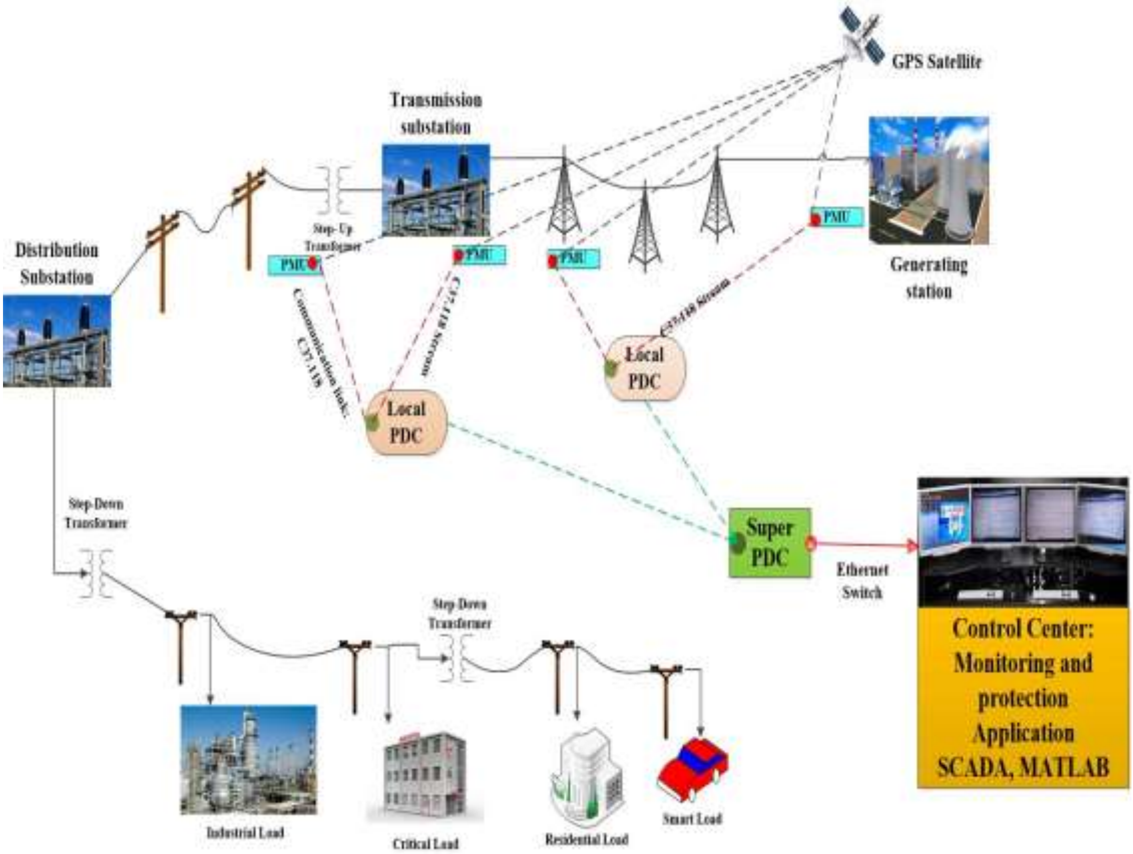

Fig.2.2 Wide Area Measurement System with installed PMU

The Wide Area Monitoring System (WAMS) is an advanced idea for retaining Dynamic stability of the transmission system, primarily based on Phasor Measurement Unit (PMU). Presently, numerous nations have been anticipatory enforcing WAMS in their power grid. In contrast to past observing system, WAMS is built dependent on time-synchronized estimation, novel processing innovation, and correspondence innovation to accomplish the synchronization of information procurement and real-time recording from equipment and system in appropriated areas. The continuous real-time information will be conveyed to the central control station where the system administrator will have the option to measure and examine the information anytime, any point of the power system network.

WAMS has extra functional benefits over conventional structures and would slowly substitute the conventional supervisory control and data acquisition (SCADA) system for steady-state monitoring. Additionally, WAMS has the ability to examine the oscillation present in the network, display and could analyse the static stability of the network, carry out the time-stamp for fault localization and stumble on the voltage instability of the network. To this point it is considered to be the most advanced approach to stumble on and keep away from extensive blackout. The PMUs are installed optimally in the power system, the controllers can apprehend abnormal events inside the electricity network via the computing in the network control centre.

2.4.2. State Estimation

In the Power System, the category of state estimation in actual time control capacities incorporates: scheduling generation and exchange, observing blackouts and planning alternative options, supervising scheduled outages; scheduling frequency and time corrections; organizing bias settings; and crisis recovery of system [43]. Essentially, the entirety of the state estimation contemplations above are worked by solving many equations for load flow investigations and results are determined over a long implementation time. The Phasor Measurement Units utilisation accomplish superior in time synchronization with high exactness, the state estimation can be executed dependent on complex bus voltages, this methodology is utilized in inclination to one dependent on early state estimation calculations, that use the estimation of line power flow, including both real and reactive power, to measure the magnitude and phase angle of bus voltage.

The state estimator is utilised for recognition of measurement blunders, distinguished and rectified utilizing the bad information processing procedure. This technique can be served as a major aspect of the state estimation process and could likewise be a post-estimation system [44].

The elimination of critical measurements, in any case, will prompt an undetectable system, and blunders in these sorts of estimations can't be identified. In a very much planned estimation system, the bad information processing can be practised if any critical estimation will be detected by different measuring devices [45]. On a fundamental level, including any kind of estimation will enhance redundancy. It is easy to involve synchronized phasor measurements into state estimators alongside traditional estimations, and this can be appeared to advance state estimation performance. With the existing power system measurement techniques, a couple of extra PMUs can be utilized to change over any existing critical measurements into redundant ones, in this way making every single corrupted data in the power system recognizable [46][47].

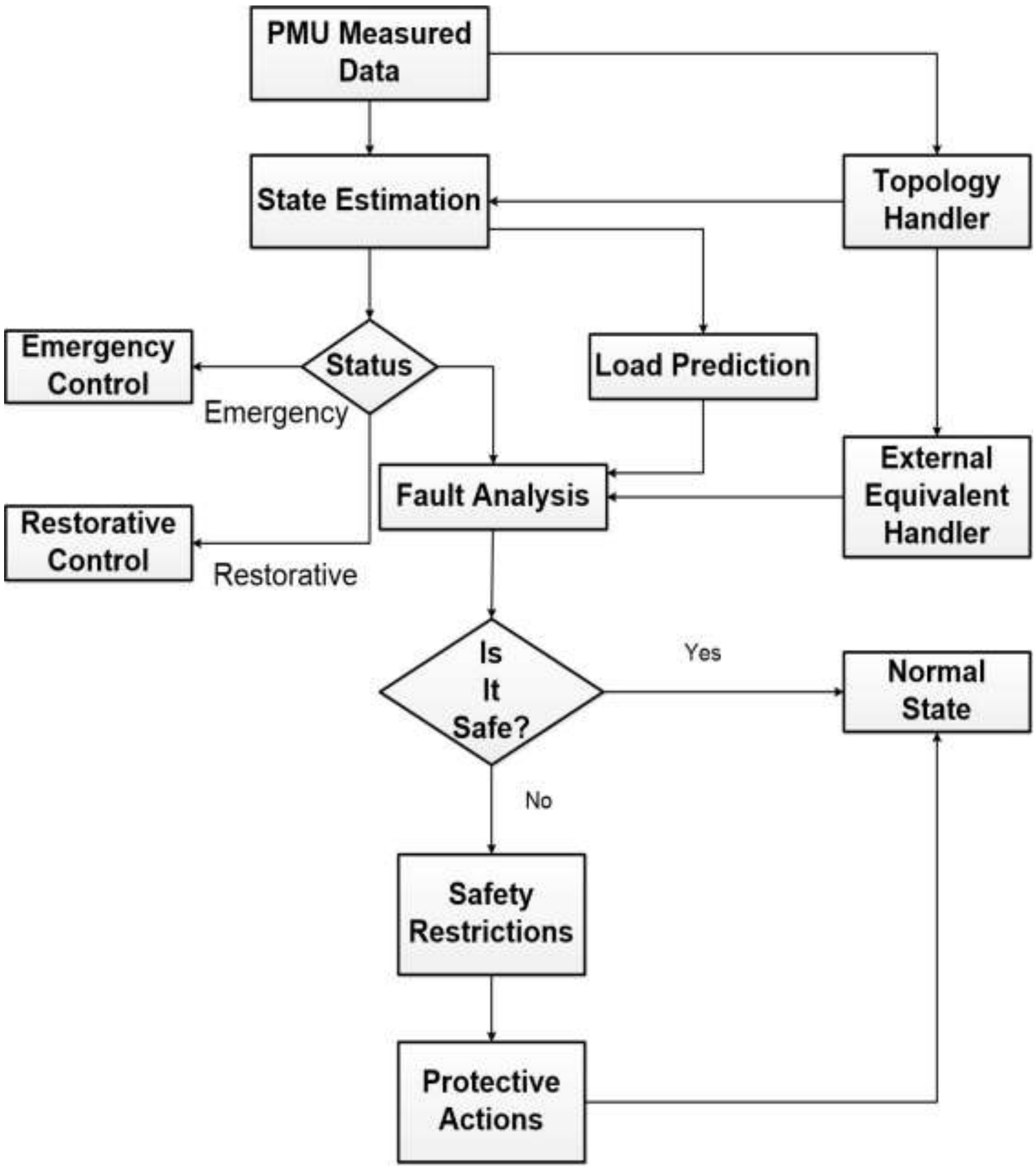

Fig.2.3 Flow chart of State Estimation based on PMUs

2.4.4. Detection of Fault

Presently, significant attempts have been devoted to the investigation and advancement of new technologies that distinguish faults that happen in the overhead transmission. The faults occurred in power system can be classified as either a permanent fault or a temporary fault. In any case, flashover on insulators can possibly prompt a full breakdown of the protector when those transient phenomena occurs frequently [49]-[51].

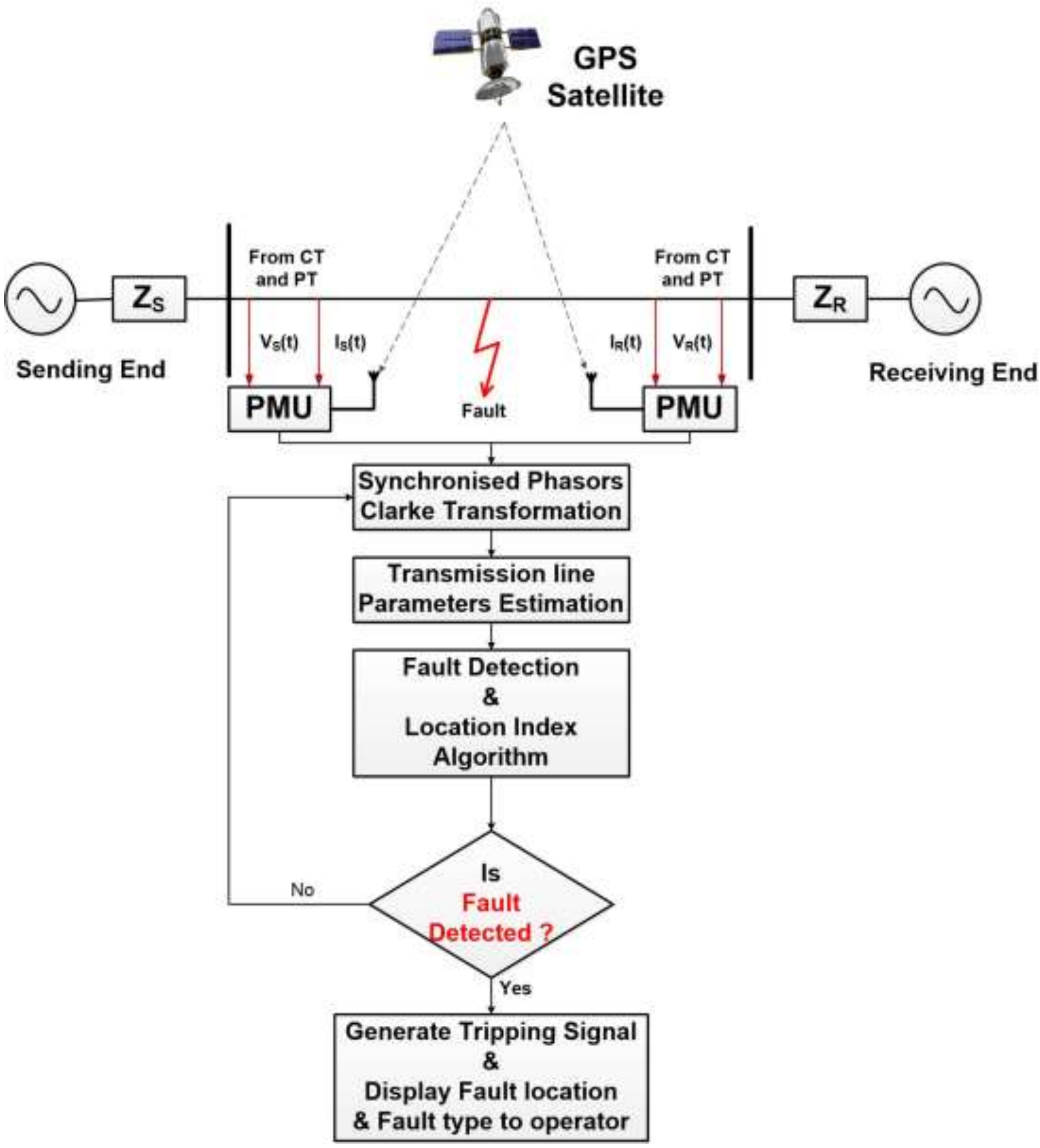

Fig.2.4 Flow chart for Fault detection based on PMU

Therefore, it is indispensable to secure and break down the entire system and need to identify the fault ahead of time. The PMU- based fault location method is capable to estimate the fault location through synchronized fault voltages as transmission lines are monitored by PMUs installed at nodes. The fault voltages measured by PMUs can be used to estimate the line currents flowing between these nodes. Using this line current, node injection fault current is estimated at two ends of terminals. Based on estimated fault node injection current, fault nodes can be concluded or fault locations in transmission lines can be determined precisely [52][53].

2.4 FLAWS IN CURRENTLY DEVELOPED PMUS

The available commercial PMUs in the market are very expensive and having guarded copyright limitations. The PMU schematics are not easily available due to company policies. The algorithms are secured by PMU copyright laws which includes the actual information of how exactly PMU works, how the measuring device is able to measure the phasors of voltage and current, what methodology applies to it and what algorithm it follows. Hence, these commercial PMUs are not allowed to use for educational and research purposes.

An open hardware platform is required to meet the desire requirements of the client. In the past, the development of low cost PMU hardware platform might be very costly but presently, the availability of advanced, high performance and low cost mirco-controller platforms gives many opportunity to developed the desired open PMU hardware platform. For research or educational purposes, an open source PMU has been manufactured which is very cost effective.

An open source PMU has been developed using LabVIEW platform. The Open Source PMU follows the IEEE (Institute of Electrical and Electronics Engineers) standards. In KTH Royal Institute of Technology, the Norwegian transmission system operator (Statnett SF) works with SmarTS lab and developed a software which provides toolkit for synchrophasor applications.

2.5 PRESENT WORK DONE IN THE AREA

2.5.1. National status

- The undertaking of URTDSM (Unified Real Time Dynamic State Measurement), offers were invited by PGCIL for presenting 1184 Phasor Measurement Units (PMUs) at 351 substations and 34 control centres across India. As this is an endeavour of national essentialness, 70% of the project cost is bolstered by the Ministry of Power through the Power System Development Fund (PSDF). The agreement covers the flexibly of both equipment and programming arrangements.
- Tetra Tech, Bangalore is taking a shot at run of the mill difficulties related with interfacing Sustainable power Sources to the Miniaturized scale lattice utilizing PMU and discovering specialized arrangement being investigated on framework augmentation, regular back up power, request side administration and in huge scope power stockpiling
- National Instruments Constrained is associated with Miniaturized scale framework robotization utilizing correspondence advancements, sensors and PMU.
- IIT Bombay has created iPDC, a free Phasor Information Concentrator.

2.5.2 International status

- Queen's College Belfast, Joined Realm, KTH, Imperial Foundation of Innovation, Sweden, Letterkenny Organization of Innovation, Ireland mutually embraced a venture to build up an Open PMU Stage.
- Sharif College of Innovation, Tehran is doing his exploration on control configuration approach on three stage matrix associated Sustainable power source Assets.
- Queens College Kingston is chipping away at this region of separating Strategies in three stage power frameworks.
- University Park, Notingham, UK is proceeding with his exploration on Control Structure and Usage for Superior Shunt Dynamic Channels in Airplane Force Matrices.

CHAPTER 3

LABORATORY SETUP

3.1 WAMS BASED ON PHASOR MEASUREMENT SYSTEM

In WAMS there are two main components, first one is the Phasor Measurement Units (PMUs) and the other one, Phasor Data Concentrators (PDCs), which are interconnected with communication technologies and time synchronized with Global Positioning Systems (GPS) [2][3].

As shown in Fig 1, WAMS infrastructure basically consist of the following units:

a). Phasor Measurement Unit (PMU)

b). Global Positioning System (GPS)

c). Phasor Data Concentrator (PDC)

d). Communication Channels

e). Control centre

PMUs have two major functions, first is to measure the analog signal and sample into digital form to estimate the phasor quantity of the signal such as, phasors of voltage and current, frequency, rate of change of frequency (ROCOF), circuit breaker and switches status with a real time tag.

PMUs are normally installed in substations across the power grid. These devices are connected to CTs (Current Transformers) and PTs (Potential Transformers) so that the line current and voltages are directly fed to these devices as shown in Fig.3.1.

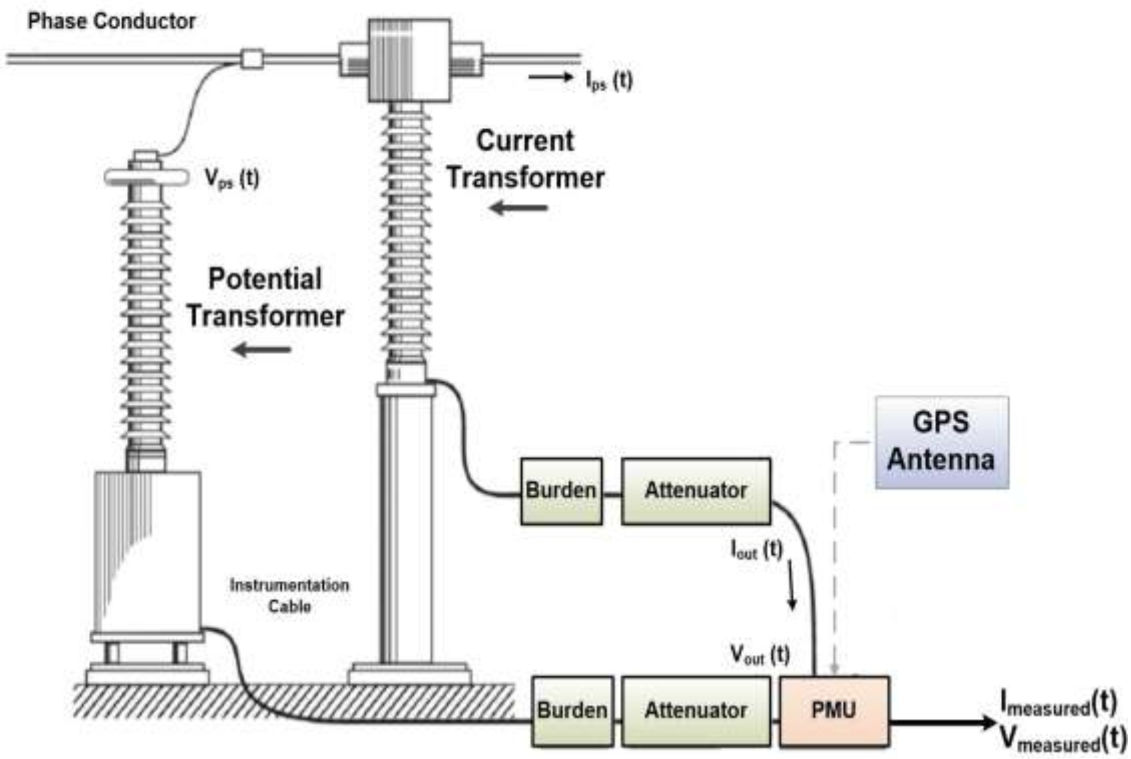

Fig.3.1 Installation of PMU In power system

3.1.1 Phasor Measurement Unit (PMU)

What is Phasor?

The Phasor is a fundamental electrical quantity which consist of magnitude and phase angle of electrical quantity with respect to reference quantity. The performance of the network is described using Phasors.

A pure sinusoid quantity is given as,

$$x(t)= X_m \cos(\omega t+\Theta) \quad (3.1)$$

and its phasor representation is given as,

$$X=(X_m/\sqrt{2})e^{j\phi} \quad (3.2)$$

Where,

X_m is the magnitude of the sinusoidal waveform,

$\omega = 2\pi f$, f is the frequency,

ϕ is the angular starting point for the waveform.

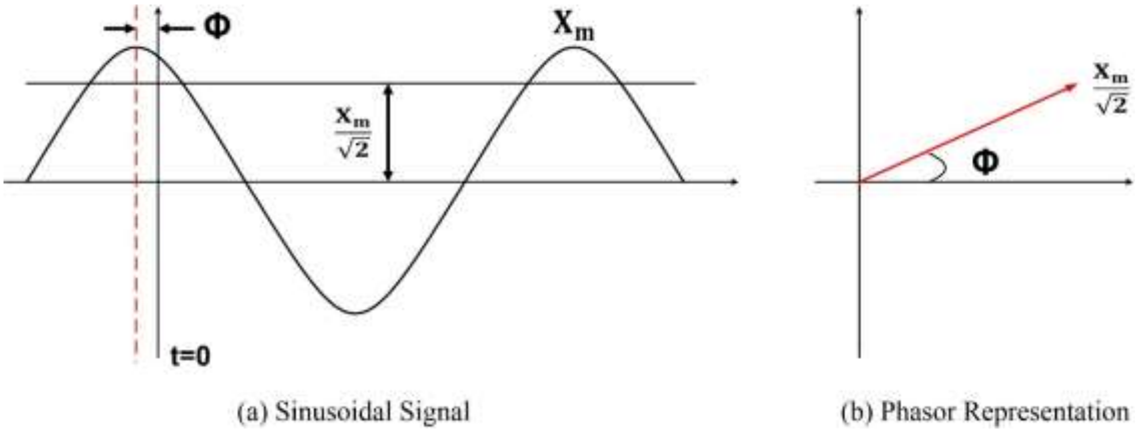

Fig 3.2. A sinusoid and its representation as a phasor

In the Fig. 3.2, the peak of the sinusoidal waveform is defined as the magnitude of the signal and the phase angle is defined as the distance between the sinusoidal peak of signal and the time reference (t = 0). Practically, the obtained signals are not pure sinusoid they consist of number of different frequencies which makes the signal corrupted. Therefore, the PMUs are synchronized with highly accurate GPS time-clock which provides the standard phase to all the PMU's installed in substations.

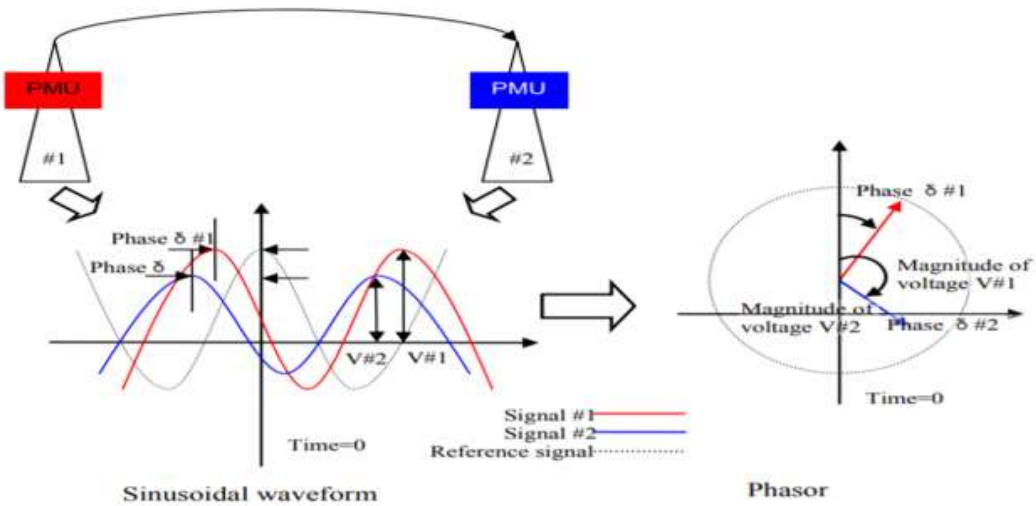

Fig.3.3 Data received by PMU

3.1.1.1 Internal Architecture of PMU

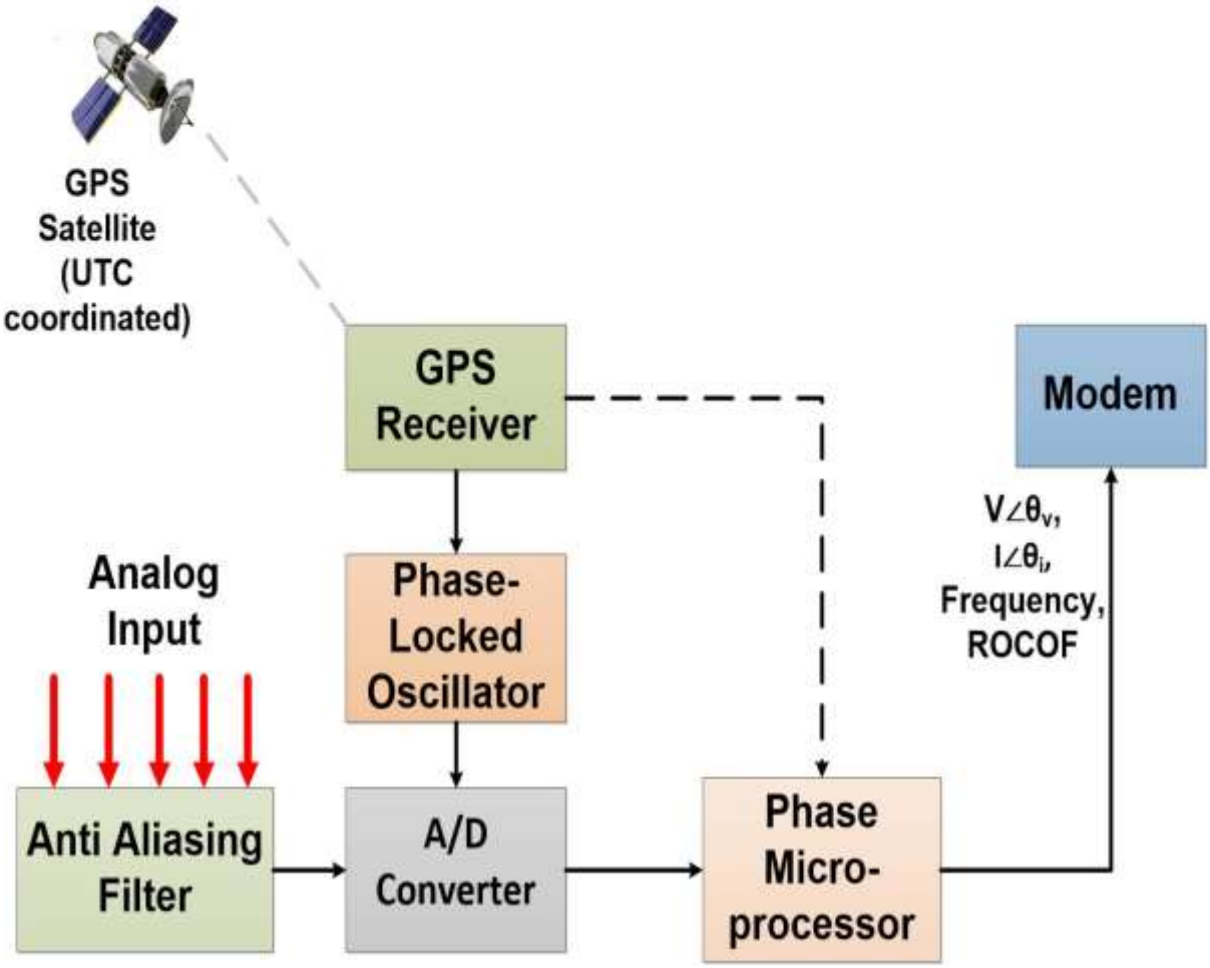

Fig.3.4 Internal Architecture of Phasor Measurement Unit

1. Anti-Aliasing Filter

The analog signals of voltage and current obtained from potential and current transformer secondaries are initially input to anti-aliasing filter for elimination of the error signals present in the received signals.

According to the sampling theorem proposed by Nyquist-Shannon, for the reformation of sampled signals,

$$fs > 2fo \quad (3.3)$$

where,

fs =frequency of sampling,

fo =maximum frequency of signal to be sampled

This filter is used to avoids the passing of signal to output, which approximately follows the sampling theorem.

2. Analog to Digital Converters

The analog to digital converter is connected at the output of the anti-aliasing filter which digitalized the samples with a sampling rate defined by phase lock oscillator.

3. Global positioning system

Global positioning system is the navigation system which is space-based satellite gives the information of time and location of the synchronized object placed at anywhere on the earth in all atmospheric conditions.

4. Phase Locked-Oscillator

The phasor measurement unit, data is directly synchronized with phase locked loop circuit (PLL) to obtained the data with reference to time. The data received from filter is phase locked with the GPS signal (i.e. one pulse per second).

5. Phasor Microprocessor

The phasor Microprocessor receives sampled data with real time stamps from Analog to digital converter and using this sampled data it determines the positive sequence components of voltage and current, using recursive algorithm, generally it is a Discrete Fourier Transform (DFT).

6. Communication

The Modem is used for the communication purpose to transmit or receive the data or other type of message formats, generate by PMU through the network either to/from Phasor data collector. The IEEE standard [40][41] defines the standard rules, protocols and message formats for data communication between the number of connected PMUs, PDCs and other connected devices for real time data measurement and transmission.

3.1.2. Phasor Data Concentrator (PDC)

Phasor Data Concentrator (PDC) receives all the Synchrophasor data from PMUs installed at different locations in power grid and this data is aligned by GPS time-tag (i.e., PDC "concentrates" the data based on real-time).

There are two type of PDCs:

a). Station Phasor Data Concentrator

b). Open source Phasor Data Concentrator (Software)

3.1.2.1 Station PDC

Synchronized data from various connected local PDCs are connected to Super Phasor Data Concentrator (Super PDC) or Station Phasor Data Concentrator at control center through Ethernet switch. This concentrated data by Super PDC is sent for control, monitoring and protection applications.

3.1.2.2 Open Source Phasor Data Concentrator

The openPDC is an information concentrator from various connected PMUs in the system. It is adaptable stage for preparing rapid time-series information that can adjust with changing innovation to give a future-proof phasor information architecture. The openPDC can be utilized to transferred information (both real-time and recorded) to expending applications and can be introduced anyplace inside the synchrophasor structure, even on PCs that run in a substation domain [42].

The openPDC actualizes various standard phasor conventions which can be utilized to get information from PMU. The supported protocols incorporate IEEE C37.118, BPA PDCstream, IEC 61850-90-5, IEEE 1344 F-NET, Macrodyne and SEL Fast Message among others.

The synchronized data with time stamped from super PDC is also send to Historian Software to store data for future requirements purpose. OpenHistorian Software has been installed from Grid Alliance Protection.

Fig.3.5. Laboratory image of OpenPDC Manager

The PMU Connection Tester is utilized to check a live stream of data is received from PDC to control center based on some defined standard protocols [43] as shown in Fig.3.6.

Fig.3.6. Laboratory image of PMU Connection Tester Software

3.1.3 PMU COMMUNICATION PROTOCOLS

The standard for communication protocols are defined for real-time synchronized phasor measurement by IEEE standard C37.118.x.2011, and data exchange takes place between various connected PMUs, PDCs and other power applications. The 2005 version of communication protocol IEEE Standard involves both measurements of synchro phasor data and real-time transfer of synchronized data [44]. The IEEE Standard C37.118-2005 was separated into two standards that accomplished the aforementioned tasks i.e., IEEE C37.118.1-2011 is defined for measurement and estimation of synchro phasor data between PMUs and connected power equipment, whereas IEEE C37.118.2-2011 is meant for synchro phasor data transfer between PMU and PDC [40][41], as shown in Fig.3.7.

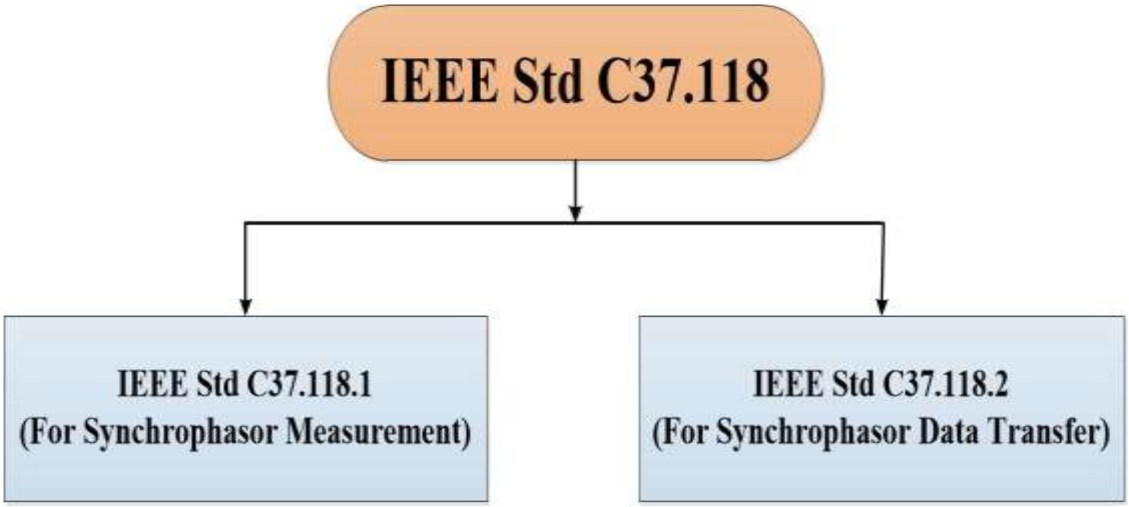

Fig.3.7. Standard communication protocols

The communication between PMU and PDC incorporates a set of four types of message types:

1. Data
2. Configuration
3. Header and
4. Command.

The first three of these i.e., the data, configuration and header message types are transmitted from PMU and PDC serving as a data source, and the last message type i.e., the command is being received by the PMU from PDC.

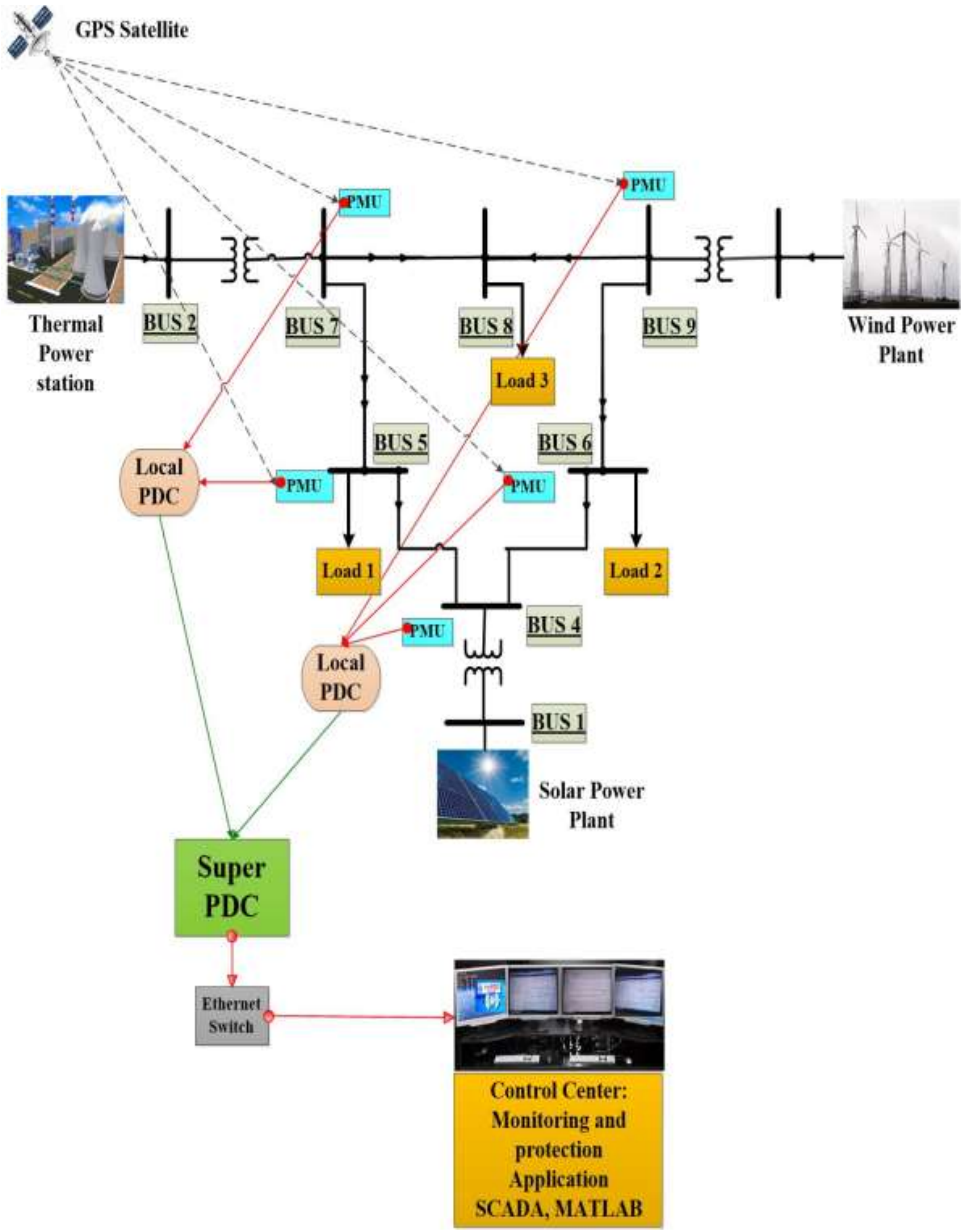

Fig.3.8. Typical Architecture of PMUs and PDCs

3.2 LABORATORY SETUP ARCHITECTURE

A laboratory scale synchro phasor data transmission IT architecture has been developed on open source products. A setup consisting of a simulator for Power system, transmission of PMU data as per IEEE Standard through TCP/IP over Ethernet switch, Phasor Data Concentrator and an application software in MATLAB has been built using following software [45],

- Student version of Power World Simulator (PWS)
- Free version of Power World Dynamic Studio (PWDS)
- Open source software Open PDC and PMU connection tester from Grid Protection Alliance
- Open source Parser software SADF from Delft University of Technology

The following steps gives the procedure of setup in two desktop PCs:

Step 1: Power World simulator is an interactive offline simulation software for analysis of Power system. Fig. 6.2 (refer Chapter 6) shows the simulation of WSCC 9 buses, 3 generators system that has been simulated in Power World Simulator Software using data given in Annexure. The simulation was performed in first desktop PC [46].

Step 2*:* To transfer the virtual PMU data from various substations in the simulation of step 1, Power World Dynamic Studio software was installed in desktop 1. This software was used to configure the data frame rate and PMU ID and IP address with port numbers for transmission of data as per IEEE standard C37.118.2.2011 as in Fig. 3.9. In this setup GPS clocks were not used for synchronization, instead local PC clock time were used.

Step 3: PMU Connection Tester software was used to test the live stream data from first desktop PC is being received or not, from the simulated power system as in Fig.3.10.The open PDC software from Grid Protection Alliance, implements a number of standard phasor protocols which can be used to receive data from devices. In this paper, IEEE C37.118.2 (2011) protocol for synchro phasor measurement units has been used for communication between these interconnected systems. The Open PDC software, PMU connection tester and application software like MATLAB are installed on second desktop PC.

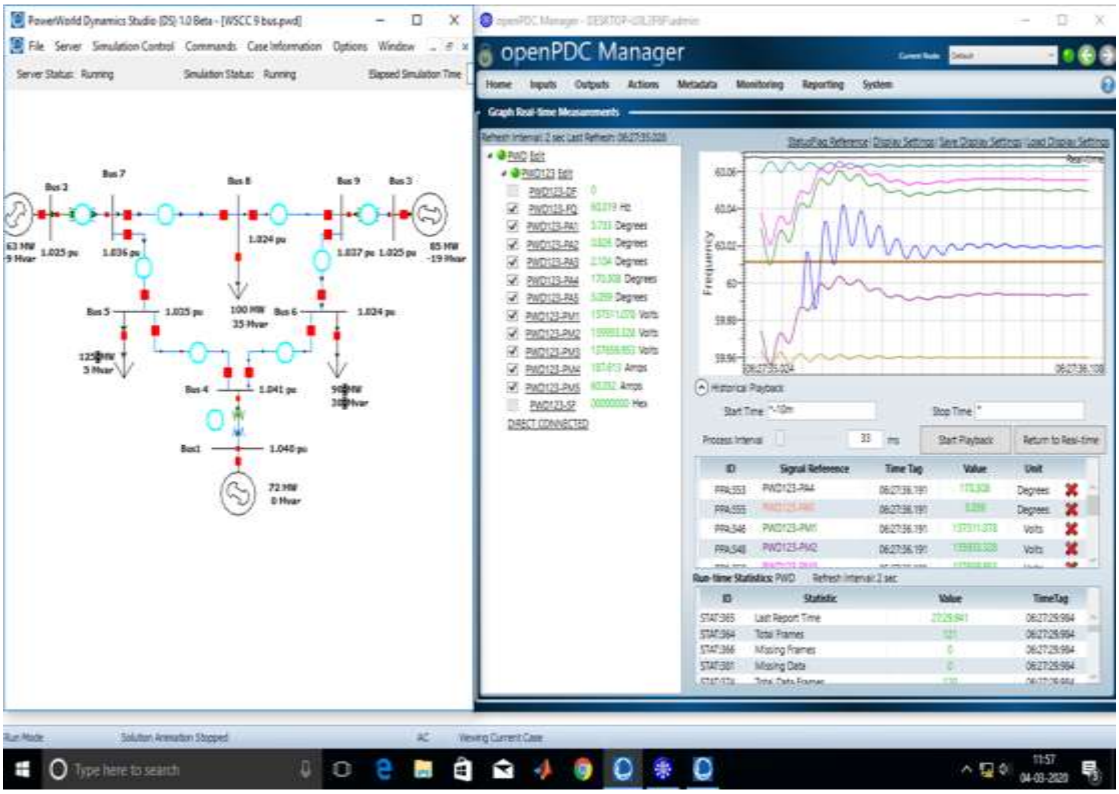

Fig.3.9. Data transferred from Power World Simulator to Open PDC through Power World Dynamic Studio

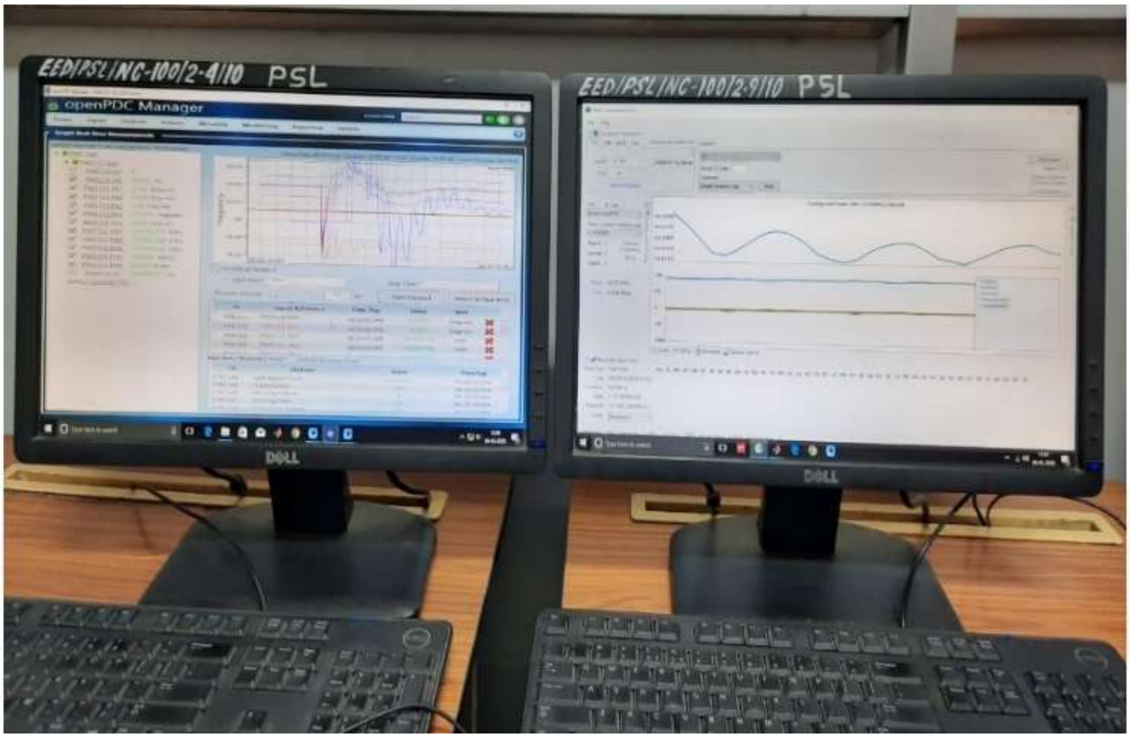

Fig.3.10. Verification of received data stream by PMU connection tester

Step 4: Parser software is required for decoding the embedded values in the protocol for analysis of the power system data. The Synchrophasor Application framework (SADF) has been developed for use with MATLAB at Delft University. This developed tool helps to parse the voltage and current flow in the simulated IEEE 9Bus system. For this purpose, the open source software SADF was installed on second desktop PC. The IP address and port numbers were configured to receive the streaming data from the Open PDC in the same desktop PC.

The overall schematic representation of the setup is given in Fig. 3.11. System I and System II are the two desktop PCs on which the open source software are installed.

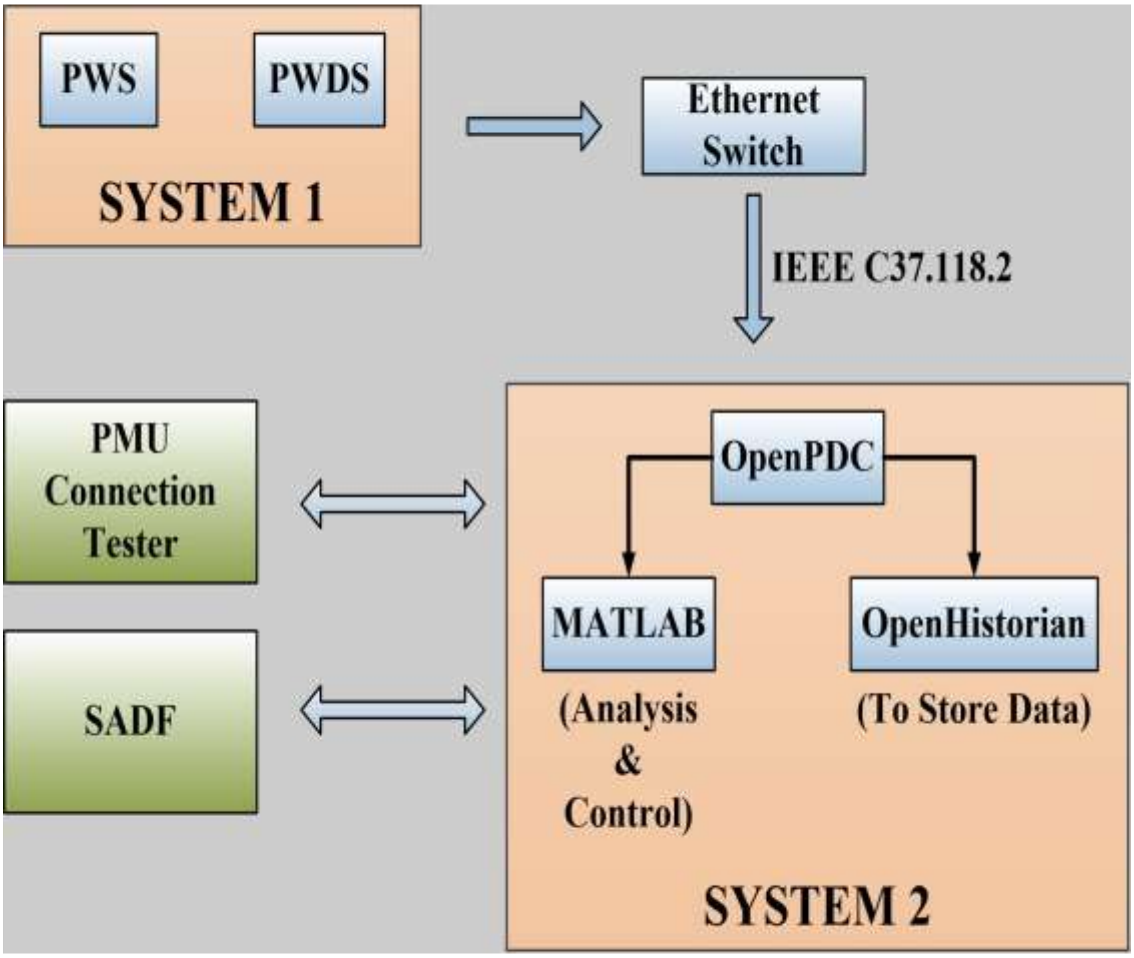

Fig.3.11. Overall schematic representation

3.3 SIMULATION RESULTS

In testing of setup, IEEE 3-machine 9-bus system has been simulated and it was assumed that all the three generator buses and transmission line buses have PMUs from which we can obtain synchronized measurement phasor data of voltage and current. Then, from received data the active power and reactive power was calculated to study the power flow in the designed system.

The setup developed was tested for two types of states in IEEE 9 bus Power system.

3.3.1. Steady state condition:

A Load flow study was performed as off line simulation in PWS. Real time transfer of data to PDC was performed with PWDS. The active power flow of branch 7-8 and branch 9-8 has been monitored in MATLAB. From the load flow result it was observed that, power transfer from bus 7 to bus 8 was 78.845 MW and from bus 9 to bus 8 was 21.658 MW. Fig.3.12 and Fig.3.13 shows the plot observed in MATLAB results developed in real time.

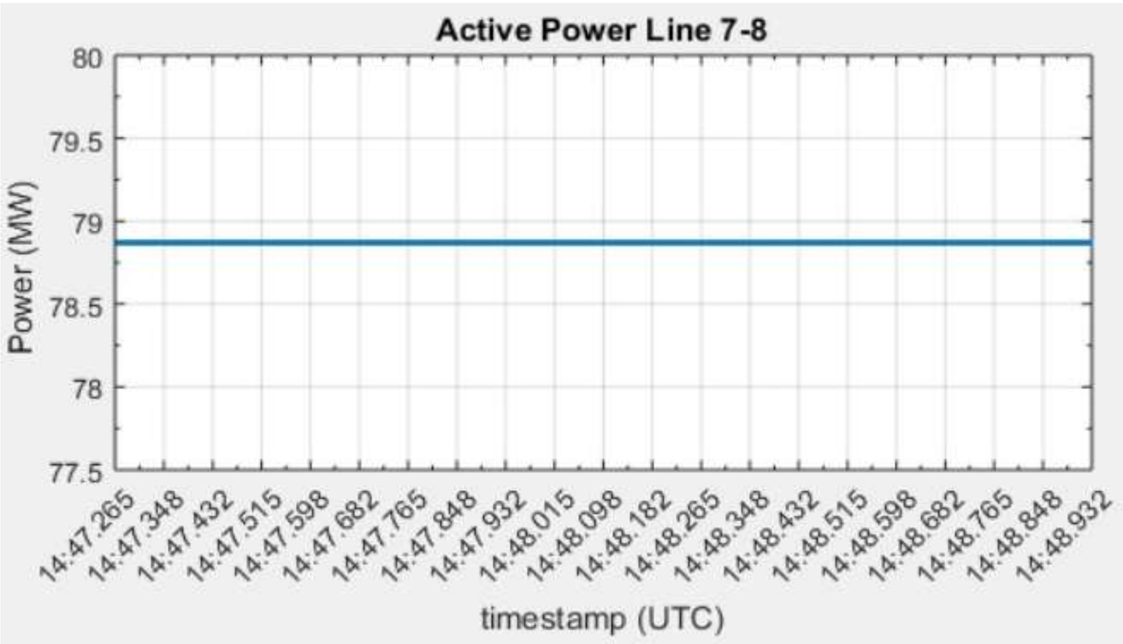

Fig.3.12. Active power waveform of branch 7-8

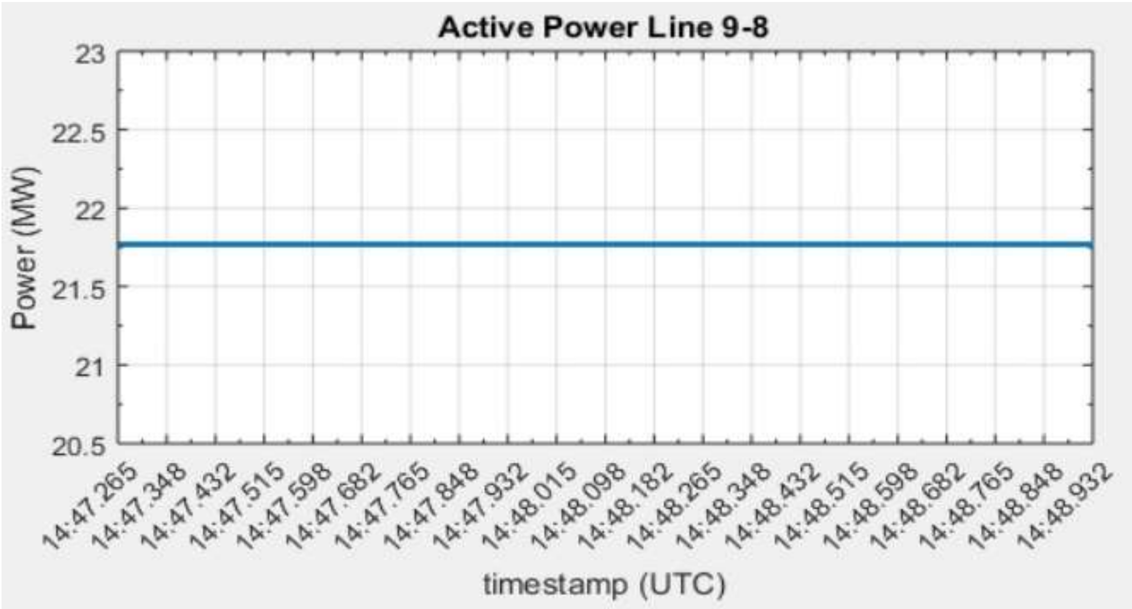

Fig.3.13. Active Power waveform of branch 9-8

Before any fault being applied the constant power is obtained from both sides to supply the required load at bus 8. in Fig.3.14.

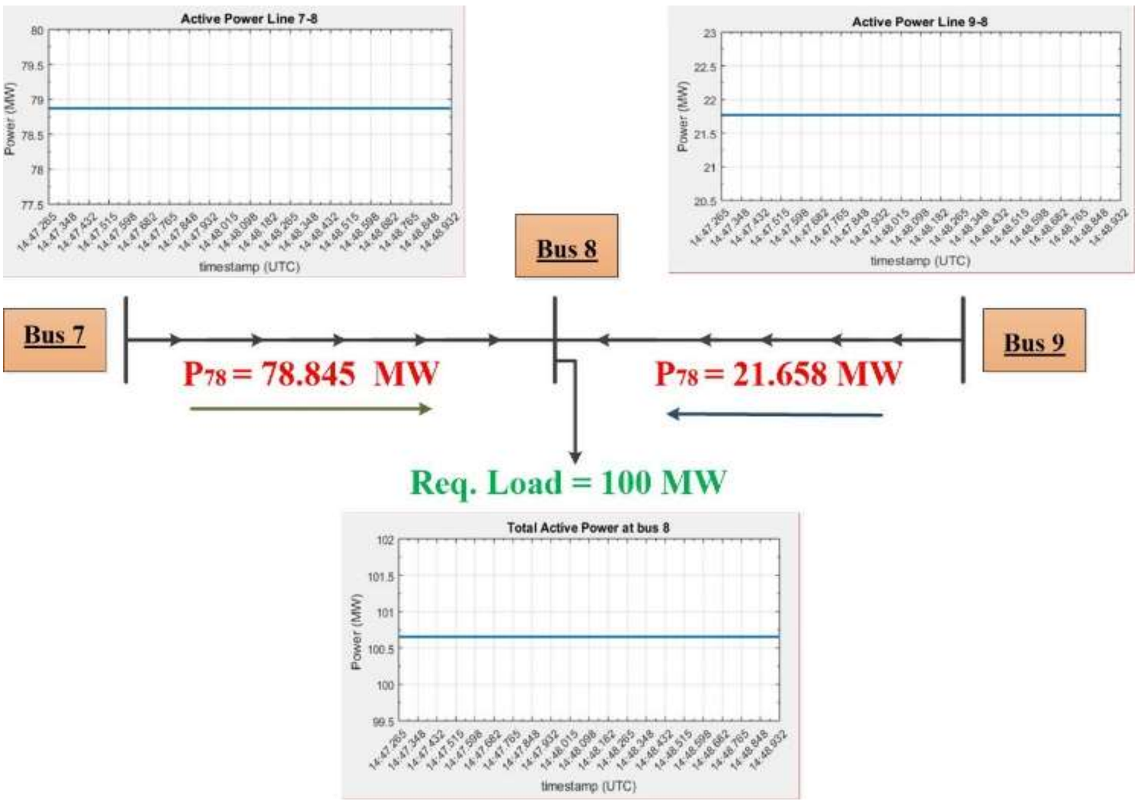

Fig.3.14. Power flow monitoring in selected branches

3.3.2. Transient condition:

A three phase balanced fault has been applied in branch 4 to 5 at 20 sec and the fault was cleared after 0.1 sec at 20.10 sec. The resultant active power waveforms observed in the MATLAB results are shown in Fig.3.15 to Fig.3.18.

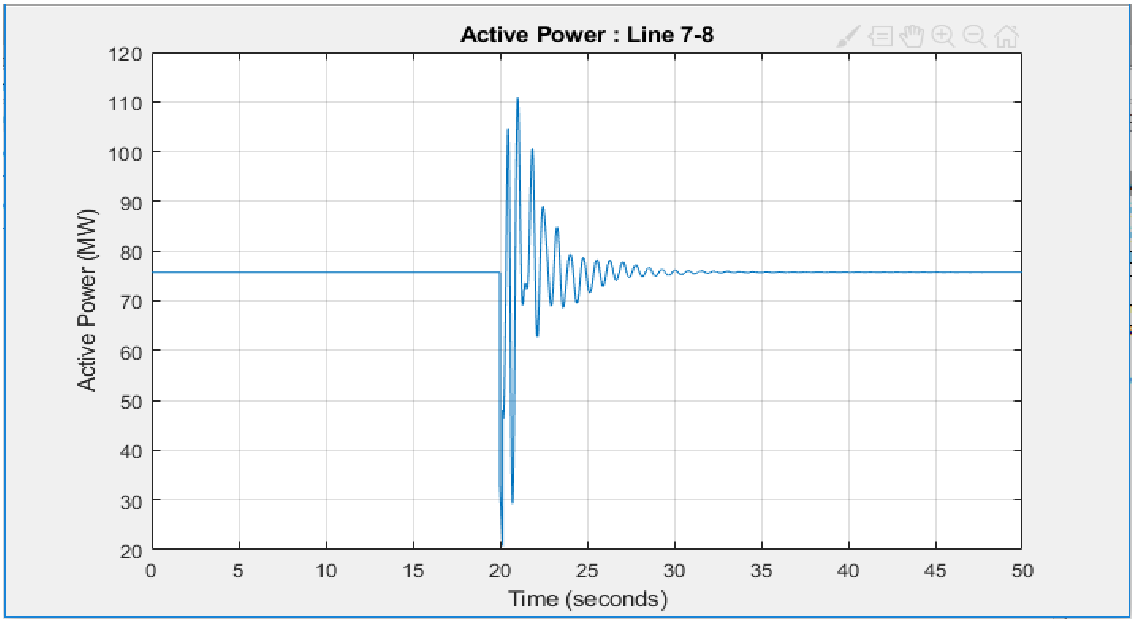

Fig.3.15. Plot of transients in branch 7-8 in PWS

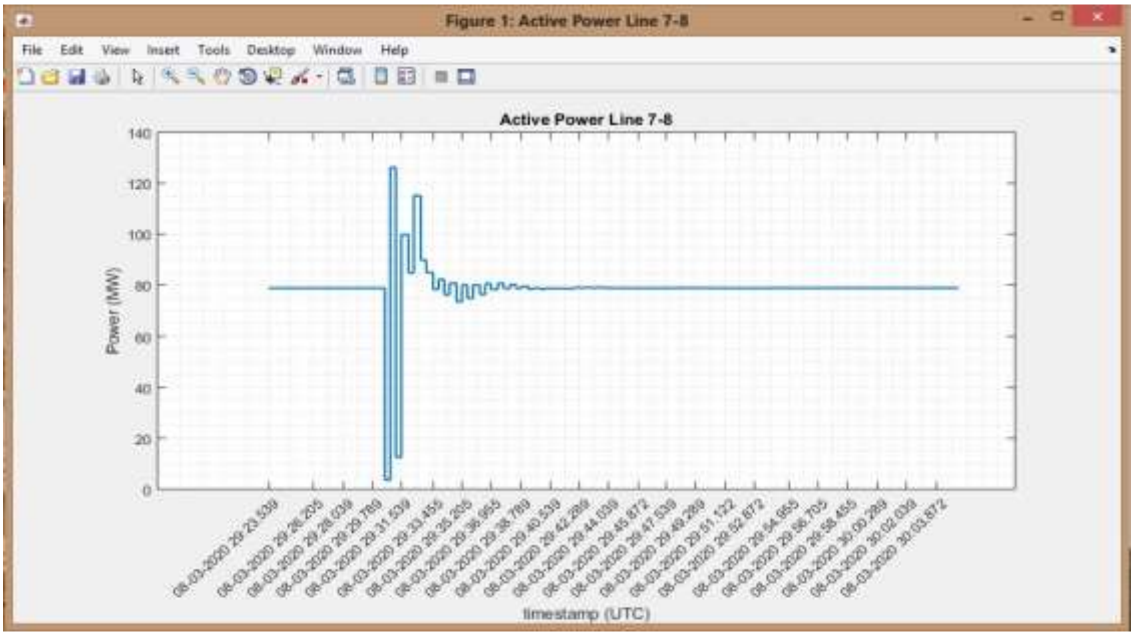

Fig.3.16. Plot of transients in branch 7-8 in MATLAB

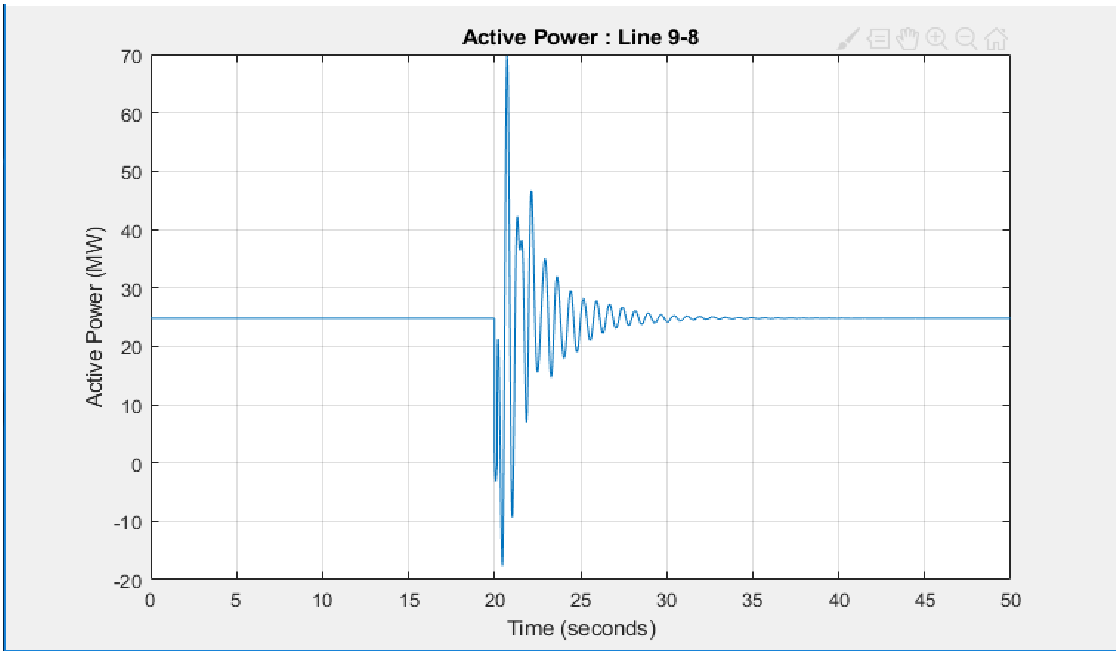

Fig.3.17. Plot of transients in branch 9-8 in PWS

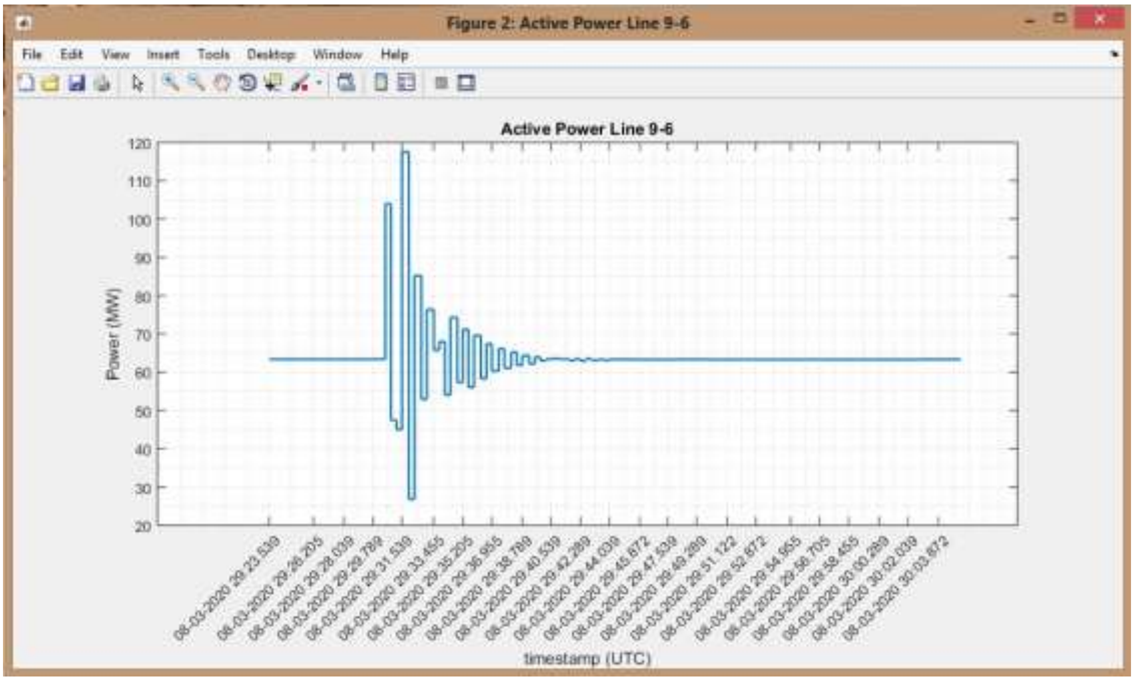

Fig.3.18. Plot of transients in branch 9-8 in MATLAB

CHAPTER 4

DYNAMIC STABILITY BASED ON PMU DATA

4.1 POWER SYSTEM STABILITY

Major objectives of power system are operational reliability and stability. Power system stability is the ability of the system to regain its operating equilibrium condition after subjected to any disturbance [47].

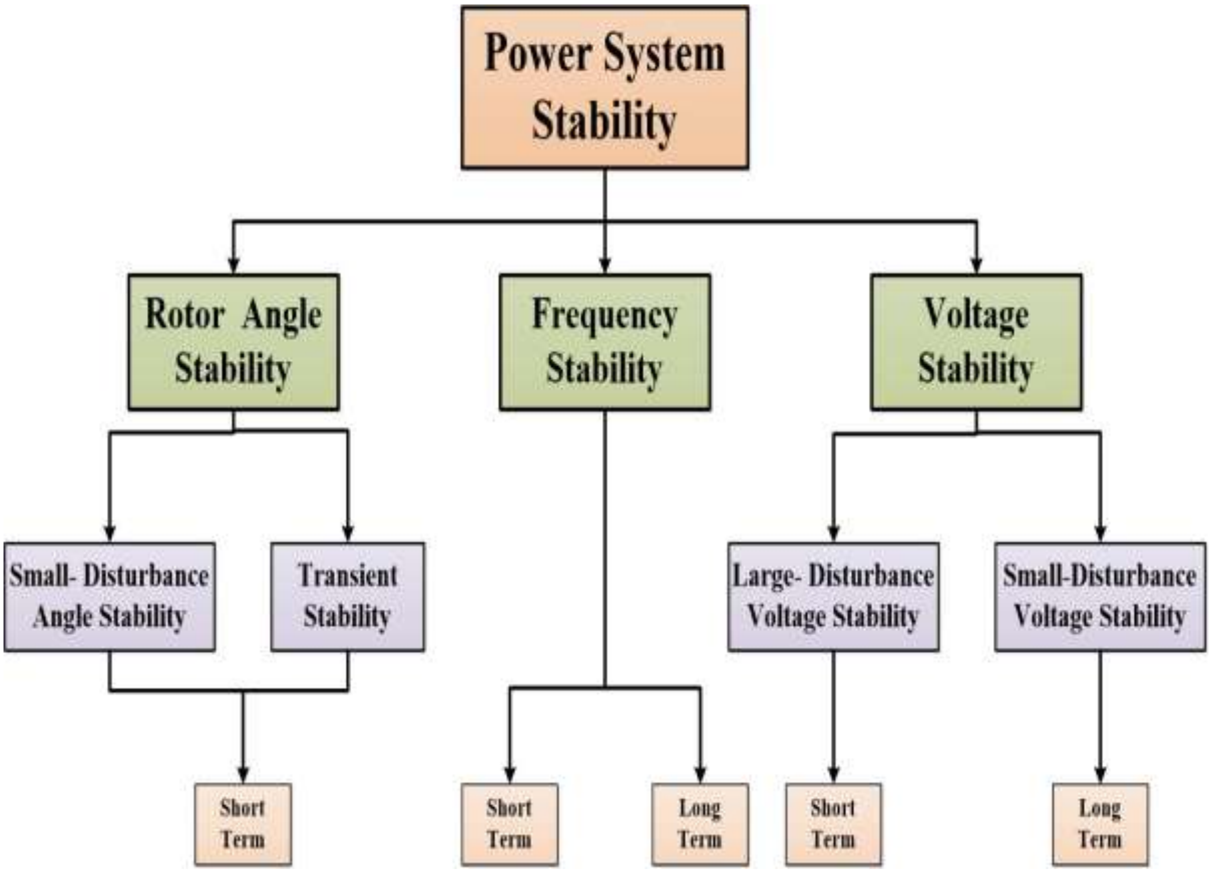

Fig.4.1 Classification of power system stability

The study of Power system stability is classified as steady-state stability (or dynamic stability) and transient stability [48][49].

a). Steady State Stability: The study of Steady State Stability is restricted to small and gradual changes in the system operating conditions. Steady-state stability is termed as the ability of the power system to maintain stability under continuous subjected small disturbances. These small disturbances are like small variations in power or rotor angle and random loads and generation levels fluctuations, over long time periods. Steady-state, or small signal, stability can be resolved from a linearized model of the power system in the area of an operating point.

b). Transient Stability: The study of Transient stability involves the impact of large disturbances such as symmetrical three- phase short circuit transmission line faults, the sudden changes in load or power angle due to sudden acceleration of the rotor shaft. Hence the transient stability is defined as the ability of the system to recover a stable equilibrium after the fault is cleared from the system or the system is supposed to be transiently stable, if all connected synchronous generator in the system comes back to acceptable point of power angles at the required synchronous frequency. The study of transient stability requires the methods for the analysis of the full nonlinear model of the system.

As shown in Fig.4.1, the power system stability study is classified as three categories: Rotor angle stability, Frequency stability and Voltage stability [50].

The motivation behind a power system is to generate and deliver electric power to consumers in a protected, reliable and economic ways. Thus, the techniques for operating and controlling the power system is very essential, particularly dynamic state estimation (DSE), short-term load forecasting, and yearly peak load forecasting. In State estimation unobservable state factors are measured from estimated system information, and can be partitioned into static state estimation (SSE) and dynamic state estimation (DSE). DSE is a significant state estimation work in energy management to give the data required to control and to evaluate the change in load demand for coming time period. The Extended Kalman (EKF) [51], [52], [53] is regularly utilized in Dynamic State Estimation applications [54]-[56].

4.1.1. The Swing Equation

An electric power system comprises of a number of synchronous machines which are operating synchronously under normal operating conditions. Under this condition, the rotor position is relatively fixed with respect to the resultant magnetic field. During any disturbance, the rotor of synchronous machine accelerates or decelerates due to which the rotor magnetic axis creates a relative motion with respect to synchronously rotating reference axis (or stator magnetic flux axis). This relative motion describes by a non-linear, second order differential equation known as the Swing Equation, which explains the swing of the rotor of the synchronous machine.

The trajectories obtained by using the swing equations are known as swing curves, and these swing curves for all the connected synchronous generators are observed to determine the stability of the system.

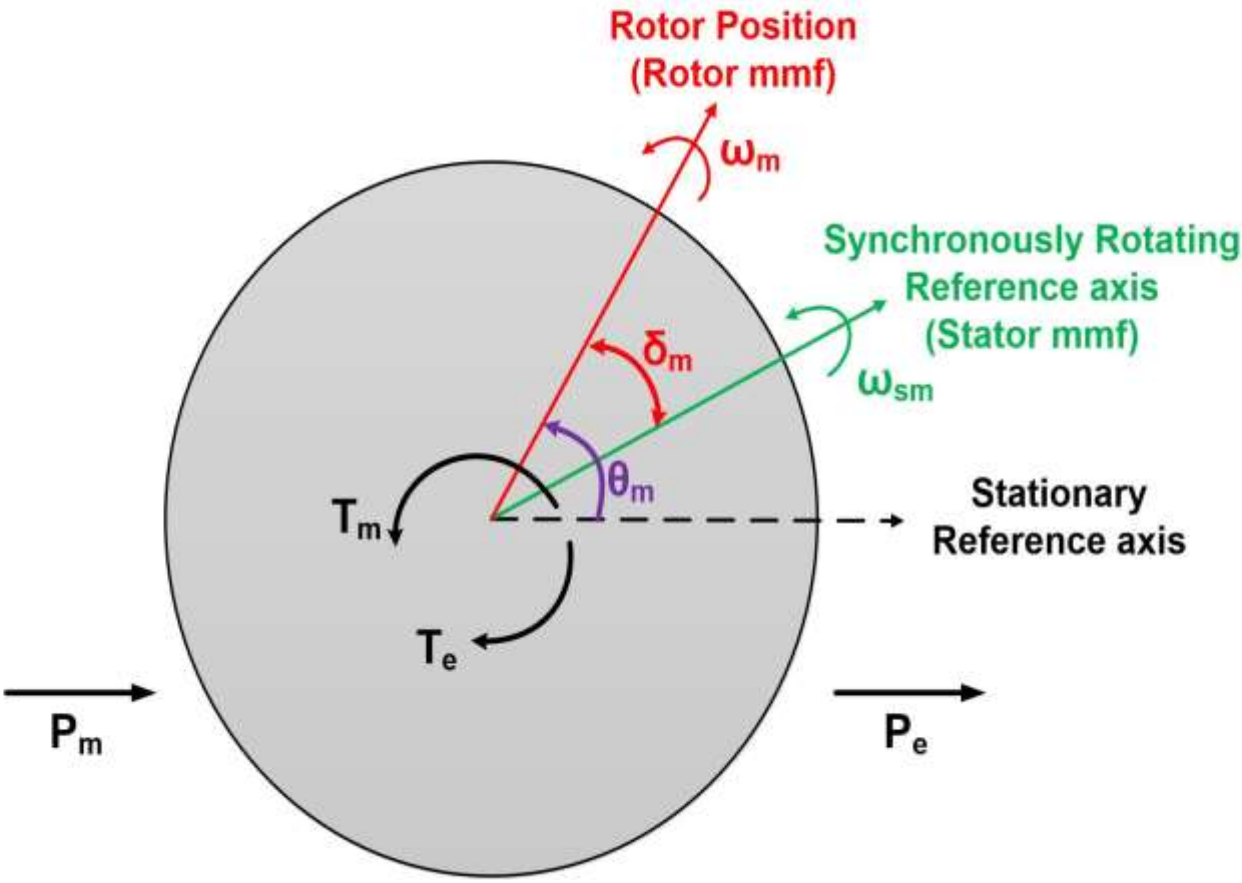

Fig.4.2. Synchronous generator: Relative Swing Motion

Where,

T_m = (mechanical torque applied by the prime mover – retarding torque due to mechanical losses) , N-m

T_e = (electrical torque applied for the electrical power output + electrical losses) , N-m

P_m = (mechanical power supplied by the prime mover –mechanical losses) , Watts

P_e = (electrical power output supplied by the generators + electrical losses) , Watts

θ_m = rotor angle position w.r.t stationary axis, rad

$\boldsymbol{\delta}_m$ = rotor angle position w.r.t synchronously rotating reference axis, rad

ω_m = angular velocity of rotor, rad/sec

ω_m = 2πf elec.rad/sec

ω_{sm} = synchronous angular velocity of rotor, rad/sec

$\omega_{sm} = \frac{2}{P}(2\pi f)$ mec.rad/sec

P= number of poles in synchronous generator

M= moment of interia

D= Damping of generator

The swing equation is given as followings:

$$M\frac{d^2\delta}{dt^2} = P_{m\ p.u.} - P_{e\ p.u.} - D\frac{d\delta}{dt} \quad (4.1)$$

$$M\frac{d\omega}{dt} = P_{m\ p.u.} - P_{e\ p.u.} - D\omega \quad (4.2)$$

Equation (4.1) is the second order, non-linear differential equation which is utilized in transient stability analysis to determine the dynamics of rotor of synchronous machines. This equation is known as per-unit Swing Equation.

4.2 ESTIMATION OF ROTOR ANGLE AND ROTOR SPEED

The power system stability is subdivided into static and dynamic phenomena. Presently, the power system stability is termed as "dynamic" phenomena of the system security. The most necessary reference electrical quantities in dynamic security evaluation and control of power system consisting of large number of synchronous machines is "Rotor angle" and "Rotor speed". The two techniques proposed in [52][53] depends on supposed classical generator model to derive rotor angles based on PMU measurements and calculation of rotor speeds numerically. The authors of [54] concluded that the estimated rotor angles are more accurate by using measurements extracted from PMUs installed at extra high voltage (EHV) side of the step-up transformer.

The significant electrical engineering perceptions are:

- The most necessary reference electrical quantities in power system transient stability evaluation and control of system consisting of large number of synchronous machines is "Rotor angle" and "Rotor speed".
- The measured quantities obtained from PMUs are electrical variables due to which they may undergo quick changes not at all like rotor angles which are mechanical variables. Therefore, under switching conditions in the electrical network, the PMU measured data experience discontinuity.
- Erroneous or noisy estimated rotor angles and speeds may bring about wrong transient security expectation and wrong assurance of control activities.

There are various techniques available to estimate the generator parameters (rotor angle and rotor speed) using real-time measurements from PMU such as artificial Neural Networks and classical generator model.

4.2.1. Rotor Angle Algorithm

The changes in rotor angle directly effects the electrical nature of the generator, but rotor angle is mechanical quantity so cannot be measured directly by PMU. Therefore, the rotor angle is estimated using electrical quantities measured from PMU. At each instant, the rotor angle is estimated based on PMU measurements received as magnitude and phase angle of generator terminal voltage ($V\angle\theta$) and output current ($I\angle\phi$). Using Wide Area Measurement System (WAMS) techniques, the phasors of generator terminal voltage and output current is measured in real-time by PMU with respect to variables of slack bus (reference bus).

The rotor angle is estimated by considering equivalent generator model which represents the aggregated equivalent of all the machines connected in the power system. The electrical parameters are calculated by using phasor diagram of voltage- current of synchronous generator as shown in Fig. 4.3 (the sub-transient variables are ignored).

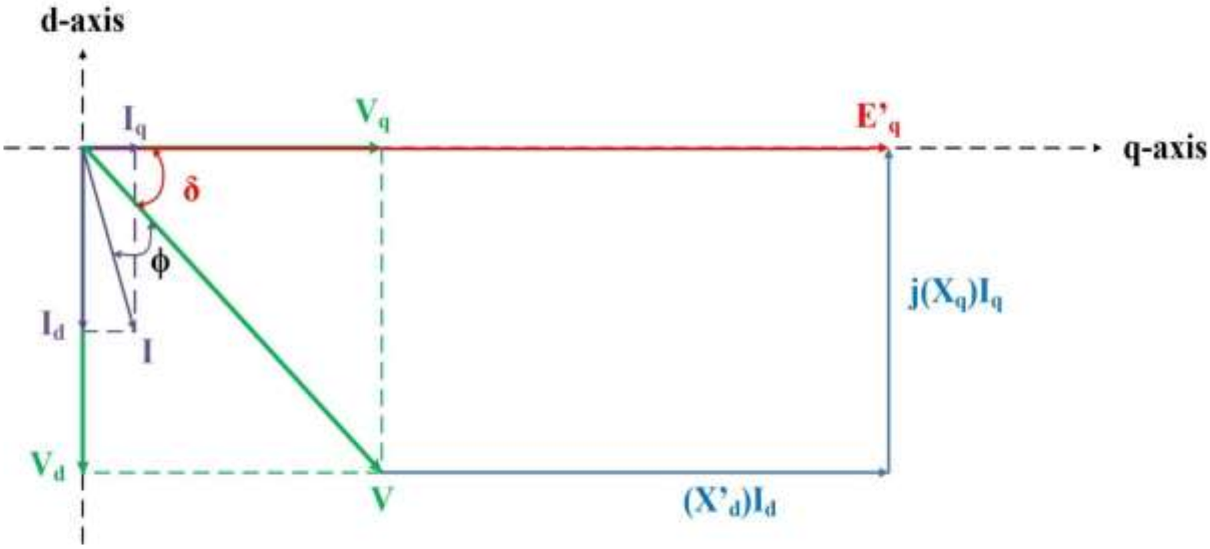

Fig.4.3. Phasor Diagram of generator equivalent system

where:

δ : generator rotor angle w.r.t terminal voltage

V_t : generator terminal voltage magnitude measured by PMU

I_a : generator current magnitude measured by PMU

Φ : phase angle of the generator current w.r.t its terminal voltage measured by PMU

$$V_d = X_q I_q \tag{4.3}$$

$$V_t \operatorname{Sin}(\boldsymbol{\delta}) = X_q \; I_a \times \operatorname{Cos}(\boldsymbol{\delta} + \phi) \tag{4.4}$$

$$V_t Sin(\boldsymbol{\delta})=X_q\ I_a \times [Cos(\boldsymbol{\delta}).Cos(\phi) - Sin(\boldsymbol{\delta}).Sin(\phi)] \quad (4.5)$$

$$V_t\ Sin(\boldsymbol{\delta})+X_q I_a.Sin(\boldsymbol{\delta}).Sin(\phi) = X_q\ I_a\ .Cos(\boldsymbol{\delta}).Cos(\phi) \quad (4.6)$$

$$[V_t+X_q I_a.Sin(\phi)]\times Sin(\boldsymbol{\delta}) = [X_q\ I_a\ .Cos(\phi)] \times Cos(\boldsymbol{\delta}) \quad (4.7)$$

$$\tan(\boldsymbol{\delta}) = \frac{X_q I_a\ Cos(\phi)}{V_t + X_q I_a\ Sin(\phi)} \quad (4.8)$$

We need to estimate the rotor angle with respect to network slack bus or machine connected to the slack bus by using equations (4.9) and (4.10) from estimated rotor angle of each generator (i) w.r.t terminal voltage.

$$\boldsymbol{\delta}_{iS} = \theta_i + \boldsymbol{\delta}_i \quad (4.9)$$

$$\boldsymbol{\delta}_{iR} = \boldsymbol{\delta}_R - \boldsymbol{\delta}_{iS} \quad (4.10)$$

Where:

$\boldsymbol{\delta}_i$: generator i rotor angle w.r.t its terminal bus (i)

$\boldsymbol{\delta}_R$: reference machine rotor angle w.r.t its terminal bus (slack)

θ_i : the phase angle of the generator terminal voltage w.r.t the network slack measured by PMU.

$\boldsymbol{\delta}_{iS}$: rotor angle of generator i w.r.t network slack bus.

$\boldsymbol{\delta}_{iR}$: rotor angle of generator i w.r.t system machine connected to slack bus.

4.3.2. Rotor Speed Estimation

The rotor speed of generator is measured by approximation method utilising estimated rotor angles at different instants of time using equation (4.11) as,

$$\omega(t) = \frac{\delta(t+1) - \delta(t)}{\Delta t} \quad (4.11)$$

CHAPTER 5

STATE JACOBIAN MATRIX AND STATE MATRIX

5.1 BACKGROUND OF THE METHOD

In system state estimation the general power system dynamic model is represented as,

$$\dot{x}=a(x,y) \tag{5.1}$$

$$0=b(x,y) \tag{5.2}$$

where, a and b are continuous functions. The generator dynamics is represented by equation (5.1), and electrical transmission system and the internal static behaviour of passive devices is represented by equation (5.2) in which x is state variable describes generator rotor angle and rotor speed and y is algebraic variable describes bus voltage and bus voltage angles [60][61].

Small signal stability is considered in this work, in which power system shows ambient oscillations around steady state. When power system operates around the steady state, the ambient information is received without subjected to any extra disturbances. Therefore, we mainly focus on ambient oscillations around the steady state which is dominated by the dynamic of generator angles. Therefore, under this condition classical generator model is considered which represents dynamics of all connected generators in coherent conditions. [63]

On considering Swing equation, equation (5.1)-(5.2) written as, [21][23][62]:

$$\dot{\delta} = \omega \tag{5.3}$$

$$M\,\dot{\omega} = P_m - P_e - D\omega \tag{5.4}$$

Where,

$$P_e = \sum_{j=1}^{n} E_i E_j (G_{ij} Cos(\delta_{ij}) + B_{ij} Sin(\delta_{ij})) \quad (5.5)$$

$\boldsymbol{\delta} = [\delta_1,...\delta_n]^T$ generator rotor angles,

$\boldsymbol{\omega} = [\omega_1,...\omega_n]^T$ generator rotor speeds,

$\boldsymbol{P}_m = [P_{m1},...P_{mn}]^T$ generators input mechanical power,

$\boldsymbol{Pe} = [P_{e1},...P_{en}]^T$ generators output electrical power,

$M = diag(M_1,...M_n)$ generator inertia constants,

$D = diag(D_1,...D_n)$ generator damping factors,

$E_i = [E_1,\ldots,E_n]^T$ emf magnitude behind the transient reactance,

$Y_{ij}\angle\varphi_{ij} = G_{ij} + jB_{ij}$ is the reduced admittance matrix of the system which also includes generators impedances and rotor saliency is assumed to be neglected.

5.1.1 Calculation of Reduced Admittance Matrix

To calculate the Reduced admittance matrix from the bus admittance matrix Y_{bus}, the network admittance is reduced to all the generator buses and elimination of all other buses.

The node voltage equation with respect to ground reference is given as:

$$[I_{bus}] = [Y_{bus}]\,[V_{bus}] \quad (5.6)$$

$$\begin{bmatrix} I_1 \\ \vdots \\ I_n \\ I_{n+1} \\ \vdots \\ I_{n+p} \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1n} & Y_{1(n+1)} & \cdots & Y_{1(n+p)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & \cdots & Y_{nn} & Y_{n(n+1)} & \cdots & Y_{n(n+p)} \\ Y_{(n+1)1} & \cdots & Y_{(n+1)n} & Y_{(n+1)(n+1)} & \cdots & Y_{(n+1)(n+p)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Y_{(n+p)1} & \cdots & Y_{(n+p)n} & Y_{1(n+p)(n+1)} & \cdots & Y_{(n+p)(n+p)} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_n \\ V_{n+1} \\ \vdots \\ V_{n+p} \end{bmatrix} \quad (5.7)$$

Where,

n is the number of generator buses and (n+p) is the total number of buses

I_{bus} is the current injected in the bus,

V_{bus} is the voltage of the bus with respect to ground and

Y_{bus} is the bus admittance matrix, in which Y_{ii} (the diagonal elements) is the sum of the admittance of all the branches connected to bus i and Y_{ij} (the off-diagonal elements) is the negative of the admittance between two buses i and j. For reduced admittance matrix all nodes other than the generator nodes are eliminated.

To eliminate all buses other than the generator terminal buses, make their injected bus current to be zero.

Let us assume that $[I_1,\ldots, I_n]$ are the generating buses, equation (5.7) is rewrite as followings:

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{pp} & Y_{np}^{t} \\ Y_{np} & Y_{nn} \end{bmatrix} \begin{bmatrix} V_n \\ V_p \end{bmatrix} \tag{5.8}$$

$$I_n = [Y_{pp} - Y_{np}^{t} Y_{nn}^{-1} Y_{np}]\, V_n \tag{5.9}$$

Therefore, the reduced admittance matrix is defined as,

$$Y_r = [Y_{pp} - Y_{np}^{t} Y_{nn}^{-1} Y_{np}] \tag{5.10}$$

We assumed that network loads are encountering Gaussian variation around base case loading, which is the most well-known assumption to model load variation [54]. These load variations are included in the diagonal elements of reduced admittance matrix as [42] [43],

$$Y(i,i) = Y_{ii}\,(1+ \sigma_i\, dW_i) \angle \phi_{ii} \tag{5.11}$$

Where,

W : Standard Wiener process

σ_i^2 : variance of load variation

5.2 STUDY OF PROPOSED METHOD

In this paper, we assume that the designed power system is experiencing the stochastic load variations [42]. To reveal the random load variations the power system model is now represented as,

$$\dot{\delta} = \omega \tag{5.12}$$

$$M\,\dot{\omega} = P_m - P_e - D\omega - E^2 G \sum \mathcal{E} \tag{5.13}$$

Where,

$G = \text{diag}([G_{11},...,G_{nn}])$ equivalent conductance ;

$\Sigma = \text{diag}([\sigma_1,...,\sigma_n])$ variance of load variation ;

$\mathcal{E} = [\,\dot{\omega}_1,..., \dot{\omega}_n]^T$ standard Gaussian random variable.

As we are considering ambient oscillations due to random load variations, the aforementioned system is linearized around steady state and equations are as followings:

$$\begin{bmatrix} \dot{\delta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{d\dot{\delta}}{d\delta} & \frac{d\dot{\delta}}{d\omega} \\ \frac{d\dot{\omega}}{d\delta} & \frac{d\dot{\omega}}{d\omega} \end{bmatrix} \begin{bmatrix} \delta \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{d\dot{\delta}}{d\mathcal{E}} \\ \frac{d\dot{\omega}}{d\mathcal{E}} \end{bmatrix} \mathcal{E} \tag{5.14}$$

$$\begin{bmatrix} \dot{\delta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & I_n \\ -M^{-1}\frac{dP_e}{d\delta} & -M^{-1}D \end{bmatrix} \begin{bmatrix} \delta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ -M^{-1}E^2 G\mathcal{E} \end{bmatrix} \mathcal{E} \tag{5.15}$$

Let, $x = \begin{bmatrix} \delta \\ \omega \end{bmatrix}$,

$$A = \begin{bmatrix} 0 & I_n \\ -M^{-1}\frac{dP_e}{d\delta} & -M^{-1}D \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ -M^{-1}E^2 G\mathcal{E} \end{bmatrix}$$

Where,

I_n : Identity matrix, with n being the size of the system, The equation (5.15) describes the set of stochastic differential equations which follows Vector Ornstein Uhlenbeck process [17] as followings:

$$\dot{x} = \mathrm{A}x + \mathrm{B}\mathcal{E} \tag{5.16}$$

If the obtained state matrix A of the system is stable, then the stationary covariance matrix, C_{xx} can be used to satisfy the following Lyapunov equation of the model [18]:

$$\mathrm{A}C_{xx} + C_{xx}\mathrm{A}^{T} = -\mathrm{B}\mathrm{B}^{T} \tag{5.17}$$

Where,

$$C_{xx} = \begin{bmatrix} C_{\delta\delta} & C_{\delta\omega} \\ C_{\omega\delta} & C_{\omega\omega} \end{bmatrix}$$

Let J= Jacobian matrix $=\frac{dP_e}{d\delta}$, using aforementioned equations (5.15),(5.16) and (5.17),

$$\begin{bmatrix} 0 & \mathrm{I_n} \\ -\mathrm{M}^{-1}\mathrm{J} & -\mathrm{M}^{-1}\mathrm{D} \end{bmatrix} \begin{bmatrix} \mathrm{C}_{\delta\delta} & \mathrm{C}_{\delta\omega} \\ \mathrm{C}_{\omega\delta} & \mathrm{C}_{\omega\omega} \end{bmatrix} + \begin{bmatrix} \mathrm{C}_{\delta\delta} & \mathrm{C}_{\delta\omega} \\ \mathrm{C}_{\omega\delta} & \mathrm{C}_{\omega\omega} \end{bmatrix} \begin{bmatrix} 0 & -\mathrm{M}^{-1}\mathrm{J} \\ \mathrm{I_n} & -\mathrm{M}^{-1}\mathrm{D} \end{bmatrix} =$$

$$(-1)\begin{bmatrix} 0 \\ -\mathrm{M}^{-1}\mathrm{E}^2\mathrm{G}\mathcal{E} \end{bmatrix} \begin{bmatrix} 0 & -\mathrm{M}^{-1}\mathrm{E}^2\mathrm{G}\mathcal{E} \end{bmatrix} \tag{5.18}$$

$$\begin{bmatrix} \mathrm{I_n}\mathrm{C}_{\omega\delta} & \mathrm{I_n}\mathrm{C}_{\omega\omega} \\ -\mathrm{M}^{-1}(\mathrm{J}\mathrm{C}_{\delta\delta} + \mathrm{D}\mathrm{C}_{\omega\delta}) & -\mathrm{M}^{-1}(\mathrm{J}\mathrm{C}_{\delta\omega} + \mathrm{D}\mathrm{C}_{\omega\omega}) \end{bmatrix} + \begin{bmatrix} \mathrm{I_n}\mathrm{C}_{\delta\omega} & \mathrm{M}^{-1}(\mathrm{J}\mathrm{C}_{\delta\delta} + \mathrm{D}\mathrm{C}_{\delta\omega}) \\ \mathrm{I_n}\mathrm{C}_{\omega\omega} & \mathrm{M}^{-1}(\mathrm{J}\mathrm{C}_{\omega\delta} + \mathrm{D}\mathrm{C}_{\omega\omega}) \end{bmatrix} =$$

$$\begin{bmatrix} 0 & 0 \\ 0 & \mathrm{M}^{-2}\mathrm{E}^4\mathrm{G}^2\mathcal{E}^2 \end{bmatrix} \tag{5.19}$$

On solving above equation,

$$C_{\delta\omega} + C_{\omega\delta} = 0 \tag{5.20}$$

$$C_{\delta\omega} + C_{\delta\omega}^{T} = 0 \tag{5.21}$$

$$C_{\omega\omega} - M^{-1}(JC_{\delta\delta} + DC_{\delta\omega}^{T}) = 0 \tag{5.22}$$

$$M^{-1}(JC_{\delta\omega} + DC_{\omega\omega}) + (C_{\delta\omega}^{T} J^{T} + C_{\omega\omega}D)M^{-1} = M^{-2}G^{2}E^{4}\mathcal{E}^{2} \quad (5.23)$$

On solving equation (5.23), J is obtained as followings:

$$J = MC_{\omega\omega}C_{\delta\delta}^{-1} + DC_{\delta\omega}C_{\delta\delta}^{-1} \quad (5.24)$$

On putting equation (22) in (21),

$$C_{\delta\omega} = 0 \quad (5.25)$$

$$C_{\delta\delta} = \left(\frac{\partial P_e}{\partial \delta}\right)^{-1} M\, C_{\omega\omega} \quad (5.26)$$

$$C_{\omega\omega} = \frac{1}{2} M^{-1}D^{-1}\Sigma^{2} \quad (5.27)$$

The expressions for the Jacobian and damping matrix is obtained as followings:

$$\left(\frac{\partial P_e}{\partial \delta}\right) = M\, C_{\omega\omega}\, C_{\delta\delta}^{-1} \quad (5.28)$$

$$D = \frac{1}{2} M^{-1}\Sigma^{2} / C_{\omega\omega} \quad (5.29)$$

From the equation (5.28), it can be concluded that Jacobian Matrix can be calculated by using covariance matrices $C_{\delta\delta}$ and $C\omega\omega$ and inertias, M of all the connected generators. As M is generally known and covariance matrices are calculated from the data extracted based on PMU measurements. It is also noticed that the estimation of Jacobian matrix using equation (5.28) does not require the network topology and parameters. The standard deviation of load variations $\sum$ is not included in the equation (5.28) indicates that the estimation of Jacobian matrix using proposed technique does not affected by the noise disturbances.

For estimation of system state matrix, A the additional Damping factor, D of the generators must be known. In some cases of classical model D is not known, which can be calculated using (5.29). However, to estimate D some of the network parameters need to be known such as generator emf, conductance and variance of load variation. In this paper, we have assumed that damping factor is known so that it is easy to calculate the state matrix, A.

5.2.1. Determination of Sample Covariance Matrices

The covariance matrix of generator rotor speed is defined as:

$$C_{\omega\omega} = \begin{bmatrix} C_{\omega_1\omega_1} & C_{\omega_1\omega_2} & \cdots & C_{\omega_1\omega_n} \\ C_{\omega_2\omega_1} & C_{\omega_2\omega_2} & \cdots & C_{\omega_2\omega_n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{\omega_n\omega_1} & C_{\omega_n\omega_2} & \cdots & C_{\omega_n\omega_n} \end{bmatrix} \quad (5.30)$$

The element entries is defined as followings:

$$C_{\omega_i\omega_j} = E\,[(\omega_i - \overline{\omega}_i)\,(\omega_j - \overline{\omega}_j)] \quad (5.31)$$

Where, $\overline{\omega}_i$ is the mean of ω_i and E is the emg's of generator.

In this work, the window size is selected around 200sec. As limited PMUs are connected so it is difficult to estimate the covariance matrix. Therefore, covariance matrix is replaced by sample covariance matrix whose entries are independent of network parameters. The entries of sample covariance matrix is defined as,

$$Q_{\omega_i\omega_j} = \frac{1}{N-1}\sum_{k-1}^{N}(\tilde{\omega}_{ki} - \overline{\tilde{\omega}_{\iota}})(\tilde{\omega}_{kj} - \overline{\tilde{\omega}_{j}}) \quad (5.32)$$

Where, N is the sample size. In this paper, we assumed that the PMU provides samples at the rate of 50 samples per sec.

Similarly, the sample covariance matrix of generator rotor angle is defined as,

$$Q_{\delta_i\delta_j} = \frac{1}{N-1}\sum_{k-1}^{N}(\tilde{\delta}_{ki} - \overline{\tilde{\delta}_{\iota}})(\tilde{\delta}_{kj} - \overline{\tilde{\delta}_{j}}) \quad (5.33)$$

As inertia, M of all generators is known, therefore the state Jacobian matrix is defined by using equation (5.28) as follows:

$$\left(\frac{\partial P_e}{\partial \delta}\right) = M\, Q_{\omega\omega} Q_{\delta\delta}^{-1} \quad (5.34)$$

5.2.2. The Proposed Method Flow Chart

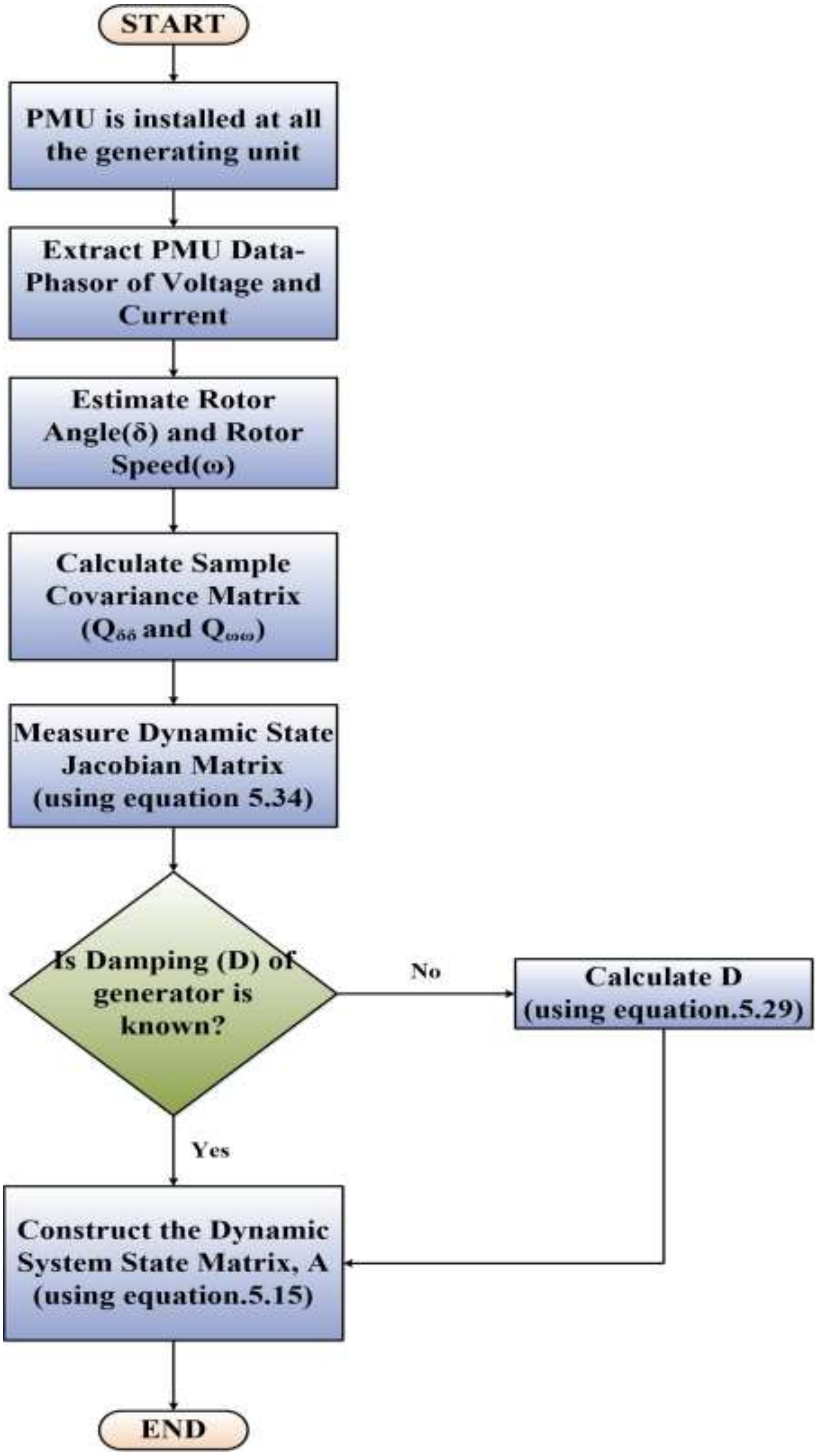

Fig.5.1 Flow chart of proposed algorithm based on PMU

5.3 SYSTEM MODEL BASED METHOD

The stochastic load variation is considered in System model by using the center-of-inertia (COI) approach which is represented as below [16]:

$$\dot{\tilde{\delta}}_i = \tilde{\omega}_i \tag{5.35}$$

$$M_i \dot{\tilde{\omega}}_i = P_{mi} - P_{ei} - \frac{M_i}{M_T} P_{coi} - D_i \tilde{\omega}_i + \sigma_i \varepsilon_i \tag{5.36}$$

Where $\tilde{\delta}_i$ and $\tilde{\omega}_i$ shows the center-of-inertia reference frame of the classical generator models, which are obtained by using following equations:

$$M_T = \sum_{i=1}^{n} M_i \tag{5.37}$$

$$\delta_0 = \frac{1}{M_T} \sum_{i=1}^{n} M_i \delta_i \tag{5.38}$$

$$\omega_0 = \frac{1}{M_T} \sum_{i=1}^{n} M_i \omega_i \tag{5.39}$$

$$\tilde{\delta}_i = \delta_i - \delta_0 \quad \text{and} \quad \tilde{\omega}_i = \omega_i - \omega_0$$

$$P_{ei} = \sum_{j=1}^{n} E_i E_j \left(G_{ij} \mathrm{Cos}\left(\tilde{\delta}_i - \tilde{\delta}_j\right) + B_{ij} \mathrm{Sin}\left(\tilde{\delta}_i - \tilde{\delta}_j\right)\right) \tag{5.40}$$

$$P_{coi} = \sum_{i=1}^{n} (P_{mi} - P_{ei}) \tag{5.41}$$

$$P_{coi} = \sum_{i=1}^{n} P_{mi} - \sum_{i=1}^{n} E_i^2 G_{ii} - 2\sum_{i=1}^{n-1} \sum_{j}^{n} E_i E_j G_{ij} Cos\delta_{ij} \tag{5.42}$$

Using equation (5.15), the State Matrix using Model based method is obtained as following:

$$A = \begin{bmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \begin{matrix} 1 & 0 \\ 0 & 1 \end{matrix} \\ -M^{-1}\left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi} & \begin{matrix} \frac{-D_1}{M_1} & 0 \\ 0 & \frac{-D_2}{M_2} \end{matrix} \end{bmatrix} \tag{5.43}$$

Where,

$$J= -M^{-1}\left(\frac{\partial P_e}{\partial \tilde{\delta}} + \frac{M}{M_T}\frac{\partial P_{coi}}{\partial \delta}\right)$$

For diagonal elements (i=j), $\left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi}$ is calculated as following:

$$\left[\left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi}\right]=\sum_{k\neq i} E_i E_k\left[-G_{ik}Sin\left(\tilde{\delta}_i-\tilde{\delta}_k\right)+B_{ik}Cos\left(\tilde{\delta}_i-\tilde{\delta}_k\right)\right] + \frac{M_i}{M_T}\frac{\partial P_{coi}}{\partial \delta} \quad (5.44)$$

For off-diagonal elements (i≠j), $\left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi}$ is calculated as,

$$\left[\left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi}\right] = E_i E_j\left[G_{ik}Sin\left(\tilde{\delta}_i-\tilde{\delta}_k\right)-B_{ik}Cos\left(\tilde{\delta}_i-\tilde{\delta}_k\right)\right] + \frac{M_i}{M_T}\frac{\partial P_{coi}}{\partial \delta} \quad (5.45)$$

where , $\frac{\partial P_{coi}}{\partial \tilde{\delta_i}} = 2\sum_{k\neq i}^{3} E_i E_k\left(G_{ik}Sin\left(\tilde{\delta}_i-\tilde{\delta}_k\right)\right)$

Here both matrices are calculated using generator 1 and 2 parameters only, the third generator parameters having COI formulation is estimated by using the other state variables without any integration, as shown in equation (5.46) and (5.47):

$$\widetilde{\delta_3} = -\frac{M_1\widetilde{\delta_1}+M_2\widetilde{\delta_2}}{M_3} \quad (5.46)$$

$$\widetilde{\omega_3} = -\frac{M_1\widetilde{\omega_1}+M_2\widetilde{\omega_2}}{M_3} \quad (5.47)$$

Therefore, the system based method is dependent on the network topology and parameters which sometimes may causes error in the estimation of the Dynamic state Jacobian matrix and dynamic state system matrix.

CHAPTER 6

CASE STUDY: WSCC 9BUS, 3 MACHINE SYSTEM

WSCC 9 bus, 3 machine system has been used as case study in this work. This benchmark model represents the approximation equivalent model of Western System Coordinating Council (WSCC) with nine buses, three two-winding transformers, three synchronous machines with built-in voltage and speed regulators, six constant parameters lines and three loads. This system is also known as P.M Anderson 9 Bus.

This system comprises of 9 buses, 3 generators, 3 two-winding force transformers, 6 lines and 3 loads. The base KV levels are assumed as 13.8 kV, 16.5 kV, 18 kV, and 230 kV and the line complex power is taken as 100MVA of the whole system.

In this work, WSCC 9buses 3 generators system has been developed in Digsilent Power factory software using data provided by WSCC.

The simulated WSCC 9 bus, 3 machine system has been introduced with stochastic load variations and the result is obtained for rotor angle and rotor speed for 200 seconds. Two cases are taken one without load variations and second one with stochastic load variations.

6.1. BASIC DATA AND CHARACTERISTICS

The data shown below [8] are based on following base values:-

MVA base = 100MVA

Frequency = 50 Hz

Voltage base= 230kV (assumed)

6.1.1. Parameters of Generators

The values of Parameters for the two-axis model of the system synchronous generators are given in Table 6.1 as follows. All per unit values are given on the same system base 100 MVA.

Unit no.	**H**	**R_a**	**X_d**	**X'_d**	**X_q**	**X'_q**	**T'_{do}**	**T'_{qo}**	**D**
Gen 1	23.64	0.00	0.1460	0.0608	0.0969	0.0969	8.96	0.310	0.01
Gen 2	6.40	0.00	0.8958	0.1198	0.8645	0.1969	6.00	0.535	0.005
Gen 3	3.01	0.00	1.3125	0.1813	1.2578	0.2500	5.89	0.600	0.005

Table.6.1. Values of parameters for each Generating unit

Where,

H: inertia constant(sec)

R_a : Resistance(pu)

X_d : d-axis sychronous reactance(pu)

X'_d: d-axis transient reactance(pu)

X_q : q-axis sychronous reactance(pu)

X'_q : q-axis transient reactance(pu)

T'_{do} :d-axis open-circuit time constant(sec)

T'_{qo} : q-axis open-circuit time constant(sec)

D: damping coefficient(pu)

6.1.2. Parameters of Line/Transformers

The transmission lines of the designed system are modelled using the pi equivalent model. Table 6.2 summarizes the transmission line parameters and transformer tap including per unit voltage at each bus.

Line Data					**Transformer Tap**	
From Bus	**To Bus**	**R Resistance (pu)**	**X Reactance (pu)**	**B Susceptance (pu)**	**Magnitude**	**Angle**
1	4	0.0000	0.0576	0.0000	1.040	0
4	6	0.0008	0.0128	0.1342	0.000	0
6	9	0.0390	0.1700	0.3580	0.000	0
3	9	0.0000	0.0586	0.0000	1.025	0
9	8	0.0119	0.1008	0.2090	0.000	0
8	7	0.0085	0.0720	0.1490	0.000	0
7	2	0.0000	0.0625	0.0000	1.025	0
7	5	0.0320	0.1610	0.3060	0.000	0
4	5	0.0008	0.0128	0.1342	0.000	0

Table.6.2 Values of parameters for Line and Transformers

6.1.3. Power and Voltage Set Points

The designed system loads are modelled as a constant PQ load with values of parameters as given in Table 6.3.

Bus	Type	Voltage (pu)	Load		Generator		
			MW	MVAR	MW	MVAR	Unit No.
1	Swing	1.040	0	0	-	-	Gen1
2	PV	1.025	0	0	163	-	Gen2
3	PV	1.025	0	0	85	-	Gen3
4	Transformer	-	0	0	0	0	-
5	PQ	-	125	50	0	0	-
6	PQ	-	90	30	0	0	-
7	Transformer	-	0	0	0	0	-
8	PQ	-	100	35	0	0	-
9	Transformer	-	0	0	0	0	-

Table 6.3. Data of load and generating unit power

6.2 DESIGNING OF WSCC 9 BUS, 3 MACHINE SYSTEM

6.2.1. Single Line Diagram

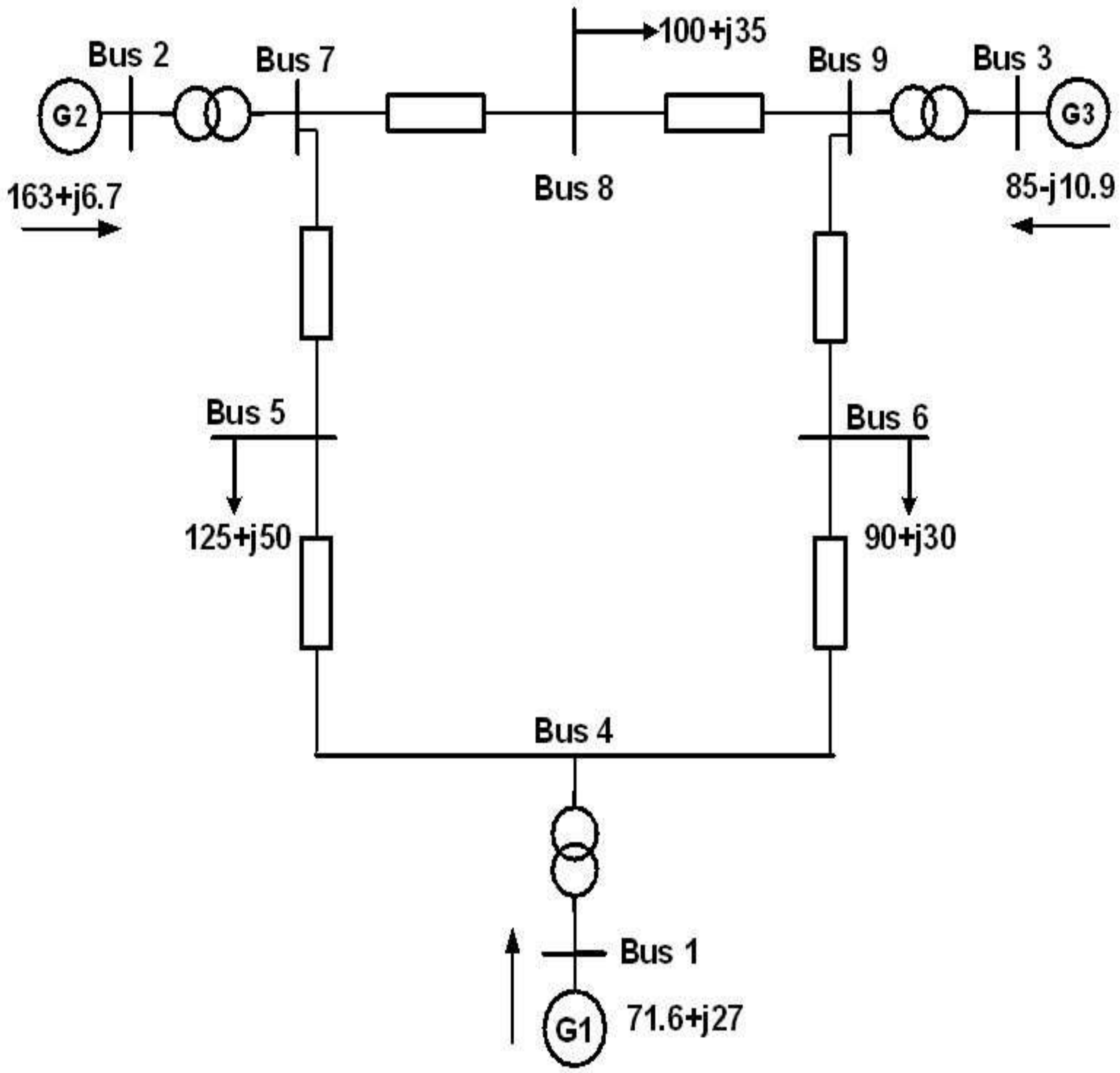

Fig. 6.1 Single-line diagram of WSCC 9bus 3machine system

6.2.3 Simulation in PowerWorld Simulator

PowerWorld Simulator is an intelligent simulation software used to designed high voltage power system operation with a time stamps ranging from few minutes to few days. This software provides an effective solution for power flow analysis and capable design and solve the power system consisting of up to 250,000 buses.

In this work we have use free student version of PowerWorld Simulator which have bus limit of 13 buses only therefore we have designed a system of 9 buses. This system consists of 9 buses, 3 generators, 3 two-winding power transformers, 6 lines and 3 loads at 60Hz frequency and 100MVA base.

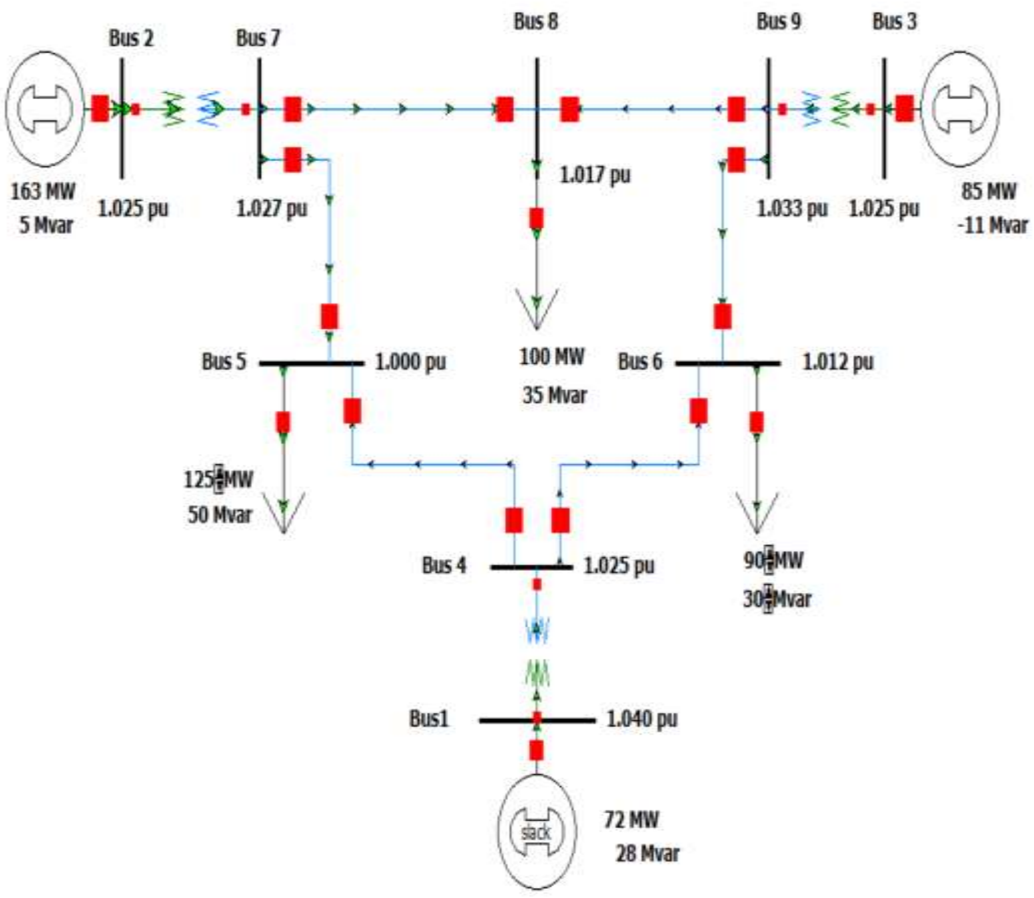

Fig. 6.2. Simulation of WSCC 9bus system in PowerWorld Simulator

6.2.3 Simulation in Digsilent Power factory software

DIgSILENT is a software used to simulate electrical power system operations such as transmission, distribution, generation and industrial plants. In this work the WSCC 9 bus, 3 machine system has been designed.

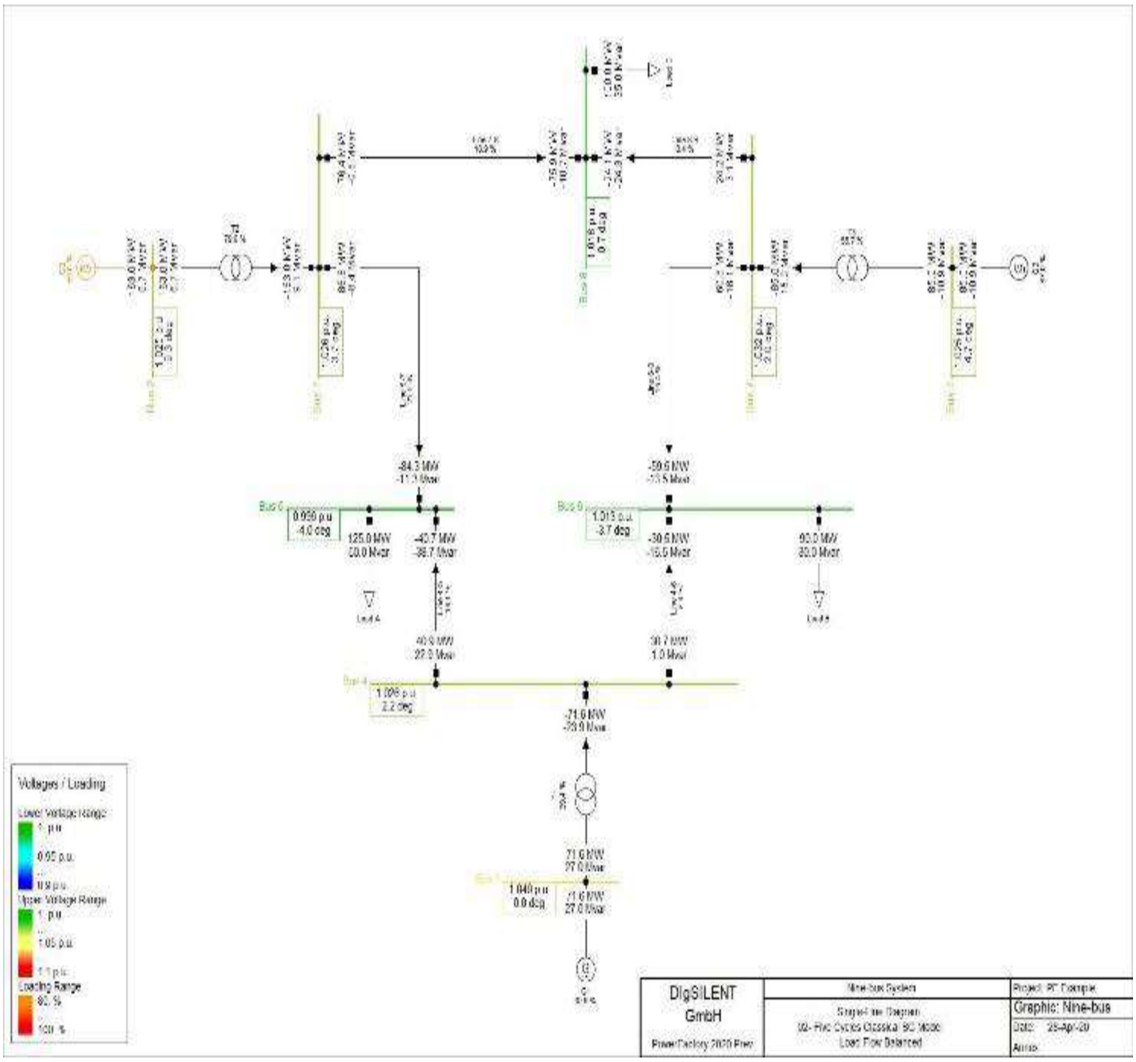

Fig.6.3 WSCC 9 bus, 3 machine system simulation in Digsilent Power factory software

6.3 TRAJECTORIES OF ROTOR ANGLE AND ROTOR SPEED

In designed WSCC 9 bus, 3 machine system is introduced with a standard deviation of stochastic load variations (σ= 0.01). The trajectories obtained of the system rotor angle and rotor speed is oscillating around their respective steady state values. The sample size of the results is 200 sec, and the sample rate is 50samples per second. Therefore, sampling size is 10,000.

The values of parameters required for estimation of dynamic state Jacobian matrix and whole dynamic system state matrix are Mechanical power input, Electromotive force (Emf), Moment of inertia (M) and Damping Coefficients (D) is shown in Table 6.4.

Generating unit 1	**Generating unit 2**	**Generating unit 3**
P_{mech1} = 0.72	P_{mech2} = 1.63	P_{mech3} = 0.85
Emf_1 = 1.057	Emf_2 = 1.050	Emf_3 = 1.060
M_1 =0.630	M_2 =0.340	M_3 =0.160
D_1 =0.630	D_2 =0.340	D_3 =0.160

Table 6.4. Parameter values of all the 3 generators in Per Units

The resultant plots are obtained with two cases:

a). Rotor angle and speed without load variations

b). Rotor angle and speed with load variations

6.3.1 Plots of rotor angle and rotor speed of generator 1

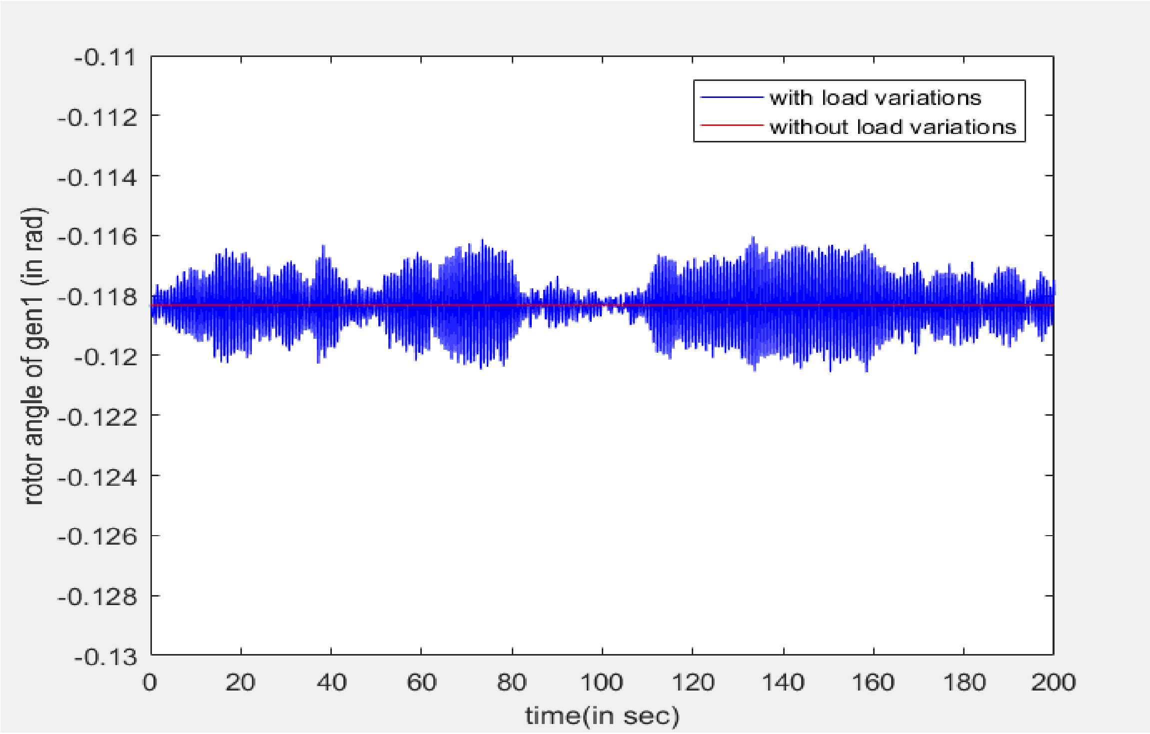

Fig.6.4. Trajectory of generator-1 rotor angle ($\widetilde{\delta_1}$)

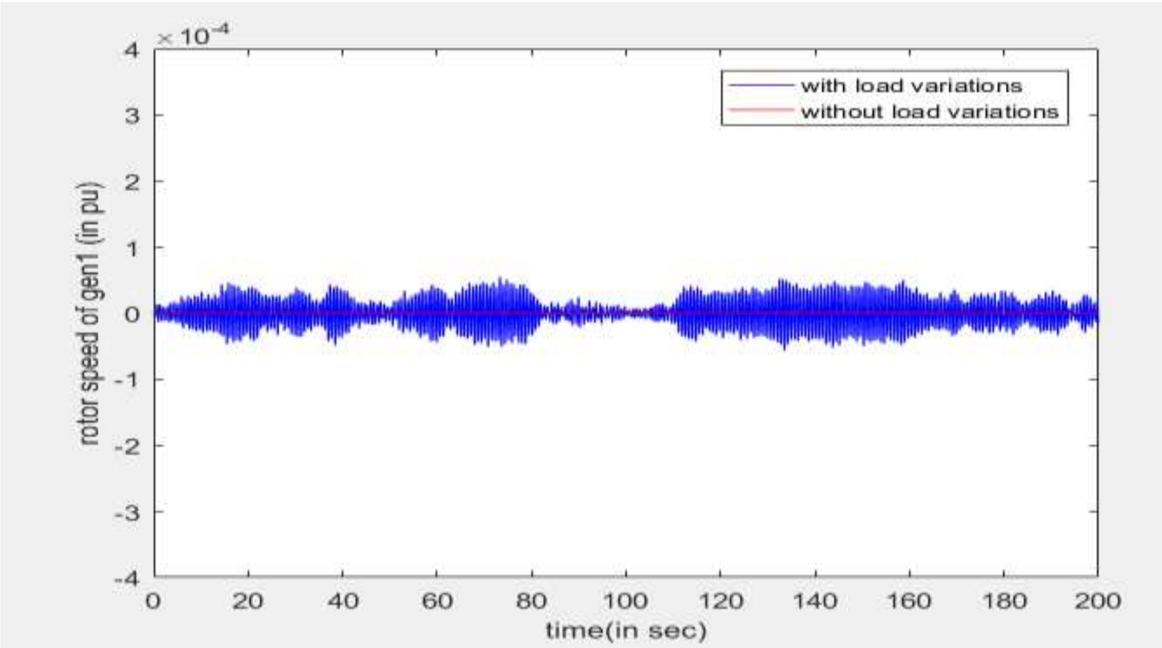

Fig.6.5. Trajectory of generator-1 rotor speed ($\widetilde{\omega_1}$)

6.3.2 Plots of rotor angle and rotor speed of generator 2

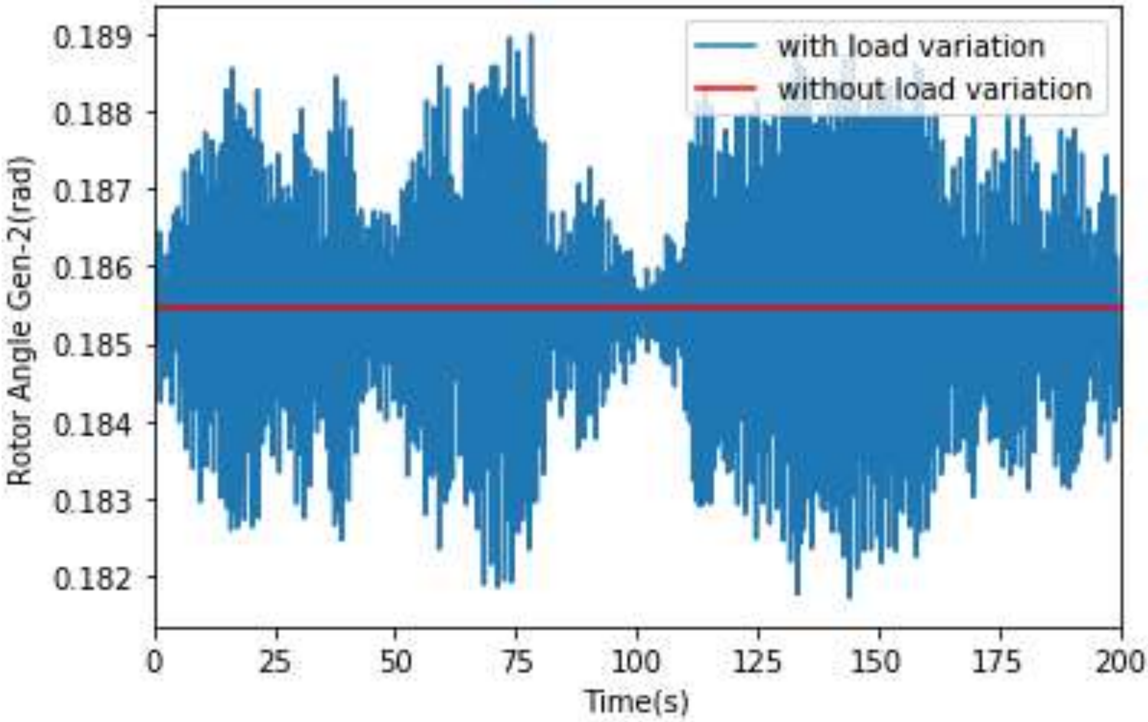

Fig.6.6. Trajectory of generator-2 rotor angle ($\widetilde{\delta_2}$)

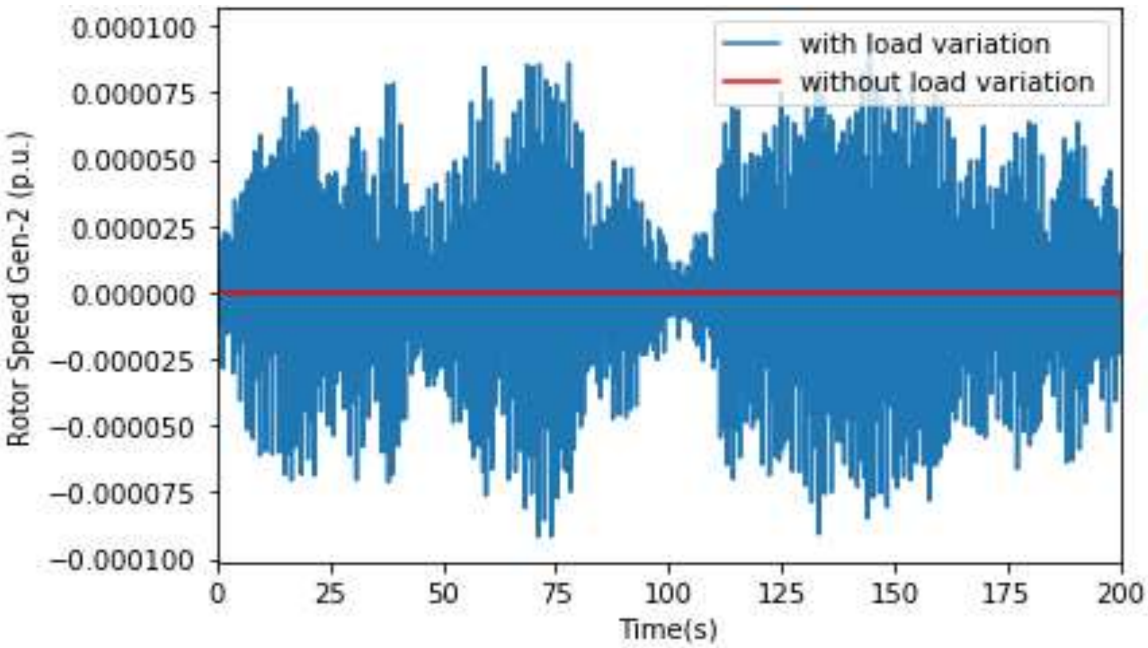

Fig.6.7. Trajectory of generator-2 rotor speed ($\widetilde{\omega_2}$)

6.3.3 Results obtained by using proposed algorithm

The Jacobian Matrix and system state matrix, A is estimated using the proposed approach which is based on PMU measurements. The system is provided with stochastic load variations of σ = 0.01p.u. The sampling rate of data obtained from PMU is 50 samples per sec for 200sec. The sample covariance matrices are calculated as followings:

$$Q_{\tilde{\delta}\tilde{\delta}} = 10^{-4} \text{ x} \begin{bmatrix} 0.78160 & -0.11847 \\ -0.11847 & 0.19338 \end{bmatrix} \quad (6.1)$$

$$Q_{\tilde{\omega}\tilde{\omega}} = 10^{-4} \text{ x} \begin{bmatrix} 0.44389 & -0.63491 \\ -0.63491 & 0.11271 \end{bmatrix} \quad (6.2)$$

Hence, the Jacobian matrix is calculated using equation (5.34):

$$\left(\frac{\partial \mathrm{P_e}}{\partial \tilde{\delta}}\right)_{coi}^{P} = \begin{bmatrix} 6.2099 & 1.7363 \\ 3.4000 & 4.0649 \end{bmatrix} \quad (6.3)$$

$$\mathrm{A^P} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -9.85698 & -2.75603 & -1 & 0 \\ -10.0000 & -11.9555 & 0 & -1 \end{bmatrix} \quad (6.4)$$

6.3.4 Results obtained by using Network Model

We calculate the Jacobian Matrix and system state matrix using model-based method, considering no load variations (σ = 0). Therefore, the Jacobian Matrix and system state matrix, A is obtained as:

$$\left(\frac{\partial \mathrm{P_e}}{\partial \tilde{\delta}}\right)_{coi} = \begin{bmatrix} 6.3861 & 1.9868 \\ 3.2017 & 4.1392 \end{bmatrix} \quad (6.5)$$

$$A=\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -10.1366 & -3.1536 & -1 & 0 \\ -9.41676 & -12.174 & 0 & -1 \end{bmatrix} \tag{6.6}$$

6.3.5. Error Estimation

As we have observed that the estimated matrices are close to each other. Now the error is estimated as:

$$\frac{\left\| \left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi}^{P} - \left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi} \right\|_F}{\left\| \left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi} \right\|_F} = 4.38\% \tag{6.7}$$

Where, $\| \quad \|_F$ is known as Frobenius Norm which is used to calculate the matrix error percent.

Similarly we can also estimate the error for Dynamic System state Matrix, A as:

$$\frac{\left\| \left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi}^{P} - \left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi} \right\|_F}{\left\| \left(\frac{\partial P_e}{\partial \tilde{\delta}}\right)_{coi} \right\|_F} = 3.64\% \tag{6.8}$$

The estimated error indicated that the proposed method is provides the accurate results of calculated Jacobian matrix for stability purpose.

6.3.6. Plots to show proximity of Instability

In this work, utilizing the estimated dynamic state system matrix the critical eigenvalues are evaluated that are the right most points of the eigenvalue plots which provides the good information of the proximity of instability of the designed system [58]. The estimated left and right eigenvectors of the critical eigenvalues may additionally be assessed to anticipate the response of the system and accordingly design the emergency control actions [56] [59]. The Eigen Values are calculated of the both the estimated state matrix and plotted to show the proximity of instability by observing the right most eigen values [64].

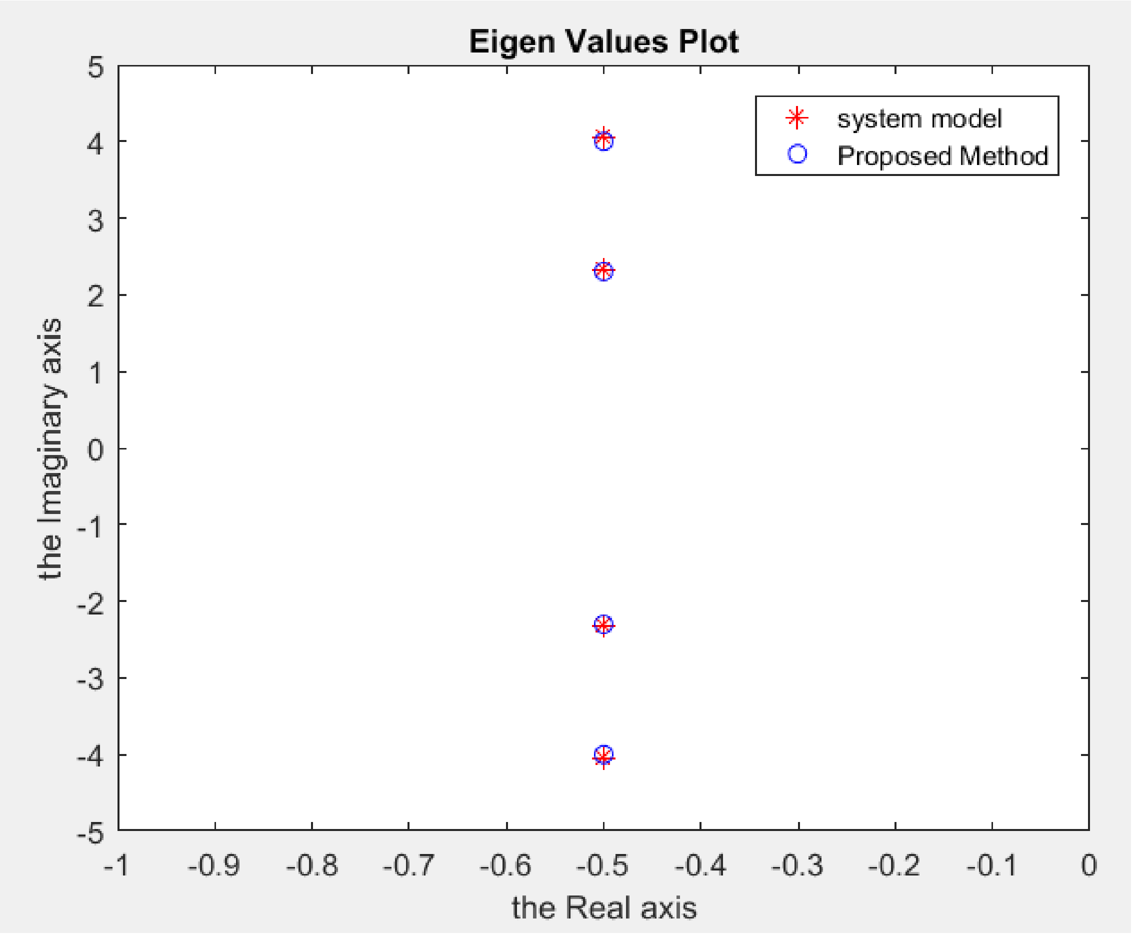

Fig.6.8. Plotting of the eigenvalues of state matrix estimated by both the methods

CHAPTER 7

CONCLUSION AND FUTURE SCOPE OF WORK

7.1. CONCLUSION

Thesis work has been carried out at two stages:

1.Laboratory scale setup of PMU

2.Estimation of dynamic state Jacobian matrix and dynamic system state matrix based on PMU measurements

The laboratory scale setup is developed of PMU architecture for development of PMU applications in MATLAB platform. Standard WSCC 9 Bus, 3 machine power system has been simulated in free version of commercial Power World Simulator and PMU data has been transferred to Open PDC from Power World Dynamic Studio. The data from OpenPDC has been parsed with open source software and for monitoring and analysis purpose the data is then loaded in MATLAB workspace using ethernet switch. The data measured by PMU and then transferred to PDC follows standard rules and functions known as communication protocols defined in 2005 version as IEEE C37.118.

In stage second, we have estimated the dynamic state Jacobian matrix and system state matrix for analysis of ambient stability of the system. For this purpose the standard WSCC 9bus, 3 machine system is simulated in Digsilent Power factory software and this system is introduced with stochastic load variations (σ =0.01). These matrices are estimated in near real time based on PMU data and then compared with the matrices calculated based on system model to show the reliability and accuracy of the proposed method. The Eigen values are calculated using dynamic system state matrix A and plotted to estimate the proximity of instability of both the methods. The paper has introduced numerical establishments for the technique confirmed by simulation tests.

7.2 FUTURE SCOPE OF WORK

Using synchrophasor technology in wide area monitoring system (WAMS), the real-time monitoring, control and protection can be achieved. In the future work, we plan to research this proposed technique for estimation of Dynamic state Jacobian matrix and dynamic system state matrix based on PMU measurements for higher order models, large system consisting of large number of buses, system consisting of renewable generators, high series resistance transmission lines, non-symmetric Y-bus cases, series/shunt compensation applications, and so on. The estimated dynamic state Jacobian matrix and dynamic system state matrix can also be utilized for future work in evaluation of online oscillations analysis, model validation and other electric power system control and protection operations such as economic dispatch, system security, state estimation, congestion relief and preventive control design.

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