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DYNAMIC EQUIVALENCE OF A LARGE POWER SYSTEM USING POWER SYSTEM SIMULATOR FOR ENGINEERS (PSS/E)

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ABSTRACT

In this paper the step-by-step procedure of obtaining the network equivalent of a large power system using Power System Simulators for Engineers (PSS/E) is presented. Coherency among the generators of the study system is identified using the non-linear time domain simulation obtained by PSS/E. Generators with the most identical swing are considered to be coherent. Dynamic aggregation of the coherent group of generators is performed based on the Zhukov's method. The accuracy of the procedure is demonstrated by comparing the steady state and dynamic results of the original and the equivalent system. The comparisons clearly indicate excellent level of accuracy achieved from this work. The step-by-step procedure of building dynamic equivalent presented in this paper will be extremely helpful for the researchers to understand and work with the commercial PSS/E software.

Keywords: *Dynamic equivalent, Coherency identification, Dynamic Aggregation.*

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1 INTRODUCTION

One of the mostly discussed issues for the power system engineers is the stability of power system following small or large disturbances which are frequently occurring in any power system network. Usually the stability study is confined within some predefined area and detail modeling of the whole power system is not required. The portion of the power system that is not of major concern during the study period can be reduced to an equivalent one. Equivalent model is the reduced order model of the overall system which retains the important features of the system. Dynamic equivalence is the process of reducing the complexity of the system model by eliminating different generators, loads, buses and branches.

Modal equivalent methods and coherency based methods are the two major ways to obtain dynamic equivalent of a large interconnected power system. In the modal equivalent method [1] the external and the study areas are defined in an arbitrary manner. There is always a possibility of significant degradation in the simulation results obtained using these equivalents if the study and equivalent areas are not weakly coupled. In the coherency based methods the process of building the dynamic equivalent comprises of three major parts, namely, (i) identification of the coherent machines, (ii) aggregation of the coherent machines and (iii) reduction of the network.

Coherency index is used in [2] to identify the coherent group of machines. Based on this index, the generators are grouped if the index falls within a certain predefined value. A comparison between slow and inertial algorithm for generator aggregation is presented in [3]. It is shown that the slow aggregation algorithm might yield inaccurate result when a power network is reconstructed because of the error in the approximation in one of the coefficients. Author in [4] has proposed an aggregation method based on structure preservation of the coefficient matrices in nonlinear time domain representation of generating units with detailed models. An adaptive reduction technique is proposed in [5] which automatically determined the buses to be eliminated such that maximum advantage of network sparsity is taken.

Different software packages are also used for the purpose of dynamic reduction of large power system. DYNRED, a dynamic reduction program, was developed under the ERPI project RP2447 [6]. However, the generator terminal bus aggregation in this method produces infinite admittances linking the coherent generator terminal buses, thereby stiffening the system. Integrated application of a designed software tool and the CEPEL software package is presented in [7].

Although it is shown that the work simplifies and speeds up the overall process of building dynamic equivalent, the user need to have the knowledge of three additional applications besides the proposed one. Packages like EMTDC/PSCAD can be used for the stability run but they have a limitation in the maximum allowable size. Real time simulators like RTDS is used in [8] which can counter the various problems that occur in real power systems but it requires the equivalent power system with proper size due to the constraints resulting from the capacity of the hardware/software in the simulator. The NETOMAC program of Siemens [9] developed the evaluation equivalent method which does not require the complete structure and parameters of the external system. The software package PSS/E [10] is found advantageous than the aforementioned software in the following ways:

- It can handle real large networks with more than 1,25,000 buses.
- Nonlinear time domain simulation can be performed.
- Graphical user interface enables the user to have a clearer view about the proceedings.
- It is stand-alone software, i.e., does not need the support of other application software.
- Good level of accuracy can be achieved.

This paper mainly presents the software PSS/E which will help the fresh students and researchers to understand and work with this software comfortably. Specifically, the dynamic reduction feature of the PSS/E software is discussed step-wise. To perform the dynamic reduction on the example system the coherency based reduction is adopted. First the external and the internal or study system is distinguished, then the external network is reduced by PSS/E software with a step-by-step description, then coherent machines are identified from the study system using the non-linear time domain simulation of the system and finally, the coherent machines are aggregated. The effectiveness of the reduction process is validated through the comparison of non-linear time domain simulation results of the original and the reduced system. First the methodology for the identification of external and internal areas, step-by-step network reduction process in PSS/E and the generator coherency identification and aggregation method is presented. Next the results and discussion of the work is presented which shows the effectiveness of the applied method. Finally the conclusion is drawn.

2 METHODOLOGY

The overall reduction procedure is performed through the following steps:

- Distinguishing the external and study areas
- Netting generation with the load
- Building network equivalent for the external system
- Identifying the coherent groups of generators in the study system
- Getting dynamic equivalent for each coherent group

2.1 Distinguishing the external and study areas

The system portion which is not of particular interest is classified as the external area and the remaining portion is termed as the study area. Some criteria like bus KV levels can be set to distinguish these areas.

2.2 Netting generation with the load

In PSS/E there are several bus type codes starting from 1 to 7. Bus code 1, 2 and 3 are used to designate the PQ bus, the PV bus and the slack bus respectively. Code 4 is used to define the inactive buses. Codes 5 to 7 are special bus types with the following meaning:

Type 5: This is used to specify the load buses during equivalence process which are to be retained after reduction.

Type 6: This is used to specify the generator buses during equivalence process which are to be kept after reduction.

Type 7: This is used to specify the slack bus during equivalence process.

Before performing network equivalence or if is desired to reduce the number of generators modeled, generators can be replaced by combining their output with the load at the buses. Generators at all type 2 and 3 buses will be replaced with equivalent negative load with the following exceptions:

• Buses that are designated by the user at the start of the activity.

• Buses which are indicated by type codes 6 or 7 to be retained buses.

This netting process should not hamper the pre-reduction power flow results. The activity NETG/GNET performs the job of netting generation with the loads in PSS/E. A snapshot view of network equivalence activity of PSS/E is shown in **Fig.1**.

The steps for performing this netting process are given below:

- After opening the saved case file in the spreadsheet view in PSS/E the activity NETG/GNET can be accessed by the path: POWER FLOW → EQUIVALENCE NETWORK → NETG/GNET

- Netting of generation can be performed either inside or outside the selected area. The option INSIDE SELECTED SUBSYSTEM or OUTSIDE SELECTED SUBSYSTEM has to be selected by the user.
- If selective buses are to be handled for the netting process, the selection can be made either by subsystem or by mentioning the individual bus names. This can be done by selecting SELECTED BUS SUBSYSTEMS or THE FOLLOWING BUSES. If the option "THE FOLLOWING BUSES" is selected, the user needs to specify the list of buses for which the netting process will be conducted.

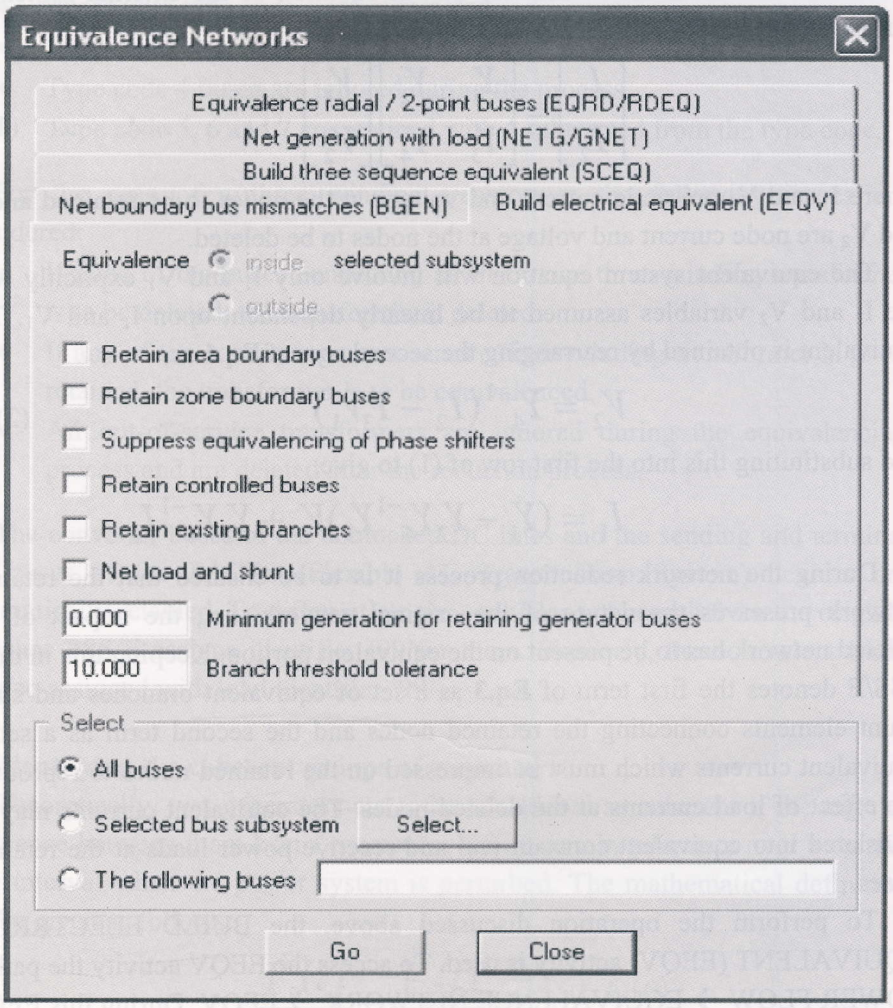

Figure 1: Snapshot of network equivalence activity in PSS/E.

As the generation is converted to negative loads at the respective buses, the type codes of all the selected type 2 and 3 will be converted to 1 after the netting process. The diagram view of PSS/E will show newly introduced loads at the buses. Also the load real and reactive powers are converted to negative generation of real and reactive powers respectively.

2.3 Building Network Equivalent for the External System

An electrical equivalent is constructed by performing a reduction operation on the admittance matrix of the external system that is to be represented by the equivalent. In PSS/E the admittance matrix equation of the external system is partitioned according to the following form:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad \dots \quad \dots \quad (1)$$

where I_1 and V_1 are node current and voltage at the nodes to be retained and I_2 and V_2 are node current and voltage at the nodes to be deleted.

The equivalent system equation will involve only I_1 and V_1 explicitly with the I_2 and V_2 variables assumed to be linearly dependent upon I_1 and V_1. The equivalent is obtained by rearranging the second row of **Eq.1** as,

$$V_2 = Y_4^{-1}(I_2 - Y_3 V_1) \qquad \dots \quad \dots \quad (2)$$

and substituting this into the first row of (1) to give,

$$I_1 = (Y_1 - Y_2 Y_4^{-1} Y_3)V_1 + Y_2 Y_4^{-1} I_2 \qquad \dots \quad (3)$$

During the network reduction process it is to be ensured that the retained network preserves the nature of the original network, i.e., the impact of the deleted network has to be present on the equivalent portion. Keeping this in mind PSS/E denotes the first term of **Eq.3** as a set of equivalent branches and static shunt elements connecting the retained nodes and the second term as a set of equivalent currents which must be impressed on the retained nodes to reproduce the effect of load currents at the deleted nodes. The equivalent currents may be translated into equivalent constant real and reactive power loads at the retained buses.

To perform the operation discussed above, the BUILD ELECTRICAL EQUIVALENT (EEQV) activity is used. To access the EEQV activity the path is POWER FLOW → EQUIVALENCE NETWORK → EEQV. During this EEQV activity PSS/E performs the following steps:

- External system is isolated from the study system. Buses to be retained are identified and the selected generators are switched to negative loads, if desired.
- Electrical equivalent of the external system is formed by performing the matrix operation discussed in **Eq.1-3**.
- The equivalent of the external system is attached to the study system to form a complete network model.

The activity EEQV creates the equivalent on the following basis:

- Buses with type code 1 are eliminated.
- Buses with type code 2 and 3 are retained.
- Type code 4 buses are ignored during the process.
- Type code 5, 6 and 7 are retained with 4 subtracted from the type code.

For the case of a three winding transformer the following issues are considered:

- If none of the buses connecting an in-service three-winding transformer is to be deleted, the transformer is deleted.
- If any of the connecting an in-service three-winding transformer is to be retained, the transformer is to be equivalenced.
- All out-of-service transformers are ignored during the equivalencing process and are deleted after the reduction process.

The converter buses of the unblocked DC lines and the sending and terminal end buses of the FACTS (Flexible AC Transmission System) devices are automatically retained. To differentiate the equivalenced branch from the original branches PSS/E assigns identifier '99'for them. Similarly, the equivalent loads are also assigned with load identifier '99'.

2.4 Identifying the coherent groups of generators

Theoretically, two generators are to be considered as coherent if the angular difference between them keeps constant within a certain tolerance over a certain time interval when the power system is perturbed. The mathematical definition can be given as follows:

$$\frac{\dot{V}_i(t)}{\dot{V}_j(t)} = \frac{V_i(t)}{V_j(t)} e^{j[\delta_i(t)-\delta_j(t)]} \qquad \dots \dots (4)$$

$$= \frac{V_i(0)}{V_j(0)} e^{j[\delta_i(0)-\delta_j(0)]}$$

$$= const.$$

Considering the voltage magnitude of the coherent buses to be constant, **Eq.4** can be further simplified as:

$$\delta_i(t) - \delta_j(t) = \delta_{ij}(t) = \delta_{ij}(0) = const. \quad \dots \quad (5)$$

where $\delta_i(0)$ and $\delta_{ij}(0) = \delta_i(0) - \delta_j(0)$ are the initial values of the variables calculated for the reduced model.

In this paper the machines dynamic response simulated by PSS/E following a disturbance is used to determine the coherency of the generators. The swing curves of the generators of the study system are observed by applying a fault and those generators with the most identical swing curves are classified as coherent.

2.5 Getting equivalent for each coherent generator group

The dynamic equivalent of a coherent group of generating units is a single generating unit that exhibits the same speed, voltage and total mechanical and electrical power as the group during perturbation where those units remain coherent.

The coherent generators of each group can be aggregated to an equivalent one. If the voltage level of the coherent generator buses are found to be the same, applying the Zhukov's method [11] one can obtain the KV level for the equivalent generator bus. In the Zhukov's model the voltage of the equivalent bus is defined as the average voltage of the coherent generator buses, which can be mathematically expressed as:

$$V_t = \frac{\sum_{k=1}^{n} V_k}{n} \quad \dots \quad \dots \quad (6)$$

$$\theta_t = \frac{\sum_{k=1}^{n} \theta_k}{n} \quad \dots \quad \dots \quad (7)$$

The turns-ratio of the ideal transformer is given by:

$$\dot{a}_k = \frac{\dot{V}_k}{\dot{V}_t} \quad \ldots \quad \ldots \quad (8)$$

where $\dot{V}_k$ and $\dot{V}_t$ are the voltages at buses k and t respectively. This process is illustrated in **Fig.2** where the buses k, k-1 and k-2 represent the generator buses in a coherent group, while the bus t indicates the equivalent bus formed by these generator buses.

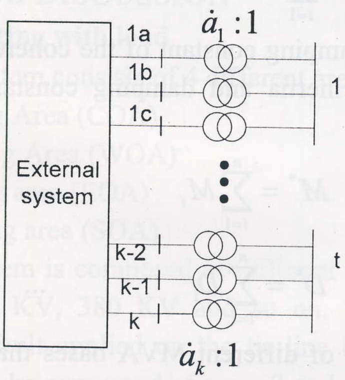

Figure 2: Aggregation of coherent generator buses.

The electrical real and reactive power output of the equivalent generator are the sum of the electrical power of all the individual generators in the same coherent group. These can be represented as follows:

$$P_e^* = \sum_{i=1}^{n} P_{ei} \quad \ldots \quad \ldots \quad (9)$$

$$Q_e^* = \sum_{i=1}^{n} Q_{ei} \quad \ldots \quad \ldots \quad (10)$$

where P_e^*, Q_e^* are the real and reactive power outputs of the equivalent machine and P_{ei}, Q_{ei} are those of the individual machines of each coherent group.

For the dynamic modeling of the multi-machine system equivalence of the dynamic parameters have to be determined. The swing equation of the rotor is:

$$M_i \frac{d\omega_i}{dt} = P_{mi} - P_{ei} - D_i\omega_i, \quad i = 1, 2, \ldots\ldots n \quad \ldots \quad \ldots \quad (11)$$

where ω_i, P_{ei}, P_{mi}, M_i and D_i are the angular speed, mechanical power, electrical power, inertia and damping constants of generator i; n denotes the number of coherent generators in a group. From the definition of coherency it follows that the coherent generators have most identical angular frequencies and thus can be assumed to be equal to ω, the swing equation can then be described as:

$$(\sum_{i=1}^{n} M_i)\frac{d\omega}{dt} = \sum_{i=1}^{n} P_{mi} - \sum_{i=1}^{n} P_{ei} - (\sum_{i=1}^{n} D_i)\omega \ , \quad i = 1,2,.......n \qquad \ldots \qquad (12)$$

Therefore the inertia and damping constant of the coherent generator can be expressed as the sum of the inertia and damping constants of the coherent generators, respectively:

$$M^* = \sum_{i=1}^{n} M_i \qquad \ldots \qquad \ldots \qquad (13)$$

$$D^* = \sum_{i=1}^{n} D_i \qquad \ldots \qquad \ldots \qquad (14)$$

The obtained constants are of different MVA bases than the system MVA base. So, the M and H constants are then converted to the equivalent system base value by the following relation:

$$M_{new,i} = M_i^* \frac{MachineMVABase_i}{SystemMVABase_i} \qquad \ldots \qquad (15)$$

$$D_{new,i} = D_i^* \frac{MachineMVABase_i}{SystemMVABase_i} \qquad \ldots \qquad (16)$$

The transient and sub-transient d and q axis reactance of the equivalent generator can be obtained by paralleling the corresponding reactance value of all the coherent generators:

$$X' = \frac{1}{\sum_{i=1}^{n} \frac{1}{X_i}} \qquad (17)$$

These can be converted to system base by the following relation:

$$X_{d_{systembase}} = X_{d_{machinebase}} \frac{systembase}{machinebase} \quad \dots \quad \dots \quad \dots \quad (18)$$

The equivalent machine d and q axis time constants T'_{do} and T'_{qo} are kept as the same as those of the original machines as each machine of the coherent group is having equal valued time constants.

3 RESULTS AND DISCUSSION

3.1 Generation netting with load

The original system consists of 4 different areas, namely:

1. Central Operating Area (COA)
2. Western Operating Area (WOA)
3. Eastern Operating area (EOA)
4. Southern operating area (SOA)

The overall system is composed of different KV level buses like 13 KV, 33 KV, 132 KV, 230 KV, 380 KV and so on. The dynamic analysis will be performed with a fault applied on the tie-line between area 1 and 3. So, the external system will be composed of areas 2 and 4 whereas the study system will be composed of areas 1 and 3. The complete external system will be represented by one equivalent load. This reduction will be performed in PSS/E. The focus of the study revolves around the 230 and 380 KV network buses. So the remaining network has to be reduced, too. A partial view of the overall network is presented in **Fig.3**. An overview of the original system is provided in **Table 1.**

The netting of generation with the load is performed in the following way:

External system

Area WOA and SOA comprise the external system. From this part of the system only bus 21900 is kept because it is this bus through which WOA and COA (380 KV) are interconnected. All the remaining network loads are lumped with the generation of the respective buses. This is done by PSS/E. A total of 175 generators are netted with their loads at this stage.

Study System

Area COA and EOA comprise the study system. Here first those generator buses are identified which are not connected to either 230 or 380 KV network through transformers. These are the buses to be netted with their respective loads. Total 127 buses (56 from COA and 71 from EOA) of this category are found from the external area.

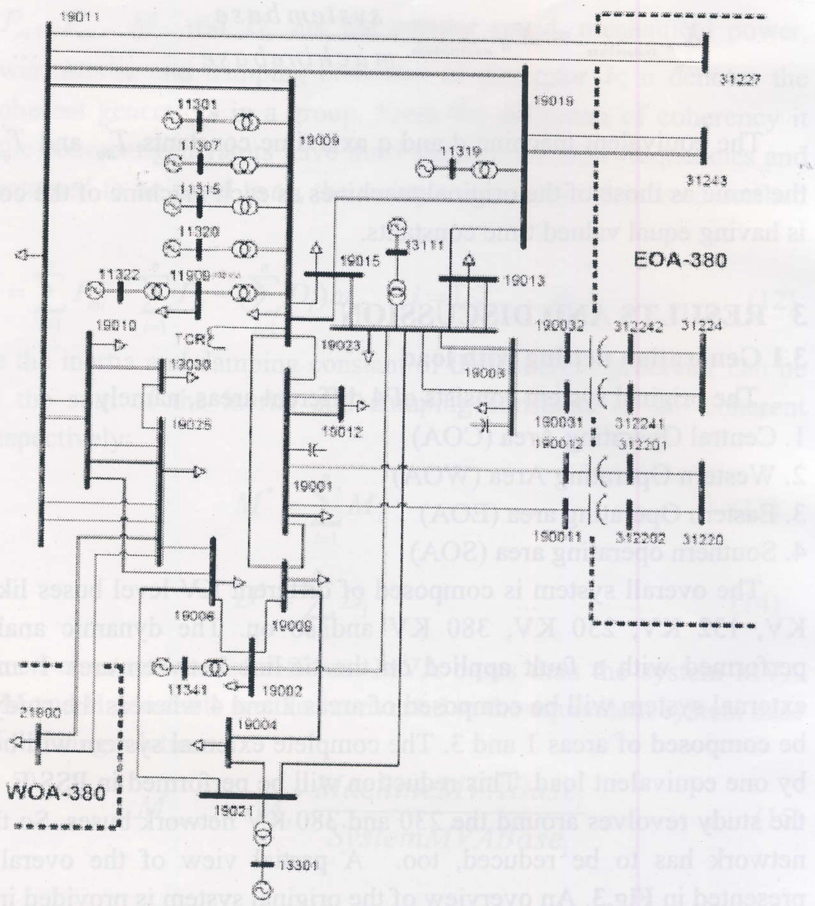

Figure 3: Single line diagram of area COA (380 KV network).

Table 1: Overview of the actual system

Number of Areas	4
Number of generators	466
Number of buses	2251
Number of lines	3533
Number of transformers	1508
Number of loads	1520
Number of shunt elements (switched and fixed)	55 and 275
Network KV levels	380, 230, 132, 115, 69, 34.5
Number of tie-lines	250

Next, the network equivalence process is performed. Here the information on the generator and load buses to be kept and retained after network reduction is required by PSS/E. This information is to be provided by the user. The way for this is as follows:

- The type codes of the slack, generator and load buses to be retained are to be changed by the user from 3, 2 and 1 to 7, 6 and 5 respectively on the spreadsheet view.

OR

- Go to POWER FLOW→ EQUIVALENCE NETWORK
- Select the tab BUILD ELECTRICAL EQUIVALNET
- Select INSIDE SELECTED SUBSYSTEM
- In the SELECT option choose THE FOLLOWING BUSES and enter the bus numbers list.

In this case 127 generator buses (31 from COA and 96 from EOA) and 135 load buses (23 from COA and 112 from EOA) are kept after reduction.

The comparison between the original and the equivalent system obtained after the network reduction in PSS/E is presented in **Table 2.**

3.2 Comparison by steady state results

To show the effectiveness of the adopted technique of network equivalence the load flow result of the reduced and the actual system are compared. Only the line flows through the interconnections are listed below to show the correctness of the steady state results and for the sake of brevity. Only three interconnections are found to be present among the areas. **Table 3** clearly indicates that the interconnection carries the same amount of real and reactive power before and after reduction. Other line flows are also monitored and found satisfactorily matching.

Table 2: Comparison between original and the equivalent system

	Buses	Branches	Generators	Loads	Transformers
Original	2251	3353	466	1540	1508
After network reduction	261	410	167	124	144
Final Equivalent	140	267	30	94	47

Table 3: Comparative power flow result among the actual and equivalent system

From bus no.	To bus no.	P_{line} (actual) in MW	Q_{line} (actual) in MVAR	P_{line}(equivalent) in MW	Q_{line} (Equivalent) in MVAR
19011	31227	-501.8	115.0	-501.8	115.0
19019	31243	-271.8	-36.8	-271.8	-36.8
19025	21900	251.8	-13.8	251.8	-13.8

3.3 Coherency Identification

Time domain simulation is performed on the system with a three phase bolted fault applied at 0.1 sec and cleared at 0.2 sec in the interconnection between areas COA and EOA in order to determine the coherent generator groups. The simulation is carried out by the dynamic simulation feature of PSS/E. The result shows the existence of thirty families of swing curves among the study system. Therefore, thirty coherent groups of generators are defined which include the generators in area 1 and 3. To show the similarity in the angular deviation among the coherent machines, one group of generator from each area is selected.

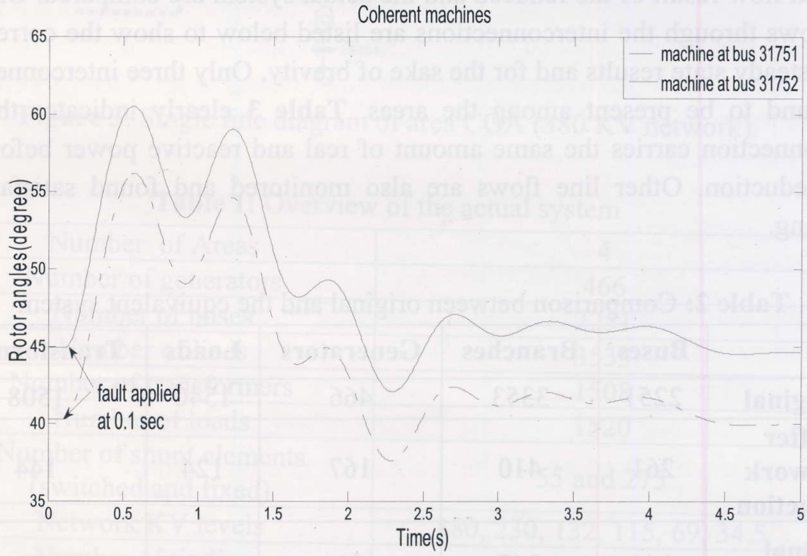

Figure 4: Coherent machines from area 3 (at bus 31751).

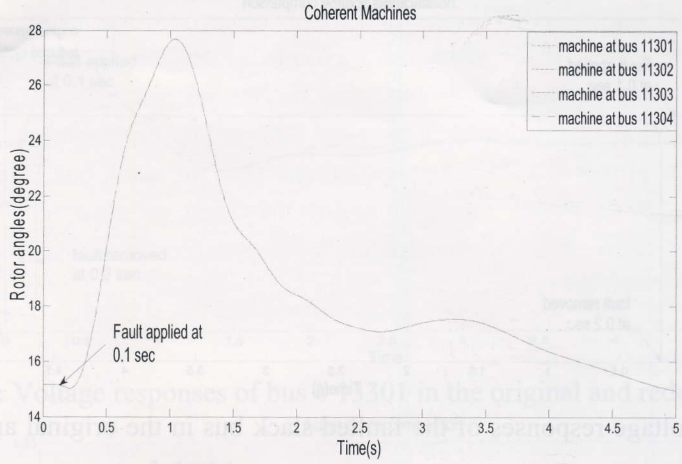

Figure 5: Coherent machines from area 1 (at bus 11301).

In **Fig.4** it is seen that the two machines from area 3 are swinging coherently by keeping a certain angular distance. The machines at bus 11301-11305 have identical dynamic data and thus have exactly the same pattern of oscillation following a fault. So, in this case the angular difference is zero among the coherent group of machines which is depicted in **Fig.5**. Similar kind of relative swings as shown in **Figs. 4-5** are observed among the remaining 28 coherent groups.

Lastly the dynamic aggregation of the thirty generator groups is performed as discussed previously. The final reduced system comprises of 3 areas, 287 lines including the transformer branches, 140 buses and 30 generators.

3.4 Comparison of dynamics result

A three phase fault is applied at 0.1 sec on the system slack bus situated in the area-1- 380 KV network and is self-cleared after 0.1 sec. Simulation is performed on the original and equivalent system respectively for 5 sec. From area-3 the generator connected to the slack bus and from area-1 bus #13301 is chosen for comparative results of the actual and the reduced system.

Figs. 6-8 and **9-11** demonstrates the comparison of terminal voltage, active power output and rotor angle for the slack bus and the other bus respectively.
The results show good agreement among the variations of the reduced system and the original system. The terminal bus voltage variation matches the best for the faulted slack bus in **Fig.6**. Deviation in the variation of active power between the reduced and actual system of the slack bus is also minimum as seen in **Fig.7**.

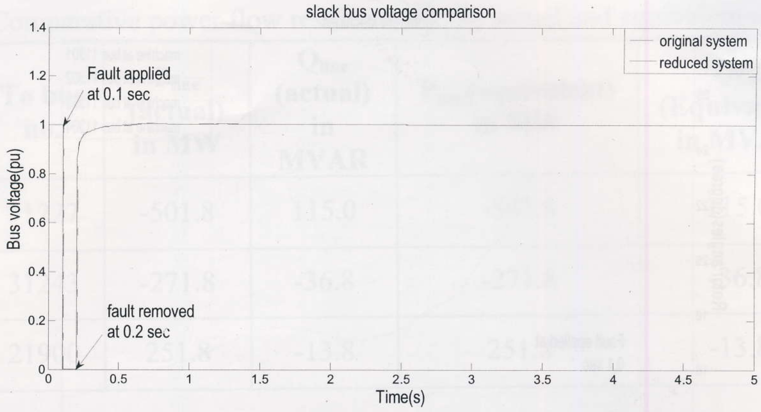

Figure 6: Voltage responses of the faulted slack bus in the original and reduced system.

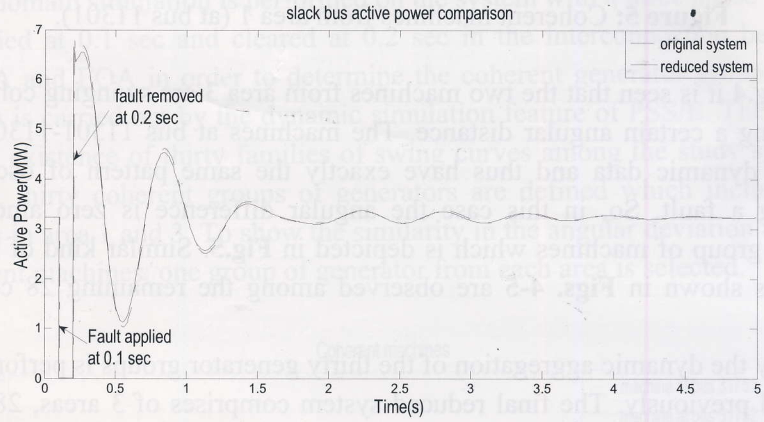

Figure 7: Active Power responses of the faulted slack bus in the original and reduced system.

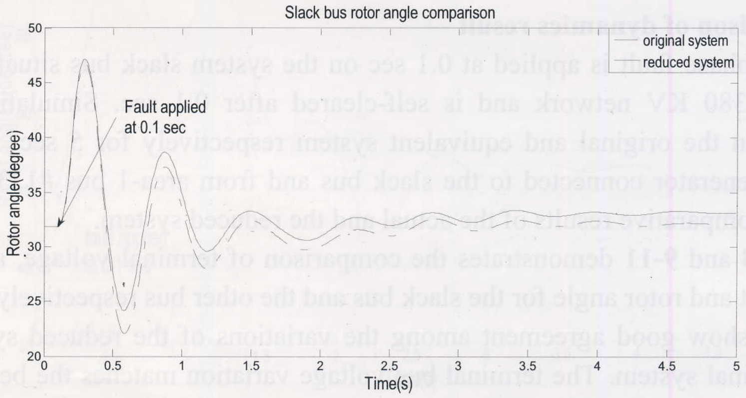

Figure 8: Rotor Angle responses of the slack bus in the original and reduced system

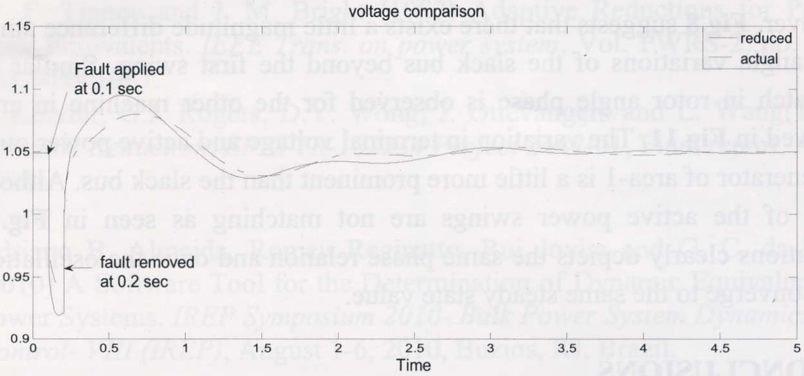

Figure 9: Voltage responses of bus # 13301 in the original and reduced systems.

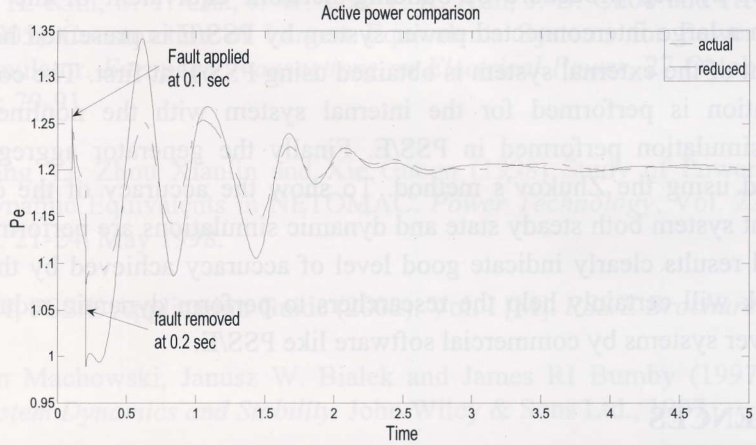

Figure 10: Active power responses of bus # 13301 in the original and reduced systems.

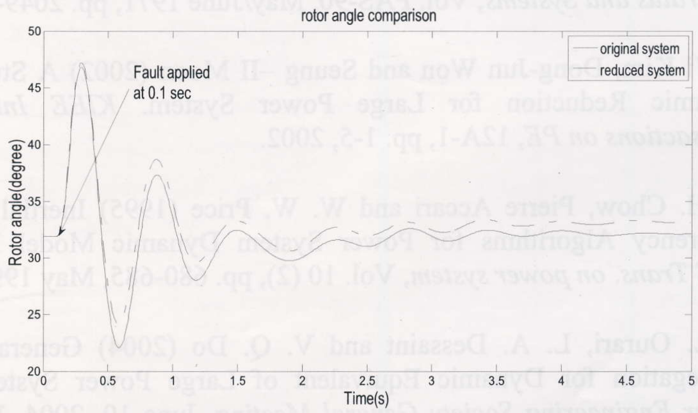

Figure 11: Rotor angle responses of bus # 13301 in the original and reduced systems.

However, **Fig.8** suggests that there exists a little magnitude difference among the rotor angle variations of the slack bus beyond the first swing. Similar kind of mismatch in rotor angle phase is observed for the other machine in area-1 as observed in **Fig.11**. The variation in terminal voltage and active power output for the generator of area-1 is a little more prominent than the slack bus. Although the peaks of the active power swings are not matching as seen in **Fig.10**, the oscillations clearly depicts the same phase relation and once the oscillation dies, they converge to the same steady state value.

4 CONCLUSIONS

A step-by-step procedure of building network equivalent of the external system in a large interconnected power system by PSS/E is presented here. The equivalent of the external system is obtained using PSS/E at first. The coherency identification is performed for the internal system with the nonlinear time domain simulation performed in PSS/E. Finally the generator aggregation is performed using the Zhukov's method. To show the accuracy of the dynamic equivalent system both steady state and dynamic simulations are performed. The presented results clearly indicate good level of accuracy achieved by the work. This work will certainly help the researchers to perform dynamic reduction of large power systems by commercial software like PSS/E.

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