Modeling and Analysis of Power systems using Synchrophasors

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A Thesis Submitted to
Indian Institute of Technology Hyderabad
In Partial Fulfillment of the Requirements for
The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
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July 2012

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Acknowledgements

I would like to express my profound respect for my supervisor Dr. Vaskar Sarkar. He is the person who has sculpted me to my current shape and has shown me the right direction to discover myself. The little work that I have done has been possible only because of his excellent guidance during the two years of my M.Tech work.I am also grateful to Prof.Mohammed Zafar Ali Khan for the valuable suggestions and inputs that they have provided from time to time.

I am extremely lucky to have lovingly friends such as Poornima,Ramesh,Sastry, Shyam. I would also like to thank my batch mates Goud, Alok, Madhav, Ramanuj, Ummayya,Prashanth, somu, teja, seenaih, yatendra, kiran, sarath, meher. I specially thank K.Manjunath for his valuable suggetions. I would also like to thank my cousins Naga laxmi and Suribabu for their support. I appreciate their patience to tolerate a disturbing person like me. The moral support that they have provided is unforgettable.

My special gratitude is due to my sister Bindu for their endless loving support in all walks of my life. I am indebted for life to my mom Jyothi and dad Ravukumar, for believing in me more than myself. To them, I dedicate this thesis.

Abstract

More recent technological advancements in microprocessor relays, combined with Global Positioning Systems (GPS) Clocks for synchronization and accurate time stamping to provide users with flexible proetction with synchronized measurements referred as Synchrophasors. Synchrophasors gradually gained importance since its invention. Major blackouts had given great emphasis to this technique for better disturbance analysis and more situational awareness. Synchrophasor technology can help control operators for delivering better real-time tools that enhance system performance. Synchronous phasor measurements from different network locations are combined and processed in a central computer system to provide users to get the knowledge of absolute phase angle difference between distant network buses with better accuracy.

In the present work, Phasor Measurement Unit (PMU) is modeled so that Magnitude and Phase of Voltage and Current vectors at a bus can be obtained. Integral Programming algorithm based optimal placement is applied on IEEE 14 bus test system such that each PMU will monitor a specified zone instead of placing PMU at each node. The remote bus of a subsystem is modeled as a classical synchronous generator which acts as a controllable three phase source. Bus angles at the remote bus are estimated through various methods in various events. These methods prove that synchronous phasor measurements are reliable for power system monitoring and better situational awareness as Matlab/Simulink results confirmed the power equation.

Contents

Nomenclature

$\boldsymbol{V_d}$	Voltage d-axis component
$\boldsymbol{V_q}$	Voltage q-axis component
$\boldsymbol{P_e}$	Active electric power output of Synchronous Generator
$\boldsymbol{Q_e}$	Reactive electric power output of Synchronous Generator
$\boldsymbol{X_d}$	Synchronous reactance d-axis
$\boldsymbol{X_q}$	Synchronous reactance q-axis
$\boldsymbol{I_d}$	Current d-axis componant
$\boldsymbol{I_q}$	Current q-axis componant
$\boldsymbol{E_q}$	Internal voltage of generator
$\boldsymbol{\delta}$	Rotor angle
$\boldsymbol{\omega_e}$	Electrical rotational velocity
$\boldsymbol{V}$	Terminal voltage of synchronous generator
$\boldsymbol{T_m}$	Mechanical torque
$\boldsymbol{T_e}$	Electrical torque
$\boldsymbol{H}$	Inertia constant of Synchronous generator
$\boldsymbol{J}$	Moment of inertia of Synchronous generator
$\boldsymbol{K_d}$	Damping constant
$\boldsymbol{X_a}$	Armature reactance of Synchronous generator
$\boldsymbol{\omega_m}$	Mechanical speed of synchronous generator
$\boldsymbol{X_c}$	Cosine componant DFT
$\boldsymbol{X_s}$	Sine componant of DFT

$\boldsymbol{X_1}$	Fundamental componant of DFT
$\boldsymbol{N}$	Number of samples
$\boldsymbol{T}$	Time period of input periodic signal
$\boldsymbol{E_1}$	Voltage magnitude at Bus 12
$\boldsymbol{E_2}$	Voltage magnitude at Bus 13
$\boldsymbol{X_l}$	Line reactance
$\boldsymbol{X_c}$	Series capacitance of line
$\boldsymbol{\delta_1}$	Bus angle at bus12
$\boldsymbol{\delta_2}$	Bus angle at bus23
$\boldsymbol{PMU}$	Phasor Measurement Unit
$\boldsymbol{GPS}$	Global Positioning System

Chapter 1

Introduction

1.1 Need for new technology

Operating of electric power systems is becoming more and more complex and is posing more and more challenges every day as they are operated close to their stability limits. Operational constraints have grown and the amount of user stress while various blackouts have happened in present Power systems across the world. This situation introduces a range of new requirements for development and implementation of tools and equipment that will help the system operators and the electrical engineers in improving the system security & stability when an event/fault occurs that may lead to a wide area disturbance.

1.2 Measurement with global reference

Electric power systems are very large and may cover parts of several states. To measure phase angles across a power system, you need a global reference. This global reference must somehow tie, measuring instruments together in substations which were hundreds of kilometers apart. The global reference currently in use is the microsecond timekeeping provided by the U.S. Department of Defenses Global Positioning System (GPS). GPS is sometimes called the NAVSTAR system. The GPS is a satellite-based military navigational and positioning system that is nearly complete. The system uses 21 middle-altitude satellites to provide users with three dimensional position and velocity fixes. Because GPS uses the speed of lighting ranging calculations, the same system also provides sub micro second timekeeping.

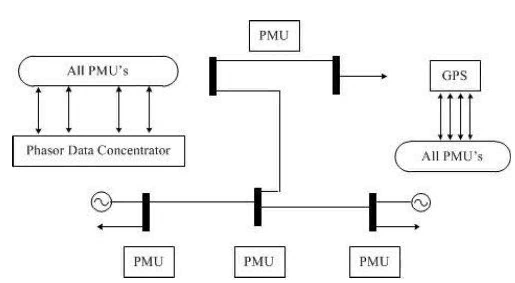

Figure 1.1: Placement of PMU's in a transmission network

1.3 Phasor representation of a sinusoid

Consider a pure sinusoidal quantity given by

$$x(t) = \sqrt{2}X\cos(w_0 t + \phi) \tag{1.1}$$

ω being the frequency of the signal in radians per second, and ϕ being the phase angle in radians. X is the root mean square (R.M.S.) value of the signal. Peak value of the input signal is ($\sqrt{2}$ X).

$$x(t) = Re\{Xe^{j(\omega t+\phi)}\} \tag{1.2}$$

We have to eliminate the term in the expression above, with the understanding that the frequency is ω. The sinusoid of Eq. 1.3 is represented by a complex number known as its phasor representation in equation as well as in Fig. 1.2.

$$\bar{X} = X(\cos\phi + i\sin\phi) \tag{1.3}$$

The phasor representation is only possible for a pure sinusoid. In general practically a waveform will be corrupted with other signals of different frequencies. It then becomes necessary to extract a single frequency component of the signal (mostly the principal frequency of interest in an analysis, in this case fundamental) and then represent it by a phasor [1]-[2].

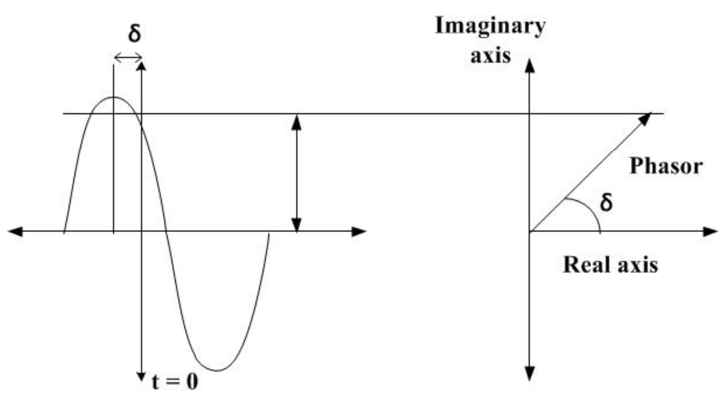

Figure 1.2: A sinusoid and its representation as Phasor. The Phase angle will be arbitrary based on reference axis at t=0. Length of phasor will be equal to RMS value of the sinusoid.

Extracting a single frequency component is often done with Fourier transform calculation. In sampled data systems, this becomes the Discrete Fourier transform.

1.4 Motivation & Objective of the work

When a major disturbance occurs, protection and control measures will have the greatest role to prevent further degradation or collapse of the system, restore the system to a normal state, and minimize the impact of the disturbance. Electrical measurements of the system, which may include synchronized phasors, are supplied to one or more controllers, which in turn perform a control function improving the damping of electromechanical oscillations or voltage performance in the utility system. The benefits will be improved damping to electromechanical oscillations and better voltage profile and ultimately more efficient utilization of assets, reducing the necessity for installing new equipment.

Synchrophasor measurements from different network locations when combined and processed in a central computer system will provide users with the absolute phase angle difference between distant network buses with an accuracy of tenths of an electrical degree. So in IEEE-14 bus standard system PMUs are optimally placed so that total system is observable. Phase angles from different buses were combined in order to calculate phase angle difference. Main objective is to prove that synchronous phasor measurements are reliable for analysis of power systems which were large and complex. Also to prove that phasor measurement units, equipped with wide-area protection and control algorithms, will be able to address future system critical conditions and other system problems in better way, because they give us a better knowledge of what happens throughout the power system.

Chapter 2

Scheme of Work

2.1 Basic scheme of work

In the present work we modeled a PMU in Matlab/Simulink, placed it optimally in IEEE 14 bus system. Boundary bus of a subsystem is modeled as Classical synchronous generator acting as three phase controllable source. Subsystem response of the system at various events is simulated. Main scheme of work described as a Block diagram in Fig. 2.1.

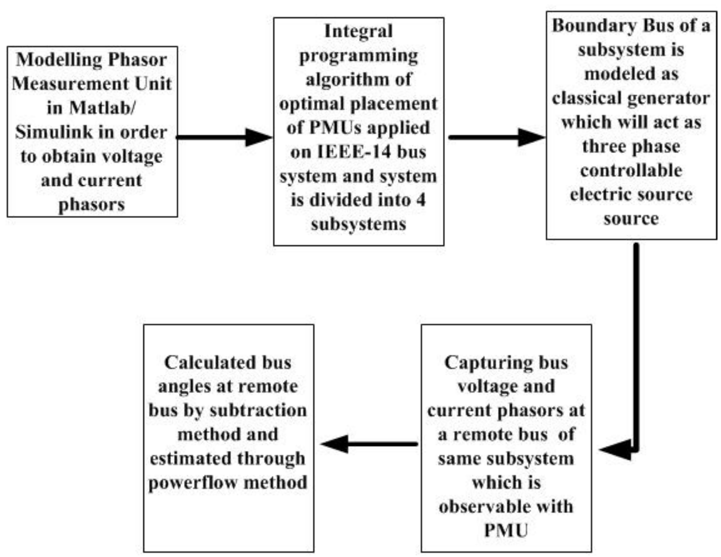

Figure 2.1: Main scheme of work

2.2 Basic goal of PMU

The basic idea of PMU is as shown in Fig. 2.2. The goal is to measure the difference between the positive going zero crossings of same phase voltage at different substations.

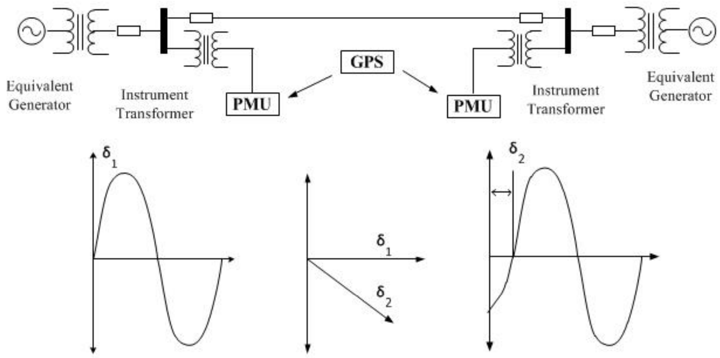

Figure 2.2: PMU connected to a power system network.

PMU lock their internal clock to GPS and measure the time of zero crossing. This will be converted into degrees based on the frequency reference (50 Hz). The phase angle of one substation will be taken as reference, will have some value with respect to GPS. This bias is subtracted from other sub stations in order to obtain a system wide picture.

PMU lock their internal clock to GPS and measure the time of zero crossing. This will be converted into degrees based on the frequency reference (50 hz). The phase angle of one substation will be taken as reference, will have some value with respect to GPS. This bias is subtracted from other sub stations in order to obtain a system wide picture [3].

2.3 Calculating power angle

The computation of rotor angle will be done in two ways. One is direct subtraction of phase angles at two buses and another is calculating bus angle through real power flow equation by taking account of two bus voltage magnitudes given by PMU.

2.3.1 Direct method

Phase angles at reference bus and remote bus which is connected through long transmission line can be obtained simultaneously by Phasor measurement units modelled in Matlab/simulunk which will be discussed in later chapters, as both having same simulink time of reference. When we obtain both, we can get the phase angle difference between them. Power angle δ is given by,

$$\delta = \text{Phase angle at reference bus } \text{ Phase angle at remote bus}$$

2.3.2 Real Power flow equation method

In Power systems simple relation between Real Power flow in transmission line and remaining quantities developed. When ever the transmission resistance is neglected in the network real power flow in the line is directly related to the phase angle across the line, with the following relation as equation

2.1.

$$P = \frac{(E_1 * E_2)}{(X_1 - X_c)} \sin\delta \tag{2.1}$$

Here P is the real power flow in transmission line between buses whose voltage magnitudes are E_1, E_2 and X_l, X_c are the line and capacitive reactance respectively. We can obtain magnitude of bus voltages at two buses with Phasor measurement units placed in respective buses. From the above relation δ will have expression as

$$\delta = \sin^{-1}\{\frac{P(X_l - X_c)}{(E_1 E_2)}\} \tag{2.2}$$

If the voltages, real power flow, and net reactance are known, Equation 2.2 can be used to solve for δ. Less error between calculated and values obtained through PMU model would help to validate the technique of time synchronized phase angle measurement. But that can be possible only if value of real power flow P is known. Since we are having synchronized voltage and current signals, the angle between those two phasors can be known. Which is also known as ϕ, cosine of which gives the power factor. For a single bus Real power P given as

$$P = |E||I| \cos\phi \tag{2.3}$$

Where P is the real power, $|E|$ is the magnitude of Voltage phasor, $|I|$ is the magnitude of current phasor, ϕ is the angle between Voltage and Current Phasors.By substituting P in power angle equation 2.2, we get δ so that we found Magnitude and phase of voltages and currents at a particular bus. We can get all the needed information from PMU blocks at particular buses to solve Equations 2.2 and 2.3 for angle. The calculated value of will be compared with the measured value of δ through PMU block. δ value measured from PMU can be used for reconstruction of wave form with fundamental frequency which will be discussed in further sections.

2.4 Modeling of synchronous generator

The boundary bus of the sub system (Bus voltage and angle) is modeled a classically modelled synchronous generator with large inertia constant. Based on swing equation generator is modeled in Matlab/simulink, which will be used as three phase controllable source. Mechanical input to the generator is varied and electrical output checked accordingly. Voltage and current response of the system at remote bus in various cases like Pre fault, During fault and Post fault captured. Variation in bus angle through both the methods mentioned earlier at different events captured.

Chapter 3

Phasor Measurement Unit

3.1 Basic scheme of PMU

The basic Phasor measurement process is that of estimating Magnitude and a positive-sequence(also negative and zero are available), fundamental frequency phasor representation from voltage or current waveforms. As indicated by Fig. 3.1, the analog power signal is converted into digital data by the analog to digital converter. For example, if the voltage is needed to be measured, the samples are taken for each cycle of the waveform and then the fundamental frequency component is calculated using (DFT).

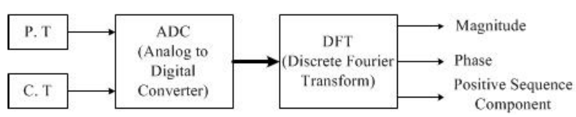

Figure 3.1: Scheme of Phasor Measurement Unit

Potential and current transformers reduce the Power system voltages and currents to safe working level. Phasor measurement unit records real and imaginary parts of Voltage and currents with various channels. Analog- to- Digital converter samples it 2400 times a second. Analog-to-Digital converters in each PMU are synchronize up to 1 micro second. Discrete fourier transform is used mainly to calculate Magnitude and Phase 600 times a second. When the Power system is in steady state we can say DFT calculations are exact. When short circuit fault occurs it can only estimate the Voltage or Current phasor. Simultaneously we can find out positive sequence component. We can find out positive sequence componant by following equation 3.1.

$$V_1 = \frac{1}{3}(V_a + \alpha v_b + \alpha^2 V_c) \tag{3.1}$$

Where $\alpha = 1\angle 120^0$ and V_a, V_b, and V_c are the phasors computed with the help of DFT of each of the three phases.

3.2 Phase computation by DFT

It was stated earlier that the phasor representation is only possible for a pure sinusoid. But it becomes necessary to extract a single frequency component of the signal from corrupted or signal having different frequency components. Extracting a single frequency component is often done with a Fourier transform calculation. In sampled data systems, this becomes Discrete Fourier transform (DFT).

Consider a sinusoidal input signal of frequency ω_0, given by

$$x(t) = \sqrt{2}X\cos(w_0 t + \phi) \tag{3.2}$$

This signal is conveniently represented by a phasor X.

$$\bar{X} = X(\cos\phi + i\sin\phi) \tag{3.3}$$

Assume that signal is sampled N times per cycle such that $T = Nt_0$. Then signal will be represented as

$$x_k = \sqrt{2}X\cos(\frac{2\pi}{N}K + \phi) \tag{3.4}$$

The Discrete Fourier Transform of x_k contains the fundamental frequency component given by

$$X_1 = \frac{2}{N}\sum_{k=0}^{N-1} x_k e^{-i\frac{2\pi}{N}k} = X_c - iX_s \tag{3.5}$$

where $X_c = \frac{2}{N}\sum_{k=0}{}^{N-1} x_k\cos(\frac{2\pi}{N}K)$ and $X_s = \frac{2}{N}\sum_{k=0}{}^{N-1} x_k\sin(\frac{2\pi}{N}K)$

However, in all practical cases, it is only possible to consider a portion of time span over which the phasor representation is considered.[4] This time span also known as the data window, is very important in phasor estimation of practical waveforms. Say ${x_c}^w$ and ${x_s}^w$ are indicating x_c and x_s components of DFT for w_{th} window. Window number is number of the first sample of the active window then.

$$X_c^w = \frac{2}{N}\sum_{k=0}^{N-1} x_{k+w}\cos(\frac{2\pi}{N}K) \tag{3.6}$$

similarly

$$X_s^w = \frac{2}{N}\sum_{k=0}^{N-1} x_{k+w}\sin(\frac{2\pi}{N}K) \tag{3.7}$$

Therefore

$$\bar{X} = \frac{1}{\sqrt{2}}X_1 = \frac{1}{\sqrt{2}}(\bar{X_c}^w + j\bar{X_s}^w) \tag{3.8}$$

This was achieved by multiplying input sampled signal with discrete cosine and sinusoid functions which is sampled again by 2400 times second,calculated Discrete mean value for one window of 0.02 sec.Once both real and imaginary parts of Voltage and Current phasors are obtained, we can easily find out magnitude by square root of both and phase angle by arc Tan function.Data can be be analyzed in multiple window format [5].

3.3 Phasor Measurement Unit in Matlab/Simulink

The external time source is an absolute time reference from a global positioning system (GPS) receiver, which delivers a phase-locked sampling clock pulse to the Analog-to-Digital converter system. The samples from the voltage and current inputs are collected by the A/D (Analog to digital converter) at the rate of 48 samples/cycle but independent of the1pps input .The sampled data are converted to a complex number which represents the phasor of the sampled waveform. Phasors of the three phases are combined to produce the positive sequence measurement. Matlab/Simulink model of Phasor Measurement unit and computation of DFT will be as per Fig. 3.2, 3.3.

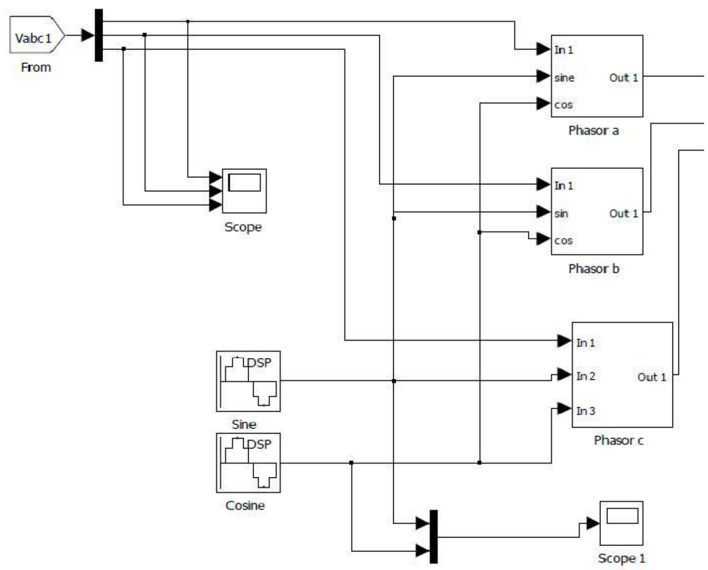

Figure 3.2: Phasor Measurement unit modeled in Simulink

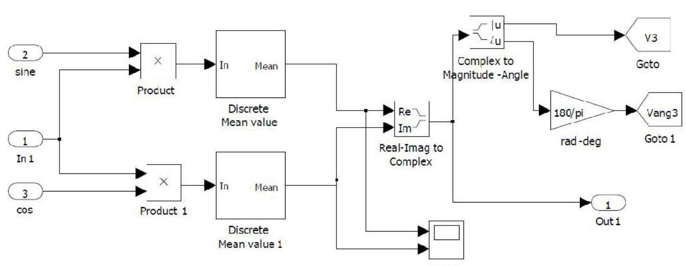

Figure 3.3: DFT computation for Phasor calculation in Simulink

Positive-sequence voltages of a network constitute the state vector of a power system, and it is of fundamental importance in all of power system analysis. So along with 3-phase phasors, Positive sequence component can be computed by equation 4.1.1 and by Fig. 3.4.

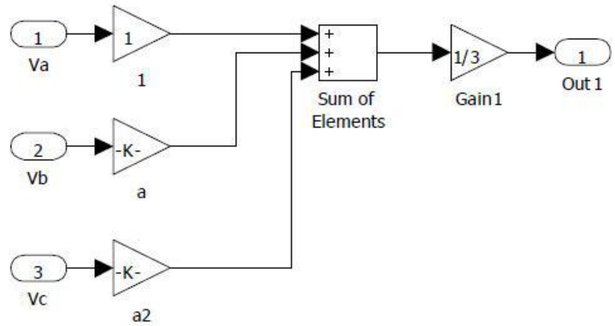

Figure 3.4: Positive sequence computation in simulink

3.4 Reconstruction of signal from data obtained from PMU

We will obtain Magnitude and Phase of a quantity like voltage and currents. Those magnitude and Phase related to fundamental component of input wave form which may contain several frequency components in it. So we can reconstruct a signal based on the quantities we get from a Phasor measurement unit at a particular bus. Here is an example. Consider a sinusoidal signal Having magnitude variation as per h(t) and Phase variation as per r(t). So, it can be represented wyth,

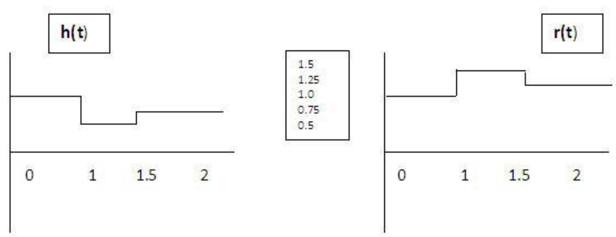

Figure 3.5: Magnitude and Phase functions

$$F(t) = h(t)\sin\{\omega t + r(t)\}$$

So signal generation in Simulink will be done as shown in Fig. 3.6

Now when ever we found the phase and magnitude through DFT, signal can be reconstructed as shown in Fig. 3.7. We can observe original wave form and Reconstructed wave form can be seen from Fig. 3.8.

So for given fundamental frequency of 50 Hz of sinusoid the re constructed wave form will be compared original signal that is applied to Phasor measurement unit as shown in Fig. 3.9. Magnitude an Phase angle measurement also captured as shown in Fig. 3.8.

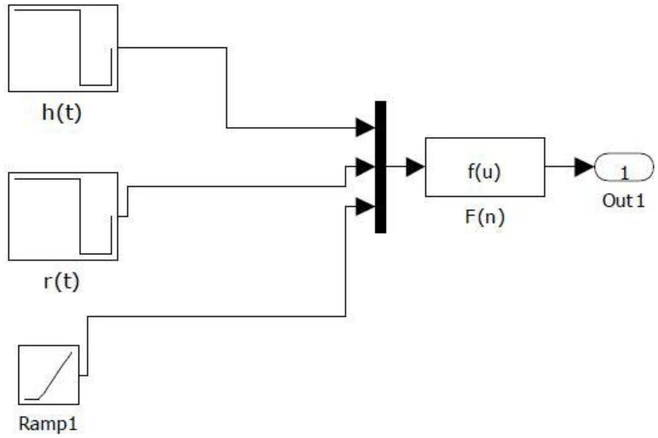

Figure 3.6: Signal F(t) generation in simulink

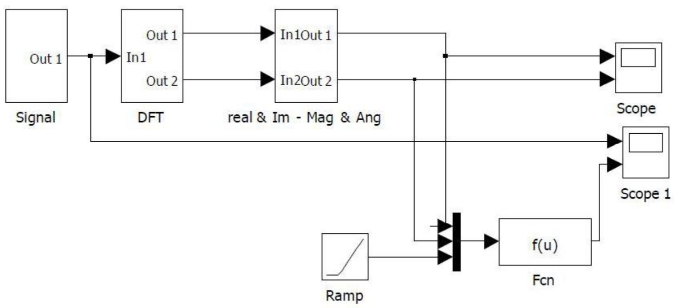

Figure 3.7: Reconstructing signal in Simulink

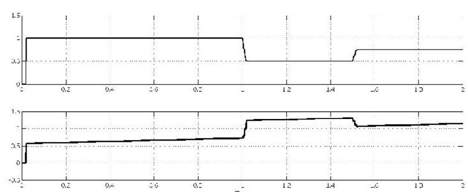

Figure 3.8: Magnitude and Phase angle of signal

3.5 Optimal Placement of PMU(Integer quadratic Programming technique):

When a PMU is placed at a bus, it can measure the voltage phasor at that bus, as well as at the buses at the other end of all the incident lines, using the measured current phasor and the known line parameters. PMU has a sufficient number of channels to measure the current phasors through all the branches connected to the bus at which it is placed. Integer quadratic Programming technique

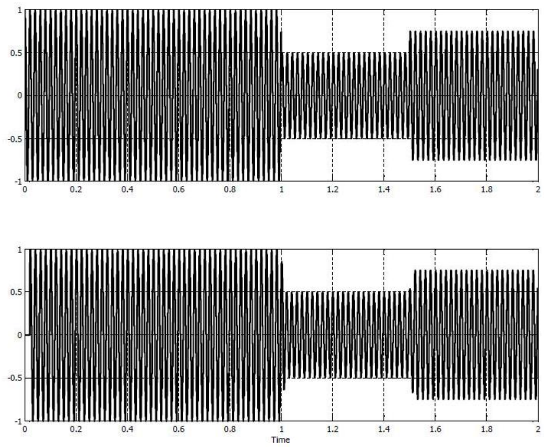

Figure 3.9: Reconstructed wave form in comparison with original waveform

can be used to determine minimum number and optimal location of PMUs.

Formulation of optimization problem will be done through Connectivity Matrix H ,which can be treated as representation of Power system and elements are
h_{ij} = 1, if i=j
= 1, if i connected to j
= 0, otherwise
Binary coloumn vector X of PMU Placements is defined as
x_{ij} = 1, if PMU placed at i bus
= 0, otherwise
Product HX represent the number of times a bus is observed by the PMU. The objective function V(x) for optimization is formulated as in an integer quadratic programming problem

$$V(X) = \gamma(N - HX)TR(N - HX) + X^T QX \tag{3.9}$$

N = Upper limit of observability R = Diagonal Matrix Representing significance of Bus Q = Diagonal Matrix Representing Cost of PMU γ = Normalizing factor The first part in computes the distance between the maximum possible number of times a bus can be observed and the actual number of times it is observed, for all buses in the system. Second part minimizes the no of PMUs to be placed in order to obtain complete observability. Generally all buses are significant and PMU installation cost at each bus is same[8]. So R, Q always represent Identical matrices. Coefficient γ is used as normalizing factor, such that

$$\gamma = (N^T RN)^{-1} \tag{3.10}$$

If we expand V(X) we get,

$$V(X) = (N^T RN) - 2\gamma N^T RHX + \gamma X^T H^T RHX + X^T QX \tag{3.11}$$

$$V(X) = \frac{1}{2} X^T(2\gamma H^T RH + 2Q)x + (-2\gamma N^T RH) + \gamma N^T RH + \gamma N^T RN \tag{3.12}$$

The optimization problem can therefore be formulated in an integer quadratic programming frame-

work Minimize $\frac{1}{2}x^TGX + f^Tx$
Subject $H_x \geq b$
Which is constraint for observability.
Where

$$G = (2\gamma H^TRH + 2Q), f = (-2\gamma N^TRH)^T \quad (3.13)$$

and $b = I_{n\times1}$ Since various optimization techniques are available, With the help of Matlab Tool we can solve above two equations and we can get X [8]. If we try above technique for a simple IEEE 14 Bus test system we can get X as,

$$X = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Which means $x_i \in 4$, we can place 4 PMUs at 2,6,8,9 buses respectively. We can observe that it is the only possible way. Now PMU-1 placed at Boundary bus-13 is taken as reference bus which

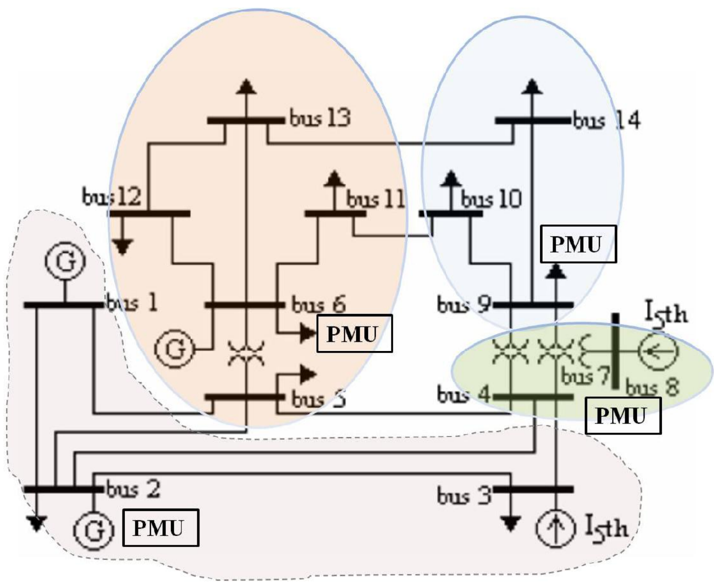

Figure 3.10: Optimal placement of PMU in IEEE14 bus system

is modeled as a classical generator in the form of three phase programmable voltage source and its response is observed at Bus- 12 through PMU-4.

Chapter 4

Synchronous Generator

With the development of the technology and the way in which human labour is getting minimized and the comforts increasing tremendously the use of electrical energy is ever increasing. Basically electric power is the main source of energy for carrying out many functions, as it is a clean and efficient energy source, which can be easily transmitted over long distances. With the availability of Transformer for changing the voltage levels to a very high value (of say 132kv to 400kv) the use of AC power has increased rapidly and the DC power is used only at remote places where AC power cannot be supplied through power lines or cables or for a few social purposes.

An understanding of characteristics and modeling of dynamic performance of synchronous machine are very essential for studies of power system stability. Synchronous generators can be loosely classified as either high-speed generators, driven by steam or gas turbines (and often called turbo generators), or low-speed generators, driven by water turbines. To reduce centrifugal forces, high-speed turbo generators have relatively low diameter but large axial length and are mounted horizontally. Typically they will have two or four electrical poles so that in a 50Hz system a generator would be driven at 3000 or 1500 rpm respectively. In contrast, low-speed generators operate at typically 500 rpm and below, have a large number of electrical poles, large diameter and shorter axial length. The actual number of magnetic poles depends on the required speed and nominal frequency of the power system

All generators have two main magnetic parts termed the stator and the rotor, both of which are manufactured from magnetic steel. The stator contains a three-phase armature winding. When a source of three-phase ac is connected to this winding, a magnetic field of constant amplitude is produced within the machine; in a two-pole machine, this field rotates at frequency equal to the frequency of the applied ac. The rotor contains a field winding that is excited by dc. This winding behaves as an electromagnet, producing a field of strength proportional to the applied field current that is aligned with the axis of the field winding. The rotor excitation winding is supplied with a direct current to produce a rotating magnetic flux the strength of which is proportional to the excitation current. This rotating magnetic flux then induces an electromotive force (emf) in each phase of the three-phase stator armature winding which forces alternating currents to flow out to the power system. Constructional details of rotors were summarized in Fig. 4.1.

As we discussed earlier, synchronous machine rotor contains field winding which is excited by DC. Stator winding consists of three phases which were 120 degrees apart. Generally there is

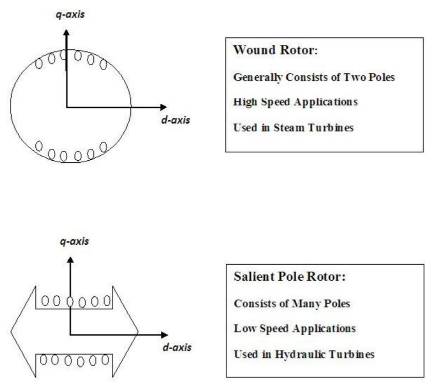

Figure 4.1: Constructional details of rotors of synchronous machine

constructional difference in the rotors we use for different applications. Wound type rotor will be used for High speed steam turbines which will have very less number of poles. Where as salient type rotors used for low speed applications.

The frequency per revolution, is therefore, equal to the number of pairs of poles. Since the frequency depends directly on the speed (rpm/60) and also on the number of pairs of poles (P/2), we may combine these into a single equation in which

$$\omega = \frac{120f}{P} \tag{4.1}$$

Where ω is angular speed, f is system frequency, P is the no.of poles.

4.1 dq Transformation

In the case of balanced three-phase circuits, application of the dqo transform reduces the three alternating quantities to two fixed and non varying quantities. Simplified calculations can then be carried out on these imaginary quantities before performing the inverse transform to recover the actual three-phase alternating results.

The dqo transformation can be thought of in geometric terms as the projection of the three separate sinusoidal phase quantities onto two axes rotating with the same angular velocity as the sinusoidal phase quantities. The two axes are called the direct, or d, axis; and the quadrature or q, axis; that is, with the q-axis being at an angle of 90 degrees from the direct axis. The direct axis will be centered magnetically in the center of north pole, where as quadrature axis 90 degrees ahead of direct axis.

The first step in the development of a suitable model is to transform the armature winding variables to a coordinate system in which the rotor is stationary. We identify equivalent armature windings in the direct and quadrature axes. The direct axis armature winding is the equivalent of one of the phase windings, but aligned directly with the field. The quadrature winding is situated so that its axis leads the field winding by 90 electrical degrees. The transformation used to map the armature currents, fluxes and so forth onto the direct and quadrature axes is the celebrated

Parks Transformation, named after Robert H. Park, an early investigator into transient behavior in synchronous machines.

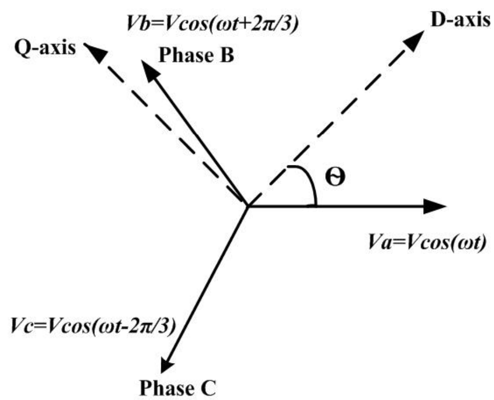

Figure 4.2: Vector Diagram of dq transformation

$$p = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta + \frac{2\Pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\Pi}{3}) & \sin(\theta + \frac{2\Pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4.2}$$

$$p^{-1} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\Pi}{3}) & \sin(\theta - \frac{2\Pi}{3}) & 1 \\ \cos(\theta + \frac{2\Pi}{3}) & \sin(\theta + \frac{2\Pi}{3}) & 1 \end{bmatrix} \tag{4.3}$$

$$V_{dq0} = PV_{abc} \tag{4.4}$$

There are three windings in the synchronous machine separated by 120 physical degrees. The three phase voltages are equal in magnitude and are separated from one another by 120 electrical degrees. The d-q axis is shown rotating with angular velocity equal to ω, the same angular velocity as the phase voltages and currents. The d axis makes an angle θ with the stationary reference axis.

4.2 Equivalent circuit of a synchronous machine

Power can be expressed in terms of direct and quadrature components as

$$P_e + jQ_e = (V_d + jV_q)(I_d + jI_q) \tag{4.5}$$

As we know that position of rotor with respect to stator can be measured with the help of angle δ, which is angle between direct axis and magnetic axis of Phase “a winding. Also spatial angle between field and air gap flux. So if we can say E_q or E_f as field or internal voltage, V is terminal phase voltage then rotor angle δ will be angle between E_q and V+I(R_a+jX_l) , Where X_d, X_q are synchronous reactance of d,q axis respectively. As per simplified phasor diagram of synchronous machine relating internal and terminal voltage shown in Fig. 4.3. As X_l ¡¡X_a we can say

$$X_d = X_a + X_l \simeq X_a \tag{4.6}$$

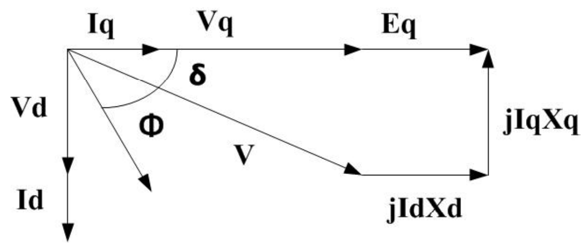

Figure 4.3: Phasor diagram of synchronous machine in rotor reference frame

Then E_q becomes

$$E_q = v + (R_a + jX_d)I \tag{4.7}$$

Now we can write

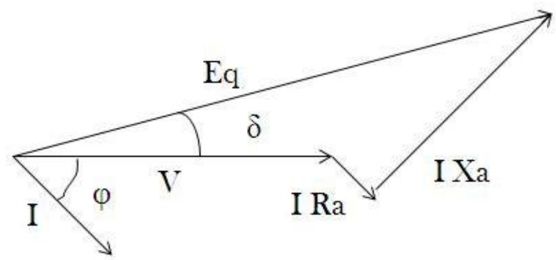

Figure 4.4: Phasor diagram of synchronous machine

$$V_d + jV_q = V(\sin\delta + j\cos\delta) \tag{4.8}$$

$$I_d = \frac{(E_Q - V_q)}{X_d} \tag{4.9}$$

$$I_q = \frac{V_d}{X_q} \tag{4.10}$$

Now substituting in Power equation we get expressions for Active and Reactive power as follows

$$P_e = \frac{E_q * V}{X_d}\sin\delta - \frac{V^2}{2}(\frac{1}{X_d}) - \frac{1}{X_q}\sin 2\delta \tag{4.11}$$

$$Q_e = \frac{E_q * V}{X_d}\sin\delta - v^2(\frac{\sin\delta^2}{X_d} + \frac{\cos\delta^2}{X_q}) \tag{4.12}$$

4.2.1 Swing Equation

In developing equations for synchronous machine for representing it in stability studies, Swing equation came into picture. Swing equation can be expressed as two first order differential equations as.

$$\frac{dw(t)}{dt} = \frac{1}{T}(T_m - T_e - Kd\Delta W(t)) \tag{4.13}$$

$$\frac{d\delta}{dt} = \Delta w(t) \tag{4.14}$$

Often, we need to represent the dynamic behavior of the machine, including electromechanical dynamics involving rotor inertia. If we note J as the rotational inertia constant of the machine system, the rotor dynamics are described by the two ordinary differential equations. It is customary to define an "inertia constant" which is not dimensionless but which nevertheless fits into the per-unit system of analysis. Which is rotational kinetic energy per unit base power.

Replacing moment of inertia with inertia constant H we can write relation as,

$$H = \frac{\frac{1}{2}JW_m^2}{S_{base}} \tag{4.15}$$

Where H is inertia constant, J is moment of inertia of generator, w_m is mechanical speed in radians, S_{base} is base MVA of generator.

There are 180 electrical degrees between the centres of two adjacent north and south poles. Since 360 electrical degrees represents a full cycle of sinusoidal EMF, we are interested in determining how many sinusoidal cycles are generated in one complete mechanical rotation, i.e., 360 mechanical degrees for a machine having P poles. The number of electrical degrees per min (i.e) electric speed as a function of degrees of mechanical rotation per min mechanical speed is

$$w_m = \frac{2}{p}\omega \tag{4.16}$$

where P is the number of poles (always an even integer), p is the number of pole-pairs, and is mechanical speed. Thus, a two-pole machine generates one cycle of sinusoid a four-pole machine generates two cycles and so on, in one full revolution of the armature.

$$\frac{1}{w_0}\frac{dw(t)}{dt} = \frac{1}{2H}(P_m)(p.u) - p_e(p.u) \tag{4.17}$$

$$w(t) = \frac{1}{2H}\int_0^t p_m - p_e - kd\Delta wt \tag{4.18}$$

$$w(t) = w_o t\Delta wt \tag{4.19}$$

In above equations t in seconds, rotor angle and w_0 will be expressed in electric radians. For the stability analysis of large scale power systems stator transient terms must be neglected. With these terms neglected stator voltage contains only fundamental frequency component and stator voltages can be represented as algebraic equations. This allows steady state relationship for representing inter connected transmission lines. Modeling of system based on two swing equations considering them as state equations we can have Matlab/Simulink model as shown in Fig. 4.5.

4.3 Governor and prime mover model

The load on the turbo-generator does not remain constant but vary as per the consumer (Grid) demand requirements. The presence of a perpetual mismatch between the generation and the demand in a larger network results into variations in frequency and necessitates a continuous adjustment of generation at the turbo-generators. If not, the speed / frequency will be oscillating which is an

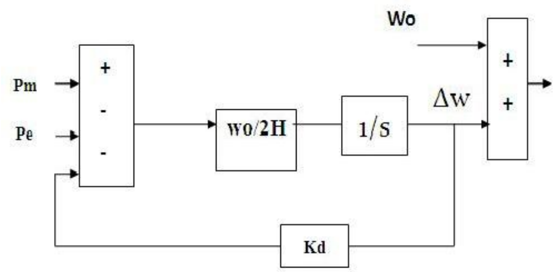

Figure 4.5:

indication of poor power quality. A state of unchanging system frequency and zero acceleration indicates that the generation meets the system demand. The governing system provides for this regulation /adjustment, when the turbo-generator is on bars, by controlling the steam inflow to the turbine. The regulation is envisaged by various control logics and by operating the control valves in the turbine.

Governor of steam generators generally will have speed regulation of 5-6 percent from zero to full load speed governing system acts as a comparator whose output is difference between reference set power and change in speed per unit speed regulation from speed power characteristics it can be approximated with a single time constant T_g.

The source of mechanical power, commonly known as the prime mover, may be hydraulic turbines at water falls, steam turbines whose energy comes from the burning of coal, gas and nuclear fuel and gas turbines. The model for the turbine relates changes in mechanical power output to changes in steam valve position. Different types of turbines will vary widely in characteristics. The simplest prime mover model for steam turbine can be approximated with time constant T_t which varies from 0.2 to 2 sec [12].

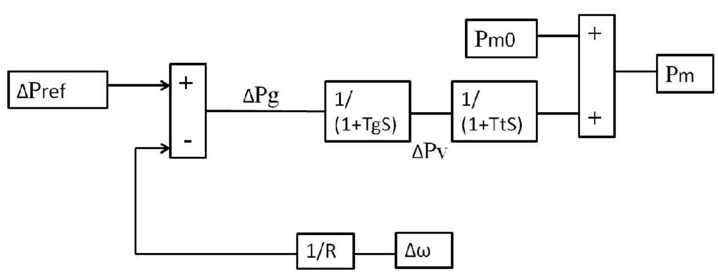

Figure 4.6: Governor turbine model

4.4 Classical model of synchronous generator

First order simplification of a synchronous machine is to reduce the computational effort. It reduces the order of the model as well as allows larger integration steps in time domain simulations.

For studies in which period of analysis is less when compared to Transient open circuit time constant , synchronous machine model can be simplified by assuming internal voltage E_q is constant through out the analysis period. This assumption eliminates only electrical differential equation associated with synchronous machine. A further approximation makes computation much easier. That significant approximation is ignoring transient saliency by assuming $X_d = X_q$. i.e., assuming the synchronous reactance of both d , q-axis. The flux linkages also remains constant. With these assumptions voltage behind transient impedance $(R_a + jX_{d1})$ will have constant magnitude.

This model offers significant flexibility in computational complexity in modeling of synchronous machine. With this model we can represent transient behavior of synchronous machine by a simple voltage source of constant magnitude behind a reactance. This model can be referred as Classical model, since it will be used in stability studies frequently. So equivalent circuit of synchronous machine in transient state can be represented with following Figure. 4.7.

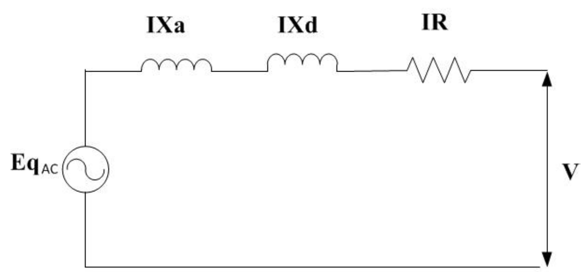

Figure 4.7: Equivalent circuit of synchronous machine in transient state

These simple models are applicable for all the three time frames. i.e., Transient, sun transient. Steady state. In Sub transient and transient states rotor flux linkages constant, where as in steady state operation constant field current is assumed to be constant. So major assumptions made in classical model of synchronous generator are, internal voltage (E_q) is constant behind synchronous reactance (X_d) constant. Mechanical power input(Pm) will be constant through out the analysis period. No transient or subtransient or steady state saliency, so $X_d = X_q$. Damping will be negligible, so Damping factor Kd=0(sometimes very less). Based on the assumptions made in the classical model of the generator, the phasor diagram when we scale it by (V/Xd) will be come as shown in Fig. 4.8.

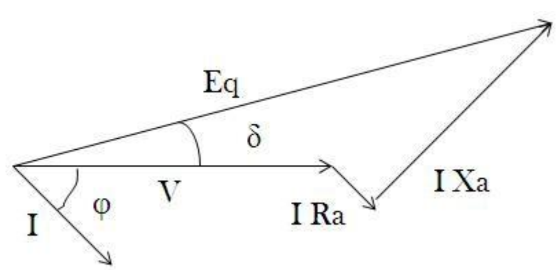

Figure 4.8: Phasor diagram

Modified phasor diagram in the classical model of Synch generator Now based on $X_d = X_q$ the power equations discussed earlier becomes as

$$P_e = \frac{E_q * V}{X_d} \sin\delta \tag{4.20}$$

$$Q_e = \frac{E_q * V}{X_d} \cos\delta - \frac{V^2}{X_d} \tag{4.21}$$

Where P_e , Q_e are active power and reactive power respectively As damping is neglected in classical model, by considering both the state equations in swing equation we can have final model of a synchronous machine considering all the assumptions in classical model of it as shown in Fig. 4.9.

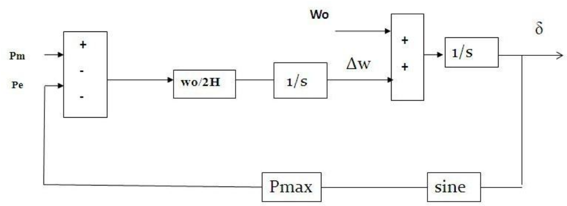

Figure 4.9: Phasor diagram

So synchronous Generator is modeled classically, based on some assumptions which will reduce computational complexity as above. Steady state model of it is as shwon in figure, where $P_{max} = \frac{E_q V}{X_d}$ and as a closed loop control system. Modelled system in the matlab will be shown in Fig. 4.10.

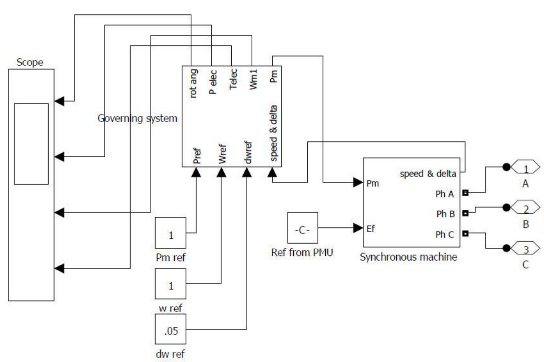

Figure 4.10: Matlab/simulink Classical model of synchronous machine

Now the response of generator is recorded in terms of speed, rotor angle, voltage, 3-Ph currents, electrical power output etc. captured in Matlab/simulink and Discussed in Results and analysis.

Chapter 5

Results and Analysis

Boundary bus of the sub system (Bus voltage and angle) is modeled a Classical synchronous generator which will act as three phase controllable source. The response of the system at another bus of subsystem observable by PMU is observed. Bus angles estimated without fault and with fault in Matlab/Simulink.

5.1 Capturing response of synchronous generator

Classical model of a generator is modelled in Matlab/Simulink with following parameters and Internal Voltage, Electrical power, Phase currents, Rotor angle, speed of shaft captured respectively in Fig. 5.1, 5.2, 5.3 when there is a transition of Mechanical Power from 500MW to 1000MW. Clearly Transition is observed in electric power. Specifications of generator were as per Fig. 5.1.

Machine specification	description
Rotor type	Wound Rotor type
Machine Rating	1000MVA
Voltage Ln-Ln (RMS)	315KV
Frequency	50 Hz
Synchronous speed	1800 rpm
Pair of poles	2
Moment of Inertia	16880
Internal impedance	0.0204+j0.814*e-3
Mechanical input	500MW-1000MW

The K_d damping coefficient simulates the effect of damper windings normally used in synchronous machines. Here we considered the effect of damping factor When the machine is connected to an infinite network (zero impedance), the variation of machine power angle delta (δ) resulting from a change of mechanical power (Pm) can be approximated with second order transfer function.

The damping factor K_d is adjusted in order to obtain a damping ratio $\xi = 0.3$. According to the formula derived from second order equation, the required K_d value is

$$K_d = 4\varepsilon\sqrt{\frac{2}{\omega H P_{max}}} = 64.3 \tag{5.1}$$

The Load Flow option of the Powergui has been used to initialize the machine in order to start simulation in steady state with the machine generating 500 MW. Response of the system is captured when ever there is a transaction of Mechanical Power input from 500MW to 1000MW at 0.5 sec.

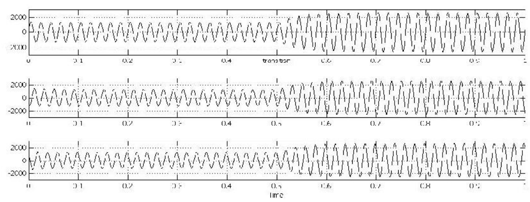

Figure 5.1: Current response of the system when transition took place.

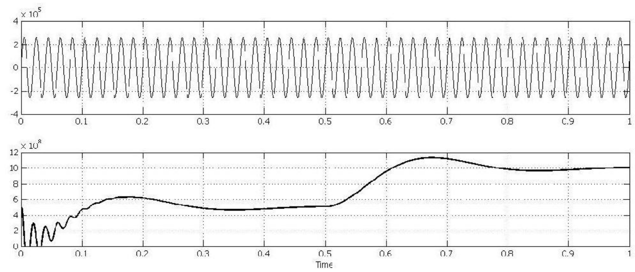

Figure 5.2: Response of E_q and P_e when transition happened at 0.5 sec.

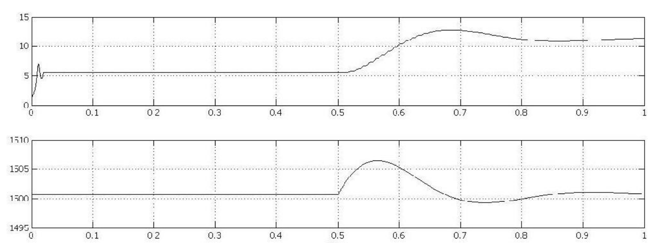

Figure 5.3: Response of rotor angle and speed when transition happened at 0.5 sec

For an initial electrical power P_e = 500 MW (0.5 pu), the load angle δ is 1.65 degrees, which corresponds to the expected value

$$P_e = \frac{E_q V}{X_d}\sin\delta = 0.5 p.u \tag{5.2}$$

When transition happened it reached 1.0 p.u that is 1000MW. Similarly load angle also from the initial value 1.65 degrees it reached 11.3 degrees when transition happened at 0.5 sec.

5.2 Capturing Phasor quantities with PMU

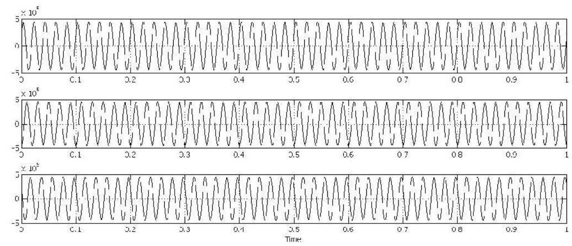

Figure 5.4: Voltage input wave form to PMU.

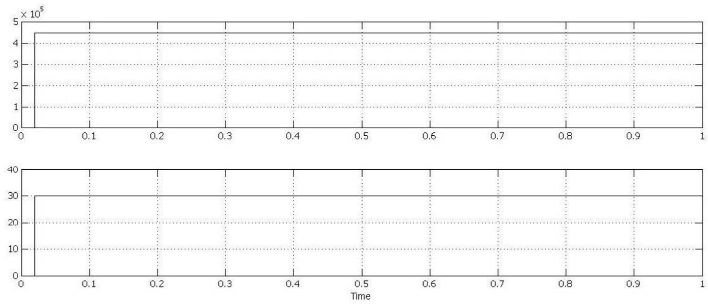

Figure 5.5: Magnitude (peak to peak) and phase of input voltage

Phasor measurement unit placed at generator and the captured response of the voltage and current magnitudes and angles. As the line to line rams voltage of generator 315 kv magnitude(Peak to peak) will be 1.414*315 that gives 4451 kv. Similarly current phasor also. We can observe the above figures. These responses are recorded through Phasor measurement unit modeled in Matlab/Simulink when there is change in mechanical power input of generator, we observed clear transition in actual response and response captured through Phasor measurement unit both.

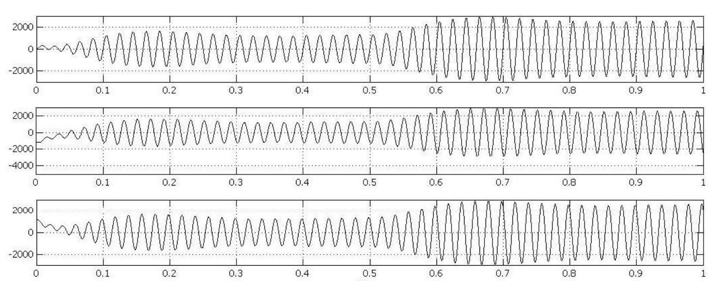

Figure 5.6: Current input wave form to PMU

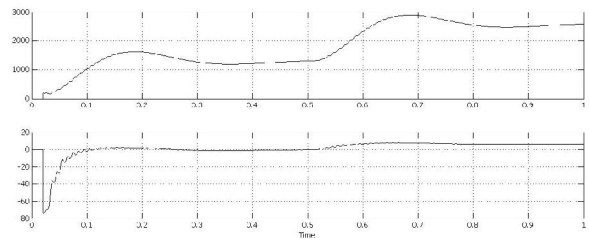

Figure 5.7: Magnitude (peak to peak) and phase of input voltage

5.3 Calculation of rotor angle at various events

Initially Voltage Phasor is replaced by Classical model of Generator, Reference voltage is given as boundary bus voltage response is Phase angle is taken as 0 degrees or other vise phase of the terminal voltage of generator is taken as reference. Voltage and Current phasors of another bus which is connected to it through a long transmission line were capture with fault and with out fault. Detailed modeling is in Simulink given in Fig. 5.8.

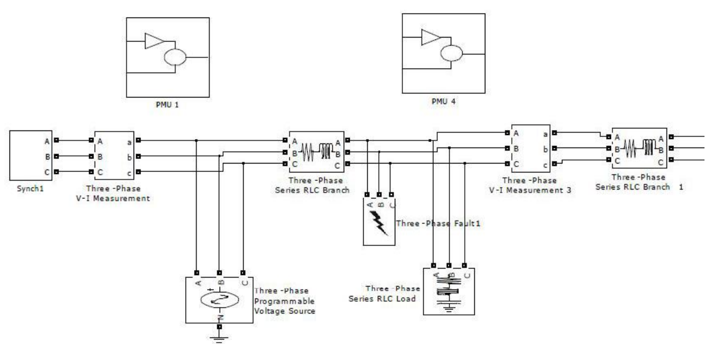

Figure 5.8: Modeling of generator placed subsystem at boundary

PMU1 placed at reference bus and PMU4 at remote bus which is connected through a transmission line of reactance 80.3 ohm. A Single phase to ground fault is created on Phase A at bus other than reference bus at 0.3 sec and cleared at 0.7 sec with ground resistance 0.001 ohm . Then Voltage and current magnitudes and Variation in Bus angle were observed. These responses were captured through Phasor Measurement unit. We can observe voltage and current magnitude variation when fault was created at 0.3 sec and cleared at 0.7 sec having grounding resistance 0.001 ohm in Fig. 5.9.

Now the phase angle difference between the two zero crossing points of voltage and currents or power angle at bus 4 can be calculated in Both the methods mentioned in earlier Chapter 3. In first method we directly subtracted phase angles at both the buses as they were time stamped with simulation time.

In second method we can calculate power angle with the help of following equation shown below

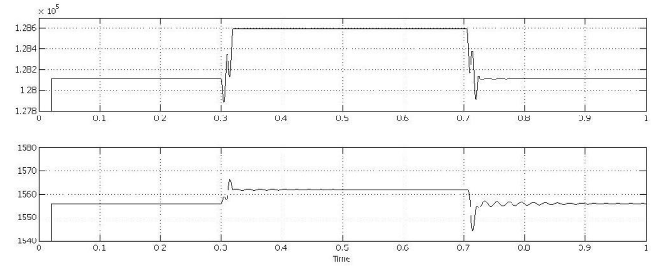

Figure 5.9: Voltage and Current magnitudes captured through PMU4

as discussed earlier.

$$\delta = \sin^{-1} \frac{P(X_l - X_c)}{E_1 E_2} \tag{5.3}$$

But we know that Voltage and Current phasors at a particular bus are synchronized with respect to simulation time. So subtracting their phases we get the angle ϕ, with following equation we can find out Real power.

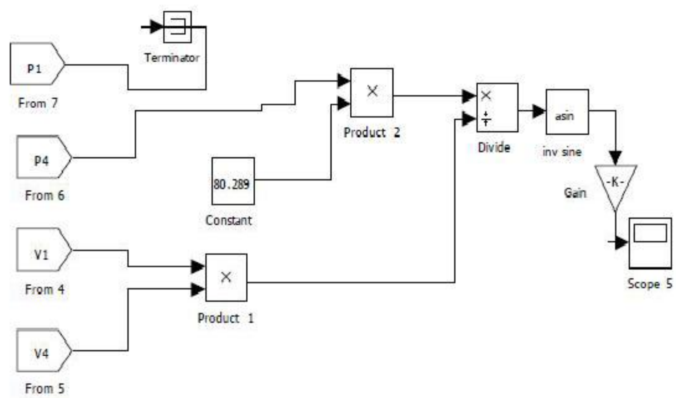

Figure 5.10: Computation of bus angle

$$P = |E||I| \cos \phi.$$

Now computation of Real Power flow at Bus4 can be done this Simulink model based on above equation in Fig. 5.11.

Here V4, I4 are the voltage and current magnitudes from Bus4, Vang4, Iang4 are phase angles of bus voltage and currents which were extracted from PMU4. From the equation above when we calculated Real power flow at bus4, P4 .Now we can observe the wave forms representing power angle values computed in both the methods.

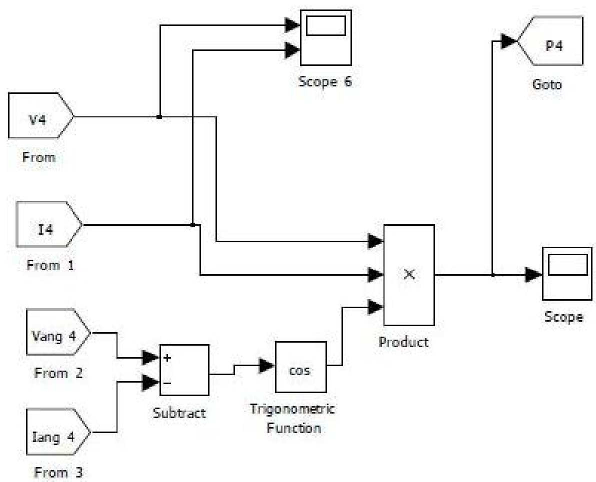

Figure 5.11: Computation of power at Bus4

5.3.1 Computation of bus angles with and without fault

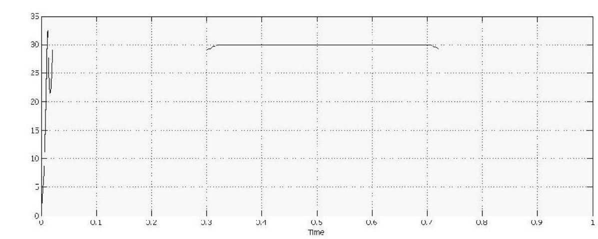

Figure 5.12: Computation of bus angle through direct method without fault.

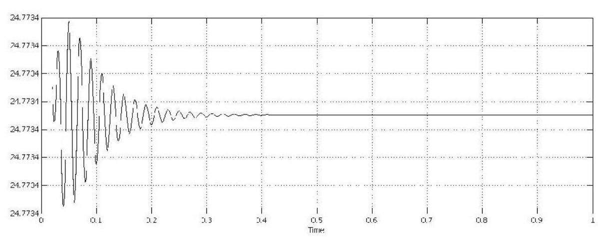

Figure 5.13: Computation of bus angle through power flow method without fault.

Now same power angles can be calculated when ever there is fault occurred at 0.3 sec and cleared at 0.7 sec. we can observe power angles in both the methods in Prefault condition. During fault condition and Post fault condition.

Now the power angle values obtained from both the methods at Pre fault, during fault, post fault condition with respect to time were tabulated.

In two cases one is, as both Substations were synchronized direct subtraction of voltage Angles at

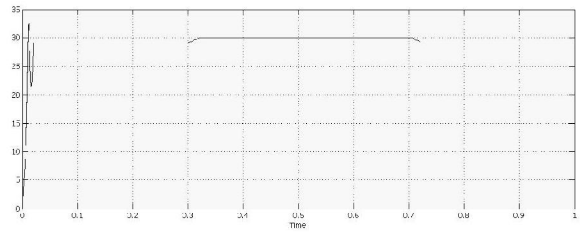

Figure 5.14: Computation of bus angle through direct method with fault.

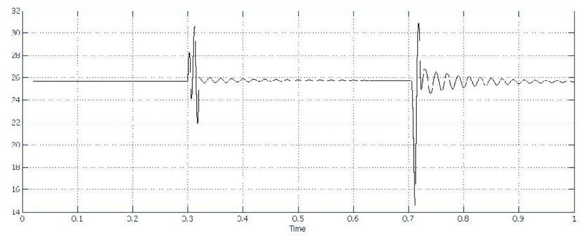

Figure 5.15: Computation of bus angle through power flow method with fault.

Event	Time	Directly Sub. δ	Calculated δ	Error
Pre fault	0.1	28.4	25.9	2.5
	0.2	28.4	25.9	2.5
	0.28	28.4	25.9	2.5
During fault	0.32	31.2	28.6	2.6
	0.36	31.2	31.1	0.1
	0.6	31.2	27.1	4.1
post fault	0.8	28.4	27.2	1.2

Table 5.1: Bus angles obtained in both methods.

two buses were subtracted and it was compared to delta obtained through real power flow equation in all the events with respect to time. The average error value of power angle (δ) is 1.9 degrees. If we observe plot of power angle(δ) with respect to time in both the cases, we can observe more oscillations in calculated wave form due to oscillations in power and current in real power flow calculation.

Chapter 6

Conclusion

As many of the planning and operational considerations in a power network are directly concerned with the flow of real power, measuring angle differences across transmission has been of concern for many years, this project we modeled a phasor measurement unit. With the help of integral programming technique we found the optimal locations of PMUs for standard IEEE-14 bus system so that total system is observable. Now we divided system into subsystems based on PMU locations.

We modeled the boundary bus of a subsystem which is observable by a PMU with a classically modeled generator which can be utilized as controllable three phase source. We captured phasor data including phase angles at boundary bus and a remote bus through PMU. The bus angle difference at different buses were estimated directly with PMU model and power flow method with phasor data. Bus angle from the results of both the methods had an agreement with an error of 1.6 degrees. We can say synchronous phasor measurements were reliable for power system monitoring and better situational awareness as Matlab/Simulink results confirmed the power equation.

IEEE-14 bus system

Single line diagram IEEE 14 bus system

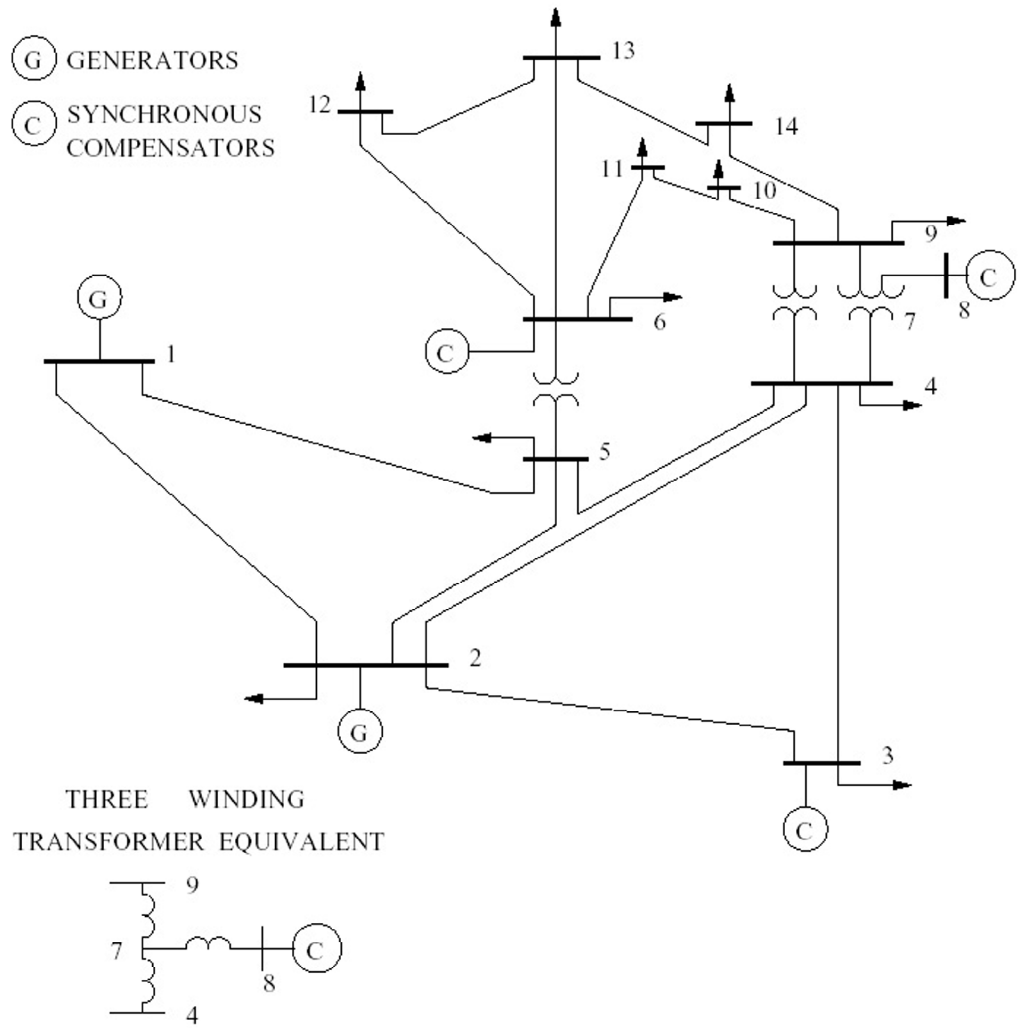

Figure 1: IEEE 14 bus system

Line data of IEEE 14 bus system

Line No	Bus Code (p-q)	Resistance (p.u)	Reactance (p.u)	Half line shunt Conductance (p.u)	Half line shunt Susceptance (p.u)	Off-nominal ratio
1	1-2	0.01938	0.05917	0.00	0.0264	1.00
2	2-3	0.04699	0.19797	0.00	0.0219	1.00
3	2-4	0.05811	0.17632	0.00	0.0187	1.00
4	1-5	0.05403	0.22304	0.00	0.0246	1.00
5	2-5	0.05695	0.17388	0.00	0.1700	1.00
6	3-4	0.06701	0.17103	0.00	0.0173	1.00
7	4-5	0.01335	0.04211	0.00	0.0064	1.00
8	5-6	0.0000	0.25202	0.00	0.0000	0.932
9	4-7	0.0000	0.20912	0.00	0.0000	0.978
10	7-8	0.0000	0.17615	0.00	0.0000	1.00
11	4-9	0.0000	0.55618	0.00	0.0000	0.969
12	7-9	0.0000	0.11001	0.00	0.0000	1.00
13	9-10	0.03181	0.08450	0.00	0.0000	1.00
14	6-11	0.09498	0.19890	0.00	0.0000	1.00
15	6-12	0.12291	0.25581	0.00	0.0000	1.00
16	6-13	0.06615	0.13027	0.00	0.0000	1.00
17	9-14	0.12711	0.27038	0.00	0.0000	1.00
18	10-11	0.08205	0.19207	0.00	0.0000	1.00
19	12-13	0.22092	0.19988	0.00	0.0000	1.00
20	13-14	0.17093	0.34802	0.00	0.0000	1.00

Table 1: Line data of IEEE 14 bus system

Bus data of IEEE 14 bus system

Bus No	Voltage magnitude	Load		Generation	
		MW	MVAR	MW	MVAR
1	1.06	0	0	0	0
2	1.045	21.7	12.7	40	42.4
3	1.01	94.2	19	0	23.4
4	1	47.8	-3.9	0	0
5	1	7.6	1.6	0	0
6	1.07	11.2	7.5	0	12.2
7	1	0	0	0	0
8	1.09	0	0	0	17.4
9	1	29.5	16.6	0	0
10	1	9	5.8	0	0
11	1	3.5	1.8	0	0
12	1	6.1	1.6	0	0
13	1	13.5	5.8	0	0
14	1	14.9	5	0	0

Table 2: Bus data of IEEE-14 bus system

Regulated Bus Data of IEEE 14 bus system

Bus No	BUS Voltage(mag) p.u.	Minimum MVAR	Maximun MVAR
2	1.045	-40.00	50.00
3	1.010	0.00	40.00
6	1.070	-6.00	24.00
8	1.090	-6.00	24.00

Table 3: Regulated bus data of IEEE 14 bus system

Shunt capacitor Data of IEEE 14 Bus system

Bus No.	Susceptance(p.u.)
9	0.190

Table 4: Shunt capacitor data of IEEE 14 bus system

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