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Enhanced measurement-based dynamic equivalence using coherency identification

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Abstract— **Power system dynamic simulation demands substantial computation due to extensive interconnection among power systems. Traditionally, the computational burden has been reduced by using dynamic equivalent methodologies, such as modal, coherency and measurement-based. Measurement-based method replaces an external system with a simple equivalent and estimates its parameters through optimization method with measurement. However, the conventional method does not clearly present the model structure for the external equivalent. This ambiguity, then, may lead to poor performance of the equivalent. The proposed method uses generator equivalent model and shows how to choose a proper number of generators for the equivalent model structure using coherency concept. The approach preserves relevant modes from the external and thus enhances the simulation performance of the dynamic equivalent. Test results of a simple power system are presented and show a high level of accuracy of the proposed method.**

***Index Terms*—Power system dynamic simulation, Dynamic equivalent, measurement-based method, coherency identification**

I. Introduction

Power systems have been required to operate more efficiently and economically since the deregulation of the power industry. These objectives can be accomplished when power systems control centers have an ability to analyze system conditions accurately and quickly. However, such analysis is a computationally demanding problem in large modern interconnected power systems, particularly for power system dynamic simulation. Construction of simplified dynamic equivalent is a common technique to reduce the computational requirements.

Since 1970's, a vast amount of research to construct dynamic equivalents have been proposed based on different techniques. The equivalent approach partitions the electric power system into the internal system (often called the study system), the external system, and a group of boundary buses. The power system model size is reduced by replacing the external system with the simple equivalent. A performance of the equivalent method is fully dependent on how the equivalent mimics the impact of the external system on the internal system. Electromechanical oscillation modes are the key information to analyze the interaction between the internal and the external. Those oscillations are interarea modes associated with the swinging of many machines in one part of system against machines in other parts. They are typically in the range of 0-2 Hz [1]. Three main methods to reduce the generator number and the network nodes are modal, coherency and measurement-based [2].

1) Modal method [3-4] : based on a linearized model, the unexcited or insignificant modes in the external system can be eliminated
2) Coherency method [5-6]: coherent groups of generators are identified and are aggregated by an equivalent generator
3) Measurement based method [7-8]: measured data are used to estimate parameters of an equivalent model using curve-fitting or optimization techniques

Conventional measurement-based method first selects an equivalent model structure which is usually a generator form. The parameters of the selected equivalent model are then estimated by solving minimization problem using measurements [8]. However, the equivalent model structure is not clearly presented to maintain the effects from the external system. In other words, a proper generator number for the equivalent is not obviously answered. Therefore, the equivalent may not show a required high level of simulation accuracy.

This paper presents a new measurement-based approach to enhance the simulation performance. It incorporates coherency concept to identify the generator groups in the external and construct the related equivalent model. The proposed method enables the dynamic equivalent to preserve modes which represents an impact of the external system on the internal. This work aims to improve accuracy level of the dynamic equivalent simulation. This paper is organized as follows. Section II presents a brief summary for conventional measurement-based method and its limitation. The proposed approach is presented in Section III. Section IV illustrates simulation results with the simple test case. The conclusion is presented in Section V.

II. CONVENTIONAL MEASUREMENT BASED METHOD

The conventional measurement-based approach is summarized and its limitation is also presented in this section.

A. Methodology

The procedure of measurement-based approach is explained with the simple power system in Fig. 1. The example case has 9 buses, 4 transmission lines and 4 generators which are all classical models. Machine parameters are given in Tab. 1.

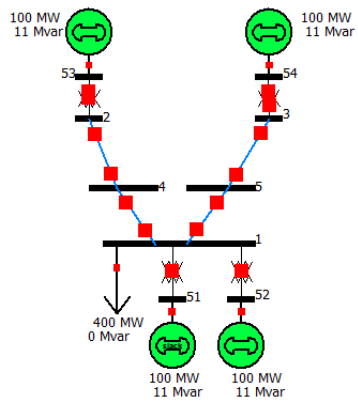

Figure 1. Simple 9 bus case (Case I)

Table 1. Dynamic machine parameters for Case I

Generator Bus number	Machine inertia(H)	Damping (K_d)	Transient reactance(X_d)
51	5	0.2	0.2
52	5	0.2	0.2
53	10	0.5	0.1
54	50	1.2	0.05

The equivalence method starts with dividing the power system into the internal system, boundary buses and the external system. The internal system is where the dynamic responses are to be studied. The rest of the power system is denoted as the boundary or the external system. For example in Fig 1, it is assumed that the internal system consists of bus 1, 51, and 52. Then the boundary buses, which have a connection to a bus in the internal one, are buses 4 and 5 and the remaining buses, 2, 3, 53 and 54 are the external system.

- Step 1 : Construct a reduced model

All nodes and branches in the external system are eliminated, and fictitious generators equivalent to the external system are attached at the boundary buses. The generator form of the equivalent is used in the Fig. 2. Another form such as generator and load can be used. The model of the equivalent generator can be of any order [9]. For simplicity, the classical model for the equivalent generator is used for the example.

The steady state operating conditions must be preserved. The complex power flows from the reduced model should be matched with those from the unreduced model by adjusting the power injection and voltage magnitude of the fictitious generators.

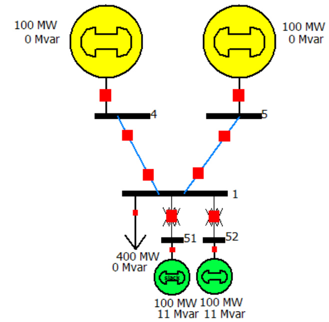

Figure 2. Reduced model of Case I

- Step 2 : Estimate parameters of the fictitious generator

The model parameters to be estimated for the example are machine inertia (H), damping coefficient (K_d), and transient reactance (X_d). These parameters are identified through optimization procedure with measurements from the unreduced model. This can be written mathematically as the following least square minimization problem :

$$\underline{p}^* = \arg\min\{\sum_{i\in B}\sum_{j\in I}(P_{ij}^{original} - P_{ij}^{reduced}(\underline{p}))^2\}$$

where $\underline{p} = [H_4, K_{d4}, X_{d4}, H_5, K_{d5}, X_{d5}]^T$, B is the set of boundary nodes, and I is the set of buses in the internal system connected to boundary buses

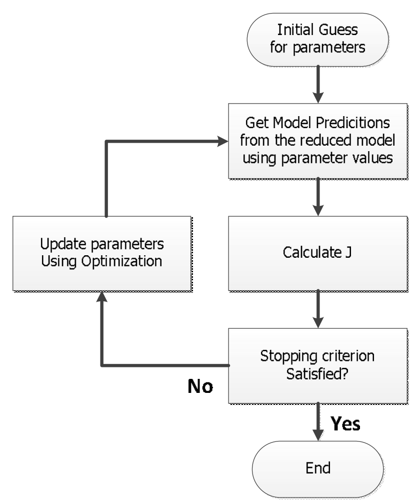

Figure 3. Flowchart for parameter estimation

A set of measurements are required to estimate the parameters. The responses of the dynamic simulation with the full model are used for the measurements. The example assumes that measurements are 10 sec simulation data of real power flows, P_{41} and P_{51} when Bus 52 has a three-phase solid ground fault at 1 sec for 0.1 sec. Matlab function *fminsearch* is used to solve the minimization problem [10]. And PowerWorld is used to get model prediction from the reduced model in the estimation procedure [11]. Fig. 3 shows the flow chart for estimating the parameters.

Table 2. Estimated machine parameters for Case I

Fictitious Gen Bus number	Machine inertia(H)	Damping (K_d)	Transient reactance(X_d)
4	10.0001	0.5	0.2099
5	50	1.2	0.1599

Identified parameters for the example case are in Table 2. Estimated machine inertia and damping are same as those in Tab. 1 and transient reactance is increased by transmission line and transformer impedance. Figure 4 shows trajectories of Bus 1 voltage magnitude and Gen 52 rotor angle respectively. And the responses both from the full model and from the reduced model are plotted. The approach shows very good performance with the example.

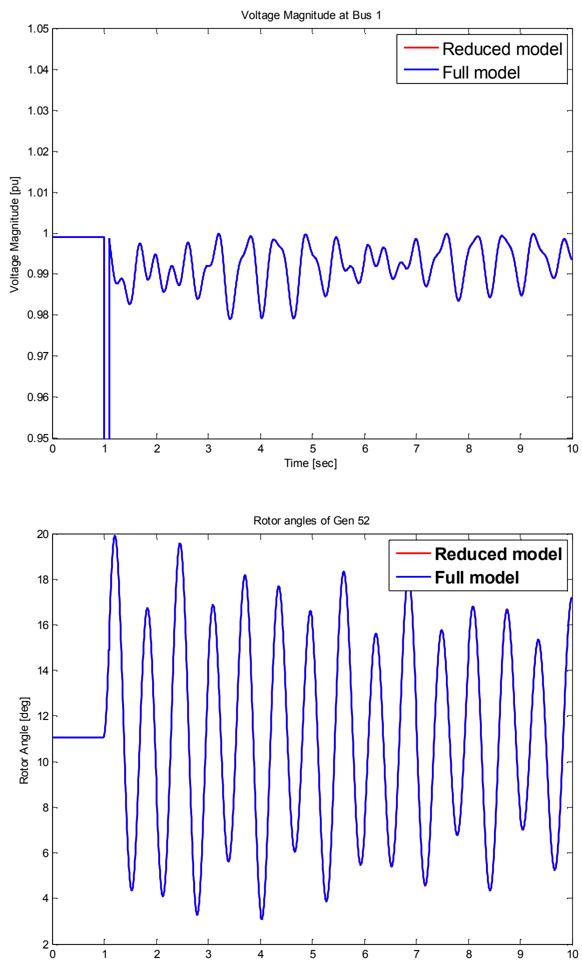

Figure 4. Trajectories of Full model and reduced model for Case I

B. *Limitation of conventional method*

Different case is shown in the Fig. 5 (left). The new case (Case II) is similar network configuration with the Case I. But, it has only one boundary bus and 2 loads are added to the external system. All generator parameters are same as those in Tab. 1. When the conventional method is used for dynamic system reduction, the reduced power system model is shown in Fig. 5 (right). The optimization method with measurement P_{41} evaluates the equivalent machine parameters, which is shown in Table. 3.

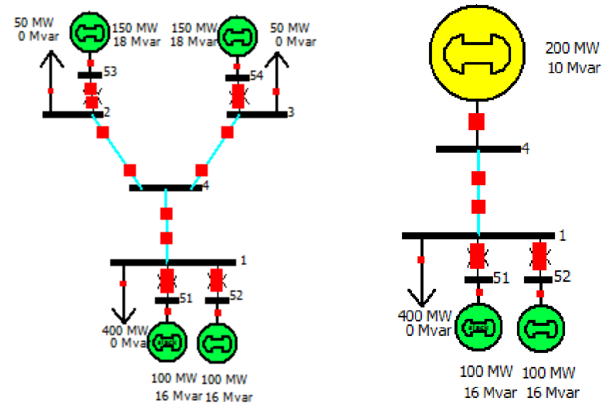

Figure 5. New 9 bus case (Case II) and its reduced model

Table 3. Estimated machine parameters for Case II

Fictitious Gen Bus number	Machine inertia(H)	Damping (K_d)	Transient reactance(X_d)
4	17.907	5.0065	0.1259

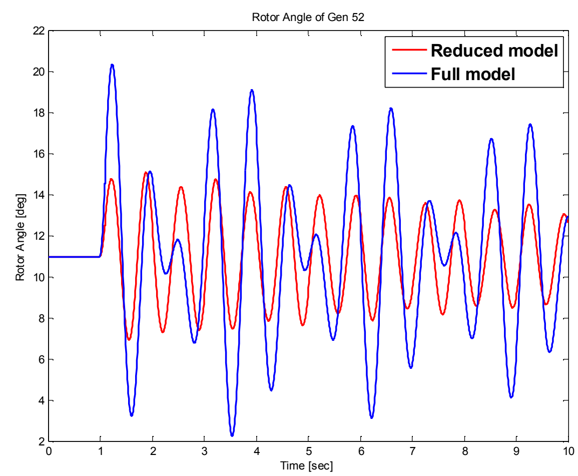

Figure 6. Trajectories of Full model and reduced model for Case II

The response of Gen 52 rotor angle is shown in Fig. 6, which shows big differences between the trajectories of the reduced model and those of the full model. Here questions arise where these differences came from even though same approach is used as before. Because the boundary bus in Fig. 5 has two connections to the external system, which means the external has two different characteristics, one generator cannot represent the two modes. It is thus necessary to attach one more generator in order to represent all low frequency modes from the external system. For general case, the number of fictitious generators should be matched with the number of interarea modes from the external system. The appropriate number should be the number of coherent generator groups in the external.

III. PROPOSED METHODOLOGY

A. Coherency

The concept of coherent generators is that a number of groups of generating units are swinging together at the same frequency and at close angles from a transient stability analysis [12]. The models for each coherent group of generators are combined into one equivalent model. The coherent groups are identified by analyzing the system response to a disturbance or by studying eigenvalues, eigenvectors and participation factors from a linearized method. This paper does not cover the method to identify the coherent groups in depth. Those methods can be found in [5-6].

B. Proposed method

The boundary bus may be connected to one coherent group or many groups. Coherency-based method says each coherent group can be aggregated into one equivalent generator. The equivalent generator presents the low frequency oscillation which is related to interaction between the group in the external and the internal system. Therefore, the number of equivalent generators at the boundary bus should be same as the number of coherent groups in the external system. Each equivalent generator can maintain the system mode from each coherent group. And the preserved mode with the equivalent generator can improve the performance of dynamic equivalent simulation. Fig. 7 shows the proposed method.

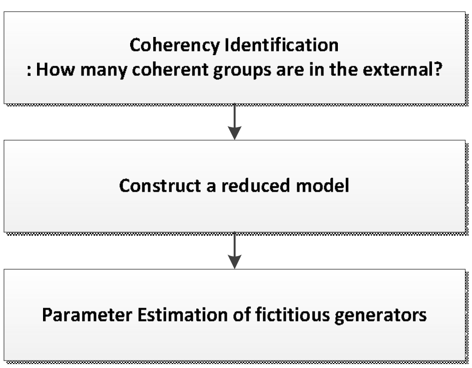

Figure 7. Proposed methodology

IV. CASE STUDY

A. Non-coherent case

The case II power system is tested as a non-coherent case. Dynamic simulation with a fault in the internal system identified that Gen 53 and Gen 54 are non-coherent generators. To maintain the effect of each generator in the external system on the internal system, two fictitious generators are required at the boundary bus. The reduced system is shown in Fig. 7. And the simulation results are shown in Fig. 8. The results confirm quite good performance of the proposed method.

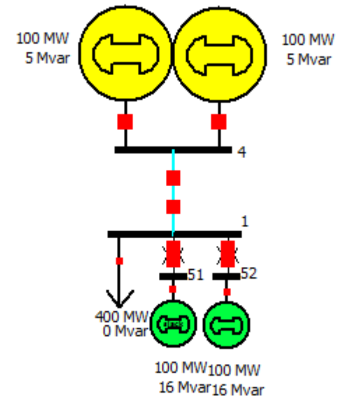

Figure 7. The reduced model with proposed method for Case II

Table 2. Estimated machine parameters for Case I

Fictitious Gen Bus number	Machine inertia(H)	Damping (K_d)	Transient reactance(X_d)
4	8.871	0.78	0.2411
5	47.04	1.46	0.1709

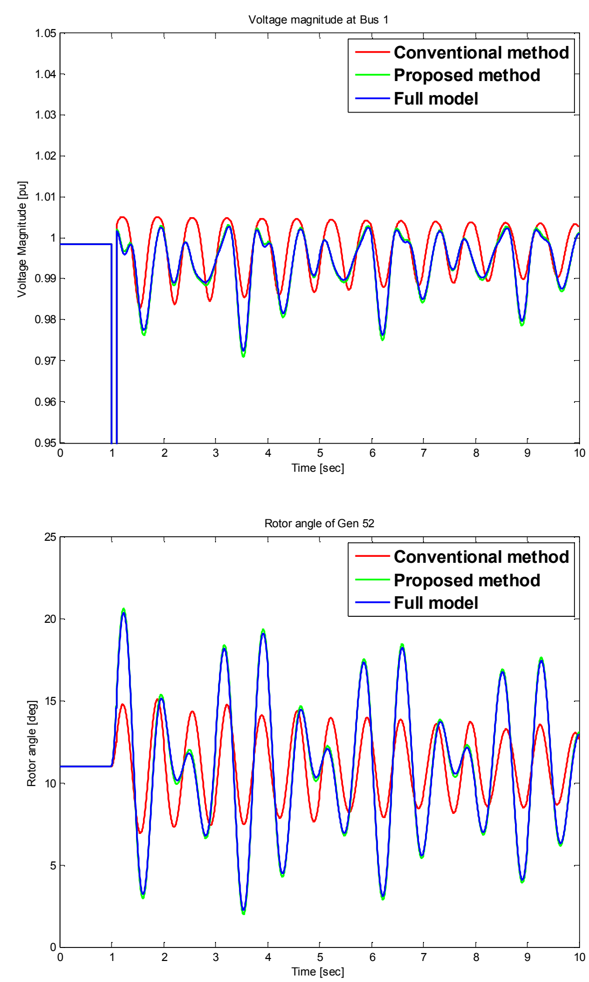

Figure 8. Trajectories of Full model and reduced model for Case II

B. Coherent case

For coherent case, an additional transmission line between Bus 2 and 3 is added to Case II and it is shown in Fig. 9. Coherency is identified from Gen 53 and Gen 54 responses shown in Fig. 11. Because Gen 53 and 54 are coherent, only one fictitious generator is attached to the boundary according to the proposed method.

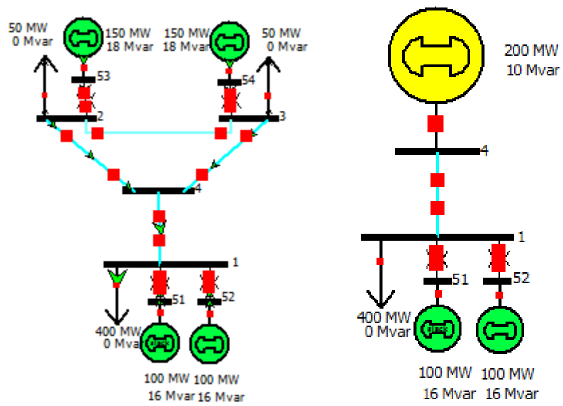

Figure 9. New 9 bus case (Case III) and its reduced model

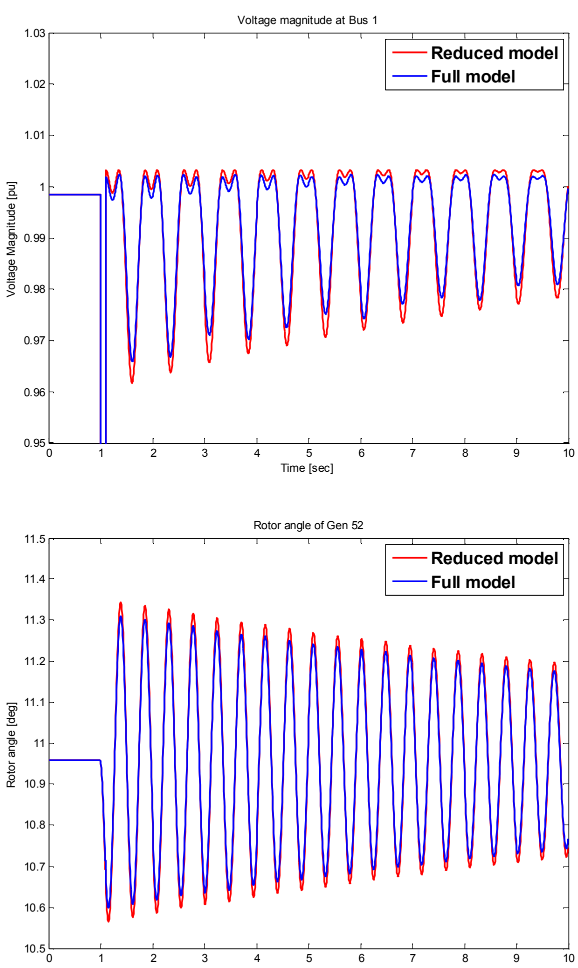

Figure 10. Trajectories of Full model and reduced model for Case III

Table 3. Estimated machine parameters for Case III

Fictitious Gen Bus number	Machine inertia(H)	Damping (K_d)	Transient reactance(X_d)
4	61.808	-2.7863	0.1029

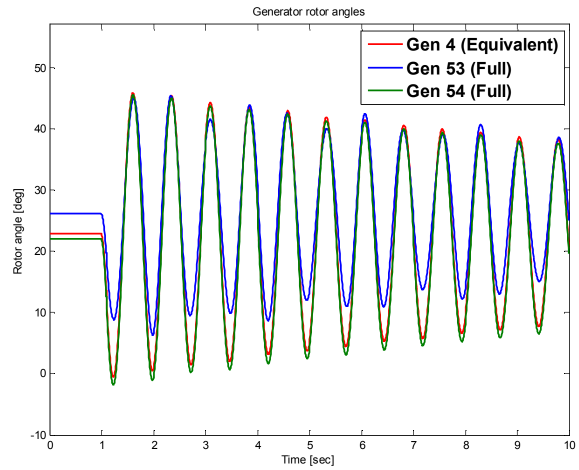

Figure 11. Generator rotor angles of full model and reduced model

Fig. 10 shows the simulation results and provides comparison between the reduced and the full model. The responses from the equivalent model are very close to those from the full model. Minor differences are mostly from the elimination of the load in the external system. It is shown in Fig. 11 that the equivalent generator replaces the coherent generator 53 and 54 well.

Test results for coherent and non-coherent case confirm that the proper number of generators at the boundary bus improves the accuracy of dynamic simulation for measurement-based equivalent. The generator number can be determined by identifying the number of coherent groups in the external. Therefore, all impacts on the internal system from the external system can be represented by the fictitious generators.

V. CONCLUSION

This paper explores the development of measurement-based dynamic equivalent approach to improve the simulation performance. It combines the coherency concept with the conventional method. The approach constructs the equivalent model structure by identifying the coherent groups in the external in order to maintain relevant electromechanical modes. A simple power system is used to validate the approach as a preliminary study. Test results show the accuracy of the dynamic equivalent system can be improved when the proper equivalent model structure is built based on coherency concept. However, further study with a larger system is necessary to validate the approach. It will be the future work.

VI. Acknowledgement

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