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Modelling and Simulation of a two area system using a Phasor Measurement Unit

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Abstract—The character played by phasor measurement units (PMU) in power grid monitoring systems today showcases the significance and usefulness of this device. There is a major challenge regarding the design and implementation of PMUs today as the commercial PMU vendors strongly look after their hardware and software designs keeping it away from researchers. Wide Area Monitoring is becoming an emerging challenge for power system engineers and researchers due to complexity in the power system network. So, PMU is one such device that can challenge such issues in the power system. The proposed paper presents the design and implementation of a two area system in MATLAB/Simulink. The two area system is synchronized together and then the two PMUs are introduced in it to measure the respective parameters. The PMUs that are used in the analysis follows the IEEE C37.118-2011 standard. The functionality of the PMU was tested by performing experiments which measured magnitudes of voltage, current, phase angle and frequency of a balanced three phase signal from PMU. After this analysis, we have introduced a fault in the system to observe the post-measurements of PMU. The conducted experiments confirmed that the PMU protected the power system and also synchronized and estimated voltage magnitude, phase angle and frequency approximately.

Keywords*— Phasor Measurement Unit, Two Area System, Synchrophasor, Power System Stability, Wide Area Monitoring Protection And Control(WAMPAC).*

I. INTRODUCTION

The power system of today is a complex interconnected network which is split into four important parts: generation, transmission and sub-transmission, distribution and loads. The intricate nature of the power system makes it necessary to regularly monitor the elements that make up the power system in order to protect these elements and in the long run avoid major contingencies in the power system [1]. The concept of monitoring the power system network has become very important today as an outcome of different power system contingencies that have occurred in the past years. Widespread power system outages in different parts of the world have made it necessary to monitor the power system parameters such as amplitude, phase angle, and frequency to ensure that these parameters are constantly within statutory limits [2].

Monitoring the power system simply involves taking readings or measurements from power systems at specified time intervals while these systems are in service. Measurements of specific parameters on power systems are carried out by specific devices. One such device is the phasor measurement unit (PMU) which is actually a key tool in providing situational awareness, operation and reliability of the power system network. In today's scenario we observe that stress on the power system has increased as the competitive structure of the energy market increased the utilization of the power system [3]-[4]. The real time data measurement and monitoring on a wide area basis are required to make the present grid more efficient and reliable. Wide Area Monitoring System (WAMS) has been implemented worldwide for the synchronized monitoring, protection, and control of the power system from blackouts and outages and are being upgraded continuously. The wide area monitoring system (WAMS) consists of a huge number of PMUs which are geographically dispersed in different locations [5]-[7]. We know that we obtain synchronized measurements of voltage or current phasors from PMU. The synchronization is achieved by using a very high precision time reference i.e., GPS (Global Positioning System) which gives a 1 pulse per second signal with the synchronizing efficiency of less than 1 [8]. Many kinds of research have been carried out regarding optimal placement of PMUs but very less work has been done for its modelling. The contribution of the proposed work is the development of two area power system in Matlab/Simulink and also synchronizing the network with PMU for its protection [9]-[10].

Section I is briefly introduced about the Phasor Measurement Unit device and its gradual upliftment. Section II shows a detailed elaboration of PMU, its utilization in the energy market, and also about the standardization of PMU. Section III shows the important applications of PMU. Section IV gives the functional detail about the block diagram of the Matlab/Simulink based model of PMU. Section V shows the implementation and designing of the proposed work with various parameters involved in the functioning of the model. Section VI shows details about the case study with their respective results. Section VII is discussed with the conclusions regarding the performance of the proposed work.

II. PHASOR MEASUREMENT UNIT (PMU)

Power System networks are very complex and becoming more and more difficult to predict the contingencies in this ever growing world of technology. Occurrences of many main blackouts in major power stations in different parts of the world led to the development of Phasor Measurement Technology in Wide Area Measurement system (WAMS). PMU is a measuring device by which we get the synchronized measurement data such as frequency, amplitude and Rate of change of frequency (ROCOF) with a time tag (UTC) that is provided by GPS (Global Positioning System). This data that can give us an accurate real time measurement and helps a system to track any event (such as blackout) also determined to analyze the sequence of events thus finds out the exact malfunction that may have led to a system failure. The concept of PMU was given by Charles Proteus Steinmetz, a German-Austrian mathematician and Electrical Engineer for solving a circuit problem in the representation of phasor waveform. In 1980, an appropriate PMU technology came into existence due to the research which was conducted on computer relaying of transmission lines. First, modern PMU prototype was developed by A. Phadke in 1980 at Virginia Tech University and this prototype as later tested at few substations at North America and utilized to obtain the measurement.

The IEEE C37.118 working group maintain the standard of PMU devices. The latest standard setup by the IEEE governing body is divided into two different parts: i) describe requirements and methods for measurement verification of phasor (IEEE C37.118.2-2011). ii) data exchange while measuring data at collection and application equipment.

The different measurement of PMU from a different location in a power system with a UTC time tag provided by GPS is transmitted to Phasor Data Concentrator (PDC). This data is processed by PDC and can also be stored in the database for future use.

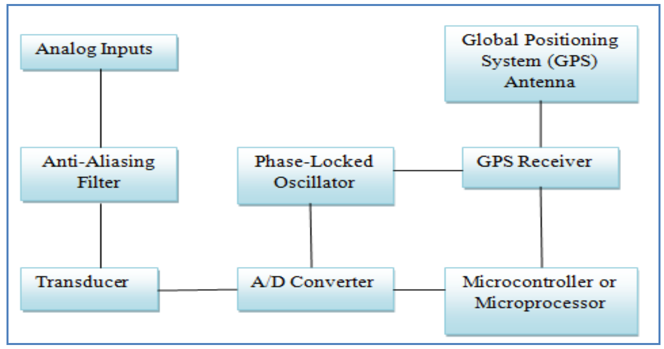

Figure.1. shows the block diagram of a PMU

III. APPLICATION OF PMU IN POWER SYSTEMS

PMUs have made various applications possible to be applied in important fields of a power system. The major ones are discussed below:

1. *Control of back up relay performance*
   There might be situations taking place when false tripping of relay occurs during certain system malfunctions. Here, PMUs supervise such controls in relays to overcome such a problem.
2. *Security and dependability of power system*
   At times, tripping of relay does not take place properly which causes failure in their operation. This is the time when the PMU plays its vital role and makes sure that more than one relay sees the fault before even the breaker is actuated.
3. *Improvement of control*
   Including PMUs in the power system has added even better robustness in the systems. The PMU controllers can react to threatening situations without any continuous control of the feedback.
4. *Loss of Mains*
   PMUs help in recovering loss of mains or other issues like islanding when a section of utility with at least one distributed generator is separated from the system.
5. *Wide area measurements*
   Wide area monitoring system (WAMS) has become extensively popular these days because of its proactive feature and applications in power systems. Wide area measurements of swing angles can determine stability directly.

IV. RELATED WORK

In paper [1], the authors have discussed the wide area monitoring, protection and control i.e., WAMPAC. It is an important feature of Phasor Measurement Unit. Initially, they have designed a PMU model in Matlab/Simulink then later they have used this information for the protection of their system. Then, they have designed an interconnected two area system where the PMU was used and later the comparative analysis was done. They have also prepared a novel controller which will monitor their system as well as protect it from any damage. Also, a back-up protection format was developed which will restore the proposed power. After their evaluation they have found that PMU is an efficient and fast control electrical device which will pre-control and pre-protect the power system from any disturbances. Thus, their results were compared with the conventional analog protection procedure in the concluding portion and concluded that under similar working conditions, PMU is way better than the conventional course of action.

In paper [2], the authors came up with a wide area protection system which is connected with a PMU. Their scheme is all about recognition of various faults by utilizing data from different PMUs at various locations in the power system. Their work is about the identification of major and minor faults in the power system. The concept was to identify a single line to ground fault on the transmission line by using three phase sequence analyzer which works similar to the PMU by providing voltages of all the three sequences. Their procedure was completely done in Matlab. They concluded that a central main protection unit for collecting and storing the data and forwarding the tripping signal in case of even small faults was developed.

In paper [3], the authors have drawn attention towards the phenomenal extension of a power system. They explained how the power system is growing complex today and everyday because of system-wide disturbances and how continuous innovations in technology are being made. They proposed a modelling and testing analysis of PMU for two bus transmission line in their paper using Matlab/Simulink. They explained that for testing and modelling, software based analysis is a positive approach. Here, they've designed a Simulink model of doubly fed 2 bus system with PMUs. Individual set ups of PMUs were modeled to determine the module wise output. The results of both the PMUs are compared to analyze the process of synchronization.

In paper [4], the authors provide us wide information about PMU and its application. Here, they have build up a PMU model and connected it at the starting and ending sections of the transmission line of a simple power system network in Matlab. Here, different types of networks were also used to test system stability and controllability. Some of the function of WAMPAC such as dynamic recording, detection of phase angle, estimation of load parameter etc. also protects and control the power system. Here, the authors clearly described the importance and the idea of WAMPAC application for controlling and monitoring of power system because in the future power system network will be more complex.

III. Proposed Approach

MATLAB/SIMULINK BASED PMU MODEL

In order to develop the complete network an accurate setup of PMU is to be introduced we need to understand the complete execution of the PMU which will protect the power system and take necessary measurements. So, a functional block diagram of a simulation based model of PMU is shown below:

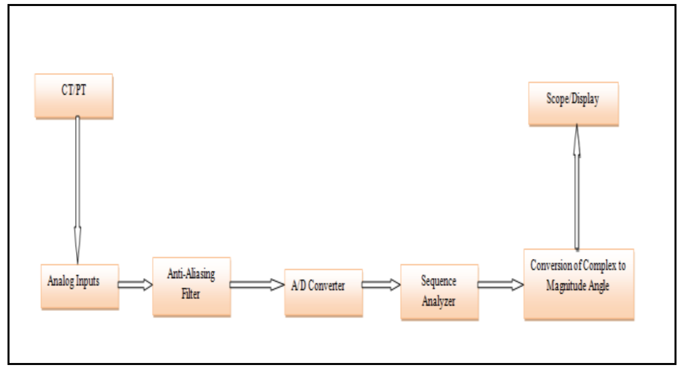

Fig.2. Functional Block Diagram of MATLAB based PMU

The working principle of the different blocks of the Simulink based PMU are described below:

a) *Current transformer/Voltage transformer (CT/PT)*: The CT and PT measure current and voltage waveforms which are fed into the analog input module.
b) *Anti-aliasing filter (AAF)*: The conversion of analog signals to digital is very important and it is done through sampling and quantization. According to the Nyquist sampling theorem, the sampling rate should be at least twice the maximum frequency component of the signal of interest. In other words, the maximum frequency of the input signal should be less than or equal to half of the sampling rate. Now, if the sampling rate is less and doesn't follow the Nyquist theorem, then, it becomes tricky to obtain the complete information from the sampled signal and valuable data may be lost. This is termed as aliasing error and to remove it, the AAF is used.
c) *Analog to Digital Converter (ADC)*: As the ADC is fed by the anti-aliasing filter, it then converts the continuous analog input into a discrete digital signal through the discrete Fourier transformation (DFT) block which converts it into a complex signal. The output is sent to the sequence analyzer.
d) *Sequence Analyzer*: Here the sampled current & voltage waveform from ADC is computed through this sequence analyzer block following the below equation:

$$V_1 = \frac{1}{3}(V_a + V_b + V_c)$$

$$V_2 = \frac{1}{3}(V_a + aV_b + a^2 Vc)$$

$$V_3 = \frac{1}{3}(V_a + a^2 V_b + aV_c)$$

Where, a=-0.5+0.866i and V_1, V_2, V_3 are zero, positive and negative sequence respectively. While V_a, V_b, V_c are the phase components.

e) *Conversion of Complex to Magnitude Angle*: This block gives the magnitude and phase angle of the different sequence components of the voltage.

f) *Scope/Display*: It displays the different measurements of parameters from the Phasor Measurement Unit.

A flow chart representation of our work is shown below:

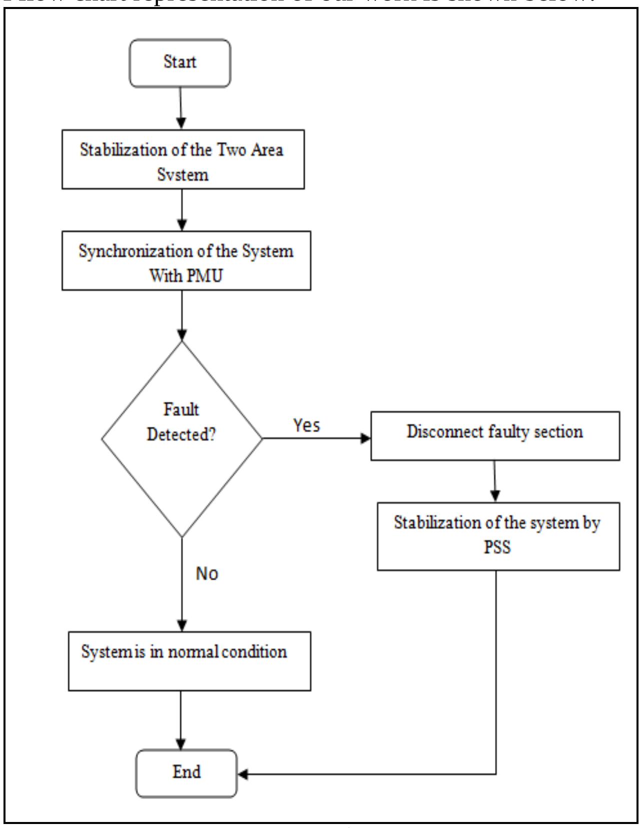

Fig.3. Flow diagram of proposed work.

V. Methodology

The proposed work is developed by designing a two area power system and connecting the area with PMUs in MATLAB/SIMULINK version 2017b. SIMULINK includes numerous basic power system components along with variable features, all of which can be utilized for designing and modelling all types of power system network simulations. The Simulink library has got an extensive platform which routes us to easily draw or design any power system network and also interact with each electrical component.

A Single Line Diagram of Two Area System of the proposed model is shown below:

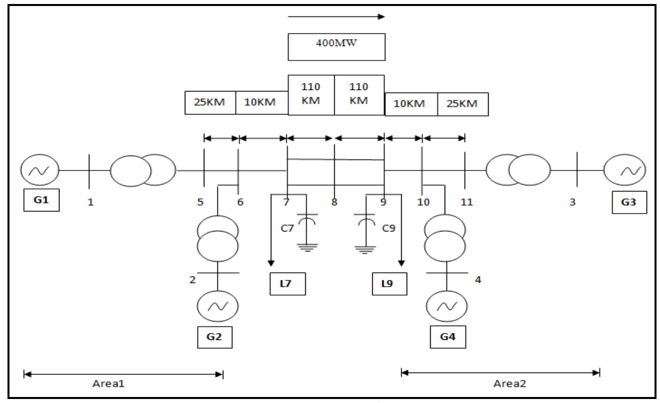

Fig.4. Single Line Diagram of Two Area System

The proposed model consists of eleven buses of two similar areas connected by a weak-tie line between bus 7 and 9. The system has the fundamental frequency of 60 Hz. Each area consists of two coupled units, each having a rating of 900MVA & 20 KV. The generators parameters in per unit on the rated MVA & KVA base are as follows:

TABLE 1: Generators Parameter in per unit

X_d= 1.8	X_q= 1.7	X_l= 0.2	X'_d= 0.3	X'_q= 0.55
X''_d=0. 25	X''_q= 0.25	R_a= 0.0025	T'_{d0}= 8.0 s	T'_{q0}= 0.4s
T''_{d0}= 0.03 s	T''_{q0}= 0.05 s	A_{Sat}= 0.015	B_{Sat}= 9.6	Ψ_{T1}= 0.9
H= 6.5 (for G1 & G2)	H=6.175 (for G3 & G4)	K_D= 0		

Each step-up transformer has an impedance of 0+ j0.15 per unit on 900 MVA & 20/230 KV base & has an off nominal ratio of 1.0. The transmission system nominal voltage is 230 KV. The length is identified in the above figure 2.3. The parameters of the line in per unit on 100 MVA, 230 KV base are:

r = 0.001 pu/km x_L= 0.001 pu/km b_C= 0.00175 pu/km

The system is operating with area1 exporting 400MW to area 2, and the generating units are loaded as follows:

TABLE 2: Generators Parameter (P,Q & Et)

G	**P (MW)**	**Q(MVAr)**	**Et**
G1	700	185	$1.03\angle 2.2^\circ$
G2	700	235	$1.01\angle 10.05^\circ$
G3	719	176	$1.03\angle -6.8^\circ$
G4	700	202	$1.01\angle -17.0^\circ$

Totally two loads are applied to the system at bus 7 and 9. The loads and reactive power supplied (Q_c) by the shunt capacitor at buses 7 & 9 are as follows:

TABLE 3: Active Load & Reactive Load in bus 7 & 9

Bus	P_L(MW)	Q_L(MVAr)	Q_C (MVAr)
7	967	100	200
9	1767	100	350

SIMULATION & MODELLING OF TWO AREA SYSTEM IN MATLAB

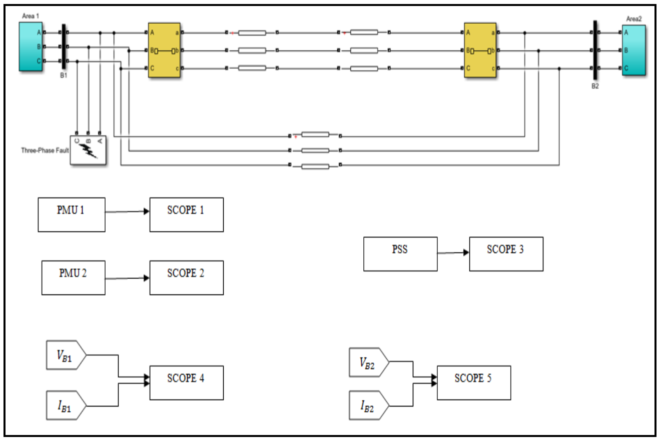

Fig.5. Simulation model of two area system using PMU

Here, an important role is played by the Power system stabiliser which is PSS. A PSS has the ability to regain the state of equilibrium when the system undergoes any physical disturbance. So, a PSS keeps the system intact so that it operates normally. Similarly, in this model when the system undergoes a fault for 2seconds the PMU senses it and clears the fault within 0.1 seconds. This is when the PSS does its job and brings the dynamic position of the system in an equilibrium stable state. So, PSS plays a very vital role in a power system.

VI. CASE STUDY WITH RESULTS AND DISCUSSION

a) *Steady state operation of the system (Before the introduction of fault)*: We have done 25seconds of simulation here both in faulty as well as non faulty condition. When the system is steady, it runs smoothly giving out steady results i.e., stable output waveforms and the machine remains normal. The results obtained are shown below:

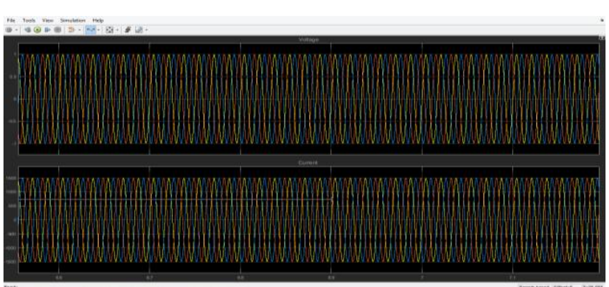

Fig.6. Voltage & Current Waveform of Bus1

In fig.6.we observe 3phase sinusoidal voltage (V_{B1}) and current (I_{B1}) waveform of bus 1 displayed in scope 4 of area 1 as shown in fig.5. Here top portion shows the voltage and bottom portion shows the current which are absolutely in steady state condition.

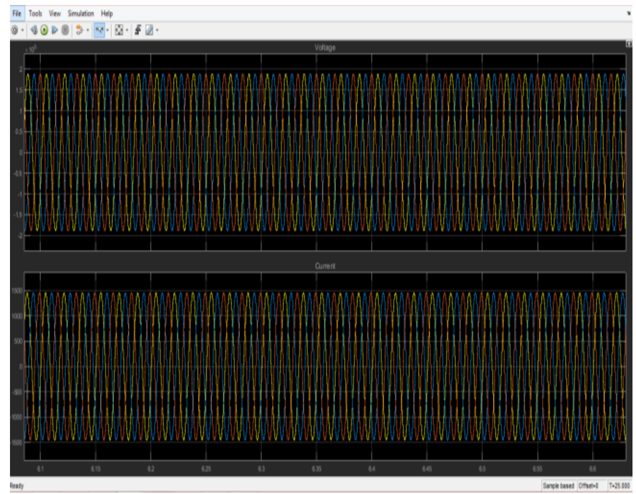

Fig.7. Voltage & Current Waveform of Bus 2

Similarly, in fig.7.we observe 3phase sinusoidal voltage (V_{B2}) and current (I_{B2}) waveform of bus 2 displayed in scope 5 of area 2 as shown in fig.5. Here also top portion shows the voltage and bottom portion shows the current which are absolutely in steady state condition.

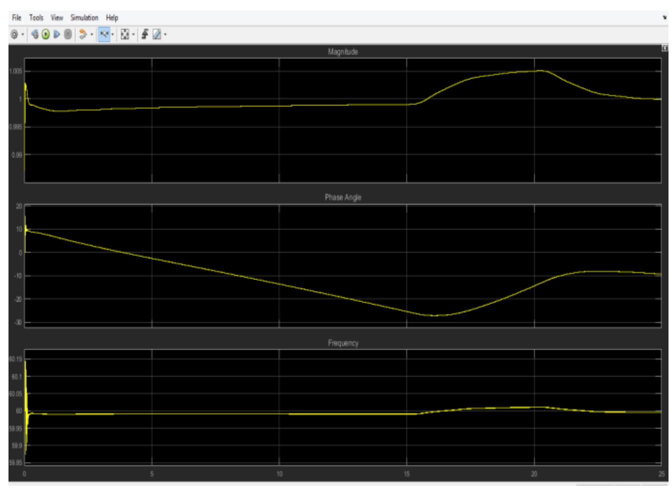

Fig.8. Output of PMU1

The waveform obtained in scope 1 is the output acquired from PMU 1 connected with area 1. This is the voltage waveform of a bus (B1) and here we get the amplitude, phase angle and frequency of voltage respectively. At the beginning of the simulation, the system takes time to be stable but gradually steady state condition is achieved.

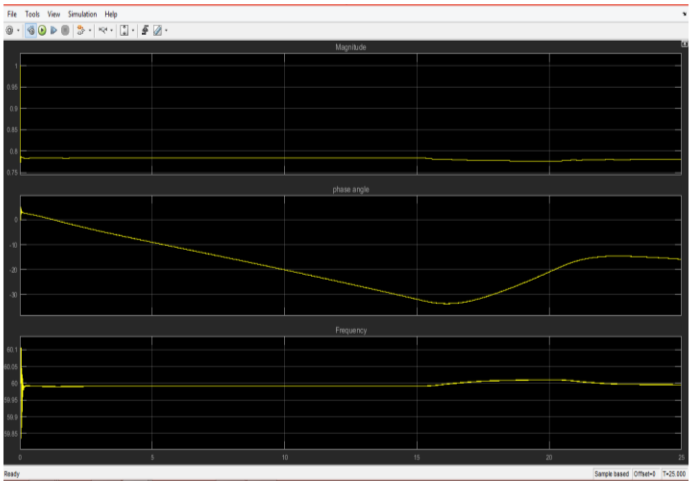

Fig.9. Output of PMU2

The waveform obtained in scope 2 is the output acquired from PMU 2 connected with area 1. This is the current waveform of a bus (B1). This shows the amplitude, phase angle and frequency of current respectively. Here also during the simulation the system takes some time to stabilize but a progressively steady state of the amplitude, phase angle and frequency is achieved.

Fig.10. Output Waveform of PSS &Machines

Figure.10 is a graph of Power System Stabilizer (PSS) & Machines observed in scope 3. Here, d_theta vs M1 (deg) gives the generator's power angle deviation which deviates initially for a short time but it gets stabilized gradually due to PSS, w(pu) shows the generator's speed in pu which shows a steady speed when stabilised, Pa(pu) shows the mechanical power of the synchronous machine in pu and Vt(pu) shows the terminal voltage of the synchronous machine.

b) *Faulty state:* As mentioned earlier here also we have done 25seconds simulation. We introduced a line to ground (L-G) fault in phase A and ground to observe the post behaviour of the system as a case study. This fault occurs for 2seconds and immediately gets cleared within 0.1 seconds. After this, a new steady state is achieved until the end of 25seconds simulation.

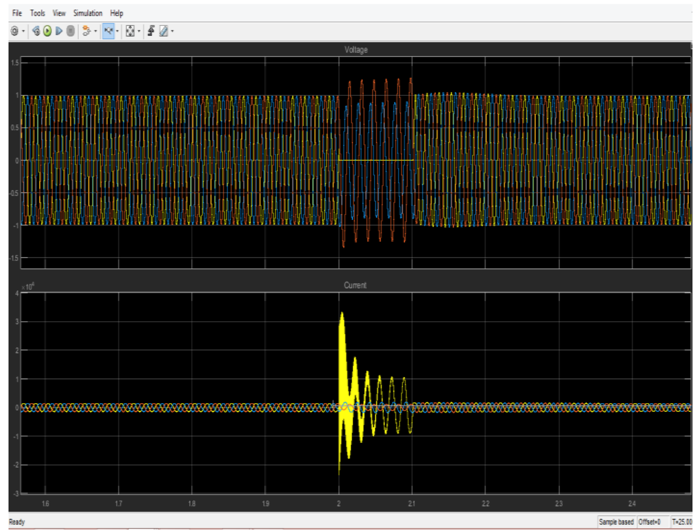

Fig.11. Voltage & Current Waveform of Bus 1

As we can see in fig.11, initially the 3 phase voltage and current waveform remains steady and runs smoothly but as soon as an L-G fault is introduced in the system there is a drastic change. As we can observe in the middle portion, the fault occurs for 2seconds and immediately thereafter, the fault is detected and cleared within 0.1 seconds. So, we observe a steady graph in the later part once again.

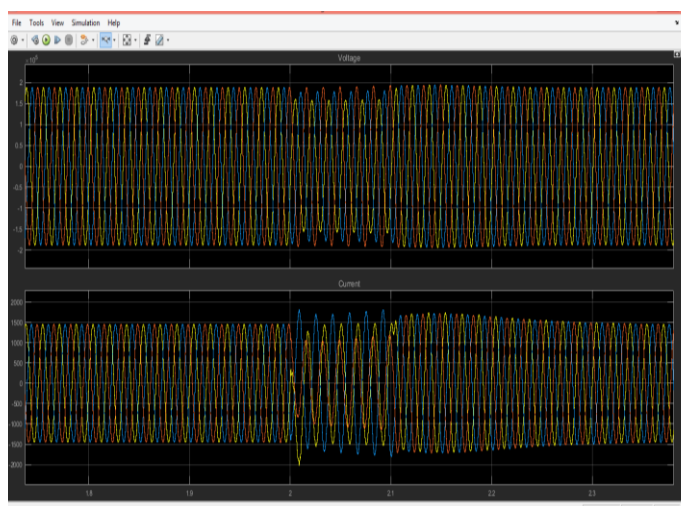

Fig.12. Voltage & Current Waveform of Bus2

Similarly, in fig.12 at 2 sec, a small disturbance is observed in the subsystem area2 due to L-G fault and stable system is achieved in the later part again because the faulty portion is detached.

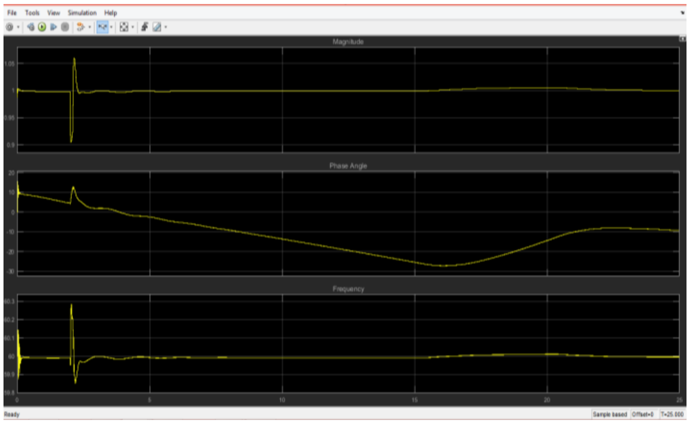

Fig.13. Output of PMU 1

Here PMU 1 quickly detects the fault of area1 and as we can see the detailed results of scope 1which are magnitude, phase angle and frequency of voltage. Also, PMU is able to clear the fault within 0.1 sec as mentioned above and after the fault is cleared a steady state of the system is maintained.

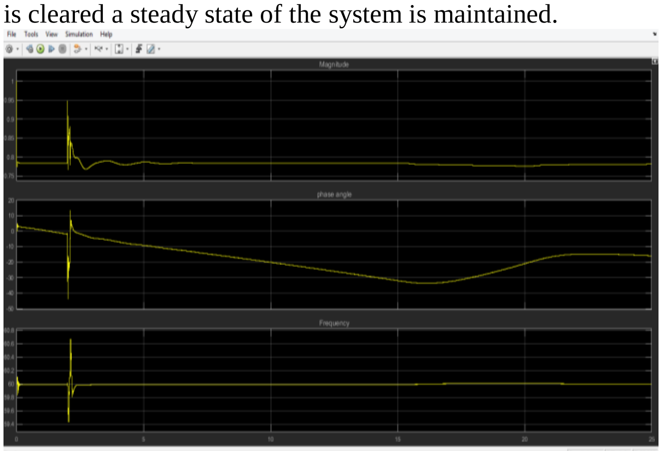

Fig.14. Output of PMU 2

Here PMU 2 quickly detects the fault of area1 and as we can see the detailed results of scope 2 which are magnitude, phase angle and frequency of the current. Also, PMU is able to clear the fault within 0.1 sec as mentioned above and after the fault is cleared a steady state of a system is maintained.

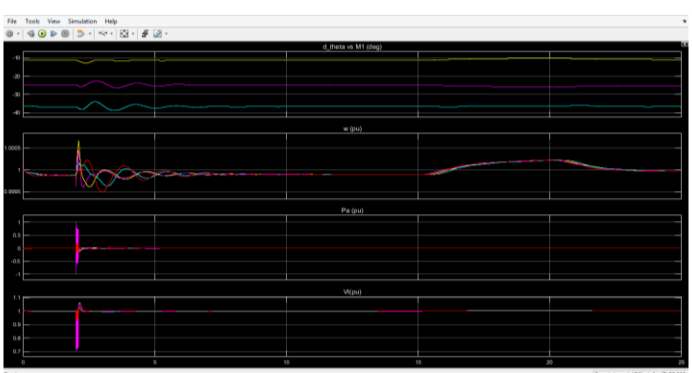

Fig.15. Output of PSS & Machines

Figure.15 is a graph of Power System Stabilizer (PSS) & Machines observed in scope 3. Here, d_theta vs M1 (deg) gives the generator's power angle deviation which deviates when fault occurred but it gets stabilized gradually due to PSS, w(pu) shows the generator's speed in pu which shows a steady speed when the fault gets cleared and gets stabilised, Pa(pu) shows the constant mechanical power of the synchronous machine in pu and Vt(pu) shows the constant terminal voltage of the synchronous machine.

VII. Conclusion and Future Scope

In this paper, we have focused on designing of MATLAB based modelling of PMU which is connected with a two area power system network. Here, the PMU contributes to synchronizing the phasor as well as protecting the power system network. The efficiency of the PMU determines the performance of the wide area monitoring system (WAMS) of the modern power system. A simulation of 25seconds for the designed model was performed in Matlab. It is observed that in this work after the introduction of L-G fault, the PMU can detect the fault and is able to clear it within 0.10 sec and is also able to bring back the system in normal operating condition. So, this proves the contribution of PMU that how efficiently it can monitor and control the system. We are aware of the fact that how expensive the PMUs are for which it's very difficult to actually analyse things on the basis of hardware, so considering that, software based analysis is applicable. So, the PMUs are very efficient and reliable for the overall stability of a power system network.

PMUs can give an accurate measurement of different parameters along with this a UTC time tag that is provided by GPS, helps a system to track any event (such as blackout) for its analysis and also finds out the cause of any problem in the system. So, GPS is very important equipment for the monitoring of wide area networks in PMU devices. But unfortunately the GPS service in this model is unavailable and the measured value that we are obtaining from PMU has the simulation time tag only. However, the PMU has done its job excellently. So, the usefulness of such a device can be extended further in a wide manner especially in the field of protection, monitoring of wide area networks and also in renewable energy sectors.

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Authors Profile

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