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Study of Three Different Approaches for Development of Power System Aggregated Load Area Models

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Abstract— **The paper presents three different approaches for development of aggregated load area models (ALAM) in power systems. Among the three, the first one is Voltage-Two-Step (VTS) approach, which identifies ALAM parameters based on a Voltage-Match scheme implemented in two steps. The second is Current-Two-Step (CTS) approach. Similar to the VTS, this approach identifies ALAM parameters based on a Current-Match scheme realized in two steps. Direct-One-Step (DOS) approach is the third one. It identifies the ALAM parameters based on a Bus-Match scheme in one step. Theoretical explanation and analysis to these three approaches are reported in the paper and simulation studies were carried out using the model of the IEEE-14 Bus Power System. Three approaches were compared in the paper and some positive suggestions were proposed.**

I. INTRODUCTION

Unlike gas and water, electricity cannot be easily stored and the supplier has small control over the load at any time [1]. Stable operation of a power system depends on the ability to continuously match the electrical output of generating units to the electrical load demand on the system [2, 3]. It has been shown in a number of reports that power system load characters can have a significant impact on the power system stability analysis [1, 2, 4]. Unfortunately deriving an accurate model of electricity load is a difficult task, due to several factors, such as, a large number of diverse load components; ownerships and locations of load devices in customer facilities that are not directly accessible to the electric utility; changing load composition with time of hours, days and weeks, seasons and weather; lack of precise information on the composition of load; uncertainties regarding the characteristics of many load components; difficulties in on-line measurement for wider range of voltage and frequency variations [5, 6]. In modern power systems, almost all distribution systems and load areas (load centres) are supplied by more than one power source to improve the security and reliability of the whole system [7]. As a number of source buses are distributed and connected to the load area rather than single unified bus, the bus load model is reluctant to represent the load area.

To model the load for a specified area, Wen *et al* proposed an aggregate load area model (ALAM) in 2003 [6, 8]. It represents the load subject to the "area" rather than the "bus" and gives a degree of network reduction, where there are numbers of unknown equivalent parameters needed to be identified. The parameters include resistance, reactance and susceptance for the fictitious branches in the load area, and also the six ZIP load model coefficients to the fictitious load in the load area. To identify all the parameters, different approaches could be used and three of them are introduced in this paper, namely, Voltage-Two-Step (VTS) approach, Current-Two-Step (CTS) approach, and Directly-One-Step (DOS) approach.

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II. AGGREGATED LOAD AREA MODEL

In power system engineering, the term "load" normally means a portion of system that is not explicitly represented in a system model, but treated as if it were a single power-consuming device connected to a bus [9]. The aggregated load represented at a transmission substation usually includes, in addition to the connected load devices, the effects of substation step-down transformers, sub-transmission feeders, distribution feeders, distribution transformers, voltage regulators, and reactive power compensation devices [4]. A load model for a bus is therefore a mathematical representation of the relationship between a bus voltage (magnitude and frequency) and the power (active and reactive) consumed in the load bus, which can be calculated approximately by [4, 9].

$$P = \left[a_1 V^2 + a_2 V + a_3 \right] \quad (1)$$

$$Q = \left[a_4 V^2 + a_5 V + a_6 \right] \quad (2)$$

where P is the per unit value of active power transmitted in the load bus; Q is the per unit value of reactive power transmitted in the load bus; V is the per unit value of the load bus voltage magnitude; and $a_1 \sim a_6$ are the parameters of the load model. This model is actually called a "ZIP" model with respect to constant impedance (*Z*), constant current (*I*) and constant power (*P*) terms.

The ALAM is proposed to model an aggregate load area, wherein the load subjects to an area rather than a bus. Similar to the load model for an individual bus, an ALAM is a mathematical representation of the relationship between the total power injected (active and reactive) and the voltage (magnitude and frequency) at the load area. As a result, for modeling the area load, not only the overall characteristic of the load in the area but also the transmission and distribution network should be considered. For example, the load area that composes of seven load buses (see Figure 1.) can be aggregately modeled as a fictitious load bus with an equivalent load connected, where the fictitious load bus is connected with the original power system by a couple of the fictitious transmission lines (see Figure 2.). Since the active power P and reactive power Q in each load bus of the power system can be represented by Equations (1) ~ (2), the fictitious load bus therefore can also be modeled as follows:

$$P_f = \left[a_{f1}V_f^{\ 2} + a_{f2}V_f + a_{f3}\right] \tag{3}$$

$$Q_f = \left[a_{f4}V_f^{\ 2} + a_{f5}V_f + a_{f6}\right] \tag{4}$$

where P_f is the per unit value of active power transmitted in the fictitious load bus; Q_f is the per unit value of reactive power transmitted in the fictitious load bus; V_f is the per unit value of fictitious load bus voltage magnitude; and $a_{f1} \sim a_{f6}$ are the parameters of the model for the fictitious load bus. As the fictitious load bus does not physically exist, all the values of the model parameters $a_{f1} \sim a_{f6}$ together with the branch parameters of the fictitious transmission lines are unknown, and they could be identified using three different approaches proposed in the next sections.

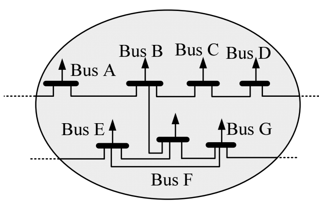

Figure 1. A load area composed of seven load buses

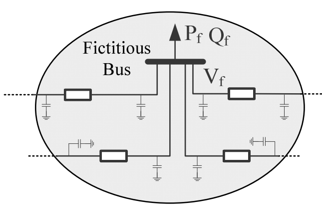

Figure 2. The fictitious load bus and its connected tranmission lines

III. VOLTAGE-TWO-STEP (VTS) APPROACH

The VTS approach is originally developed by Wen *et al* in 2003 [6, 8]. The identification process for the unknown parameters of the ALAM are organised into two steps:

STEP1: the branch parameters of the fictitious transmission lines are identified using GAs under a Voltage-Match scheme;

STEP2: the six coefficients of the ALAM in (3) ~ (4) are identified using GAs based on the identified transmission line parameters from STEP1.

Employing the nominal π circuit to represent the fictitious transmission lines of the load area considered, the branch parameters that need to be identified in STEP 1 include the resistance R, reactance X and susceptance B of each transmission line [10]. All the values of these parameters of the fictitious lines are unknown, and they will be identified using the Voltage-Match scheme. The Voltage-Match scheme is proposed based on the idea that each receiving end voltage of the fictitious load bus calculated should be equal to the one calculated by each fictitious transmission line. The receiving end voltages of the fictitious load bus that connected with m and n buses in Figure 2 can be derived as follows [10]:

$$\begin{aligned}\vec{V}_f^{\,n} &= \left(1 + \left(R_n + jX_n\right)\frac{jB_n}{2}\right)\vec{V}_n \\ &\quad - \left(R_n + jX_n\right)\vec{I}_n\end{aligned} \tag{5}$$

$$\begin{aligned}\vec{V}_f^{\,m} &= \left(1 + \left(R_m + jX_m\right)\frac{jB_m}{2}\right)\vec{V}_m \\ &\quad - \left(R_m + jX_m\right)\vec{I}_m\end{aligned} \tag{6}$$

where I_n, I_m are the current in per unit flow into the fictitious load bus from the bus *n, m* via the fictitious transmission line, which can be measured in the power system; V_n, V_m is the voltage of the buses *n*, *m*.

Following the Voltage-Match scheme, the receiving end voltages $\vec{V}_f^{\,n}$ and $\vec{V}_f^{\,m}$ should be same in values. Therefore, the fitness function for the STEP1 to identify R, X and B of the fictitious transmission lines can be defined as follows:

$$e^{os\_i}{}_{\mathrm{STEP1}}(R,X,B) = \sum_{\substack{m,n(m\neq n)\\ m,n=1,2\ldots}} \left|\vec{V}_f^{\,m} - \vec{V}_f^{\,n}\right| \tag{7}$$

$$Fitness1 = \sum_{os\_i=OS1,OS2,\ldots} e^{os\_i}{}_{\mathrm{STEP1}}(R,X,B) \tag{8}$$

where m, n are the buses that connected with the fictitious load bus outside of the load area; *os_i* represents one of the varied operation states of the power system adopted for the identification.

In the identification STEP2 of the Voltage-Two-Step approach, the GA is applied again to identify the six parameters of the ALAM ($a_{f1} \sim a_{f6}$). The fitness function is given as follows.

$$P_M = \sum_{i=1,2,\ldots} \left(\vec{V}_f \vec{I}_f^{\,i} \cos\theta^i{}_f\right) \tag{9}$$

$$Q_M = \sum_{i=1,2,\ldots} \left(\vec{V}_f \vec{I}_f^{\,i} \sin\theta^i{}_f\right) \tag{10}$$

$$P_f = \left[a_{f1}V_f^{\ 2} + a_{f2}V_f + a_{f3}\right] \tag{11}$$

$$Q_f = \left[a_{f4}V_f^{\ 2} + a_{f5}V_f + a_{f6}\right] \tag{12}$$

$$e^{os}{}_{\mathrm{STEP2}}(a_{f1},\ldots,a_{f6}) = w_1\left|P_M - P_f\right| + w_2\left|Q_M - Q_f\right| \tag{13}$$

$$Fitness2 = \sum_{os\_i=OS1,OS2,\ldots} e^{os\_i}{}_{\mathrm{STEP2}}(a_{f1},\ldots,a_{f6}) \tag{14}$$

where i is the bus that connected with the aggregate load area via the fictitious transmission line; $\vec{V}_f$ is the voltage of the fictitious load bus in per unit, which is identified in STEP1; $\vec{I}_f^{\,i}$ is the current in per unit flow into the fictitious load bus via the i fictitious transmission line, which can be measured in the power system; $\theta^i{}_f$ is the phase angle between $\vec{V}_f$ and

$\bar{I}_f^i$; P_f , Q_f are the per unit value of the active and reactive power consumed in the fictitious load bus, which can be calculated by Equations (11) and (12); and $w_1 \sim w_2$ are the weights for the individual errors, which are set to be 1 in this study.

In order to illustrate the performance of the VTS, a simple power system, the IEEE-14 bus power system (see Figure 3) is employed for the simulation studies. The load area marked inside of the dotted oval area can be aggregately modeled as a fictitious load bus with an equivalent load connected as shown in Figure 4, where the two conjunctive load buses, bus 12 and bus 13, are modeled aggregately as a fictitious load bus, bus 15. Three typical operation states have been used to evaluate the fitness functions as shown in Equations (8) and (14):

OS1: Normal operation state, wherein all the data are kept in the same as the original IEEE 14-bus power system.

OS2: Normal operation conditions but the active power generated in bus 1 decreases 5%, the active power generated in bus 2 increases 10%.

OS3: Normal operation conditions but the terminal voltage of generator 1 (bus 1) increases 10%, the tap ratio of the transformer between bus 5 and bus 6 decreases 5%.

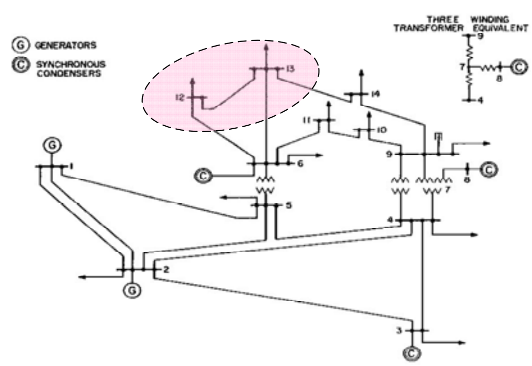

Figure 3. The IEEE 14-bus power system

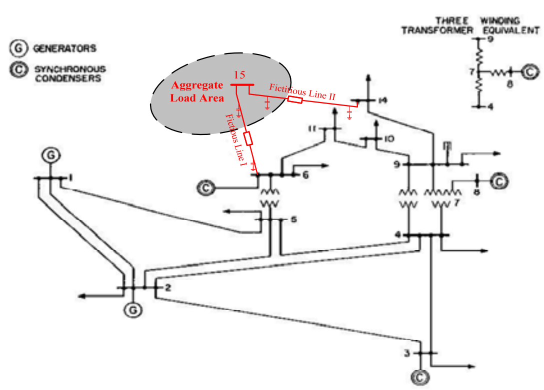

Figure 4. Equivalent power system from IEEE 14-bus power system

Following the two step identification scheme, the real-value SPGA [11-13] is employed for the model parameters' identification in each step. The twelve unknown parameters of the equivalent IEEE-14-Bus power system (see Figure 4) that are identified by VTS approach are given in Table I.

TABLE I. THE TWELVE IDENTIFIED PARAMETERS OF THE EQUIVALENT IEEE-14-BUS POWER SYSTEM

$R_{6\text{-}15}$ = 0.1656 $p.u.$	$X_{6\text{-}15}$ = 0.3936 $p.u.$	$B_{6\text{-}15}$ = 0.0127 $p.u.$
$R_{14\text{-}15}$ = 0.1082 $p.u.$	$X_{14\text{-}15}$ = 0.7550 $p.u.$	$B_{14\text{-}15}$ = 0.0033 $p.u.$
a_{f1} = 0.1270	a_{f2} = -0.1702	a_{f3} = 0.0010
a_{f4} = 0.2179	a_{f5} = -0.3514	a_{f6} = 0.0762

Two series tests are applied to verify the accuracy of the identified equivalent system. In each operation state of the tests, the maximum errors between the buses in the equivalent system (Figure 4) and the relevant buses in the original system (Figure 3) are compared, which are shown as follows:

Test1: Assume the system operates in normal conditions, but the tap ratio of the transformer between bus 5 and bus 6 changes from -10% of its normal value to +10% of its normal value in 1% increment. The maximum errors of the bus voltages (magnitudes and phase angles) in each operation state are shown in Figure 5.

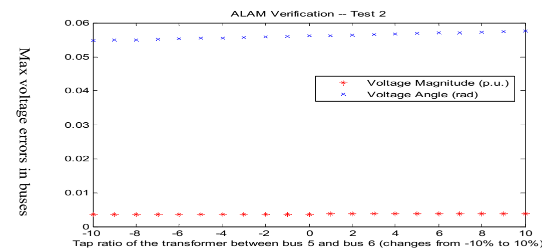

Figure 5. Max errors of the bus voltages of the equivalent power system approached by CTS in verification Test1.

Test2: Assume the system operates in normal conditions, but the value of voltage outputs from generator 2 (bus 2) changes from -10% of its normal output to +10% in 1% increment. The maximum errors of the bus voltages (magnitudes and phase angles) in each operation state are shown in Figure 6.

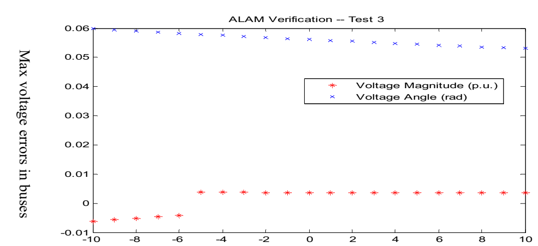

Figure 6. Max errors of the bus voltages of the equivalent power system approached by CTS in verification Test2.

From the results, it can be seen that the equivalent power system embodied ALAM can give a good degree of equivalent approximation to the original power system even under the conditions of the series changes in the generators outputs and transformer tap ratios.

IV. CURRENT-TWO-STEP (CTS) APPROACH

The CTS is a newly developed approach for the ALAM in this paper. Similar to the CTS, the identification process of the unknown parameters in the ALAM has also been organised into two steps, which are shown as follows:

STEP1: the branch parameters of the fictitious transmission lines are identified firstly using GAs under the Current-Match scheme.

STEP2: the six unknown parameters of the ALAM in Equations (3) and (4) are identified using GAs based on the identified transmission line parameters from the first step.

Different from VTS, the CTS employs the Current-Match scheme for identifying the branch parameters in the first step. The Current-Match scheme is based on the idea that total current flow into the fictitious load bus should be equal to the total current flow into the load area, which can be measured in power systems. Similar to Section III, employing the nominal π circuit to represent the fictitious transmission lines of the load area, the current flow into the receiving end of the transmission line in Figure 2 can be given as follows [10]:

$$\vec{I}_R = \left[1 + \frac{Y}{2}Z\right]\vec{I}_S - \left[Y + \left(\frac{Y}{2}\right)^2 Z\right]\vec{V}_S \tag{15}$$

where $\vec{I}_R$ is the current in per unit at the receiving end of the transmission line; $\vec{V}_S$ is the voltage in per unit at the sending end of the transmission line; $\vec{I}_S$ is the current of the transmission line in per unit at the sending end; Z is the impedance of the transmission line in per unit; Y is the admittance of the transmission line in per unit; $\vec{I}_R$, $\vec{V}_S$, $\vec{I}_S$ are all complex variables.

Following the Current-Match scheme, the fitness function for STEP1 for identification of R_i, X_i and B_i of the fictitious transmission line is given as follows:

$$\vec{I}_f^n = \left[1 + \frac{jB_n}{2}(R_n + jX_n)\right]I_n - \left[jB_n - \frac{B_n^2}{4}(R_n + jX_n)\right]V_n \tag{16}$$

$$I_{f\_Simulated} = \sum_{n=1,2,\dots} \vec{I}_f^n \tag{17}$$

$$e^{os}{}_{\text{STEP1}}(R, X, B) = \left|I_{f\_Measured} - I_{f\_Simulated}\right| \tag{18}$$

$$Fitness1 = \sum_{os\_i = OS1, OS2, \dots} e^{os\_i}{}_{\text{STEP1}}(R, X, B) \tag{19}$$

where n is the bus that is connected with the aggregate load area via the fictitious transmission line; $\vec{I}_f^n$ is the current flow into the fictitious load bus in per unit, which is derived based on the connecting bus n; I_n is the current in per unit flow into the fictitious load bus via the n fictitious transmission line, which can be measured in the power system; V_n is the voltage of bus n, which can be measured as well. $I_{f\_Simulated}$ is the simulated current flow into the fictitious load bus, which is the total effect of current flowed into the fictitious load bus via all the fictitious transmission lines; $I_{f\_Measured}$ is the total effect of current flow into the load area, which is measured in the power system.

Similar to VTS, in STEP2 of the Current-Two-Step approach, the GA is adopted as well to identify the six parameters of the ALAM ($a_{f1} \sim a_{f6}$). The fitness function is defined as follows:

$$\vec{V}_f = \frac{1}{n}\sum_n \left[\left(1 + (R_n + jX_n)\frac{jB_n}{2}\right)\vec{V}_n - (R_n + jX_n)\vec{I}_n\right] \tag{20}$$

$$P_M = \vec{V}_f \vec{I}_{f\_Measured} \cos\theta \tag{21}$$

$$Q_M = \vec{V}_f \vec{I}_{f\_Measured} \sin\theta \tag{22}$$

$$P_f = \left[a_{f1}V_f^2 + a_{f2}V_f + a_{f3}\right] \tag{23}$$

$$Q_f = \left[a_{f4}V_f^2 + a_{f5}V_f + a_{f6}\right] \tag{24}$$

$$e^{os}{}_{\text{STEP2}}(a_{f1}, \dots, a_{f6}) = w_1\left|P_M - P_f\right| + w_2\left|Q_M - Q_f\right| \tag{25}$$

$$Fitness2 = \sum_{os\_i = OS1, OS2, \dots} e^{os\_i}{}_{\text{STEP2}}(a_{f1}, \dots, a_{f6}) \tag{26}$$

where n is the bus that connected with the aggregate load area via the fictitious transmission line; $\vec{V}_f$ is the voltage of the fictitious load bus in per unit, which is derived based on the identified R, X, B from the first step using the Current-Two-Step approach; $I_{f\_Measured}$ is the total effect of the current flow into the load area, which is measured in the power system; θ is the phase angle between $\vec{V}_f$ and $\vec{I}_{f\_Measured}$; P_f, Q_f are the per unit value of active and reactive power consumed in the fictitious load bus; and $w_1 \sim w_2$ are the weighting coefficients for the individual errors, which are set to be 1 in this study.

Applying the real-value SPGA again for the parameter identifications in STEP1 and STEP2 of the CTS approach, the twelve unknown parameters of the equivalent IEEE-14-Bus power system (see Figure 4) are identified and given in Table II.

TABLE II. THE TWELVE IDENTIFIED PARAMETERS OF THE EQUIVALENT IEEE-14-BUS POWER SYSTEM

$R_{6\text{-}15}$ = 0.6303 *p.u.*	$X_{6\text{-}15}$ = 0.7888 *p.u.*	$B_{6\text{-}15}$ = 0.0016 *p.u.*
$R_{14\text{-}15}$ = 0.2944 *p.u.*	$X_{14\text{-}15}$ = 0.7645 *p.u.*	$B_{14\text{-}15}$ = 0.0002 *p.u.*
a_{f1} = 0.0689	a_{f2} = -0.3552	a_{f3} = 0.3498
a_{f4} = 0.1415	a_{f5} = -0.3376	a_{f6} = 0.2005

Conducting the two series tests introduced in Section III to verify the ALAM for the identified parameters, the results are shown in Figures 7 & 8. From the results, it can be seen that the equivalent power system embodied ALAM can give a good degree of agreement to be equivalent to the original power system with the identified parameters using the CTS approach under a series changes in the generators outputs and transformer tap ratios. Comparing with the verification results obtained from the VTS approach, the CTS provide a set of results which are slightly better than those obtained by the VTS, where the maximum errors of the bus voltages in each operation state are getting smaller.

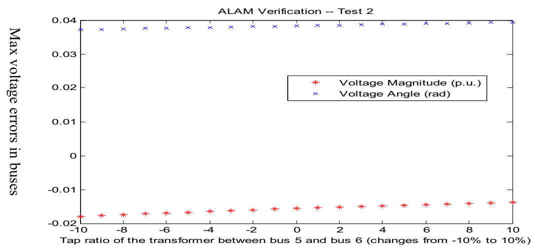

Figure 7. Maximum errors of the bus voltages of the equivalent power system approached by CTS in verification Test1.

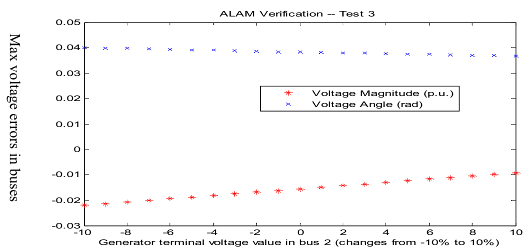

Figure 8. Maximum errors of the bus voltages of the equivalent power system approached by CTS in verification Test2.

V. Direct-One-Step (DOS) Approach

The DOS approach is a simplified approach that combines both the STEPs 1 and 2 in the VTS and CTS into one. All the unknown parameters include the parameters of the fictitious transmission lines and the coefficients of the ZIP load model are identified in one step under the scheme namely Bus-Match, which is shown in Figure 9. The Bus-Match scheme can be explained as that the bus variables in the equivalent power system should match the bus variables in he original power system. The whole procedure is based on the network calculation in power systems. The parameters ($R, X, B, a_{f1} \sim a_{f6}$) identified using GAs are substituted into the equivalent power system for the power flow calculations and then the simulated bus variables are derived. By matching the simulated bus variables to the measured bus variables, the GA evolves, and the parameters will be identified at the end of the process.

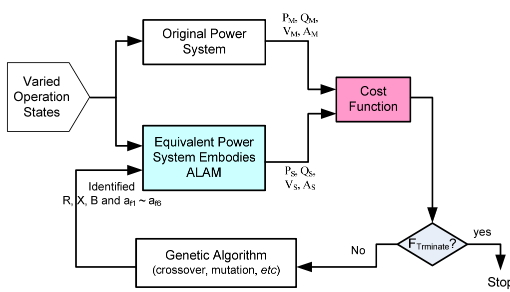

Figure 9. The identification process of the DOS approach

The variables (active power, reactive power, voltage magnitude, voltage angle) of the buses outside of the load area between the original power system and the equivalent power system are compared to construct the fitness function for GAs, which is given as follows:

$$Fitness(R, X, B, a_{f1} \sim a_{f6}) = \sum_i \Big(w_1 \left| P_{Mi} - P_{Si} \right| + w_2 \left| Q_{Mi} - Q_{Si} \right| + w_3 \left| V_{Mi} - V_{Si} \right| + w_4 \left| A_{Mi} - A_{Si} \right| \Big) \tag{27}$$

where, i is the notation of the buses outside of the fictitious load area in the power system; $w_1 \sim w_4$ are the weighting coefficients for the individual errors; P_{Mi} is the measured active power consumed/generated in Bus i from the original power system; P_{Si} is the simulated active power consumed/generated in Bus i from the fictitious ALAM equivalent power system; Q_{Mi} is the measured reactive power consumed/generated in the bus i from the original power system; Q_{Si} is the simulated reactive power consumed/generated in the bus i from the fictitious ALAM equivalent power system; V_{Mi} is the measured voltage magnitude in the bus i from the original power system; V_{Si} is the simulated voltage magnitude in the bus i from the fictitious ALAM equivalent power system; A_{Mi} is the measured voltage angle in the bus i from the original power system; and A_{Si} is the simulated voltage angle in the bus i from the fictitious ALAM equivalent power system. All the variables of the buses in power systems (*e.g.* P_{Mi}, P_{Si}) are calculated in per-unit.

TABLE III. The Twelve Identified Parameters of the Equivalent IEEE-14-Bus Power System

$R_{6\text{-}15}$ =0.0624 *p.u.*	$X_{6\text{-}15}$ = 0.0852 *p.u.*	$B_{6\text{-}15}$ = 0.0046 *p.u.*
$R_{14\text{-}15}$ = 0.1081*p.u.*	$X_{14\text{-}15}$ =0.3764 *p.u.*	$B_{14\text{-}15}$ = 0.0005 *p.u.*
a_{f1} =0.1563	a_{f2} = -0.1583	a_{f3} = 0.1893
a_{f4} = 0.0414	a_{f5} = -0.2467	a_{f6} = 0.2929

Similar to the last two sections, the IEEE-14-Bus power system (see Figure 4) has been employed for the simulation study of this direct ALAM approach as well. Using the DOS approach, the twelve unknown parameters of the IEEE-14-Bus power system are identified and shown in Table III. The three series tests introduced in Section III are repeated again to verify the twelve identified parameters, wherein the verification results are shown in Figures 10 & 11. Comparing with the results obtained using VTS and CTS approaches, it can be seen that the DOS approach offers a more accurate identifications to the ALAM parameters, where much less errors between the equivalent power system and the original power system.

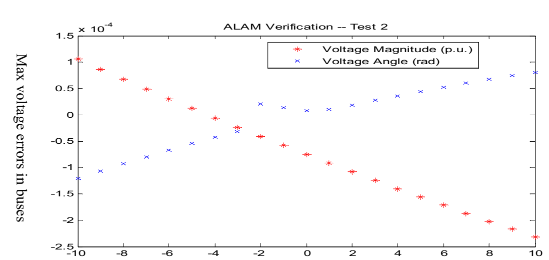

Figure 10. Maximum errors of the bus voltages of the equivalent power system approached by DOS in verification Test1

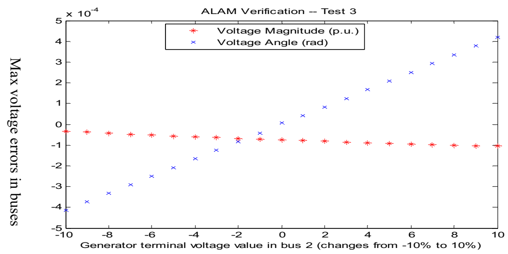

Figure 11. Maximum errors of the bus voltages of the equivalent power system approached by DOS in verification Test2

VI. Conclusion

In order to identify the unknown equivalent parameters in the ALAMs, three different approaches were introduced in this paper, which are VTS, CTS and DOS. Different parameter identification schemes are employed in corresponding to these schemes.

The VTS approach adopts the Voltage-Match scheme, which matches the fictitious voltage calculated by each transmission line to identify the branch parameters of the fictitious transmission lines in the first step of the approach. In the second step, the six parameters of the ZIP load model coefficients are identified by matching the simulated power consumptions in the fictitious load bus calculated by the ZIP load model with the measured power consumes in the load area derived from the first step of the identification process.

The CTS approach is similar to the VTS approach but it is based on the Current-Match scheme. By matching the simulated total current flow into the load area with the measured current flow into the load area, the scheme identifies the branch parameters first. In the second step, it applies the same rule as used in the VTS.

The DOS approach is an extension of the identification STEP2 of the VTS and CTS. The DOS approach uses the Bus-Match scheme to identify all the parameters of the ALAM (branch parameters and ZIP load model coefficients). By matching the simulated values of the bus variables with the measured values of the bus variables from the original power system, all the parameters of the ALAM are identified in one step.

The IEEE-14-Bus power system is selected as a simulation model to illustrate the performances of these three different approaches. Three different operation states of the power system were adopted in the parameter identification process to enhance the robustness of the identification process. A series of simulation studies for verification are carried out to test the accuracy of the ALAM while the systems suffer varied disturbances and uncertainties. From the simulation results, it can be seen that DOS gives the most accurate results comparing with the other two approaches. The paper suggests DOS method for the power system with scales as those illustration examples.

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