Dynamic Equivalence of Large-Scale Power Systems Based on ANFIS

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Abstract—**How to reduce the model of a large-scale power system while keeping its dynamic behavior under various disturbances has long been a hot issue, as it is computationally burdensome when the dynamic analysis is performed based on detailed models. To solve this problem, the artificial neuro-fuzzy inference system (ANFIS) is employed to identify and represent the dynamic behavior of the external system, when disturbances are incepted in the study area. Based on the wide-area measurements obtained by the phasor measurement unit (PMU), the real-time active power and reactive power of the external area are predicted by the bus-voltage and bus-frequency at the opposite side of the tie lines. Case studies are conducted on the Northeast Power Coordinating Council (NPCC) under generator-trip contingencies and bus-fault contingencies. Case studies are performed based on the co-simulation of PSS/E and MATLAB, indicating that the proposed method has satisfactory performance in various conditions, including the generator-trip contingency and the bus-fault contingency.**

Index Terms— **Dynamic equivalent; system identification; artificial neuro-fuzzy inference system; model reduction**

I. INTRODUCTION

With the expansion of modern power systems, large-area-interconnection becomes the trend of modern power system development [1]. By this means, electrical resources can be organized and distributed in an optimal way, thereby increasing the reliability of power supply.

However, large-scale interconnection increases the difficulty of dynamic analysis using detailed models, since very complicated non-linear dynamic responses are included during various types of disturbances and the model of each electrical component, such as generators, buses, transformers, etc. is described by its own algebraic and differential equations. In addition, the limited processing capability of the simulation software will take a long time if the size of the power system is extremely large. Thus, dynamic reduction of the large-scale power system while keeping the original dynamic characteristics at an acceptable level of error has long been an unresolved issue [2-5].

In the past half century, extensive work has been done and plenty of achievements have been made on the dynamic equivalence of large-scale power systems. Up till now, the state-of-the-art approaches to solving this problem mainly fall into the following three categories:

1) The coherence-based equivalent approach, which consists three steps: the coherence-based division, system equivalence, and the parameter aggregation. When a fault occurs, generators showing similar dynamic characteristics are detected by an algorithm and then grouped as coherent generators. For these generators, an equivalent generator is employed to represent their dynamic behavior [6]. To achieve this goal, detailed parameters and model of the system are required. At present, many practical programs, such as the DYNERD [7], are based on the coherence-based equivalent approach. However, there are still some unsolved problems. First of all, there is not yet a good way to determine the groups of coherent generators. Second, the equivalence of network reduction, especially the elimination of the shifting transformer, will induce some errors. Last but not the least, the parameter aggregation process has some errors.

2) The model-equivalent-based approach, which is achieved by establishing the differential equation of the external system, linearization of the above equation, obtaining the state-equation, and obtaining the final reduced-order state equation. Therefore, the external system can be eliminated by keeping those characteristic roots that have significant impact on the study area, ignoring those characteristics that decay very fast. Thus, the external system can be reduced to a low-order system described by a linearized state equation rather than the actual one. For this type of approach, the detailed model and parameters are also needed, and the theory is comparatively simple and with good performance. However, in terms of actual engineering applications, the computation burden is quite high to determine the characteristic roots. Also, the equivalent system is represented by a reduced order linearized equation of state, which is not based on actual power system elements and cannot be directly applied.

3) For online dynamic security assessment, the knowledge of the external system is usually unknown so measurement-based methods offer advantages of authenticity and speed [8]. Compared with previous two approaches, the measurement-based dynamic equivalence approach is a promising method because it is not required to know the structure and parameters of the external system. This allows its application in systems with fast-changing operating conditions and structures. By using the phasor measurement unit (PMU) and the frequency disturbance recorder (FDR), the impact of the external area on the research area can be studied according to the power flow, voltage, frequency, etc. on tie lines.

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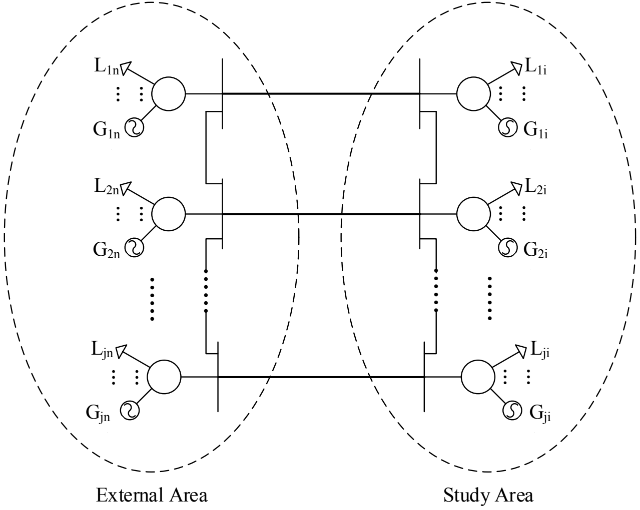
In previous works, this type of equivalence method was realized by employing the autoregressive model [9]. However, only the zero-order autoregressive model is available when writing the PSS/E user-defined model, which will cause a certain degree of error. Later in [8], a transfer-function is introduced to represent the mapping of the wide-area voltage and frequency to the reactive and active power of tie lines. However, accuracy depends on the order of the transfer function. Although it is proved that the second-order system is the most accurate, there is still room for enhancement.

This paper will develop a novel dynamic equivalence method to increase the accuracy of previous ones based on the artificial neuro-fuzzy inference system (ANFIS), which is organized as follows. In Section II, the basic theory, the established model, and the flowchart for the ANFIS-based approach are introduced. In Section III, the proposed scheme are verified by simulations, followed by the conclusions in Section VI.

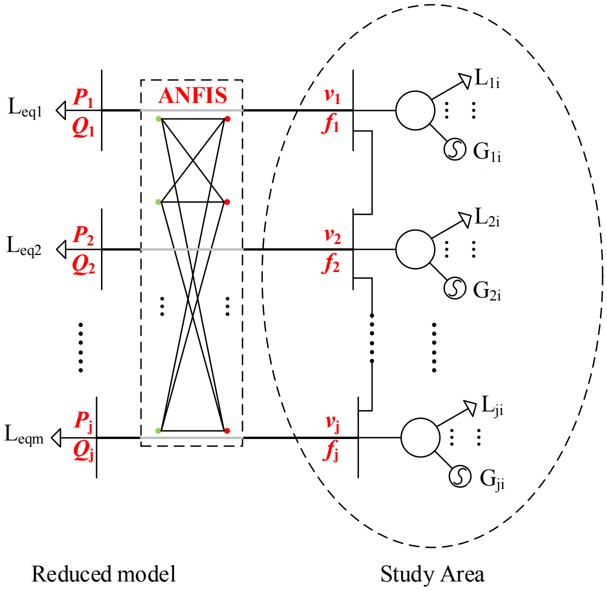
II. DYNAMIC EQUIVALENCE APPROACH

A. Model of dynamic equivalence

As shown in Fig. 1 (a), a typical large-scale power system can be divided into the external area and study area. The study area is where disturbances are applied and simulated, and the external area is the one that should be reduced. If an external system is connected to the study area via a long-distance transmission line, all generators in the corresponding external system can be regarded as in a coherent group. In this paper, each part of an external system that connected to its unique tie-line is modeled by a flexible load. Considering the perfect system-dynamic modeling capability of the ANFIS, the active power and the reactive power of this load is tuned by the pre-trained ANFIS in real time, according to the bus-voltage and bus-frequency in the study area, as shown in Fig. 1 (b). The voltage and frequency of the tie lines at the boundary of the study area, which is essential for the determination of real-time active power and reactive power, are provided by PMUs.



(a) The original model



(b) The reduced equivalent model

Fig. 1 The original model and the reduced model

B. The structure and training of ANFIS

The type of ANFIS can be divided into Mamdani-based ANFIS and Takagi-Sugeno (TS) -based ANFIS, and they both have their unique advantages. For the Mamdani-based ANFIS, its rules are in accordance with mankind's habits of thinking and language expression, and thus expert-knowledges can be easily represented. However, the structure of the Mamdani-based ANFIS is too complicated to be analyzed in mathematical ways. The Takagi-Sugeno-based ANFIS provides an excellent way to solve this problem, which can be easily combined with control methods such as PID control, adaptive control, etc. According to above characteristics, the Takagi-Sugeno fuzzy inference system has been proposed, working in conjunction with the neuro-network. According to former studies [10], the TS-based ANFIS has been proved to be an excellent tool with an adaptive learning capability and the system dynamic representation capability. The structure of the TS-based ANFIS is shown in Fig. 2.

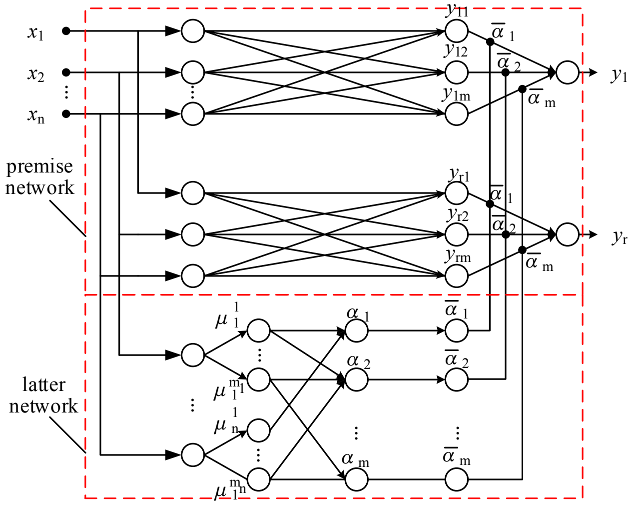


Fig. 2 The structure of the TS-based ANFIS

The description of the TS-based ANFIS is as follows.

1) The premise network. For the first level, each node is connected directly with the input $\mathbf{x} = \left[x_1 \quad x_2 \quad \cdots \quad x_n\right]^{\mathrm{T}}$. After that, the membership function is calculated in the second level, which is given by:

$$\mu_i^j = \mu_{A_i^j}\left(x_i\right) \tag{2}$$

where i =1, 2, … ,n, and j= 1, 2, … m_i. n is the dimension of the input vector, and m_i is the number of the fuzzy division. In the third level, each node represents a unique fuzzy rule, whose function is to calculate the fitness of each rule:

$$a_j = \min\left\{\mu_1^{i_1}, \mu_2^{i_2}, \cdots, \mu_n^{i_n}\right\} \tag{3}$$

where $i_1 \in \left\{1,2,\cdots,m_1\right\}, i_2 \in \left\{1,2,\cdots,m_2\right\}, \ldots, i_n \in \left\{1,2,\cdots,m_n\right\}$, j=1,2,…,m, and $m = \prod_{i=1}^{n} m_i$. In the 4th level, the number of node is equal to that of the 3rd level, where inputs are normalized here, which is given by:

$$\bar{a}_j = a_j \Big/ \sum_{i=1}^{m} a_i \quad \left(j = 1,2,\cdots,m\right) \tag{4}$$

2) The latter network, which contains r sub-networks in parallel with the same structure, and each of them generates an output, naming the input level, the rule level, and the output level. Each output is the weighted sum of the normalized input, which is given by:

$$y_i = \sum_{j=1}^{m} \bar{a}_j y_{ij} \tag{5}$$

Using such algorithms as the back-propagate and the least square method, the rule of the ANFIS can be determined automatically.

C. The proposed approach for dynamic equivalence

As shown in Fig. 3, the logic of the proposed method can be described as in the following steps.

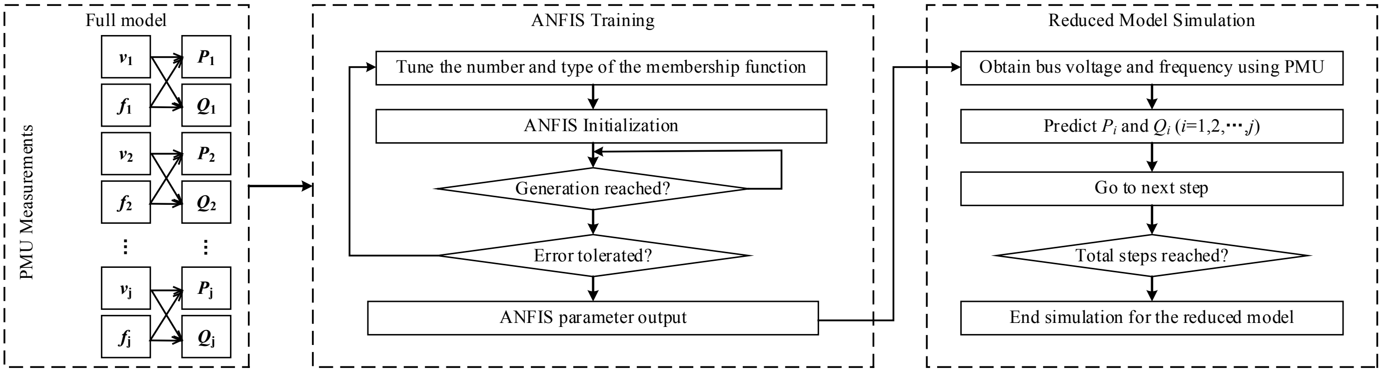


Fig. 3 The flowchart of the proposed method

Step 1) Collect measurement data from the original model in Fig. 1 (a). The bus-voltage and the bus-frequency of each tie line as well as the power flow on the tie lines are monitored by PMUs [11]. In this paper, generation trip events are simulated to obtain PMU data.

Step 2) Initialize an ANFIS using default parameters. The location of the fault incident, the time, the measured bus-voltage, and the measured bus-frequency are used as inputs, whereas the reactive power and the active power of the equivalent flexible load in Fig. 1 (b) are outputs. Using the back propagation algorithm, the ANFIS is trained to optimize the characteristics of the membership function, and the total generation is set to 20 steps. After that, if the error is tolerable, the training process will be terminated and the parameter of the ANFIS will be used for the on-line prediction of the equivalent active power and the reactive power of the flexible load. Otherwise, we need to select the number of membership function again, and then repeat the above process until the estimation data fit the original ones.

Step 3) On-line simulation using the reduced model. In every time-step, the real-time bus-frequency and the real-time bus-voltage in the study area are employed to predict the parameter change of the flexible load connected to the opposite side of the corresponding tie line, until the termination of the simulation after reaching the end of simulation horizon.

III. CASE STUDY

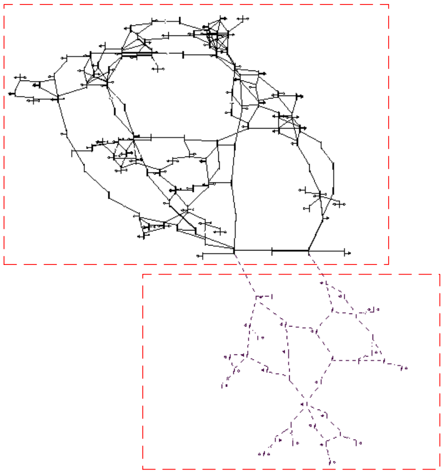
Based on the PSS/E software, a full model of the Northeast Power Coordinating Council (NPCC) is used as the original system, as shown in Fig. 4. The solid lines represent the study area, and the dashed lines represent the external area.

To reduce the system, we set two tie lines as the model reduction boundaries, which are from bus-37 (study area) to bus-29 (external area), and from bus-73 (study area) to bus-35 (external area), respectively. On the opposite side of each tie line, a flexible load is connected, and its real-time active and reactive power are emulated by the ANFIS.

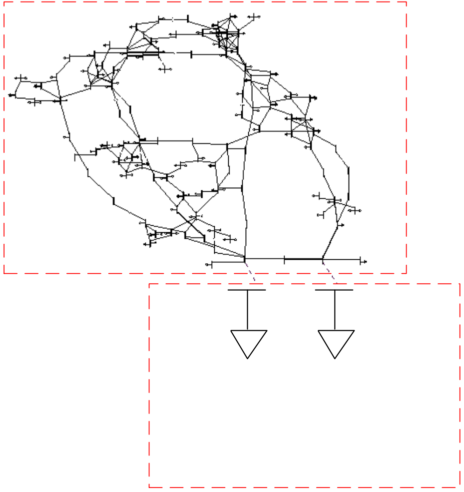
Case 1) To assess the performance of the proposed method in generation-trip contingencies, the following cases are considered, as shown in Tab. 1. In each contingency, the corresponding generator trips at t=1 s. The simulation ends at t=5 s.

For contingency 1, the first generator connected to bus-79 trips at t=1 s, Since the reactive power of this generator is as high as 257.34 MVar before this contingency, the voltage dips to about 1 pu soon after the occurrence of this contingency. Similarly, the frequency also dips because of the loss of 1000 MW active power.

By using the TS-based ANFIS, both the bus-voltage and the bus-frequency match quite well with the original curves. The oscillation mode of the reduced model is also in high accordance with the original model, showing that the reduced model has kept most dynamic characteristics of the original model.



(a) The original system



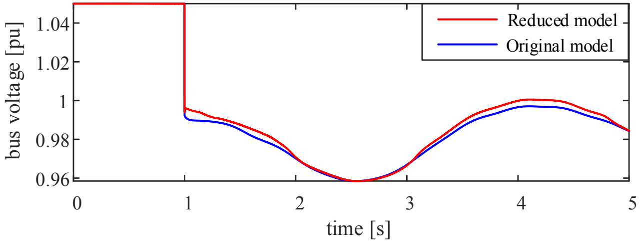
(b) The equivalent system

Fig. 4 The equivalence of the NPCC system

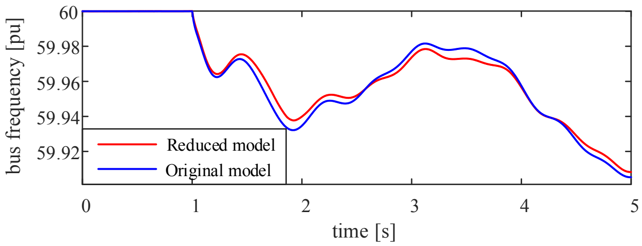
Tab. 1 Test contingencies

Contingency	Bus of Generation-trip	ID	Trip Amount	
			P [MW]	Q [MVar]
1	79	1	1000.00	257.34
2	80	1	720.00	-0.08
3	82	1	460.00	125.10
4	86	1	1650.00	577.47
5	91	1	930.00	1000.38
6	92	1	450.00	324.47
7	97	1	600.00	93.17

For contingency-1, the performance of the proposed method is shown in Fig. 5.



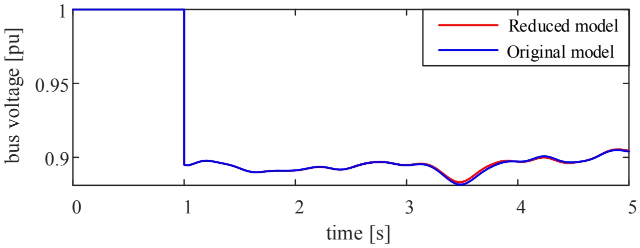
(a) The comparison between bus voltages



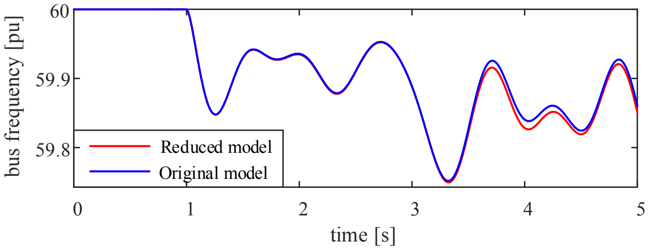
(b) The comparison between bus frequencies

Fig. 5 The performance of the ANFIS-based approach

Taking contingency 4, 5, 6, as examples, the performance is shown from Fig. 6 to Fig. 8. As seen, they match quite well in these contingencies.

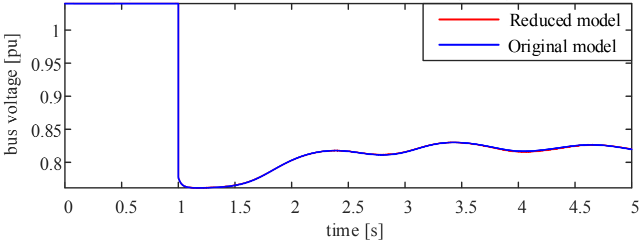


(a) The comparison between bus voltages

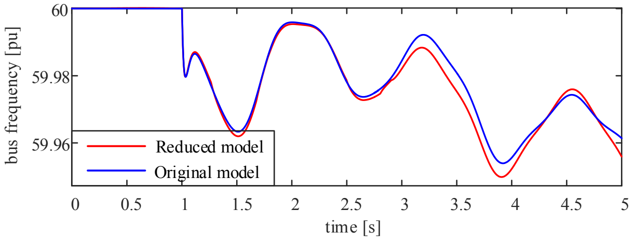


(b) The comparison between bus frequencies

Fig. 6 Performance under contingency-4

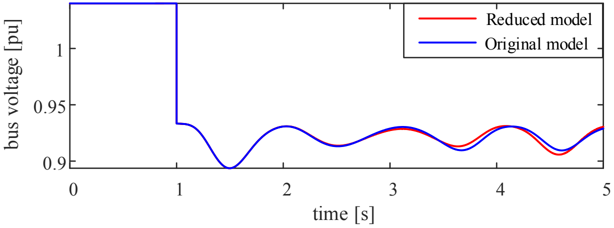


(a) The comparison between bus voltages

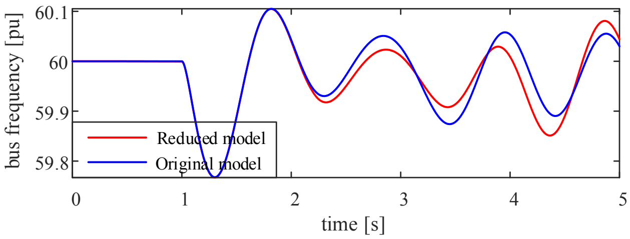


(b) The comparison between bus frequencies

Fig. 7 Performance under contingency-5



(a) The comparison between bus voltages



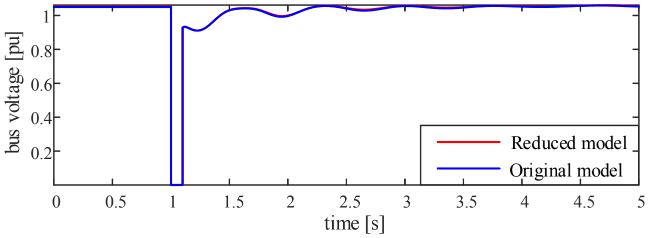
(b) The comparison between bus frequencies

Fig. 8 Performance under contingency-6

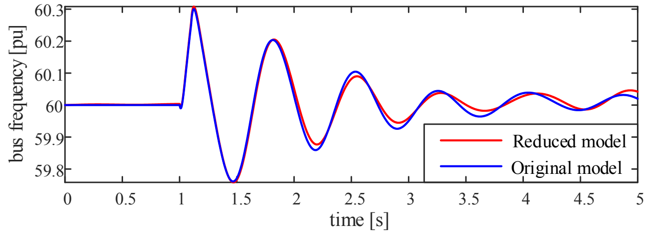
Case 2) Bus-fault transients usually include larger magnitudes of system dynamics, compared with generator-trip contingencies. To investigate if the proposed method can apply to different types of faults, the performance of the proposed method is assessed in various bus-fault conditions. The following equation is employed to calculate the correlations between the curves using the original model and the reduced model, respectively:

$$\rho\left(A,B\right)=\frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i-\mu_A}{\sigma_A}\right)\left(\frac{B_i-\mu_B}{\sigma_B}\right) \qquad (6)$$

where A and B represent the curves of the simulation using the original model and the reduced model, respectively. For the bus fault at bus-79, the performance of the proposed method is as follows.



(a) The comparison between bus voltages



(b) The comparison between bus frequencies

Fig. 9 Performance under bus-fault conditions

As seen, although the training data of the ANFIS does not take bus-faults into account, it copes very well under bus-fault condition, indicating that the proposed method has sufficient universality. In this scenario, the correlation of voltages is 0.987, and the correlation of frequency is 0.995.

In Fig. 10, there provides correlations between the curves of voltage and the curves of frequency in all bus-fault conditions. As seen, wherever the fault occurs, the simulation result using the reduced model is in high accordance with the one using the original model, highlighting the universality of the proposed method coping with all types of disturbances.

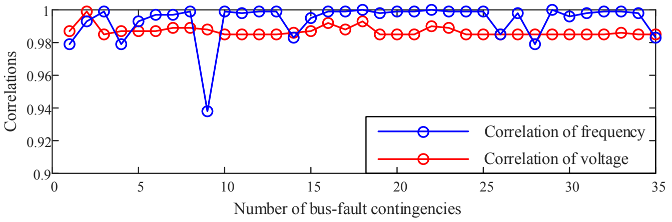


Fig. 10 The correlations under bus-fault conditions

IV.CONCLUSION

In this paper, an ANFIS-based model dynamic reduction approach is proposed. The active and the reactive power of the external system is predicted in real-time using the boundary voltages and the boundary frequencies measured by PMUs. Conclusions of this study are as follows.

1) For generation-trip contingencies, the dynamic response of the reduced model is almost the same with the full model.

2) For bus-fault contingencies, the dynamic response of the reduced model matches quite well with original ones. The voltage and frequency profiles between the reduced model and the full model are very similar (correlation is very close to 1).

3) In future studies, we plan to apply this method to power systems that have more buses, such as the 70,000-bus Eastern Interconnection (EI) model.

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