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RESEARCH ARTICLE

STATE ESTIMATION BY USE OF WLS STATE TECHNIQUE AND PHASOR MEASUREMENT UNIT

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ABSTRACT

The conventional technique for power flow measurement of a network system are bulky in nature. The newer technique of Phasor Measurement Unit would be used for measurement of bus voltage and power flow. On usual, the concept of full weighted least square state estimator is follow a nonlinear technique, but in co-operation with PMUs it may improves the accuracy of the measurement without doing a bulky iteration process. In this paper the way of formation of measurement by using Full weighted least square state estimation and PMU device with conventional method will be investigated. A number of cases are tested by use of PMUs and their effect on variables accuracy on Real Power and Reactive Power flows over a system are demonstrated. The assessment of parameter obtained on IEEE 14 bus and IEEE 30 bus system will be discussed.

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INTRODUCTION

A phasor measurement unit (PMU) (Aminifar *et al*., 2009; Aminifar *et al*., 2011; Cho *et al*., 2001; Dua *et al*., 2006; Ebrahimpour *et al*., 2011; Gou, 2008) endow with synchronised phasor measurements of voltages and currents from widely isolated locations in an electric power grid. Since PMU was invented, there has been growing interest in developing methodologies for finding the minimum number of PMUs for complete system observability. The problem was initially introduced in (Baldwin *et al*., 1993; Madtharad *et al*., 2003; Meshram and Sahu, 2011; Phadke, 2002); then, several approaches, that can be classified into two groups, the meta-heuristic optimisation technique and conventional deterministic techniques, have been proposed. Examples of the meta-heuristic methods include canonical genetic algorithm (Marın *et al*., 2003), non-dominated sorting genetic algorithm (Milosevic and Begovic, 2003), Tabu search (Peng *et al*., 2006), simulated annealing combined with Tabu search (Cho *et al*., 2001), particle swarm optimisation (Hajian *et al*., 2007), adaptive clonal algorithm (Xiaomeng and Jiaju, 2006), differential evolution algorithm (Al-Mohammed *et al*., 2011) and immunity genetic algorithm (Aminifar *et al*., 2009). The disadvantage of such methods is the long execution times, which may restrict their applications to large power systems, and the possibility of obtaining a non-optimal solution. On the other side, several research studies based on deterministic approaches have been developed. For instance, in (Xu and Abur, 2004), the integral programming approach is correlate to the PMU placement problem. A method, using integer linear programming for power networks with and without conventional measurements, was proposed in (Gou, 2008). The model presented in (Gou, 2008) was extended in (Gou, 2008) to consider the zero-injection effect, incomplete observability and measurement redundancy. In (Dua *et al*., 2006), a formulation was planned which applies integral linear programming and incorporates the effect of zero-injection; in addition, a multistage scheduling structure for PMU placement in a given time horizon was suggested. The PMUs placement and conventional flow measurements location are simultaneously considered as decision variables in (Kavasseri and Srinivasan, 2011). The formulation is initially cause as a non-linear integer programming problem and then transformed into an equivalent integer linear programming. The PMU placement problem using integer quadratic programming was discussed in (Chakrabarti *et al*., 2009) without consideration of the effect of the zero-injection buses.

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In (Caro *et al*., 2012), it is presented a participation factor-based approach to optimally allocate a pre-defined number of PMUs throughout decipherable system in order to maximise the accuracy of the estimated state.

The intention of these papers was to find the nominal number of PMUs that ensures full observability without consideration of transmission line outages. Consequently, the substantial optimal placement of PMUs may not guarantee complete system observability in case of any contingency. In order to design a robust wide-area monitoring system (WAMS), which can make sure that the complete system observability will be under the failure of any transmission line or even a PMU, some works have measured power system contingencies and measurement losses (failure of a PMU or its communication links). For instance, in (Sodhi *et al*., 2009) Sodhi *et al*. offered a method for optimal placement of PMUs that ensures system observability under a pre-specified number of critical contingencies, which are identified by performing beforehand a voltage stability analysis. Although such contingencies are critical for the stability of a system, they could have small probability of occurrence; therefore the contingencies by means of higher probability of occurrence and highly negative effect on the system observability could be omitted. In (Chawasak *et al.*, 2007; Zhao *et al*., 2011), a method for the optimal placement of PMUs that considers two types of contingencies (single loss measurement and branch outage) was presented. The methodology uses a sequential addition approach to search of necessary candidates for single measurement of loss and single-branch outage conditions, which are optimised by binary integral programming and a heuristic method. In (Chakrabarti *et al*., 2009), the integer quadratic programming approach was used to diminish the total number of PMUs under an outage of a single transmission line or one PMU; however, a list of individual outages of branch to be considered beforehand. This model, which was based on numerical observability analyses, is computationally expensive. In (Milosevic and Begovic, 2003), an optimal set of PMUs, which maximise the measurement redundancy, was found using a non-dominated sorting genetic algorithm and topological observability. The algorithm starts with a set of PMUs that ensures entire observability of the system and the additional PMUs are added in an iterative way until a predefined measurement redundancy has been achieved. In (Aminifar *et al*., 2010), integer linear programming was proposed for solving the optimal placement of PMU anticipating the losses of a PMU or a line outage. The single line outage effect is added directly to the model by using auxiliary variables. The technique for placing the PMUs in a multiple stages over a given time period that ensures complete power system observability still under a branch outage or a PMU failure was presented in (Sodhi *et al*., 2011). The approach proposed in (Aminifar *et al*., 2010; Chakrabarti *et al*., 2009; Chawasak *et al*., 2007; Madtharad *et al*., 2005; Milosevic and Begovic, 2003; Sodhi *et al*., 2009; Sodhi *et al*., 2011) does not take into account the stochastic nature of power system behaviour, so the WAMS could be designed for ensure observability of either the system under unlikely contingencies or all N − 1 contingencies.

Although the monitoring system may be healthy enough to maintain the system observability anticipating all possible contingencies, the number of PMUs could be very high and the implementation of the system monitoring would be expensive. On the other hand, the random nature of contingencies derives that some transmission lines have higher probability of failure than others. Therefore it is necessary to design a methodology that considers the random nature of the transmission line outages and WAMS component failures. The PMU placement allowing for random operating scenarios and random topologies was initially proposed in (Kamwa and Grondin, 2002). The authors proposed a methodology to find the optimal location of PMUs for wide-area monitoring and control on large disturbances caused in system; the methodology places a least number of PMUs that maximises the useful information to monitor the dynamic performance of system. In (Aminifar *et al*., 2011), Aminifar *et al*. find the optimal number of PMUs to enhance the system observability by considering random component outages. Through an iterative process, author's find the probability of observability associated among all buses, which are averaged to acquire a system index.

This index is subsequently used to select the best solution from all their possible ones. Although author also consider casual outages of the WAMS components, and methodically reliable evaluation methods used to calculate the probability of observability, the algorithm requires finding all the optimal solutions of the PMU placement problem, which might be very large for comparatively large-scale systems with thousands of buses. The approach proposed in our papers avoid finding of the entire optimal solutions, it defines the WAMS reliability as the probability of observing all the buses under N − 1 contingencies and it finds the optimal solution without an exhaustive search of the possible PMU placements. The conventional processes of measurement are too iterative and bulky in nature for the measurement of power flow and voltages on system buses. The full weighted least square state technique (Abur and Exposito, 2005; Kumar Jitender, 2016; Kumar Jitender *et al*., 2012; Phadke *et al*., 2009; Rahman *et al*., 2001) is a nonlinear equation but with first order Taylor series become a linear equation. Some research work are already conducted in formulation of a relation between full weighted least square state and PMUs. The natural technique for measurement of parameters will treat PMU as additional computational problem on measurement and calculation. The problem of finding optimal location of PMU placement strategy for state estimation of power system is investigated. This paper imitate the measurement accuracy with or without using PMU on state estimation parameters. In case 1, the state estimation of system by conventional process without using any PMU device. But in case P, the measurement of parameter done with the use of all PMUs (Kumar Jitender *et al*., 2012; Miljanic *et al*., 2012) is discussed.

II. Full weighted least square state estimation method

Let us consider the set of measurements given by the vector z are as:

$$z = \begin{matrix} z_1 \\ z_2 \\ z_3 \\ \cdot \\ \cdot \\ z_m \end{matrix} = \begin{matrix} {}_1(x_1, x_2, x_3, \dots \dots \dots .. x_n) \\ {}_2(x_1, x_2, x_3, \dots \dots \dots .. x_n) \\ {}_3(x_1, x_2, x_3, \dots \dots \dots .. x_n) \\ \cdot \\ \cdot \\ {}_m(x_1, x_2, x_3, \dots \dots \dots .. x_n) \end{matrix} = \begin{matrix} e_1 \\ e_2 \\ e_3 \\ \cdot \\ \cdot \\ e_m \end{matrix}$$ = h(x) + e (1) Where:

$${}^T = ({}_1\ x\ ,\ {}_2\ x\ ,\ {}_3\ x\ , \dots \dots \dots ..\ {}_m\ x\ ) \quad (2)$$

h_i (x) is the nonlinear function relating measurement i to the state vector x

$x^T = (x_1, x_2, x_3, \dots \dots \dots .. x_n)$ is the system state vector
$e^T = (e_1, e_2, e_3, \dots \dots \dots .. e_m)$ is the vector of measurement errors.
The WLS estimator (1)(25) will minimize the following objective function:

$$J\ x\ = \sum_{i=1}^{m} \frac{(z_i - h_i\ x\ )^2}{R_{ii}} = (z - \quad x\ )^T R^{-1} (z - \quad x\ ) \quad (3)$$

At the minimum value of the objective function, the first-order optimality conditions have to be satisfied. These can be expressed in compressed form as follows:

$$g\ x\ = \frac{\partial J(x)}{\partial x} = -H^T\ x\ R^{-1}\ z - \quad x\ = 0 \quad (4)$$

The non-linear function g(x) can be expanded into its Taylor series (Abur and Exposito, 2005; Kumar Jitender, 2016; Kumar Jitender *et al*., 2012; Phadke *et al*., 2009; Rahman *et al*., 2001) around the state vector x^k neglecting the higher order terms.

$$g\ x\ = g\ x^k\ +\ G\ x^k\ \ x - x^k\ +\ \dots \dots .. = 0 \quad (5)$$

An iterative solution scheme known as the Newton method is used to solve above equation:

$$x^{k+1} = x^k - \ (G\ x^k\ )^{-1} . g(x^k) \quad (6)$$

where, k is the iteration index and x^k is the solution vector at iteration k . G(x) is called the gain matrix and it expressed by:

$$G\ x\ = \frac{\partial g(x)}{\partial x} = H^T(x^k) R^{-1}\ H(x^k) \quad (7)$$

$$g\ x^k\ = -H^T(x^k) R^{-1}\ \ z - \quad x^k \quad (8)$$

Generally, the gain matrix is quite sparse and decomposed into its triangular factors. At each iteration k, the following sparse linear set of equations are solved using forward/backward substitutions, where

$$\Delta x^{k+1} = \ x^{k+1}\ -\ x^k:$$
$$(G\ x^k\ )\Delta x^{k+1} = H^T(x^k) R^{-1}\ \ z - \quad x^k\ \ = \ H^T(x^k) R^{-1} \Delta z^k \quad (9)$$

These iterations are going on until the maximum variable difference satisfies the condition, 'Max $\left|\Delta x^k\right| < £$ '.

III. Conventional method

The conventional method (Abur and Exposito, 2005; Kumar Jitender, 2016; Kumar Jitender *et al*., 2012; Phadke *et al*., 2009; Rahman *et al*., 2001) of measurement is basically consider relation of power injection or power flow with respect to line current and line voltage are as

$$I_{ij} = \ \overline{((V_i^2 +\ V_j^2 - 2V_iV_j\ Cos\theta_{ij})(g_{ij}^2 +\ b_{ij}^2))}$$
$$= \frac{\sqrt{P_{ij}{}^2 + Q_{ij}{}^2}}{V_i} \quad (10)$$

The Real and Reactive Power injection at bus i can be expressed as,

$$P_i = |V_i| \sum_{j=1}^{N} |V_j| (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \tag{11}$$

$$Q_i = |V_i| \sum_{j=1}^{N} |V_j| (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \tag{12}$$

The Real and Reactive Power Flow from bus i to bus j are as,

$$P_{ij} = |V_i|^2 (g_{si} + g_{ij}) - |V_i| |V_j| (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}) \tag{13}$$

$$Q_{ij} = -|V_i|^2 (b_{si} + b_{ij}) - |V_i| |V_j| (g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij}) \tag{14}$$

So the structure of the measurement of Jacobian H will be as

$$H = \begin{bmatrix} \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \\ \frac{\partial I_{mag}}{\partial \theta} & \frac{\partial I_{mag}}{\partial V} \\ 0 & \frac{\partial V_{mag}}{\partial V} \end{bmatrix} \tag{15}$$

IV. WLS with conventional method

A PMU will measure multiple current with one voltage phasors. The transmission line normally formed as pie network due to their benefit on system parameters. Fig. 1 shows a 4-bus system example which has single PMU at bus 1. It has one voltage phasor measurement and three current phasor measurements, namely $V_1 \angle \theta_1$, $I_1 \angle \delta_1$, $I_2 \angle \delta_2$ and $I_3 \angle \delta_3$

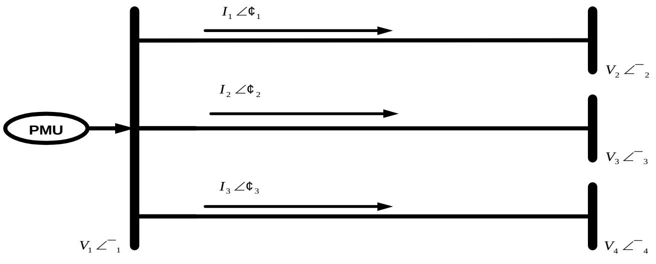

Fig.1. Single PMU Measurement Model

If we define y as the series admittance and y_{shunt} as the shunt admittance, current phasor measurements can be written in rectangular coordinates as shown in Fig 2.

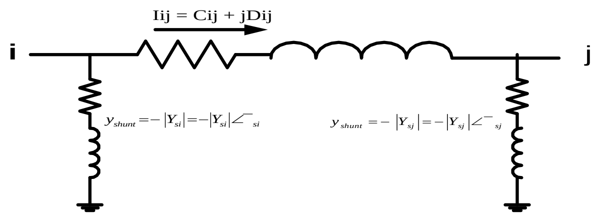

Fig.2. Transmission Line Model

The expressions for C_{ij} and D_{ij} are:

$$C_{ij} = \left|V_i Y_{si}\right| \cos(\delta_i + \theta_{si}) + \left|V_j Y_{ij}\right| \cos(\delta_j + \theta_{ij}) - \left|V_i Y_{ij}\right| \cos(\delta_i + \theta_{ij}) \tag{16}$$

$$D_{ij} = \left|V_i Y_{si}\right| \sin(\delta_i + \theta_{si}) + \left|V_j Y_{ij}\right| \sin(\delta_j + \theta_{ij}) - \left|V_i Y_{ij}\right| \sin(\delta_i + \theta_{ij}) \tag{17}$$

where, the state vector is given as:

$$x = [\left|V_1\right| \angle 0^0, \left|V_2\right| \angle \delta_2, \left|V_3\right| \angle \delta_3 \ldots\ldots\ldots \left|V_N\right| \angle \delta_N]^T \tag{18}$$

The ingress of the measurement of Jacobian H corresponding to the real and reactive parts of the current phasors are as:

$$\frac{\partial C_{ij}}{\partial V_i} = \left|Y_{si}\right| \cos(\delta_i + \theta_{si}) - \left|Y_{ij}\right| \cos(\delta_i + \theta_{ij}) \tag{19}$$

$$\frac{\partial C_{ij}}{\partial V_j} = \left|Y_{ij}\right| \cos(\delta_j + \theta_{ij}) \tag{20}$$

$$\frac{\partial C_{ij}}{\partial \delta_i} = -\left|V_i Y_{si}\right| \sin(\delta_i + \theta_{si}) + \left|V_i Y_{ij}\right| \sin(\delta_i + \theta_{ij}) \tag{21}$$

$$\frac{\partial C_{ij}}{\partial \delta_j} = -\left|V_j Y_{ij}\right| \sin(\delta_j + \theta_{ij}) \tag{22}$$

$$\frac{\partial D_{ij}}{\partial V_i} = \left|Y_{si}\right| \sin(\delta_i + \theta_{si}) - \left|Y_{ij}\right| \sin(\delta_i + \theta_{ij}) \tag{23}$$

$$\frac{\partial D_{ij}}{\partial V_j} = \left|Y_{ij}\right| \sin(\delta_j + \theta_{ij}) \tag{24}$$

$$\frac{\partial D_{ij}}{\partial \delta_i} = \left|V_i Y_{si}\right| \cos(\delta_i + \theta_{si}) - \left|V_i Y_{ij}\right| \cos(\delta_i + \theta_{ij}) \tag{25}$$

$$\frac{\partial D_{ij}}{\partial \delta_j} = \left|V_j Y_{ij}\right| \cos(\delta_j + \theta_{ij}) \tag{26}$$

The measurement vector z contains δ, C_{ij}, D_{ij} as well as the power injections, power flows and voltage magnitude measurements.

$$z = [P_{inj}{}^T, Q_{inj}{}^T, P_{flow}{}^T, Q_{flow}{}^T, \left|V\right|^T, \delta^T, C_{ij}{}^T, D_{ij}{}^T]^T \tag{27}$$

Generally, measurements obtained from PMUs are more precise and accurate as compared to the conventional measurements. Therefore, measurements done with the help of PMUs are expected to generate more precise and accurate result as estimated by conventional methods.

V. State estimation with PMUs

The state vector and measurement data can be expressed in rectangular coordinates. The voltage measurement ($V = \left|V\right| \angle \theta$) can be expressed as (V = E + jF), and the current measurement can be expressed as (I = C + jD). Where ($g_{ij} + jb_{ij}$) is the series admittance of the line and ($g_{si} + jb_{si}$) is the shunt admittance of the transmission line. Line current flow I_{ij} can be expressed as a linear function of voltages.

$$\begin{aligned} I_{ij} &= [(V_i - V_j) \times (g_{ij} + jb_{ij})] + [V_i \times (g_{si} + jb_{si})] \\ &= V_i \times [(g_{ij} + jb_{ij}) + (g_{si} + jb_{si})] - V_j \times (g_{ij} + jb_{ij}) \end{aligned} \tag{28}$$

The measurement vector z is expressed as z = h(x) + e, (where x is a state vector, h(x) is a linear equations matrix, and 'e' is an error vector). In rectangular coordinates:

$$z = (Hr + jHm)(E + jF) + e \tag{29}$$

where, $H = Hr + jHm$, $x = E + jF$ and $z = A + jB$.

A and B are expressed by:

$$A = Hr \times E - Hm \times F \tag{30}$$

$$B = Hm \times E + Hr \times F \tag{31}$$

In matrix form,

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} Hr & -Hm \\ -Hm & Hr \end{bmatrix} \begin{bmatrix} E \\ F \end{bmatrix} + e \tag{32}$$

Then, the estimated value $\hat{x} = \hat{E} + j\hat{F}$ can be obtained by solving the linear equation below:

$$\Delta\hat{x} = (H^T R^{-1} H)^{-1} H^T R^{-1} \Delta z = G^{-1} H^T R^{-1} \Delta z \tag{33}$$

If we define the linear matrix H_{new} as

$H_{new} = \begin{bmatrix} Hr & -Hm \\ -Hm & Hr \end{bmatrix}$, then the above equation can be rewritten by:

$$\hat{x} = \begin{bmatrix} \hat{E} \\ \hat{F} \end{bmatrix} = (H_{new}{}^T R^{-1} H_{new})^{-1} H_{new}{}^T R^{-1} \begin{bmatrix} A \\ B \end{bmatrix} \tag{34}$$

Therefore, the equation for rectangular formed variable $\hat{x}$ can be given by the rectangular forms of H matrix and z vector. In respect of the system accuracy and reliability, PMU can deliver more precise measurement data. Several cases to be tested with PMUs added to the conventional measurement set.

The simulations and analysis of different cases are as shown in Table 1 are done with several IEEE bus systems in the next section.

Table 1. Different cases PMU addition in IEEE System

Cases	Measurements
1	Conventional with No PMUs
P	Only PMUs

VI. Simulation results

For investigate the system accuracy with or without PMU on system variables, some cases are tested with the help of MATLAB software. The testing parameters are available on conventional process with or without PMU.

Table 2. PMU Locations for Each IEEE System

Type of System	PMU locations at Bus
IEEE 14 System	Bus 2, 3, 6, 8, 14
IEEE 30 System	Bus 2, 5, 8, 11, 13, 19, 23, 30

The circuit diagram will be shown as in Fig.3 and Fig.4 for IEEE 14 bus and IEEE 30 bus system respectively.

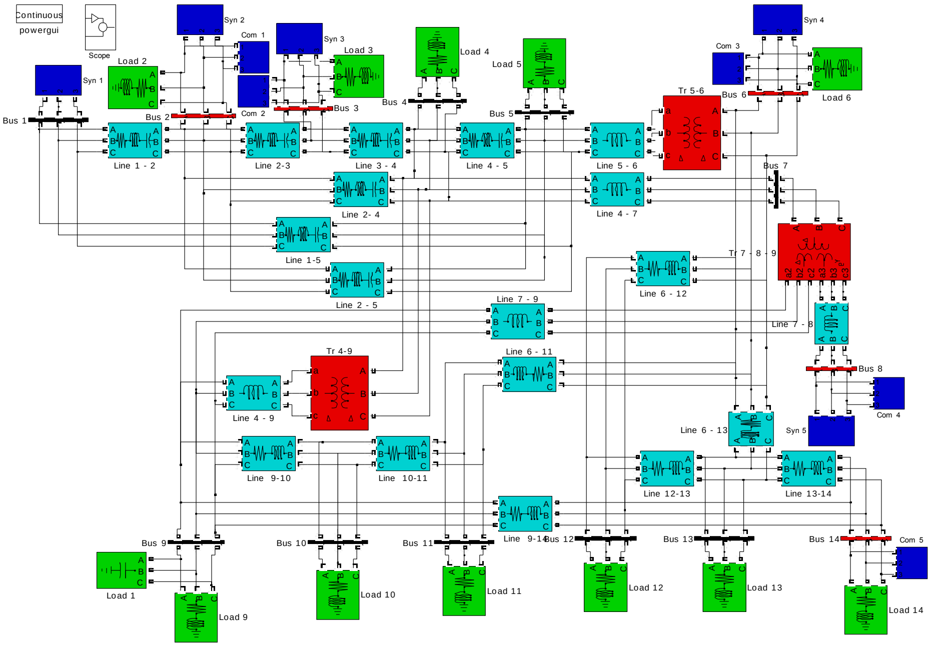

Fig.3. IEEE 14 Bus System

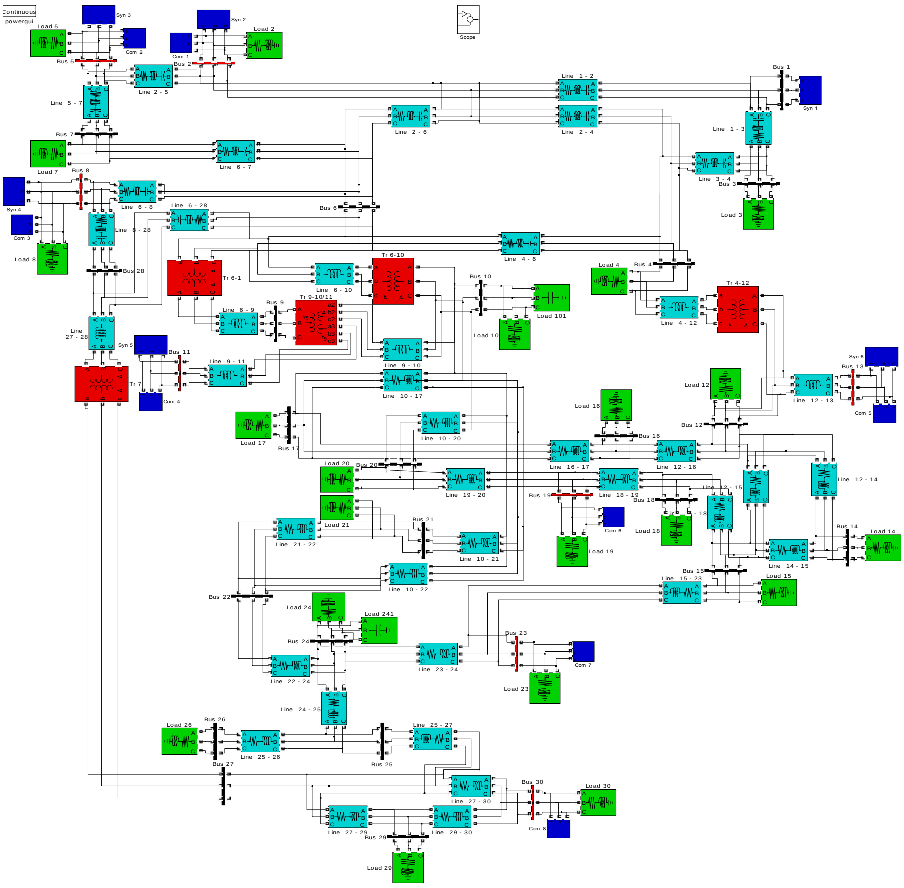

Fig.4. IEEE 30 Bus System

In this segment, IEEE 14 bus system (Kumar Jitender, 2016; Kumar Jitender *et al*., 2012; http://www.phasor rtdms.com) and IEEE 30 bus system (Ebrahimpour *et al*., 2011; Kumar Jitender *et al*., 2013) are tested with their with or without PMU cases to find out the consequences of the PMUs to the precision of the estimated variables. The parameters measured are Real Power and Reactive Power (flow & injected) measurements. The variation of parameters with or without PMU easily reflected in the fig.5 – 12 as below:

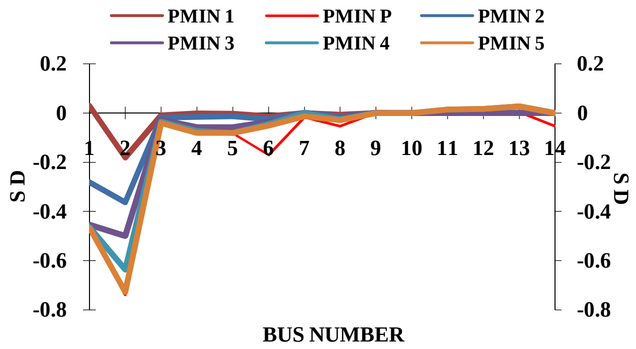

Figure 5. Graph P (SD) vs Bus Number

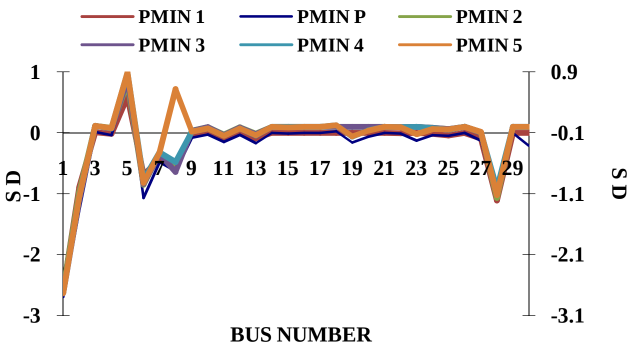

Figure 6. Graph P (SD) vs Bus Number

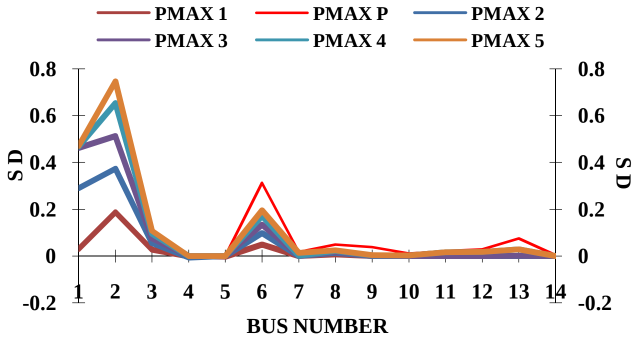

Figure 7. Graph P (SD) vs Bus Number

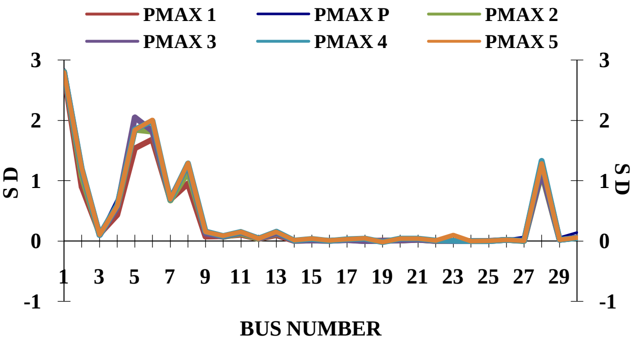

Figure 8. Graph P (SD) vs Bus Number

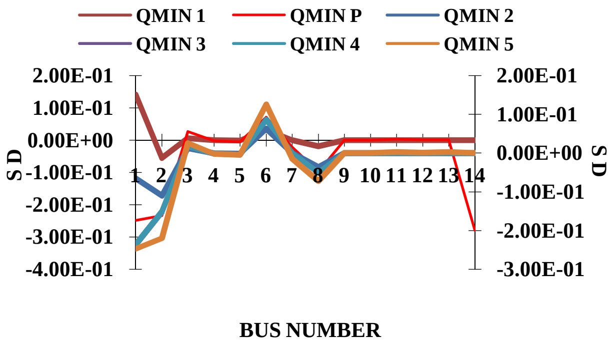

Figure 9. Graph Q (SD) vs Bus Number

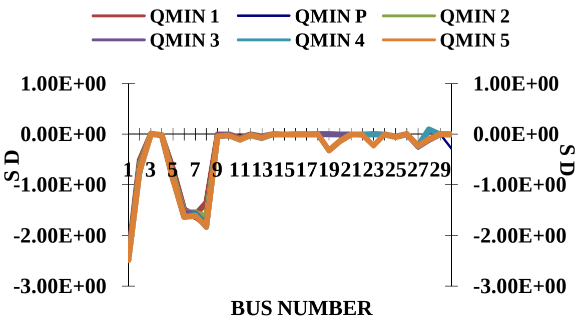

Figure 10. Graph Q (SD) vs Bus Number

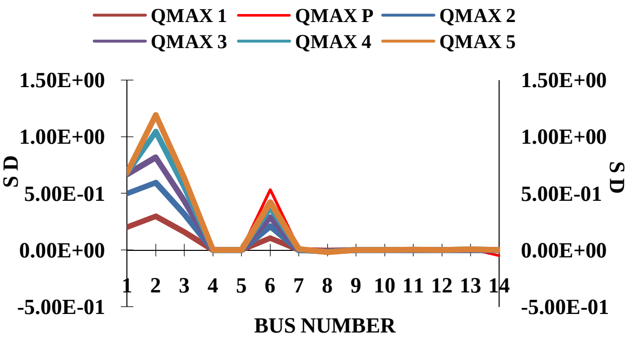

Figure 11. Graph Q (SD) vs Bus Number

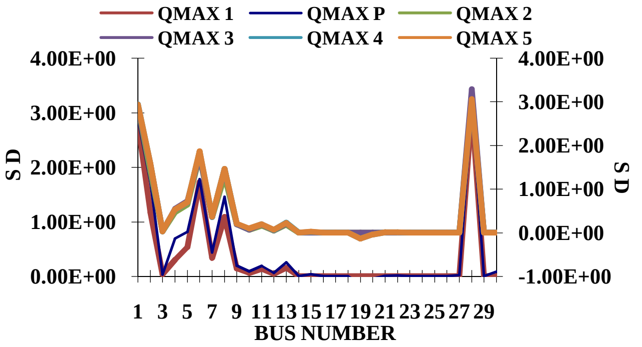

Figure 12. Graph Q (SD) vs Bus Number

Table 3. Average Std. Dev. of the Estimated Variables

Type of Var.	Type of System	Case 1		Case P	
		Min	Max	Min	Max
Real Power (P)	14 Bus	-0.0132	0.02107	-0.1210	0.1349
	30 Bus	-0.2006	0.36544	-0.2544	0.430102
Reactive Power (Q)	14 Bus	0.00754	0.05437	-0.0563	0.216506
	30 Bus	-0.2845	0.38847	-0.3699	0.45857

The table 3 shows that how the S.D. values at each case are increases as compared to the S.D. of ‘Case P’. In IEEE 30 bus system, the S.D. of the estimated current magnitude is approximately 0.02663 when there is no PMUs, but after adding PMUs to the system, it becomes nearly 0.046256. It means that the S.D. of ‘No PMUs’ is increased by adding of PMUs. The interesting thing is that the standard deviation increasing as increasing PMU. Therefore, this result shows that the effectively installing of PMUs is reducing the chances of error in measurement of estimated variables.

The Average Current and Average Real Power (flow & injected) are analyze on IEEE 14 Bus & IEEE 30 Bus System (where 141 & 301 for without PMU device and 14P & 30P for with PMU device). The variation of these parameters with or without PMU reflected in the fig.13 – 20 as below:

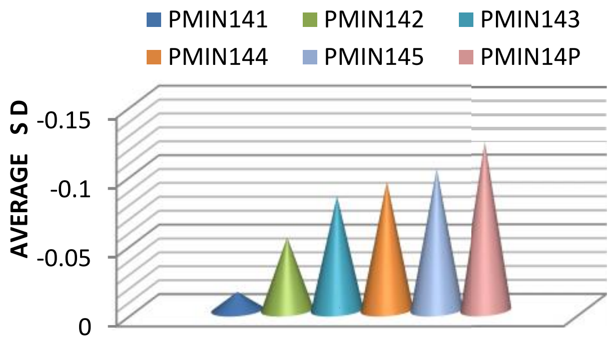

Fig. 13. Real Power(for 14 Bus System

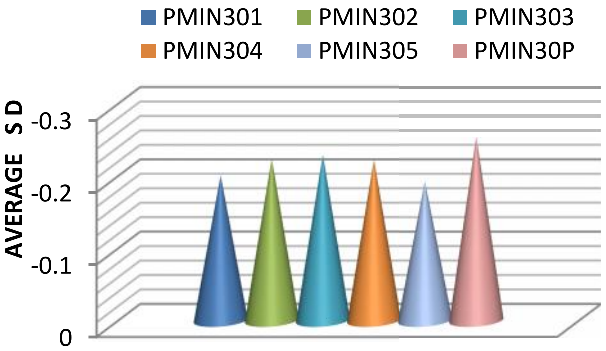

Fig. 14. Real Power for 30 Bus System

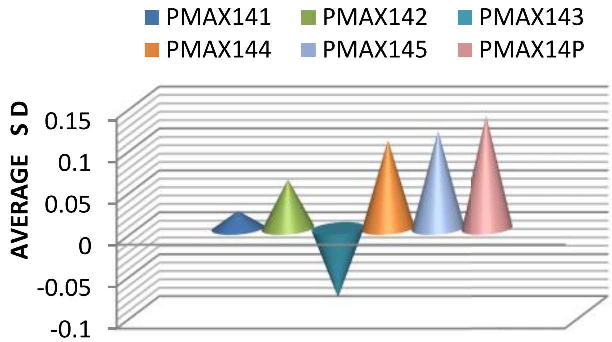

Fig. 15. Real Power for 14 Bus System

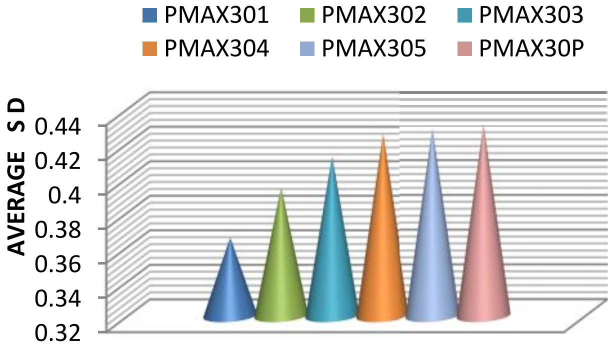

Fig. 16. Real Power for 30 Bus System

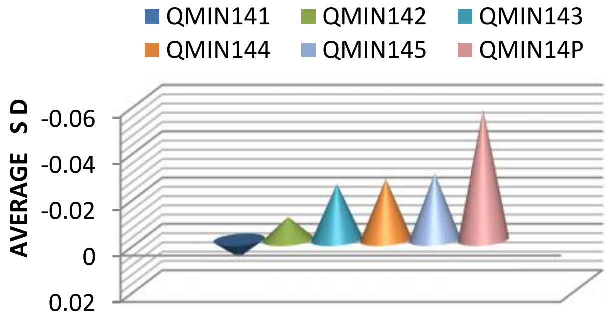

Fig. 17. Reactive Power for 14 Bus System

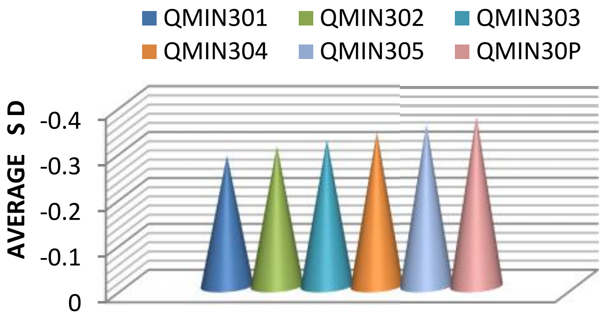

Fig. 18. Reactive Power for 30 Bus System

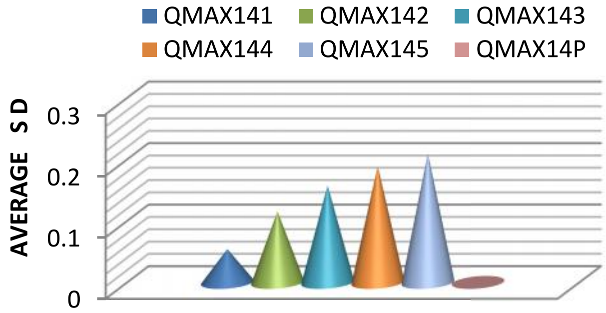

Fig. 19. Reactive Power for 14 Bus System

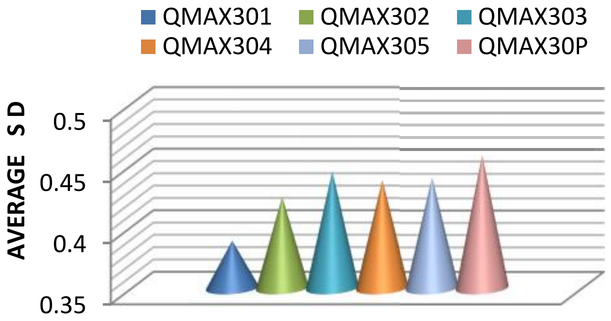

Fig. 20. Reactive Power for 30 Bus System

VII. Conclusion

This paper proposes an integral linear technique for an optimal contingency - constrained related to PMU placement in electric networks. The methodology also considers the failure probability of the system components that might be prevent operation of the PMUs. The approach of selecting an appropriate quantity of PMUs to meet the desirable observability and reliability criteria on considering N − 1 contingencies. The intention of the classical optimisation model was modeled in order to find solutions that increase the availability of the measuring equipment. Therefore the model will locates the PMUs at specific buses which result in the best global reliability of the WAMS. Results showed that the proposed model finds the least number of PMUs to make sure a desired level of reliability, which increase the monitoring system robustness bearing in mind the most likely transmission lines outages. The PMU availability for measuring channels was incorporated in the model, so more realistic and useful results can be obtained. Results show that the system observability is reached and WAMS reliability is also improved with increase of PMUs. The objective function was formulated in such a way that the minimisation of the number of PMUs has a high priority with the maximisation of covered contingencies and the channel limit constraint increase the number of PMUs as per the boost of power required by respective load buses.

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