PMU Based Real Time Power System State Estimation using ePHASORsim

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***Abstract*—State estimation is an useful tool that helps in monitoring of a power system. With changes occurring constantly in the system, a real time estimation is of utmost importance. It is an important tool for modern control center operation in the smart grid. With the implementation of synchrophasor technology, efficient and real-time state estimation has become simpler. PMUs are not connected to all the buses of the network and so real time estimation is required to know the status of those buses. In this paper, real time simulation of two systems, viz., WSCC 9-bus system and IEEE 39-bus system, have been performed using ePHASORsim, a power system simulator that uses phasor data.**

***Index Terms*—Linear state estimation, real time estimation, synchrophasor, ePHASORsim, WSCC 9-bus, IEEE 39-bus.**

I. Introduction

Power system needs to be operated to satisfy high reliability standard, low operational cost and minimum environmental effect. For the power system to work efficiently, proper monitoring is to be done and accordingly, control actions are to be taken. Monitoring of the power system is done through poling whereby the measurements from the different buses are obtained serially through supervisory control and data acquisition (SCADA) system and therefore, they are not time synchronized. The data scanning rate through a SCADA system is 5$\sim$8s typically [1] and larger the network, more the time taken to monitor the entire system. The status of the system may have changed even before the entire set of data is scanned and that leads to erroneous monitoring. Real time analysis of the system is thus not possible. Technology advanced and phasor measurement unit (PMU) is introduced in power systems resulting in real time wide area management system (WAMS) having a data scanning rate as high as 50/60 frames per second. The added advantage is that the PMUs are time synchronized and data are obtained from various buses at the exact same time. Thus, dynamic variations of a power system can be monitored through WAMS. PMUs are placed strategically at some particular buses across a network, to make the system observable, due to its high cost. The data obtained at the control centre from PMUs may be erroneous for practical reasons [2]. Such raw measured data are inappropriate to conclude on the health of a power system. A best estimate of the system states from such measurement data is obtained through state estimation. The power system state is being estimated in a control centre from SCADA data using non-linear estimation techniques [2]-[4]. With the availability of PMU data at a high rate of 25 frames at the control centre, performing state estimation in real time is possible. Moreover, state estimation using PMU data uses linear equations which are easy to solve and less time consuming.

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A lot of research is happening over the world in using different tools to go for real-time state estimation of power system networks using synchrophasor data. In [5], a real-time simulation model of IEEE 39 bus system is developed in real time digital simulator (RTDS) and it streams phasor data from real-time simulation. The concept of real-time state estimation has been practically validated on a 20 kV active distribution system network in [6] and the estimated states are found to refresh every after 20ms. In [7], a new methodology has been proposed to perform real-time state estimation using multilayer neural networks. Research is going in real-time state estimation in microgrids as in [8] and also for fault identification in active networks using synchrophasor based real-time state estimation as in [9].

In this paper, a method has been proposed in which the power system network is modeled in "ePHASORsim Real-time Transient Stability Simuator" on MATLAB 2013A platform. Disturbances are created in the system and real time simulation is performed. With the help of synchrophasor technology, system operators are able to monitor the system every after 40 ms [10] and hence state estimation is performed every after 40 ms time duration. With the real time simulated data obtained through ePHASORsim, state estimation is performed in real time and the accuracy of the estimator is compared.

This paper is divided into five sections. The method implemented to perform the real-time simulation and the state estimation has been discussed in section II. Section III compares the goodness of the estimated results with the true simulated data. Sections IV and V contain the discussion and conclusion of the work respectively.

II. Real-time State Estimation Method

ePHASORsim uses MATLAB Simulink model for the real-time simulation. The model has two subsystems as shown in Fig. 1. The subsystem *sm_master* consists of all the network details that are fed into the server for real-time analysis. The *sm_master* gives the real-time simulated output of the system under study. The *sc_console* subsystem is basically like a GUI interface through which various disturbances can be incorporated into the system through the bus voltage phasors fed from *sm_master* and then the system can be monitored. The disturbances are then fed back to *sm_master* subsystem for the effects to take place in real-time.

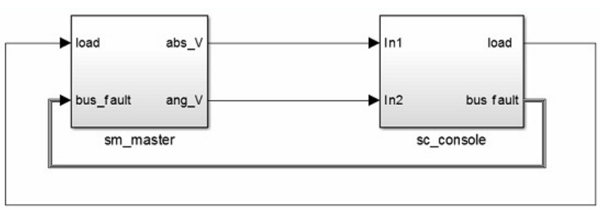

Fig. 1. Basic simulink model for ePHASORsim

The master subsystem has a *Solver* block which is the brain of the ePHASORsim. It has the entire power system network data in the form of PSSEv32 files. The generator dynamic data are also provided in the solver block for transient analysis of the system. The solver block generates the transient data of the system under various scenarios. The bus voltage phasors and the branch current phasors generated by the solver block are fed into a subsystem *State Estimator* which contains the algorithm for linear state estimation. The output from estimator is voltage phasor of all buses in the network. The schematic block diagram of the method is shown in Fig. 2.

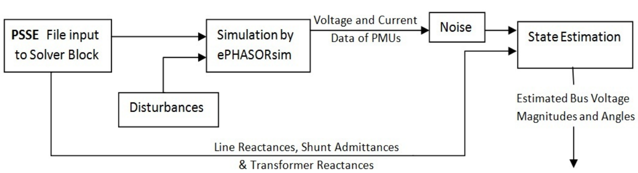

Fig. 2. Schematic block diagram showing various steps of real-time state estimation of a power system network

2% random white noise is incorporated to the voltage phasors and current phasors that enter the state estimator block to account for the practical errors that occur during measurement and communication. The state estimator then estimates the states in real-time using the input phasors and the network parameters to provide the estimated voltage phasors at all the buses. The time step size for ePHASORsim simulation is 10ms. As the scanning rate of WAMS is 25 samples per second on an average, the simulated data is taken for estimation after every 4 time steps, that is, after every 40ms.

Let there be a power system network with n_b number of buses. If there are n_v number of voltage measurements and n_i number of current measurements obtained from PMUs, the measurement vector $[M]$ can be arranged as [11]:

$$[M] = \begin{bmatrix} U \\ yA + y_s \end{bmatrix} [V_b] = [B][V_b] \tag{1}$$

where,
$[M]$ is a column vector of n_v voltage measurements and n_i current measurements,
$[V_b]$ is the state vector of order $n_b \times 1$,
$[U]$ is a unit matrix of order $n_v \times n_b$ in which all row elements except those corresponding to the PMU buses are zero,
$[y]$ is a diagonal matrix of series admittances of order $n_i \times n_i$,
$[A]$ is an $n_i \times n_b$ incidence matrix based on the topology, and,
$[y_s]$ is the line shunt admittance matrix of order $n_i \times n_b$.

The estimated state vector $[\hat{V}_b]$ can be obtained by [11]:

$$[\hat{V}_b] = [[B]^T [W]^{-1} [B]]^{-1} [B]^T [W]^{-1} [M] \tag{2}$$

where, $[W]$ is the weight matrix for the PMU measurements based on the accuracy level of the units.

The estimated voltage phasors and the measured voltage phasors are saved into respective files and they are compared to calculate the accuracy of the real-time estimation. The voltage profiles of some buses are also observed.

III. Simulation and Results

A. *Test Systems*

The real-time state estimation was tested upon two different systems, viz, WSCC 9-bus system [12] and IEEE 39-bus system. The WSCC 9-bus test case represents a simple power system network consisting of 9 buses, 6 branches and 3 generators as shown in Fig. 3. The base voltage levels are at 13.8 kV, 16.5 kV, 18 kV and 230 kV.

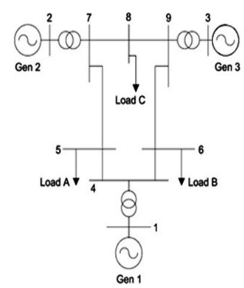

Fig. 3. Single line diagram of WSCC 9-bus system

The IEEE 39-bus system consistes of 39 buses, 46 lines and 10 generators as shown in Fig. 4.

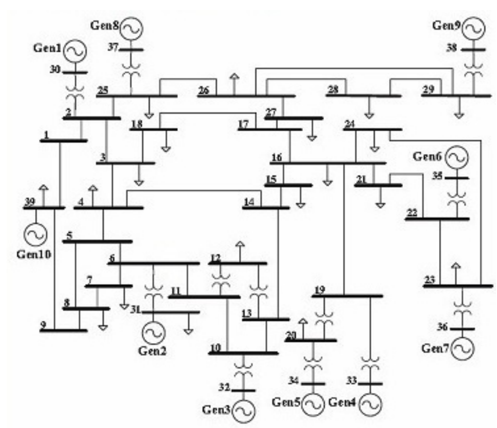

Fig. 4. Single line diagram of IEEE 39-bus system

B. Data Generation

The model is simulated in real-time to obtain the voltage profiles of the buses. Both the systems are initially in their steady state conditions. A three phase bolted fault at bus 6 was simulated in the 9-bus system at 10s after the simulation started for a duration of 0.1s. Voltage magnitude and angle profiles at buses 4 and 6 are shown in Figs. 5 and 6.

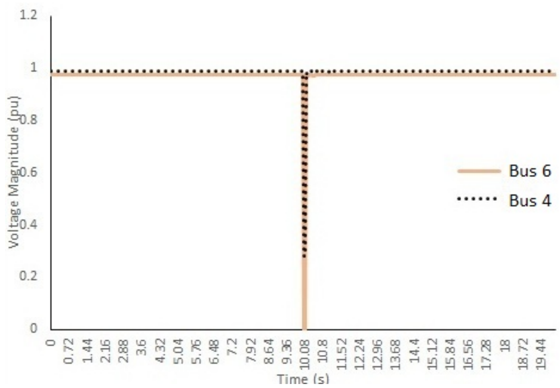

Fig. 5. Simulated voltage magnitude at buses 4 and 6 in the WSCC 9-bus system due to fault at bus 6

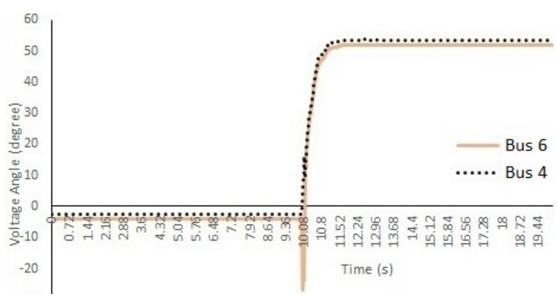

Fig. 6. Simulated voltage angle at buses 4 and 6 in the WSCC 9-bus system due to fault at bus 6

For the IEEE 39-bus system, two different cases were studied at buses 4 and 6. The first case is a 20% load increment at bus 4 from 500MW, 84MVAR to 600MW, 100.8MVAR at 12s from start of the simulation as shown in Figs. 7 and 8.

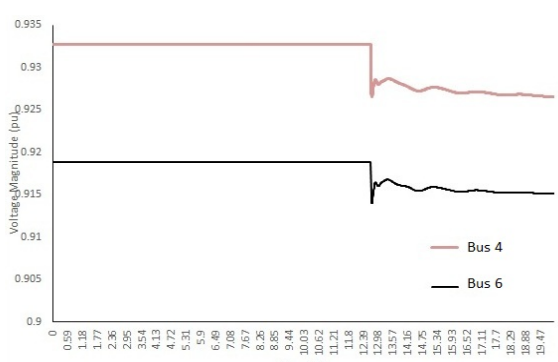

Fig. 7. Simulated voltage magnitude at buses 4 and 6 in the IEEE 39-bus system due to load increment at bus 4

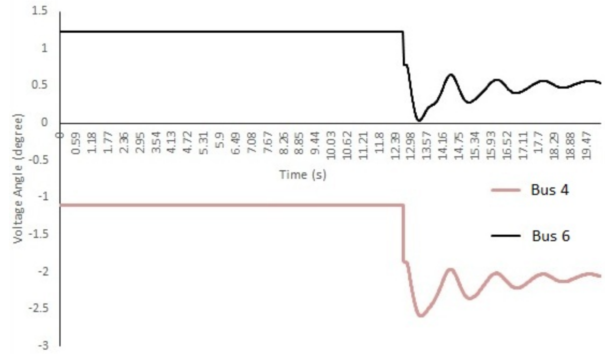

Fig. 8. Simulated voltage angle at buses 4 and 6 in the IEEE 39-bus system due to load increment at bus 4

The second case involves a three phase bolted fault at bus 6 for a time duration of 0.1s. The fault occurs at 10s after the start of simulation. The voltage profiles of buses 4 and 6 are shown in Figs. 9 and 10.

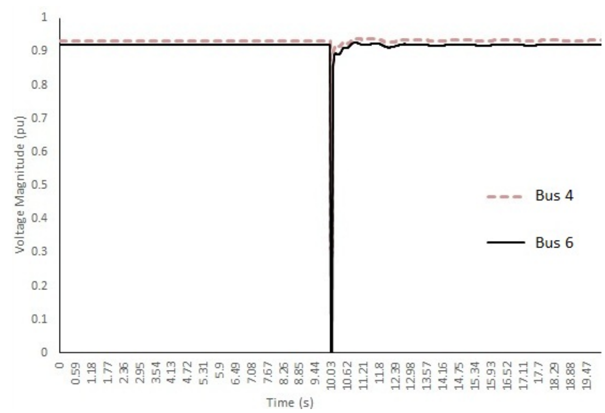

Fig. 9. Simulated voltage magnitude at buses 4 and 6 in the IEEE 39-bus system due to fault at bus 6

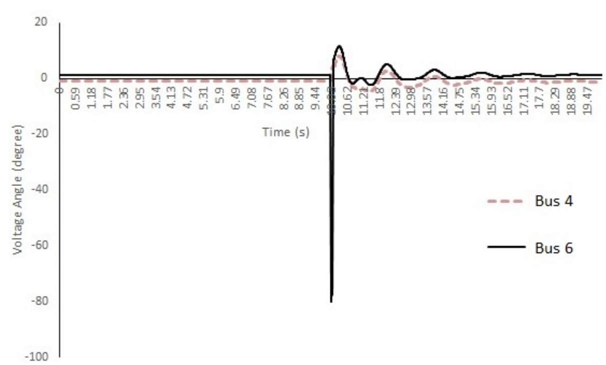

Fig. 10. Simulated voltage angle at buses 4 and 6 in the IEEE 39-bus system due to fault at bus 6

PMU placements are done at these two systems as per [13] so that the entire system remains observable with the minimum number of PMUs. There are 3 PMU buses in the WSCC 9-bus system and 13 PMU buses in the IEEE 39-

bus system. The system is simulated in ePHASORsim and the voltage and current phasors as observed across the PMU buses are obtained. 2% random noise is incorporated to these simulated data to take into account the practical disturbances. The simulated data along with the noise acts as the measured data (equivalent to the practical data read by the PMUs where the data consists noise). The measured data is then used for state estimation of the entire system and thus the estimated results are calculated.

C. State Estimation

1) WSCC 9-bus system: The estimated voltage profiles for bus 4 are compared with the simulated and measured data as in Figs. 11 and 12 whereas, for bus 6, the estimated results are compared only with the simulated data, because bus 6 is not a PMU bus, as shown in Figs. 13 and 14.

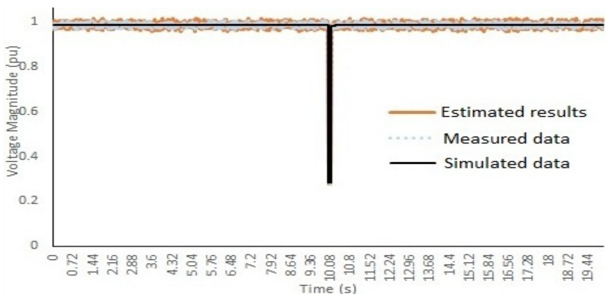

Fig. 11. Simulated, measured and estimated voltage magnitudes at bus 4 in WSCC 9-bus system

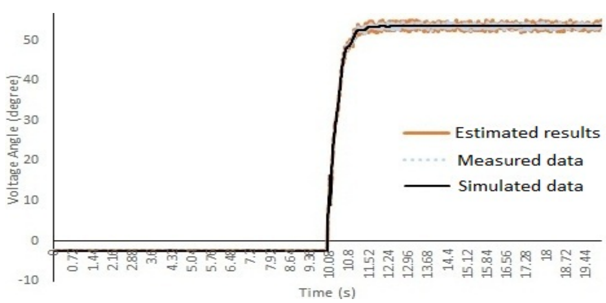

Fig. 12. Simulated, measured and estimated voltage angles at bus 4 in WSCC 9-bus system

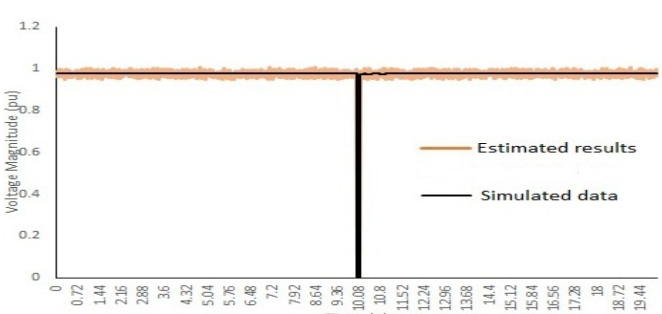

Fig. 13. Simulated and estimated voltage magnitudes at bus 6 in WSCC 9-bus system

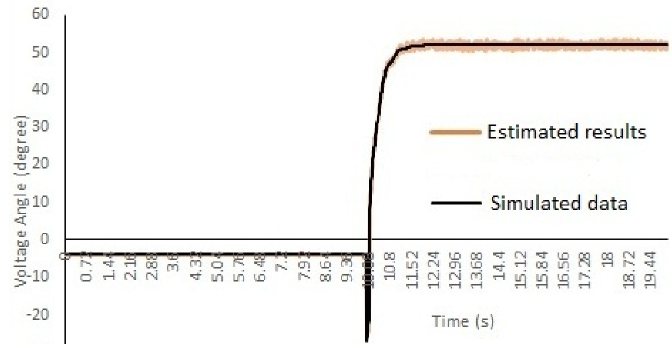

Fig. 14. Simulated and estimated voltage angles at bus 6 in WSCC 9-bus system

Next, the accuracy of the estimated results is studied at these two buses as shown in Table I.

TABLE I
COMPARISON OF ACCURACY OF REAL-TIME STATE ESTIMATOR AT BUSES 4 AND 6 IN WSCC 9-BUS SYSTEM

Criteria	Bus 4 Voltage Magnitude	Bus 4 Voltage Angle	Bus 6 Voltage Magnitude	Bus 6 Voltage Angle
Maximum Error (%)	0.309	-0.363	0.938	0.233
Minimum Error (%)	-0.714	-1.116	-1.104	-2.115
RMS Error (%)	0.625	0.923	1.019	1.918

The figures showing the voltage profiles reflect that the estimated and simulated voltage profiles are close to each other and that is confirmed by the table showing that the errors are within 2%. The estimation at each time step took 12ms to complete for the 9-bus system.

2) IEEE 39-bus system: The estimated voltage profiles obtained for bus 4 are compared with the simulated and measured data as in Figs. 15 and 16 for the fault condition.

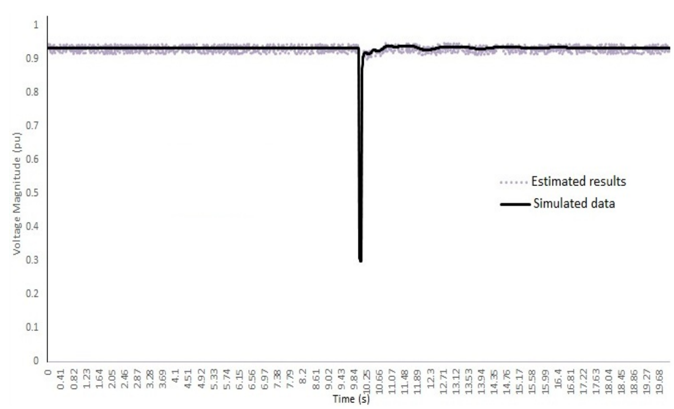

Fig. 15. Comparison of simulated and estimated voltage magnitude at bus 4 in IEEE 39-bus system under fault condition

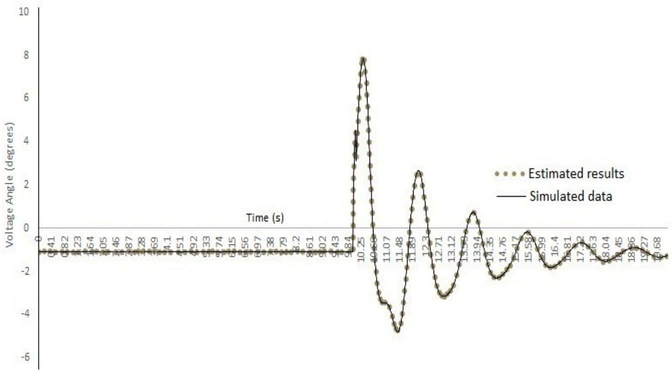

Fig. 16. Comparison of simulated and estimated voltage angle at bus 4 in IEEE 39-bus system under fault condition

Voltage profiles of bus 6 are shown in Figs. 17 and 18 under the fault condition.

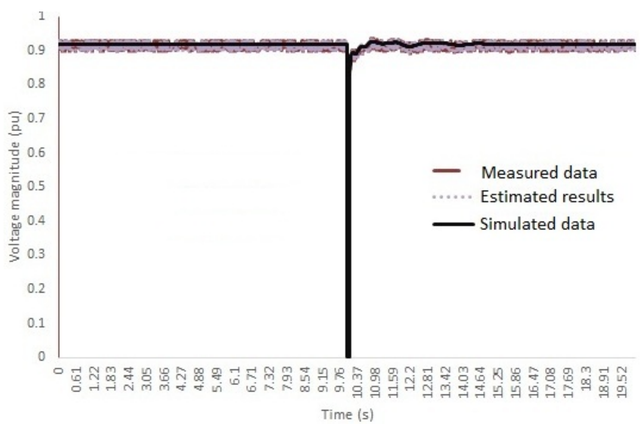

Fig. 17. Comparison of simulated, measured and estimated voltage magnitude at bus 6 in IEEE 39-bus system under fault condition

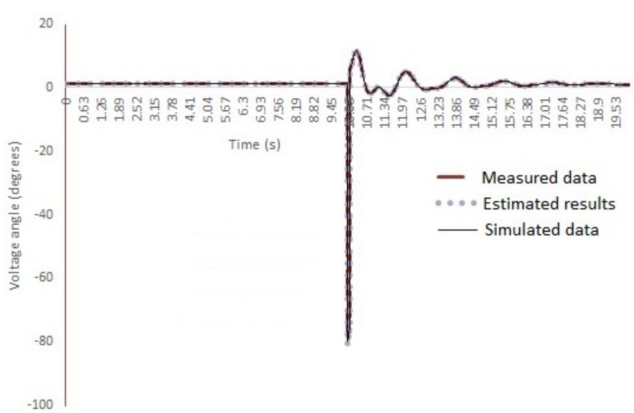

Fig. 18. Comparison of simulated, measured and estimated voltage angle at bus 6 in IEEE 39-bus system under fault condition

For the load change, the estimated voltage profiles obtained for bus 4 are compared with only the simulated data due to the absence of PMU as in Figs. 19 and 20.

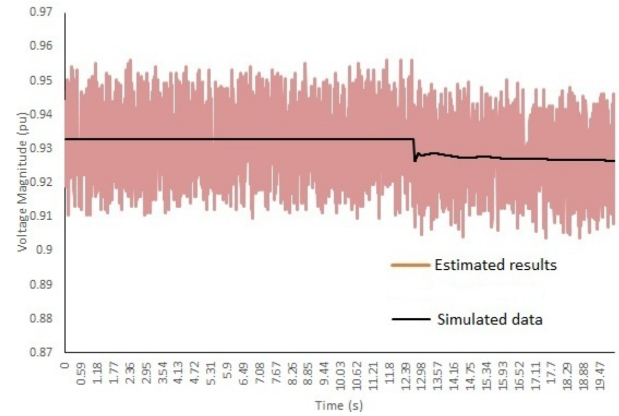

Fig. 19. Comparison of simulated and estimated voltage magnitude at bus 4 in IEEE 39-bus system under load change condition

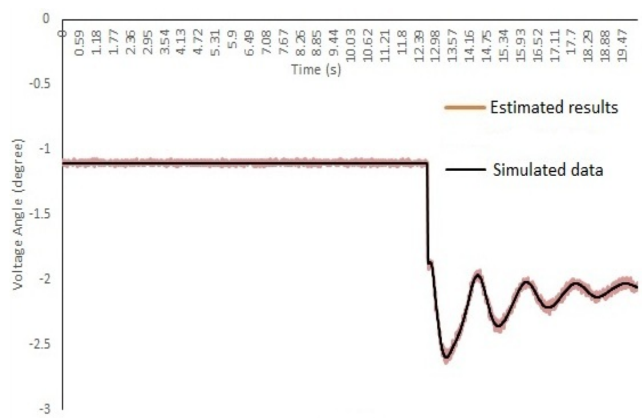

Fig. 20. Comparison of simulated and estimated voltage angle at bus 4 in IEEE 39-bus system under load change condition

Voltage profiles for bus 6 are compared with simulated and measured data as in Figs. 21 and 22 due to the presence of PMU at that bus.

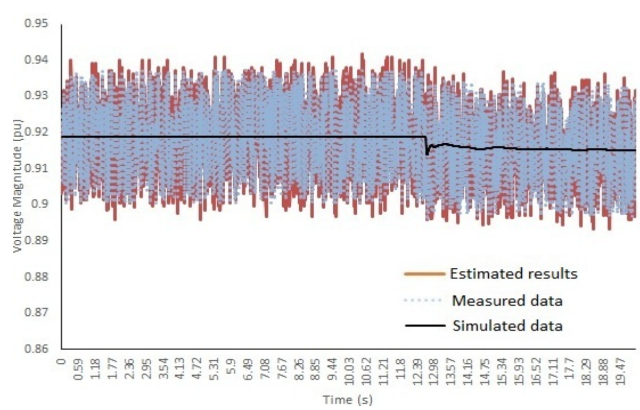

Fig. 21. Comparison of simulated, measured and estimated voltage magnitude at bus 6 in IEEE 39-bus system under load change condition

The accuracy of the estimator is studied on buses 4 and 6 under both the conditions, viz., bus fault and load change. For

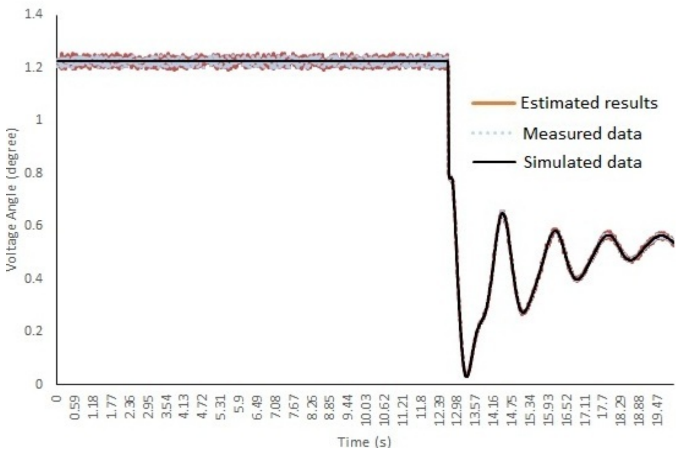

Fig. 22. Comparison of simulated, measured and estimated voltage angle at bus 6 in IEEE 39-bus system under load change condition

bus 4, comparison is done between estimated and simulated data, whereas for bus 6, estimated and measured data are considered. The comparison due to fault condition is shown in Table II and that due to the load change is shown in Table III.

TABLE II
COMPARISON OF ACCURACY OF REAL-TIME STATE ESTIMATOR AT BUSES 4 AND 6 IN IEEE 39-BUS SYSTEM DUE TO FAULT

Criteria	Bus 4 Voltage Magnitude	Bus 4 Voltage Angle	Bus 6 Voltage Magnitude	Bus 6 Voltage Angle
Maximum Error (%)	0.609	-0.363	0.038	0.0633
Minimum Error (%)	-1.214	-2.016	-0.604	-0.815
RMS Error (%)	0.925	1.623	0.419	0.682

TABLE III
COMPARISON OF ACCURACY OF REAL-TIME STATE ESTIMATOR AT BUSES 4 AND 6 IN IEEE 39-BUS SYSTEM DUE TO LOAD CHANGE

Criteria	Bus 4 Voltage Magnitude	Bus 4 Voltage Angle	Bus 6 Voltage Magnitude	Bus 6 Voltage Angle
Maximum Error (%)	0.715	0.118	0.021	0.072
Minimum Error (%)	-0.986	-1.919	-0.684	-0.915
RMS Error (%)	0.625	1.623	0.539	0.582

The state estimation at each time step took 19ms to complete and as observed from the tables as well as the voltage profiles, the estimated results have a good accuracy with respect to the simulated results.

IV. DISCUSSION

Real-time state estimation was performed on two systems, viz., WSCC 9-bus system and IEEE 39-bus system. Estimation of the system was found to be over before the next set of data arrived. However, the systems being small, estimation takes relatively less time. The same procedure needs to be redone using a larger system and it needs to be checked if the real-time state estimation is possible in that case also. For much larger systems, parallel processing may be a good idea that will help in real-time state estimation.

V. CONCLUSION

Real-time state estimation is performed based on synchrophasor data using ePHASORsim on MATLAB 2013A environment. It is tested on WSCC 9-bus system and IEEE 39-bus system under various disturbances, both slow as well as fast. The estimator is found to give accurate results and the estimated states were obtained well before the next set of measurements arrived.

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