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Original Research Article

EIGEN-PROPERTIES BASED COHERENT MACHINE IDENTIFICATION AND STABILITY ENHANCEMENT USING WIDE AREA PSS IN MULTI MACHINE POWER SYSTEM

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Abstract: This paper describes coherent areas and their tolerances in the inter-connected power system networks, non-generating buses are assigned to each group of coherent generator using similar coherency detection techniques. The method is evaluated with four test systems and coherent generators and areas are obtained for different operating points to render a more accurate grouping approach which is valid across a wide range of naturalistic operating points of the system.

Index Terms—*Inter Area Oscillations, Coherency, Transient Stability, Eigen value analysis.*

Introduction: Coherency analysis in interconnected large power systems is a crucial task which can provide very significant information about the behavior of power systems [20]. Coherency analysis has been extensively used in stability studies, to reduce the computational effort by aggregating coherent generators into a unique equivalent area. In the case of perturbation in multi-machine power systems [3], some of the machines exhibit similar responses to the disturbance which means the difference between their swing curves is so small that they can be considered to be oscillating together and coherent[4-6]. In power system dynamic performance, coherency between generators is an important factor, which has several applications including dynamic reduction of power systems and emergency protection and control schemes [7-9].

In the recent days the inter connected electrical network becomes large and complex due to the reason of increasing power demand and deregulation of electrical energy market. This increasing power demand and deregulation of electric energy market results bulk amount of power exchange. The heavy power transfer needs either new lines to be added or need high voltage compensation such as series compensation to damp low frequency inter area oscillations.

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However there are lot of restrictions like environmental factors, cost factors etc. in expansion of new lines and installation of compensation devices. Therefore in order to achieve the maximum transfer capacity of the power system and to maintain better system security, improvement in damping of electromechanical oscillations become more important. The conventional approach to damp inter area oscillation is to provide the supplementary control signal to the excitation system by installing Power System Stabilizer (PSS) at the generator location. The PSS use the local stabilizing signal such as deviation of generator speed and provides the supplementary control input to the excitation. But the PSS taking local signal may not be always effective to damp inter area oscillations, because the local controllers are having lack of global observations. It is also observed that the local signals have lack modal controllability and observability. But it is proved that under certain operating condition the inter area mode may be controllable from one area and observable from another control area [1]. In this case the local controllers cannot provide effective damping.

It is observed that the remote signals from one or more distant locations are more effective to damp inter area oscillations. [41] The meaning of effective damping mechanism is that the damping torque of synchronous generator is enhanced through proper field excitation. The application of remote signal for damping controller has become successful due to the recent development of Phasor Measurement Units (PMUs). PMUs have very useful contribution in newly developed Wide Area Measurement System (WAMS) technology. The signals obtained from PMUs are referred to as remote stabilizing signals for the controllers.

Hence the most important task to design the wide area damping control is to select the most effective wide area signals. The basic criteria for selection of the signal is to have good observability and controllability of the signal for the system's inter area mode. So the signal which allow maximum observability and controllability of system's mode has to be selected as the most effective stabilizing signal for the controllers.

The issue of communication delay consideration in robust damping controller design becomes a pertinent topic in stability of large scale power system.

There are various techniques proposed for WADC synthesis including time delay effects such as multi-agent , predictor-based , and mixed controllers for time-delayed systems, where referred to as Henkel Norm [6-8]. Communication delay in remote signal transmission can be subdivided into two parts; time taken from measurement site of PMU to the phasor data concentrator and then to the control site or the location of the local PSS where the compensating output signal of the WADC is added in supplement to the output of the local PSS and exciter voltage reference.

Test System Description: The test system is carried out to implement the coherent area identification analysis using PST (Power System Toolbox), a MATLAB based power system simulation and control design package [5]. Four test systems have been considered for the analysis as follows:

- A system consisting of 16 machines, 68 buses.
- A 50 machine system consisting of 145 buses from IEEE 453 lines.
- A system consisting of 48 machines, 140 buses is taken as third test system.
- Kundur's benchmark two area four machine system has been carried out to analyze the different types of oscillations that occurs in the integrated power system [11].

Linearized Model: The stability of the operating point of a dynamic system to small disturbances is termed small signal stability. To test for small signal stability the system's dynamic equations are linearized about a steady state operating point to get a linear set of state equations.

$$\dot{x} = Ax + Bu$$
$$y = Cx + D$$

The theory of linear system provides very useful information about the operating behaviour and dynamic behaviour of the interconnected power system. In fact low frequency oscillations are linear when small disturbance. An interconnected power system network can be represented by the following set of non-linear differential and algebraic equations

$$\dot{x} = f(x,z,u)$$
$$0 = g(x,z,u)$$
$$y = h(x,z,u)$$

Where f and g are vectors of differential and algebraic equations respectively and h is vector of output equations. The notation $x \epsilon R^n$, $z \epsilon R^m$, $u \epsilon R^p$ and $y \epsilon R^q$ are the state, algebraic, input, output vectors respectively. is the dimension of system, is the no. of inputs, is the no. of outputs. A linear model of the network is used for selection of control signal. After linearizing the system around an operating point the state space model of the system can be represented

$$\dot{x} = Ax + Bu$$
$$y = Cx \qquad (2)$$

Where $u \epsilon R^p$ *and* $y \epsilon R^q$ *are state, input and output vector respectively. Where as* $A \in R^{n \times n}$, $B \in R^{n \times p}$, $C \in R^{q \times n}$ *are state, input and output matrix respectively.*

Electromechanical Modes: Interconnected power systems exhibit several kinds of oscillations when subjected to a perturbation. These oscillations are also named as power swings and to maintain the system stability these oscillations must be effectively damped. Oscillations in power systems are separated by the system factors. Some of the major oscillations attributed to system collapse are as follows:

1) ***Intraplant mode:*** Machines on the same power generation site oscillate against each other at 2.0 to 3.0 Hz depending on the unit ratings and the reactance connecting them.
2) ***Local plant mode:*** In local mode, one generator swings against the rest of the system at 1.0 to 2.0 Hz. The impact of the oscillation is localized to the generator and the line connecting it to the grid.
3) ***Inter-area mode oscillations:*** This phenomenon is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less. The oscillation frequency is approximately 0.3 Hz.
4) ***Control mode oscillations:*** These are associated with generators and poorly tuned exciters, governors, HVDC converters and SVC controls. Loads and excitation systems can interact through control modes.
5) *Torsional mode oscillations:* These modes are associated with a turbine generator shaft system in the frequency range of 10-46 Hz. Usually these modes are excited when a multi-stage turbine generator is connected to the grid system through a series compensated line.

Case Study: All Eigen values, other than theoretically zero Eigen value, have negative real parts, i.e, the system is stable. The nature of each mode may be identified from the corresponding Eigen vector. The states in the small signal model are associated with each generator and they are grouped in order.

16 machines, 68 bus: The single line diagram for the test case of 16 machines, 68 bus test system is shown in figure 5.1

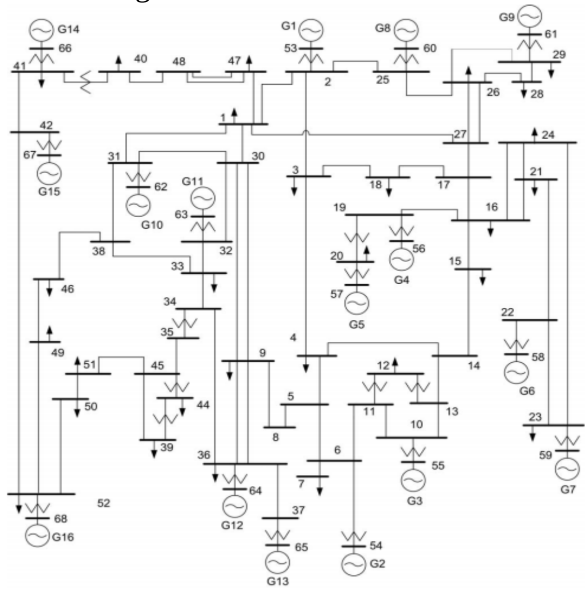

Figure 5.1 Single line Diagram of 16 machine 68 bus test system

Critical inter area modes are obtained by checking the eigen values whose real part is positive and frequency lies in the range 0-1 Hz. Now through the eigen values obtained we get the following critical mode as shown in table I.

Table I Critical Mode of 16 machines 68 bus system

Critical Modes	Eigen values	Damping ratio	Frequency

Mode 7	-0.36174 - 3.93784i	0.0915	0.6267

The compass plot of the rotor angle state terms corresponding to the critical mode is shown in figure 5.2.

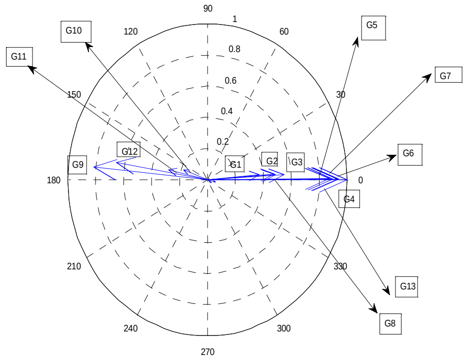

Figure 5.2 Compass Plot for 16 Machine System

The arrows represent the generators. The length and direction of each arrow is corresponding to the magnitude and phase angle of respective eigenvector for the critical mode of machine. There are two areas for the given system. It is observed that 4 generators are there in one area and 12 generators are there in another area.

50 machines145 bus: The single line diagram for the test system with 50 machines consisting of 145 buses from IEEE 453 lines is shown in figure 5.3

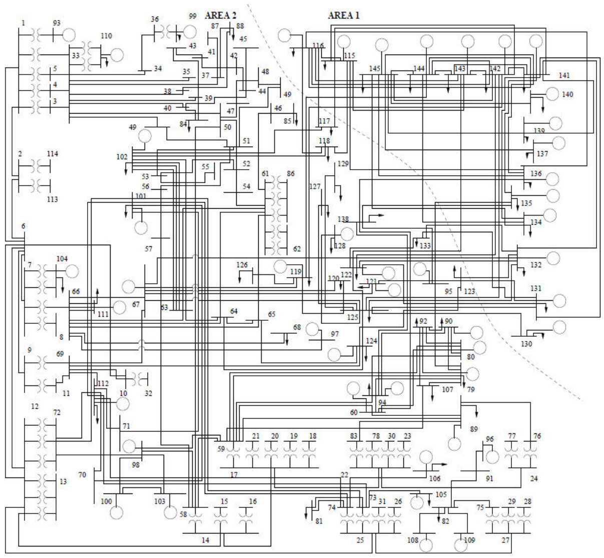

Figure 5.3 Single line Diagram of 50 Machine 145 bus System

The area of the system can be identified by the range of frequency of critical modes. The critical mode is indicated in table II,

Table II Critical Mode of 50 machines 145 bus system

Critical Modes	Eigen values	Damping ratio	Frequency
Mode 62	0.1608-8.9285i	-0.0180	1.4210

Here the critical frequency lies in the range of 1-2 Hz. The type of mode is local plant mode

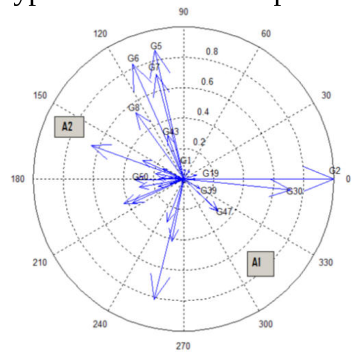

Figure 5.4Compass Plot for 50 Machine System

It can be realized that the given system is two area system. PSS affects the system positively leading it towards stable operation. The compass plot of the rotor angle state terms for the critical mode is obtained as depicted in figure 5.4. Through this plot we can identify that the following system is two area system.

48 machine 140 buses: The third test case is a 48 machine system consisting of 140 buses is considered for the analysis.

Table III Critical Mode of 48 machines 140 bus system

Eigen values	Damping ratio	Frequency
-0.0000 - 1.6342i	0.0000	0.2601

The compass plot of the rotor angle state terms for the critical mode for 48 machine 140 bus test system is depicted in Figure 5.6.

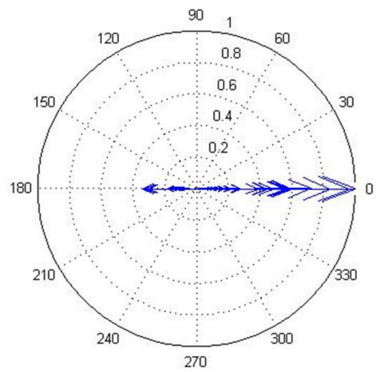

Figure 5.6: Compass Plot for 48 Machine System

The test system is found to be two area system and it is found that 28 number of generators are observed with zero degree phase angle and 20 generators are observed with 180 degree phase angle.

2-area 4-machine system: Power system dynamic components of the studied system are modeled according to the Kundur's benchmark system database. With the detailed modal analysis, it came to know that each generator has 11 states and the total order of the nonlinear model is 44. In normal operating condition, the power transfer through tie-line connecting two areas is 413 MW and load consumption of area 1 is 967 MW and of area 2 is 1767 MW. The nonlinear model of the studied system is linearized around the initial operating point of tie-line power $(P_{tie} = 413$ M. After performing modal analysis with Power System Toolbox (PST), 44 modes with their eigenvalues, damping ratio and frequency are obtained.

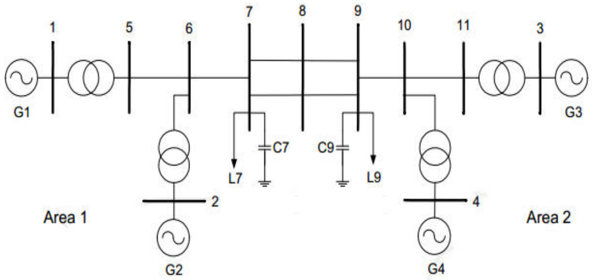

Figure 5.7Kundur's 2 area 4 machine system

The critical mode is found to be mode 15 with eigen value, damping ratio and frequency as shown in table IV.

Table IV Critical Mode of 16 machines 68 bus system

Critical Modes	Eigen values	Damping ratio	Frequency
Mode 15	0.0453 - 4.1135i	- 0.011	0.6547

There is only one inter area modes having frequency of 0.6547 Hz, presented in the system. This mode is referred to lightly damp inter-area mode 15 with eigenvalue (0.0453 - 4.1135i) and damping ratio of -0.011. The objective of the proposed PSS is aimed at achieving adequate acceptable damping for this mode. The compass plot for the critical mode is obtained as depicted in figure 5.8.

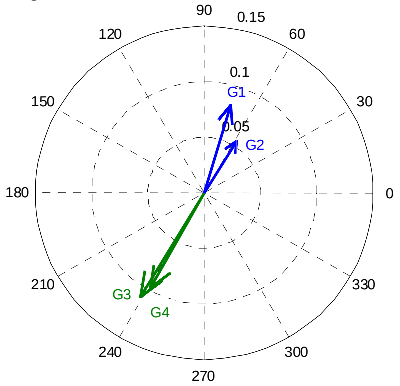

Figure 5.8 Compass Plot for 2-Area, 4- Machine System

In addition to the critical mode identification, modal analysis was also performed for coherent machine identification where the one group of generators forms one area and oscillating with another group of generators. Compass plot of the rotor angle state terms for the critical mode shows the coherent areas in the studied system.

As seen from the compass plot, it is clear that generator 1 and generator 2 forms area 1, and generator 3 and generator 4 forms another area so that the studied system termed as two area system when area 1 is oscillating with respect to area 2. The small signal stability analysis is performed under no fault condition and by applying small disturbance of 0.05 to the voltage reference of exciter in generator 1 of area 1.

Closed Loop Verification And Non-Linear Time Domain Simulation*:* The critical inter-area oscillation phenomenon is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less. The oscillation frequency is approximately 0.3 Hz. This complex phenomenon involves many parts of the system with highly non-linear dynamic behavior. The damping characteristic of the inter-area mode is dictated by the tie-line strength, the nature of the loads and the power flow. Through the inter connection and the interaction of loads with the dynamics of generators and their associated controls. The operation of the system in the presence of a lightly damped inter-area mode is very difficult.

The responses of field voltage of generator with respect to time under small signal performance assessment of the test systems for the different test cases i.e. 16 machines 68 bus system, 50 machines 145 bus system, 48 machines 140 bus system, and 2 area 4 machine system have been performed with and without power system stabilizer for each case.

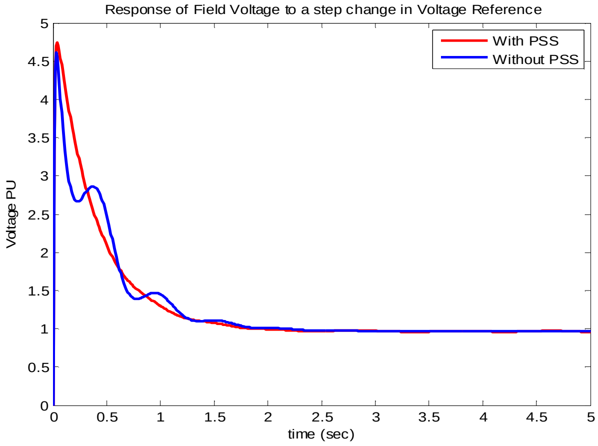

Figure 6.1Response of NPCC 16 machine 68 bus system

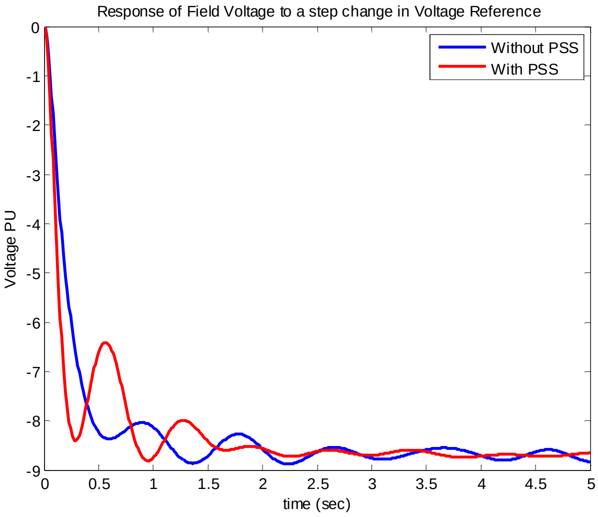

Figure6.2Response of IEEE 50 machine system

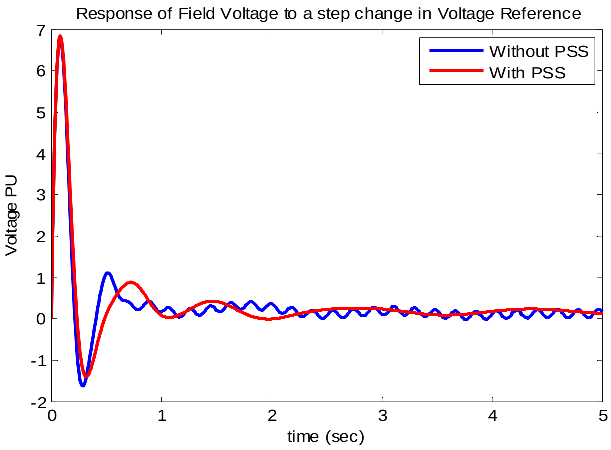

Figure 6.3Response of NPCC 48 machine 140 bus system

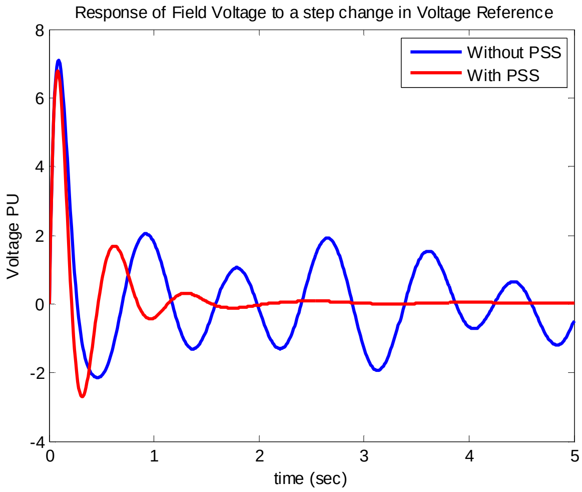

Fig. 6.4Response of Kundur's Two Area Four Machine System

It can be seen from the responses obtained for the different test cases that as for the system without PSS, there are kinds of low frequency oscillations with the very weak damping ratios, which is disadvantage to the normal operation of multi machine test system.

Conclusion: The use of the coherency indexes have been successfully verified and results show the validity and practical applications of the developed procedure. It should be noticed that the use of the coherency index is very straightforward and attractive from a computational point of view in spite of the dependency on engineering judgment for specifying an appropriate tolerance. The most important parameter for coherency behavior of generator is the electrical distance between them. It is possible to estimate the coherent generator groups just by considering generator and system parameters without taking up time consuming calculations and simulations. This approach is promising for applications where a fast decision is needed. This technique requires simple calculation involving little time and, hence, can be thought of as a possible tool for frequent identification of the coherent generators/buses and the corresponding weak tie lines. The results of generator and bus coherency calculation in a study system has been presented. The objective of the proposed coherency identification technique is to determine the optimized coherent groups of generators with respect to the dynamic response.

For this purpose, the coherency between generators is first evaluated using the dynamic simulation time response, and is used to define a dissimilarity index. This index provides the criterion for determining the coherent generator groups in the new procedure.

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