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Multi-Area State Estimation Based on PMU Measurements in Distribution Networks

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Abstract- *State estimation in the energy management center of active distribution networks has attracted many attentions. Considering an increase in complexity and real-time management of active distribution networks and knowing the network information at each time instant are necessary. This article presents a two-step multi-area state estimation method in balanced active distribution networks. The proposed method is based on the location of PMU measurements of the network. The network is divided into several sub-areas about PMUs in the first step. A local sate estimation is implemented in each sub-area. The estimated values of the first step along with real measurements are used as measurements for second step estimation. The measurements are located in each sub-area using these values based on the ellipse area method, and the best location of measurements is extracted. Therefore, a second step state estimation including integrated state estimation of the whole network is performed by using the measurements obtained and located from the first step. The estimation results of the first step are used in the second step which improve the estimation accuracy. Simulations are performed on a standard IEEE 69-bus network to validate the proposed method.*

Keyword: Measurements location, State estimation, Synchronous measurements, Two-step state estimation, Zoning distribution networks.

1. INTRODUCTION

Electrical energy distribution systems are designed so that to be capable of transferring energy from the limited number of nodes (main substations) to large number of energy consumers. Today, the passive distribution networks (DNs) have undergone major and fundamental changes, including the extensive presence of distributed generation, renewable energy sources, electrical vehicles, energy storage systems, and the high-efficiency commercial and residential loads. Therefore, today's DN is referred to as an active DNs [1]. Furthermore, new control and management functions should be designed and implemented to ensure the safety and reliability of these networks functions [2]. For this purpose, system operators must be fully aware of the network conditions and information. The state estimation (SE) could provide the required network information with respect to the mathematical relation between state variables and measured data according to the network structure [3].

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The distribution system state estimation (DSSE) algorithm is designed to identify the grid functional modes, while it uses limited number of meters and is economically feasible [4]. The control operators of the electrical power systems have an essential need for SE to operate properly [1]. The SE in DN is reviewed briefly in Ref. [5], and some aspects of that have been somewhat investigated.

Phasor measurement units (PMUs) have been widely used for SE since they measure different values of the voltage and current [6, 7]. PMUs have a high reporting rate and high accuracy and they are being developed significantly in power networks [8, 9]. Moreover, it is expected that they will be used in DSSE [1, 10]. Considering a small number of the measurements in DNs, DSSE employs load prediction information with high uncertainty as a pseudo-measurement to make the network observable [11, 12]. According to various studies, the best method for SE in DNs is the weighted least square error (WLSE) method [13, 14].

As it is studied in Ref. [15], the fast decouple state estimation (FDSE) method is presented with high convergence speed and high efficiency. The branch current magnitude measurements are formulated as active and reactive power losses of the branches and are directly used in the FDSE method.

According to reference [16], researchers were considered the network reconfiguration and various uncertainties of measurements and DGs in the DSSE. Researchers also provided a robust measurement placement method based on measurement saturation analysis and a heuristic algorithm.

Multi-area state estimation (MASE) methods have become one of the important research topics in recent decades. Several MASE techniques, which are mainly used in transmission systems, have been proposed in the literature [17, 18]. Collecting and processing large amount of data at a single location for increasing reliability, computational efficiency and maintenance are not logical. Thus, the zoning measure is considered [19]. MASE methods are generally developed in transmission systems, therefore, a MASE method, which may be suitable for DNs, should be designed. Considering large number of schemes proposed for the MASE in power systems, the efficient design of MASE for DN has not been solved yet. According to a research in [20], the MASE based on a differential evaluation algorithm has been investigated. A network state is obtained using local estimators which require information exchange with adjacent sub-areas at each iteration of the estimation algorithm which it requires a high communication rate. In reference [21], the MASE is based on local WLSE estimators. The total voltage profile of the network is obtained using a central synchronizer which employs results of local estimations. In Ref. [14], multi-area two-step DSSE methods have been proposed. Local estimators are executed in each sub-area in parallel and independently. Outputs are synchronized with minimum information exchange among adjacent sub-areas to improve total estimations of the sub-areas. This synchronized estimation is performed on a decentralized path. As it is studied in Ref. [22], estimation algorithm is comprised of a two-step method which the first step in local estimation is modified by an estimation in the second step which exploits estimations obtained from adjacent sub-areas, and considers correlation of the measurement process. In Ref. [23], the same idea of reference [22] is used and a fast WLSE method including voltage estimation at one node in each sub-area is also used. The SE algorithm employs a branch current based SE (BC-DSSE) which is proposed by [1].

According to Ref. [24], researchers were investigated the detection, identification, and isolation possibility of anomalies in the power system that may arise during the SE problem. It is concluded that large percentage of the electric system state variables can be estimated, while the isolation possibility of anomalies from the power system leads to divergence for the estimator.

As it is investigated by above-mentioned articles, many studies have been carried out on the SE in the active DN, and many of the problems of SE have been studied by researchers. In this paper, the problem of the accurate measurements shortage in electrical DNs is mentioned, which has been less addressed in the previous researches. In this work, some methods which are based on network zoning and the two-step SE will be presented to solve the problem of the accurate measurements shortage and the removal of a large number of pseudo-measurements.

In the second section of this work, the WLSE method is explained briefly. Subsequently, function of different measurements, which is one of the main problems in SE procedure. This problem is addressed in section 3. In section 4, a measurements placement is presented. In section 5, the MASE is investigated, and the proposed multi-area method is presented in section 6. And finally, simulation results and conclusion are given in sections 7 and 8, respectively.

2. WEIGHTED LEAST SQUARES ERROR METHOD

The SE is a mathematical tool which describes a set of measurements along with a mathematical model [3, 13]. The SE method used in DNs is based on WLSE. The WLSE is a probabilistic method which employs error between measured values and estimated values [25, 26]. The measurement equation is as shown in Eq. (1):

$$Z_{meas} = Z_{esti} + \varepsilon = h(\hat{x}_i) + \varepsilon \tag{1}$$

Z_{meas} and Z_{esti} are measurement and estimation vectors. $h(\hat{x}_i)$ is a linear or nonlinear function which describes the relationship between measured values and network states. ε is the error between the estimated value and measured value. $\hat{x}_i$ indicates i^{th} state variable of the network. The probability distribution function (PDF) of ε is considered as a normal Gaussian distribution with zero mean and a specific variance. In order to solve the objective function and simplify it for optimization, the objective function is assumed to be exponential and described using Eq. (2):

$$Min\ J = \sum_{i=1}^{m} \left(\frac{Z_{meas,i} - f_i(\hat{x})}{\sigma_i} \right)^2 \tag{2}$$

J is the total residual of the weighted squares error of measurements. The matrix form of Eq. (2) is as follows:

$$J(\hat{x}) = \left[Z - F(\hat{x})\right]^T R^{-1}\left[Z - F(\hat{x})\right] \quad (3)$$

Where:

$$Z = \left[Z_{meas,1}, Z_{meas,2}, \ldots, Z_{meas,m}\right]^T$$
$$F(\hat{x}) = \begin{bmatrix} f_1(x_1,\ldots,x_n) \\ \vdots \\ f_m(x_1,\ldots,x_n) \end{bmatrix}, R = \begin{bmatrix} \sigma_1^2 & & & \\ & \sigma_2^2 & & \\ & & \ddots & \\ & & & \sigma_m^2 \end{bmatrix} \quad (4)$$

n is the number of state variables of the system, $h(\hat{x}_i)$ represents a measurement function vector, Z is considered as measurement vector, R shows covariance matrix of measurements which is diagonal and σ_i^2 is variance of the i^{th} measurement [27]. A method which is usually used to optimize the objective function $J(\hat{x})$ is based on the Gauss-Newton (G-N) iteration method. The estimated value of the state variable is obtained as follows:

$$x^{k+1} = x^k - \left[G(x^k)\right]^{-1} g(x^k) \quad (5)$$

k is considered as counter of G-N iteration. x is a state variable vector of the system. While $G(x^k)$ and $g(x^k)$ are obtained as follows:

$$\begin{gathered} H(\hat{x}) = \frac{\partial F(\hat{x})}{\partial \hat{x}}, g(x^k) = H^T(x^k) R^{-1}\left(Z - F(x^k)\right) \\ G(x^k) = \frac{\partial g(x^k)}{\partial x^k} = H^T(x^k) R^{-1} H(x^k) \end{gathered} \quad (6)$$

$G(x^k)$ and $H(\hat{x})$ are gain and Jacobin matrixes of the WLSE method where $H(\hat{x})$ is a relative derivative of each measurement function with respect to state variables [28].

3. MEASUREMENTS EQUATIONS IN BALANCED THREE-PHASE DISTRIBUTION NETWORKS

The SE in DNs is performed according to measurement equations and their effect on the SE performance. Subsequently, the measurement equations are presented, and the Jacobian function as the method of calculation for each type of meters is expressed in the Cartesian form Ref. [29].

The state variable vectors for the DSSE are considered as Eq. (7) in the Cartesian form Ref. [1]:

$$x = \left[V_{Slack}^{\mathrm{Re}}\ V_{Slack}^{im}\ I_1^{\mathrm{Re}}\ I_2^{\mathrm{Re}} \ldots I_b^{\mathrm{Re}}\ I_1^{im}\ I_2^{im} \ldots I_b^{im}\right]^T \quad (7)$$

V_{Slack}^{Re} is the real part of the slack bus voltage phasor, V_{Slack}^{im} depicts the imaginary part of the slack bus voltage phasor, I_k^{Re} shows the real part of k^{th} branch current phasor, and I_k^{im} is the imaginary part of k^{th} branch current phasor, where $k=1, 2, \ldots, b$, and b is the number of distribution network branches; hence, the x vector dimension is equal to $(2b+2)*1$.

3.1. Synchronized Measurements

The Synchronized measurements have a high sampling rate and accuracy. The PMUs in the DSSE have greatly improved the accuracy, convergence speed, and the real-time concept in the SE [1]. Therefore, in recent years, using of these types of measurement has been increased in DNs [30, 31]. When a synchronized meter is installed at a bus, it measures the node voltage phasor along with the current phasor of the branches that are connected to that bus [1, 3].

In the following, assuming the state variables according to the Eq. (7), the equations concerned with PMU measurement functions are presented. Also, the Jacobian elements corresponding to these types of measurements are calculated. When the PMU is placed at a node (for example, the node h), it measures the node voltage Phasor (V_h).

$$\begin{aligned} & V_h = V_{Slack} - \sum_{i \in \eta_h} Z_i * I_i \\ & V_h = V_h^{\mathrm{Re}} + jV_h^{im},\ Z_i = R_i + j.X_i,\ I_i = I_i^{\mathrm{Re}} + j.I_i^{im} \\ & V_h^{\mathrm{Re}} = V_{Slack}^{\mathrm{Re}} - \sum_{i \in \eta_h} (R_i * I_i^{\mathrm{Re}} - X_i * I_i^{im}) \\ & V_h^{im} = V_{Slack}^{im} - \sum_{i \in \eta_h} (R_i * I_i^{im} + X_i * I_i^{\mathrm{Re}}) \end{aligned} \quad (8)$$

Equation (8) shows the measurement functions ($f_k(x_1,\ldots,x_n)$) for the PMU voltage meter. $V_h = V_h^{\mathrm{Re}} + jV_h^{im}$, $Z_i = R_i + jX_i$ and $I_i = I_i^{\mathrm{Re}} + jI_i^{im}$ represent the h[th] node voltage, i^{th} branch impedance and i^{th} branch current, respectively. η_h depicts the h^{th} node path to the slack bus. The elements of the Jacobian matrix ($H(\hat{x})$), which are the relative derivative of the

$$\begin{aligned} & \frac{\partial V_h^{\mathrm{Re}}}{\partial V_{Slack}^{\mathrm{Re}}} = 1,\ \frac{\partial V_h^{\mathrm{Re}}}{\partial V_{Slack}^{im}} = 0 \\ & \frac{\partial V_h^{\mathrm{Re}}}{\partial I_i^{\mathrm{Re}}} = \begin{cases} -R_i & if \quad i \in \eta_k \\ 0 & if \quad i \notin \eta_k \end{cases},\ \frac{\partial V_h^{\mathrm{Re}}}{\partial I_i^{im}} = \begin{cases} X_i & if \quad i \in \eta_k \\ 0 & if \quad i \notin \eta_k \end{cases} \\ & \frac{\partial V_h^{im}}{\partial V_{Slack}^{\mathrm{Re}}} = 0,\ \frac{\partial V_h^{im}}{\partial V_{Slack}^{im}} = 1 \\ & \frac{\partial V_h^{im}}{\partial I_i^{\mathrm{Re}}} = \begin{cases} -X_i & if \quad i \in \eta_k \\ 0 & if \quad i \notin \eta_k \end{cases},\ \frac{\partial V_h^{im}}{\partial I_i^{im}} = \begin{cases} -R_i & if \quad i \in \eta_k \\ 0 & if \quad i \notin \eta_k \end{cases} \end{aligned} \quad (9)$$

measurement function of the state variables, are obtained from Eq. (7) and Eq. (8).

According to Eq. (9), the Jacobian elements consist of constant numbers of zero and one, and as well as the branches impedance fixed elements. Therefore, it can be said that the Jacobian elements related to the PMU voltage measurement function involve fixed elements, which is considered as an important feature in SE. If the Jacobian elements are fixed, or in other words, the Jacobian matrix is fixed, there is no need to calculate the inverse of the gain matrix at each step of iteration in the SE procedure, and this feature affects the SE performance and accuracy [1].

The measurement function equations and the Jacobian elements of the branch current measurement by the PMU can be considered as follows. Line current is measured according to an assumption that the k^{th} branch is connected to the node where the PMU is installed.

$$I_k = I_k^{\mathrm{Re}} + j.I_k^{im} \Rightarrow \begin{cases} f_m(x_1,x_2,...,x_n) = I_k^{\mathrm{Re}} \\ f_{m+1}(x_1,x_2,...,x_n) = I_k^{im} \end{cases}$$
$$\Rightarrow \frac{\partial f_m}{\partial I_j^{\mathrm{Re}}} = \begin{cases} 1 & if \quad j = k \\ 0 & if \quad j \neq k \end{cases}, \frac{\partial f_m}{\partial I_j^{im}} = 0 \qquad (10)$$
$$\frac{\partial f_{m+1}}{\partial I_j^{im}} = \begin{cases} 1 & if \quad j = k \\ 0 & if \quad j \neq k \end{cases}, \frac{\partial f_{m+1}}{\partial I_j^{\mathrm{Re}}} = 0$$

3.2. Power Measurements

Power measurements are categorized in real and pseudo-measurements. The real power measurements are installed in the main substation, which measure the active and reactive power absorbed by the network [3]. Given that using of meters in each node of the DN is not economically and technically feasible, therefore, the DSSE uses the initial or previous network information as a pseudo-measurement [13]. Pseudo-measurements consider predictions or primary network information to approximate the nodes consumption loads or power generated by a distributed generation that is available in the network. Therefore, these types of measurements include active and reactive power that are injected absorbed by the network. Pseudo-measurements include low precision and low-reliability data that affect the SE accuracy and thus, Their only benefit are that they make network observable [32].The actual or pseudo power measurements could be modeled using equivalent current, which is performed to linearize the measurement functions by selecting the branch current as the state variable [1].

Fig.1 shows the different locations to place a load at the node. The measurement function and Jacobian elem-

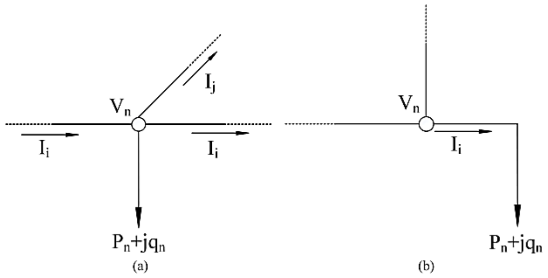

Fig.1. (a) The load connected to the branching node. (b) The load connected to the feeder end node.

-ents are presented for power meters regarding to the conditions shown in Fig.1.

$$I_{eq,l}^{\mathrm{Re}} + j.I_{eq,l}^{im} = (\frac{P_l + j.Q_l}{V_n})^* \Rightarrow \begin{cases} f_m(x_1,x_2,...,x_n) = I_{eq,l}^{\mathrm{Re}} = I_i^{\mathrm{Re}} \\ f_{m+}(x_1,x_2,...,x_n) = I_{eq,l}^{im} = I_i^{im} \end{cases}$$
$$\Rightarrow \begin{cases} \frac{\partial f_m}{\partial I_b^{\mathrm{Re}}} = \begin{cases} 1 & if \quad b = i \\ 0 & if \quad b \neq i \end{cases} \\ \frac{\partial f_{m+1}}{\partial I_b^{im}} = \begin{cases} 1 & if \quad b = i \\ 0 & if \quad b \neq i \end{cases} \end{cases} \qquad (11)$$

Equation (11) is defined according to Fig.1b, where the load is located at the end of the feeder and only one line is connected to that node. Given the state variables and employing the equivalent current, the obtained Jacobin elements corresponding to the power measurements in Eq. (11) are constant. It should be noted that any node voltage is calculated at each step of the G-N iteration, and the WLSE is used in the next process. Therefore, at each iteration step, the network state variables (network branches current) are calculated. Also, using a direct method as well as the Kirchhoff voltage-current law, the phasor voltage of a node is calculated using the network states values from the beginning of the slack bus to the end of feeder [1].

$$I_{eq,l}^{\mathrm{Re}} + j.I_{eq,l}^{im} = (\frac{P_l + j.Q_l}{V_n})^*$$
$$\Rightarrow \begin{cases} f_m(x_1,x_2,...,x_n) = I_{eq,l}^{\mathrm{Re}} = I_i^{\mathrm{Re}} - I_j^{\mathrm{Re}} - I_k^{\mathrm{Re}} \\ f_{m+}(x_1,x_2,...,x_n) = I_{eq,l}^{im} = I_i^{im} - I_j^{im} - I_k^{im} \end{cases} \qquad (12)$$
$$\Rightarrow \begin{cases} \frac{\partial f_m}{\partial I_b^{\mathrm{Re}}} = \begin{cases} 1 & if \quad b = i \\ -1 & if \quad b = j \ or \ k \\ 0 & if \quad b \neq i \ or \ j \ or \ k \end{cases} \\ \frac{\partial f_{m+1}}{\partial I_b^{im}} = \begin{cases} 1 & if \quad b = i \\ -1 & if \quad b = j \ or \ k \\ 0 & if \quad b \neq i \ or \ j \ k \end{cases} \end{cases}$$

Equation (12) also shows the measurements function and Jacobin elements for Fig.1a, which is connected to the desired node by several branches. In this case, the load current is obtained from the Kirchhoff current law in the node containing the load, which is used instead of the load current.

3.3. Current and Voltage Magnitude Measurements

In most cases, the voltage and current magnitude measurements are located in the main station of distribution network and measure the voltage magnitude and main station current. The equations related to these types of measurements are as follows:

$$\begin{aligned}
&|V_{Slack}| = f_m(x_1, x_2, ..., x_n) = \sqrt{(V_{Slack}^{\text{Re}})^2 + (V_{Slack}^{im})^2} \\
&\Rightarrow \frac{\partial f_m}{\partial V_{Slack}^{\text{Re}}} = \frac{V_{Slack}^{\text{Re}}}{\sqrt{(V_{Slack}^{\text{Re}})^2 + (V_{Slack}^{im})^2}} \\
&\frac{\partial f_m}{\partial V_{Slack}^{im}} = \frac{V_{Slack}^{im}}{\sqrt{(V_{Slack}^{\text{Re}})^2 + (V_{Slack}^{im})^2}} \\
&|I_b| = f_{m+1}(x_1, x_2, ..., x_n) = \sqrt{(I_b^{\text{Re}})^2 + (V_n^{im})^2} \\
&\Rightarrow \frac{\partial f_{m+1}}{\partial I_i^{\text{Re}}} = \begin{cases} \frac{I_i^{\text{Re}}}{\sqrt{(I_i^{\text{Re}})^2 + (I_{ib}^{im})^2}} & if \quad i = b \\ 0 & if \quad i \neq b \end{cases} \\
&\frac{\partial f_{m+1}}{\partial I_i^{im}} = \begin{cases} \frac{I_i^{im}}{\sqrt{(I_i^{\text{Re}})^2 + (I_{ib}^{im})^2}} & if \quad i = b \\ 0 & if \quad i \neq b \end{cases}
\end{aligned} \tag{13}$$

In Eq. (13), unlike the measurements stated above, the Jacobian elements are not constant. However, these types of meters are rarely used in the DN, especially the voltage magnitude measurement which is only used in the main station. In the case where the DSSE equations are written based on the branch currents, the current measurements will be of great importance, and voltage measurements are used less [1].

3.4. Virtual Measurements

The virtual measurements are extracted from system characteristics. The zero injection node is one example of this kind of measurements, which includes error-free information. The zero injection node does not involve any consumption load and power generation source, and hence, the net power is zero at the zero injection node. The data of the zero injection node are used in the SE with very low uncertainty, so these measurements have a prominent role in improving the SE accuracy [33].

4. MEASUREMENTS LOCATION

In DNs, how the measurement is added to the network, is important from different aspects and a significant problem is the type and location of measurements. In Ref. [34], Measurement's location problem has been proposed for identifying the optimal location, type and number of measurements. The complete formulation of measurement location is given by reference [34]. The measurement location procedure includes the following steps:

Step 1. The WLSE of the SE is performed on the main network to the number of Monte-Carlo simulations (N_{mc}), and relative voltage and voltage angle errors in each Monte-Carlo simulation is extracted for all buses.

Step 2. If in more than 95% of cases, relative voltage and node angle errors are 1% and 5% below the threshold, stop the process; otherwise go to step 3.

Step 3. If only relative errors in voltage estimations of step 2 are provided, go to step 6; otherwise, go to step 4.

Locating voltage measurements:

Step 4. Average error covariance matrix of node voltage is calculated in N_{mc} Monte-Carlo simulations, and the sub-matrices corresponding to voltage and voltage angle (real and imaginary parts of each node or branch) of each bus are extracted.

Step 5. Ellipse error area is calculated at each node using the determinant of the sub-matrix and the node with a larger area in which voltage measurement should be located, is specified. If there exists a measurement in that node, the next node with the largest ellipse error area is selected. Go to step 1.

Locating the current measurement or power flow of the feeder:

Step 6. Average error covariance matrix corresponding to the current of branches is calculated in N_{mc} Monte-Carlo simulations. Sub-matrices corresponding to the current amplitude, and angle of each branch (real and imaginary parts of the current of each branch) are extracted.

Step 7. Ellipse error area is calculated for each branch of the network, and the current measurement is located in the branch with the largest area. If there exists a current measurement in that branch, a current measurement is located in the next branch with the largest ellipse error area. Go to step 1.

5. MULTI-AREA STATE ESTIMATION

The main purpose of analysis of SE problem is to divide the volume and complexity of the SE into several reduced parts. Dividing the network to smaller areas is performed considering a measurement system of the network, geographical constraints or topology of the network [14]. MASE methods are separated based on different measures, including dividing again to areas, type of estimator and synchronization scheme adopted for multi-area synchronization [17, 18, 21, 35]. The most important problem is that the number of available measurement devices are limited [19]. An important problem with MASE methods is the proper distribution of the SE problem among several sub-areas. Estimation accuracy, using any method depends on the measurement system. In order to exchange information among sub-areas, a singular distribution system operator (DSO) is required, which manages all sub-networks [14]. In general, the design of the multi-area DSSE methods should be a proper trade-off between low computational load, minimum information exchange and high-performance accuracy.

The desired characteristics of the MASE compared to integrated design can be classified as follows [19]:

- Convergence to desired solution under different conditions
- Obtaining estimation states with the desired accuracy
- One of the expected features of the MASE is increasing in speed whenever algorithm complexity regarding separation-synchronization remains still limited.
- Information exchange among processors should be kept minimum so that the increase in time delays and response time is prevented.

In the hierarchical scheme, a central processor divides the task among auxiliary computers, which execute local sub-area SE and synchronize local estimations. In this design, auxiliary processors are only connected to the central computer. Therefore, local estimations are executed in each sub-area, and each sub-area transmits its estimated value to the central processor [19].

Local processors might be executed through synchronous or asynchronous methods. In decentralized architecture, the procedure is inherently asynchronous such that each local processor executes iteration with its speed using the best information from its neighbors. But in the hierarchical scheme which is used for SE in this work, there are two synchronization modes:

a) When synchronization is performed at the SE level, each local processor executes the SE with its speed. The central processor uses the last estimation provided by each sub-area. It is not important if these local estimations are not related to the same instant.

b) When synchronization is employed at the iteration level, if the central computer considers the information of slower local processors, the procedure is synchronous. Otherwise, the procedure is asynchronous.

6. THE PROPOSED MULTI-AREA METHOD

In this article, three-phase SE in balanced DNs is presented considering the proposed criterion for dividing the network into several sub-areas. This estimation method is comprised of two steps where the first step divides the network into several sub-areas around the existing PMUs through considering the location and redundancy of PMUs. The number of selected sub-areas would be different regarding network size and available measurements and the local SE performs in each sub-area. At the end of the first step, estimated values are extracted. The values estimated in the first step which have proper accuracy are used as the measurement with low uncertainty along with real measurement of the network in a second estimation step. Using these values, measurements are located in each sub-area, and the best location for the measurements is obtained. The second estimation step including integrated state estimation (ISE) of the whole network can be performed by using the measurements obtained in the first step and locating them. The advantage of this method is employing a large number of measurements with low standard deviation which are existed in the network extracted from the first estimation step. Redundancy of accurate measurements improves the total estimation accuracy of the network and speeds up estimation procedure. The structure of the proposed method is shown in Fig.2. Furthermore, the two-step estimation method can be divided into the following steps:

- ✓ Dividing the standard IEEE DN to a multi-area network
- ✓ Performing initial SE in the sub-areas locally
- ✓ Locating measurements using values extracted from the first step
- ✓ Performing integrated secondary the SE on the standard IEEE DN using the measurement system and estimated information of the first step

Voltage and current values of the initial estimation can be further analyzed by their transmission as processing information to the energy management center (EMC). In this case by the existence of errors in sensitive points of the network, the required commands can be sent to network operators. Since the extracted and estimated information are obtained with proper accuracy in a short time from first estimation step, sensitive points of the network are monitored in real-time so that failures in these points can be detected by EMC and proper actions may be performed to resolve the problem. In the proposed method, according to the f-

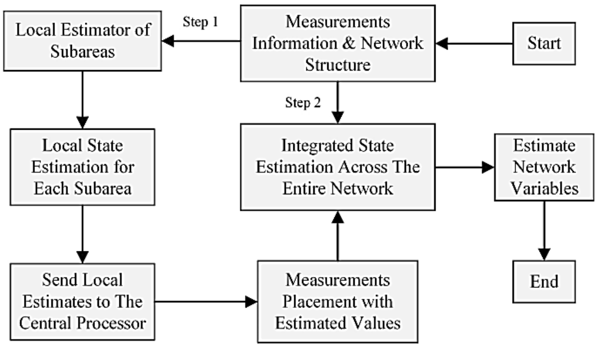

Fig.2. The proposed structure

-act that the selected sub-areas are small, required execution time to perform initial SE on each sub-area of the DN would be very low. Therefore, EMC can detect sensitive points of the network in real-time. The high accuracy in SE is due to increase in the number of both the accurate measurements and measurements with low uncertainty. The proposed method is implemented on a standard IEEE 69-bus network.

7. SIMULATION RESULTS

The two-step estimation method is implemented on the balanced standard IEEE 69-bus to investigate the proposed method. This network is divided into several sub-areas based on the location of PMUs existing in the network. The proposed criterion for dividing the network is investigated, and the results are compared with the common ISE method and reference values. The BC-DSSE method mentioned in Ref. [1] has been selected as the common ISE method in this paper. In order to evaluate the performance of the SE, Monte-Carlo simulations are used so that the uncertainty of initial estimated values is obtained. To initialize estimation, reference values obtained in power flow of the network are used, and measurements are extracted randomly using their PDF. The following assumptions are considered during the estimation procedure [1, 2]:

- ✓ The number of Monte-Carlo simulations (N_{mc}) is *25000*.
- ✓ The measurements distribution function is a Gaussian distribution function with a standard deviation which is one-third of maximum error compared to real values.
- ✓ Maximum error for different measurements is as follows: pseudo-measurement: 50%, voltage and current amplitude PMU: 1%, voltage and current phase angle measurement: 0.01 radian, asynchronous voltage amplitude measurement: 1%, current amplitude and feeder power flow asynchronous measurement: 3%.

7.1. Standard IEEE 69-bus Distribution Network

The following diagram shows the proposed method for dividing the 69-bus DN into multiple sub-areas. Subsequently, the proposed method is presented, and discussed in the following cases:

1) The zoning of the 69-bus network is presented.
2) The initial SE is implemented on the each sub-areas in parallel and independently, and the results are shown.
3) The results of the measurement placement process are given which include the nodes and branches that serve as candidates for the measurement placement.
4) The secondary SE is simulated using the results of the measurement placement and the initial SE implemented in each sub-area in the 69-bus network. The results are depicted by figures and tables.
5) The sensitivity analysis of SE is discussed on the pseudo-measurement uncertainty.

The network is divided into sub-areas A, B and C considering PMUs at nodes 3, 9 and 12 and one PMU is located in each sub-area. These measurements measure the voltage of nodes 3, 9 and 12 and current of branches ended to these three nodes.

These are the only real measurements which comprise the first estimation step along with the zero-injection and pseudo-measurements. In this step, the local SE is performed in parallel and independently in each sub-area. The first step estimation is implemented aiming to fast estimation of the network. Numbering nodes of the three sub-areas are shown independently in Fig.4. Results of estimated values at the end of the first step are given in Fig.5.

When the first estimation step is terminated, i.e., the iteration process has converged, and estimated state variables are accessible, the measurement location is im-

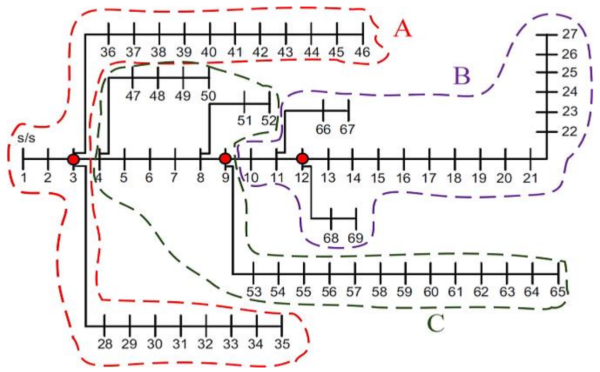

Fig.3. Dividing the IEEE 69-bus network into multiple sub-areas

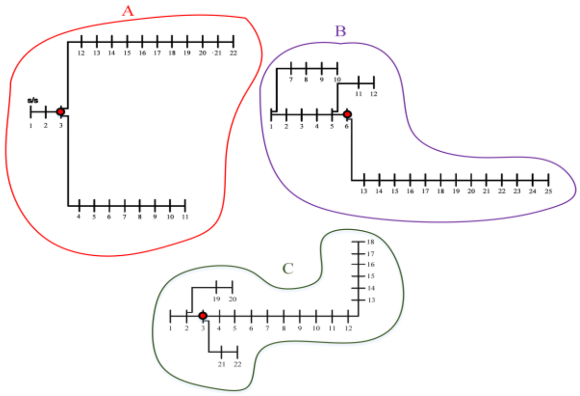

Fig.4. Numbering nodes of sub-areas A, B and C

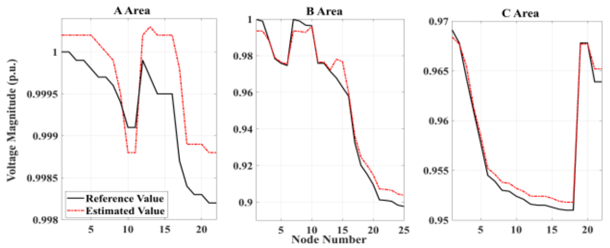

Fig.5. First step estimation of voltage amplitude in sub-areas A, B and C

Table 1. Standard deviation of current of branches to be employed in the second state estimation step

Average error estimation	Branch number
0.0033	6, 32, 33, 65
0.0034	15, 16, 17, 18, 20, 21, 22, 25, 26, 38, 39, 40, 44, 49, 50
0.0035	58
0.0036	47, 48, 60, 61, 63, 64
0.0037	53

-plemented based on the ellipse error method. Locations obtained from this method are branches 32, 33, 38, 39, 40 and 44 in sub-area A, branches 6, 47, 48, 49, 50, 53, 58, 60, 61, 63 and 64 in sub-area B and branches 15, 16, 17, 18, 20, 21, 22, 25, 26 and 65 in sub-area C for locating current measurements and one voltage amplitude measurements at node 27. The second step is executed by Measurements' utilization obtained and located from the first step and PMUs of the first step along with zero-injection measurements and pseudo-measurements. In order to use the values estimated in the first step as a measurement in the second estimation step, the standard deviation of the parameters estimated in the first step should be determined. Thus, Table 1 shows average estimation error values for the current of specified branches.

The average estimation error is selected as the standard deviation of the branch currents estimated in the first step to be employed in the second estimation as a measurement. Second estimation step includes ISE of the network. Therefore, using the proposed method, the number of accurate measurements is increased in comparison with the common single-step ISE method. Also, the number of pseudo-measurements is decreased from 46 in the common ISE method to 24 in the proposed method. Fig.6 compares to reference values with the proposed two-step SE method and common ISE method. As can be seen in this figure, values estimated in the proposed method are matched to the reference values. Furthermore, to investigate the SE accuracy, the root mean squared error (RMSE) as shown in (14) is used:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(z_i - \hat{z}_i)^2}{n}} \tag{14}$$

Here, n is the number of variables, z_i shows the real value of the variable, $\hat{z}_i$ represents the estimated value of the variable.

Fig.7 and Fig.8 show RMSE values for the voltage amplitude and phase angle in all nodes of the network using common and the proposed method. Considering the results obtained from simulations, it can be seen that the RMSE of the proposed method is reduced significantly.

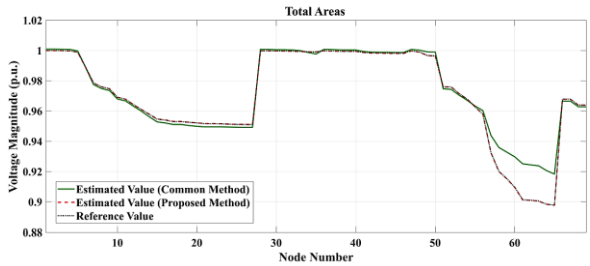

Fig.6. Voltage amplitude state estimation values of the proposed method and the common method.

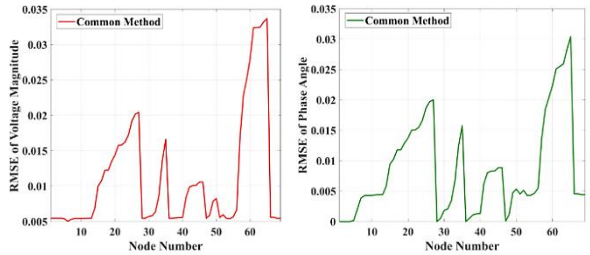

Fig.7. RMSE values for voltage amplitude and phase angle for all nodes of the network in the common method.

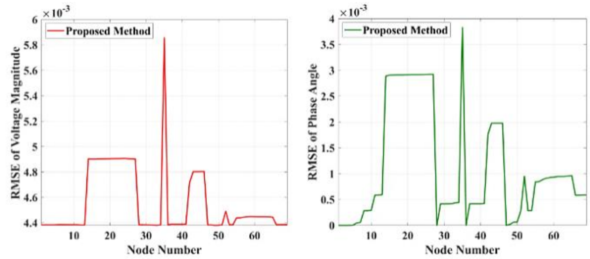

Fig.8. RMSE values for voltage amplitude and phase angle in all nodes of the network in the proposed method.

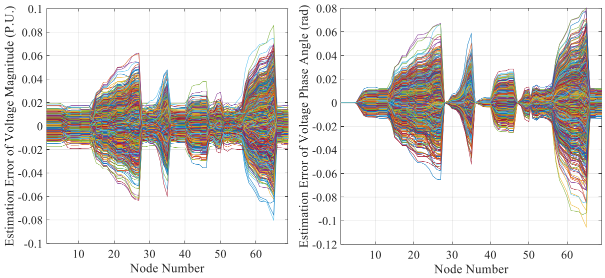

Fig.9. The voltage estimation error of magnitude and phase angle in the common method.

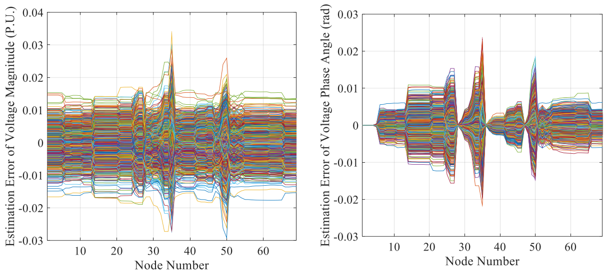

Fig.10. The voltage estimation error of magnitude and phase angle in the proposed method.

Fig. 9 and 10 are shown to evaluate the proposed method performance and compare it with the common used in Ref. [1]. The performance of both SE methods in each Monte-Carlo simulation is based on the voltage estimation error of magnitude and phase angle of the nodes.

In addition, using the proposed method, the SE execution time is reduced from 375.7409 ms to 148.7108 ms. Therefore, the SE speed is increased and total estimated time is decreased. The total time is the summation of the first and second SE steps. Table 2 shows the total execution time of the proposed two-step method and common ISE method for the 69-bus network.

Table 2. Execution time

Common method Ref. [1]	Execution time (ms)			
	375.7409			
Proposed method	Step 1		Step 2	Total
	A	14.6548	105.5127	148.7108
	B	15.4981		
	C	13.0452		

7.2. Sensitivity Analysis

Due to the low presence of precise measurements in DNs, pseudo-measurements are widely used in DNs. Pseudo-measurements are extracted from the load prediction information, therefore, the accuracy of these measurements will have an impact on SE performance. In Table 3, the accuracy effect of these types of measurements on the performance of the common and proposed method is presented. Given that the number of pseudo-measurements are more in the common method, increasing the accuracy of pseudo-measurements has a significant effect on the SE accuracy. Furthermore, accurate measurements obtained from the initial SE have replaced the pseudo-measurements in the proposed method; the improvement of the precision of the pseudo-measurements has little effect on the SE accuracy.

Table 3. Relative error average of estimated voltage magnitude and phase angle

The standard deviation of pseudo-measurements (%)	REA_v (%)		REA_θ (rad)	
	Proposed method	Common method	Proposed method	Common method
50	0.95	1.53	0.6	1.02
40	0.89	1.23	0.55	0.87
30	0.78	1.01	0.51	0.76
20	0.69	0.85	0.48	0.65
10	0.55	0.65	0.32	0.51

The average relative total error of the voltage amplitude and the phase angle is expressed in terms of the following equations, and are defined with REA_v and REA_θ, respectively.

$$REA_v = \sum_{i=1}^{N_{mc}} \frac{\left|\frac{V_i - \hat{V}_i}{\hat{V}_i}\right| \times 100}{N_{mc}} \tag{15}$$

$$REA_\theta = \sum_{i=1}^{N_{mc}} \frac{\left|\frac{\theta_i - \hat{\theta}_i}{\hat{\theta}_i}\right| \times 100}{N_{mc}} \tag{16}$$

8. CONCLUSIONS

The proposed SE is implemented through accurate modelling of all types of measurements in DN. To implement the SE method, the WLSE approach is used. The technique employed in this work for the SE is based on a two-step method which is performed around PMU measurements of the network. Small sub-areas selected around PMU measurements, perform the first estimation step. Each sub-area performs LSE by its local estimator. Results are given to the central processor in parallel and decentralized form. This unit processes data obtained from the first estimation step, and adjusted measurements and measurements placement are used to perform second estimation step which includes total network estimation. One of the main features of the proposed scheme is the reduction of the number of pseudo-measurements. Furthermore, by zoning the network into smaller sub-areas in the first step, total estimated time is reduced significantly. Performance accuracy is represented using RMSE.

REFERENCES

[1] M. Pau, P. A. Pegoraro and S. Sulis, "Efficient branch-current-based distribution system state estimation including synchronized measurements", *IEEE Trans. Instrum. Meas.*, vol. 62, pp. 2419-2429, 2013.

[2] A. Ranković, B. M. Maksimović and A. T. Sarić, "A three-phase state estimation in active distribution networks", *Int. J. Electr. Power Energy Systems.*, vol. 54, pp. 154-162, 2014.

[3] M. E. Baran and A. W. Kelley, "A branch-current-based state estimation method for distribution systems", *IEEE Trans. Power Syst.*, vol. 10, pp. 483-491, 1995.

[4] C. Muscas, M. Pau, P. A. Pegoraro and S. Sulis, "Uncertainty of voltage profile in PMU-based distribution system state estimation", *IEEE Trans. Instrum. Meas.*, vol. 65, pp. 988-998, 2016.

[5] A. Primadianto and C. N. Lu, "A review on distribution system state estimation", *IEEE Trans. Power Syst.*, vol. 32, pp. 3875-3883, 2017.

[6] S. Chakrabarti, E. Kyriakides and M. Albu, "Uncertainty in power system state variables obtained through synchronized measurements", *IEEE Trans. Instrum. Meas.*, vol. 58, pp. 2452-2458, 2009.

[7] S. Chakrabarti, E. Kyriakides, G. Ledwich and A. Ghosh, "Inclusion of PMU current phasor measurements in a power system state estimator", *IET Gener. Transm. Distrib.*, vol. 4, pp. 1104-1115, 2010.

[8] M. Lixia, A. Benigni, A. Flammini, C. Muscas, F. Ponci and A. Monti, "A software-only PTP synchronization for power system state estimation with PMUs", *IEEE Trans. Instrum. Meas.*, vol. 61, pp. 1476-1485, 2012.

[9] K. Mazlumi, M. Mohammad Gholiha, R. Abbasi and F. Mazlumi, "Presenting a new method based on branch placement for optimal placement of phasor measurement units", *J. Oper. Autom. Power Eng.*, vol. 2, pp. 32-39, 2014.

[10] F. Aminifar, M. Shahidehpour, M. Fotuhi-Firuzabad and S. Kamalinia, "Power system dynamic state estimation with synchronized phasor measurements", *IEEE Trans. Instrum. Meas.*, vol. 63, pp. 352-363, 2014.

[11] I. Roytelman and S. Shahidehpour, "State estimation for electric power distribution systems in quasi real-time conditions", *IEEE Trans. Power Delivery*, vol. 8, pp. 2009-2015, 1993.

[12] H. Wang and N. N. Schulz, "A revised branch current-based distribution system state estimation algorithm and meter placement impact", *IEEE Trans. Power Syst.*, vol. 19, pp. 207-213, 2004.

[13] M. E. Baran and A. W. Kelley, "State estimation for real-time monitoring of distribution systems", *IEEE Trans. Power Syst.*, vol. 9, pp. 1601-1609, 1994.

[14] C. Muscas, M. Pau, P. A. Pegoraro, S. Sulis, F. Ponci and A. Monti, "Two-step procedures for wide-area distribution system state estimation", *in Instrum. Meas. Technol. Conf. (I2MTC) Proceedings, 2014 IEEE Int.*, pp. 1517-1522, 2014.

[15] Y. Ju, W. Wu, F. Ge, K. Ma, Y. Lin and L. Ye, "Fast decoupled state estimation for distribution networks considering branch ampere measurements", *IEEE Trans. Smart Grid*, vol. 9, pp. 6338-6347, 2018.

[16] H. Wang, W. Zhang and Y. Liu, "A robust measurement placement method for active distribution system state estimation considering network reconfiguration", *IEEE Trans. Smart Grid*, vol. 9, pp. 2108-2117, 2018.

[17] L. Zhao and A. Abur, "Multi area state estimation using synchronized phasor measurements", *IEEE Trans. Power Syst.*, vol. 20, pp. 611-617, 2005.

[18] A. J. Conejo, S. de la Torre and M. Canas, "An optimization approach to multiarea state estimation", *IEEE Trans. Power Syst.*, vol. 22, pp. 213-221, 2007.

[19] A. Gómez-Expósito, A. de la Villa Jaén, C. Gómez-Quiles, P. Rousseaux and T. Van Cutsem, "A taxonomy of multi-area state estimation methods", *Electr. Power Syst. Res.*, vol. 81, pp. 1060-1069, 2011.

[20] N. Nusrat, M. Irving and G. Taylor, "Development of distributed state estimation methods to enable smart distribution management systems", *Ind. Electron. (ISIE), 2011 IEEE In.l Symp.*, pp. 1691-1696, 2011.

[21] L. D. A. Garcia and S. Grenard, "Scalable distribution state estimation approach for distribution management systems", *In Innovative Smart Grid Technol. (ISGT Europe), 2011 2nd IEEE PES Int. Conf. Exhibition*, pp. 1-6, 2011.

[22] C. Muscas, M. Pau, P. A. Pegoraro, S. Sulis, F. Ponci and A. Monti, "Multiarea distribution system state estimation", *IEEE Trans. Instrum. Meas.*, vol. 64, pp. 1140-1148, 2015.

[23] C. Muscas, P. A. Pegoraro, S. Sulis, M. Pau, F. Ponci and A. Monti, "Fast multi-area approach for distribution system state estimation", *Instrum. Meas. Technol. Conf. Proc. (I2MTC), 2016 IEEE Inter.*, pp. 1-6, 2016.

[24] P. Ren and A. Abur, "Avoiding divergence in multi-area state estimation", *IEEE Trans. Power Syst.*,vol. 34, pp. 3178-3187, 2019.

[25] B. Hayes and M. Prodanovic, "State estimation techniques for electric power distribution systems", *Modell. Symp., 2014 Eur.*, pp. 303-308, 2014.

[26] S. M. Mahaei and M. R. Navayi, "Power system state estimation with weighted linear least square", *Int. J. Electr. Compu. Eng.*, vol. 4, pp. 169-178, 2014.

[27] A. Rabiee, "An Advanced State Estimation Method Using Virtual Meters", *J. Oper. Autom. Power Eng.*, vol. 5, pp. 11-18, 2017.

[28] K. Amiri and R. Kazemzadeh, "Two-stage estimation method presentation to improve electrical distribution networks state estimation", *J. Nonlinear Syst. Electr. Eng.*, vol. 5, pp. 22-38, 2019.

[29] O. Eghbali, K. Amiri and R. Kazemzadeh, "A Study on Types of Measurements in Distribution System State Estimation", *2019 5th Conf. Knowl. Based Eng. Innovation* , pp. 223-229, 2019.

[30] P. A. Pegoraro, J. Tang, J. Liu, F. Ponci, A. Monti and C. Muscas, "PMU and smart metering deployment for state estimation in active distribution grids", *Energy Conf. Exhibition, 2012 IEEE Int.*, pp. 873-878, 2012.

[31] F. Ahmad, A. Rasool, E. Ozsoy, R. Sekar, A. Sabanovic and M. Elitaş, "Distribution system state estimation-A step towards smart grid", *Renewable Sustainable Energy Rev.*, vol. 81, pp. 2659-2671, 2018.

[32] A. Alimardani, F. Therrien, D. Atanackovic, J. Jatskevich and E. Vaahedi, "Distribution system state estimation based on nonsynchronized smart meters", *IEEE Trans. Smart Grid*, vol. 6, pp. 2919-2928, 2015.

[33] W. M. Lin and J. H. Teng, "State estimation for distribution systems with zero-injection constraints", *Power Ind. Comput. Appl. Conf.*, pp. 523-529, 1995.

[34] R. Singh, B. C. Pal and R. B. Vinter, "Measurement placement in distribution system state estimation", *IEEE Trans. Power Syst.*, vol. 24, pp. 668-675, 2009.

[35] D. M. Falcao, F. F. Wu and L. Murphy, "Parallel and distributed state estimation", *IEEE Trans. Power Sys.*, vol. 10, pp. 724-730, 1995.