People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific research
M'hamed Bougara University, Boumerdes
Institute of Electrical and Electronic Engineering,
Laboratory of Signals and Systems (LSS)

ALGERIAN JOURNAL OF SIGNALS AND SYSTEMS

ISSN : 2543-3792

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Page range: **149- 161**

Volume : 2 Issue : 3 (September 2017)

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Fault Detection in Wide Area Monitoring Systems via PMU Optimal Placement

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Abstract: The Phasor measurement units (PMUs) have become more and more attractive in power engineering as they can provide synchronized measurements of real-time voltage and currents phasors. The objective of this work is twofold: first, the optimal placement of PMUs is done in the standardized IEEE systems. Next, fault location is determined based on the measurements collected from these PMUs. The simulations are carried out using MATLAB SIMULINK. The results show that it is possible to exploit the PMU measurement data to locate and hence cure the faults in the power system.

Keywords: Smart grids, Phasor measurement units, PMU placement, fault location.

1. INTRODUCTION

Wide Area Measurement System (WAMS) based on synchronized phasor measurement technology has been gaining increasingly interests due to its great value in power system dynamic monitoring, potential applications in system modeling and validation and system wide protection and control [1]. Phasor Measurement units (PMUs) can offer accurate node voltage and current phasors referring to the same time-space coordinate. They can enhance many applications such as state estimation and bad data detection [2], stability control [3], remedial action schemes [4], and disturbance monitoring [5]. As the voltage and current phasors are measured, the equations of state estimation problem become linear and the solution can be obtained straightforwardly [6].

It is neither reasonable nor practical to install a PMU at each bus of a wide-area power network. As a result, the problem of optimal PMU placement (OPP) concerns where and how many PMUs should be implemented to a power system to achieve full observability at minimum number of PMUs [7-9]. Using the data provided by PMUs installed in some appropriate bus nodes of a power network, one can construct a new type of measuring system to improve the observability and the precision of the power system state estimator. The observability depends on the type, the number and the geographic distribution of measurements [10].

Several works have been done to efficiently place phasor measurement units (PMUs) in terms of both measurement accuracy and cost effectiveness. The problem has been addressed in [11-13]. Phadke ***et*** al. [11] explored the possibility of providing al. the nodes of the system with PMU's for state estimation purpose. The problem which has been defined in [13] is to determine the placement of the minimal set of PMU's which makes the system observable. Attention has been also drawn to the use of evolutionary heuristic algorithms in optimal PMU placement. In [14] a modified bisecting search and simulated annealing method based on topological observability have been used. In [15], a genetic algorithm is used to find the optimal PMU locations. In [16] and [17], the authors use integer programming to find the minimum number and locations of PMUs. In [18] and [19] the authors propose an exhaustive search based methodology to determine the minimum number and optimal locations of PMUs for complete observability of the power system. The particle swarm optimization (PSO) technique has been used successfully in a number of power system applications [20-21].

In this work, interest goes to the implementation through simulation of the results already obtained in previous works [8-9]. The complete system is implemented with the PMUs placed at their optimal locations. The measurement data obtained through simulation are compared to the healthy case to find where the fault has occurred and to correct this fault so that it does not propagate in the remaining parts of the system.

2. PMU OPTIMAL PLACEMENT

2.1. PMU placement for state estimation

The PMUs receive signals from GPS satellites and provide synchronized measurements from different locations to the desired destination known as the phasor data concentrator (PDC**)** [22]. In this work, the PDC is represented as the graphical user interface GUI. The measurement data can be used for wide area monitoring; real time dynamics and stability monitoring; dynamic system ratings, and improvements in state estimation, protection, and control [23].

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 current phasor and the known line parameters. It is assumed that the PMU has a sufficient number of channels to measure the current phasors through all the branches incident to the corresponding bus, It is to be noted here that the errors in the voltage and current measurements by the PMU and the transmission line parameters induce uncertainties in the estimated voltage phasor at the other end of the line [23].

The current measurement capability of PMUs was examined so as to estimate the voltage phasors at some buses by using Kirchhoff's current law (KCL) (when applicable) [24]. In the case of a power injection measurement at a bus, if the voltage phasors of all but one connected bus are known, the remaining one can be estimated by using KCL. However, it is clear that the measurement errors propagate further due to the use of KCL. In this chapter, the use of current measurements by the PMUs to estimate voltage phasors is therefore proposed to be limited only to the relative buses [23].

The location of the PMUs makes the system observable as a normal operating condition, as well as for the outage of a single transmission line. A topological observability analysis is carried out to identify the unobservable branch flows in the system. The terminal buses of the branches with unobservable flows are taken as the candidate locations for placing the PMUs [25].

2.2. System description

The idea of using phasor measurements unit for system monitoring applications is not new. Earlier work done introduces the use of PMUs for such applications. This work is later extended to the investigation of optimal location of PMUs where each PMU is assumed to provide voltage and current phasors at its associated bus and all incident branches. It is therefore possible to fully monitor the system by using relatively small number of PMUs much less than the number of buses in the system. The whole process starts with the sensors that are connected to the indicated busses (2, 6 and 9) and (3, 5, 10, 12, 18, 23, 27) for 14 bus and 30 bus systems respectively. That optimal placement for the PMUs was treated using non-linear constraints [22]. Then depending on the type of PMUs which provide two types of measurements: bus voltage phasors and branch current phasors; in this report .A dedicated low-latency PDC has been presented as a Graphical User Interface [26].

2.3. Bus systems

Two standardized IEEE bus systems are considered: the 14 and 30 bus systems. For the 14-bus system, PMUs are installed in network system to measure the voltage and current samples from various location points. For IEEE 14 bus, previous work found that one needs to place the PMUs in 2-6-9, respectively [22]. As PMUs are interlinked to Global positioning system, samples from both PMUs and GPS are analyzed using MATLAB/ SIMULINK [27].

Validation of results of the 14 bus system

As it has been found in past works [8-9], there must be three PMUs to be placed at buses 2, 6 and 9, respectively. Bus 7 is the only zero injection bus. The PMU at bus 2 can not only measure the voltage of bus 2, but also the current of branches 2-1, 2-3, 2-4 and 2-5. Using Ohm's law, the voltage at buses 1, 3, 4 and 5 can be obtained from the branch currents and the voltage at bus 2. Having determined voltage at buses 1, 2, 3, 4, and 5, the current of branches 1-5, 3-4 and 4-5 can be calculated.

By following the same logic, PMU at bus 6 can measure the voltage at bus 6 and the current of branches 6-5, 6-11, 6-12 and 6-13, thus allowing the calculation of the voltage at buses 5, 11, 12, 13 and the current of branch 12-13.

PMU at bus 9 can measure the voltage at bus 9 and the current of branches 9-4, 9-7, 9-10, 9-14 and allow the calculation of the voltage at buses 4, 7, 10, 14, and the current of branches 4-7. As voltage of buses 10, 11, 13, 14 are known, current of branches 10-11 and 13-14 can now also be calculated.

Using the known current of branches 4-7 and 9-7, and the zero injection at bus 7, the current of branch 7-8 can be derived using the Kirchhoff's Current Law. The only remaining unknown voltage at bus 8 can now be calculated by using the voltage at bus 7 and the current of branch 7-8. Thus the entire system becomes observable by placing only three PMUs at buses 2, 6, 9 and by considering the zero injection at bus 7.

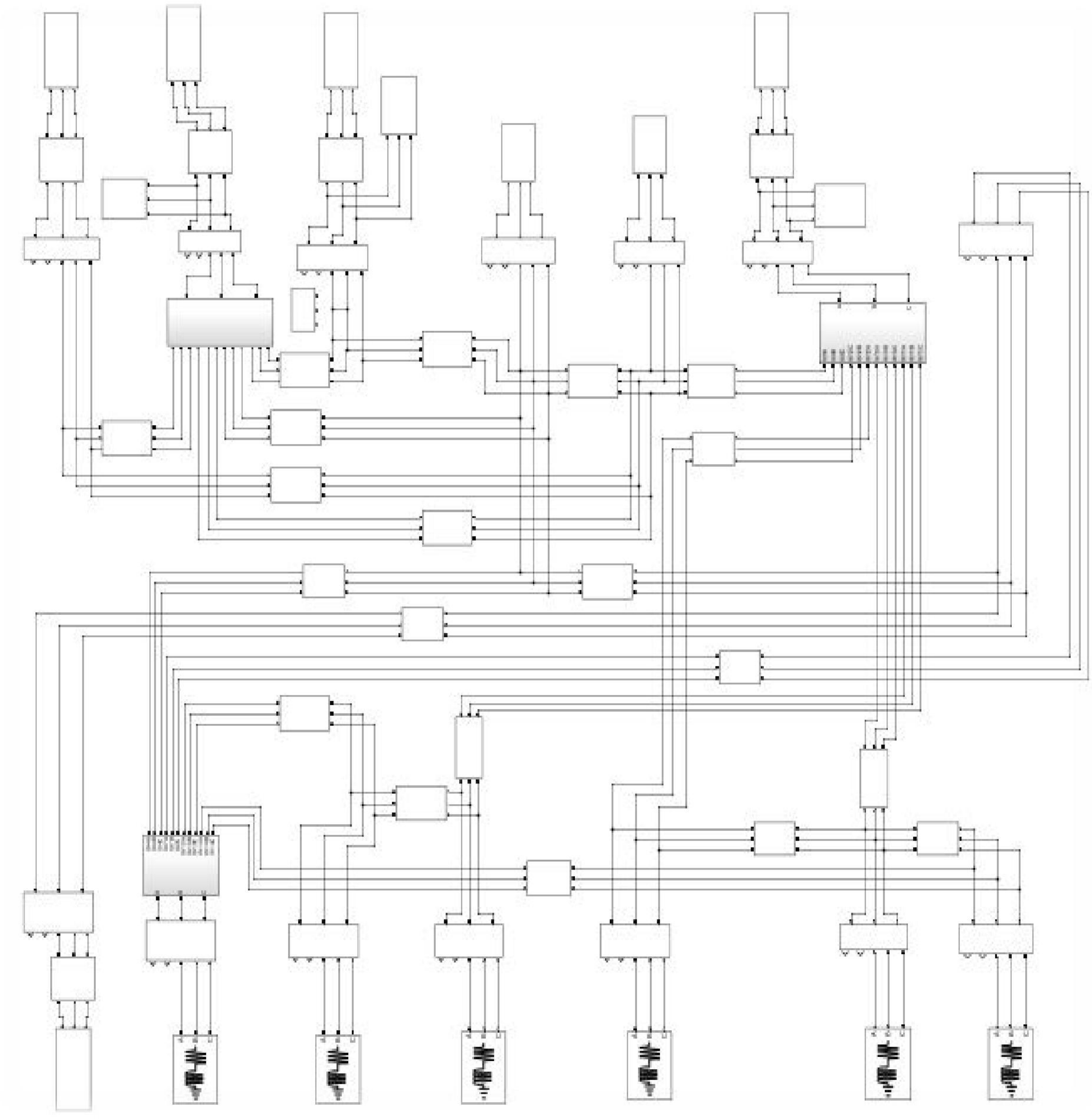

Fig. 1 IEEE 14 buses with PMUs

The PMUs collect phasors data from busses 2,6 and 9 then sends to the PDC. The simulation of the system show results as it must be represented in PDC (GUI in our case) Figure 2 represents a control center as a GUI; it was designed by a MATLAB script language. This shows the results of the measurements in the IEEE 14 bus network; where PMUs collect phasor data of indicated busses.

The ability of PMU is to measure the voltage phasor of a bus at which it is placed and the current phasors of all lines connected to that bus. It means PMU can make the installed bus and its neighbouring buses observable. The values ate others buses are calculated by applying KCL.

Figure 3 shows the variation of the Voltage V with respect to time for all 14 nodes. We can see that the system is healthy and stable and we can deduct from its stability that no fault is occurring in the system. The values are in a range between 0.4 pu and 1.3 pu.

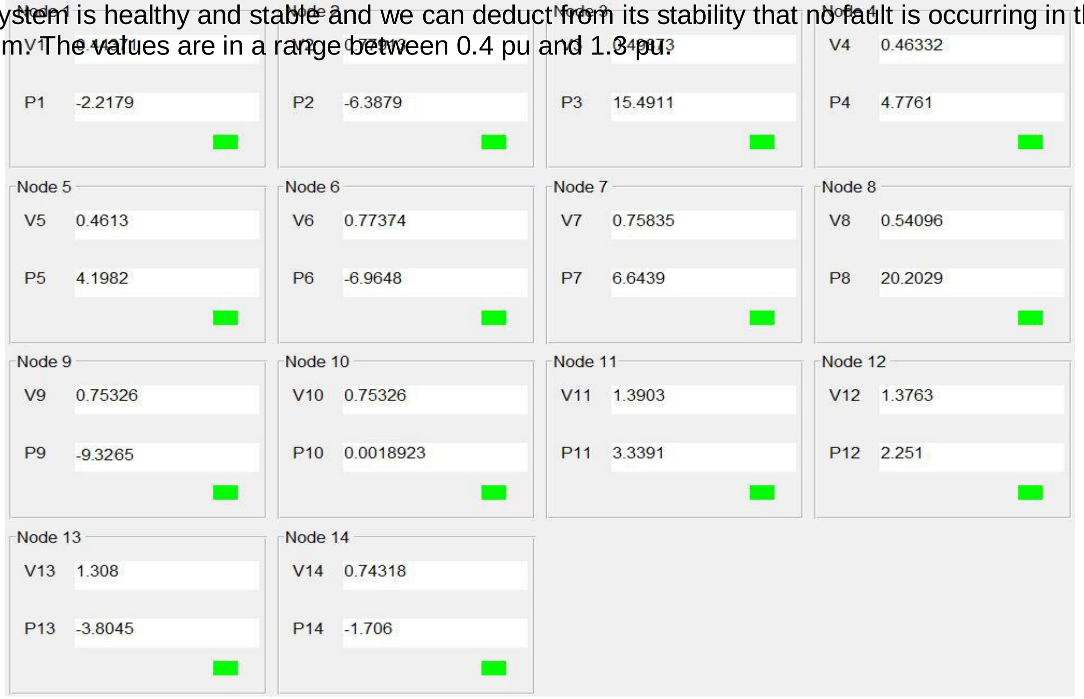

Fig. 2. The graphical user interface for IEEE 14 buses

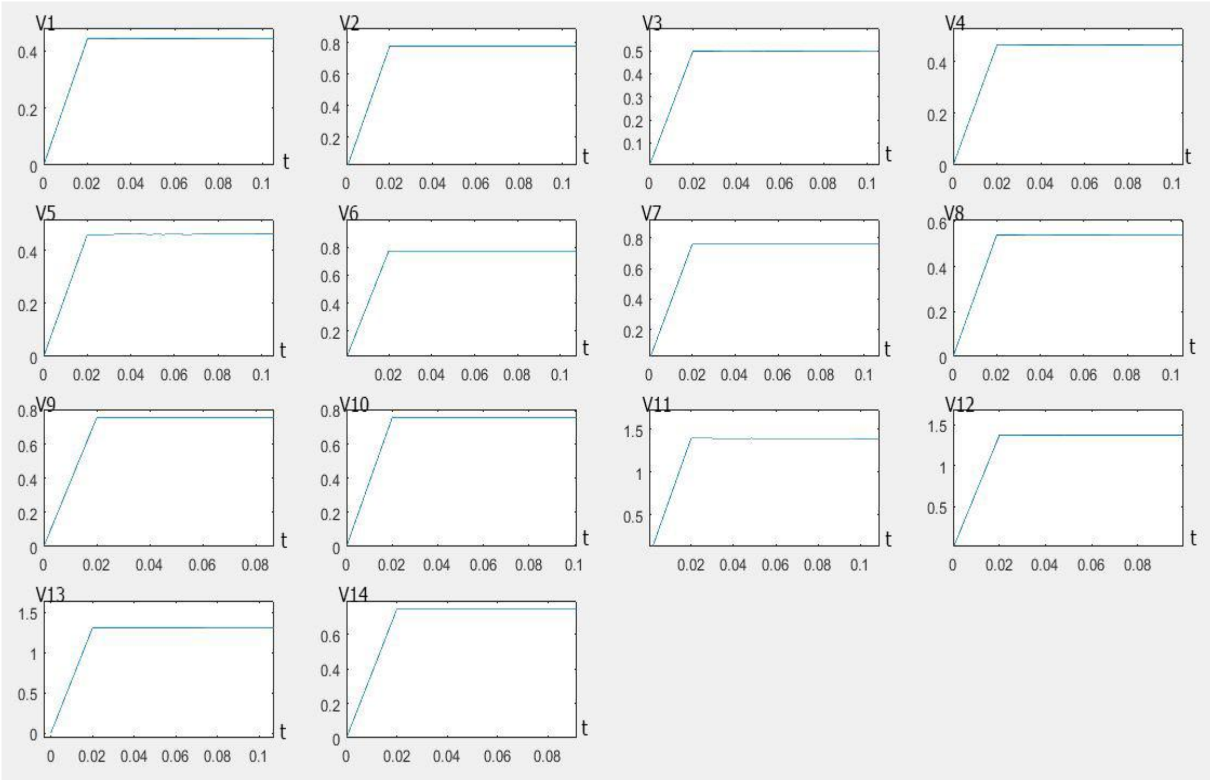

Fig. 3 The corresponding voltages (voltage in PU versus time in 1 second) for IEEE 14 buses respectively.

For the IEEE 30-bus system, a similar work is done as for the 14-bus system in MATLAB/SIMULINK as shown in fig. 4. Taking into consideration a system with zero injections and the Non-linear constraints algorithm to determine the optimal placement, PMUs are placed in the 3, 5, 10, 12, 18, 23 and 27 in IEEE 30 buses [8-9].

Analysis and results of the system

There are seven PMUs placed at buses 3, 5, 10, 12, 18, 23 and 27. Bus 6, 9, 11, 25, 28 are the zero injection buses [22]. The PMU at bus can not only measure the voltage of bus 3 but also the current of branches 3-1, 3-4, Using Ohm's law, the voltage at buses 1 and 4 can be obtained from the branch currents and the voltage at bus 3. Having determined voltage at buses 1, 3 and 4, the current of branches 1-2 and 2-4 can be calculated. By following the same logic steps for the PMUs at 10, 12, 18, 23 and 27. Thus the entire system becomes observable by placing only seven PMUs. A MATLAB script is written to display bus voltages in per units and angles in degrees as shown in fig. 5.

Figure 6 shows the variation of the Voltage V with respect to time for all 30 nodes. The PDC represented in GUI makes the state of the system network observable. The voltage magnitude and phase angle at each bus is displayed with stable values. The evaluated system is said to be healthy.

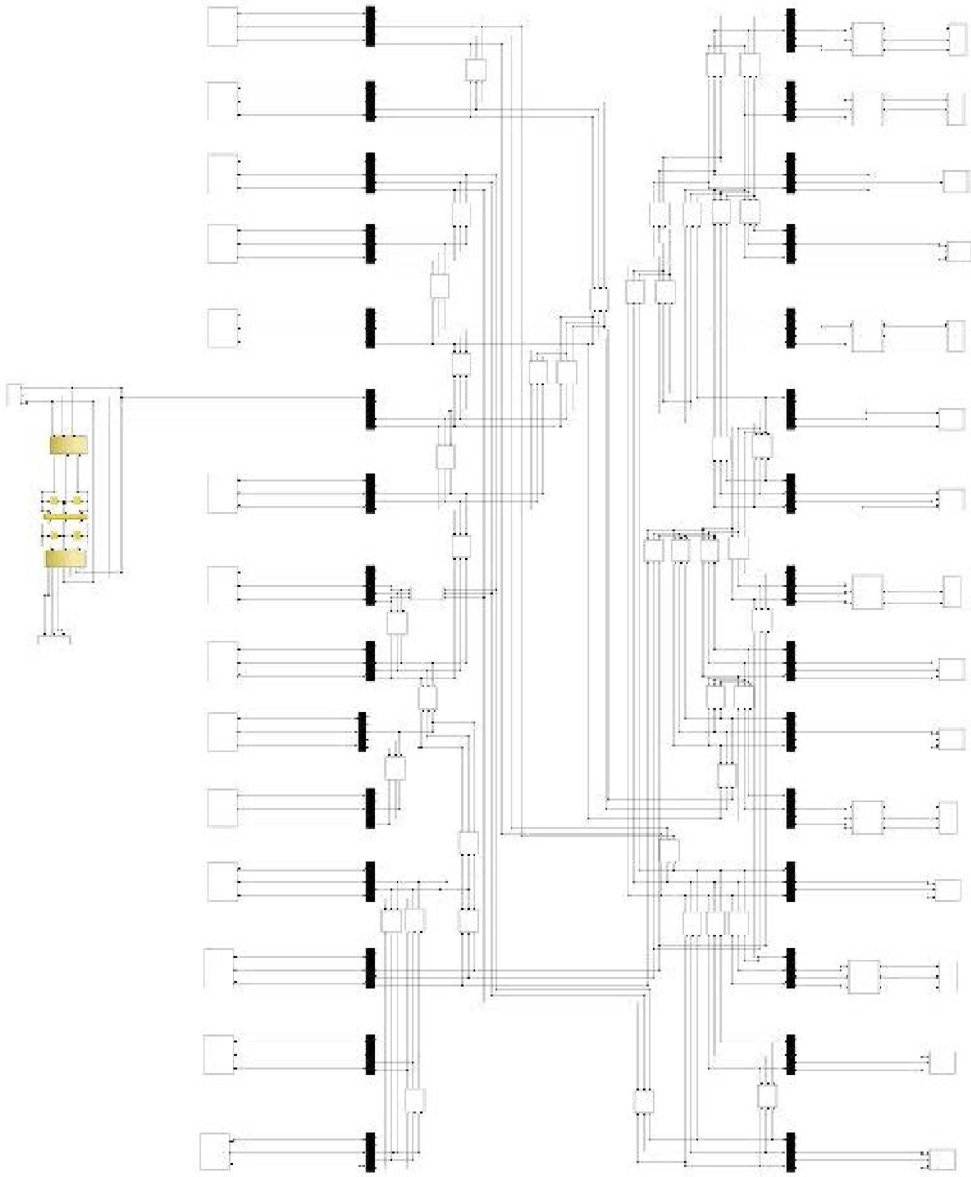

Fig. 4 IEEE 30-bus system Simulink model

Fig. 5 The graphical user interface for IEEE 30-bus system

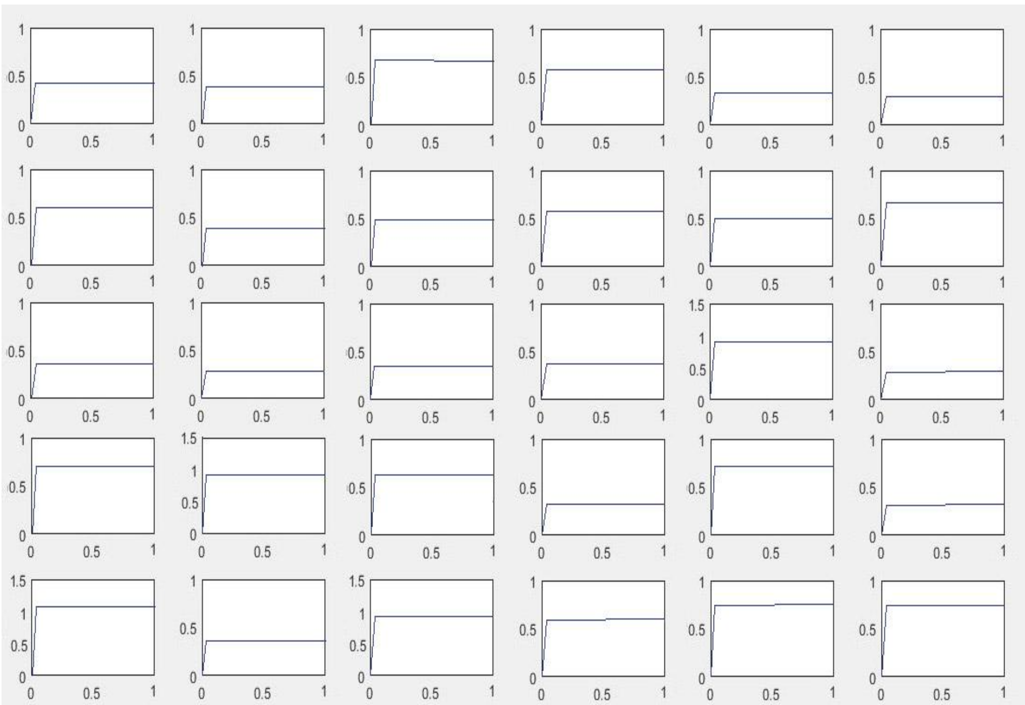

Fig. 6 The corresponding voltages (voltage in PU versus time in 1 second) for IEEE 30 buses respectively

3. FAULT DETECTION USING PMUs

In this section, different types of faults are to be induced each time in different location placement. The synchronized fault voltages are monitored by neighboring PMUs installed at indicated busses. These detects the measurements abnormalities either a voltage drop in bus or a current spike between two busses. Based on the calculated fault node injection, fault nodes can be deduced or fault locations in transmission lines can be calculated.

3.1. Faults in IEEE 14 bus system

Fault in a bus carrying a PMU

A line to ground fault is placed in bus 2; a bus carrying PMU.

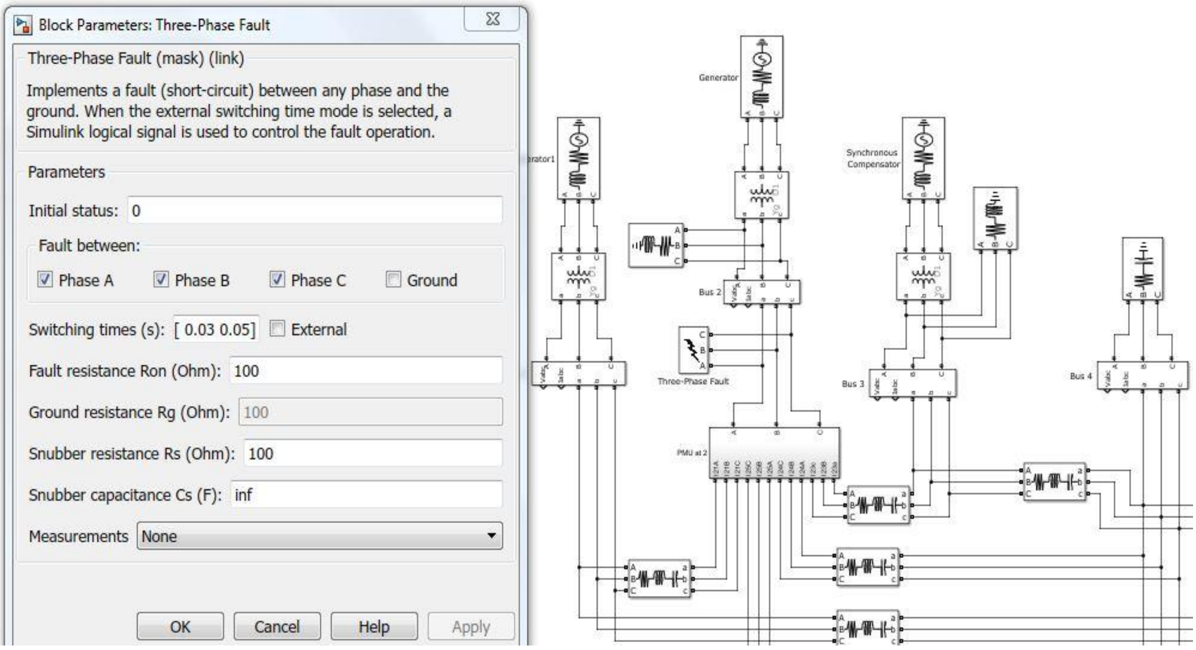

Fig. 7 Simulink model for a fault in bus 2

By creating a three phase balanced fault in bus 2 the PDC (GUI in our case) displays what is presented in the fig. 8.

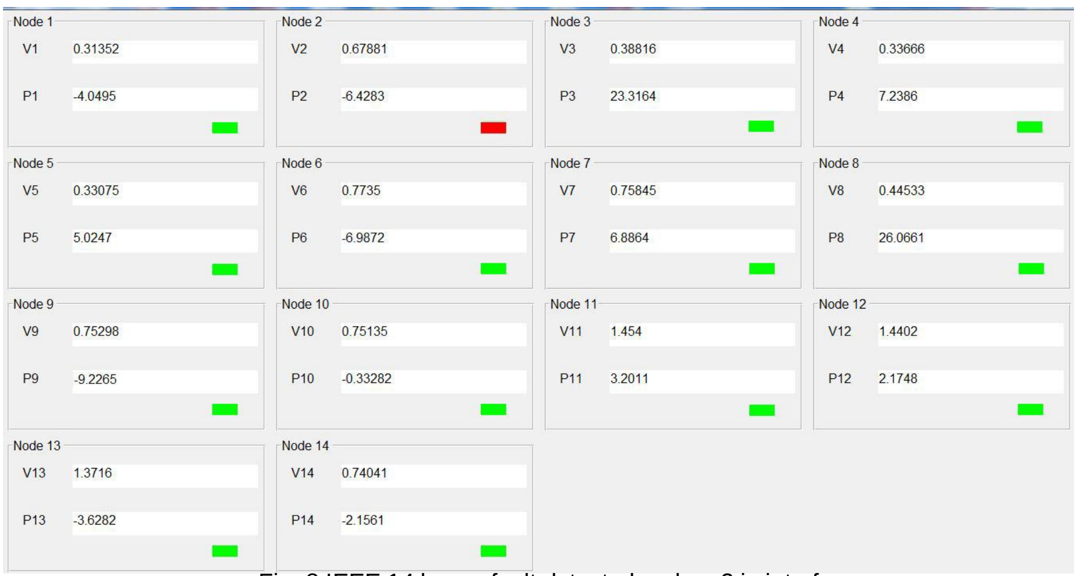

Fig. 8 IEEE 14 buses fault detected on bus 2 in interface

The program written in MATLAB script reacts when difference in voltages occurs for healthy system and unhealthy system, then it detects the fault in the defected bus 2.

Fig. 9 is a graph representation of the fault happening during time period [0.3; 0.5] in bus 2, the changes of voltages are remarkable comparing with the GUI in chapter 3. During this fault the graph of voltages V in each bus is changed because of the current spike. Voltage changes occur in the all interconnected busses.

According to the graph the voltages decreases when the fault occurs, the changes happened in bus 2 (the faulty bus) and the buses interconnected with it , bus 1,3,4,5 and 8. We can see that the system is unhealthy and unstable and we can deduce that the system is faulty. So, the system will be unstable.

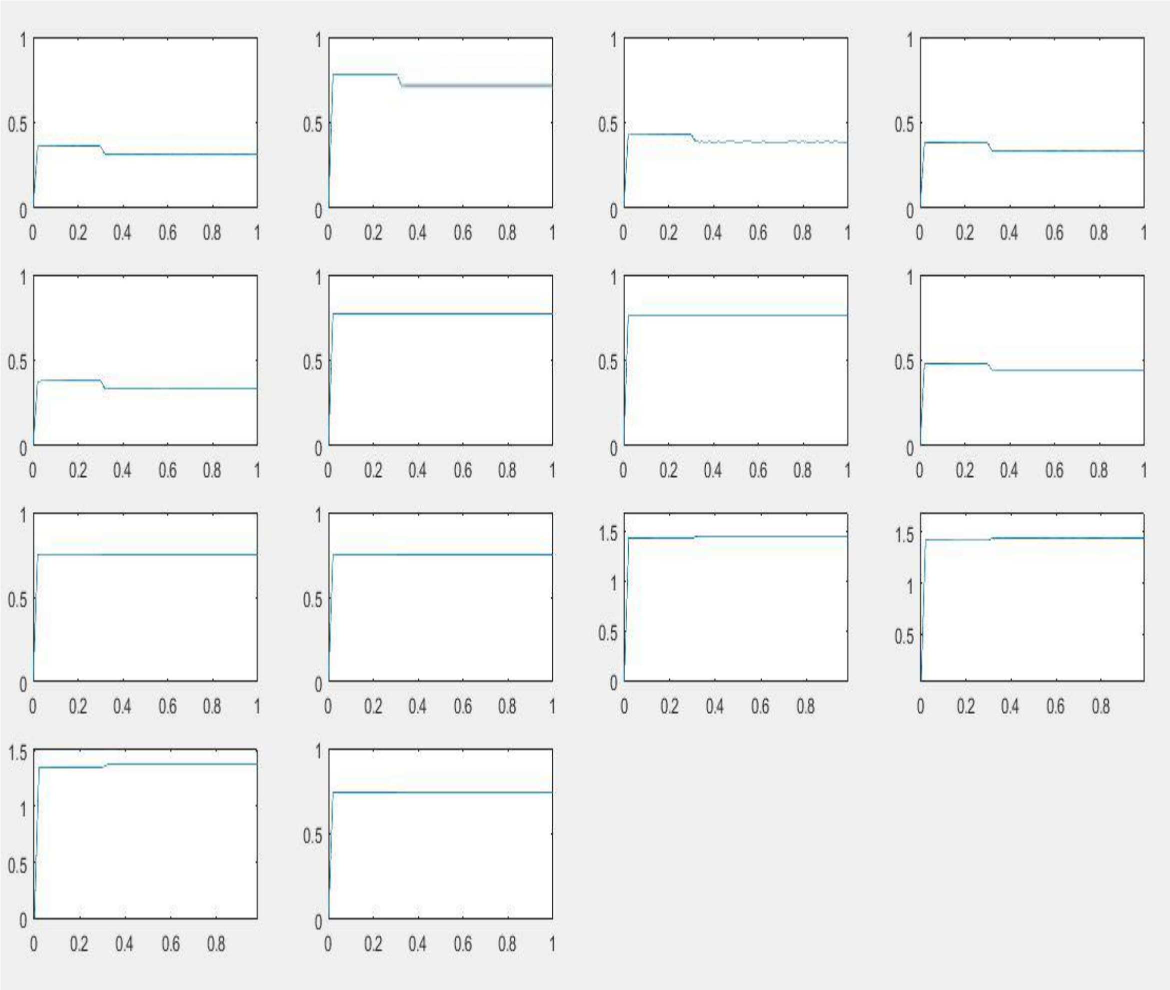

Fig. 9 voltage graph (voltage in PU versus time in 1 second) IEEE 14 buses respectively

Fault in a bus without PMU

Now a line to ground fault is induced in the transmission line between bus 11 and bus 12, those two busses do not carry PMU. By creating a line to ground fault between bus 11 and bus 12, the results are displayed in the figure 10.

Even there is no PMU placed in buses 11 and 12, the fault is detected in GUI due to the collected data from the related PMU, so the optimal placement of PMU makes the whole system observable and the fault is detectable.

Figure 11 shows the change of voltage that occurs when this type of fault happens, the graph points that the interconnected busses are affected by the fault happened in the transmission line between bus 11 and bus 12.

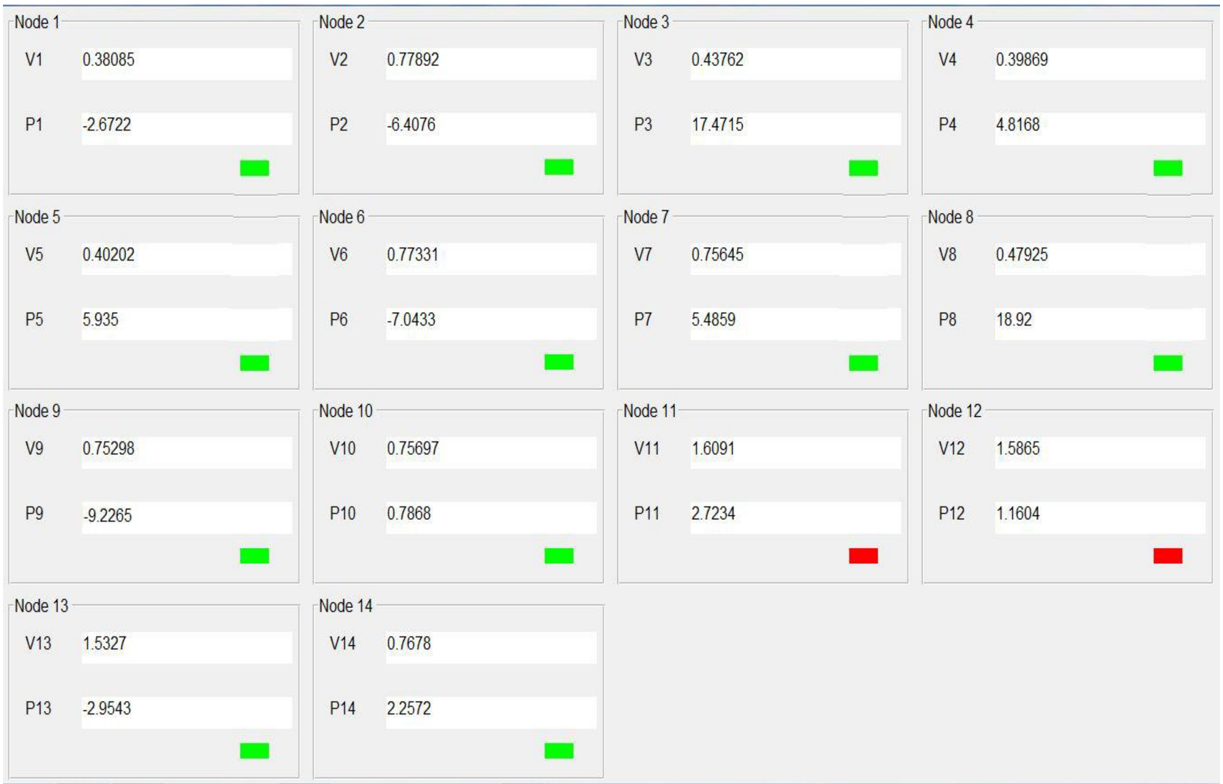

Fig. 10 Voltage (in PU) versus time in 1 second- IEEE 14 buses fault detected between buses 11 and 12

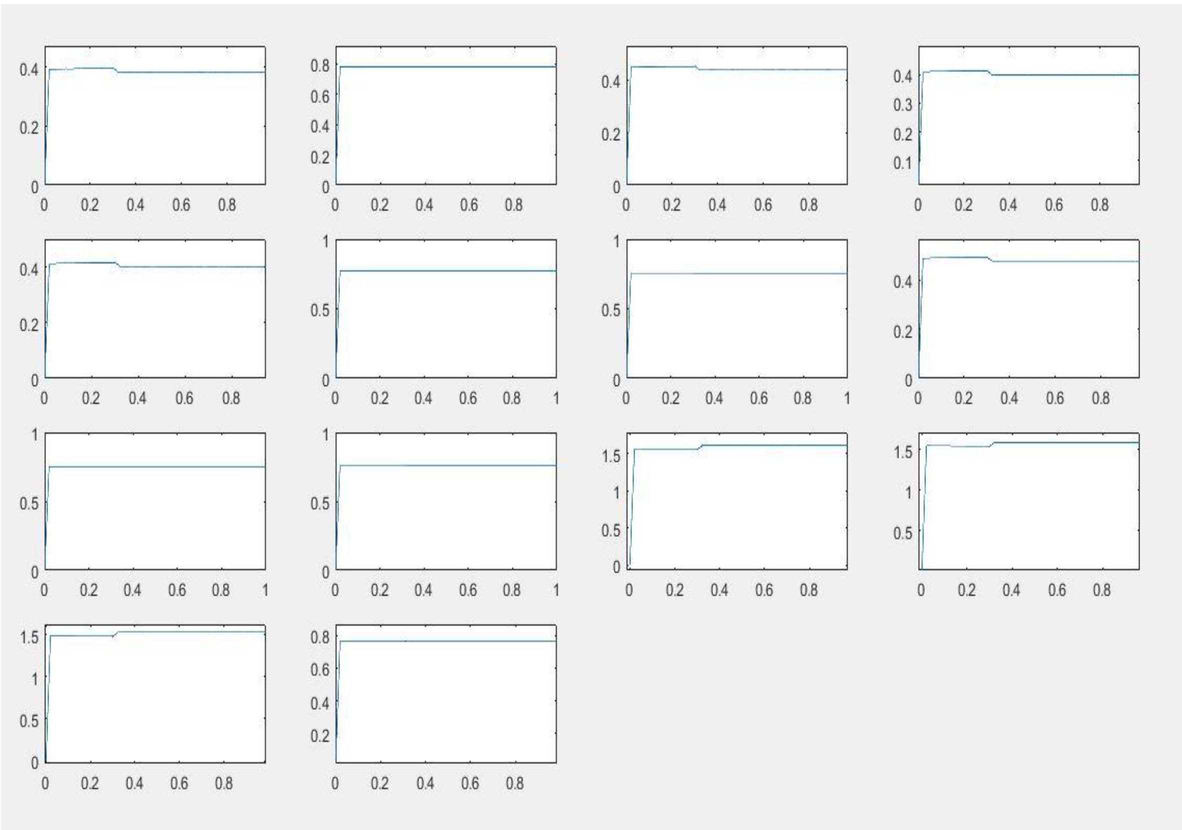

Fig. 11 Voltage (in PU) versus time in 1 second- IEEE 14 bus system

3.2. Faults in IEEE 30-bus system

Fault in a bus carrying PMU

We applied The same work that we have done for IEEE 14 buses in IEEE 30 buses , first the fault locates in bus 3 the bus carried PMU.
The PMU detects the fault and indicates in Graphical User Interface which is used as a control center to facilitate the observability of the system for the workers as shown in Figure 12.

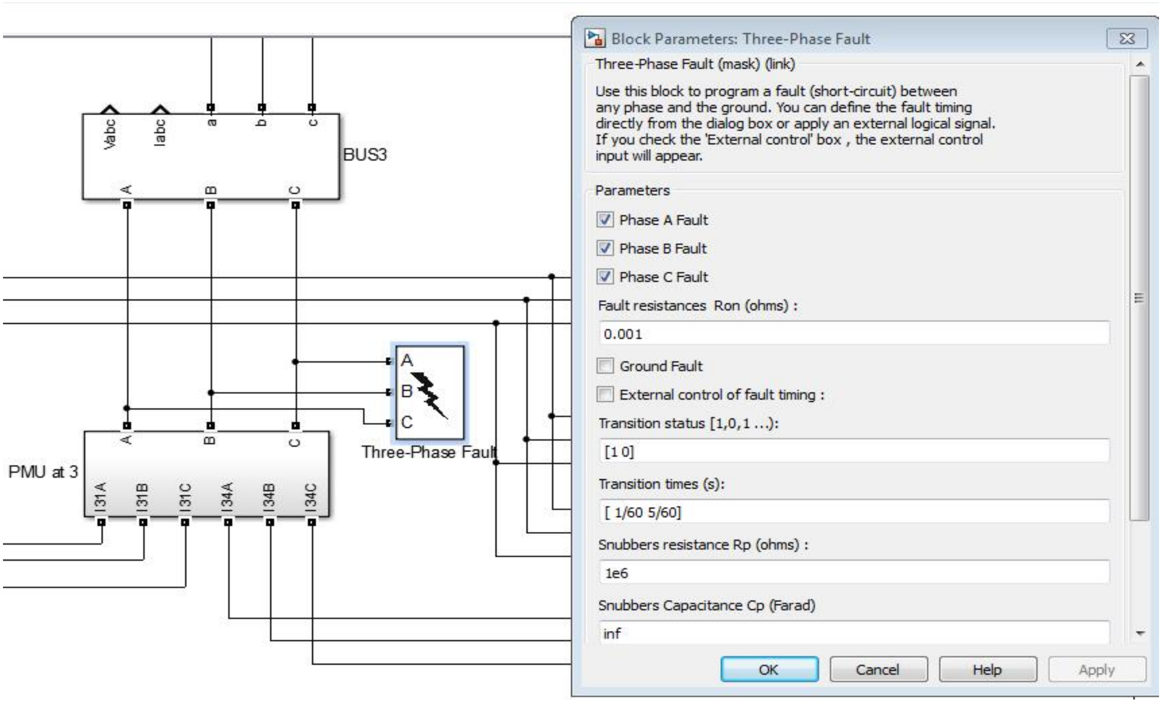

Fig. 12 Simulink model for a fault in bus 3

Fig. 13 IEEE 30-bus system fault detected for bus 3 in interface.

There is a decrease of voltages in the nodes interconnected with the faulty bus (three balanced fault).

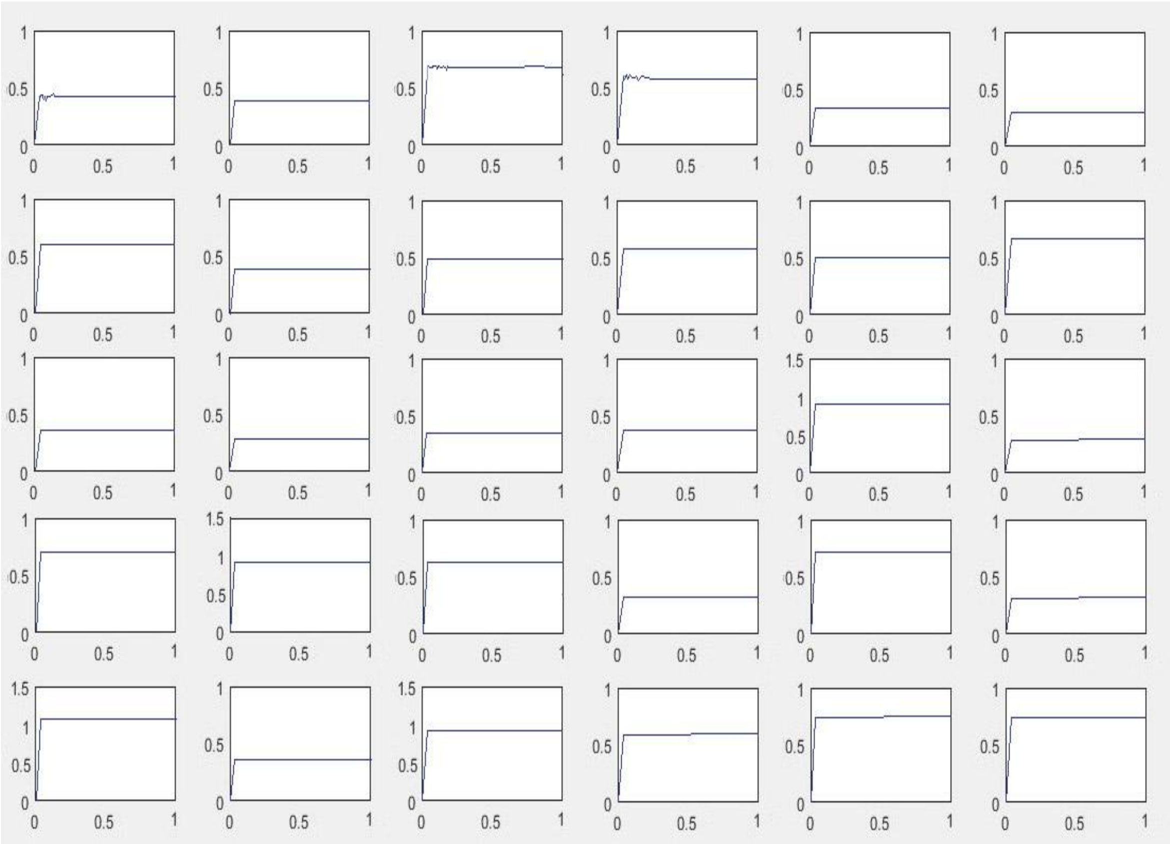

Fig. 14 (voltage in PU versus time in 1 second) IEEE 30 buses respectively

Fault in a bus without PMU

The fault is created between buses 22 and 24 in Simulink.

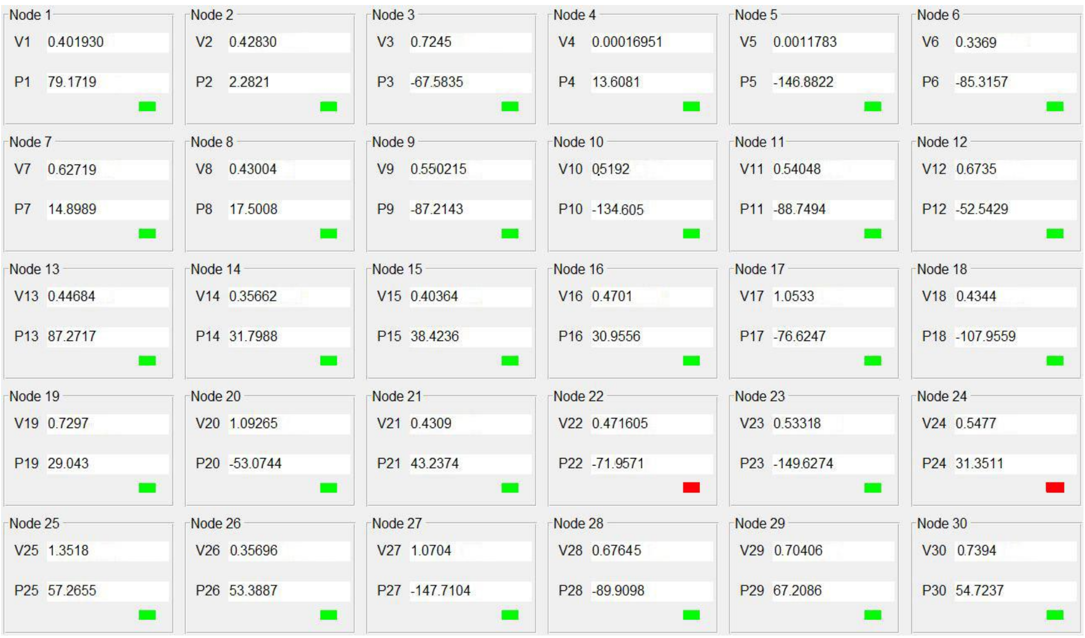

Fig. 15 IEEE 30 buses fault detected between buses 22 and 24 in interface

The figure below shows the variation of the Voltage V with respect to time for all 30 nodes. We can see that the system is unhealthy and unstable and we can deduct from that that a fault is occurring in the system. So, the system will be unstable. There are also changes in voltages.

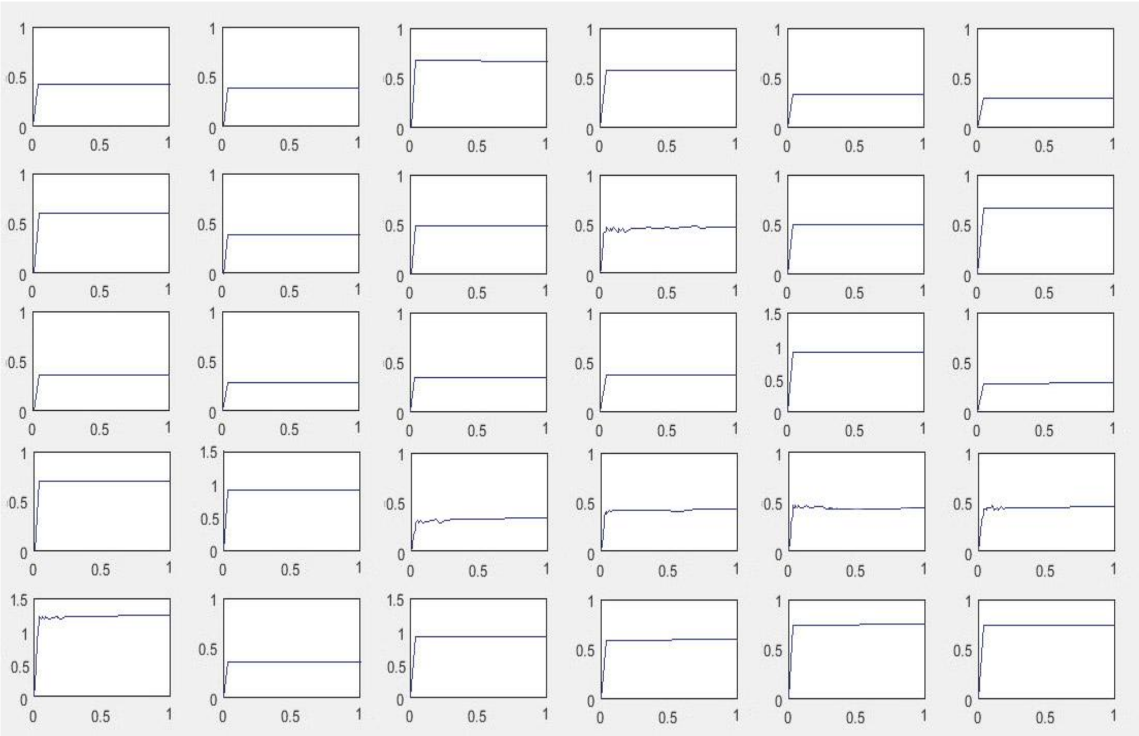

Fig. 16 Voltage (in PU) versus time in 1 second for IEEE 30 buses

CONCLUSION

In this work, the use of PMUs to detect and locate faults in a power system has been investigated. The purpose is to locate and isolate the faulty part of the system so that to prevent the propagation of the fault to the remaining parts of the power system and find a solution to the problem. The idea was to compare the measurement data using the PMUs under the faulty conditions to those recorded for the healthy system. The technique adopted here resembles the neural network training and the simulation results have shown the successfulness of the adopted approach.

An extension of the work would be to use renewable energy sources to correct the detected faults and heal the system and restore it to its healthy state. A final product would be a self healing system that automatically detects, locates and corrects the fault.

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