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Implementation of The Test Bench System For Wide Area Monitoring System

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ABSTRACT

The present work accentuates on the creation of the test bench for wide area monitoring systems (WAMS). With the dawn of the Phasor Measurement Units (PMUs), it has become to a certain extent that it is elegant to monitor and control the power system networks in Real Time. PMUs provide the Phasor Measurements of the Voltage and Currents using the Global Positioning System (GPS) Satellites, in microseconds. Discrete Fourier Transform (DFT) technique is used by the PMU to Estimate the Phasors. Power System Network Observability plays a major role in demanding that the system should be fully observable through PMUs. A Novel Algorithm is developed for optimal placement of PMUs using Greedy and Breadth First Algorithms (BFA). The IEEE -14 Bus test Systems have been modeled in MATLAB/SIMULINK, the proposed method has achieved good results with optimal no of PMUs required.

Keywords: Hybrid Dynamic Simulation, Model Validation, Network Observability, Optimal PMU Placement, WAMS

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1. INTRODUCTION

Wide Area Monitoring System (WAMS) has become one of the most important technologies in the present scenario of upgrading the traditional Electric grid. For reliable electricity supply, up gradation of the grid is necessary. The concept of creation of test bench system gives us the analysis of the simulation measurements and real time measurements, which is possible by validating the model. The model validation can be done by different methods, the selected method in present work is Hybrid Dynamic Simulation, and its applications include model validation of Generator model and single area load frequency model. For maintaining stability in power system network each bus must be fully observable and to maintain observability of the system, PMUs must observe each and every bus which is interconnected. Suitable and optimal bus locations are selected by implementing the necessary algorithms for PMU.

This chapter is organized as follows: section II explains the Hybrid Dynamic Simulation concept. Section III reviews the concepts of the phasor representation. Section IV Phasor Measurement Unit, Section V Describes the Test Bench system for WAMS, section VI presents the results and Section VII presents the conclusions drawn from analysis of the results.

2. CONCEPT OF HYBRID DYNAMIC SIMULATION

The concept of Hybrid Dynamic Simulation is that it injects the external signals into the simulation process and it allows interacting with the conventional simulation loops, which interact with the external signals. The Term "Hybrid" refers to sagacity of associating the Real Time Measurements with the Simulation Measurements.

2.1. Problem Formulation

Power System Dynamics can be described by set of equations

$$\left\{\begin{array}{l}\dfrac{dx}{dt} = r(x, y) \\ 0 = s(x, y)\end{array}\right\} \tag{1}$$

where x=[$x_1,\ldots x_P$] are state variables , y=[$y_1,\ldots y_Q$] are the algebraic variables, the functions **r** and **s** are containing P and Q equations respectively.

$$\left\{\begin{array}{l}\dfrac{dx}{dt} = r(x, y', y^*) \\ 0 = s'(x, y', y^*)\end{array}\right\} \tag{2}$$

where y'= [$y_1,\ldots y_{i-1}, y_{i+1}, y_Q$], and s' contains algebraic equations, having one less than y_i compared to s. s' can be solved with available variables.[4]

2.2. Functioning of Hybrid dynamic Simulation.

Let us assume that actual model is unknown and it can be assumed as a black box, the process will inject the external signals into the black box at the boundaries of it.

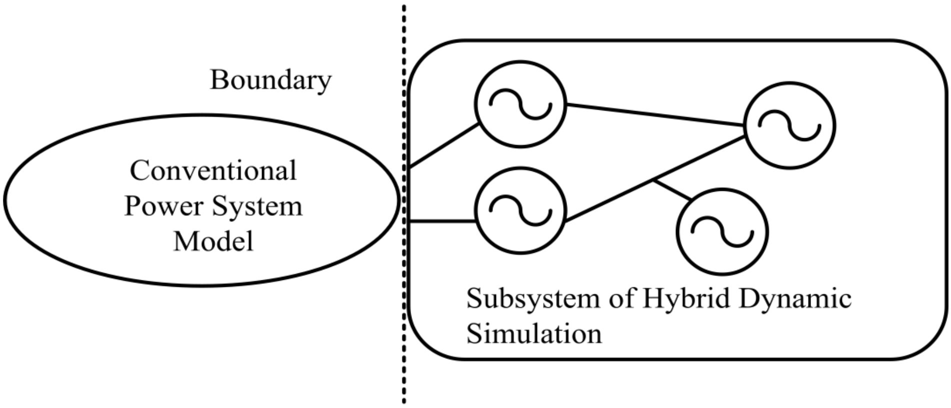
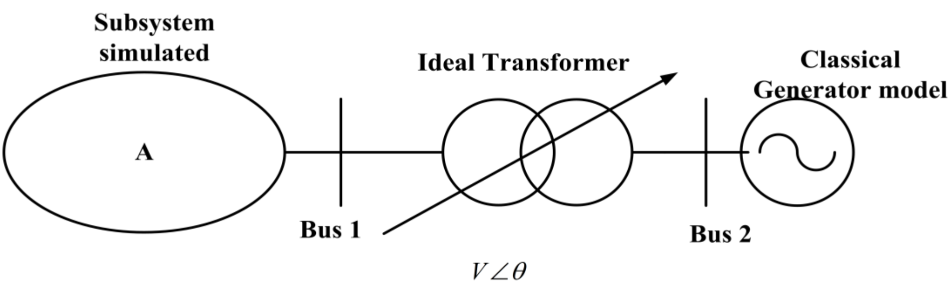


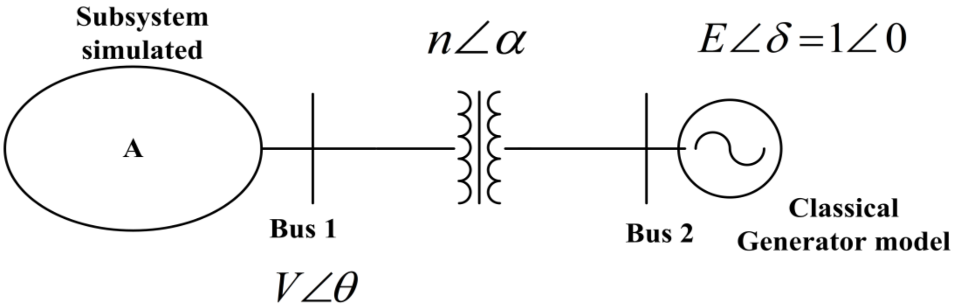
Fig. 1. Hybrid Dynamic Simulation with known boundary conditions

The injection of the external signals into the black box can be implemented by a method known as Phase shift method [5]. The phase shift method will inject the signals at boundary of a bus with the bus voltage and phase angle, such that it consists of an ideal phase shift transformer along with the classical generator are placed at the boundary bus of subsystem as shown in Fig 2, at boundary bus the voltage and its phase angle can be adjusted accordingly to match the conventional measurement by the equation (3), (*rec* = Recorded values).

$$\left\{ \begin{array}{c} n = \dfrac{V_{rec}}{E} = V_{rec} \\ \alpha = \theta_{rec} - \delta = \theta_{rec} \end{array} \right\} \tag{3}$$

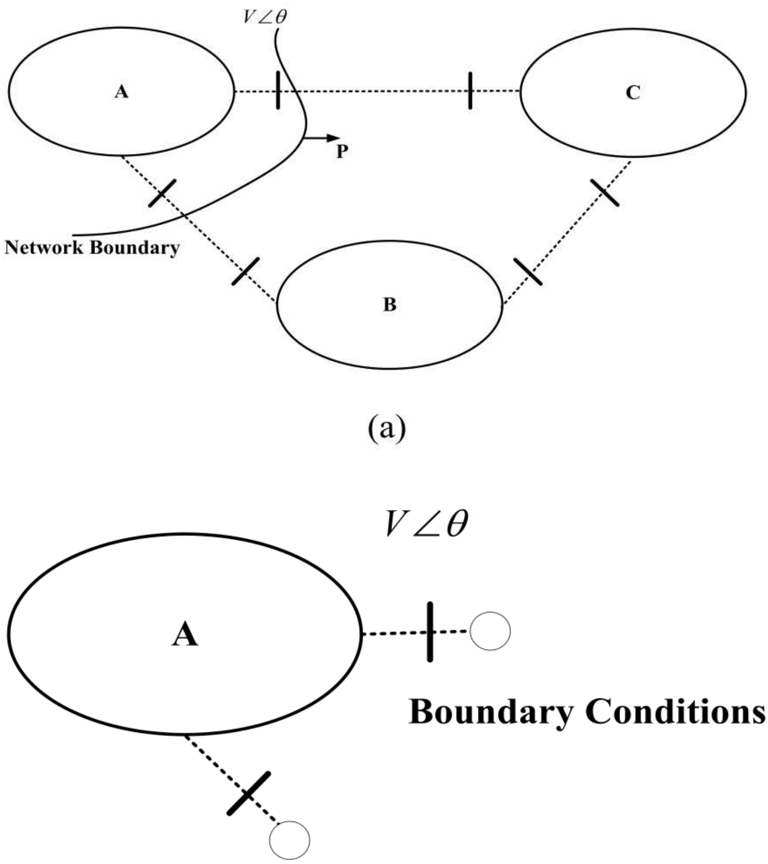


(a)



(b)

Fig. 2. (a) Phase Shifter method topology (b) Equivalent Circuit



(b)

Fig. 3. (a) Interconnected subsystems (b) Reduced System

For, simulating a subsystem, its equivalent model is required, as it is considered, there is a chance of few errors might be crept into simulation, so to represent the conventional system exactly, previous available measurements can be accessed by hybrid dynamic simulation to avoid the errors.

2.3. Procedure of Hybrid Dynamic simulation for the test bench system

Load flow studies are carried out in interconnected network, based on parameters like magnitude of voltage, phase angle, frequency, active and reactive power. Out of these parameters, mostly available parameters are voltage and phase angle or frequency for carrying out a load flow analysis, similarly for hybrid dynamic simulation we can consider any of the signals which are available for us, here in voltage and phase angle are taken into consideration.

The input signal data for simulation model is taken from the physical test system through the LabVIEW Data Acquisition System (DAQ) [9] and the hybrid simulation is carried out, for model validation of the simulation model developed in SIMULINK, the simulation measurements are compared with the physical test measurements.

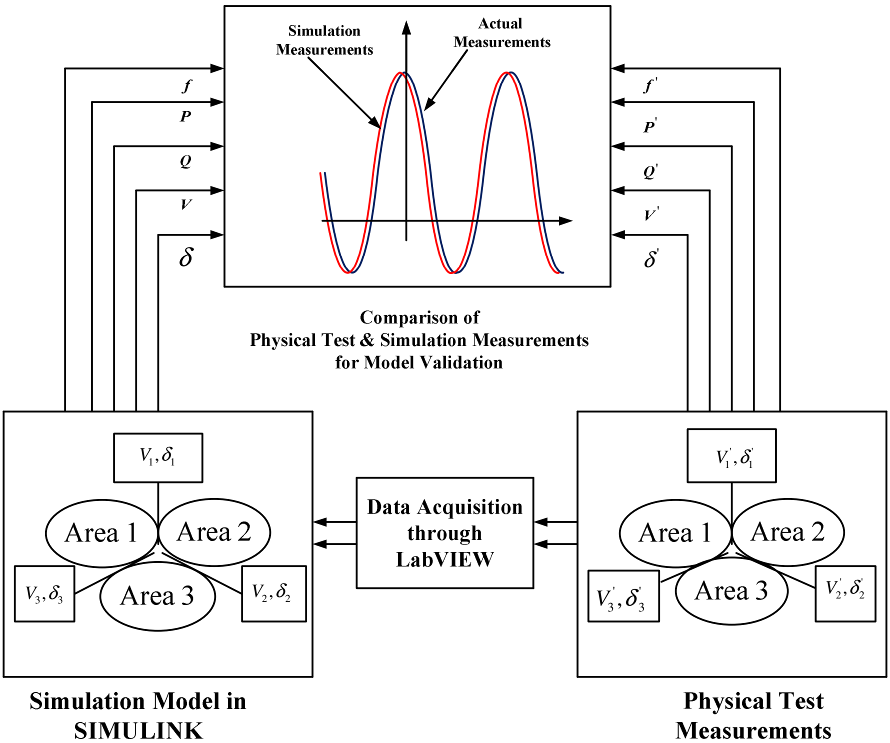


Fig. 4. Block Diagram of the Hybrid Dynamic Simulation

2.4. Classical Generator Model

The generator can be defined as a classical model by considering the field current is assumed to be constant and while the exciter dynamics are not considered, so that the generator induced voltage is constant.
The generator with high Inertia and low value of Impedance are taken into consideration. The saliency and effect of damper windings are neglected. The generator considered is having the voltage setting of 1 p.u.

2.5. Phase Shifting Transformer

The basic concept of phase shifting transformer (PST) is that to change the phase displacement between the input voltage and output voltage of a line. The PST is considered with having a near-zero impedance, hence it is considered as the Ideal transformer.

3. PHASOR MEASUREMENT

3.1 Classical definition of Phasor

Phasor is a vector representation and it is an elementary function of a sinusoidal signal, which is represented by magnitude and phase angle. [1]

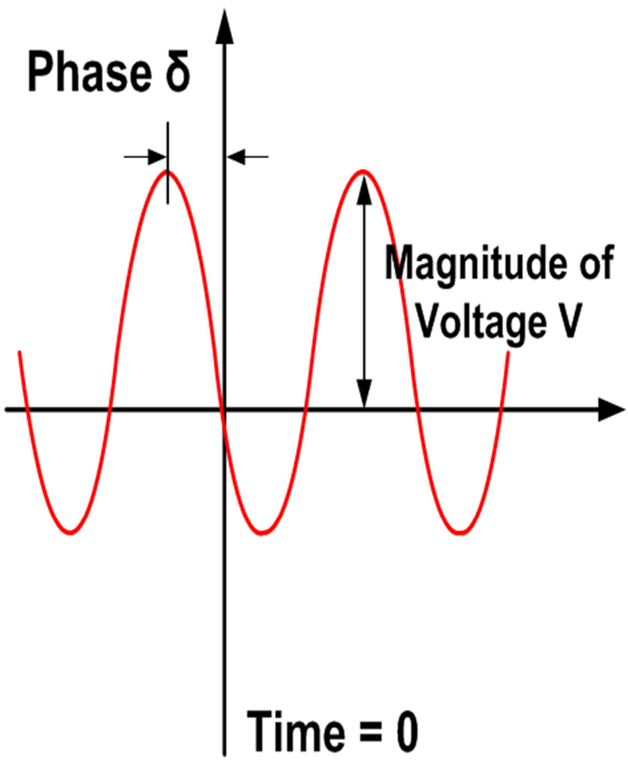


Fig. 5. Sinusoidal Wave

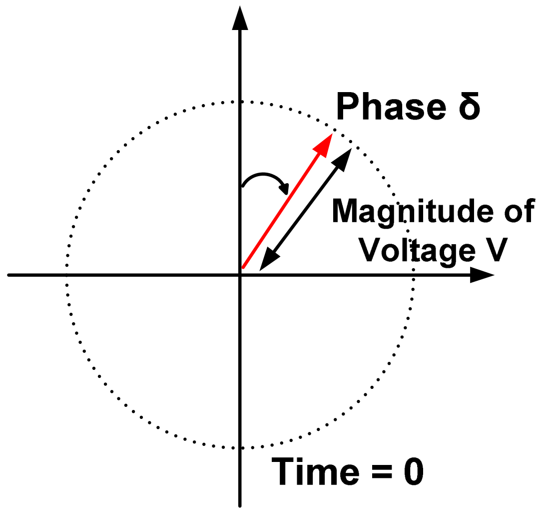


Fig. 6. Phasor Representation

3.2 Phasor Measurement concept

There are different methods to estimate the phasor of a system, which consists of the Magnitude and a Phase angle. For phasor estimation Discrete Fourier Transform (DFT) is a simple method which is widely used in practice. [2, 3]

Let Us consider a 3-ph balanced system at fundamental frequency f_o, sinusoids are given as

$$x_1(t) = X_m \cos(2\pi f_o t + \phi_1) \tag{4}$$

$$x_2(t) = X_m \cos(2\pi f_o t + \phi_2) \tag{5}$$

$$x_3(t) = X_m \cos(2\pi f_o t + \phi_3) \tag{6}$$

Where X_m is magnitude of signal, ϕ_1, ϕ_2 and ϕ_3 are the phase angles $2\pi/3$ radians apart. N Samples per cycle is considered by sampling unit, the three phases of the balanced system are sampled and time domain samples are represented by following equations.

$$x_{n1} = X_m \cos\left(\frac{2\pi n}{N} + \phi_1\right) \tag{7}$$

$$x_{n2} = X_m \cos\left(\frac{2\pi n}{N} + \phi_2\right) \tag{8}$$

$$x_{n3} = X_m \cos\left(\frac{2\pi n}{N} + \phi_3\right) \tag{9}$$

where N is the integral multiple of f_o and the sample index is represented by n and which lies in range 0 to N-1. Formula for DFT is given below

$$X = \frac{1}{N}\sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi n}{N}\right) - j\sin\left(\frac{2\pi n}{N}\right)\right] \quad (10)$$

Here no of samples is N, sample number is given by 'n' and input sample is x_n.

DFT is calculated by,

$$X_k = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi kn}{N}\right) - j\sin\left(\frac{2\pi kn}{N}\right)\right] \quad (11)$$

Here 'k' represents harmonic index.

Fundamental frequency is considered in phasor, then taking k = 0 in above equation gives

$$X_{norm} = X_1 = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi n}{N}\right) - j\sin\left(\frac{2\pi n}{N}\right)\right] \quad (12)$$

Real and imaginary equations are represented by

$$X_r = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left[\cos\left(\frac{2\pi n}{N}\right)\right] \quad (13)$$

$$X_i = -\frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left[\sin\left(\frac{2\pi n}{N}\right)\right] \quad (14)$$

or

$$X_{norm} = X_r + jX_i \quad (15)$$

The Complex quantity X_{norm} is the phasor estimate, its magnitude is given by $\left|X_{norm}\right|$ and the phase angle is calculated by

$$\phi_{norm} = \tan^{-1}\left(\frac{X_i}{X_r}\right) \quad (16)$$

4. PHASOR MEASUREMENT UNIT

PMU is a component of WAMS. It is used in monitoring and recording the data in WAMS. It is a Data Acquisition which estimates the phasors of voltage, current and frequency. A number of PMUs are installed at different nodes, the total monitored data to be time synchronized we use a common time reference. [15] The Main components of the PMU are:

- Analog Inputs
- Anti Aliasing Filter
- Analog to Digital converter
- PLL Oscillator
- Phase Micro Processor
- Modem
- GPS Device

The analog inputs, voltages and currents are obtained from the potential and current transformers from the secondary windings , acquired signals are given to low pass filter , Analog to Digital (A/D) converter is used to filter out the actual frequencies which are required for digitizing the analog signal to digital signal, for high speed synchronized sampling the phase locked oscillator is considered.[6] & [7] The Phase Micro-Processor calculates the positive sequence estimates of all the required current and voltage signals using the Discrete Fourier Transform (DFT) Technique, as the signals are in the form of digital data, so we make use of the modem, which is a device for conversion of digital to analog signals and vice-versa.

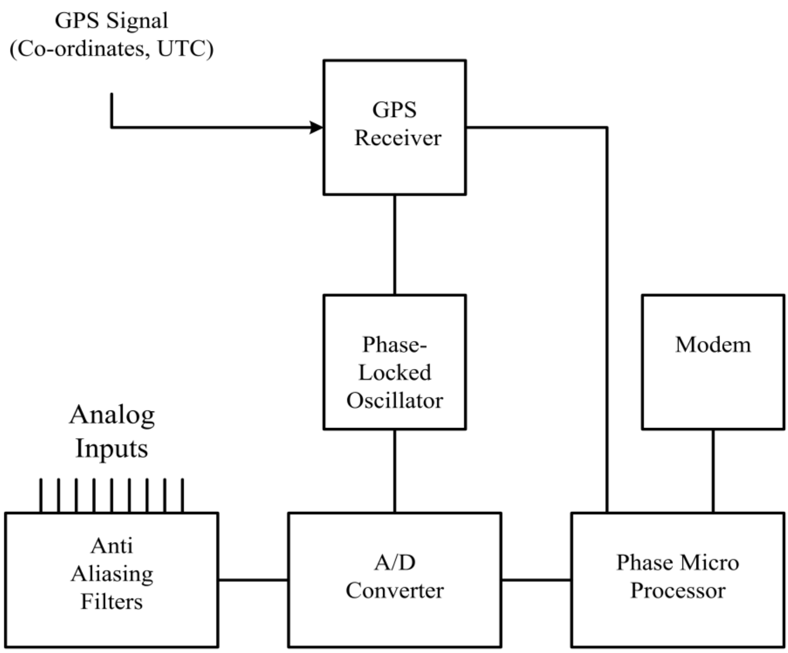


Fig. 7. Block Diagram of PMU

The major benefits of the PMU are such as , the system events can be universally time synchronized at different reporting ratings, dynamic observability can be tracked, wide areas can be monitored and phasors can be estimated locally even at the substation level.

5. TEST BENCH SYSTEM FOR WAMS

Here the test bench system is created such that the real time physical test measurements and the simulation measurements are carried out and compared simultaneously, with the Simulation Interface Tool which is available in LabVIEW, an interface is created between the LabVIEW and SIMULINK , such that the hybrid dynamic simulation can be easily carried out, based on the hybrid dynamic simulation here, two test bench case studies have been developed, one among them is model validation LFC model and the other one is model validation of OPTIMAL PMU PLACEMENT.

5.1. Model Validation of LOAD FREQUENCY MODEL (LFC)

The standard LFC model of single area is considered , which consists the speed governor, turbine, generator and load, the standard parameters of the single area LFC model are tabulated in Table 3 the hybrid simulation is carried for the actual measured signals for change in frequency as well as change in power for a step load change of 0.01 p.u power demand, after obtaining the results, the simulated measured signals of the LFC model are compared with the actual measured signals and thus model validation of the standard LFC model is carried out.

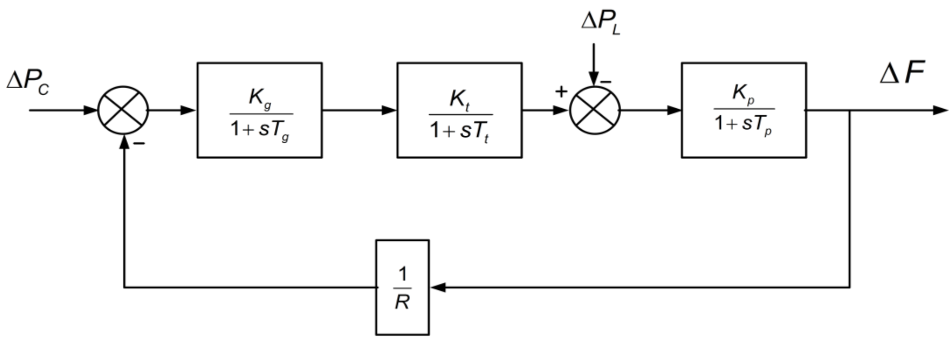


Fig. 8. Block Diagram of the Single Area LFC model

5.2. Model validation of OPTIMAL PMU Placement

Model validation is carried out based on the following procedure.

- Optimal Placement of PMUs by different placement techniques in base case.
- Obtaining the results from base case and now carrying out the Hybrid Dynamic Simulation procedure that is, the external signals are injected into the IEEE Test bus system.
- After obtaining results, if the compared results are within the acceptable agreements, then the model is validated by carrying out the validation algorithm.

- If the compared results are not within the acceptable limits then proper investigation should be done whether taken model is actual one or not and necessary modifications have to be carried out.

As of now base case for placement of PMUs in optimal locations and further work with hybrid dynamic simulation is in progress.

5.3. Placement of PMUs in optimal locations

Placement of PMUs in present work uses the combination of the Binary Search Algorithm [8], breadth first algorithm (BFA) [13] and greedy algorithm [13] & [14] by referring to bus admittance matrix from [10] selected bus system [5]. The Breadth first and binary search algorithms are used to find out and list the interconnection among the adjacent nodes and root nodes. Greedy algorithm is used to trace the bus locations with full Observability of the system.

5.3.1 Case Study without considering the Zero Injection Bus System

In selected system, initially PMU is placed at bus number 7 to cover the single bus number 8, then highest degree bus is selected and the greedy algorithm is applied to it. The solutions of optimal placement of PMUs are obtained at buses 2,6,9,7 or buses 2,10,13,17 or 2, 11, 13, 7. Based on the SORI the optimal solution is 2,6,7,9. Each solution SORI is mentioned in Table 2.

5.3.2 Case Study with Zero injection Bus System

A bus without generator and load connection is defined as zero injection bus (ZIB) [11]. In selected system bus number 7 is identified as zero-injection bus, since it is not having any connection to either generator or load. The Adjacent bus 8 is now connected to buses 4 and 9 and the greedy algorithm is applied to it. After that, by applying the SORI the only optimal solution is obtained at buses 2, 6, 9 and which offers the maximum SORI index value, in turn which shows that the system is more consistent and reliable in nature.

The minimum no of Optimal PMUs required in both Case I and Case II are tabulated in Table 1. System Observability redundancy index (SORI) [12] , plays an important role in selecting the optimal solution of PMU placement, SORI will calculate the total sum of the bus coverage in active system, the higher the SORI, the system is more reliable.

5.4. Flow Chart of the proposed algorithm

As we seen from the figures 11 & 12 the Bus 2 is covering {1,2,3,5,4}, Bus 6 is covering {5,6,11,12,13}, Bus 7 is {4,7,8,9} and Bus 9 is covering {7,9,10,14}, from this inference we can say that the Observability of the total network is fully observable, the network is also fully observable by taking bus number 7 as ZIB, Bus 2 is covering {1,2,3,5,4} , Bus 6 is covering {5,11,12,13} and Bus 9 is covering {4,8,9,10,14}.

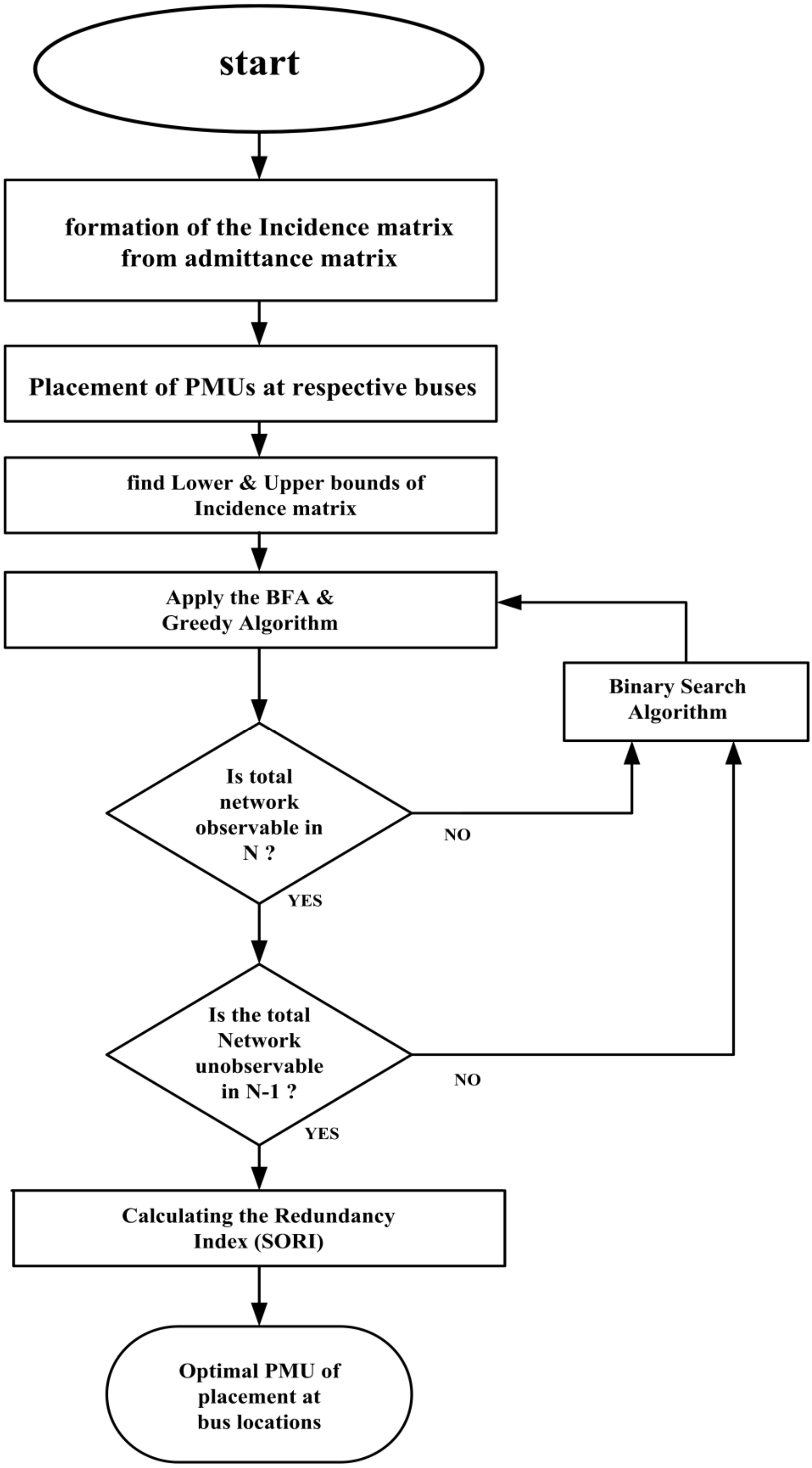


Fig. 9. Flow Chart For Optimal Placement of PMU

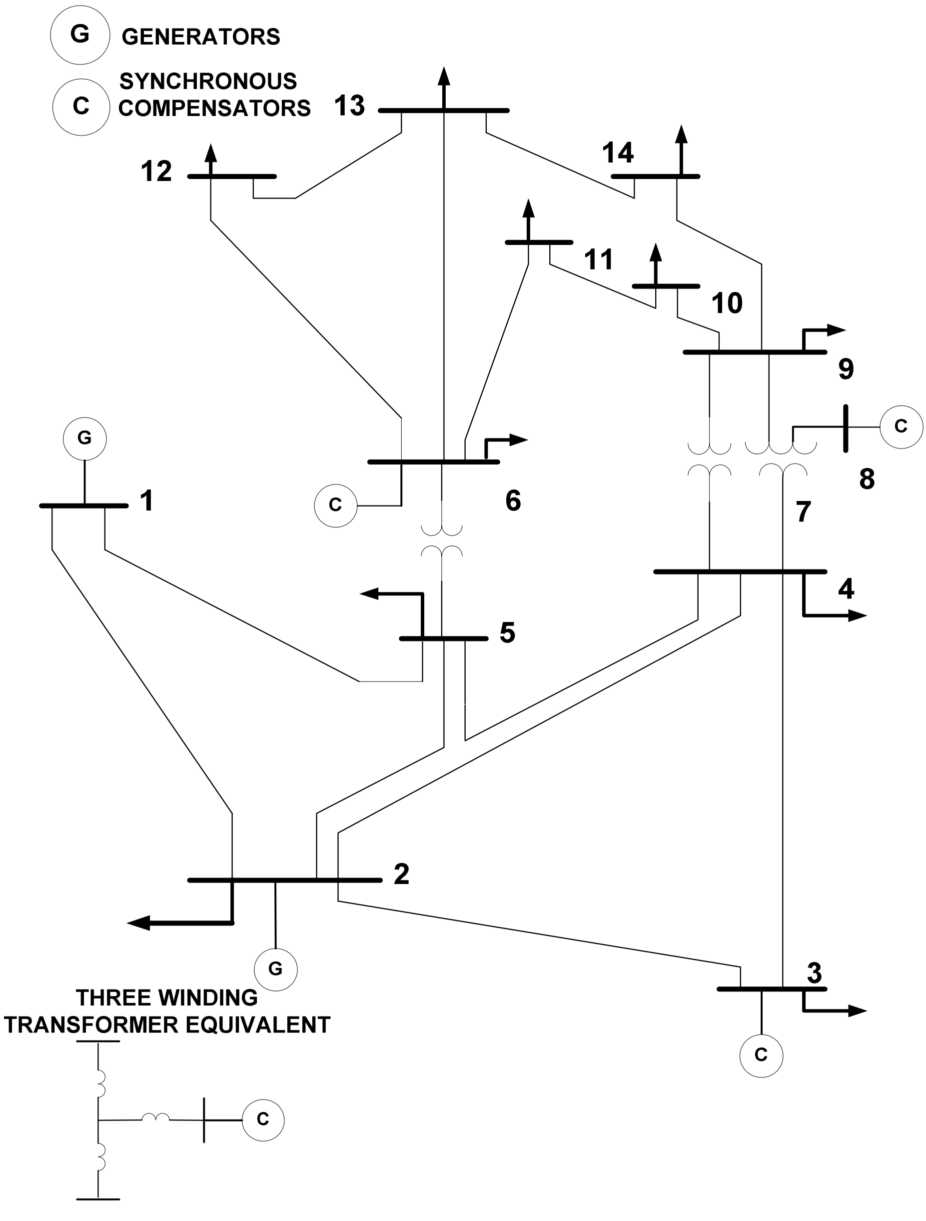


Fig. 10. IEEE-14 Bus Test System

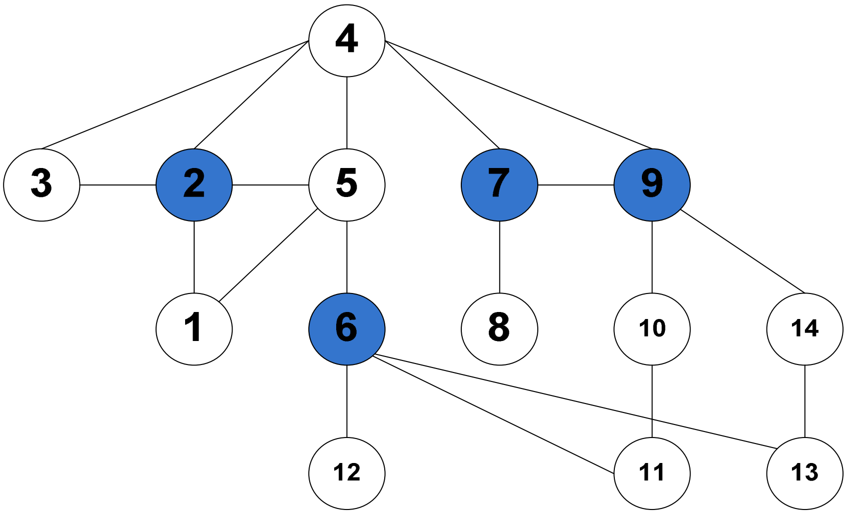


Fig. 11. Tree topology of the placement of PMUs at normal without zero injection bus

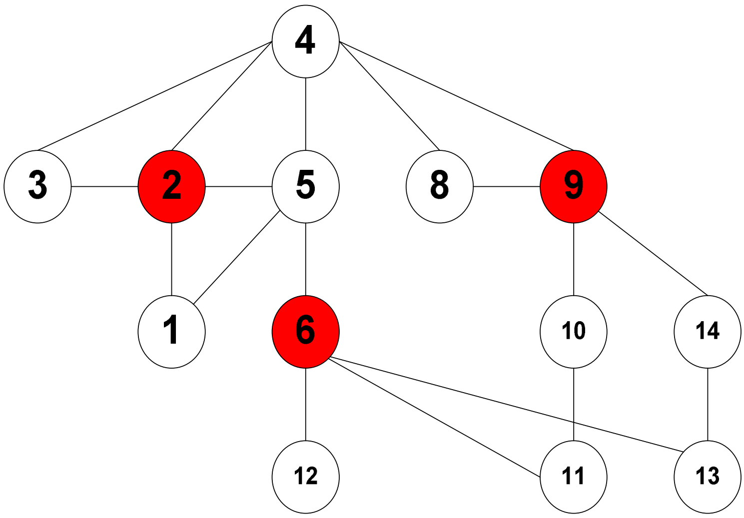


Fig. 12. Tree topology of the placement of PMUs with zero injection bus

6. RESULTS AND DISCUSSIONS

The algorithms are developed in MATLAB Program as a function, the selected system, generator model, standard Load Frequency Control (LFC) model are developed in SIMULINK.

Table 1. Optimal PMU Placement Locations and Minimal PMUs Required

Case No	Location of PMUs	No of PMUs
CASE I	2,6,7,9	4
CASE II	2,6,9	3

Table 2. System Observability Redundancy Index

Case. No	Location of PMUs	SORI
CASE I	2,6,7,9	20
	2,7,10,13	16
	2,7,11,13	16
CASE II	2,6,9	19

Placement of PMUs in respective optimal locations is carried and base case is simulated. Voltage magnitudes, Phase Angles and frequencies at each PMU Bus is recorded. The different plots are displayed below.

The modeling of the classical generator is also carried out in SIMULINK and its Voltage and Phase angle are also recorded.

Table 3. Parameters of Single Area LFC Model

Sr. No	Description	Parameter	Value
1	Governor Gain	K_g	1
2	Turbine Gain	K_t	1
3	Load Model Gain	K_p	120
4	Governor Time Constant(s)	T_g	0.08
5	Turbine Time Constant(s)	T_t	0.30
6	Load Model Time Constant(s)	T_p	20
7	Speed Regulation	R	2.4

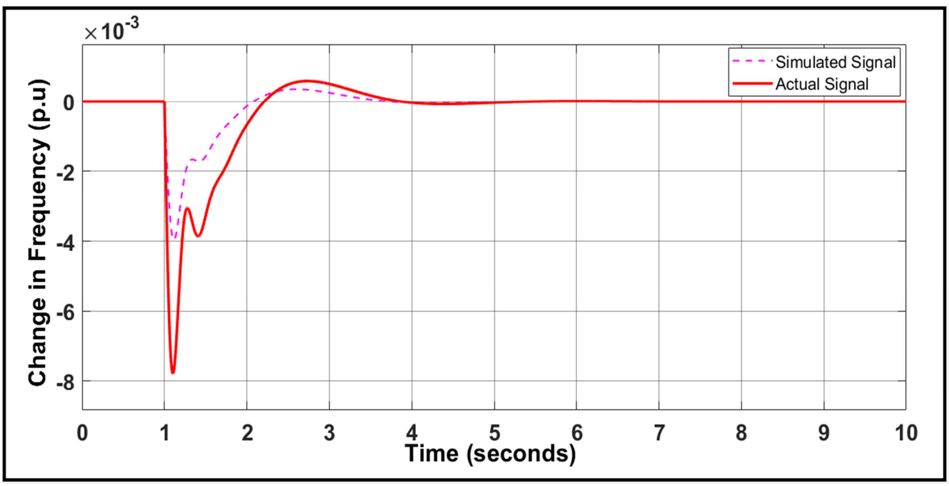


Fig. 13. Change in frequency for 0.01 step load change

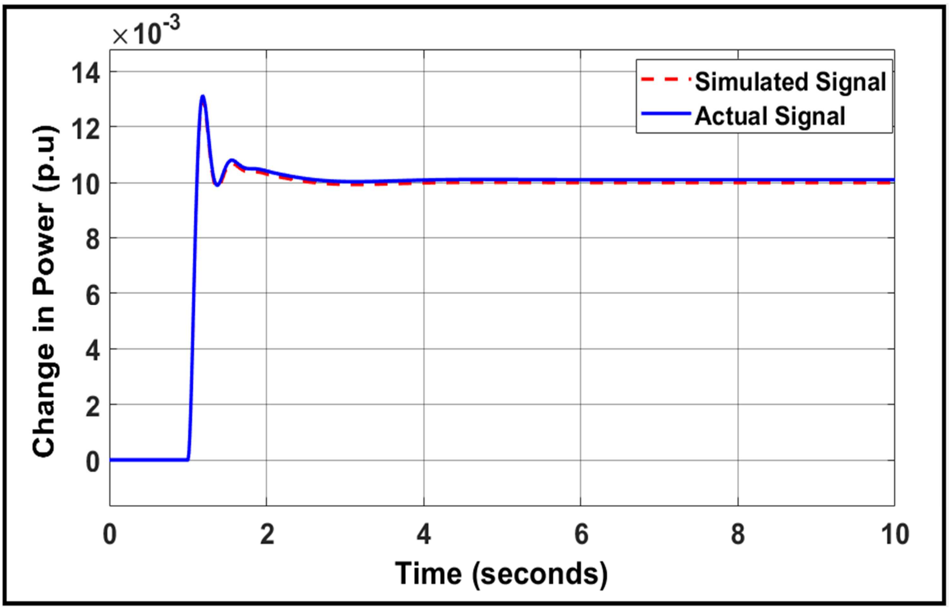


Fig. 14. Change in power for 0.01 step load change

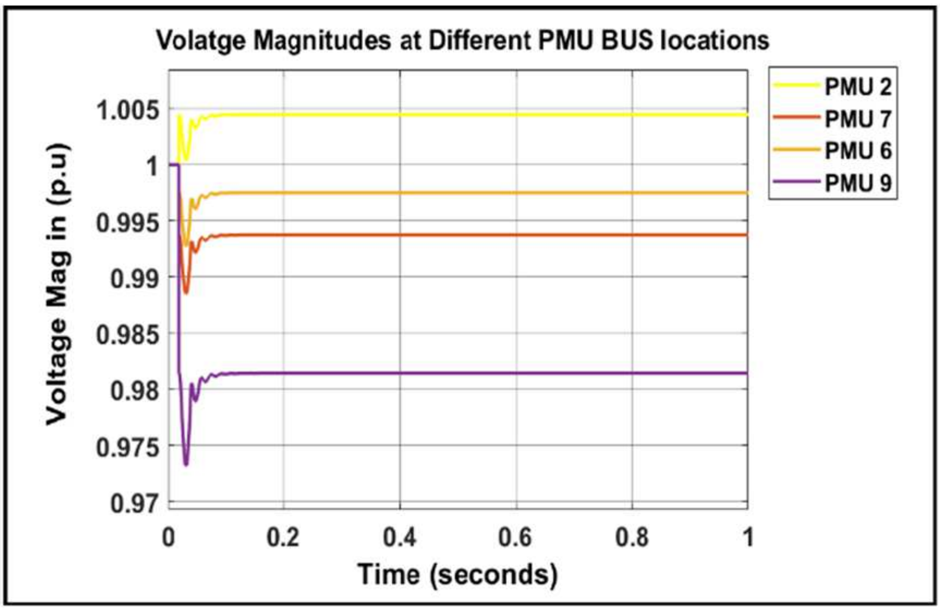


Fig. 15. Voltage Magnitudes at different PMU Bus locations

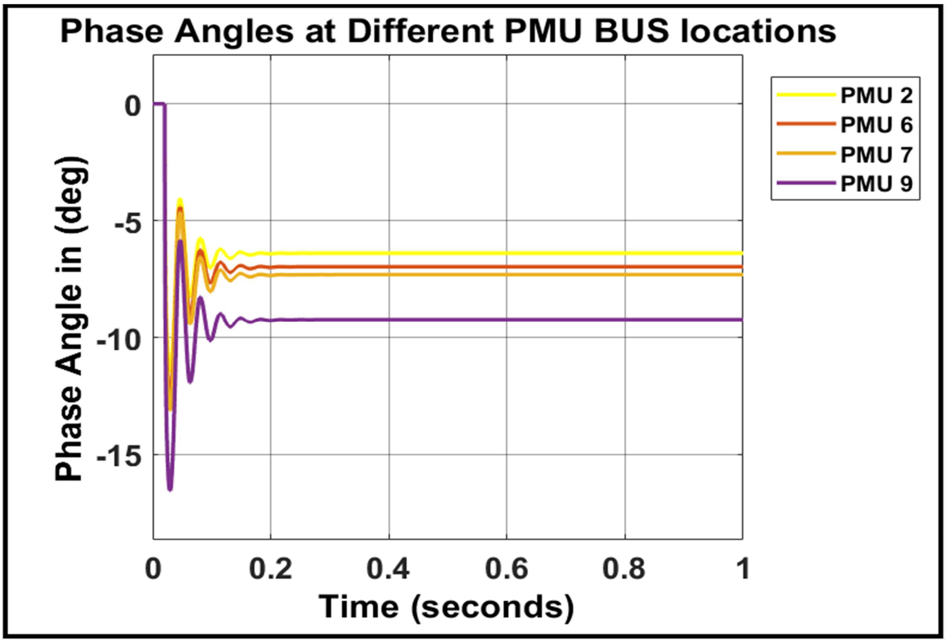


Fig. 16. Phase Angles at different PMU Bus locations

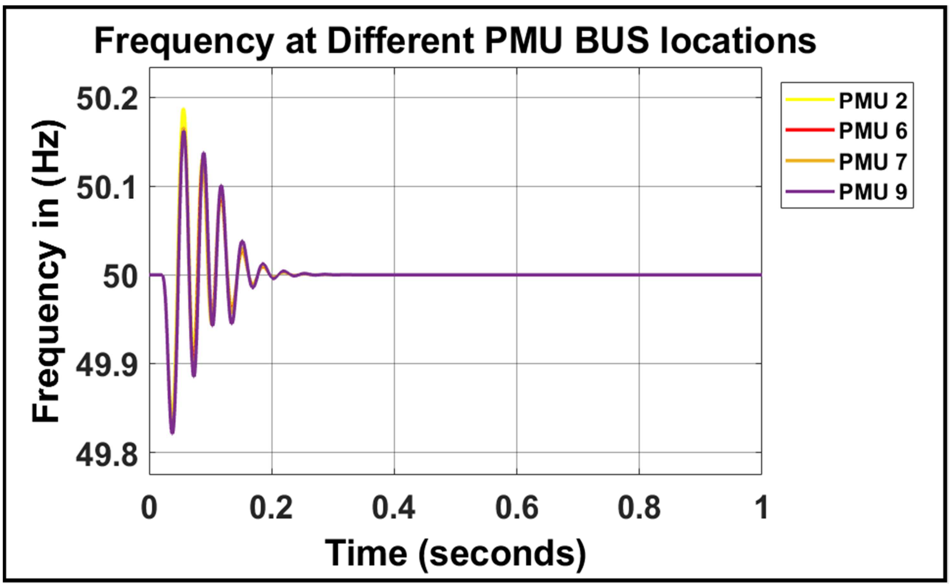


Fig. 17. Frequency at different PMU Bus locations

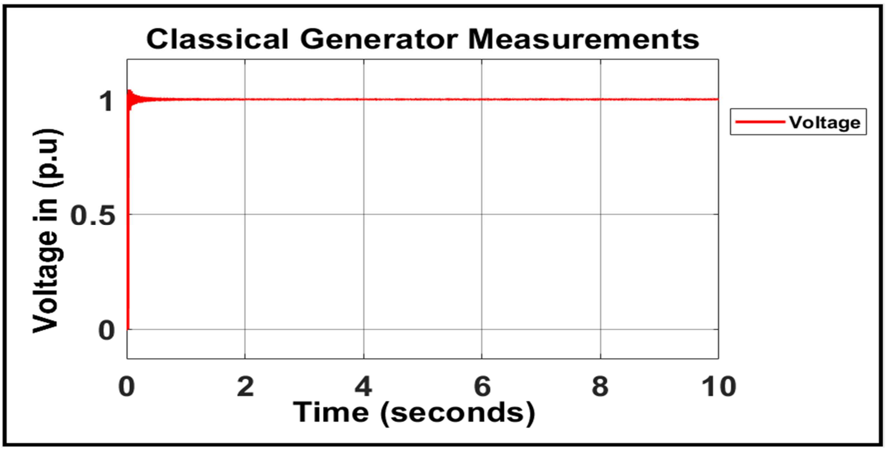


Fig. 18. Voltage Magnitude of classical generator

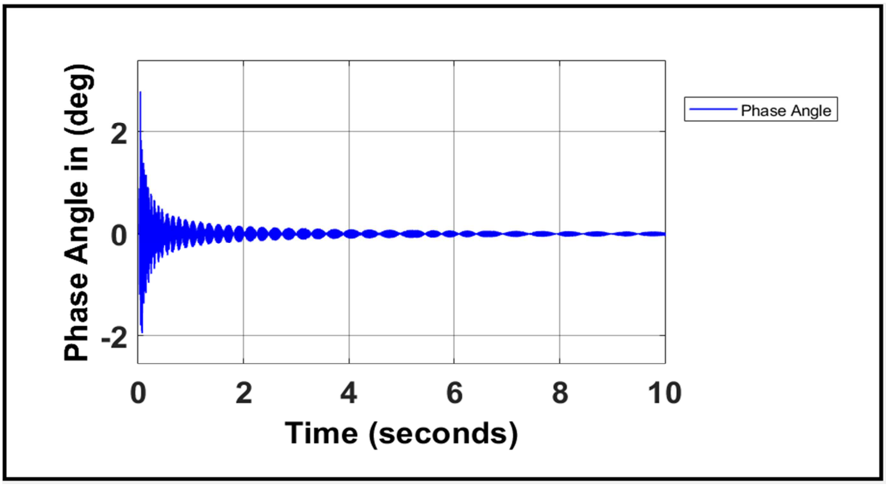


Fig. 19. Phase angle of classical generator

7. CONCLUSION

Present work carried out is implementation of breadth first algorithm and greedy algorithm for selected system and in obtained results the system is fully observable with placement of PMUs in optimal bus locations with high SORI Values. In process of implementation of test bench system for WAMS, a test data of single area LFC is taken and modeled in LabVIEW and simulation is carried out. The results are compared with the test data and are exported to Matlab/Simulink, where the single area LFC model is developed in Simulink, hybrid dynamic simulation is carried out and model is validated by comparing the both the results. Further work presents, the phase shifting transformer, is to be modeled in Matlab/Simulink for Hybrid dynamic simulation which is to be carried out and by comparison of results, the models can be validated.

NOMENCLATURE

ΔF	:	Change in Frequency
ΔP_c	:	Change in Power
ΔP_L	:	Change in step Load
E	:	Internal Voltage Magnitude
f	:	Frequency in 50Hz
P	:	Active Power
Q	:	Reactive Power
V	:	Voltage Magnitude at boundary bus
δ	:	Internal Phase Angle
θ	:	Phase Angle at boundary bus

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