Introduction

Network reduction in power systems refers to the process of simplifying and optimizing complex power system models using software simulation tools. This reduction process involves reducing the size and complexity of the network model while preserving its essential characteristics. Representing in a simpler network gives a better understanding on its behavior. Some advantages of reducing a network includes, Computational Efficiency, Ease of Analysis, Planning and Optimization, Scenario Analysis etc. Large power system models can be computationally intensive and require significant processing power and memory. Network reduction reduces the model's size, making simulations faster and more efficient, which can save time and computational resources. A simplified network model is easier to analyze and understand. When a fault occurs, the rest of the network which are distant form the fault area need not to be analyzed in detail while simulating the whole network. In that case, reduced network focusing only on the faulty area part is very useful.

In this report, we are going to discuss the methods of reducing a very large power system network in PSS/E which is IEEE 39 bus system and validate the results by comparing voltages of the remaining buses with the original network. We will also apply the same method in a smaller system which is IEEE 14 bus system to show that our analysis method is applicable to any system. Time domain simulation in both original and reduced network will be performed in PSS/E.

Theory:

Network reduction in electrical systems serves two primary purposes, classified as static and dynamic reduction. Static reduction is utilized for power flow calculations and planning studies, simplifying the network by aggregating loads and generators of similar kinds.

On the other hand, dynamic reduction is employed for system dynamics analysis, requiring modifications to generator parameters before aggregation to maintain consistent time-domain behavior. It is worth noting that PSS/E includes a built-in network reduction tool, enabling the identification of generator coherency through dynamic simulations within the software.

The process of coherency-based network reduction consists of three steps: first, identifying the coherent generators; second, aggregating these coherent generators; and finally, reducing the network.

A. Identifying Coherent Generator

A coherent group of generators is a collection of power-generating units that exhibit synchronized oscillations, operating at the same angular speed, and maintaining a constant complex voltage ratio during a disturbance.

$$\frac{\mathrm{V_i(t)}}{\mathrm{V_j(t)}} = \frac{\mathrm{V_i(t)}}{\mathrm{V_j(t)}} e^{[\delta_i(t)-\delta_j(t)]} = Constant \qquad (1)$$

Considering the voltage magnitude of the coherent buses to be constant,

$$\delta_i(t) - \delta_j(t) = \delta_{ij}(t) = Constant \qquad (2)$$

This project entails the identification of coherent generators through time-domain simulations conducted in PSS/E. Specifically, a bus fault is introduced within the internal subsystem, and after a certain duration, the fault is rectified. Subsequently, the rotor angle vs. time characteristics of all generators within the system are observed using PSS/E.

Typically, the rotor angles of different generators exhibit variations from one another. However, a subset of generators displays similar swing angles, and these generators are referred to as coherent generators. Consequently, the groups comprising coherent generators are established.

It is worth noting that alterations in the operating conditions of the power system lead to changes in the dynamics of the generators, resulting in varying coherent groups. Thus, the coherency of the generators is influenced by factors such as the duration, location, type, and magnitude of the disturbance.

B. Dynamic Aggregation of Generators

Coherent generator groups are condensed into an equivalent generator using the Zhukov method. The equivalent bus voltage is calculated as the average of the voltages from the coherent generator buses, expressed mathematically as:

$$V_{t,a} = \frac{\sum_{i=1}^{m} V_{ti}}{m} \tag{3}$$

$$\theta_{t,a} = \frac{\sum_{i=1}^{m} \theta_{t,i}}{m} \tag{4}$$

The equivalent generator's mechanical and electrical powers result from the sum of mechanical and electrical powers of all generators within the same coherent group, represented as follows:

$$P_{ma} = \sum_{i=1}^{m} P_{mi} \tag{5}$$

$$P_{ma} = \sum_{i=1}^{m} P_{mi} \tag{6}$$

From a mechanical perspective, the rotors of electromagnetically coherent generators can be treated as if they are all rotating on a single rigid shaft. A cluster of these generators can be substituted with a single equivalent generator, characterized by inertia constant Ma and damping constant Da, defined as:

$$M_a = \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{M_i} \tag{7}$$

$$\mathrm{D_a} = \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{D_i} \tag{8}$$

The transient reactance of the equivalent generator can be determined by connecting the transient reactance of all coherent generators in parallel, as depicted below:

$$X_{da} = \frac{1}{\sum_{i=1}^{m}\left(\frac{1}{X_{d,i}}\right)} \quad (9)$$

$$X_{qa} = \frac{1}{\sum_{i=1}^{m}\left(\frac{1}{X_{q,i}}\right)} \quad (10)$$

C. Reducing Network:

In the process of removing load buses and aggregating generator buses, it's imperative to maintain the constancy of voltages and currents at the retained nodes. Additionally, the active and reactive power of the equivalent node must equal the cumulative power injections at the aggregated nodes.

Following this, the aggregated equivalent model is constructed by establishing equivalence within the admittance matrix. This can be expressed through the admittance matrix equation as follows:

$$\begin{pmatrix} I_R \\ I_D \end{pmatrix} = \begin{pmatrix} Y_{RR} & Y_{RD} \\ Y_{DR} & Y_{DD} \end{pmatrix} \begin{pmatrix} V_R \\ V_D \end{pmatrix} \quad (11)$$

IR and VR refer to the current injection and voltage at the retained nodes. Meanwhile, ID and VD represent the current injection and voltage at the nodes scheduled for deletion. The equations for VD and ID can be derived as follows:

$$V_D = Y_{DD}^{-1}(I_D - Y_{DR}V_R) \quad (12)$$

$$\mathrm{I_R} = \left(\mathrm{Y_{RR}} - \mathrm{Y_{RD}^{-1}}\mathrm{Y_{DR}}\right)\mathrm{V_R} + \mathrm{Y_{RD}}\mathrm{Y_{DD}^{-1}}\mathrm{I_D} \quad (13)$$

Methodology:

While analyzing a large system, the behavior of a certain part of the system is point of interest. Such a part of the large system is called internal subsystem (area) and the rest of the system is referred to as external subsystem. A fault is applied in the internal subsystem and rest of the network is reduced

The 3 main tasks of the project are- coherent generator identification, dynamic aggregation of generators and reduction of network. In order to find the coherent generators-

1) First, we loaded the .sav file of the system (39 bus and 14 bus. From the power flow menu, selecting 'Convert Load And Generators and checking the Convert Generators and Convert Load boxes- loads and generators were converted.
2) Then from the power flow option-solution-Solution for switching studies, we marked the Fact and use voltage vector as start point boxes.
3) Then dynamic data (data of Generator models, Exciter models, Turbine Generator models), which is a .dyr file, is loaded. Then the simulation is run.
4) We checked the speed option of the channel setup wizard in the dynamics menu to observe the speed and find the coherent generators. Then marked the set relative machine angles and relative to average system in dynamic simulation option.
5) Then to perform dynamic simulation, a bus fault is applied to bus no 30 and the fault was cleared after some time.
6) Then from the output plot, by observing the speed, the coherent generators were identified.

For the network reduction-

1) In the power flow-Equivalence network, we marked the 'inside' box of net generation and marked the include conventional machines box.
2) Then we marked the Selected bus subsystem and went to the select menu and selected the necessary buses in the bus subsystem selector dialogue and clicked apply. The numbers of buses can be given as input manually for which netting process will be conducted. Every bus numbers are separated by a comma
3) An electrical equivalent of the network is constructed by performing a reduction operation on the admittance matrix. There is a tool for building reduced electrical equivalent named "Build Electrical Equivalent (EEQV)". This tool can be accessed by the path is power flow à equivalence network à EEQV. One bus from each coherent group remains and the other buses are reduced. In the Building Electrical Equivalent (EEQV) window, the numbers of buses that need to reduced can be given manually. The bus numbers of all load buses and generator buses of coherent groups can be written manually. PSS/E assigns identifier '99' for the equivalenced branches and equivalent loads. In the selected buses of the Bus

Subsystem Selector of EEQV the external network buses are given as input. And, in the unselected buses section, the internal subsystem is given as input.

Result and Discussion

To reduce the IEEE 39 bus network, we first identified the Coherent generators. This is done by applying a fault at Bus 30 and observing the rotor speed and angles of all the ten generators after clearing the fault in PSS/E software. The speed and rotor angle vs time plot for all the generators is given below:

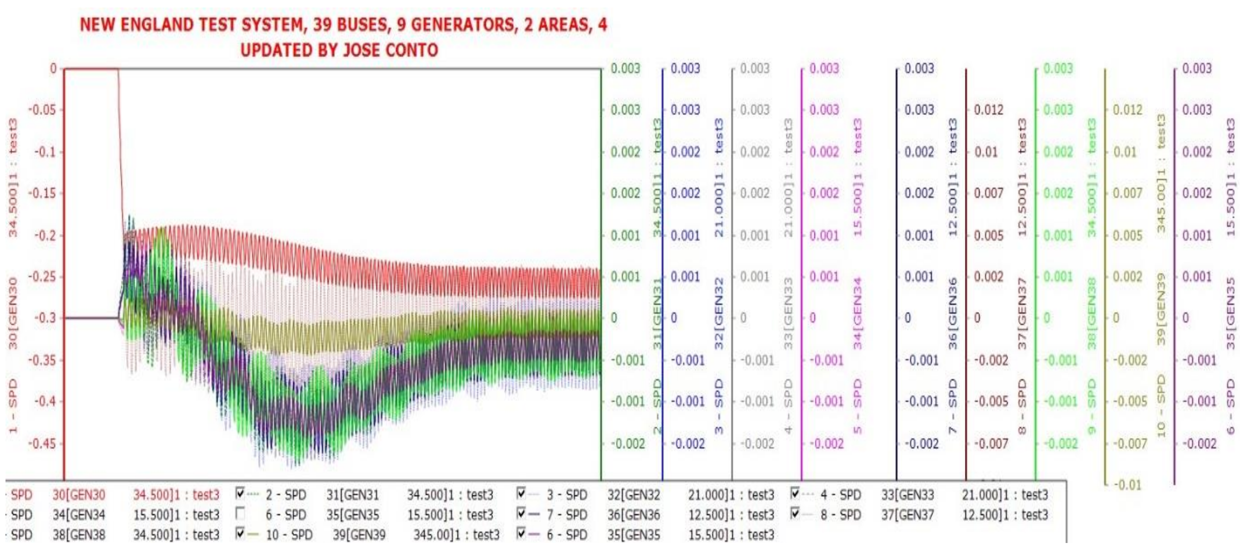

Fig: Rotor Speed vs time plot

From the plot we can see there are similarities in the rotor angle and speed of some generators. For better understanding we now observe the rotor angles separately:

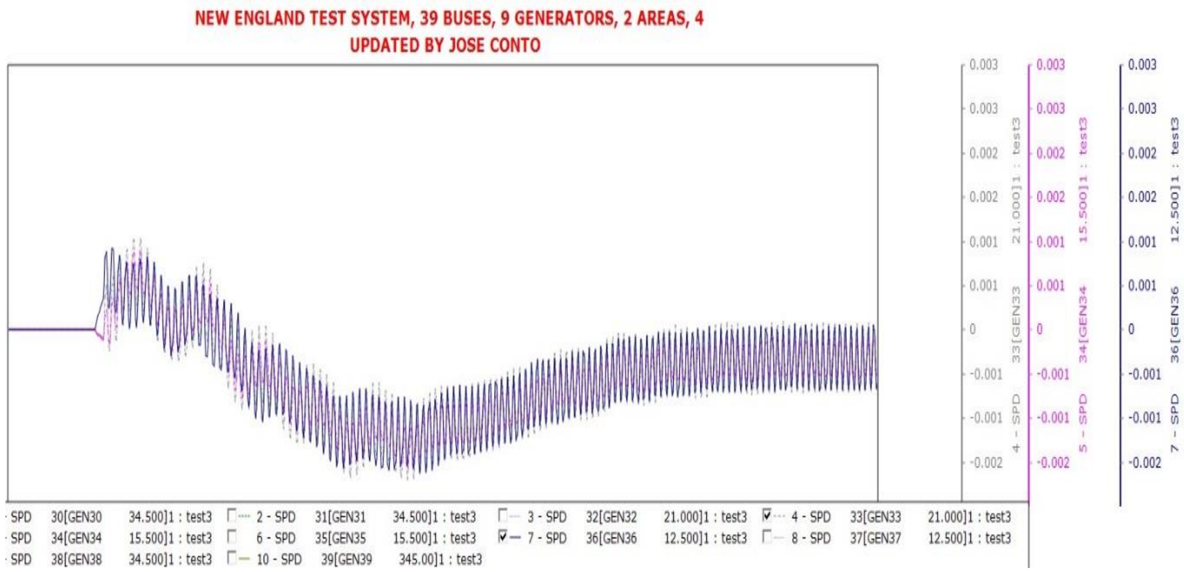

Fig: Rotor angle vs time plot of generator 33, 34 and 36

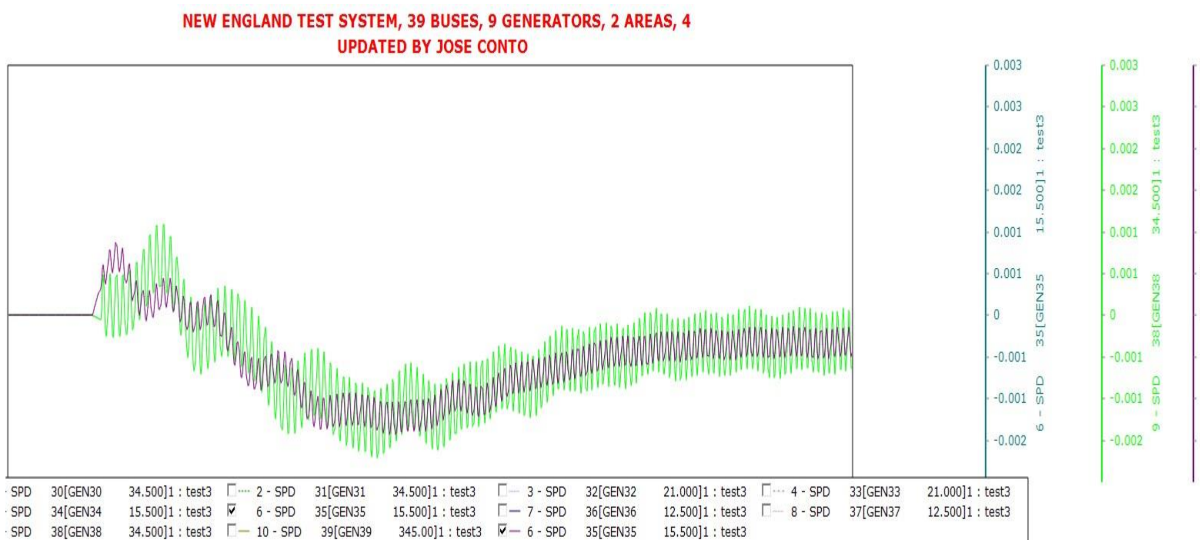

Fig: Rotor angle vs time plot of generator 35 and 38

We can see there are two groups of coherent generators as their Rotor angle vs time plot is similar and follows same pattern. One group contains generator 33, 34 and 36 while another coherent generator group contains 35 and 36 number generators. The same is true for rotor speed also. Now that coherent generators are detected network reduction is performed by dynamic simulation.

The original network of IEEE 39 bus system had 39 buses, 10 generators, 19 loads and 34 transmission lines. After performing network reduction, the system is reduced to 18 buses, 7 generators, 21 loads and 27 transmission lines. The comparison is shown in a table:

TABLE I. STATIC NETWORK REDUCTION

Component	Original	After Reduction
Bus	39	18
Generator	10	7
Load	19	21
Transmission lines	34	27

Before reducing the network, the iteration required to perform Decoupled Newton Raphson solution was 11 and after reducing the network it became 9. So, we can see our objective to reduce the simulation time by reducing the network has been achieved.

The system parameters are preserved before and after performing network reduction. All the parameters after reducing the system are close to the value of the original system as it is supposed to be. The speed, frequency and voltage plot of generator 30 provided below proves this statement. Again a fault is applied to the same bus to observe the before and after characteristics of a generator of our interest.

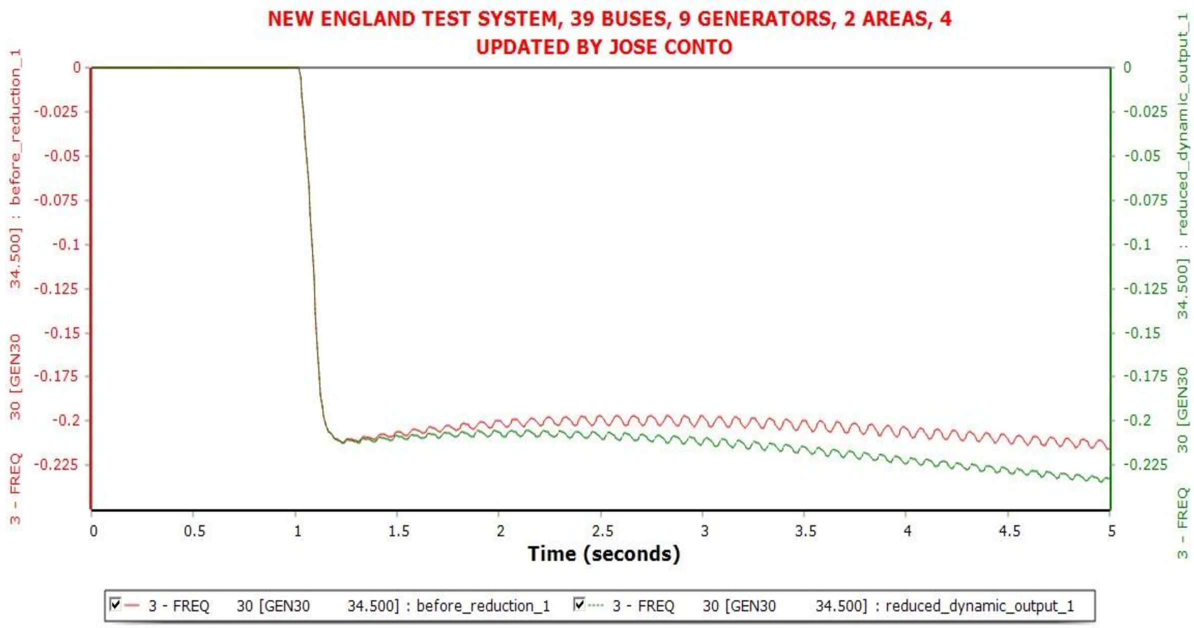

Fig: Frequency vs time curve before (red) and after (green) reducing the network.

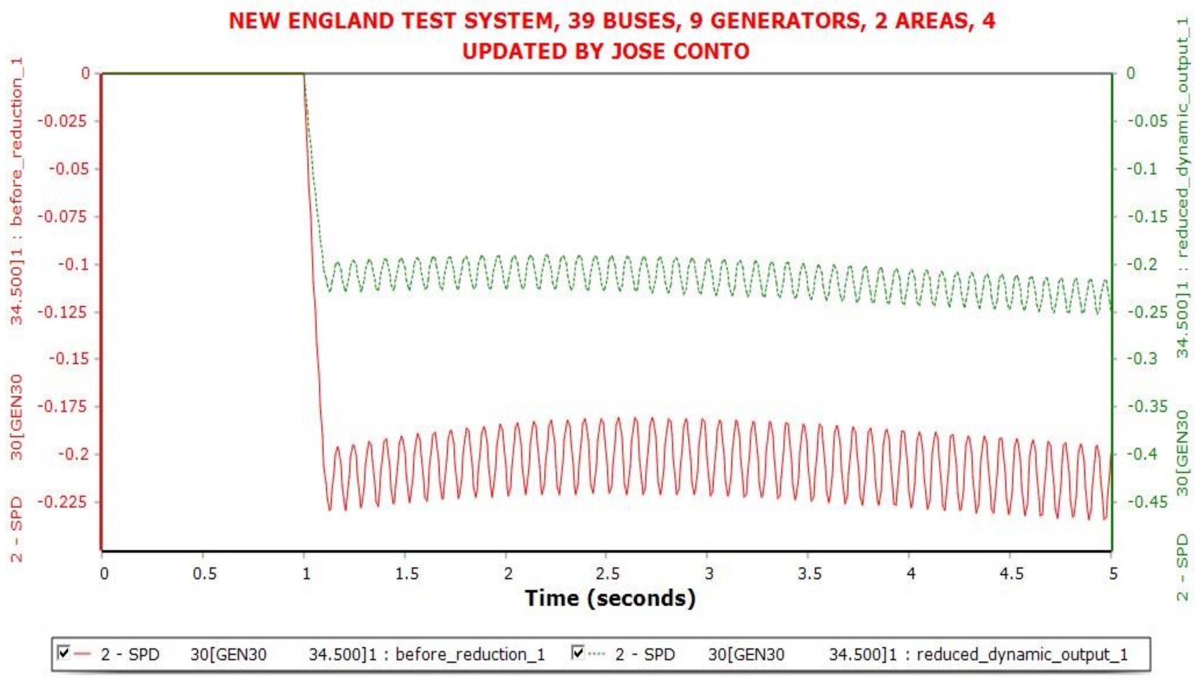

Fig: Speed vs time curve before (red) and after (green) reducing the network.

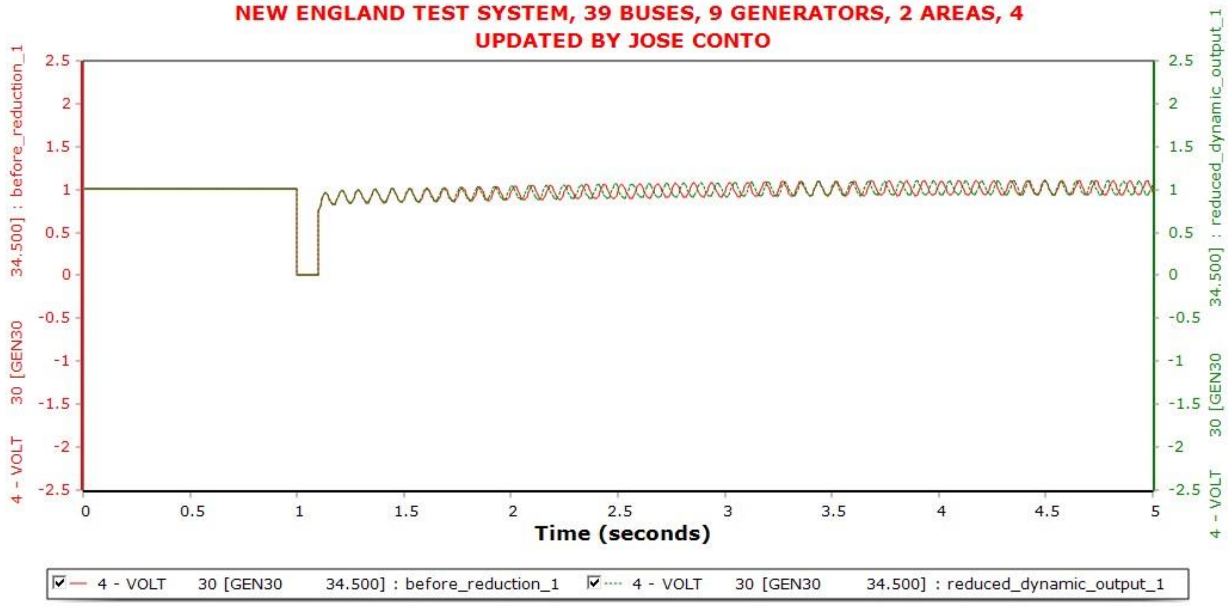

Fig: Voltage vs time curve before (red) and after (green) reducing the network.

Therefore, our objective to reduce the network to lessen simulation time while keeping the system parameters unchanged is accomplished.

The efficiency of the equivalent model can be measured in terms of reducing the number of buses. The term is called Reduction Ratio (RR) , which is given below.

$$RR(\%) = \frac{F_{nobus} - R_{nobus}}{F_{nobus}} \times 100\%$$

RR(%) of 39 Bus = $\frac{39-18}{39} * 100\%$

=53.856%

Reduction Ratio achieved in IEEE 39 Bus is 53.856%.

Result and Discussion on IEEE 14 Bus System:

To identify the coherent generators and minimize the IEEE 14 bus network, we created a bus fault on bus number 1 and monitored the rotor speed of all 5 generators. Once the fault was cleared in 1.1 seconds, we observed the speed vs. time for each generator. The following graph shows the speed vs. time for each generator:

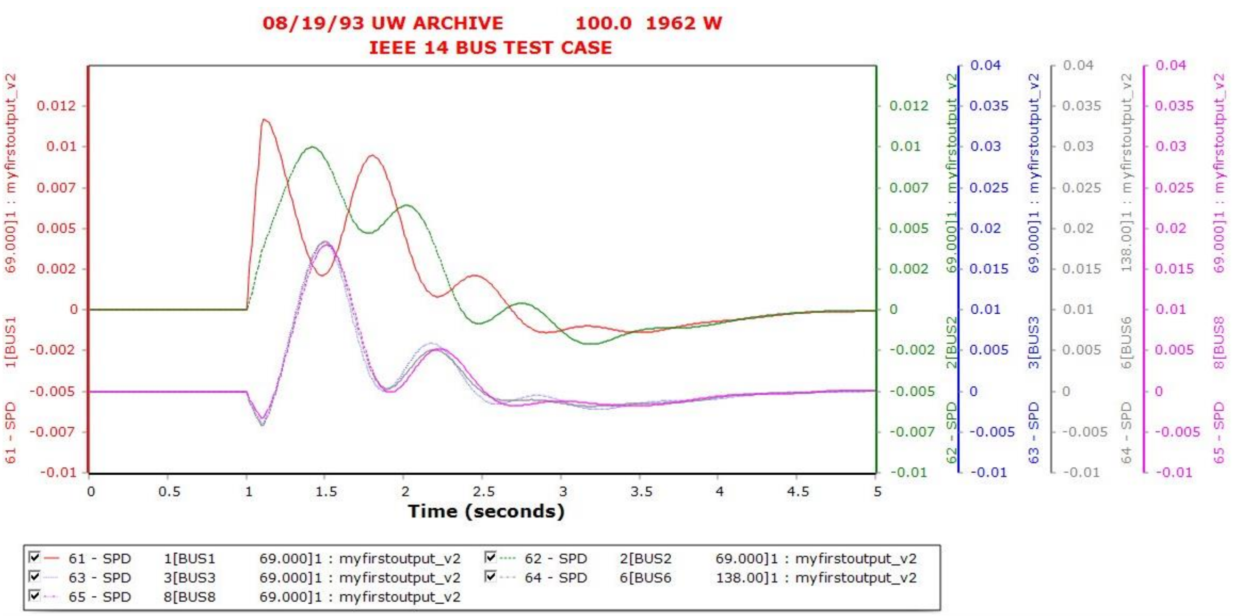

Fig: Speed vs. time

Based on our analysis of the rotor speed vs time plots, we have identified one group of coherent generators consisting of generator 3, 6, and 8. Their plots follow a similar pattern, while generator 1 and 2 do not show any similarities. With this information, we can now proceed with network reduction using dynamic simulation techniques.

14 buses, 5 generators, 11 loads, and 20 transmission lines connect the various components of the test network. After reduction, there are now just 8 buses, 4 generators, 10 loads, and 12 transmission lines. The bus voltages are almost unchanged between before and after the reduction. The comparison is shown in a table:

TABLE1. STATIC NETWORK REDUCTION (14 BUS SYSTEM)

Component	Original	After Reduction
Bus	14	8
Generator	5	4
Load	11	10
Branch	20	12

After applying a bus fault to bus number 1 and removing it after 0.1s, we conducted a simulation on both the original and equivalent systems for 5.0s. Upon evaluation of the faulty bus profile of both systems, we found that they were almost identical, as depicted in the Figure below. This indicates that the equivalent model's accuracy is reliable and can be used for further analysis and simulations.

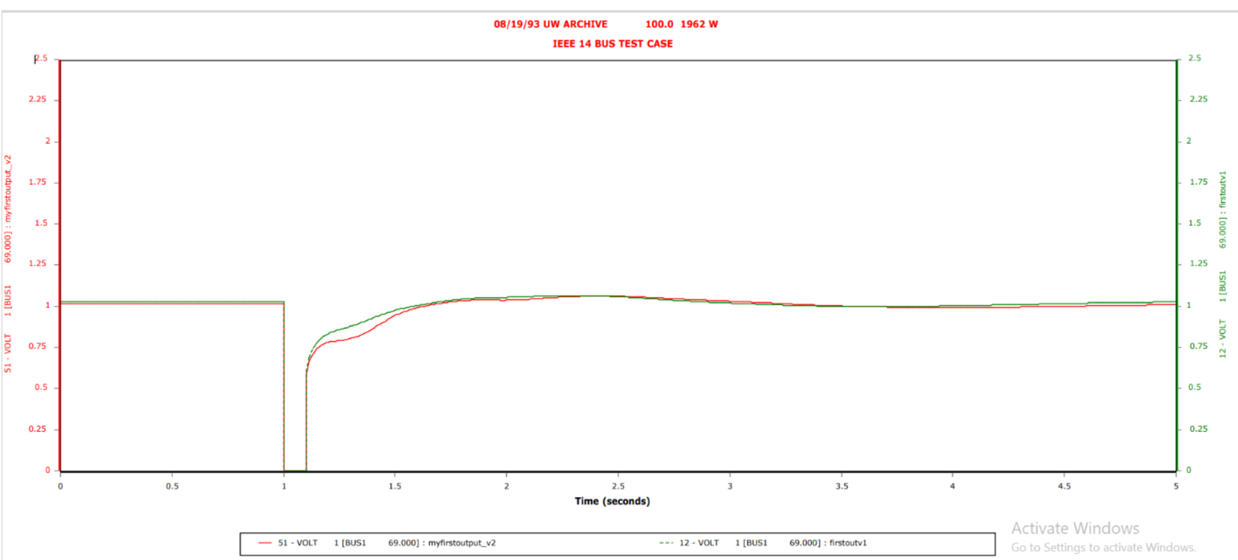

Fig: Voltage vs time curve before (red) and after (green) reducing the network.

Here is the voltage plot, speed, and frequency of Bus 1 before and after performing network reduction, which proves that the system parameters are preserved:

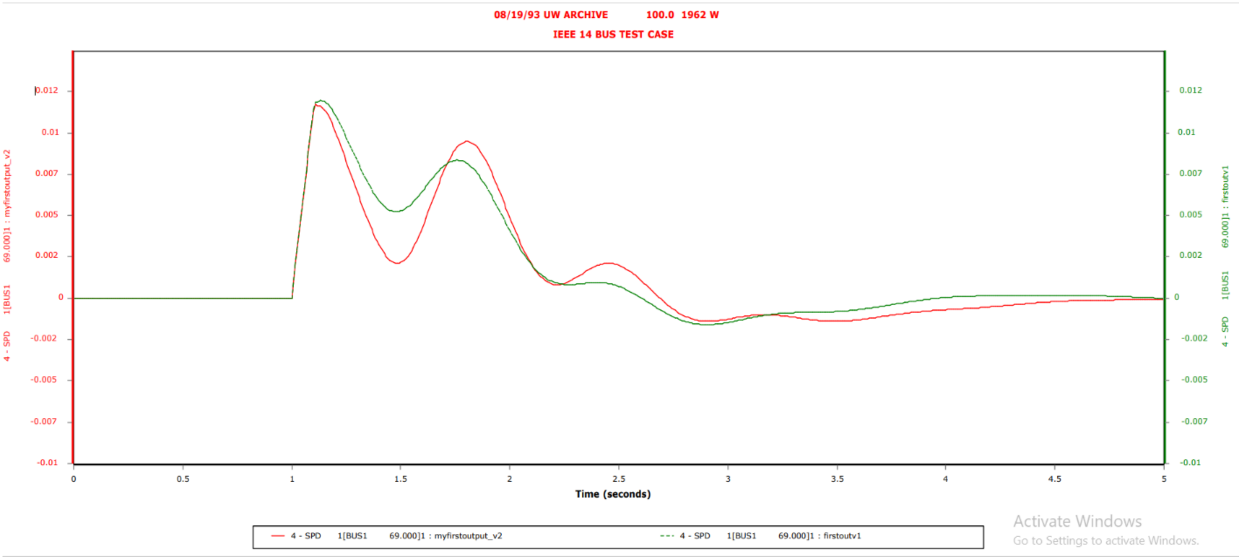

Fig: Speed vs time curve before (red) and after (green) reducing the network.

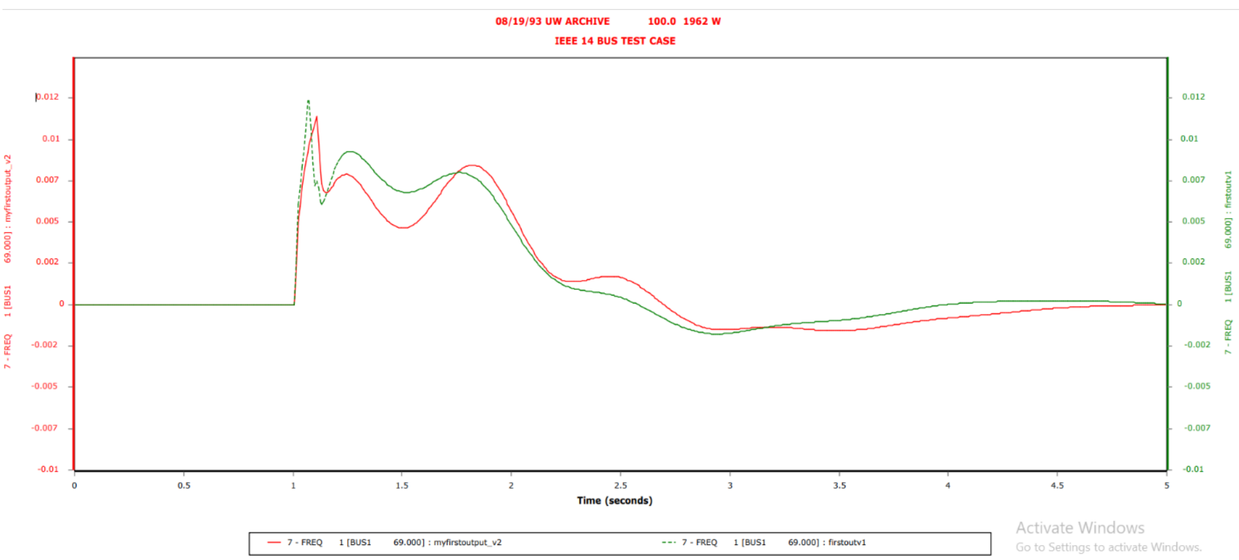

Fig: Frequency vs time curve before (red) and after (green) reducing the network.

The efficiency of the equivalent model can be measured in terms of reducing the number of buses. The term is called Reduction Ratio (RR) , which is given below.

$$RR(\%) = \frac{F_{nobus-}R_{nobus}}{F_{nobus}} \times 100\%$$

RR(%) of 14 Bus = $\frac{12-8}{12} * 100\%$

=33.33%

Reduction Ratio achieved in IEEE 14 Bus is 33.33%.

Based on the data , it can be observed that the iteration required to perform Decoupled Newton Raphson solution was 5 before reducing the network. However, after the network reduction, the iteration required was reduced to 4. This indicates that our objective to reduce the simulation time by reducing the network has been achieved while keeping the system parameters unchanged. Therefore, we have successfully accomplished our objective to reduce the network and lessen simulation time.

Conclusion:

Coherency-based reduction techniques using PSS/E offer a valuable approach for simplifying large power systems while retaining their essential dynamic characteristics. Based on the proposed methodology in this project , the New England 39 Bus System and IEEE 14 Bus System were successfully reduced by 53.846% and 33.33% accordingly while maintaining the dynamic characteristics of the original system. In 39 Bus System, the original network included 39, 10, 19, and 34 buses, generators, loads, and branches, correspondingly. In the reduced network, 18, 7, 21, and 27 are the respective numbers. In 14 Bus System, the original network included 14, 5, 11, and 20 buses, generators, loads, and branches, correspondingly. In the reduced network, 8, 4, 10, and 12 are the respective numbers. Dynamic simulations were conducted to ensure the accuracy of the reduced equivalent model, and the results showed that the reduced network can accurately represent the original system. This network reduction has also led to a reduction in simulation time, which is a great achievement. Overall, this methodology is a promising approach for reducing large-scale power systems while maintaining accurac