A new procedure based on continuous RTU measurement to estimate multi-port Thevenin equivalent circuit parameters of an external power system

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***Abstract*— In this paper, a novel method is presented that can accurately estimate the Thevenin equivalent circuit parameters of an external power system by RTUs. The presented method is based on the simultaneous measurements of the desired points in the boundary system, which includes the bus voltage amplitude, the current amplitude of the boundary transmission lines, as well as active and reactive power, and is continuously active until the Thevenin equivalent circuit model is be available online. The practical application of the proposed method is related to online monitoring and control of wide area power systems as well as their development design. Also, the innovation of the method is the accurate estimation of the Thevenin equivalent circuit model from part of the power network that information is not available. In the proposed method, an additional measurement and the least squares method are used to eliminate measurement errors in order to accurately estimate the parameters of the equivalent circuit model. In order to avoid providing the wrong equivalent circuit model due to external system changes, a method is presented that can track the correct system changes to continuously monitor the disturbances. The proposed method performance has been implemented and validated by DigSILENT software.**

***Index Terms*— Thevenin equivalent circuit, Continuous synchronized amplitude measurement, Equivalent external system, Remote measurement unit (RTU).**

I. INTRODUCTION

The ever increasing development of power grid and industrial electronic devices has turned power systems into extensive systems that are wide area and complex in terms of dimensions and performance. With the increase in power consumption, these vast systems are forced to exchange power between each other and further develop, which will require online or offline analysis of the systems and will have a large computational burden. Therefore, in the design of network expansion, their online monitoring and control, the Thevenin equivalent circuit of the power network is needed due to the connection of several systems with many connection points.

For reasons such as the lack of parameters measurement facilities, the only existing power system connected to several other systems is often considered in calculations. Equalization techniques can make computations possible due to the system size reduction. The accuracy of equalization in the external network connected to the main network determines the degree of superiority in different methods. Some cases, such as the unavailability of error-free information in measuring devices, ignoring a part of the network that determines important parameters such as the voltage level, and changes that occur from the external network side, cause large errors in equalization calculations. According to the mentioned cases, the accuracy of the results is different with the practical limitations of the methods [1-3].

Thevenin equivalent circuit has various applications for a part of the power system that is not available or the focus of calculations and control is not on it. The use of Thevenin equivalent network is quite common in the online investigation of various types of line faults, generator faults and transient state stability investigation of the developed power system [4]. The equivalent circuit model can be used in applications that monitor the power grid online, such as state estimation, system analysis, and determining the location of disturbances in the power grid [5].

The presented method in [6] suggests the use of the equivalent circuit model for a part of the power network in order to the validation and calibration of the production unit model, which is implemented using synchro phasor measurements. Also, other applications of external network modelling can be mentioned in voltage stability analysis [7].

Studying the range of voltage stability in the power network for operation is an important issue that, if not correctly diagnosed, will cause errors in the calculation of the transmission lines load factor and may eventually cause voltage instability, blackouts and other disturbances in the power system. The use of accurate and fast calculations will increase the stability of the voltage in the power system. In [8], a method based on using the Thevenin equivalent circuit of the power system is presented to determine the power transmission with the condition of keeping the voltage level constant, which uses the PMU measurement unit as well as the load model simultaneously. The basis of the method is based on checking the collapse point in the characteristic curves of the reactive power on the receiver side and the reactive power on the bus side, which has the lowest voltage level, which leads to the determination of the equivalent model, but the percentage of error in the presented method is very high.

Existing methods to determine the equivalent circuit model of the external system use readymade models that require measurement data from the power system and are impractical if the data is not available. In [9], the behavior of the power system assays in the normal state and at the moment of fault which is one of the applications of using modeling that considers the power system radially. In a more recent method for approximate analysis of developed power systems, the Thevenin equivalent circuit model is used, whose parameters are determined through discrete Fourier transform calculations based on local phasor measurements (PMU) in the entire power network [10]. The Thevenin's equivalent estimation model is used to investigate all types of power flow studies. Because the proposed method in [11] is based on measurement (PMU), it uses a comparative method to reduce the effects of measurement noise so that it can use the most complete data for use in the method. The use of full phasor in calculations, the time-consuming algorithm and also the inability to estimate the modeling component are among the defects of that method.

With the advancement of power system parameters measurement technology, data collection and sending them for use in SCADA has made significant progress. Model-based methods and data measurements can be used to determine the parameters of the Thevenin equivalent circuit. Due to the extent and complexity of the power system, the possibility of a part of the network being unavailable for various reasons has increased, which has led to the division of each independent power system. Therefore, the division of the power system is of particular importance to obtain network parameters, network development and control.

According to [12], the independent power system is generally divided into three parts: a) the internal system which is visible and its parameters can be measured (the focus of calculations and analysis is on the internal system), b) the boundary system which includes all the boundary buses between two internal and external systems. These buses are visible by SCADA and measuring equipment can be installed in this area. c) the external system whose buses or their parameter data are not available for any reason, which is replaced in the analysis of the system with the Thevenin equivalent circuit and there are no other measurement data. Reference [13] has introduced a computationally intensive method to determine the equivalent circuit of the power grid, which is used to evaluate the security reliability of the system. One of the main problems of this method is the use of a ready-made model, which must always be changed and will cause standard deviation. The need to measure in the external network is another weakness. In [14], a methodology has been presented to obtain system equivalent of external systems for on-line security evaluation. Drawback of this method is in model selection of the internal variable and approximate system in the calculations, which leads to the equivalent circuit of the external network with errors.

PMUs measuring equipment have recently attracted the attention of researchers for measuring and exchanging data in different parts of the wide power system, and the use of these measuring devices is increasing. In [15], a practical method for dynamic control of the system and damping control of electro-mechanical oscillations of complex power systems is presented, which can be implemented by replacing the Thevenin equivalent circuit model or reducing different parts of the power network with real mode that can be used from models based on measurement. One of the fastest methods of calculating power system state estimation based on large number of measured data and power network modeling is the least squares method, which is generalized in [16].

In the applied methods presented in [17-19] for network condition estimation and modeling for monitoring and control of the developed power system, PMU and RTU measurements are used as a combination devices connected to SCADA, which is continuously is gathering information. Methods for power system state estimation have been introduced, which are used to formulate the method of nonlinear measurement functions with PMU simultaneously, which has a fundamental application in the field of power system analysis [20-22]. The problem of these estimation methods is that thay need to data phasor.

In another practical experiment, a method has been accurately proposed to evaluate the voltage stability of power systems with presence of wind power, which could reduce the error of network voltage stability monitoring by increasing the influence of wind power. The basis of the work of that method is the Thevenin equivalent circuit analysis for power systems that have a wind power source and existing resources. Finally, it provides the user with the correct stability criterion according to the impedance analysis of the Thevenin equivalent circuit with the change of wind force [23]. In [24], a methodoloy based on the parameters of the Thevenin network equivalent model have been used in order to accurately evaluate the voltage stability of effective buses in the power system, and the sensitivity equations have been generalized using PMU measurements. The voltage and reactance parameters of the Thevenin network, which is finally modeled using the comparative algorithm by spending a lot of time and using modern devices in the condition of discontinuous loading of the network, which compared to other methods is more complexity and the cost is inefficient. The presented method in [25] tracks the changes of the system and by generalizing the equations, it was able to reduce the cost function and obtain the final formula of the Thevenin equivalent modeling of the power system using an expensive measurement system with a high error value. A method is proposed in this paper that is based on simultaneous and continuous measurement to find the Thevenin equivalent of the external system and can solve the modeling problems of the studied external network. The presented algorithm does not need to have external system data and will be responsible for finding the Thevenin equivalent circuit parameters in all modes and the accuracy of its results has increased compared to other methods. The Thevenin equivalent circuit of the external network is determined using the least squares method for multiple measurements collected from the boundary buses. Also, a method is proposed to check the changes of the external system from the measurement data collected at the boundary nodes to verify that the external system does not change during detection. Meanwhile, the calculation volume of the proposed method has been significantly reduced compared to other methods, which makes it suitable for continuous work and creating a real-time Thevenin equivalent circuit model of the external system. The external network cannot be reached due to the remoteness or inaccessibility of the physical part of the power system, or the connection with the measuring devices of that part is disconnected due to atmospheric or telecommunication disturbances. Therefore, in such conditions, the proposed algorithm provides a new accurate methodology for online modeling of the external network with the lowest amount of error, which increases the reliability of command and control of the comprehensive power system in any situation. The application cases of the presented method are: power system development, communicating to two or more adjacent power networks, power system islanding, power system startup blocked out by the adjacent system, or modeling before any switching in the subset, checking the voltage stability. It is obvious that the transient state is electrically much faster than the dynamic state, which brings the time required for the entire transient electrical state to a few hundredths of a second to reach the permanent state. Therefore, considering that the presented method has the ability to set the time of receiving continuous measurements through dispatching centers, and if it has the ability to continuously measure and send parameters every second, the algorithm is able to calculate and provide Thevenin's equivalent.

The functional and economic advantage of the presented method compared to the previous experiences is that the method proposed in this article, unlike other methods, does not have data collected by equipment such as PMUs. They are very expensive communication-measuring tools that are usually accessible at a high cost in developing countries due to the backwardness of technology. The basis of the proposed method in this paper is based on the data received from the simple and conventional tools as RTUs, which are installed in all substations. Therefore, the implementation of this method requires a lower cost compared to other methods due to the use of simpler peripheral hardware and greater accessibility.

II. THE PROPOSED METHOD DESCRIPTION

In this section, the proposed method is presented for accurate estimation of Thevenin equivalent circuit of the external system. Fig. 1 shows the desired equivalent circuit model which can be multi-ports. Also, the unknown parameters of the equivalent circuit are estimated by calculating the formulas derived from the proposed method. In this part, a plan for measuring power network data is presented, which, together with the principles of circuit theory, will lead to the extraction of the formulas of the proposed method.

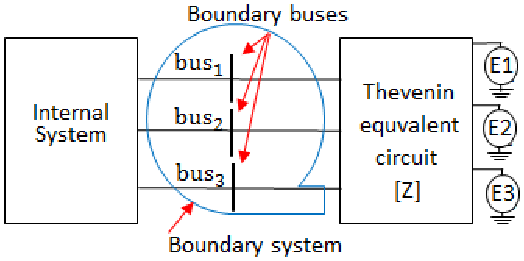

Fig. 1. Multi-port Thevenin equivalent of the external system

A. Presentation of Thevenin equivalent circuit model

The external network is replaced by a multi-port Thevenin equivalent circuit in the proposed method, which is introduced by (1) [26].

$$\left[V_{bus-N}\right]=\left[Z\right]\left[I_{Line-N}\right]+\left[E\right] \tag{1}$$

where V_{bus-N} and I_{Line-N} are the boundary phase voltage and current, respectively. Also, Z and E are Thevenin impedances and equivalent voltage sources, respectively.

B. The proposed method for measuring data

In the presented method, the measurement of the required data is done in boundary buses as shown in Fig. 2. The data includes the amplitude of voltage and current as well as the transmitted complex power, which is continuously measured and sent to SCADA for processing according to the proposed method.

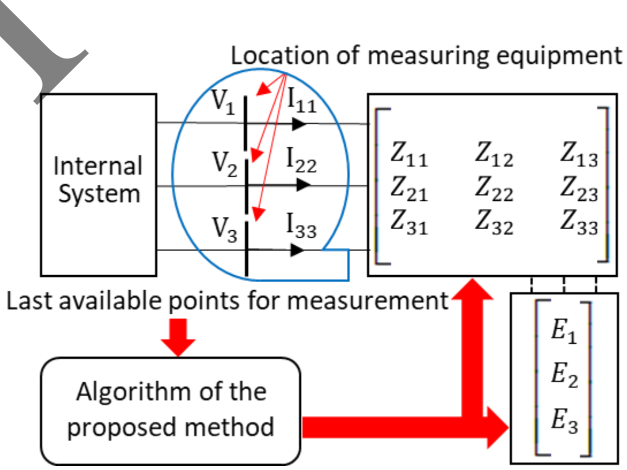

Fig. 2. Data measurement scheme

Equation (2) fully shows the parts of the matrix of unknowns presented in Fig. 2.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}=\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}\begin{bmatrix} I_{11} \\ I_{22} \\ I_{33} \end{bmatrix}+\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{2}$$

Due to the multi-port connection of the Thevenin equivalent circuit, simultaneous measurements of the voltage and current amplitudes are required to accurately estimate the unknown parameters of the equivalent circuit. Based on the proposed method, the measurements are performed using RTU that can measure the amplitude of voltage and current as well as the mixed power transmitted to the external system in the boundary buses. Contrary to previous experiences in the proposed method, there is no need to have the phasor of the data, which proves the superiority of the method.

SCADA system is widely used to model, control and monitor the power system network, and their operation is intelligent and continuous. SCADA is a processor that needs data sent from the measurement equipment connected to it. One of these inputs is RTU. Remote terminal units are used to collect the data and then transfer it to the SCADA center. The boundary system is of particular importance due to the presence of boundary buses and measurement equipment. In the presented method, it uses only the equipment data that are in the boundary area. The boundary bus on the internal system side is connected to at least one other bus by a line, which is called an auxiliary bus.

C. Calculation of Boundary Bus Phasor Data

Bus voltage amplitude, line current amplitude, active and reactive power transmitted between nodes are collected by RTUs according to the presented method. But to calculate the parameters of the Thevenin equivalent circuit using linear equations, the phasor of the measured parameters is needed.

Therefore, according to the middle line model, as shown in Fig. 3 for all connection lines between the boundary bus and the auxiliary bus, voltage equations are given to calculate the boundary bus voltage phasor for the selected model.

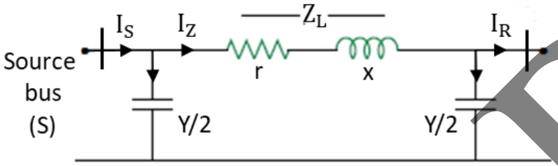

Fig. 3. The midline line model

Considering that the direction of power transfer and current injection is not always constant, the equations are written in two ways, which can be detected by the auxiliary bus in the internal system. In the first model, the boundary bus is the source of the current and the auxiliary bus is the sink of the current, and in the second model, the boundary bus is the sink of the current, which are shown in equations (3-10). If the boundary bus is the source of the current:

$$V_S = V_R + Z_L I_Z \tag{3}$$

$$I_Z = I_R + (\frac{Y_L V_R}{2}) \tag{4}$$

$$V_S = V_R + Z_L (I_R + \frac{Y_L V_R}{2}) \tag{5}$$

$$V_S = V_R (1 + \frac{Z_L Y_L}{2}) + Z_L I_R \tag{6}$$

If the boundary bus is the sink of the current:

$$V_R = V_S - Z_L I_Z \tag{7}$$

$$I_Z = I_S - (\frac{Y_L V_S}{2}) \tag{8}$$

$$V_R = V_S - Z_L (I_S - \frac{Y_L V_S}{2}) \tag{9}$$

$$V_R = V_S (1 + \frac{Z_L Y_L}{2}) - Z_L I_S \tag{10}$$

Where Z_L . Y_L . V_S . V_R . I_S . I_R and I_Z are line series impedance, parallel line admittance, source bus voltage phasor, sink bus voltage phasor, injection current, output current and passing current from middle line model respectively. This basic data is available in the internal system. To use this method, the correct current direction must be considered to select the correct equation. The internal system has known parameters that are measured by measuring equipment such as RTUs or PMUs.

According to the obtained equations (3-10) and having auxiliary bus parameters inside the internal system, the boundary bus voltage phasor is obtained. To coordinate the angles of all boundary buses and auxiliary buses, a node in the internal system is considered as a slack bus.

As shown in Fig. 4, there is an angular difference between the bus voltage phasor (S) with the line current phasor (S-R).

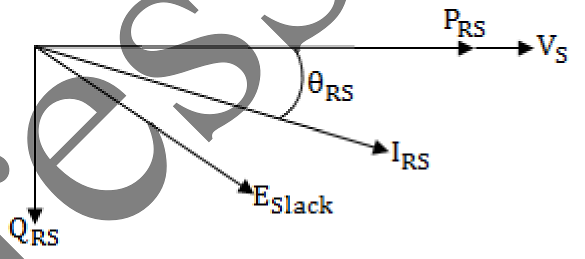

Fig. 4. Phase angle reference

According to the loose bus in the internal system, if the P and Q transmitted to the bus (S) are measured by the RTUs, the angle I_{RS} with respect to the bus (S) can be calculated without any other measurements. It is worth noting that the injection current angle of the line (R-S) is relative to the bus (S). Equation (11) has also been derived for the general state [27].

$$\theta_{RS} = \tan^{-1}(-\frac{Q_{RS}}{P_{RS}}) \tag{11}$$

Where P_{SR} and Q_{SR} are active and reactive power measurable that are transferred through the line (S-R) from bus (S) to bus (R) respectively. The values obtained due to the use of data from measuring devices are always associated with some error, which is shown in (12) and (13). Therefore, it can be used to obtain the phasor of the boundary bus voltage and the passing current angle from the accurate boundary bus of the additional measuring level to reduce the error in the actual measured values caused by the noise effects of the equipment. Each time the procedure presented using the least squares method provides more accurate final values, which are presented in the following sections.

$$V_R = (v_R + e_{v_R}) e^{j(\delta + e_\delta)} \tag{12}$$

$$I_{RS} = (i_{RS} + e_{iRS}) e^{jtg^{-1}(-\frac{Q_{RS} + e_{QRS}}{P_{RS} + e_{QRS}})} \tag{13}$$

Where V_R , I_{SR} , v_R , i_{SR} , e_{v_R} ,$e_{i_{SR}}$. δ . e_δ , $e_{p_{SR}}$ and $e_{Q_{SR}}$ are measured auxiliary bus voltage phasor, The phasor of the current transferred from the boundary bus with error values, the real auxiliary bus voltage amplitude, the real current amplitude transferred to the boundary bus, the voltage amplitude measurement error value, the current amplitude transferred to the boundary bus error value, the auxiliary bus voltage angle to bus slack, the bus voltage angle error value, the active power measurement error value and reactive power measurement error value which is transferred from bus (R) to bus (S) via (R-S) line, respectively.

D. Calculation of the Thevenin equivalent circuit unknown parameters

The impedance matrix [Z] and the voltage source vector [E] are the matrices of the unknown parameters of the equivalent circuit model according to the proposed method. For example, the extended power system with three boundary buses shown in Fig. 5, [Z] is a 3 by 3 matrix with 18 unknowns which includes the real and imaginary part of 9 elements. [E] has 6 unknowns which includes real and imaginary parts of 3 elements.

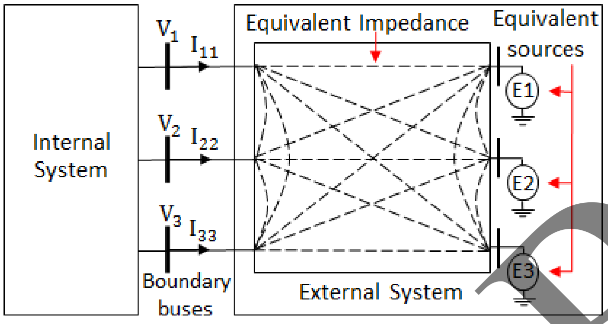

Fig. 5. Equivalent circuit model with three boundary buses

Each time, a measurement is taken from a set of boundary buses, an independent data set is considered as a data-point. Based on equation (1), each data-point generalizes 6 equations. To find 24 unknowns, at least 24 equations with 4 data-points are required. The number of data points required is shown in equation (14).

$$N_{required\ data\ point} = N_{\text{boundary buses}} + 1 \tag{14}$$

$N_{required\ data\ point}$ and $N_{\text{boundary buses}}$ are the data-points and number of boundary buses, respectively. The first step is related to the measurement of the required data, in which the number of measurement times should be proportional to the number of boundary buses. Then, in the next step, with the obtained data, the equivalent unknowns of the external network are estimated using the following equations.

$$X = P^{-1}H \tag{15}$$

$$X = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{21} & Z_{22} & \dots & Z_{33} & E_1 & E_2 & E_3 \end{bmatrix}^T \tag{16}$$

$$H = \begin{bmatrix} V_1^1 & V_2^1 & V_3^1 & V_1^2 & V_2^2 & V_3^2 & V_1^3 & V_2^3 & V_3^3 & V_1^4 & V_2^4 & V_3^4 \end{bmatrix}^T \tag{17}$$

$$P = \begin{bmatrix} I_{11}^1 & I_{22}^1 & I_{33}^1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{11}^1 & I_{22}^1 & I_{33}^1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{11}^1 & I_{22}^1 & I_{33}^1 & 0 & 0 & 1 \\ I_{11}^2 & I_{22}^2 & I_{33}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{11}^2 & I_{22}^2 & I_{33}^2 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{11}^2 & I_{22}^2 & I_{33}^2 & 0 & 0 & 1 \\ & & & & & \dots & & & & & & \\ I_{11}^4 & I_{22}^4 & I_{33}^4 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{11}^4 & I_{22}^4 & I_{33}^4 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{11}^4 & I_{22}^4 & I_{33}^4 & 0 & 0 & 1 \end{bmatrix} \tag{18}$$

where [X] is the matrix of unknowns, [H] is the known matrix of the voltage phasor and [P] is the known matrix of the current phasor, which is calculated by the proposed method. Also, V_1^1 is the voltage phasor of the first boundary bus from the first measurement and V_1^2 is the voltage phasor of the first boundary bus from the second measurement. According to the proposed method, after measuring the data amplitude by RTUs, the angle of the buses and the current angle of the lines relative to the reference bus are obtained according to equation (11). Also, the phasor values are completed for use in equation (15) until the Thevenin equivalent circuit parameters of the external network to be determined.

III. IMPLEMENTING THE PROPOSED METHODOLOGY

Implementing the proposed method requires investigating issues such as: calculating the boundary bus voltage phasor by measuring the voltage amplitude, neutralizing data measurement errors, the line current phasor in sync with bus slack, the minimum value of acceptable changes and trace location of disturbance. These topics are given in this section.

A. Calculating the boundary buses voltage phasor

The voltage phasor of the N_{th} boundary bus in the boundary system with RTU measurement can be calculated in one step using Equations (6) or (10) as shown in (19). Where, V_{S1}^1 is the voltage phasor of the first boundary bus from the first measurement, V_{R2}^N is the voltage phasor of the second boundary bus from the N_{th} measurement and I_{S2}^1 is the phasor of the line current between the first boundary bus and the auxiliary bus, which is the data of the internal system, and I_{R2}^N is the line current phasor between the second boundary bus and the auxiliary bus, from the N_{th} measurement. (S) Or (R) voltage phasor obtained depends on whether the boundary bus is a source or a sink, and according to this method, the matrix of line impedance coefficients between the boundary bus and the auxiliary bus is changed.

$$\begin{bmatrix} V_{S1}^{1} & I_{S1}^{1} & 0 & 0 & \dots \\ 0 & 0 & V_{R1}^{1} & I_{R1}^{1} & \\ \dots & & \dots & & \dots \\ V_{SN}^{N} & I_{SN}^{N} & 0 & 0 & \\ 0 & 0 & V_{RN}^{N} & I_{RN}^{N} & \dots \end{bmatrix} L = \begin{bmatrix} V_{S1}^{1} & V_{R2}^{1} & \dots & V_{SN}^{N} & V_{RN}^{N} \end{bmatrix}^{T} \qquad (19)$$

where the coefficient matrix [L] is show in (20).

$$L = \begin{bmatrix} (1+\dfrac{Z^{1}{}_{Line1}Y^{1}{}_{Line1}}{2}) \\ (Z^{1}{}_{Line1}) \\ (1+\dfrac{Z^{1}{}_{Line2}Y^{1}{}_{Line2}}{2}) \\ (-Z^{1}{}_{Line2}) \\ \dots \\ (1+\dfrac{Z^{N}{}_{LineN}Y^{N}{}_{LineN}}{2}) \\ Z^{N}{}_{LN} \\ (1+\dfrac{Z^{N}{}_{LineN}Y^{N}{}_{LineN}}{2}) \\ -Z^{N}{}_{LineN} \end{bmatrix} \qquad (20)$$

B. Neutralizing data measurement errors

Measurement errors or noise prevent the accuracy of results in equivalent circuit modeling. For this purpose, additional data points are used to have more equations and neutralize the effect of noise in the measurement. According to the proposed method to find the unknown parameters equivalent to the external network, minimum required data points are $\mathrm{N}_{\text{boundary buses}} + 1$. Assume that $N_{\text{required data point}}$ are available and Each data point gives the $\mathrm{N}_{\text{boundary buses}}$ equations shown in equations (21)-(23).

$$V_{1}^{1} = E_{1} + Z_{11}I_{11}^{1} + Z_{12}I_{22}^{1} + Z_{13}I_{33}^{1} + \dots \qquad (21)$$

$$V_{2}^{1} = E_{2} + Z_{21}I_{11}^{1} + Z_{22}I_{22}^{1} + Z_{23}I_{33}^{1} + \dots \qquad (22)$$

$$\dots$$

$$V_{N}^{1} = E_{1} + Z_{N1}I_{11}^{1} + Z_{N2}I_{22}^{1} + Z_{NN}I_{NN}^{1} + \dots \qquad (23)$$

To solve the equations obtained from the measurements using a large number of data, the least squares method is used to find the unknown parameters. Equation (24) is a method to solve the linear equations of the system (PX=H).

$$X = (P^{T} \times P)^{-1}(P^{T} \times H) \qquad (24)$$

where [P] and [H] are the measured data matrix and [X] is the unknown parameter matrix.

$$H = \begin{bmatrix} V_{1}^{1} & V_{2}^{1} & V_{3}^{1} & V_{1}^{2} & V_{2}^{2} & V_{3}^{2} & V_{1}^{3} & V_{2}^{3} & \dots & V_{1}^{N} & V_{2}^{N} & V_{3}^{N} \end{bmatrix}^{T} \qquad (25)$$

$$X = \begin{bmatrix} Z_{e11} & Z_{e12} & Z_{e13} & Z_{e21} & Z_{e22} & \dots & Z_{eNN} & E_{1} & \dots & E_{N} \end{bmatrix}^{T} \qquad (26)$$

$$P = \begin{bmatrix} I_{11}^{1} & I_{22}^{1} & I_{33}^{1} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{11}^{1} & I_{22}^{1} & I_{33}^{1} & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{11}^{1} & I_{22}^{1} & I_{33}^{1} & 0 & 0 & 1 \\ I_{11}^{2} & I_{22}^{2} & I_{33}^{2} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{11}^{2} & I_{22}^{2} & I_{33}^{2} & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{11}^{2} & I_{22}^{2} & I_{33}^{2} & 0 & 0 & 1 \\ & & & & & \dots & & & & & & \\ I_{11}^{N} & I_{22}^{N} & I_{33}^{N} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & I_{11}^{N} & I_{22}^{N} & I_{33}^{N} & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{11}^{N} & I_{22}^{N} & I_{33}^{N} & 0 & 0 & 1 \end{bmatrix} \qquad (27)$$

C. Detection of non-negligible disturbances

According to the proposed method, the new data point is actually the first change made at each boundary node that occurred in the boundary system. Considering that the proposed method is based on RTU data measurement and this equipment has some error in the measurement steps and sending to SCADA in the form of noise, any changes should not be considered as new data points. A criterion for investigating sudden changes based on active and reactive power monitoring in the desired transmission line is presented continuously, which can be used to detect non negligible disturbances, which is presented in the form of (28) [28].

$$\mathrm{MC} = (\left|\frac{P_1 - P_2}{P_1}\right| + \left|\frac{Q_1 - Q_2}{Q_1}\right|) \times 100\% \qquad (28)$$

where, MC is the minimum changes of the i_{th} line. P_1 and Q_1 are the active and reactive powers, respectively, that is transmitted by the line before the measurement. Also, P_2 and Q_2 are the active and reactive powers, respectively, that is transmitted by the line after the measurement. Each time a measurement is made by the equipment, if the MC is greater than the default value determined by SCADA, it can be saved as a new data point, otherwise the measurement noise is detected and the measurement data is deleted. to be Due to the centrality of the internal system, small changes in the external system do not affect the internal system, so the default value of MC should be chosen to detect large changes in addition to ignoring noise.

D. Tracking non negligible external system disturbances

The basis of calculations in the proposed method is based on measurements that the external system remains constant during data collection and the internal system changes. But this will not deny small changes in the external system, it should only be ensured that there are no big changes in the external system. Therefore, a criterion to find the place of non-negligible disturbance is proposed to check the accuracy of acceptable data collection for the presented method. ‘equations (29) and (30) are derived considering the relationship between the internal system and the external system. Type of systems connection are shown in Fig. 6 for sample three boundary buses.

$$[I_{line}] = \frac{\Delta E_{total}}{Z_{total}} = \frac{1}{(Z_{Ex} + Z_{In})}([E_{In}] - [E_{Ex}]) \tag{29}$$

$$[V_{bus}] = [E_{Ex}] + Z_{Ex}[I_{Line}] =$$
$$\left(\frac{[E_{In}]}{(Z_{Ex} + Z_{In})Z^{-1}_{Ex}}\right)\left(\frac{[E_{Ex}]}{(Z_{Ex} + Z_{In})Z^{-1}_{In}}\right) \tag{30}$$

where Z_{In} and E_{In} are impedance and equivalent voltage source of the internal system. Also Z_{Ex} and E_{Ex} are equivalent impedance and voltage source of the external system. Using the above equations, it is possible to calculate the boundary buses voltage and the current between them.

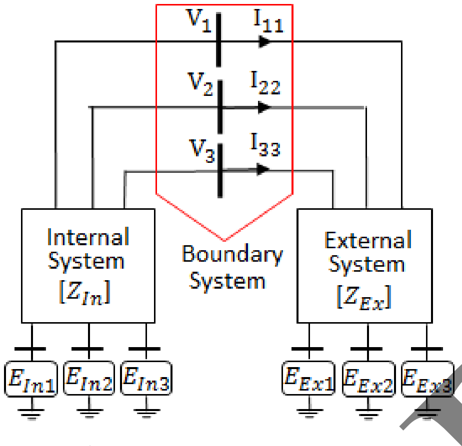

Fig. 6. The structure of connecting the internal system to the equivalent external system

In order to accurately estimate the unknown impedance matrix of the equivalent circuit based on the proposed method, large changes in the external system should not occur. For this purpose, the major disturbances in both internal and external systems are investigated. Also, for each unknown disturbance from the total systems, V_{bus} matrix and I_{line} matrix are obtained using (29) and (30). After collecting the minimum data (number of boundary crossings plus one) according to (15-18), the equivalent unknown impedances can be found. A power system with three boundary buses is investigated. One disturbance is considered for the internal system voltage source (ΔE_{In1}) and two disturbances for the external system voltage sources (ΔE_{Ex2}), (ΔE_{Ex3}). After using the presented method, the impedance matrix of the unknowns is obtained as (31).

$$Z_{eq} = \begin{bmatrix} Z_{In11} & Z_{In12} & Z_{In13} \\ -Z_{Ex21} & -Z_{Ex22} & -Z_{Ex23} \\ -Z_{Ex31} & -Z_{Ex32} & -Z_{Ex33} \end{bmatrix} \tag{31}$$

According to the obtained impedance in equation (31), some elements of the matrix are negative, which indicates changes in the external system. After registering each data point along with the previous data points, calculations are done and before presenting the online equivalent circuit model, the elements of the impedance matrix should be checked in terms of the negativity of the elements. If it has negative elements, the last new data point is not correct due to changes in the external system and it is removed from the list of data points.

E. Flowchart of the proposed method

The implementation of the proposed method is given in the form of a performance flowchart in Fig.7.

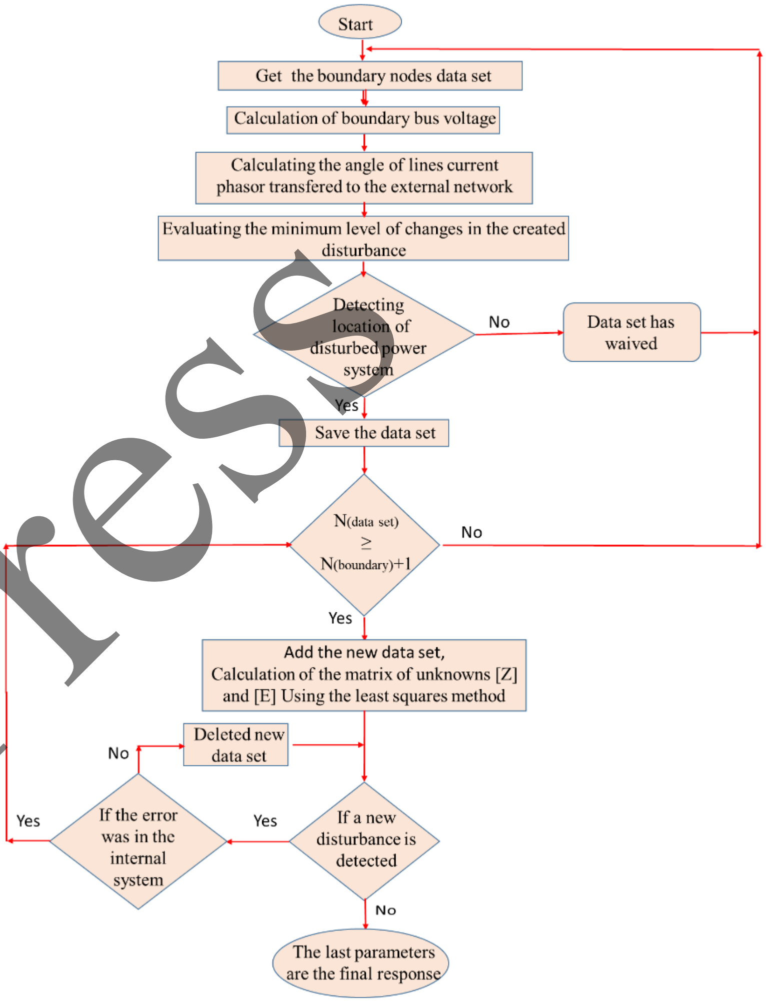

Fig. 7. Flowchart of the proposed method

F. The proposed method algorithm

The proposed method is based on the collection of data sets. But the data sets that have the origin of changes in the external system should be waived from the list. The implementation of the proposed method is described as follows:

Step1: Collect enough data sets.

Step2: Obtain the boundary bus voltage using equations (19) and (20) and complete the line current phasor by calculating the angle using equation (11).

Step3: Determine the disturbed system using equations (15-18).

Step4: If the fault is in the internal system, go to step 6, otherwise, continue to step 5.

Step5: Replace the oldest acceptable data set with the new set and go to step 1.

Step6: Record the data set as the last data and wait for the next disturbance.

Step7: Acceptable data collection should continue at least until the number of data points is equal to ($N_{\text{boundary buses}} + 1$).

Step8: Add the last acceptable set and calculate the unknowns' matrix [Z] and [E] from equations (24-27) using the least squares method.

Step9: If a new disturbance is detected and new data is recorded, use the most recent data sets ($N_{\text{boundary buses}} + 1$) to locate the disturbance using equations (15-18).

Step 10: If the disturbance is from the internal system, go to step (8), otherwise, delete the desired data set.

IV. CASE STUDIES

IEEE 39 bus system is chosen to simulate the proposed method. The internal system and the external system along with the boundary buses are shown in Fig. 8. The system is simulated in DigSILENT and the proposed method is implemented in MATLAB. In boundary buses 01, 05 and 14, RTU is placed to measure the bus voltages amplitude and the line currents amplitude injected to the external system. Measurement errors are made by adding a random noise to the recorded amplitudes to create a 2% total vector error value. Therefore, this data is assumed as RTU measurement data. First, the main IEEE 39 bus is simulated with three measurable boundary buses. The calculation of the actual equivalent parameters is presented in Appendix A.

The performance of the proposed method is simulated by replacing the Thevenin equivalent circuit instead of the real external network in the IEEE 39 bus system. A selected analysis is then performed on both the original and alternative systems, which are described comparatively in the next section. The performance of the proposed method is continuous and online, so the latest equivalent circuit model is available until the moment of receiving the last new data set by using the previous data sets. In the system under study, with three boundary buses and at least four data sets are enough to get the first equivalent model, and it is assumed that the last model is available with the previous data sets. When a new data point is received, it is replaced by the last data set.

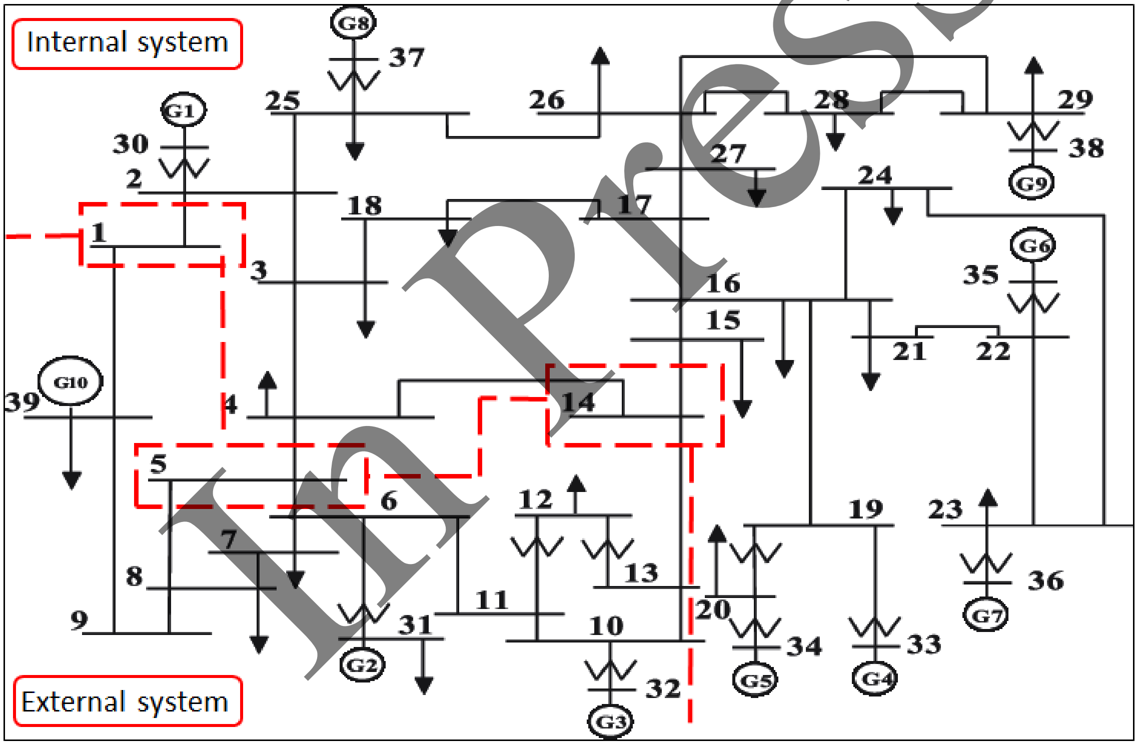

Fig. 8. Internal and external systems in the IEEE 39 bus system with three boundary buses

V. COMPARE THE RESULTS

A. IEEE 39-bus system and Thevenin equivalent circuit model

The use of additional measurements is necessary to neutralize the measurement error values. The accuracy check of the proposed method for performance analysis is performed with a number of data points and minimal changes of the internal system. In the real case, RTUs measure the voltage amplitude of the specified boundary buses, the current amplitude of the lines between the internal system and the external system, as well as the active and reactive power transferred between them, and send the data to the SCADA along with the error values. To collect the required data points, the proposed method for Simulation, the boundary bus voltage amplitude and the line current amplitude transferred to the external system with the recorded values with 2% error are randomly recorded in the boundary system. For each recorded data point, the minimum changes required to find the equivalent circuit parameters the equivalent is selected. Bus voltage changes in the system, production changes and load changes can be used as power system disturbances, which will lead to the recording of data points. With three boundary buses in the system under test, at least four measurement times it is necessary, obviously, with the increase of data points, the accuracy also increases.

Therefore, it has been measured and calculated ten times with the presented method. Only cases of confirmed disturbances are on the external system side. The parameters of the equivalent impedance and bus voltage obtained for the construction of the Thevenin equivalent circuit using the measurement of the required values and the calculation using the method presented in Fig. 9 - Fig. 17, are given in a comparative way.

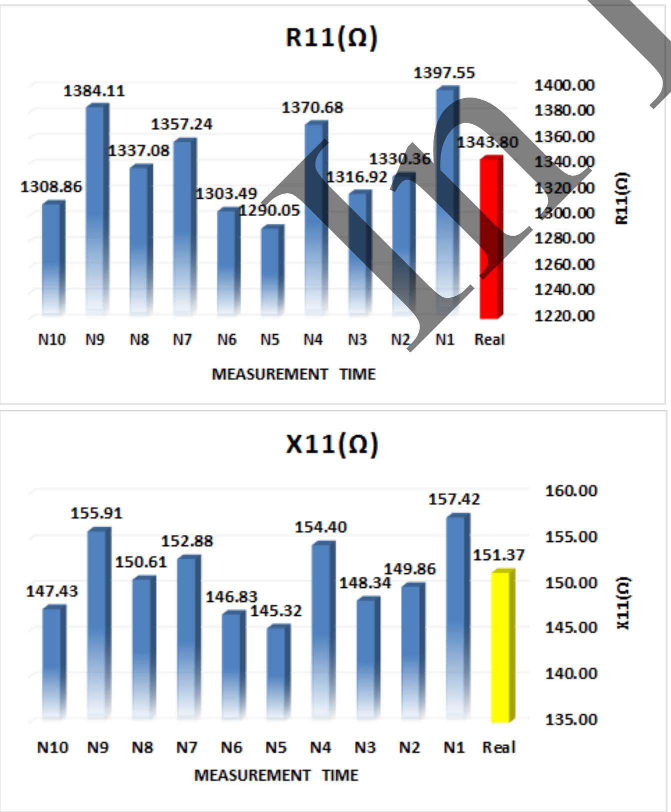

Fig. 9. Comparison of real and equivalent impedance (Z11)

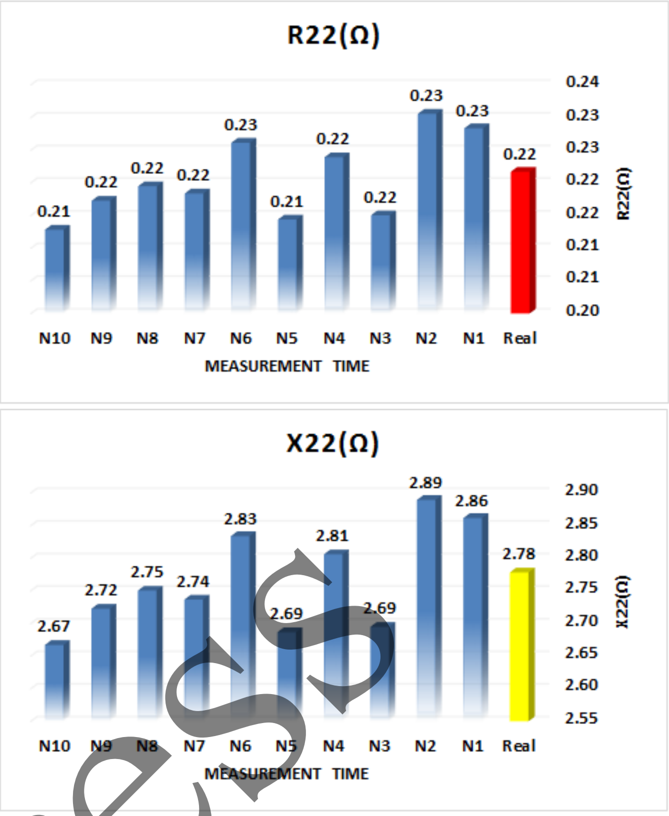

Fig. 10. Comparison of real and equivalent impedance (Z22)

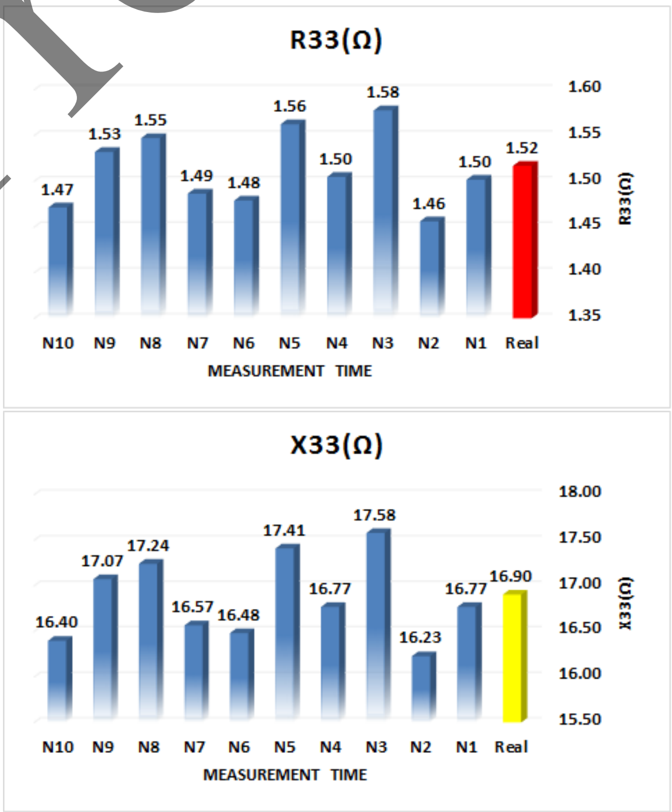

Fig. 11. Comparison of real and equivalent impedance (Z33)

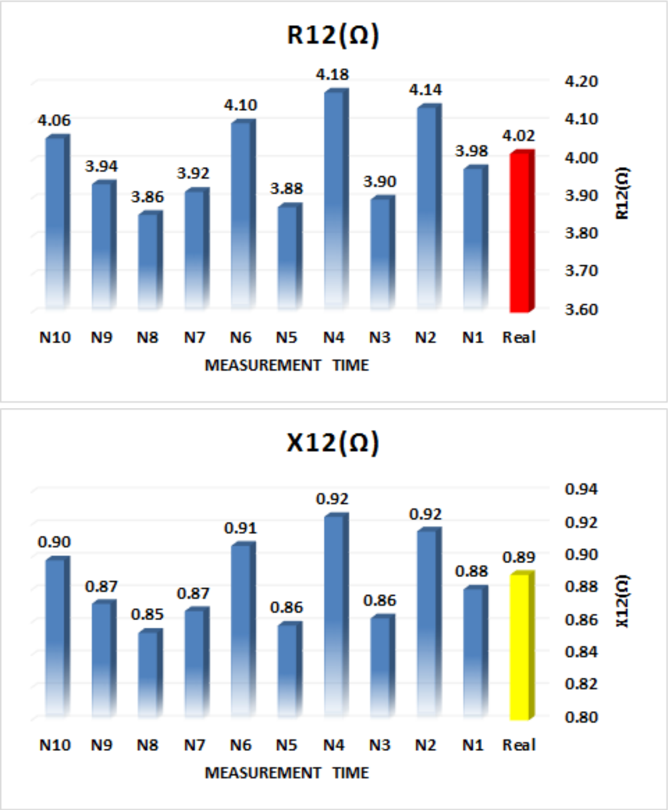

Fig. 12. Comparison of real and equivalent impedance (Z12)

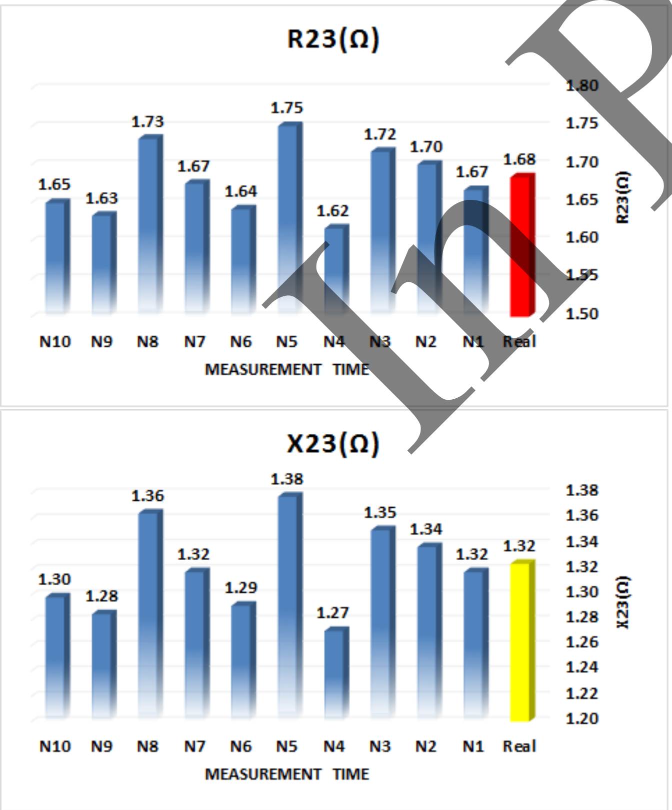

Fig. 13. Comparison of real and equivalent impedance (Z23)

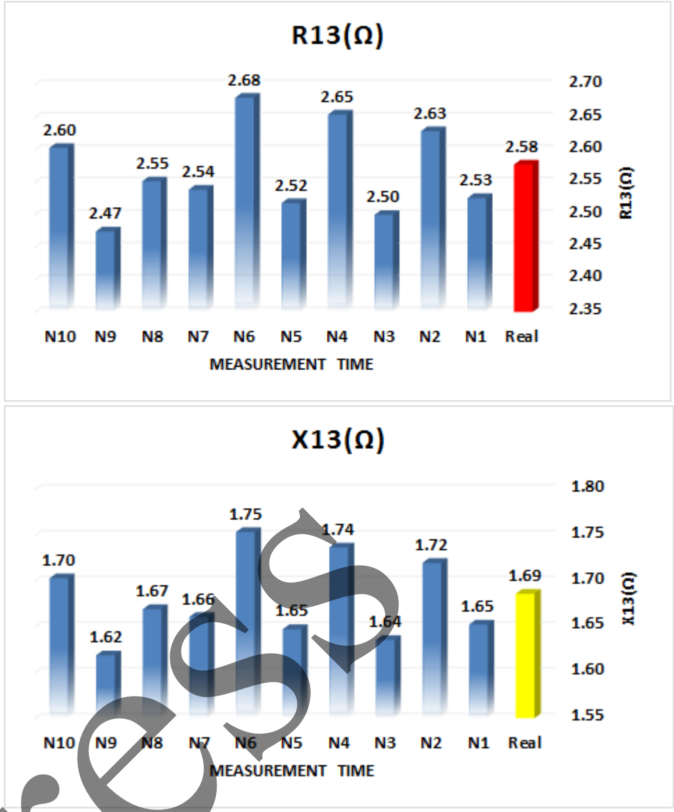

Fig. 14. Comparison of real and equivalent impedance (Z13)

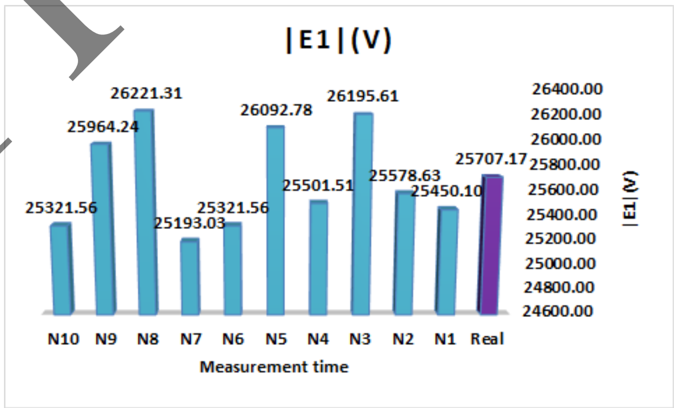

Fig. 15. Comparison of real and equivalent voltage source (E1)

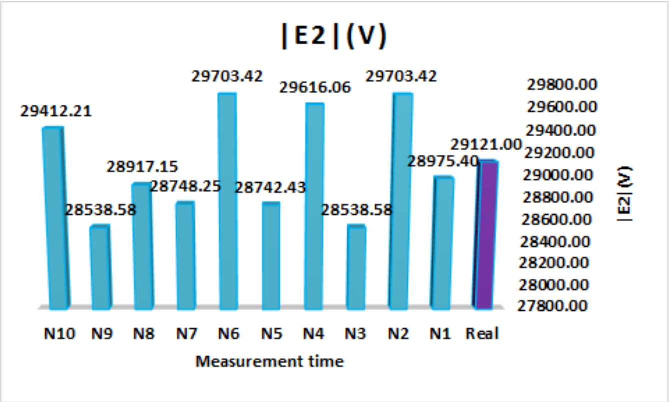

Fig. 16. Comparison of real and equivalent voltage source (E2)

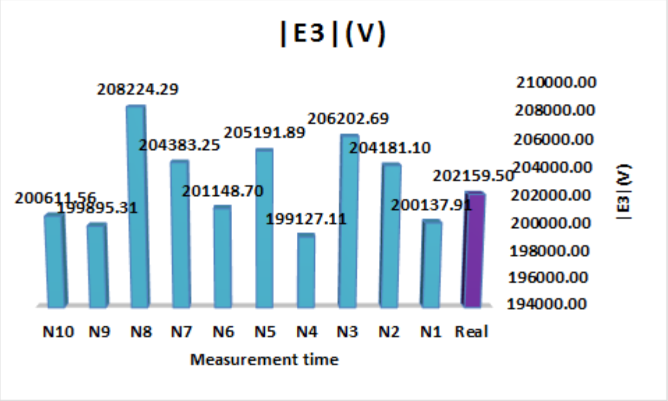

Fig. 17. Comparison of real and equivalent voltage source (E3)

The accuracy assessment of the presented method in terms of the maximum error values in the Thevenin equivalent circuit parameter values compared to the actual values is given in Table. I. Comparing the obtained results of the presented method shows high accuracy with implementing on the network under consideration.

TABLE I

ACCURATE COMPARISON OF EQUIVALENT CIRCUIT PARAMETERS

Item	Main circuit	Equivalent circuit (most error)	Comparative error percentage
R 11(Ω)	1343.8	1397.58	4%
R 22(Ω)	22.2	22.3	4.6%
R 33(Ω)	1.52	1.58	3.94%
R 12(Ω)	4.02	4.18	3.98%
R 13(Ω)	2.58	2.68	3.87%
R 23(Ω)	1.68	1.75	4.17%
X 11(Ω)	151.37	157.42	3.99%
X 22(Ω)	2.78	2.89	3.95%
X 33(Ω)	16.9	17.58	4.02%
X 12(Ω)	0.89	0.85	4.49%
X 13(Ω)	1.69	1.62	4.14%
X 23(Ω)	1.32	1.27	3.78%
E1(KV)	25.7071	25.1933	2%
E2(KV)	29.121	28.539	1.99%
E3(KV)	202.159	208.225	3%

B. Comparison of equivalent and real model analysis

The IEEE 39 bus system is replaced with three boundary buses in two states of the real circuit of the external system and the Tonen equivalent circuit model obtained from the proposed method to be tested in order to check the performance of the proposed method. The evaluation results of the proposed method have been done as a graphical comparison in two different modes.

First mode: In this mode, the three-phase short circuit fault is simulated, measured and reported based on the VDE standard in two lines of the internal system connected to the real external system.

Second mode: In this mode, three-phase short-circuit fault is simulated, measured and reported based on the VDE standard in two lines of the internal system connected to the equivalent Thevenin circuit with the external system. (In this case, it is assumed that noise is included in the measurement and the information is completely non ideal) .

As shown in Figs. 18 – 20, the simulated fault of a three-phase short circuit in the internal system connected to the real circuit of the external system and its equivalent circuit (with noise) are analysed. Each three-phase short circuit fault has three main parameters that are compared. The first parameter (S_{KSS}) is the maximum short circuit power of the three-phase line, the second parameter *(*I_{KSS}) is the maximum short-circuit current of the three-phase line, and the third parameter (I_P) is the short circuit current.

Using the standard 39 Buses IEEE shown in Fig. 8, random parameters have been selected in the internal system, which have been checked together in the equivalent state and the real state under the following two random events. Random network errors include:

1- Increasing the loads of 03, 24, and 27 and the production of generators 6, 7, and 8 (50%)

2- Cutting line 17-18.

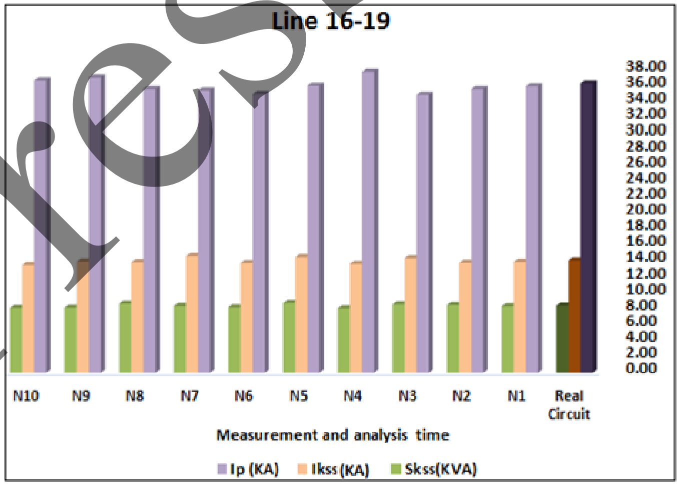

Fig. 18. Comparison of three phase short circuit parameters of line 16-19

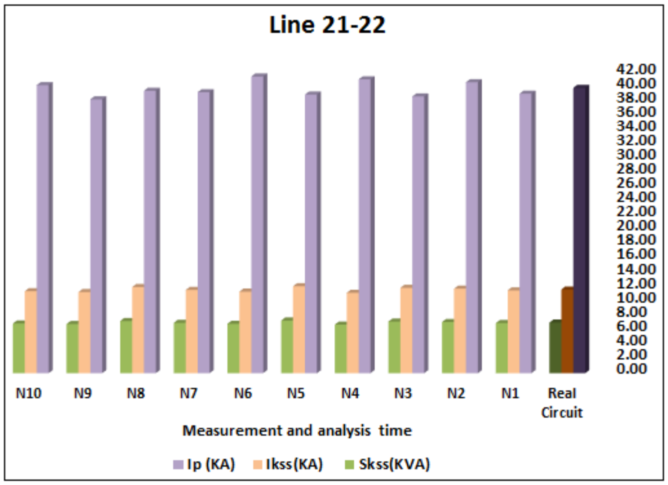

Fig. 19. Comparison of three-phase short circuit parameters of line 21-22

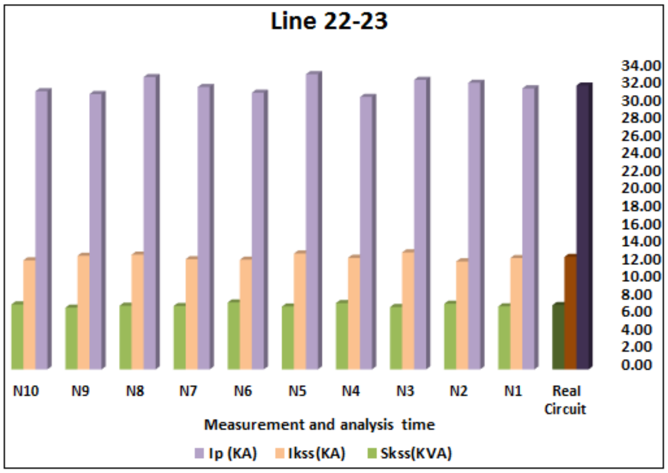

Fig. 20. Comparison of three-phase short circuit parameters of line 22-23

To compare the accuracy of the proposed method with recently published research [11], we depicted the corresponding errors for an internal system with lines disconnection and the increase of loads in Tables II and III, respectively. According obtained results, the proposed method is good agreement with [11]. Examples of comparing are the voltage amplitude of several buses and the transmission power of several lines in the internal system. As is shown in Figs. 18 –20, transfer powers are derived from short circuit current. In addition, the maximum values of error percentage along with their original values compared to the tested results with Thevenin equivalent circuit are completely given in the tables.

The accuracy assay of the analysis results using the proposed method has been carried out in IEEE 39-buses system with three boundary nodes and certain minimum changes after replacing the equivalent circuit instead of the external system in three real states. the obtained results of the proposed method and the Fourier based model [11] in order to compare different modes such as the average error percentage, the maximum error value of the equivalent parameters for the bus voltage amplitude, the power transferred between the lines of the internal system and the three phase short circuit error values in the internal system are given in Table IV. The allowed error average for all values obtained from the model of the presented method is less than 3.7%. Meanwhile, this value for all the values obtained from the presented method in [11] is about 6%. By increasing the number of data, the accuracy of the results can be reached to about 98% of the real values. Unlike the proposed method in [11], the presented method in this paper has much faster speed and simpler equations that do not require any PMUs measurement data.

TABLE II

SPECIFICATIONS OF INTERNAL SYSTEM WITH LINE DISCONNECTION 17-18 WITH MAXIMUM ERROR PERCENTAGE VALUES

Item	Main circuit	Equivalent circuit (the most error) The proposed method	Comparative error (%) The proposed method	Equivalent circuit (the most error) [11]	Comparative error (%) [11]
Bus 3 (KV)	352.43	366.88	4.1%	370.76	5.2%
Bus 19 (KV)	362.33	347.84	3.99%	380.09	4.9%
Bus 21 (KV)	356.19	346.93	2.59%	390.74	3.97%
Active power (22-23) (KW)	42.79	44.03	2.89%	41.2	3.7%
Active power (21-22) (KW)	607.21	615.10	1.29%	602.41	0.79%
Active power (2-3) (KW)	465.18	483.32	3.89%	474.74	2.1%
Reactive power (22-23) (KVAR)	41.84	43.89	4.89%	44.96	7.43%
Reactive power (21-22) (KVAR)	107.35	110.89	3.29%	101.99	4.99%
Reactive power (2-3) (KVAR)	114.74	118.07	2.9%	117.14	2.1%

TABLE III

THE SPECIFICATIONS OF THE INTERNAL SYSTEM WITH THE INCREASE OF LOADS OF 03, 24, AND 27 AND GENERATOR PRODUCTION OF 6, 7, AND 8 (50%) WITH MAXIMUM ERROR PERCENTAGE VALUES

Item	Main circuit	Equivalent circuit (the most error) The proposed method	Comparative error (%) The proposed method	Equivalent circuit (the most error) [11]	Comparative error (%) [11]
Bus 3 (KV)	348.86	335.95	3.7%	341.89	2%
Bus 19 (KV)	360.81	346.74	3.89%	385.7	6.9%
Bus 21(KV)	353.45	341.79	3.29%	343.9	2.7%
Active power (22-23) (KW)	61.11	59.95	1.89%	62.88	2.9%
Active power (21-22) (KW)	582.89	563.65	3.3%	576.89	1.03%
Active power (2-3) (KW)	383.45	398.79	4.01%	417.57	8.9%
Reactive power (22-23) (KVAR)	39.46	40.64	2.99%	40.76	3.3%
Reactive power (21-22) (KVAR)	136.49	138.83	1.71%	130.89	4.1%
Reactive power (2-3) (KVAR)	171.99	168.03	2.3%	178.73	3.92%

TABLE IV

CHECKING ACCURACY OF THE ANALYSIS RESULTS

Equivalent circuit parameter Selected parameter from the grid	Largest Error (%) The proposed method	Average Error (%) The proposed method	Largest Error (%) [11]	Largest Error (%) [11]
Applied measurement error	2	2	2	2
Resistance (Ω)	4.17	3.34	6.2	4.7
Reactance (Ω)	4	2.12	7.13	4.12
Bus Voltage (V)	2.7	1.24	2.2	1.79
Ip (KA)	4.3	3.11	3.98	3.9
Ikss (KA)	4.7	2.73	4.17	3.79
Skss (KA)	4.21	2.42	3.9	2.13
Internal system bus voltage amplitude (KV)	4.1	3.24	6.9	4.33
Internal system power flow (KW, KVAR)	4.89	3.69	8.9	5.63

VI. CONCLUSION

The presented paper is a proposed method that can estimate the parameters of the Thevenin equivalent circuit model of the external power system connected to the boundary buses using RTU measurement data with high accuracy. The contributions of the proposed method are: 1) proposing a model for the Thevenin equivalent circuit to estimate the external system, 2) presenting a method to determine the parameters of the equivalent circuit with continuous operation, 3) presenting a method to determine the system in which the disturbance occurred, 4) presenting a method To calculate the boundary bus voltage phasor with the measurement data RTUs, 5) Providing a method to eliminate measurement errors during parameter estimation of the equivalent circuit model of the external network with continuous measurements. This method is investigated for the IEEE 39 bus system. The data measured by RTUs includes data from all boundary points simultaneously. The first step examines the performance of the method to determine the system in which the disturbance occurred, which can be determined by finding the negative values of the elements of the unknown impedance matrix. Measured data from data points that are the result of internal system perturbation with minimal changes are analyzed by the proposed method, which leads to the presentation of the equivalent model of the external system. The results prove that the presented method is able to neutralize the measurement error in the estimation of the unknown parameters of the equivalent circuit model.

APPENDIX

It is possible to have a criterion for checking the results of the parameters obtained from the proposed method in estimating the parameters of the equivalent circuit model of the external system, which is implemented by having the characteristics of the external system [26]. Considering the assumptions:

- The direction of current injection is from the internal system to the external system, which is done through boundary buses.
- All voltage sources are ideal.
- Loads, constant inputs are assumed.

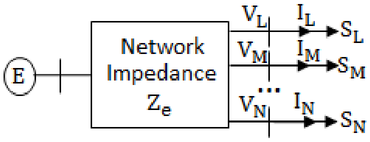

Fig 21. A voltage source with three load

The standard node equation (32) can be written for the external system connected to three boundary buses.

$$\begin{bmatrix} I_L \\ -I_M \\ I_N \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LM} & Y_{LN} \\ Y_{ML} & Y_{MM} & Y_{MN} \\ Y_{NL} & Y_{LM} & Y_{NN} \end{bmatrix} \times \begin{bmatrix} V_L \\ V_M \\ V_N \end{bmatrix} \tag{32}$$

Where [V] is the boundary bus voltages, [I] is the power system injected current, and [Y] is the transmit line admittance matrix, respectively. Buses can have a generator or a load, or only a passing bus without a generator or a load. Bus N is assumed to be a pass through bus, and the result of the current injected into it is equal to zero. Therefore, using (32), we can write:

$$I_N = Y_{NL}V_L + Y_{LM}V_M + Y_{NN}V_N = 0 \tag{33}$$

$$V_N = -Y_{NN}^{-1}(Y_{NL}V_L + Y_{LM}V_M) \tag{34}$$

$$-I_M = Y_{ML}V_L + Y_{MM}V_M + Y_{MN}V_N \tag{35}$$

By replacing V_N from (34) to (35) and rewriting the equations, (36) is obtained.

$$-I_M = (Y_{ML} - Y_{MN}Y_{NN}^{-1}Y_{NL})V_L + \\ (Y_{MM} - Y_{MN}Y_{NN}^{-1}Y_{LM})V_M \tag{36}$$

From (36), we extract V_M as follows.

$$V_M = -(Y_{MM} - Y_{MN}Y_{NN}^{-1}Y_{LM})^{-1}(Y_{ML} - Y_{MN}Y_{NN}^{-1}Y_{NL})V_L \\ -(Y_{MM} - Y_{MN}Y_{NN}^{-1}Y_{LM})^{-1}I_M \tag{37}$$

Based on the multiport Thevenin equivalent circuit equation (38) that shown in Fig. 21, the impedance ($Z_{external}$) and voltage source ($E_{external}$) of the Thevenin equivalent circuit of the external system can be extracted from (39) and (40).

$$[V] = [E_{external}] - [Z_{external}][I] \tag{38}$$

$$Z_{external} = (Y_{MM} - Y_{MN}Y_{NN}^{-1}Y_{LM})^{-1} \tag{39}$$

$$E_{external} = -Z_{external}(Y_{ML} - Y_{MN}Y_{NN}^{-1}Y_{NL})V_L \tag{40}$$

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