Phasor Measurement Unit Modeling For Wide Area Monitoring and Smart Grid Control Using Distributed Energy Sources

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Abstract—The power system is a dynamic system which needs to be monitored and controlled for a wider area. Due to the lack in wide area monitoring, there is a major blackout in the power system grid leading to major cascaded failure. There are many technologies developed, but the major drawback in technologies was in the study of phasor measurement with a precise time stamp. The real essence of this paper is to emphasize the wide area monitoring application using PMU technology and modeling of phasor measurement unit for wide area monitoring and control of grid with distributed energy resources. In this paper, the application of phasor measurement unit is being modeled using Matlab 2018a version/Simulink environment and tested for normal state and fault state.The simulation result shows that the load is not affected even during power grid islanding application.

Index Terms— Distributed Energy Resources, Grid Islanding, Phasor Measurement Unit,, Scada System, Time Synchronization, , Wide Area Monitoring System

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1 INTRODUCTION

Phasor Measurement Unit is a synchrophasor technology that is employed in power system to obtain precised synchronized measurement of voltage magnitude,phase angle and frequency which are time stamped.The power system parameters becomes observable when it is monitored at different states of power system.New technologies are employed to monitor and control the power system effectively.One of the technology used recently is the SCADA system [1].Along with automation there is also a need for time synchronization which leads to effective monitoring and restoration of the power system in the competitive electricity market.The phasor measurement technology is an advent in technology that employs the study of phasors which is time synchronized.Phasor measurement technology was developed and made use in actual power system The North American Synchrophasor Initiative(NASPI)made an effort to intrduce synchrophasor technology globally. It is very important to know the various operational paradigm of the power system employing recent technologies that are secure and efficient.

The electric transmission system transmits electric power from the grid to the load centers and blackout of such transmission system will lead to a major blackout of the power system which leads to bad impact on nations economy and security [1].Hence there is a need of wide area monitoring of the power system.The major cause for blackout are lack in wide area monitoring,inaccurate modelling of the system,inaccurate time synchronization.With the advent of this phasor measurement unit or synchrophasor technology the accurate measurement can be obtained to overcome the drawbacks of the power system.

The synchrophasor measurements are employed across globe by all utilities to monitor the performance of the power system.The measurements obtained by the synchrophasor or the phasor measurement unit are of real time and are time stamped.With precise time stamping the various parameters such as voltage magnitude ,current magnitude,frequency ,rate of change of frequency and phase angle measurement at various locations of power system are obtained[2].With new advacement in global positioning system(GPS)the application of remote monitoring and control of smart grids are made possible.

2 TRADITIONAL TECHNOLOGY AND NEED FOR NEW MEASUREMENT AND MONITORING TECHNOLOGY

The current and voltage signals are obtained from the respecitve current and potential transformers .The analog data thus obtained is sent to SCADA system and are monitored by Energy Management System(EMS).The output data rate of SCADA is 4 to 6 seconds.If there are disturbances and we need to study those disturbances or post disturbance behaviour then probably 4 to 6 seconds is of a longer duration and the data is not obtained at a faster rate.We lose the data and we cannot capture dynamic operation of the power system.We are not able to see the exact behaviour of the power system and thus we do not end up taking right control action.To justify the above statement we carried out the operation using traditional SCADA technology and PMU technology at workshop conducted by Central Power Research Institute and we could analyse the functionalities of SCADA v/s PMU and could conclude that PMU is more reselient and efficient compared to traditional SCADA technology.

In SCADA system the voltage oscillations are not represented clearely .Harmonics were not observed properly and oscillations could not be controlled easily.Hence we needed data rate to be obtained at a faster rate than 4 to 6 seconds data rate .Hence in order to observe the dynamics of power system very precisely and accurately we needed an advance technology.Likewise time synchronization for wide area monitoring is also an important parameter .The data are not time stamped in Scada System .There is no synchronization of time among various grids.Because of geographical distance ,the sybstation closer to control centre will send data much quicker than substations located at longer distances. Due to lack of time synchronization in universal and central level for all substations,the power system dynamics cant be analysed and thus we lose certain information.

Third important point is the phase angular measurement.The scada system is a scalar technology which could provide only the magnitudes of electrical quantities .For an AC network magnitude and phase angle both are equally important.If angle study is neglected or left out it may lead to wrong monitoring of the data.

The power equation is represented as

$$P_{12}=\frac{V_1V_2\,\mathrm{Sin}(\varphi_1\text{-}\varphi_2)}{X_l}$$

Power equation includes both voltage magnitude as well as the phase angle.If V1 and V2 are equal still power flow as long as there is angular difference.If φ1 and φ2 are equal then power flow is zero.Hence angle is very much important and it is a key indicator of system stress and needs to be monitored in real time.Study of angular seperation is very much important .The reason for major blackout at North east America was the lack in study of angular seperation.If the technology employed the study of angular seperation then they could monitor acon-

TABLE 1

SCADA V/S PMU

Features	SCADA	PMU
Data Rate	4 to 10 seconds	40 milliseconds
Angular Measurement	Not possible	Possible
Oscillations Monitoring	Not observed	Observed
Post Fault Analysis	Not possible in real time	Possible in real time
Dynamic Behavior	Not observable	Observable

trol the system in an effective way,thereby preventing major blackout and system could be protected and saved. The above mentioned table1 represents the comparison of SCADA and PMU technologies.Thegraphical representation of SCADA and PMU data visualization were analysed and is shown in figure1.

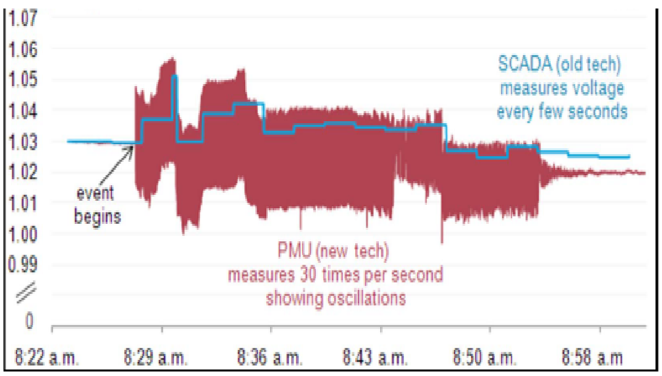

Fig. 1 SCADA v/s PMU

3 WORKING PRINCIPLE OF PMU

The figure2 given below represents how signals are fed from CT's and PT's to the PMU unit.

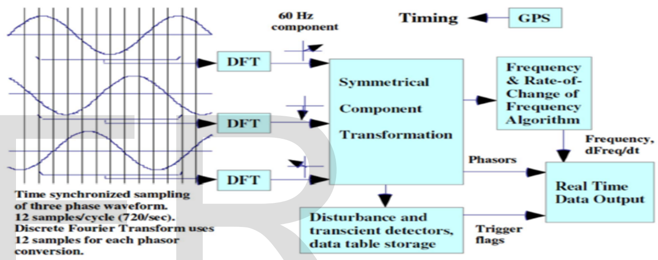

Fig. 2 Working principle of Phasor Measurement Unit

The analog signals from CT's and PT's are fed to the PMU and they are sampled at particular frequency.The sampled signals are then fed to the DFT block inside the PMU and we extract samples for the fundamental frequency component of 50Hz.Then we try to estimate using different estimation algorithms.The various quantities being estimated by the PMU comes at a particular rate.For 50Hz frequency reporting rate could be 10,25,50 frames per second and for 60 Hz frequency the reporting rate could be 10,12,15,20,30,60 frames per second.With these reporting rate the dynamic behavior of the power system could be analysed at a faster rate.

4 TIME SYNCHRONIZATION OF PMU

Our planet Earth is surrounded by 32 functional GPS satellites.The substation1 posess GPS antenna through which time signal is fed from GPS satellites to GPS clock of PMU.The substations are located at different places and at a different distances. Similar architecture is present at substation 2 which is geographically at a longer distance from substation1. GPS antenna syncs or connects atleast 4 GPS satellites.Hence proper time synchronization is possible through such arrangements.

5 PHASES EMPLOYED IN COMPLETING THE PROJECT

PHASE 1 : Studied the operational paradigm of power system monitoring and measurement through SCADA and PMU.
PHASE 2 : Hardware implementation of PMU and its working were analysed at CPRI, Bangalore
PHASE 3 : Various tests were conducted to analyse the performance of PMU at CPRI, Bangalore
PHASE 4 : The basic functions like sampling were analysed using Matlab simulink and DFT algorithms
PHASE 5 : The substation modelling were done using MATLAB 2014 Simulink and the performance were monitored at steady state and fault state with discrete w.avelet
PHASE 6 : The modelling for control of grid and load were done using MATLAB 2018a Simulink and the performance were monitored at steady state and fault state with PMU

Phase1 incuded literature survey to understand the overall operational paradigm of power system and traditional SCADA system and the comparison was made between the traditional SCADA and advanced PMU technology.The table 1 represents the same.

Phase 2 comprises of hardware implementation of PMU.The PMU hardware unit was analysed at CPRI and observed the functional operation and control of PMU measuring unit.

Phase 3 employed various tests for testing the PMU performance .It employed steady state tests like signal frequency,signal voltage magnitude test,current magnitude test,phase angle and harmonic distortion test,out of band interference test.The dynamic state tests included measurement bandwidth amplitude modulation andphase moduation,ramp of system frequency,step change in phase,step change in magnitude and finally the latency test to test PMUreporting latency.
The results were analysed based on Total vector error computation(TVE).The results are as shownbelow in figure3

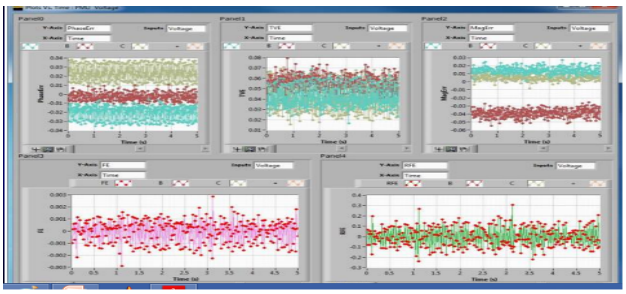

Fig. 3 Error computation wrt time

Phase4 included modelling of sampling and developing a DFT program to analyse the sampling of signals using Matlab simulink and DFT algorithm.sampling model using simulink was designed and is shown in figure 4.and the output thus obtained is shown in figure5.

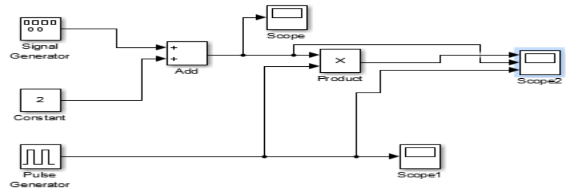

Fig. 4 Matlab simulink model for sampling

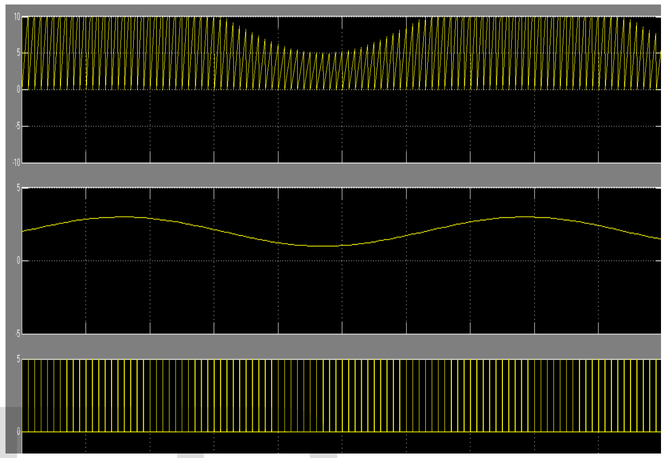

Fig. 5 Simulation waveform for sampling.

The DFT algorithm for sampling process is as mentioned below

Main program mydft.m file

```
clc;
clear all;
close all;
xn=input('Enter the sequence');
N=input('Enter the value of N=');
Xk=dft_fun(xn,N);
k=0:N-1;
subplot(2,1,1)
stem(k,abs(Xk))
xlabel('k')
ylabel('|Xk|')
title('Magnitude Plot')
subplot(2,1,2)
stem(k,angle(Xk))
xlabel('k')
ylabel('angle(Xk)')
title('Phase Plot')
```

Function program: dft_fun.m file

```
function Xk=dft_fun(xn,N)
L=length(xn);
if(N<L)
   error('N should always be greater than or equal to L')
end
xn=[xn zeros(1,N-L)];
for k=0:N-1
```

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```
    for n=0:N-1
     Wn=exp(-j*2*pi*k*n / N);
     X1(k+1,n+1)=Wn;
   end
 end
 Xk=X1*xn';
```

The simulationoutput waveform using DFT algorithm is shown in figure6.

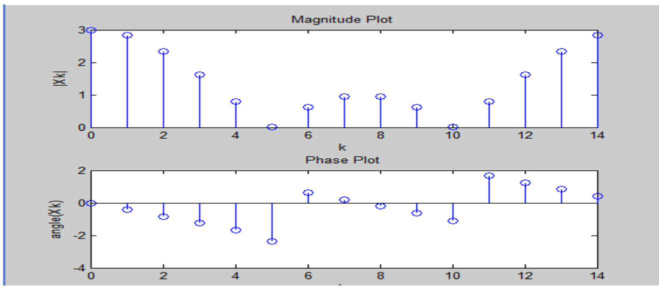

Fig. 6 . waveforms for sampling using DFT algorithm

Phase 5 employed the substation modelling using MATLAB 2014 Simulink and the performance were monitored at steady state and fault state without PMU.The model is as shown in figure 7

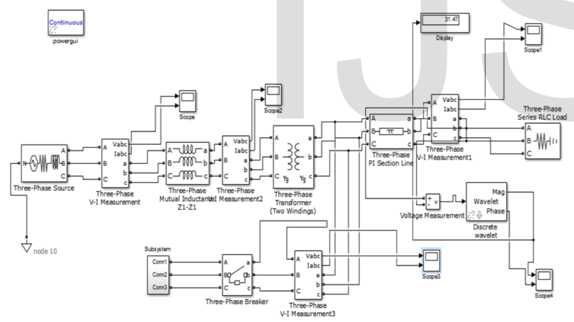

Fig. 7 Matlab simulink model representing substation with discrete wavelet to indicate fault in the system

The matlab simulink model without directly using the PMU simulink block was simulated in Matlab2014 version and the waveforms were obtained as shown in figure8.

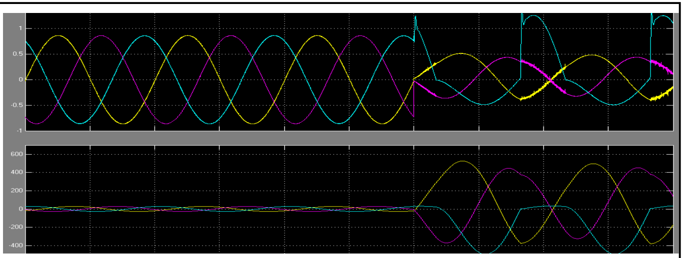

Fig. 8 Voltage and current Waveforms obtained to indicate fault in the system using discrete wavelet block in matlab2014

Phase 6 employed modeling of the proposed single line diagram using Matlab 2018 software to implement PMU block directly instead of using wavelet block.
The proposed single line diagram for modelling is shown in figure 9 given below

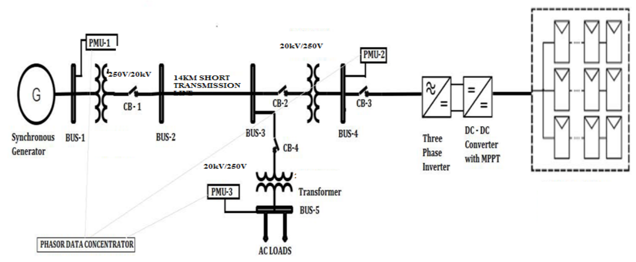

Fig. 9.Single line diagram of the proposed system

The main objective of modelling the proposed system is to monitor wide area monitoring application and evaluate the same for healthiness of transmission network connected to distributed energy resources.The performance of PMU was analysed for different test cases.

6 SYSTEM DESCRIPTION

The system consists of 100 kW generating station feeding power to load through Short Transmission Line situated at a distance of 14 km. Initially a Step up Transformer (250/11kV) is used to raise the operating voltage required for power transmission system. A Solar Photovoltaic system of 100 kW capacity is integrated into the power grid to cater the load requirements. Both the generating station (Power Plant with Synchronous Generator) and the Photovoltaic Power Plant is used to manage the load on the power system network.

Phasor Measurement units are being placed near the Generation Station, the PV Power Plant and on the load side for monitoring and control .The data from the PMU are transmitted to the Phasor Data Concentrator.Matlab model for the proposed wide area monitoring system is shown in figure10

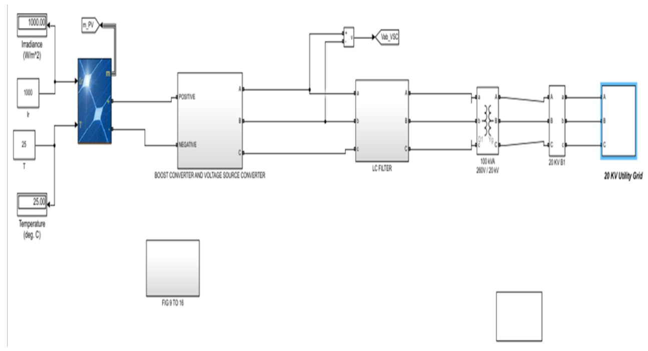

Fig. 10 Matlab model for the proposed wide area monitoring system

The Photovoltaic system is modelled to produce an optimal power output of 100kW.THe input to solar PV is the irradiance of 1000 and temperature is 25degrees.In order to maximize the power and boost the required voltage level we can employ boost transformer instead of employing an additional PV plant. Thus by doing so we can reduce the cost as well maintain constant power across DC link even if the solar input fluctuates. The generated power is fed to Three Phase Inverter.Before feeding the power to the inverter VSC plays an active role and acts as control switch of the inverter.Three Phase Inverter is used to convert a constant DC voltage into a Three Phase AC voltage. Three Phase Inverters are mostly used in Distributed Generation applications in order to produce AC output voltage from the DC bus. Whenever distributed generation is connected to grid we call it as grid conduct application.We generate pulses through the inverter by using current regulator controller.Whenever grid gets disconnected (grid islanding)only distributed generation source will feed power to the load.This time we generate pulses to inverter through voltage regulator controller employed in VSC control technique.We cannot control active and reactive power easily in three phase system .Hence we convert 3phase to 2phase.This needs transformation from abc to dq (Parks transformation)and transformation from dq to abc (inverse transformation)This is performed by PLL measurement.The Vdc voltage regulator given to PI controller gives value to compare reference value with the measured value.The dq frame values are converted to abc values .The 3 level inverter having (4*3=12)switching pulses is employed and DC to AC conversion takes place.To eliminate the dc harmonics LC filter is being employed and then the pure AC voltage is fed to the point of common coupling to feed the respective load.The simulink model representing the proposed system for wide area monitoring and control under normal healthy state is shown in figure11

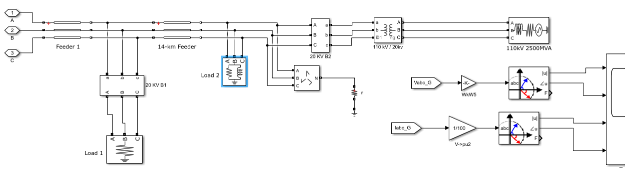

Fig. 11 Simulink modelling of grid ,pmu, distributed energy connected to load under normal state

7 Results

Simulink model was developed in Matlab2018 to study the performance of the proposed Wide Area Monitoring System for Smart Grid applications. To study the WAMS system performance, two types of tests are performed Firstly the system is monitored under healthy normal state and then the system is studied under stressed or faulted state condition.

Test under Normal Operating Conditions.:

In this test, the voltage magnitude and angle are monitored under steady state operating conditions

Fig.12 shows the Phasor Magnitude and Phase angle recorded by PMU3 placed near the grid The Voltage Phasor Magnitude was found to be 1pu and the Phasor magnitudes were found to be within the stable limits.

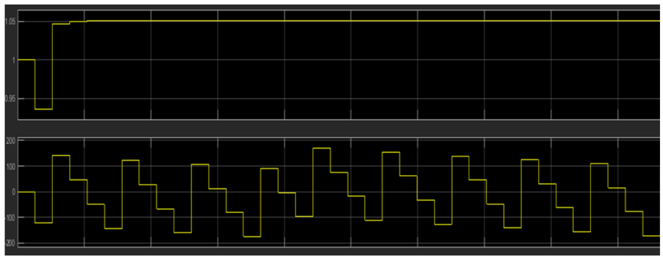

Fig. 11 Voltage Phasor Magnitude and Phase angle recorded by PMU3 at the grid

Under normal operating state the voltage phasor magnitude and angle recorded by (PMU1) placed near the bus solar PV Plant shows a stable voltage generation. Even though sun irradiation levels were varying, boost converter makes the system voltage to maintain at 1pu. Fig.12 shows the Phasor magnitude and Phase angle recorded by PMU2 placed near PV power plant.

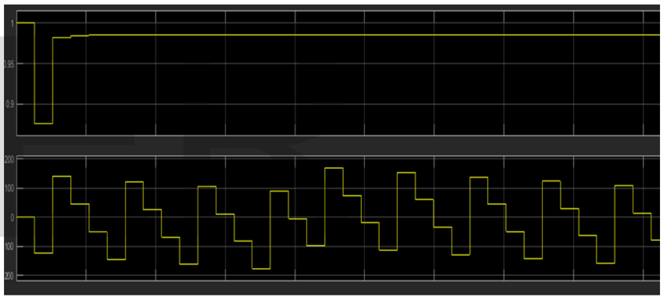

Fig. 12 Voltage Phasor Magnitude and Phase angle recorded by PMU1 at the bus

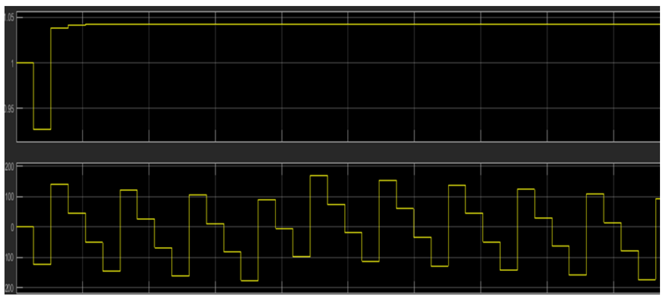

Fig. 13 Voltage Phasor Magnitude and Phase angle recorded by PMU2 at the load.

The system considered for this study is balanced loading conditions and the Phasor voltage magnitude and angle were strictly maintained within the limits. Fig.13 shows the Phasor magnitude and phase angle recorded by PMU2 placed near load.

Test under Faulted State Conditions:

The simulink model for faulted state condition is being shown in figure 14.

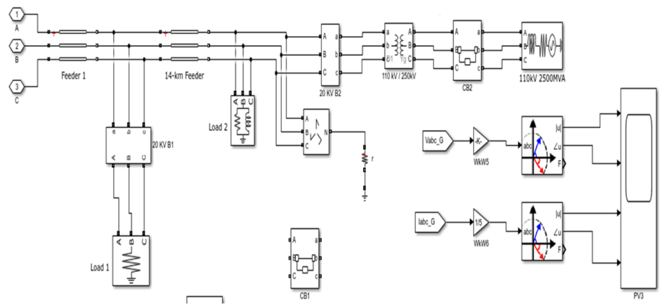

Fig. 14 Simulink modelling of grid ,pmu, distributed energy connected to load under fault state

In this test, a Three Phase Fault was created at all three locations of PMU The fault was simulated at 0.1 s and it was cleared at 0.25 s. On receiving the data from Phasor Measurement the Control Center must take necessary actions, so that a control signal must be sent to open the contacts of the Circuit Breaker in real time to protect the other power system components.

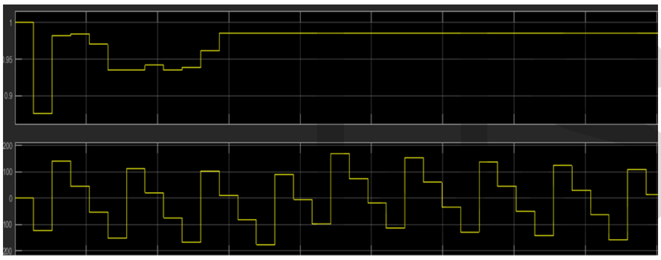

Fig. 15 Voltage Phasor Magnitude and Phase angle recorded by PMU1 at the bus under fault condition

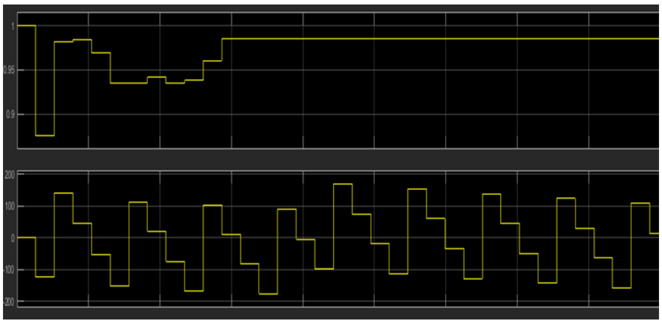

Fig. 16 Voltage Phasor Magnitude and Phase angle recorded by PMU2 at the load under fault condition.

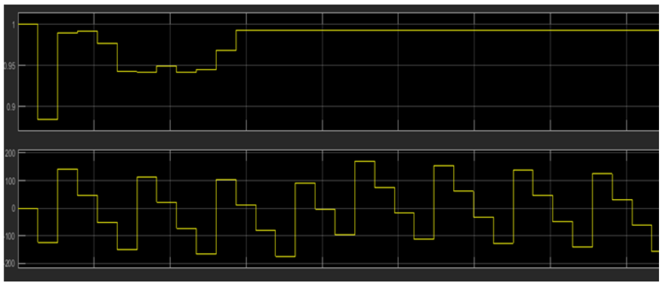

Fig. 17 Voltage Phasor Magnitude and Phase angle recorded by PMU3 at the grid under fault condition

Figure 15,16 and 17 represents the output waveform indicating voltage magnitude and phase angle recorded by respective PMU being placed near bus,load and the grid.

8 CONCLUSION

A performance analysis for a PMU based Wide Area Monitoring and Control System was carried out in MATLAB/Simulink environment. The developed system was tested under two conditions namely: Steady state and Faulted state conditions. Under steady state conditions the Phasor measurements from Simulated PMU's placed at generating station bus and at the PV plant and at the load showed measurements well within the stipulated operating conditions. Under faulted state, the Phasor measurements recorded by the PMU showed a drop in voltage indicating the fault. Also a large voltage dip near the bus ,grid and the load is also seen. Hence control signals were generated based on the data received from the PMU to PDC and hence, this area was isolated via dynamic control signals to the circuit breaker, before spreading to other parts of the power system network. All results obtained confirm the effectiveness of the developed Wide Area Monitoring System network for smart grid applications.Thus we can conclude saying that PMU is an efficient technology being developed to monitor wide area and control the load when connected to grid and distributed energy resources.

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