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A Study on the Dynamic Reduction for Large Power System

Jin-Yi Kim, Dong-Jun Won and Seung-Il Moon

Abstract - This paper presents the procedure to construct equivalent model of large power system based on nonlinear time simulation responses. It consists of coherency identification, generator aggregation and network reduction. Coherency index that can be directly implemented to this procedure is proposed. Generator aggregation based on detailed model is performed. This procedure can be used to construct equivalent model in PSS/E. It is also possible to reduce the large power system directly from the nonlinear time responses. This procedure is applied to the transient stability analysis of Korea power system that now experiences rapid changes. The equivalent model is compared with the original model in its size, accuracy, speed and performance. This paper shows that the developed equivalent model is a good estimate of the original system.

Keywords - coherency index, equivalent model, generator aggregation, system reduction

1. Introduction

The circumstance of Korea power system now experiences rapid changes, for instance, power system interconnection between South and North Korea, installation of HVDC system between Cheju-island and Haenam-mainland and installation of FACTS device, UPFC. These changes are new to Korean power system engineers, so they are trying to analyze these changes. To study the effects of these changes into existing Korea power system, transient stability must be studied at first.

Transient stability studies require exact modeling of the related power system and time-domain digital simulation to solve the nonlinear system dynamic equations. But most programs for transient stability like EMTDC/PSCAD have a limitation in their maximum system size. Due to the large size and the complexity of Korea power system, it is almost impossible to study the stability problems including the whole system. So it is required to represent Korea power system by equivalent model [1][2].

Equivalent model is the reduced order model of the entire system, which retains the important characteristics of the system. Dynamic equivalencing is the process of reducing the complexity of the system model by eliminating buses, branches and generators. In this process, it is always important to preserve the characteristics of the original system [3].

The previous studies on equivalent model include the development of the modal equivalents in the late 1960's, which was never used extensively due to the need to modify stability simulation programs to use a state matrix form of the equations of the equivalent model. An alternative approach in the 1970's was based on the concept of coherency, whose confidence was also limited. The slow coherency (or two-time scale) technique was developed in the early 1980's. It combined the insights of both modal and coherency analysis [4][5].

But all these techniques have some limitations in their application to nonlinear time simulation. So if possible, the equivalencing procedure that uses nonlinear time simulation responses can be a good alternative. PSS/E (Power System Simulator for Engineers) provides nonlinear time simulation of large power system and the data of Korea power system is mainly expressed in PSS/E data format. So in this paper, PSS/E is used to construct the equivalent model and the procedure that can be directly implemented in PSS/E is developed.

This paper mainly proposes the procedure to construct the equivalent model of large power system. This procedure has the following steps.

- Coherency identification
- Generator aggregation
- Network reduction

Coherency index that uses the swing curves of each generator is proposed to identify coherency between two generators. Based on this coherency index, generators coherent with others are selected and included in the same group. Generators in the same group are aggregated into one generator. At last the network is reduced.

This procedure is applied to Korea power system. The equivalent model of Korea power system for the simulation of HVDC system is developed. Finally this equivalent model is compared with the original model.

2. Procedures

The dynamic reduction process for forming equivalent model can be divided into three steps:

1. Determination of coherent generator groups

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2. Aggregation of generators in the group
3. Reduction of the network

The following subsections provide a brief description and a detailed procedure in each three steps.

2.1 Coherency Identification

Coherency means that the rotor angles of some generators swing together for remote disturbances[6]. The coherency condition simplifies to

$$\delta_i(t) - \delta_j(t) = \delta_{ij}(t) = \delta_{ij}(0) = const \qquad (1)$$

That is to say, if the relative rotor angle between generator i and generator j has constant value at all simulation time, then generator i and generator j are electrically coherent and can therefore be changed by a single equivalent generator. In this paper, since the system is based on nonlinear models, coherency is identified to comparing the swing curves from nonlinear time simulation.

1) Coherency Index: In order to find coherent generators, the following coherency index is proposed

$$D(I,K) = \left(\sum\{I \le J \le N\}\left[A(I,J) - A(K,J)\right]^2\right)^{1/2} \qquad (2)$$

$$\text{where } A(I,J) = \frac{\delta(I,J) - B(J)}{Max\left|\delta(I,J)\right|} \qquad (3)$$

$$B(I) = \frac{\sum\{1 \le J \le N\}\delta(I,J)}{N}$$

$$\delta(I,J) \quad \{1 \le I \le M, 1 \le J \le N\} \qquad (4)$$

A(I,J): the revised rotor angle of generator I at time J
B(I): average rotor angle at generator I
$\delta(I,J)$: the rotor angle of generator I at time J
M: number of generators in the external subsystem
N: the number of sampling
D(I,K): coherency index matrix.

In above coherency index *D(I,K)*, the dc offset is eliminated by the average rotor angle *B(I)* in order to remove the effect of the initial values. To accumulate the errors, the difference is squared before summation. Coherent groups of generators are determined by comparing the coherency indices with a specified tolerance.

2) Determination of coherent groups: Schematically, the proposed method is performed through the following procedures.

1. Calculate the nonlinear time responses
2. Determine coherency index matrix ***D*** for external subsystem using (2).
3. Search { *D(I,K)* } less than the tolerance
4. Sort the selected { *D(I,K)* } in ascending order
5. Select the minimum value of the index and then store group {i,k} as a new coherent group.
6. If generator i has already been in a existing group and generator k is not yet, try to put generator k in an existing group
7. If generator k of group A also belongs to group B, then two indices will be compared, and try to put generator k into the more coherent group.

2.2 Generator Aggregation

Once the coherent groups of generators are determined, the network data is modified to replace coherent generators with the one at a single bus, while retaining the steady-state power flows and voltages in the original system. The detailed generator model with an exciter and govenor is used to aggregate coherent generators. The procedures of generator aggregation is proposed as follows:

1. Join the buses
   In the coherency group, the reference generator bus is retained and buses of the remainders are joined to reference in parallel. The shunt elements of deleted bus are added to the shunt element of the retained bus
2. Aggregate the static model of generators
   The real and the reactive power of the deleted generators in the group are added to that of reference generator. The equivalent transient reactance is obtained by paralleling transient reactances of all generators in the group.
3. Aggregate the static model of loads
   If the generator buses in the coherent group have load, then the equivalent load consists of the sum of the PQ load of all buses in the coherency generator group
4. Aggregate the dynamic model of generators
   In dynamic model aggregation, the dynamic model of equivalent generator is obtained by adding the inertia H and paralleling transient reactance $\left(X_d^{'}, X_q^{'}\right)$.
5. Aggregate the control units
   If the control units in the coherent group have the similar characteristic, then the control unit of the reference generator is used for the equivalent control unit.

2.3 Network Reduction

Once equivalent generators are determined by using generator aggregation algorithm, the equivalent generator is substituted for the reference generator and the remainders in the group are removed. Now the modified network contains only equivalent generators and the original loads in the external subsystem. And network reduction is performed using Ward-PV method [7]. It eliminates selected load nodes of the external subsystem and provides the accurate results when applied to linear passive network. This procedure is very attractive from the practical point of view in both the steady-state analysis and the dynamic analysis. From the above consideration, the following algorithm results:

1. Read initial load flow together with network data
2. Search reference generator buses and change it by equivalent generators and delete the remainders in the group.
3. Select the external subsystem to be equivalenced.
4. Retain the boundary nodes.
5. Calculate the network reduction using Ward-PV method

3. Application to korea power system

The objective of the large system testing was to assess the equivalent models in the external subsystem on system representation of a size that are currently being used in the industry. Korea power system has been used as the sample system. Furthermore, growing concerns about the changes of Korea power system require the equivalent model for transient stability studies. In this subsection, the proposed procedure is applied to Korea power system. The tests were performed to compare the accuracy and efficiency of results of the reduced system simulations versus the original system simulations.

The procedure for testing was initiated by running fault simulation on the system for four seconds after disturbance was applied. Three-phase fault was chosen, representing the most severe contingency. Test Case Descriptions are below.

3.1 Test Case Description

Korea Power System is divided into two subsystems as illustrated in Fig. 1. One is the internal subsystem which includes 198 nodes and 409 branches, another is the external subsystem which includes 999 nodes and 2004 branches, and 28 boundary branches connect both subsystems. Where the internal subsystem is classified with 6, 9 areas and the external subsystem is classified with the remainder areas.

Table I gives a summary of the characteristic of the original system. And system classification associated with buses, loads, plants, branches, areas and zones are summarized in Table II.

Table I describes that the original test case consists of 272 generators, 1197 buses, and 2413 AC branches. Its total generation is 64922MW and 19630MVAR. And 848 loads have 63970MW and 25528MVAR.

As shown in Table II, the focus of the test case was the transient stability performance of the kawng-ju areas which is contained HVDC line and FACTS devices, therefore the reduction specifications were to retain the entire kawng-ju area and a part of the neighbouring Chang-won area. The rest of the system was assumed to be the external subsystem.

Table 1 Original power system summary

	Generation	PQ load	Swing bus
MW	64922.5	63970.5	286.3
MVAR	19630.5	25528.2	116.4

	Buses	Loads	Plants
Number	1197	848	272
	Branches	Areas	Zones
Number	2413	18	59

Table 2 Classification subsystem

	Buses	Loads	Plants
Internal	198	142	46
External	999	706	226
	Branches	Areas	Zones
Internal	409	4	13
External	2004	14	46

*The numbers of Boundary Branch: 28
*Unit: number

The geographical presentation of the test system is illustrated in Fig. 1. Each group is encircled with continuous line.

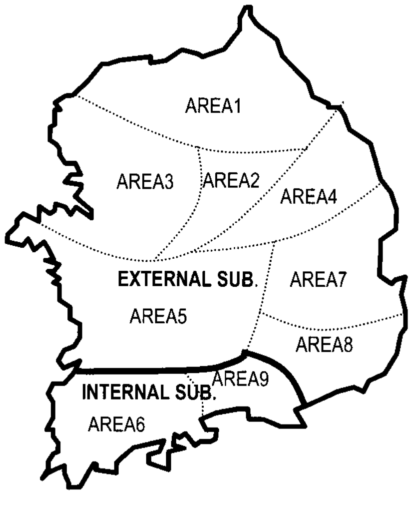

Fig. 1 Geographical presentation of Korea Power system.

3.2 Results of Transient Stability Analysis

To access the accuracy and efficiency of the equivalent model, three-phase fault was applied on 154kV at bus 7410 and cleared after 0.05 second by fault clearing. It is simulated for four seconds.

After reduction, the results of the reduced system compared with the original system are shown in Table III to Table IV. The comparison of original system with reduced system is summarized in Table III. Generally, system reduction rate is about 50%. And reduced system has 36 coherency generator groups. Table IV illustrates the simulation times for a 4-second simulation. Using the reduced system saves simulation time of as much as 66% by the original system. So the use of a reduced system can improve the computation time.

Table 3 Results of reduced system

	Original system	Reduced system	Reduction Rate (%)
Buses	1197	504	42.10
Loads	848	491	57.90
Plants	272	146	53.68
Branches	2413	1110	46.00
Coherency Groups	None	36	none

*Unit: number

Table 4 Comparison of simulation time

	Original system	Reduced system	%
Simulation time	21.640	14.390	66.50

The result in Fig. 2 shows the swing curves between the original and reduced systems. For the original system simulation, the first swing was about 10 degree peak-to-peak for the generators near the fault. The reduced system simulation, which produced a 66% reduction in running time and 54% reduction in the system size, shows very close agreement with the original system.

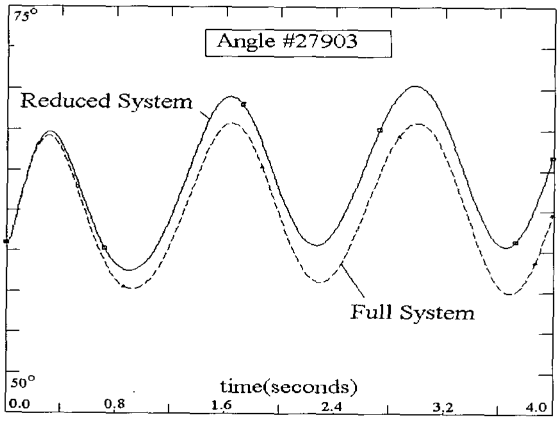

Fig. 2 Comparison of generator rotor angle at #27903

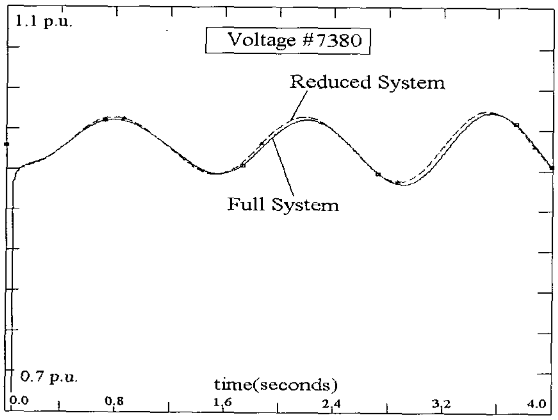

Fig. 3 Comparison of voltage magnitude at #7380

Selected voltage curves near HVDC line between Cheju-island and Haenam-mainland and near the fault are shown in Fig. 3. and Fig. 4.

Active power flows for the branches between 345kV buses and boundary buses are shown in Fig. 5.

The results obtained shows that derived equivalent model has a good accuracy and reliability for transient analysis.

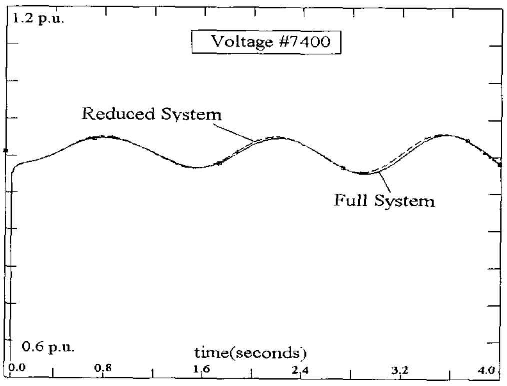

Fig. 4 Comparison of voltage magnitude at #7400

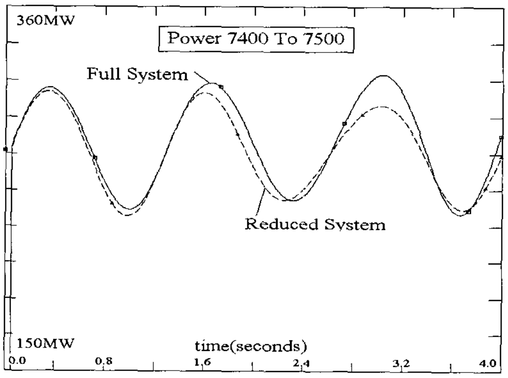

Fig. 5 Comparison of power flow from #7400 to #7500

4. Conclusions

This paper has developed the procedure to construct the equivalent model of large power system and applied it to Korea power system. This procedure has the following three steps, coherency identification, generator aggregation and network reduction. Coherency index has been developed and has efficiently determined the coherent group of generators. After that, generators in the same coherent group are aggregated in one generator that represents the group. This step has significantly reduced the size of power system about 50% of the original system. Network is also reduced by Ward-PV method and this step has also reduced the numbers of buses, branches and loads.

The main benefit of this procedure is that it can be directly applied to nonlinear time simulation program like PSS/E and can be easily used to reduce the size of large power system. The equivalent model of Korea power system constructed by this procedure can be used in transient stability studies on HVDC system and FACTS studies.

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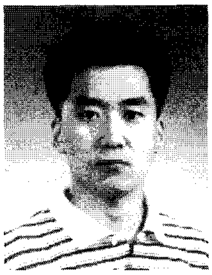

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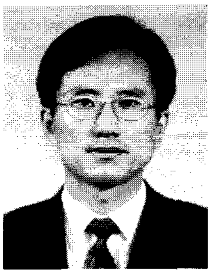

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