Critical Measurement Set with PMU for Hybrid State Estimation

K.Jamuna and K.S.Swarup
Department of Electrical Engineering
Indian Institute of Technology, Madras
Chennai 600036
Email: jamram_k@yahoo.co.in

Abstract—This paper presents a method for designing minimal measurement set that include both Supervisory Control And Data Acquisition (SCADA) and Synchronized Phasor Measurements Units (SPMU) data for a Hybrid State Estimation (HSE). The optimal location of Phasor Measurement Units (PMU) is performed by Binary Integer Linear Programming (BILP). Among these PMUs, the highest priority indexed PMUs are selected for implementation and the remaining unobservable buses are made to be observable using traditional measurements. An augmented bus matrix corresponds to each unobservable node in a network is calculated. Power Injection and Power Flow measurements are to be placed in the unobservable node and branch of the power system network based on the fixed index value. The hybrid measurement jacobian matrix is formed with the critical measurements and system observability has been proved numerically. System states are evaluated using the chosen measurements by applying Hybrid State Estimation and are validated through the simulations carried out on standard IEEE systems and New England systems and the results are compared.

Index Terms—Hybrid State Estimation, SCADA, Synchro Phasor Measurement Units, Binary Linear Integer Programming, Hybrid Measurement Jacobian Matrix.

I. INTRODUCTION

State Estimation is the process of assigning a value to an unknown system variables based on the measurements obtained from the system. State estimator has been widely used as an important tool for online monitoring, analysis and control of power systems. It is also exploited to filter redundant data, to eliminate incorrect measurements and to produce reliable state estimates. Entire power system measurements are obtained through RTU (Remote Terminal Unit) of SCADA systems which have both analog and logic measurements. Logic measurements are used in topology processor to determine the system configuration. State estimator uses a set of analog measurements such as bus voltage magnitude, real power injections, reactive power injections, active power flow, reactive power flow and line current flows along with the system configuration. Therefore the measurement placement becomes an important problem in SE requires sufficient measurements.

Optimal meter placement of Traditional State Estimation (TSE) for maintaining observability has been proposed by many researchers. In order to reduce the metering cost, meters are to be placed only at the essential location in the system. A topological algorithm proposed by Nucera [1]. Baran has developed a method for choice of measurements and loss of RTUs [2]. Bei Gou and Ali abur have contributed an algorithm for meter placement for network observability ([3] - [4]). In addition to the observability bad data measurements have been done in [5]. Optimal meter placement during contingencies are also presented in [6]. Simulated annealing is also used for obtaining optimal location of meters [7]. Static state estimation is performed based on singular value decomposition [8], which could identify unobservable islands in the system.

The synchronized phasor measurements make significant improvements in control and protection functions of the entire power system and also improves the accuracy of state variables. The PMU is a device capable of measuring voltage and current phasor in a power system. Synchronism among phasor measurements is achieved using a common synchronizing signal from Global Positioning Satellite (GPS) [9]. Many researchers have focused on the optimal location of PMU for system to be observable. Tabu search algorithm is proposed to identify the optimal placement of PMU. Bad data detection is done along with optimal PMU placement by Jain Chan and Ali abur [10]. Bei Gou [11] is proposed a new integer linear programming approach for optimal PMU placement with and without considering traditional SCADA measurements. In earlier work, loss of measurements are not included, it has been done in [6]. Recently placement of PMU problem has been solved optimally using differential evolution [12]. From early days of Schweppes [13], developments of SE were begun. The number of PMU requirements to meet sufficient measurements in a power network poses a problem. Due to the factor of price, technology, communication ability the PMU could not be implemented at all the buses in the system. When few phasor measurements are added to sufficient numbers of traditional measurements, improvements can obtained [14].

In this paper, a new method has been proposed for the selection of PMU, Power Flow measurements and Power Injection measurements, such that the entire power network is observable. Only the bus - branch model of the network is needed to identify the minimum PMUs, traditional measurements and their locations. Using these measurements, system states have been evaluated using Hybrid State Estimation. A step by step procedure for replacement of SCADA by PMU has been proposed here.
The organization of the paper is as follows. Section II talks about the selection of a critical measurement set including both PMU and SCADA measurements, which explicates in two stages. The system observability has been verified numerically in the third stage. Hybrid State Estimation and its formulation elucidates in Section III. Section IV shows the chosen measurement sets of test systems and simulation results of state estimation tested on IEEE standard systems. Finally, concluding remarks are given in Section V.

II. CRITICAL MEASUREMENT SETS

The observability of a power system depends on the number of measurement data. Meter location of SE is very essential in a power system network. The number of measurements have been increased, which improves the observability but cost increased. Therefore enough measurements have been identified to estimate states. In practice, PMUs needed to be installed in the power system network which already monitored by the traditional measurements. Suppose a PMU is installed at a particular location, the identification of essential traditional measurements have to be monitored is performed in this paper. If any one the chosen measurements is removed, then the system become unobservable. Therefore the selected measurements are named as critical measurements.

In the first stage, optimal location of PMU is identified by binary linear integer programming [11] to make the system to be observable. Priority Index (PI) is defined for each PMU based on number of buses to be observed using that particular PMU. Among these optimally located PMUs, certain PMUs (0.1 times of network buses) are chosen for implementation according to their PI. The remaining buses are considered to be unobservable or remaining system are named as unobservable island.

In the second stage, the unobservable island is made to be observable using power injection and power flow measurements. An augmented matrix \( P_{aug} \) of each network buses are evaluated. The elements of \( P_{aug} \) corresponds to the unobservable node is more than the Fixed Index (FI) value. Power Injection measurement \( \textbf{P}_{inj} \) is placed at that node. Power Flow measurement \( \textbf{P}_{pf} \) must be positioned in the branch which is connected to the unobservable node having a less fixed index.

In the third stage, the network observability checking is performed. It determines whether the selected measurements are able to estimate unique solution of SE. The hybrid jacobian measurement matrix \( \textbf{C}_h \) is formed using the above selected measurements and the rank of this matrix \( R_{C_h} \) is found. The working of the proposed strategy is shown as a flowchart in fig. 1.

A. Selection of PMU measurements

The PMU is able to measure the voltage phasor of the installed bus and current phasor of the lines connected to this bus. In the first step, the optimal location of PMU is done using binary integer linear programming. The PMU placement problem can be formulated as follows:

\[
\min \sum_{i=1}^{n} s_i \quad (1)
\]

S.T.
\[
A_{pmu} S \geq B_{pmu}
\]

\[
S=[s_1, s_2, \ldots, s_n]^{T}
\]

\[
s_i \in \{0, 1\}
\]

\( B_{pmu} \) is a unit vector (\( n \times 1 \)) and \( s_i \) is the PMU placement variable. \( n \) is number of buses in a system. The elements of \( A_{pmu} \) can be written as follows,

\[
a_{uv} = \begin{cases} 
1, & \text{if } u=v \\
1, & \text{if } u \text{ and } v \text{ are connected} \\
0, & \text{otherwise}
\end{cases}
\]

In the second step, the priority index is estimated for each optimally located PMU using eqn. (2). Here, the number of PMU for implementation is chosen only a 10% of the network buses in the system from optimal PMU set \( O_{pmu} \). Buses with high value PI values are preferred to put into practice. The number of unobservable buses or unobservable islands are also identified. In this island, SCADA measurements are going to be placed. The priority index are given below,

\[
PI(j) = N_{obs}(j)/r;
\]

where

\( \text{Pl}(j) \) Priority Index of \( j^{th} \) PMU

\( N_{obs}(j) \) Number of buses to be observed by \( j^{th} \) PMU
A PMU placed at a particular bus measures both voltage phasor of that bus and current phasor of the lines connected to that bus. A linearized measurement jacobian of PMU ($C_{pmu}$) is shown below.

\[
\begin{pmatrix}
\delta_i & \delta_j & \delta_k & \cdots & \delta_n \\
1 & 0 & 0 & 0 & 0 & 0 \\
I_{jk} & 0 & 1 & 0 & -1 & 0 & 0 & 0 \\
I_{ij} & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots 
\end{pmatrix}
\]

Consider a 7 bus system as shown in fig. 2. Optimal location of PMU is identified and located in the system. $O_{pmu}$ is optimal PMU set for the example seven bus system $O_{pmu} = \{2, 3, 7\}$. The PI of $O_{pmu}$ is estimated using the eqn. (2) and shown in Table I. Bus no.3 has the highest priority index, so PMU is implemented on this bus. The number of observable buses ($r$) is 4 due to the choice of PMU at bus no.3 and is shown as a dotted line in fig. 2. Now the unobservable buses of example systems are 1 and 4. These buses are made to be observable using SCADA measurements such as power injection and power flow.

Consider a 7 bus system as shown in fig. 2. Optimal location of PMU is identified and located in the system. $O_{pmu}$ is optimal PMU set for the example seven bus system $O_{pmu} = \{2, 3, 7\}$. The PI of $O_{pmu}$ is estimated using the eqn. (2) and shown in Table I. Bus no.3 has the highest priority index, so PMU is implemented on this bus. The number of observable buses ($r$) is 4 due to the choice of PMU at bus no.3 and is shown as a dotted line in fig. 2. Now the unobservable buses of example systems are 1 and 4. These buses are made to be observable using SCADA measurements such as power injection and power flow.

### Table I

<table>
<thead>
<tr>
<th>Optimal Loc of PMU</th>
<th>Observed Bus</th>
<th>Priority Index</th>
<th>No. of unobserve Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3,4,7</td>
<td>0.75</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2,5,6,7</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1,2,3</td>
<td>0.75</td>
<td>3</td>
</tr>
</tbody>
</table>

Suppose the PMU at bus 2 is chosen, the number of unobservable buses are 3, they are buses numbered 1, 5 and 6. Now we require 3 traditional measurements to make the system observable. But the former case required only two SCADA measurements. Hence, highest PI valued PMU is chosen for implementation.

#### B. Selection of SCADA measurements

In this paper, unobservable island made to be observable by traditional measurements such as both real and reactive power injections and also power flows. Initially, augmented bus matrix ($P_{aug}$) is evaluated using the eqn. (3), where $n$ is the number of buses in a system This matrix is found based on the unobservable bus of the previous stage. The values of unobservable vector $X_u$ is 1 for unobservable node and zero for observable node. This vector is produced with the $(A_{pmu})$ matrix, the augmented bus ($P_{aug}$) matrix is obtained.

\[
P_{aug(n,X1)} = A_{pmu(n,X_n)} X_u(n,X_1)
\]

The elements of $(P_{aug})$ corresponds to unobservable bus is more than the Fixed Index (FI) value, then power injection measurements are to be placed in that node. By running more trials, the fixed index is found to be 3 which gives less number of traditional measurements. Power flow measurements are to be positioned in the branches, when the $(P_{aug})$ of the unobservable bus will be less than FI value. The algorithm for selection of SCADA measurements is explained in the following steps.

1. Input the number of unobservable buses $N_{uno}$.
2. Calculate the augmented bus matrix $P_{aug}$ based on the unobservable buses.
3. If the elements of $P_{aug}$ correspond to unobservable bus is greater than FI value, then Power Injection measurement ($P_{inj}$) is placed at this unobservable bus $N_{uno}(i)$.
4. If $P_{aug}$ is less than FI, then Power Flow measurement ($P_{pf}$) is positioned in any one of the branches connected to that unobservable bus $N_{uno}(i)$.

### Table II

<table>
<thead>
<tr>
<th>Unobservable Bus ($N_{uno}$)</th>
<th>$P_{aug}(N_{uno})$</th>
<th>Choice of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (1-2)</td>
<td>Power Flow</td>
</tr>
<tr>
<td>4</td>
<td>2 (2-4, 4-5)</td>
<td>Power Flow</td>
</tr>
</tbody>
</table>

In this case, the PMU is placed at 3rd bus of the system. The number of unobservable buses in a system is two (1, 4). $P_{aug}$ matrix for this example is shown above. The vector $X_u$ is $[1 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0]^T$. The elements corresponds to the unobservable node is 1 and 2. Therefore, the number of power injection measurements is selected here. But the power flow measurements are to be placed at 1st and 4th branches and is shown in fig. 2. The chosen SCADA measurements for the example system is explained in Table II.

#### C. Observability Checking

Observability analysis can be carried out using fully coupled or decoupled measurement equation. Observability of $\delta$ based
only on real power (P) measurements is analyzed using DC power flow equations. The measurement jacobian matrix (C) is formed based on the measurements obtained from SCADA systems. The rank of this matrix should be equal to (n-1) for (P-δ equation); n for (Q-V equation) [15]. In this paper, both SCADA and PMU measurements have been used. So the hybrid measurement jacobian matrix (C<sub>h</sub>) is formed by joining two sub matrices C<sub>PMU</sub> and C<sub>SCADA</sub>. The rank is equal to the network buses. Then the system is fully observable, which is verified numerically.

\[
C_h = \begin{bmatrix} C_{PMU} & C_{SCADA} \end{bmatrix}
\]

The PMU at bus 3 measures voltage phasor of bus 3 and line current phasor of the lines (3,6,7 and 8). The measurement jacobian of PMU (C<sub>PMU</sub>) is framed for this case as described below.

<table>
<thead>
<tr>
<th>( \delta_1 )</th>
<th>( \delta_2 )</th>
<th>( \delta_3 )</th>
<th>( \delta_4 )</th>
<th>( \delta_5 )</th>
<th>( \delta_6 )</th>
<th>( \delta_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_3 )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( I_{32} )</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( I_{35} )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>( I_{36} )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>( I_{37} )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The traditional measurements of this example is (P<sub>12</sub>) and (P<sub>01</sub>). The measurement jacobian for SCADA measurements (C<sub>SCADA</sub>) is shown below. Bus no.1 is considered to be reference bus. The (P-δ) equation of hybrid systems is obtained by joining both C<sub>PMU</sub> and C<sub>SCADA</sub> and then remove the reference bus column, which rank is equal to 6. So the system is fully observable using these selected measurements. For the estimation of voltage, reactive power is required. The reactive power injection and power flow measurement are placed at the same location of real power injection and power flow measurement respectively. Now both voltage and angle of network buses are able to calculate.

\[
C_{SCADA} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}
\]

III. HYBRID STATE ESTIMATION (HSE)

In hybrid state estimation the SPMU are added to the existing SCADA measurements for estimating system states. The unknown state variables X and the measurement vector are related by the linear Gaussian measurement model,

\[
Z_{hse} = H_{hse}X + \epsilon
\]

where

- \( Z_{hse} \) Both SCADA and PMU measurements vector
- \( H_{hse} \) First order derivative of both SCADA and PMU measurements w.r.t state variables
- \( \epsilon \) Measurement Noise

The measurement noise \( \epsilon \sim N(0, R) \) is zero mean with standard deviation of 0.02. The measurement matrix \( H_{hse} \) is known and deterministic. Initially, flat profile is assumed for the state variables. The optimal state estimate \( \hat{X} \) is given by,

\[
\Delta X = (H_{hse}^T R_{hse}^{-1} H_{hse})^{-1} (H_{hse}^T R_{hse}^{-1} \Delta Z_{hse})
\]

\[
\hat{X} = X_0 + \Delta X
\]

Measurement matrices, Jacobian and its sub matrices for traditional measurements, voltage phasor and current phasor measurements of PMU can be written as,

\[
[ \Delta Z_{hse} ] = \begin{bmatrix} \Delta Z_{SCADA} \\ \Delta Z_{V_{pmu}} \\ \Delta Z_{I_{pmu}} \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta \theta_p \\ \Delta V_p \\ \Delta I_{ijr} \\ \Delta I_{ij_i} \end{bmatrix}
\]

\[
H_{hse} = \begin{bmatrix} H \\ H_{V} \\ H_{I} \end{bmatrix} = \begin{bmatrix} M & F \\ G & N \\ I & 0 \\ 0 & I \end{bmatrix}
\]

A typical transmission line \( \pi \) model of the network is used in the formation of \( H_I \) matrix is shown in fig. 3, where \( g_{pq} + jb_{pq} \) is the series branch of the transmission line and \( g_{sp} + jb_{sp} \) is shunt branch of the transmission line. The branch current flowing through the nodes between p and q are given in [16]. The elements of \( H_I \) matrix are the derivatives of branch currents with respect to state variables.

\[
\sigma_{I_{pq,r}}^2 = (\frac{\partial I_{pq,r}}{\partial \sigma_{I_{pq}}} )^2 \sigma_{I_{pq}}^2 + (\frac{\partial I_{pq,r}}{\partial \delta_{pq} } )^2 \sigma_{\delta_{pq}}^2
\]

\[
= (\cos \delta_{pq} )^2 \sigma_{I_{pq}}^2 + (\sin \delta_{pq} )^2 \sigma_{\delta_{pq}}^2
\]

\[
\sigma_{I_{pq,i}}^2 = (\frac{\partial I_{pq,i}}{\partial \sigma_{I_{pq}}} )^2 \sigma_{I_{pq}}^2 + (\frac{\partial I_{pq,i}}{\partial \delta_{pq} } )^2 \sigma_{\delta_{pq}}^2
\]

\[
= (\sin \delta_{pq} )^2 \sigma_{I_{pq}}^2 + (\cos \delta_{pq} )^2 \sigma_{\delta_{pq}}^2
\]
The standard deviation of the errors of voltage and current phasor measurement is set as 0.0017 rad and 0.002 pu [17]. Similarly, 0.08 pu is assumed for the standard deviation of power flows and power injections. Here the real and imaginary values of branch current measurements are used for the formation of measurement set. So that standard deviation of real and imaginary of branch current have been evaluated using eqn. (11 - 12).

\[
\sigma_{Iq,r}^2 = \left(\frac{\partial I_{pq,r}}{\partial I_{pq}}\right)^2 \sigma_{Iq}^2 + \left(\frac{\partial I_{pq,r}}{\partial \delta_{pq}}\right)^2 \sigma_{\delta}^2
\]

\[
= (\cos \delta_{pq})^2 \sigma_{Iq}^2 + (I_{pq} \sin \delta_{pq})^2 \sigma_{\delta}^2
\]  

\[
\sigma_{Iq,r}^2 = \left(\frac{\partial I_{pq,l}}{\partial I_{pq}}\right)^2 \sigma_{Iq}^2 + \left(\frac{\partial I_{pq,l}}{\partial \delta_{pq}}\right)^2 \sigma_{\delta}^2
\]

\[
= (\sin \delta_{pq})^2 \sigma_{Iq}^2 + (I_{pq} \cos \delta_{pq})^2 \sigma_{\delta}^2
\]  

(11)

The covariance matrix \(R_{hse}\) of HSE is formed using conventional covariance matrix \(R\), voltage phasor covariance \((R_v)\) and current phasor covariance \((R_i)\).

\[
R_{hse} = \begin{bmatrix}
R & 0 & 0 \\
0 & R_v & 0 \\
0 & 0 & R_i
\end{bmatrix}
\]

If enormous measurements used for estimating the system states, then it leads to iterative procedure. The chosen measurements are equal to the number of state variables. Therefore, the solution of this algorithm is direct and non-iterative [18]. The chosen measurements are essential one for the system to be observable and give unique state estimates.

IV. SIMULATION RESULTS

The working of the proposed method is tested for IEEE 14, New England 39 bus and IEEE 57 bus. The assumption made that there is no zero injection bus in the system. First stage of measurement selection is choice of PMU. Traditional measurements have been selected in the second stage. The selected measurements (both PMU and SCADA) have been used for evaluating state variables in Hybrid State Estimation. System data was obtained from [19]. The true values of state vectors are taken from Fast Decoupled Load Flow (FDLF). Bus 1 and Bus 31 are chosen as reference buses for IEEE 14 ans NE 39 systems respectively. The voltage phasor and current phasor measurements of PMUs are acquired from FDLF in addition with measurement errors. Initially optimal location of PMU is obtained by BILP and is shown in Table III. Optimal PMU set for IEEE 14 bus system is \(O_{pmu} = [2, 6, 7, 9]\). PMU is elected based on priority index. PI value for buses 2, 6, and 9 are 1 and for 7 is 0.75. Highest PI valued PMUs are chosen for implementation. So, Only one at bus 9 and 4 PMUs at bus 2, 6, 25 and 29 are opted for IEEE 14 and NE 39 bus system respectively. Suppose PMU is placed at bus no 2, the unobservable buses are [6, 7, 8, 9, 10, 11, 12, 13 and 14], totally 9 bus measurements. The \(N_{uno}\) is equal for same priority valued buses. Therefore, any one of the PMU is selected among the same priority indexed buses.

Only few buses are observable using the selected PMUs, remaining buses are considered to be unobservable. These are made to be observable by proper choice of traditional measurements. In the second stage, selections of power flow \((P_{pf})\) and power injection measurements \((P_{inj})\) have been done and listed in Table IV. This table explains the location of traditional measurements and also the number of unobservable buses \((N_{uno})\). IEEE 14 bus system have 4 power injections and 5 power flow measurements. Power injection measurements are located, if the elements of that augmented bus matrix is more than FI value else power flow measurements are positioned at the branches connected to that bus. The location of measurements for IEEE 14 bus system is shown in fig. 4.

The performance of the HSE is estimated though Mean Square Error (MSE). By increasing PMUs, MSE error of state vectors should be reduced [14]. So the simulation has been done for different number of PMUs and according to this, SCADA measurements have been selected. The results of HSE are shown in Table V. Two set of PMUs have been considered. First Case 1 and 4 PMUs (0.1 times of network bus) and second case 3 and 8 PMUs (0.2 times of network bus) are decided for IEEE 14 and NE 39 bus system respectively. The location of PMU for second case is highest PI valued buses 2, 6, and 9 for IEEE 14 bus test case. Table V also shows that MSE of state vectors are reduced by increasing PMUs. Errors lie within the tolerable limits. If the PMUs are increased, the required traditional measurements will be decreased, so calculation time for H matrix is reduced.
Therefore the computation time is very low. It is well suitable for online implementation.

TABLE V
RESULTS OF HSE WITH CRITICAL MEASUREMENT SETS

| Test systems | No. of PMUs | Comp. time | MSE of $|V|$ | MSE of $\delta$ |
|--------------|-------------|------------|-------------|----------------|
| IEEE 14      | 1           | 0.1613     | 0.0014      | 1.155e$^{-4}$ |
|              | 3           | 0.1541     | 0.022$e^{-4}$ | 3.11$e^{-5}$ |
| NE 39        | 4           | 0.1938     | 1.041$e^{-4}$ | 7.418$e^{-4}$ |
|              | 8           | 0.1808     | 4.36$e^{-5}$ | 6.56$e^{-5}$ |
| IEEE 57 bus  | 6           | 0.1047     | 0.0683      | 0.0305         |
|              | 11          | 0.0989     | 0.00174     | 0.0144         |

Fig. 5. Effect of increasing number of PMUs to the system on errors for IEEE 77 bus system

![Diagram](image_url)

The effect of increase in number of PMUs is done for IEEE 57 bus system and is shown in Fig 5. It reveals that the estimated state variables error is drastically decreasing by increase in PMU. Also selected PMUs are chosen from optimal PMU set $O_{PMU}$, which improves the estimate values. Both angle and magnitude error of bus voltage are reached to zero when all PMUs are located optimally.

V. CONCLUSION

A Hybrid State Estimation algorithm, using critical measurements including both PMU and SCADA is proposed in this paper. From the simulation study performed on standard IEEE systems, it is observed that this algorithm provides the best state estimates with less computation time. This method gives an idea about where to implement a PMU into the existing SCADA systems, which provokes a much better result. The more accurate values of state variables is obtained when the number of PMUs are increased in the system. An important advantage of this method is non-iterative which reduces the computation time and suitable to implement in the near future. In view of extension in this work, analysis can be done taking into account the loss of measurements, failure of PMU and effectiveness of PMU positions in HSE.

REFERENCES