Electrical Network Equivalent Modeling Method with Boundary Buses Interconnected

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Abstract - **This paper proposes an equivalent modeling method (EMM) based on system measurements to reduce the scale of electrical network. In this method, the equivalent network model adopts a novel framework with boundary buses interconnected to improve the accuracy of equivalent network while maintaining the simplicity of the network structure. Obtaining the unknown parameters of equivalent network is regarded as a parameter identification problem in EMM, which is actually a least square estimation (LSE). The objective function of this LSE is built upon the predictive errors without the adoption of weight tuning. The LSE is solved using interior-point method and the optimal solution is regraded as identified parameters. Simulation studies on a 5-bus test system and an IEEE 30-bus test system demonstrate the efficiency and the practicability of the EMM under different operation states.**

Keywords - **Boundary bus, equivalent modeling method, parameter identification, system measurement**

I. INTRODUCTION

With the development of electrical utility industry, electrical network has become a large-scale interconnected system in order to guarantee electricity quality and the reliability of electricity transmission and distribution. However, solving problems such as static security analysis in such a large-scale system relies heavily on computing performance and storage capacity of computers [1]. Hence, to reduce the dependency on computers performance, network equivalent techniques (NET) have been developed to reduce the system and problem scale [2]–[6].

Generally, the electrical network to be equivalenced can be divided into three parts, including internal network, boundary bus and external network [7]. The goals of NET are to simplify the external network while assuring that the analysis results between original network and equivalent network are closed enough.

Among NET, there are two general classes [8]. One is the load flow based approach, which establishes the equivalent network based on the load flow information of whole network. This kind of approaches includes the well-known Ward equivalent [7] and REI equivalent [9]. However, it is not practical to get the detailed information of the whole interconnected power system, especially for those of distribution network.

Another potential solution is the measurement based method. In measurement based method, external network is regarded as grey box and only the behavior of the stimulus/response will be used to infer the performance of this grey box. The measurement apparatus placed at boundary bus provide the data of the stimulus/response under varied operation states. The errors of analysis results between the original network and equivalent is called predictive errors. By setting the predictive errors as objective function, the unknown parameters of equivalent network can be identified with the help of optimization algorithms based on sampled data [3].

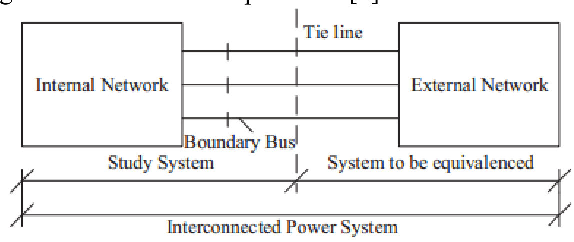

Fig. 1. Interconnected power system.

Aiming at improving the accuracy of the proposed equivalent networks, modeling an equivalent electrical network is significant, but tough since it is impossible to get access to the detailed information about the external network. Even so, some progress in electric network equivalent modeling has been made in recent years. To reduce the scale of power system load areas, Wen et:al: proposed an aggregate model n 2003 and aggregate model can deal with the network which contains not only load buses, but also transmission lines and transformers [3], [4]. Then model parameters are identified using a modified genetic algorithm (GA) in two separate steps. A modified approach to form the ALAM using particle swarm optimization (PSO) was reported in [8]. There are mainly two shortcomings in the above two methods. One is that they both employ the network framework with fictitious bus, while it is tough to determine the value of voltage at fictitious bus and therefore the uncertainty and errors of model increase. The other is that the performance of evolutionary algorithms, such as GA and PSO, depends on parameters setting, which seriously limits their practical application.

In this paper, as one kind of NET, EMM is proposed to reduce the scale of electrical network and replace the unknown external network with simple circuits. This method adopts a novel framework with boundary buses interconnected in order to improve the accuracy of equivalent network while maintaining the simplicity of the network structure. Then parameter identification of equivalent network based on measured data is transformed into NLP. The simplified objective function of this NLP is derived directly from the predictive errors of equivalent model, avoiding the weight tuning work. Lastly, the unknown parameters of equivalent network are identified together using interior-point algorithm in one-step scheme.

II. EQUIVALENT MODELING METHOD

An illustrative example of equivalent network, which has K boundary buses, obtained from EMM is described in Fig.2. It can be seen from Fig.2 that equivalent network is composed of the following parts: internal network, tie lines, boundary buses, equivalent load and fictitious lines. Among these five parts, the internal network, tie lines, boundary buses are inherited from the original network, while equivalent loads and fictitious lines are constructed based on data of system measurements.

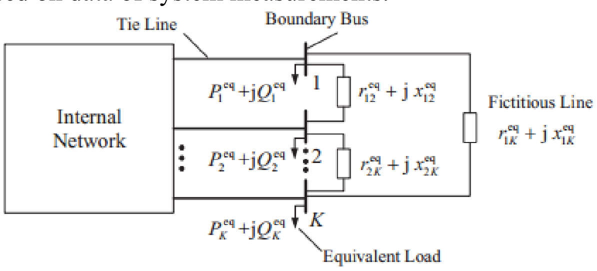

Fig. 2. An illustrative example of the EMM framework.

A. Topology of Equivalent Network

The framework proposed in [3] is characterized by introducing the fictitious bus. However, the fictitious bus does not physically exist and it is hard to determine the voltage value on this bus because the objective function can not converge to zero. The uncertainty of fictitious bus voltage may lead to inaccurate model. Instead, EMM adopts the topology which is similar to the Ward equivalent technique [7] and it can be seen from Fig.2 that EMM builds up the equivalent network without introducing the fictitious bus. All pairs of boundary buses are mutually interconnected by fictitious lines. Accordingly, the determination of line impedance parameters R and X developed in EMM is of great importance to reduce the errors of equivalent network.

EMM is one kind of the measurement based approaches, which means that the parameters of model are obtained from parameter identification methods. But the topology in Ward equivalent is obtained by performing Gaussian elimination on nodal admittance matrix of original network. Furthermore, the equivalent model of EMM relies on the sampled data only instead of operation states and topology of the whole network which are essential for Ward equivalent.

B. Equivalent Load Model

The equivalent load model adopted in this paper is [10], [11]:

$$P_i = F_p(\dot{V}_i, f), \tag{1}$$

$$Q_i = F_q(\dot{V}_i, f), \tag{2}$$

where P_i and Q_i are the p.u. value of active and reactive power consumed in the bus i, respectively, $\dot{V}_i$ is the complex voltage of bus i, f is the frequency of electric network, and F_p and F_q are the function relationships between P_i, Q_i and $\dot{V}_i$, f, respectively.

However, the frequency of voltage is relatively stable during system operational cycle while the magnitude of bus voltage may vary greatly due to the change of network structure. Hence, it is reasonable to consider only the static voltage characteristics of loads in equivalent load model of EMM, which can be represented by the following polynomial equations [11]:

$$P_i^{eq} = a_1 V_i^2 + a_2 V_i + a_3 \tag{3}$$

$$Q_i^{eq} = a_4 V_i^2 + a_5 V_i + a_6 \tag{4}$$

where V_i is the p.u. value of nodal voltage magnitude, a_1 - a_6 are the unknown parameters of the equivalent load model.

In brief, the unknown parameters of equivalent model developed in EMM include the parameters of fictitious lines resistance R and reactance X and the parameters of the equivalent load a_1 - a_6 . Parameter identification methods should be designed to determine these parameters, and we will discuss them in the next subsection.

C. Parameter Identification

Parameter identification is an essential part of equivalent modeling. The collected data from measurement apparatus is used to identify the unknown parameters. Using the squared errors between measured data and calculated value as objective function, parameter identification problem is actually a nonlinear programming problem [3], [6]. Generally, this optimization problem is a nonlinear and high-dimensions problem. Among optimization algorithms, interior-point method has been proven to be robust and efficient when solving large scale nonlinear programming problem in power system [12], [13]. Therefore, this paper adopts interior-point method as optimization algorithm.

In [3], the objective function is formed based on the minimizing the errors between the original power system and its equivalent power system. Different errors are weighted to represent the predictive errors. However, it is difficult to determine the weight. In order to avoid the weight tuning work, the objective function for the interior point method used in the EMM is formed based on the root-mean-square errors of measured value and calculated value of current at boundary buses, which is given as follows:

$$F(\mathrm{R},\mathrm{X},\mathrm{a}) = \sum_{j=1}^{J}\sum_{i=1}^{K}\left|\dot{I}_{ic}^{j} - \dot{I}_{im}^{j}\right|^2 \tag{5}$$

$$\dot{I}_{ic}^{j} = \left(P_i^{eq} + \mathrm{j}Q_i^{eq} \Big/ \dot{V}_{im}^{j}\right)^* + \sum_{i=1, l\neq i}^{K} (\dot{V}_{im}^{j} - \dot{V}_{lm}^{j}) \Big/ (r_{il} + \mathrm{j}x_{il})$$

(6)where i is the index for boundary bus, l is the index for boundary buses except i, K is the total number of boundary buses, j is the index for the typical operation states, J is the total number of typical operation states, r_{il} and x_{il} are the resistance and reactance of fictitious line between bus i and bus l, respectively, $\dot{I}_{ic}^{j}$ and $\dot{I}_{im}^{j}$ are the calculated current and measured current respectively, which are on the tie line connected to boundary bus i under j- th typical operation state, and $\dot{V}_{im}^{j}$ is the measured voltage of boundary bus i under j-th typical operation state.

The flow chart of the identification the unknown parameters of EMM is shown in Fig.3.

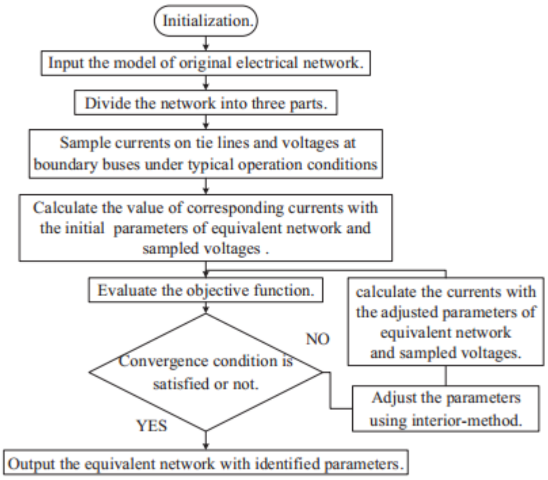

Fig. 3. Flow chart of parameter identification.

III. SIMULATION STUDIES

Simulation studies have been conducted on a 5-bus power system and IEEE 30-bus system respectively to verify the effectiveness of the EMM proposed in this paper.

A. Case 1: 5-bus Power System

The layout of five-bus power system is shown in Fig.4. This system consists of two separated generators, which supply the power for three loads via two transformers and transmission lines. The data of the test system are given in [3]. In this case, bus 2 and 3 can be regarded as boundary buses and the area with dotted rectangle can be regarded as external network. The rest of network is the internal network. In terms of external network we defined here, the framework of equivalent network in EMM provided before can be used thereby the structure of equivalent network can be obtained as in Fig.4.

There are totally 14 parameters to be identified, which include the resistance and the reactance of fictitious lines, and the twelve unknown parameters of equivalent load in bus 2 and bus 3. The parameters determine the similarity between the original network and the equivalent network. To make sure that the parameters can well adapt to different operation states, the measurements are based on three typical operation states:

OS1: Basic operation conditions.

OS2: State change of generator G1 .

OS3: Change of tap ratios of transformers.

For more details about these typical operation states, please refer to [3].

Following the steps introduced in Fig.3, the 14 unknown parameters are identified and then listed in Table I and Table II. The convergence characteristic of interior-point method is shown in Fig.5.

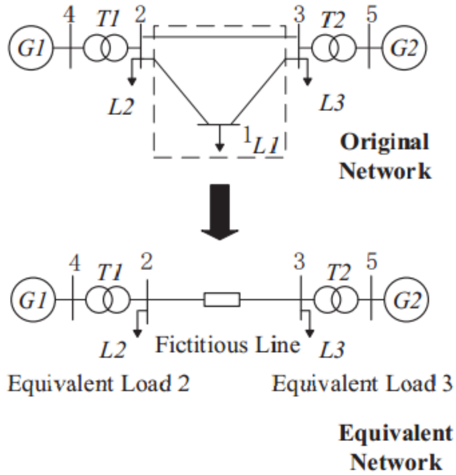

Fig. 4. The original network and equivalent network of 5-bus system.

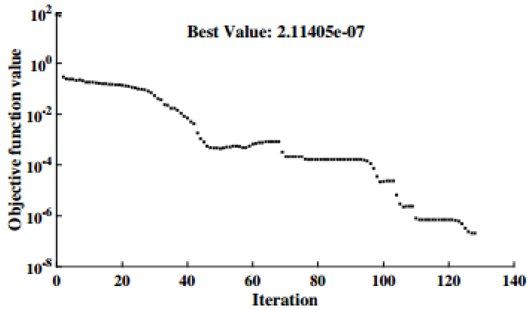

Fig. 5. The convergence characteristic of interior-point method

TABLE I
THE PARAMETERS OF EQUIVALENT LOAD AT BOUNDARY BUSES

	a_1^{eq}	a_2^{eq}	a_3^{eq}	a_4^{eq}	a_5^{eq}	a_6^{eq}
Bus 2	-1.0945	2.6675	1.1742	2.5212	-8.4690	7.1746
Bus 3	-1.1613	1.8755	4.0263	-0.3194	-0.3292	2.2573

TABLE II
THE PARAMETERS OF FICTITIOUS LINE

from bus	to bus	r(p.u.)	x(p.u.)
2	3	0.0178	0.1931

To evaluate the accuracy of the identified equivalent network in Fig.4, the bus voltages obtained from power flow calculation of original network and equivalent network under normal operation condition is shown in Fig.6, from which we can observe the accuracy of the equivalent network is pretty high because the bus voltages between these two model is very closed under normal operation condition.

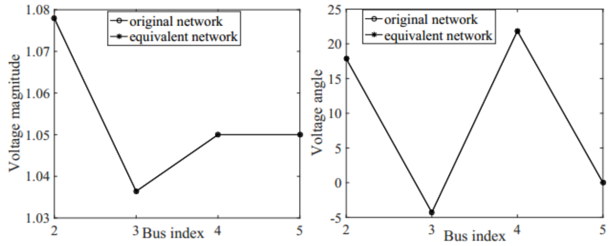

Fig. 6. Comparison of voltage between original network and equivalentnetwork under normal operation condition.

Apart from normal operation condition, three series tests are applied to demonstrate the effectiveness and robustness of EMM. In series tests, the maximum errors of the bus voltages magnitudes between the equivalent network and the original network is used to evaluate the accuracy of the equivalent network:

$$\Delta V_{\max} = \max_{\forall n \in I}\left(\frac{|V_{nm} - V_{nc}|}{V_{nm}} \times 100\%\right) \quad (7)$$

where the meaning of m and c is the same as (5), n is the index for the buses in equivalent network, and I is the total number of the buses in equivalent network.

For more details about these series tests, please refer to [3].

The results corresponding to these series tests are shown in Fig.7, Fig.8, and Fig.9, respectively.

It can be seen from these figures that equivalent network obtained from EMM can represent the original network very well under different operation states because the errors are minor. Besides, under operation states which deviate largely from typical ones, errors are relatively bigger than states closed to typical ones. Furthermore, the terminal voltages of generators have a greater impact on the accuracy of the model.

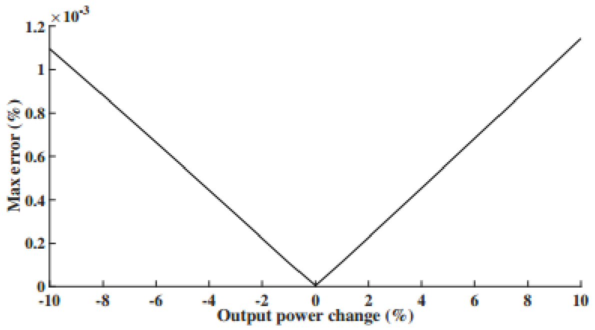

Fig.7. Maximum errors while changing the active power output.

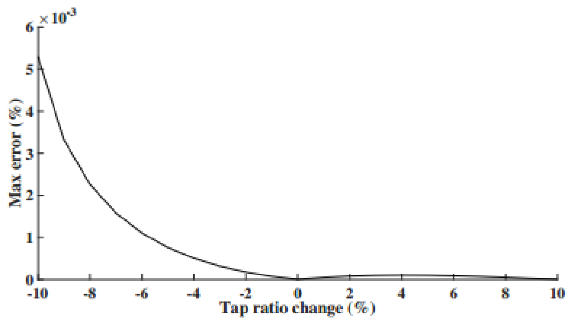

Fig. 8. Maximum errors while changing the tap ratios of transformers.

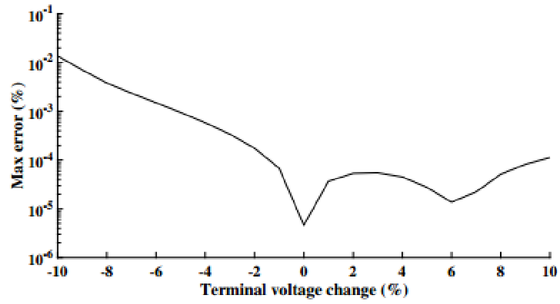

Fig. 9. Maximum errors while changing the terminal voltages.

B. Case II: IEEE 30-bus System

To evaluate the effectiveness of proposed method on larger test system, case studies have been conducted on IEEE 30-bus system which is shown in Fig.10, of which the data about this system are given in [14].

The area shown in the dotted rectangle can be considered as external network, and bus 10, 15 and 27 can be regarded as boundary buses. Using EMM, a much simpler equivalent network, which contains only 28 branches and 19 buses, can be obtained in Fig.10.

To identify the 24 unknown parameters, the measurement is based on two typical operating states as follows:

OS1: Normal operation conditions [3].

OS2: State change of generator G2, G3, and G4.

For more details about these typical operation states, please refer to [3].

The parameters of the equivalent network, are given in Table III and Table IV and the convergence process of interior point method is shown in Fig.11.

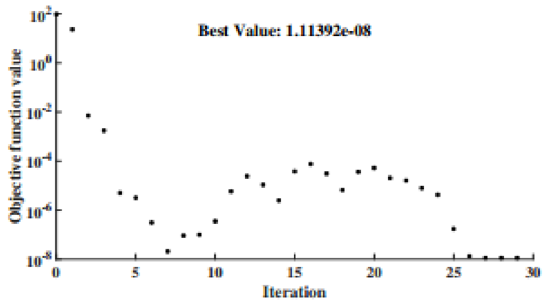

Fig. 11. The convergence process of interior-point method.

A similar test as on the 5-bus system under normal operation condition has been carried out, and Fig.12 shows that equivalent network obtained from EMM keeps high accuracy even though the system to be equivalenced is more complicated. Furthermore, three series tests similar to those of the 5-bus system have been conducted to evaluate the effectiveness and robustness of the equivalent network under varying operating points. The results are given in Fig.13, Fig.14 and Fig.15, respectively.

In addition to the conclusions obtained in the 5-bus system, we can also know the equivalent network still keeps pretty high accuracy though the scale of original network has already been reduced a lot, which illuminates the feasibility of EMM in large-scale electrical network.

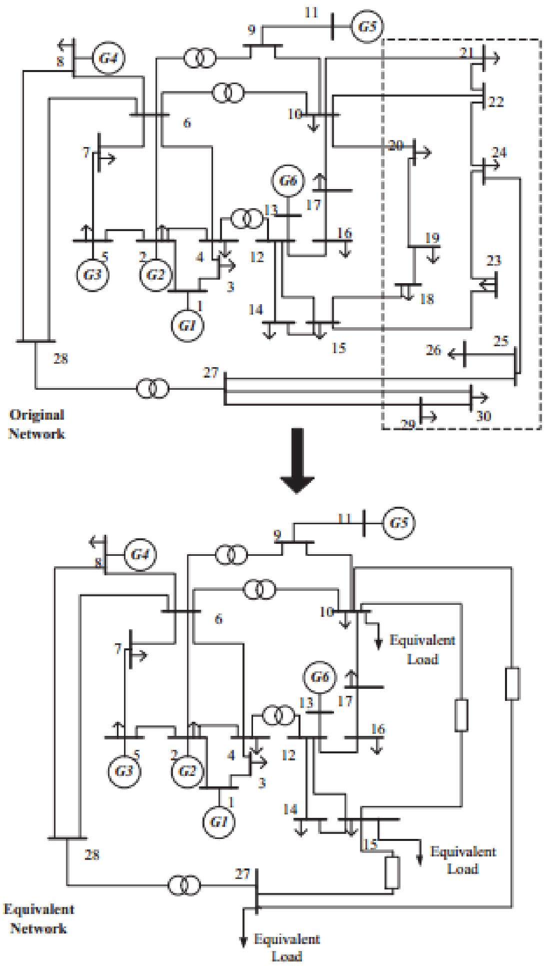

Fig. 10. The original network and equivalent network of IEEE 30-Bus system.

TABLE III
THE PARAMETERS OF EQUIVALENT LOAD AT BOUNDARY BUSES

	a_1^{eq}	a_2^{eq}	a_3^{eq}	a_4^{eq}	a_5^{eq}	a_6^{eq}
Bus 10	1.6253	0.0060	-1.4676	-0.4865	0.0936	0.6195
Bus 15	-1.8144	0.1379	1.9382	0.2302	0.0021	-0.2091
Bus 27	1.1128	0.0216	-1.0170	-0.0352	0.0148	0.0621

TABLE IV
THE PARAMETERS OF FICTITIOUS LINE

from bus	to bus	r(p.u.)	x(p.u.)
10	15	4.7594	0.7343
15	27	4.7131	1.2262
10	27	5.0879	-0.1101

IV. CONCLUSIONS AND FUTURE WORKS

This paper has proposed EMM for reducing the scale of electrical network. A novel framework with boundary buses interconnected has been employed in EMM. With respect to parameter identification scheme, the objective function based on predictive errors has been simplified to avoid the weight tuning and then the unknown parameters have been identified together using interior-point method. Simulation studies have been taken on a five-bus system and an IEEE 30-bus system. The results of simulation studies indicate that though the equivalent network obtained from EMM is much smaller than the original network, it can represent the characteristic of the original network in pretty high accuracy and well adapt to different operation states. Lastly, the simulation results from IEEE 30-bus system indicate EMM is promising in reducing the scale of large-scale electrical network.

The equivalent model derived from EMM can be employed in the applications such as static security analysis, long-term planning, and optimal power flow. In future work, the accuracy of the equivalent model can be evaluated through these applications. Besides, the quantitative criterion for the quality of the topology and the components of the equivalent model can be further investigated in our future works.

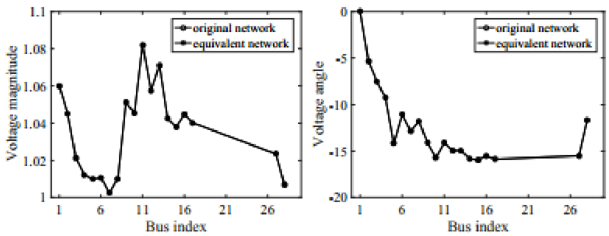

Fig. 12. Comparison of voltage between original network and equivalent network under normal operation condition.

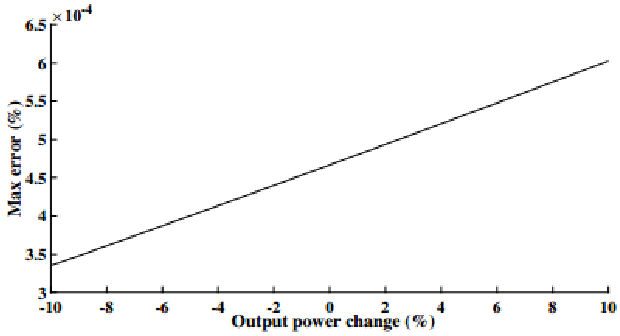

Fig. 13. Maximum errors while changing the active power output

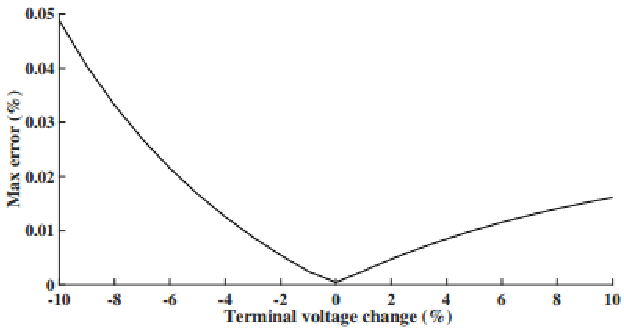

Fig. 14. Maximum errors while changing the tap ratios of transformers.

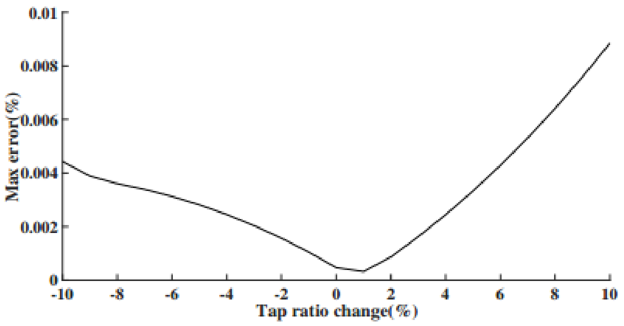

Fig. 15. Maximum errors while changing the terminal voltages.

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