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PMU and FMU Based Investigation of the Effect of Static System State Estimation on the Performance of a Transmission Network

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Abstract- The characterisation of a power system at every operating state is a requirement for reliable and secured operation. This paper presents the evaluation of the state variables of a power system with static state estimation under steady state and transient conditions. Power flow for evaluation of the initial system variables was obtained through Newton Raphson algorithm. Real time system data is obtained through the phasor measurement units (PMUs) installed at remote terminal units (RTUs) of each load points. Weighted least square estimation method is applied on the initial state parameters; power flows, voltage magnitudes and angles and frequency obtained from the load flow evaluation to obtain reliable and final system state parameters. The result obtained through simulation of a 40 bus network on MATLAB (PSAT) shows 32.5% and 50% variances of state variables above 1%. Static state estimation (SSE) with PMU also provided improvement in the network performance through transmission loss reduction and overall system stability. A real time data acquisition (PMU) and data analysis system (SSE) is required to fully model, accurately characterise and ensure secured operation of the network under steady state and transient conditions.

Keywords- State estimation, Phasor measurement units (PMU), Weighted least square, Steady state stability, Transient Stability

1. Introduction

The goal of today's power system operators (PSOs) includes developing both short term and long term roadmaps for the operation of power system networks [10]. The short term frameworks involve the implementation of innovative technologies for the enhancement of the operation of such systems. This would be in the form of reinforcements with FACTs devices, penetration of distributed generation (DG) systems and the SCADA systems. The long term road map on a conventional power system (PS) leads to the future transmission network (FTN) [19]. The FTN operation is an enhanced version of the present network with the aim of decarbonising power generation through the intense implementation on renewable energy resources (RER) based DG and smart sensors for control. Also there exists an enhanced communication and coordination through innovative, state of the art and smart devices between the transmission system operators (TSOs) and the regional operations control (ROC) for improved operational efficiency.

1.1. The Modern Transmission System

The modern power system operation involves the balancing of energy generation with load [1]. The framework of such network is based on a rigid and generalised template where transmission of power is achieved and designed assuming fully controllable sets data. The efficiency of this topology is evident from the data on system collapse around the globe as measured from the voltage and frequency violations, thermal capacities and security issues.

For a reliable operation, a power system must remain intact and be capable of withstanding a variety of disturbances [3]. A disturbance may be small and gradual or large and sudden as defined by steady state and transient stability respectively. Disturbances are unforeseen and unpredictable therefore a transmission network must be designed in such a manner to ensure secured operations at all times. As shown in [17], the state variables of a system operating in the normal state exists in the statutory permissible range while there may occur one of more state variables existing outside of the security range during emergency.

The ability to quickly detect this anomaly through real time system monitoring would impact operation decisions for improved security. This research investigates the level of impact that may be derived from such systems. The relationship between the rotor angle stability and frequency stability is shown in [21]. The instantaneous generation and loading property of a power system makes it necessary to be able to determine and predict the ROC frequencies at all times. The possibility to determine these frequencies through the frequency monitoring unit (FMU) is also shown in this research.

1.2. The Future Transmission Network

The modern power system has evolved with the implementation of control and communication technologies. The need to monitor the operating conditions of a power system is fundamental to its reliability. This monitoring/control devices measure signals such as voltages, angles, reactive and active power flows, status of switches, and transferring them to the ROCs where it is stored, analysed and utilised [6]. Data acquisition and switching capabilities, communication and control enablement between the ROC and the load points are the major objectives of a smart network. Network states are those parameters that can be used to determine all other parameters of the power system [2].

These parameters includes the bus voltage magnitude V_i, voltage phase angle δ_i, frequency, active and reactive power flows P_{ij} and Q_{ij} respectively. These parameters are captured and transmitted by remote terminal units (RTUs) at regular time interval. Due to design and technical constraint, the measurement obtained from these RTUs contains some level of errors which is a function of its standard deviation [7]. Therefore, a filtering algorithm is required to smoothen out these measurements. The phasor measurement unit (PMU) is an electronic device that receives analog current and voltage signals from CTs and PTs where these signals are further processed using fourier transform to compute the phasor angles and frequencies [4]. State estimation (SE) is a technique used to estimate unknown values of the state variables based on some predefined criteria in order to minimize the effect of corrupt data.

1.3. Why System State Estimation

Power system operation is currently undergoing a paradigm shift from the conventional methods to the future transmission network operation. Due to the economically induced stress, the grid faces new challenges it was not designed for. Some of these challenges include back flow of power, congestions, multiple contingencies, new and unexpected states, and several others. These challenges are been considered while designing the future grid for robustness, redundancy and security [14]. The innovative framework and enabling technology for an operational future network is in its early stage and therefore expensive. Some if not all of the challenges would be eradicated if there exists a real time monitoring of the states of a conventional transmission network. A close to real time network assessment can be achieved through, optimum power flow (OPF), generation scheduling and state estimation (SE). This research looks at the analysis of the result obtained from evaluation of power flow from the ‘accurate’ data obtained from the RTUs. The ‘accurate’ data is corrupted by missing data and bad data which must be filtered by SE algorithm with a phasor measurement unit (PMU).

1.4. Related Works

The quest to place the present transmission network close to the future in terms of optimization and real time operations has been the concern of contemporary power systems researchers. In [6], it presents some of the current status of the research and developments in the area of applications of PMUs in electric power system networks incorporated with FACTS controllers. In [5], the recent developments in the application of SE to power system dynamics are highlighted. The main attributes of a PMU placement are identified to include device architecture numbers, reliability, accuracy, and modern distribution network requirements. Specific PMUs placements were employed to evaluate the observability of power system states in [13]. It was discovered that a specific and optimal PMU placement proposed in [15] and [18] reduce the estimation errors thereby improving the observability of the system. Vedran in [20] presented a case of hybrid state estimator which consists of SCADA system and synchrophasors for estimation of system states. However, a clear guide for establishing the system frequency and stability state has not been provided.

2. Model of Power System Performance

The framework of operation of the present transmission network has been discussed. The network is characterised by centralised fossil fuel generation and designed to always match the load demand. The loading is erratic and unpredictable depending on season and application. For a steady state-normal operation mode of a network; voltage and frequency constraints and stability limits much be met. Also under contingencies and sudden change in loading, the N-1 stability criterion must apply. Several methods have been adopted to ensure operation optimisation of transmission networks under transient disturbances within these constraints. In the light of these, Equations 1 to 5 presents the models for operation of the present network with the aim of leading into the future grid. The model for optimization problem highlighted above is given in Eq. (1).

Given that where θ_i and θ_j are the voltage phase angles of buses i and j at normal state, B_{ij} is the imaginary part of the element *ij* of the admittance matrix, P_{Gi} is the power generation at bus *i*, P_{Di} is the power demand at bus *i*, the power flow and transmission constraints during normal and emergency operations are expressed by Eqs. (1) and (2) [21] and [11].

$$\sum_{j=1}^{N} B_{ij}\left(\theta_i - \theta_j\right) = P_{Gi} - P_{Di} \qquad \forall \quad i \subset n \qquad (1)$$

$$\sum_{j=1}^{N} B_{ij}^{m}\left(\theta_i^{m} - \theta_j^{m}\right) = P_{Gi}^{m} - P_{Di} \quad \forall \quad i \subset n \cap m \subset C(2)$$

where C is the set of contingencies, m is the contingency parameters and N is the network number of buses. Also the stability limit under steady state and transient disturbance using the N-1 criterion is expressed as;

$$b_k\left(\theta_i - \theta_j\right) \le P_k^{St} \qquad \forall \quad k \in (Lc + Le) \qquad (3)$$

$$b_k^{m}\left(\theta_i^{m} - \theta_j^{m}\right) \le P_k^{Tr} \qquad \forall \quad K \in (Lc + Le) \cap m\, C \qquad (4)$$

where P_k^{St} and P_k^{Tr} are the line *k* ratings during steady and transient states respectively; θ_i^m and θ_j^m are the voltage phase angles during a transient disturbance m; and *Le* is the set of existing lines. *Lc* is the set of candidate. b_k and b_k^m represent the *k*th line admittances in the steady and transient operation modes respectively.
In line with these constraints, Eq. (5) presents the grid optimized performance with respect to a specific and deterministic long term transmission expansion planning for the future grid with investments on renewable energy resources (RER) based distributed generation (DG) technologies and smart devices [16].

$$\begin{aligned}\mathrm{TS_{opt}} = \min_{\mathrm{P_G,I_G,I_T}} \mathrm{E}\, \Big\{ & \textstyle\sum_{ia} \int_{t_o}^{T} e^{-rt}\big[(C_{ia}(P_{ia}(t),t) + \\ & C_{ia}^{G}\left(K_{i,a}^{G}(t), I_{ia}^{G}(t), t\right]dt + \\ & \textstyle\sum_{l} \int_{t_o}^{T} e^{-rt} C_l^{T}(K_l^{T}, I_l^{T}(t), t)dt \Big\}\end{aligned} \qquad (5)$$

where $K_{i,a}^G$ is the amount of installed generation capacity at node *i* and technology *a*, K_l^T is the amount of installed transmission capacity for line *l*, I_{ia}^G is the rate of investment on generation capacity using technology *a,* $I_l^T$is the rate of investment in the transmission lines. $C_{ia}^G(K_{i,a}^G(t), I_{ia}^G(t), t)$ is the cost of investment on technology *a* at node *i*, $C_l^T(K_l^T, I_l^T(t), t)$ is the cost investment in the line *l*. C_{ia} is the cost of generation using technology a at node *i*. $P_{ia}(t)$ is the production using technology *a* at node *i* at time *t*.

2.1 Modelling System State Estimation using PMU and FMU

Before the introduction of SCADA systems, the state of a power system could only be determined by the conventional power flow using raw system data (generation, load, transmission lines and initial bus voltages). Data corruption as a result of human and equipments error has drastically affected the credibility of the static state variable obtained [19]. To overcome this challenge, PMUs are installed on the network which captures data at regular time interval. The statistical data combined with the traditional power flow equations through the state estimation algorithm to obtain accurate real time state variables. If the set of measured quantities is denoted by the vector z, which include measurements of system states (such as voltage and current) or quantities that are functions of system states (such as power flows), then;

$$z^{true} = Ax \qquad (6)$$

where x is the set of system states and A is an n x m matrix. The error vector is the difference between the measured quantities z and the true quantities:

$$e = z - z^{true} = z - Ax \qquad (7)$$

The minimum of the square of the error is desired to negate any effects of sign differences between the measured and true values. Thus, Eq. (8) gives a state estimator problem which endeavors to find the minimum of the squared error, or a least squares minimization [15]:

$$min|e|^2 = e^T.e = \sum_{i=1}^{m}\left[z_i - \sum_{j=1}^{m} a_{ij}x_j\right]^2 \qquad (8)$$

If the standard deviation of the measurements distribution is denoted by σ and the variance is given by σ^2, then it is possible to define the relationship between accuracy and the variance of the each measurement through a weighting matrix;

$$w = \begin{vmatrix} \frac{1}{\sigma_1^2} & 0 & \cdots & 0 \\ 0 & \frac{1}{\sigma_2^2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{1}{\sigma^2} \end{vmatrix} \qquad (9)$$

The weighting matrix assigns priority to each measurement in the degree of accuracy, the estimation procedure can then force the results to coincide thereby generating a more reliable and accurate data. This gives the weighted least squares estimation expressed by Eq. (10) [7].

$$min|e|^2 = e^T.e = \sum_{i=1}^{m} w_i\left[z_i - \sum_{j=1}^{m} a_{ij}x_j\right]^2 \qquad (10)$$

2.2. Modelling power stability with classical control

A power system can be modelled in terms of system state (normal, alert, emergency and In-extremis) and the state variables (voltage magnitude, angles, frequencies and line currents). If x_n is the vector of time invariant state parameters, a dynamic power system can be modelled using ODE as;

$$\dot{x} = F(x) \qquad \dot{x} = Ax \tag{11}$$

where $F(x)$ is a vector of nonlinear functions and A is a coefficient matrix [3].

A closed loop control system with negative feedback for the steady state and transient stability model shown in Fig. 1 where $u(t)$ is a control signal which affects the system to achieve the desired operating state, $z(t)$ is the contingency and $y(t)$ is an output signal to monitor/assess the desired goal is adopted.

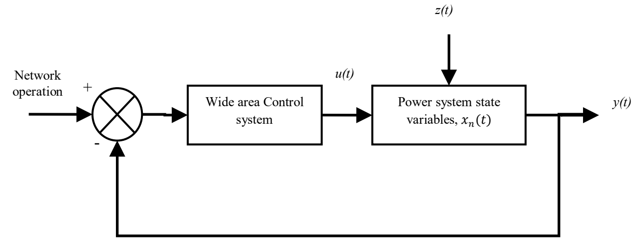

Fig. 1 Closed Loop Power System Control

Therefore incorporating the control signal with the linear dynamic system, Eq. (11) may be rewritten in the following set of differential and algebraic equations (DAE) [13];

$$\dot{x} = Ax + Bu \quad and \quad y = Cx + Du \tag{12}$$

Equation (13) is derived from applying Laplace transform on Eq. (12),

$$X(x) = (sI - A)^{-1}x(0) \tag{13}$$

$$|sI - A| = 0 \tag{14}$$

Assuming that for the characteristic equation given in Eqn.14, the coefficient of A and $|sI - A|$ are real, the solutions $\lambda_1, \lambda_2 \ldots . \lambda_n$ of the characteristic equation are the eigenvalues of the matrix A [8].

3. Test Network

The test network is the Nigerian 40 bus system with 19 generators, 32 loads centres and 66 transmission line links on PSAT toolbox in Matlab. The transmission voltage is 330kV with installed real and reactive loads of 50.63 and 17.28 p.u respectively. The voltage phasors of load centres in the north eastern area of the network (10, 15, 21, 27, and 40) is widely beyond standard value as a result of a non-redundancy and very long transmission links in the area. This situation may lead to non-convergence of the power flow evaluation. As such, reactive power controllers (condenser) are installed on these buses for voltage control as shown in Fig. 2.

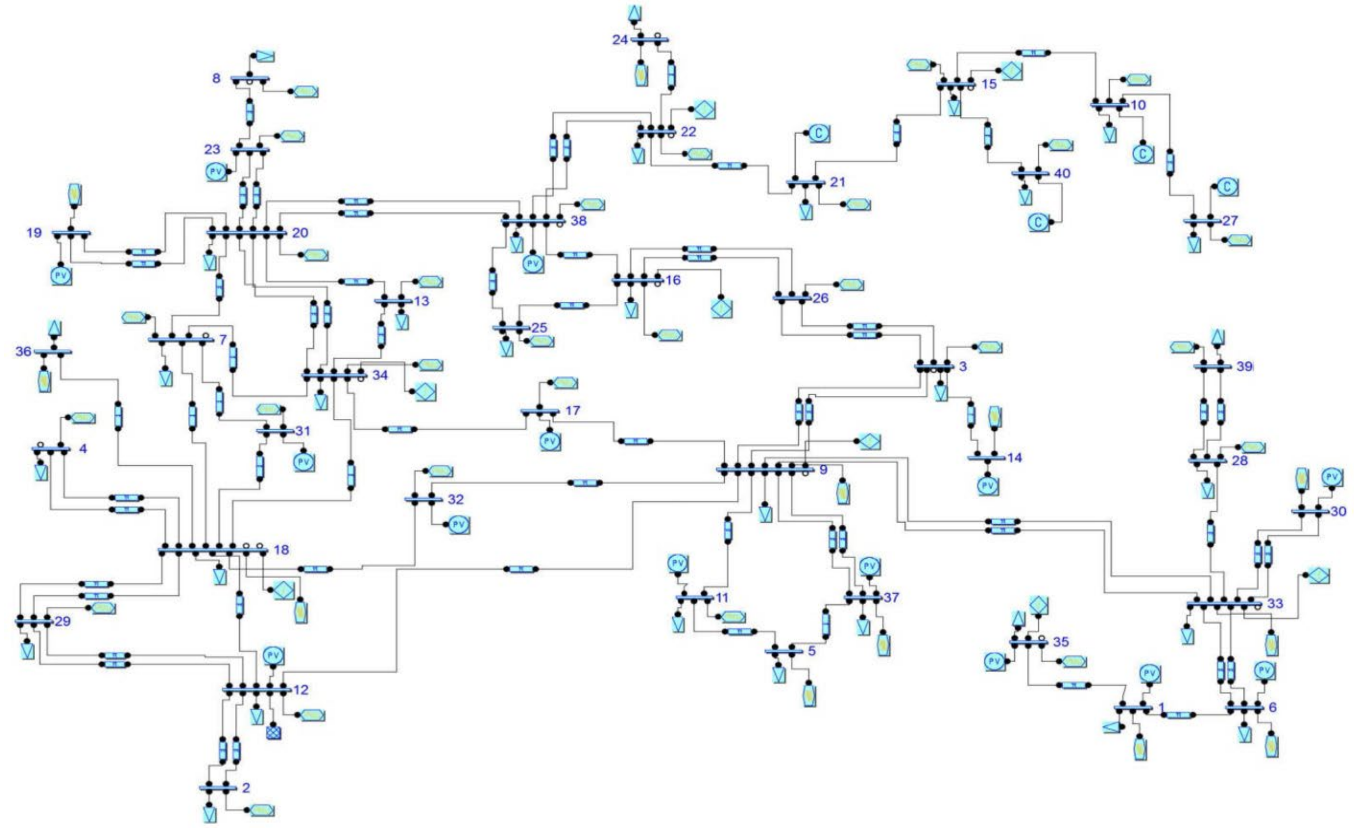

Fig. 2 A 40 Bus Test Network

The system is operated and controlled from eight regional operations centre (ROC) (9, 15, 16, 18, 22, 33, 34, and 35) which represents the system bulk load points strategically sited for optimized performance in terms of communications and coordination between the PMUs and the ROC. The frequency measurement units (FMU) are installed at these ROCs to monitor the system frequencies at specified times under steady state and contingency situations.

4. Results and Discussions

The result of simulative assessment of the voltage and frequency stability of the test system without and with SSE is presented in this section. Figure 3 shows the characteristic behaviour of the network without the installation of PMUs. Where all ROC frequencies are maintained at 1.0 p.u it was observed that buses 24, 28 and 39 are unstable as they exist below the -5% of nominal voltage with a depth of 0.919 p.u.

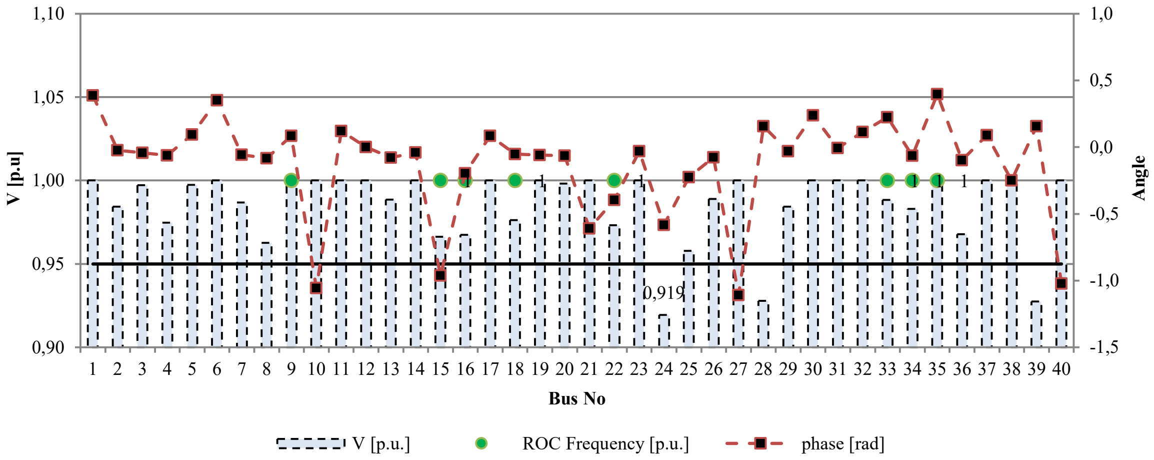

Fig. 3 Network State Variables without Static State Estimation

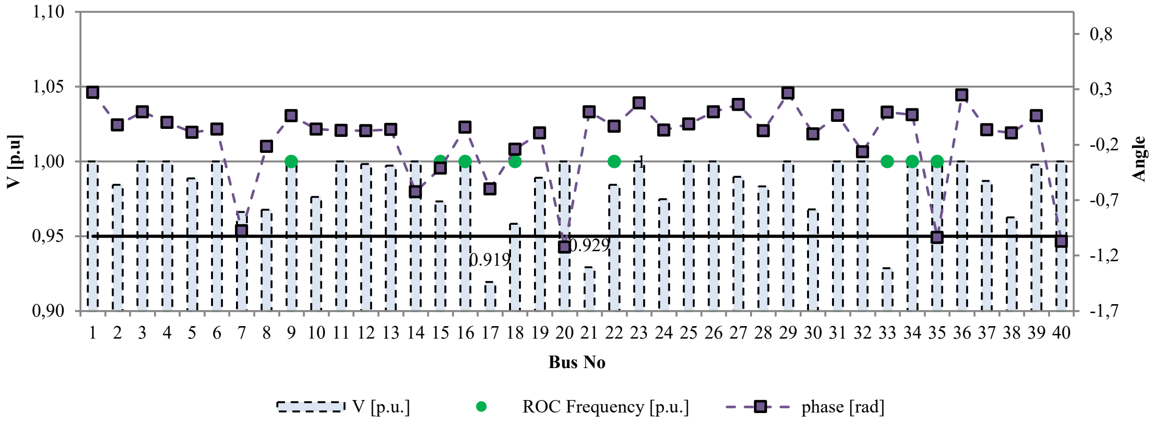

Fig. 4 Network State Variables with Static State Estimation

The true or more accurate performance of the system through the SSE is shown in Fig. 4. The disparities between the critical buses in Figs. 3 and 4 are seen in buses 24, 28, 39 and buses 17, 21 and 33 respectively. It is seen that the frequency parameter of a transmission system is not affected by a PMU based SSE under normal system operation.

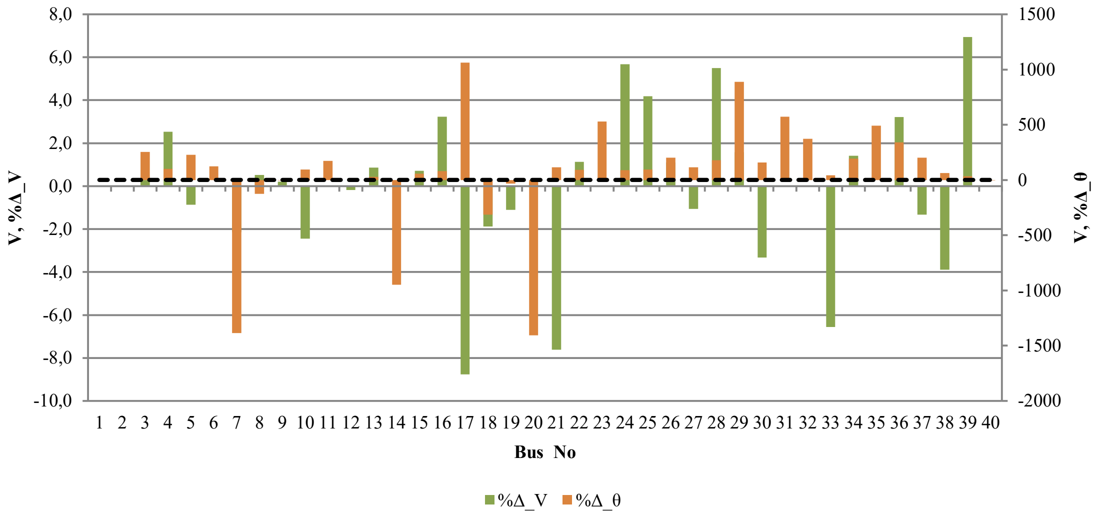

Fig. 5 Obtainable State Parameters Variance under Normal Operation

The difference between the state variables obtained from the network with and without static state estimation implemented through the placement of PMUs is shown in Fig. 5. From the result obtained, it is estimated that 32.5% of all system state variables yielded a percentage difference of greater than 1%. The operational losses of the network under normal state are shown in Fig. 6. The effect of real time and accurate measurement obtained from installed RTUs is evident from the 2.6% and 9.271% reduction in the real and reactive power losses.

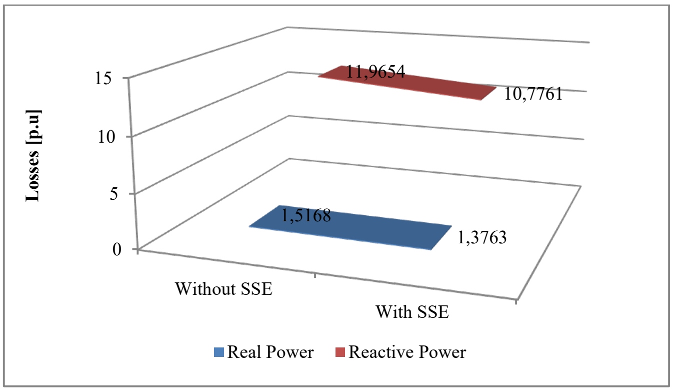

Fig. 6 System Steady State Losses

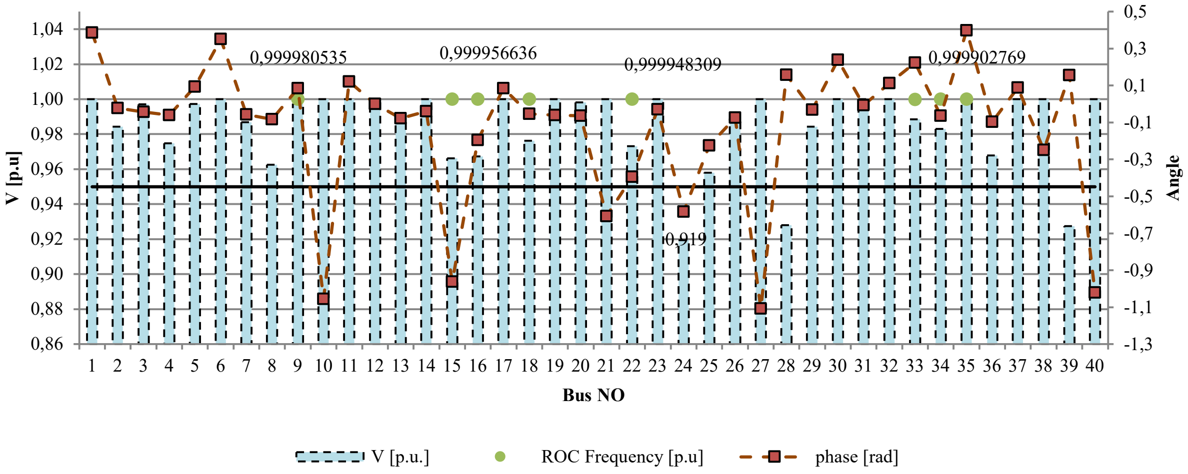

Fig. 7 Network State Variables with Contingency at Bus 18 without PMU

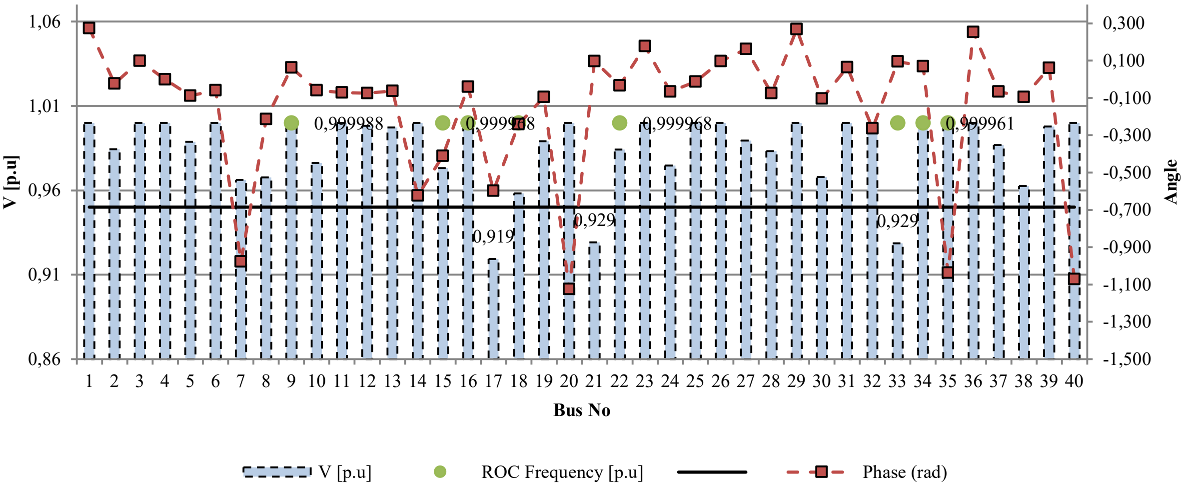

Fig 8: Network State Variables with Contingency at Bus 18 with PMU

The result of the effect of static state estimation on the transmission network under transient stability is presented in Figs. 7 to 10. Buses 18 and 34 are selected for contingency induction due to the reason of maximum effect for the worst case scenario. Analysis of result obtained from inducing a three phase short circuit fault at bus 18 in Fig. 8 substantiates the need for accurate and real time date for proper system operations and planning in order for the system to remain stable under unforeseen contingencies. The response of the system to transient stress is seen in the form of voltage ans frequency instability.

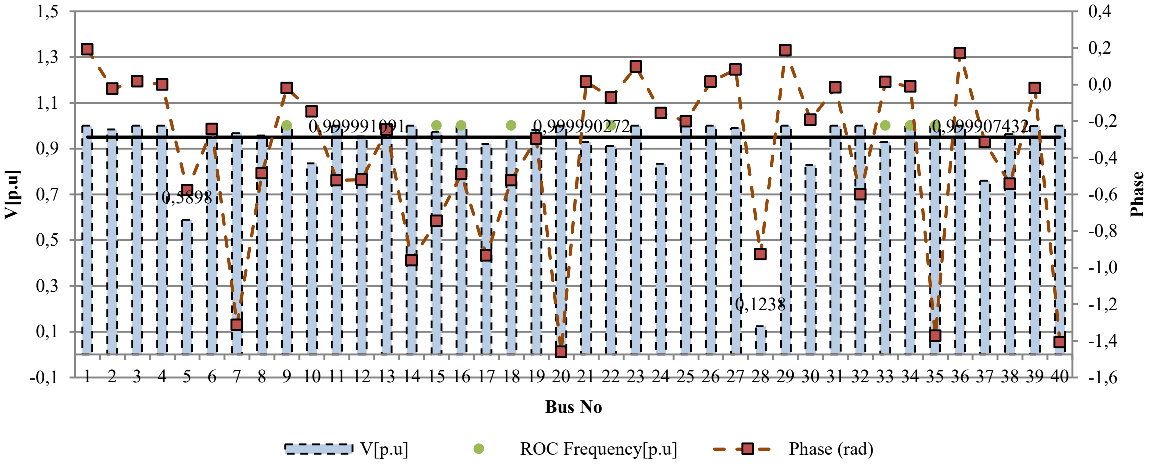

Fig. 9 Network State Variables with Contingency at Bus 33 without PMU

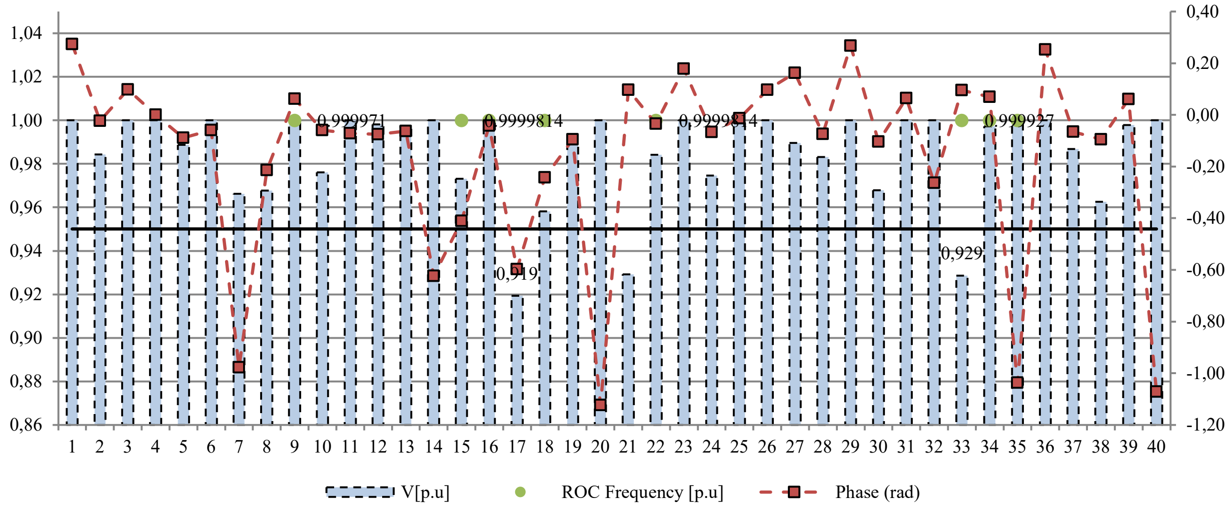

Fig. 10 Network State Variables with Contingency at Bus 33 with PMU

Figures 9 and 10 presents the state variables of the system under transient condition from bus 33 with and without state estimation. Analysis of the result shows that the network would be unstable at the occurrence of fault at this bus. The loss of voltage at bus 5, 28 and 37 would thrust the network into voltage collapse and eventually blackout. Also there may be need for increased generation capacity through distributed generation (DG) penetration in order for the system to maintain stability during contingencies.

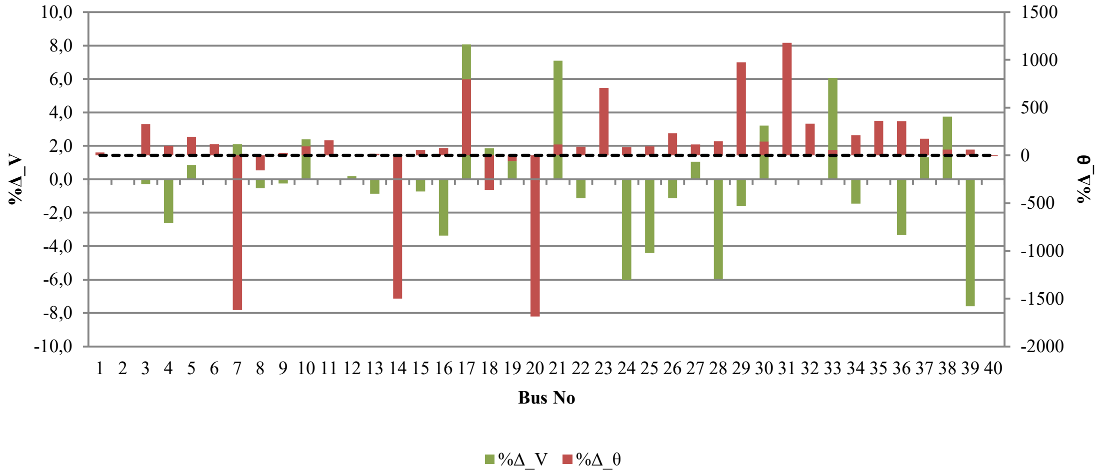

Fig. 11 Obtainable State Parameters Variance under Emergency Operation

The variance of the state variables obtained from simulation of the two evaluation scenario of the network under transient condition is shown in Fig. 11. Analysis shows that 50% of the obtained variables generated a variance greater than 1%. This validates that a system designed and aimed for best performance efficiency cannot rely on incapacitated data for operations and planning. The stability of the system obtained through evaluation of the eigenvalues from the system state space equation in presented in Fig. 12 on the s-plane. As shown in Fig. 12a all eigenvalues exist on the unit circle. In the marginal stability region, any disturbance may cause an eigenvalue to exist outside the unit circle which creates the system instability. The effect of static state estimation (SSE) obtained through the installation of PMUs on the network is seen In Fig. 12b where 50% of the system eigenvalues lie inside the unit circle which makes the system more stable under normal operations.

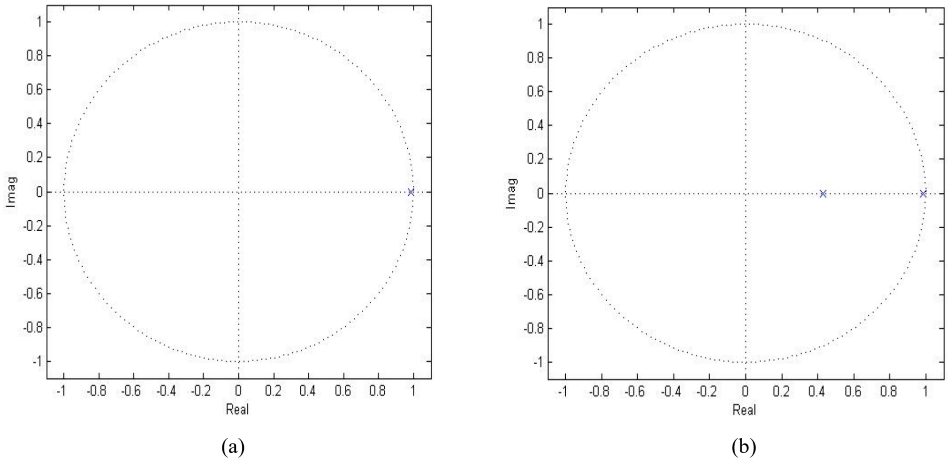

Fig. 12 Stability of System with and without PMU on the S-Plane

5. Conclusions

Power system transients take place in fractions of seconds and give no time for operators to act. Therefore in order to guarantee stability at all times, the system must be reinforced and made robust through the implementation of real time monitoring systems. This research has investigated the effect of static state estimation of the performance of a transmission system using phasor measurement units (PMU) installed at the load points. From the results obtained through this research, the need to operate a power system through a real time monitoring platform cannot be overemphasized. Through state estimation, reliable data for system analysis, operation, planning and forecast can be provided. In the bid to translate the present transmission network into the future grid through the implementation and participation of smart technologies for coordinated control and communication between smart subgrids, it is necessary to evaluate the effect of such devices. Finally, the installation of PMUs on the network has provided the true characterisation of the system state variables and consequently improved the network performance through transmission loss reduction and overall system stability.

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