The Journal of CPRI,
Vol. 11, No. 2, June 2015 pp. 247-258

Power system stability : Mode identification in the power system oscillations using wide area measurement systems

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In the past few decades power system oscillation damping remains as one of the major concerns for secure and reliable operation of power systems. In response to a continual increase in demand, power systems are driven closer to their limits, especially those of transmission capacity. As such, enhancing the transfer capability, while keeping the system stable, is one of the main goals for system operators. When we transfer a bulk amount of power over a long distance through relatively weak tie lines and high gain exciters then problem of small signal oscillation occurs. These oscillations have also resulted into instability and blackouts in the power system. In this instability problem there are different frequency components which are known as modes. This paper work consist of identification of low frequency components i.e. local area and inter area modes of oscillations in two area power system and also in IEEE 39 bus system.

Keywords: *Low frequency oscillation, local area mode, inter-area mode, wide-area measurement systems, Power System Stabilizer (PSS)*

1.0 INTRODUCTION

The oscillations in power system remains as one of the main problem for smooth and stable operation of systems. Power systems are always driven close to their limits, because of continuous increase in power demand. All of this, deals with the transmission capacity of power system. In this way, to help up the power transfer capacity, while keeping up the entire system stable, is one of the key objectives for the power system operators.

When we transfer bulk amount of power to a long distance via a relatively weak tie lines and high gain exciters, leads to the problem of small signal oscillation [1]. Resulting power system oscillations turned power system into instability and even into blackouts. In this instability problem there are different frequency components which are known as modes. These mode are called as local area modes and inter-area modes [2]. In small signal stability problems local area mode of oscillation can be reduced by installing a Power System Stabilizer (PSS) [3]. These controllers use local signals e.g. voltage in tie lines, power and frequency deviation, Rotor Speed Deviation as input. But the reliability of PSS to damp inter-area mode of oscillations is quiet less. So, satisfactory performances at an operating point is not always possible with the PSS alone. However, due to wide variation in system conditions, operating conditions in the power system,which always changes. Local area controllers i.e. PSS lack the global observations, so they are unable to damp inter-area oscillations.

So, to damp out the inter-area oscillations we need to design a Wide-Area damping controller. For

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designing the Wide Area Power System Stabiliser (WPSS), the input signal must be defined. To select the input signal for WPSS both the modes i.e. inter-area and local area modes should be known. This paper contains the identification of modes in power system oscillation while study of the effect of PSS and WPSS is not considered in this paper work. Case study has been carried out on a two area, four machine, and eleven bus power systems [1] and Ten generator, 39 bus (IEEE 39 bus) system. Designed system is linearized around an operating point and eigenvector analysis is used to identify the local and inter-area modes of oscillations present in both the cases.

2.0 FUNDAMENTALS UNDAMENTALS OF SMALL SIGNAL STABILITY – MATHEMATICAL ANANLYSIS

The equilibrium points around which the analysis takes place basically takes a snapshot of the system's response to a given input at a specific instant of time. This is found by getting all of the derivatives equals to zero and solving it further. Linear systems only have one equilibrium point and satisfy the equation $f(x_0) = 0$ and therefore contain information about the system's stability.

Linear systems possess the nature of having stability or lack thereof, independent of the input. Whether or not a system is stable depends solely on the system itself. As a result any system that is stable will return to that stable state assuming zero input [1] [2]. The stable states of a linearized system can be categorized two different ways. A system is said to be asymptotically stable if it returns to the same equilibrium point after a small disturbance. Local stability appraises the return of a system to some other equilibrium after a small disturbance, all the while remaining within a small region around the original equilibrium point.

The state space representation and subsequent linearization of a power system begins with the description of the corresponding nonlinear differential equations. These differential equations such as the swing equation, that numerically model the operation of the different elements of the power system. In the generator models, the angular dynamics between the rotor and stator axis depend on the angular difference:

$$\theta(t) = (\omega_0 + \theta_0) + \Delta\theta(t) \qquad ....(1)$$

Where ω is the rotary angle, determines the frequency.

The swing equation for modelling the dynamic behaviour of synchronous machine, is provided by Equation 2.

$$M\ddot{\delta}(t) + \mathrm{D}\dot{\delta}(t) + P_G(\delta) = P_M^O \qquad ....(2)$$

where δ is the angle of generator and P_M is the mechanical power that is converted into electrical power.

From these equations state space representation is started with the desired variable (i.e. rotor angle), defined as the independent input variable x_i.

$$\dot{x}_i = f_i(x_1, x_2, \ldots .x_n;\ u_1, u_2, \ldots \ldots u_r; t)$$
$$i = 1,2, \ldots \ldots .. n \qquad ....(3)$$

From Equation 3, a vector-matrix notation is conceived that is comprised of a state vector, input vector and function relating the two, where the function and variable vectors are of the form in Equation 4.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} f = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} \qquad ....(4)$$

This relation in turn, governs the response of the system as outside inputs are added. An output vector is also created describing what is observed involving the same state and input variables used in the state vector of Equation 5 .

$$y = g\,(x, u) \qquad ....(5)$$

Note: y and g are defined as the vectors in equation 6.

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} g = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_m \end{bmatrix} \quad ....(6)$$

Now, we specify initial state and input vectors x_0 and u_0 and utilize the zero velocity characteristic mentioned earlier in order to linearize the system.

$$\dot{x}_0 = f(x_0, u_0) = 0 \quad ....(7)$$

A small disturbance is then added in the form of deviations Δx and Δu. This allows utilization of Taylor series expansion with the higher order terms removed resulting in linearized equations.

$$\dot{x} = x_0 + \Delta x$$

$$\dot{x} = f[(\dot{x}_0 + \Delta x), (u_0 + \Delta u)] \quad ....(8)$$

$$\begin{aligned} \dot{x}_i &= \dot{x}_{i0} + \Delta\dot{x}_i \\ &= f_i[(x_0 + \Delta x), (u_0 + \Delta u)] \\ &= f_i(x_0, u_0) + \frac{\partial f_i}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_i}{\partial x_n}\Delta x_n \\ &+ \frac{\partial f_i}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_r}\Delta u_r \end{aligned} \quad ....(9)$$

$$\dot{x}_i = \frac{\partial f_i}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_i}{\partial x_n}\Delta x_n + \frac{\partial f_i}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_r}\Delta u_r \quad ....(10)$$

$$y_i = \frac{\partial g_i}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial g_i}{\partial x_n}\Delta x_n + \frac{\partial g_i}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial g_i}{\partial u_r}\Delta u_r \quad ....(11)$$

After grouping them into the form shown in Equations 12 and 13.

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad ....(12)$$

$$\Delta y = C\Delta x + D\Delta u \quad ....(13)$$

A, B, C and D are vectors defined in Equation 14.

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} B = \begin{bmatrix} \frac{\partial f_1}{\partial U_1} & \cdots & \frac{\partial f_1}{\partial U_r} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n} \end{bmatrix}$$

$$D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_r} \end{bmatrix} \quad ...(14)$$

The A matrix from above is the most important as it presents a numerical view of the system in which its inherent characteristics can be drawn out. The matrix A is equivalent to the Jacobian matrix evaluated at the equilibrium point. To extract the information stored within the system matrix A or State matrix, then we calculate the eigenvalues. This is performed by solving the A matrix's relation to the identity matrix that results in the Characteristic Equation 15.

$$|\lambda I - A| = 0 \quad ....(15)$$

Depending on the nature of the resulting values, internal system information can be derived. According to Lyapunov's theories, a system is asymptotically stable if its characteristic equation yields eigenvalues of Equation 16 with negative real parts.

$$\lambda = \sigma \pm j\omega \quad ....(16)$$

Eigenvalues calculated from the above equation gives the following results.

- If at least one eigenvalue has a positive real part, the system is unstable.
- If eigenvalues having real parts of zero yield no conclusive determination. In addition, real and complex eigenvalues differ in oscillatory nature.

- If real part of the eigenvalue is negative, it represents non oscillatory modes and stable system.
- If the real eigenvalue is positive, it excerupts that the system has aperiodic instability.

No matter the sign, magnitude corresponds to the level of behaviour in that, the larger the value the heavier the effect. For complex values (that always exist in pairs), oscillation is confirmed. This then enables us to calculate the damping value and frequency of the complex eigenvalues. The amount and tendency of damping is given by the real part of the complex eigenvalue. Negative real parts mean damped oscillation and positive real parts mean growing oscillation. The frequency of oscillation is a function of the imaginary part as shown in Equation 17.

$$f = \frac{\omega}{2\pi} \quad \text{....(17)}$$

The Equation 18 represents damping ratio.

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \quad \text{....(18)}$$

The amplitude decay using the damping ratio is given by Equation 19.

$$\varphi = \frac{1}{\sigma} \quad \text{....(19)}$$

After finding eigenvalues of the system, eigenvectors are calculated to study other aspects of the system's behaviour such as mode contribution and shape. Eigenvectors exist as right and left column and row vectors (respectively) that correspond to each eigenvalue. The right eigenvector for each eigenvalue and its mode shape can be found using column vector satisfying Equation 20.

$$AV_i = \lambda_i V_i \quad \text{....(20)}$$

Similarly, the row vector that represents the left eigenvector is satisfied by Equation 21 and gives the contribution of each eigenvalue to its particular mode.

$$V_i A = \lambda_i V_i \quad \text{....(21)}$$

The discerning distinction between right and left eigenvectors is their orthogonality for the multiplication of vectors from differing eigenvalues and a constant result for the multiplication of vectors from the same eigenvalue. The right and left eigenvectors then form Equation 22.

$$R = \left\lfloor \underline{r_1} \vdots \underline{r_2} \vdots \underline{r_3} \vdots \cdots \vdots \underline{r_n} \right\rfloor$$

$$L = [\, l_1^T \vdots l_2^T \vdots l_3^T \vdots \cdots \vdots \; l_n^T]^T \quad \text{....(22)}$$

A diagonal matrix of the eigenvalues is created as shown in Equation 2.23.

$$\wedge = \begin{bmatrix} \lambda_1 & 0 & 0\,0 \\ 0 & \lambda_2 & 0\,0 \\ 0 & 0 & \ddots\,0 \\ 0 & 0 & 0\lambda_n \end{bmatrix} \quad \text{....(23)}$$

Next, we analyse the transformation of the original state variables, such that each variable is linked to only one mode as opposed to each variable being the linear combination of all the modes of the system. This enables individual participation levels. We begin with Equations 24 and 25 and form a new state equation of Equation 26

$$\Delta x = Rz \quad \text{....(24)}$$

$$R\dot{_Z} = ARz \quad \text{....(25)}$$

$$\dot{Z} = R^{-1}ARz \quad \text{....(26)}$$

Equation 26 can be reduced to Equation 27.

$$\dot{Z} = \wedge z \quad \text{....(27)}$$

Given the time sensitive solution of Equation 28, we arrive at the expression in Equation 29.

$$z_i(t) = z_i(0)e^{\lambda_i t}$$

$$\Delta x(t) = Rz(t) \quad \text{....(28)}$$

$$= \begin{bmatrix} R_1 & R_2 & \cdots & R_n \end{bmatrix} \begin{bmatrix} z_1(t) \\ z_2(t) \\ \vdots \\ z_n(t) \end{bmatrix} \quad ....(29)$$

Using the relations in Equations 30 and 31, we see the response of any particular variable simplifies to the expression in Equation 32.

$$\Delta x(t) = \sum_{i=0}^{n} R_i z_i(0)\, e^{\lambda_i t} \quad ....(30)$$

$$z(t) = R^{-1}\Delta x(t) = L\Delta x(t) \quad ....(31)$$

$$x_i(t) = R_{i1}c_1 e^{\lambda_i t} + R_{i2}c_2 e^{\lambda_2 t} + \cdots + R_{in}c_n e^{\lambda_n t} \quad ....(32)$$

Where c_i is known as the magnitude of excitation and defined by Equation 33.

$$c_i = L_i \Delta x(0) \quad ....(33)$$

This concludes the mathematical derivations of the equations involved in modal analysis of power system.

3.0 SMALL SIGNAL STABILITY - MODE IDENTIFICATION TECHNIQUES

There are several existing methods of solution concerning the analysis of large power systems. The general approach behind each method is similar in the sense that the aim is to minimize the amount of information being considered and faster output at high reliability. In order to accomplish this, it is important to identify what information to be addressed and what eigenvalues to be focused upon. Wide Area Measurement System (WAMS) provides states of the system at faster rate.

3.1 AESOPS : Analysis of essentially spontaneous oscillations in power systems

AESOPS is an algorithm that minimizes the complexity of computation by focusing on certain eigenvalues of the system, which are involved in the rotor angle modes of the system. This is an iterative process, starts with probable guess of what the eigenvalue may be. A torque value is generated from this initial eigenvalue and applied to the rotor of one of the identified generator. Subsequently, the complex frequency response as a result of the applied torque is determined which yields a linear system response. From this response a new eigenvalue is calculated. It then results into a new torque value that is applied and the process continues until the eigen value converges. Once the desired level of convergence is achieved, it is assumed that the final value is associated with a certain mode of oscillation that the generator participates in heavily [4] [6] [8]. This technique requires large computations and analysis for mode identification, which might be too much time taking for a power operator to address power system stability problems.

3.2 MAM : Modified Arnoldi Method

MAM approach is another way of determining system characteristics efficiently using a particular reduction method. This method takes a starting vector and composes a matrix called the upper Hessenberg matrix that has the same eigenvalues as the original state matrix A. This matrix is a reduced version of the matrix A with certain properties that allow eigenvalues of A that pertains to a specific point. An iterative process will increase accuracy and other processes must be carried out during the procedure to ensure a reduction of the accumulated errors [8].

3.3 PEALS : Program for Eigenvalue Analysis of Large Systems

PEALS is a method uses both AESOPS & MAM techniques in conjunction. These two techniques are used together because they work cohesively as an analysis method. The AESOP part of PEALS determines the eigenvalues involved in the rotor angle modes [6]. Increased complexity, bulk data management and analysis could cause increasing accumulated errors.

3.4 SMA : Selective Modal Analysis

SMA is a process that deals with the task of analysis through modal order reduction technique. It is an iterative reduction technique utilizing eigenvalue matrix analysis to converge the original system down to a more concise representation of state contribution. The state variables of rotor angle, flux linkage and motor speed are used to provide a look into the sensitivity and relationships of the state variables and its modes and participation factors. The process converges to the more active modes while separating out the less relevant modes of the system.

The limitations of SMA is its impracticality on very large power system as it has got complex analysis of power systems. This is due to the large size of the matrices and its the eigenvalue analysis to be carried. Each generator have three state variables, thus a matrix is three times the number of generators in the system, so order of the matrix increases with the number of the generators in the system, so increases the difficulty to apply SMA technique [5] [7] [8] [9].

3.5 S - Method

The S-method is an analytical method that takes advantage of the state matrix by transforming the eigenvalues from one plane into the other. Instead of relating the eigenvalues as existing in the s plane, they are converted onto the z plane. This has a great effect as this transformation now places the eigenvalues into a circumferential axis as opposed the vertical imaginary axis of the s plane. The corresponding right imaginary axis / left imaginary axis designation in the z plane is the area inside of the circle and outside of the circle. In essence, this is a graphically based tool similar to other techniques that differs in eigenvalue presentation [6]. Since this technique is based on the transformation from continuous domain (s- plane) to discrete domain (z–plane), this discretisation process may cause loss the accuracy with the original system.

3.6 Q – R Transformation

The Q-R transformation technique is similar to those listed above. In this approach, the A matrix of the system is decomposed into a product of two matrices; Q and R. The R matrix is a triangular matrix and Q matrix is a unit matrix. Using the matrices Q and R, solve for the unknown variables, brings the eigenvalues in an iterative process, where the solution converges to each eigenvalue of the system [7] [8] [9].

4.0 WAMS – WIDE AREA MEASUREMENT SYSTEMS

For an affective operation of the adaptive protection of the system, very precise and consistent system monitoring parameters like magnitude and angle of voltage, current and power flows are essential. Now a day's, in most of the electrical networks asynchronous measurements that are collected in the control centre and state estimation is performed. Steady state models are used in Supervisory Control And Data Acquisition (SCADA) system while measurements of various electrical quantities (voltage & current magnitudes, active & reactive power flows and injections etc) also through a SCADA. This leads to a biased state estimation, where biases mainly originate from utilization of single phases, positive sequence models and measurement time skewness. These biases can be eliminated using Phasor Measurement Units (PMU) measurements in combination with highly accurate, three phase and asymmetric power system models [10] [11] [12]. Moreover, synchronized and time tagged measurements that are referenced to the Global Positioning System (GPS) signal eliminate biases from the geographic spread and separation of power systems.

WAMS based measurements are able to give real time power system phasors at a rate of 60 phasors / second. This is now possible with Phasor Measurement Unit (PMU) enabled wide area measurement system (WAMS) [13] [14] [21].

5.0 PROPOSED MODE IDENTIFICATION OF TWO AREA SYSTEM OSCILLATIONS

5.1 Low Frequency Oscillations

Low frequency oscillations (LFOs) are generator rotor angle oscillations having a frequency in the range of 0.1 Hz to 3.0 Hz, and are defined by how they are created or where they are located in the system. The use of poorly tuned generation excitation, high-gain generator exciters, HVDC converters or static compensators may create LFOs with negative damping in the system. This is known as a small-signal stability problem. The damping of these oscillations is commonly performed with power system stabilizers. LFOs includes local mode of oscillations, torsion modes induced by the interaction between the mechanical and electrical modes of a turbine-generator system, and inter-area modes of oscillation which may be caused by either high gain exciters or heavy power transfers across weak tie-lines.

Inter-area oscillations are in the order of 0.1 Hz to 0.7 Hz, and are characterized by groups of coherent generators swinging against each other when present in a power system. This kind of oscillation restricts the amount of power transfer on the tie-lines between the regions containing the groups of coherent generators [15] [16] [17].

5.2 Verification of Oscillatory Modes Using Normalized Eigenvector Method

Eigen value analysis helps in identifying poorly damped or unstable modes in power system. They are highly nonlinear; however, it can be assumed that these systems behave linearly under normal operating conditions. The system is linearized around an operating point. Eigen value analysis is a well-established approach for studying the characteristics of low frequency oscillatory modes. The approach has several attractive features: each individual mode is clearly identified by its Eigen values.. Eigen value analysis is commonly used to investigate the properties of low frequency oscillations in multi-machine power system models as well. In addition, the analysis also provides valuable information about sensitivities to parameter changes [18] [19] [20].

5.3 Case study : Two Area Power System Modelling

The case study has been carried out on 4 machines, 11 buses power system as given in Figure 1. The system parameters are given as follows [1].

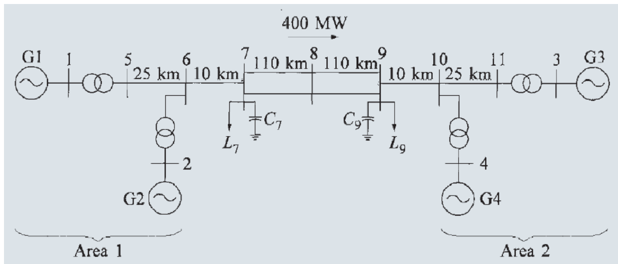

FIG. 1 TWO AREA POWER SYSTEM

The system consists of two similar areas connected through a weak tie-link. As shown in Figure 1, each area comprises of two coupled units. G1 and G2 are generators in Area-1 and G3 and G4 are generators in Area – 2. Power system consist of non-linear characteristics and hence system model is non-linear in nature. However, to analyse the small-signal stability of this non-linear system, it is linearized around an operating point so that the system can be analyse through linear control theory.

The created power system is linearized around an operating point by the command ‘linearize’ in MATLAB™. lin=linearize (‘sys’) command takes a model name ‘sys’ and returns a linear time-invariant state-space model. Linearized power system model is described as:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad ...(34)$$

$$y(t) = cx(t) \quad ...(35)$$

Where *x(t)* is state vector, *u(t)* is input vector and *y(t)* is output vector and A, B, C and D are appropriate matrices of state space. State space model of synchronous generator and other components is obtained. Given state space model consist of all the states present in the system. Each of the generator is equipped with Automatic Voltage Regulator (AVR). Two-area system data along with AVR is given in [1]

The generator present in the system is modeled using 6th order differential equation and AVR equipped with each generator is modelled using 1st order differential equation. This model gives a total of 56th order differential equation.

TABLE 1

MODE IDENTIFICATION

No	Eigen Values	Fre-quency (Hz)	Damp-ing Ratio	Modes/ Remark
1,2	-0.7519 ± 6.99445i	1.1132	0.1069	Local Area
3,4	-0.7479± 7.2177i	1.1487	0.1031	Local Area
5,6	-0.0569± 3.9397i	0.6270	-0.0144	Inter-Area
7,8	-19.109± 14.4025i	2.2922	0.7986	-
11	-11.8662	-	1	-

Above table shows the eigenvector analysis of the two area power system. The eigenvector associated with a mode indicates the relative changes in the states which would be observed when that mode of oscillation is excited. From above table we can observed that the frequency of local area modes are between 0.7 to 2 Hz and frequency of inter-area modes is between 0.2 to 0.7 Hz. It enables us to confirm that given modes in the table above is an inter-area and local area mode.

5.3.1 Results - plots of rotor angle terms of local-area mode eigen vector

When dynamics of generator oscillates against the rest of the elements of the power systems or another generator in the same area then it is called local area mode of oscillations. Typical value of local area mode of frequency lies in the range of 0.7 Hz to 2.0 Hz.

When the dynamics of one area oscillates against the dynamics of the other area then this type of oscillation is called Inter-Area oscillation. Typical value of Inter-Area mode of frequency lies in the range of 0.1 Hz to 0.7 Hz.

Since generators 1 is oscillating against generators 2 and generator 3 is oscillating against generator 4 of same area so given Figure 2 and Figure 3 plots confirms that this is a local area mode.

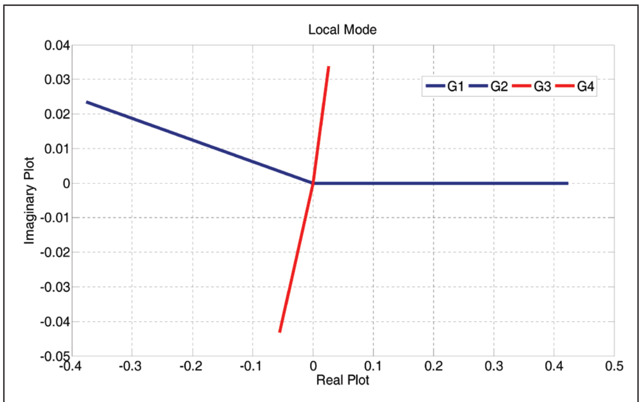

FIG. 2 LOCAL AREA MODE EIGEN VALUE : -0.7519 ± 6.9945I

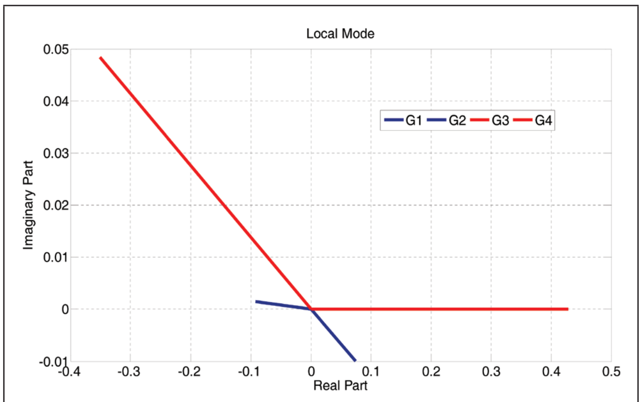

FIG. 3 LOCAL AREA MODE EIGEN VALUE: -0.7479 ± 7.2177I

5.3.2 Results - Plot of Rotor Angle Terms of Inter-Area Mode Eigen Vector

Inter-Area modes can be recognized as the dynamics of the generators of one area will oscillate against the dynamics of the Generator of second area at a phase difference of 180^0.

Here dynamics of area-1 is oscillating against dynamics of area-2 so Figure 4 is referred as inter-area modes. However, the largest components of the eigenvector are those associated with the second exciter state. This means that the inter-area mode may be most easily observed by monitoring those states. It does not mean that these states are necessarily good for controlling the inter-area mode.

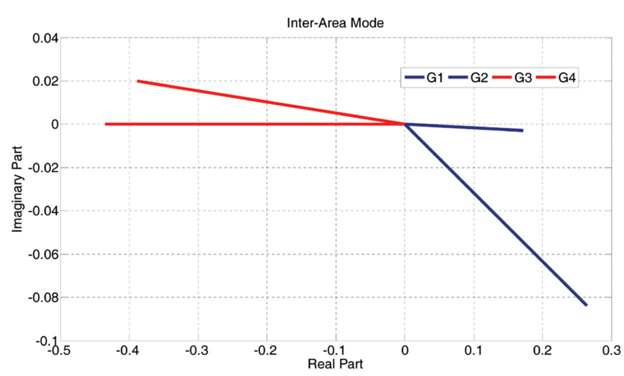

FIG. 4 INTER AREA MODE EIGEN VALUE: 0.0569 ± 3.9397I

5.4 Case study : Ten machine thirty-nine bus system (ieee 39 bus system)

The proposed method is further implemented in another larger system shown Figure 5 i.e. a 10 machine system 39 bus system [22] also knows as New England Power Grid or IEEE 39 bus system. The systemis of 10 machines and 39 buses, where G1 to G9 are equipped with static excitation and local PSSs. G10 is a equivalent unit for the study. The system data is taken from [23]. The generation system is modelled as 6th order, exciter as 1st order and LPSS is of 3rd order.

System is modeled in MATLAB^{TM}-Simulink and linearized it around an operating point. The linearized model came as 96th order. From modal analysis it has been found the three distinct inter-areamodes are present in the system shown in Table 2.

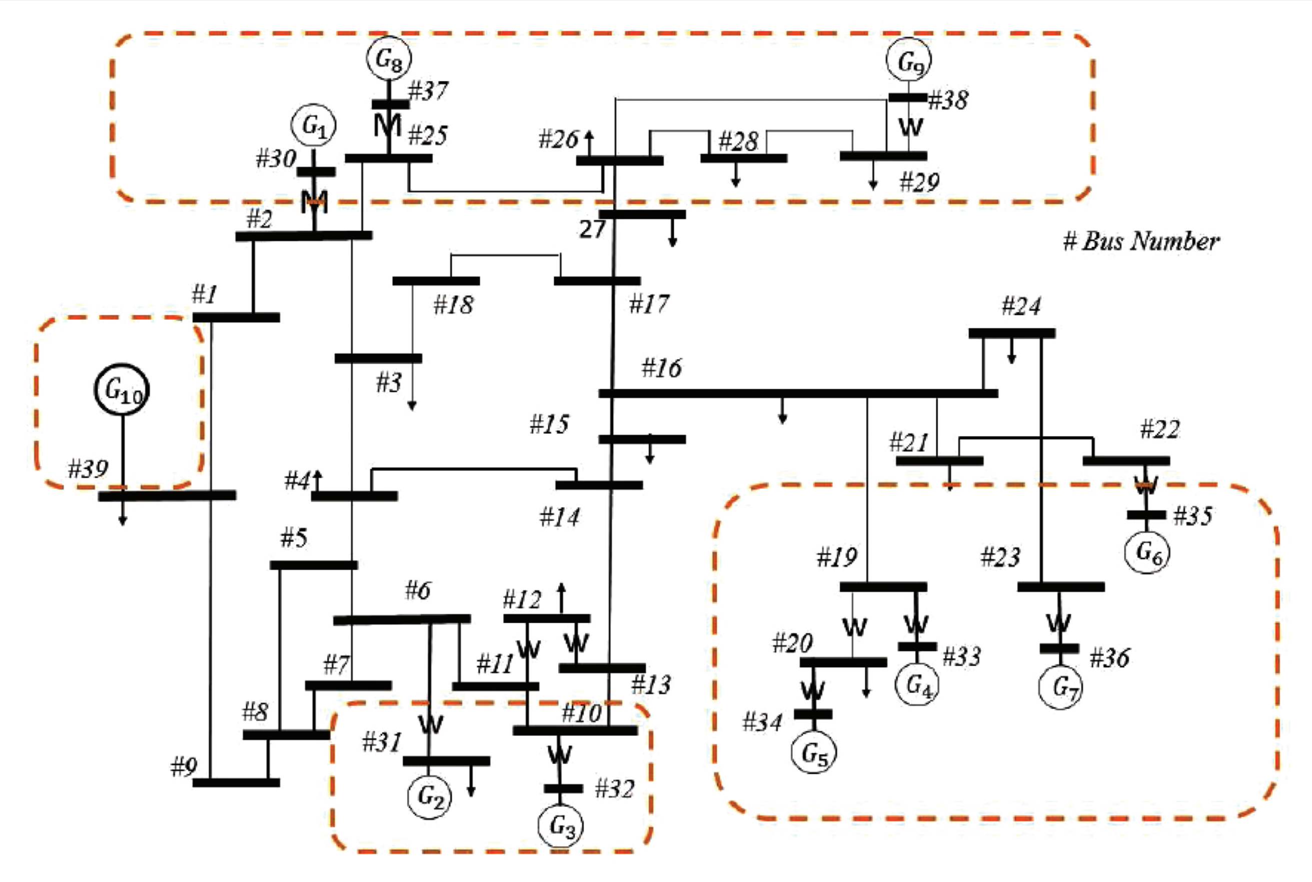

FIG. 5 SINGLE LINE DIAGRAM OF 10 GENERATORS AND 39 BUS POWER SYSTEM (IEEE 39 BYS SYTEM)

TABLE 2

MODE IDENTIFICATION

Mode	Mode shapes	Fre-quency (Hz)	Damp-ing Ratio	Modes/ Remark
1	G10 Vs G1 – G9	0.6236	0.0706	Inter Area
2	G1,G8,G9 Vs G4 – G9	1.0412	0.0702	Inter Area
3	G2,G3 Vs G4, G5	0.9687	0.0693	Inter Area

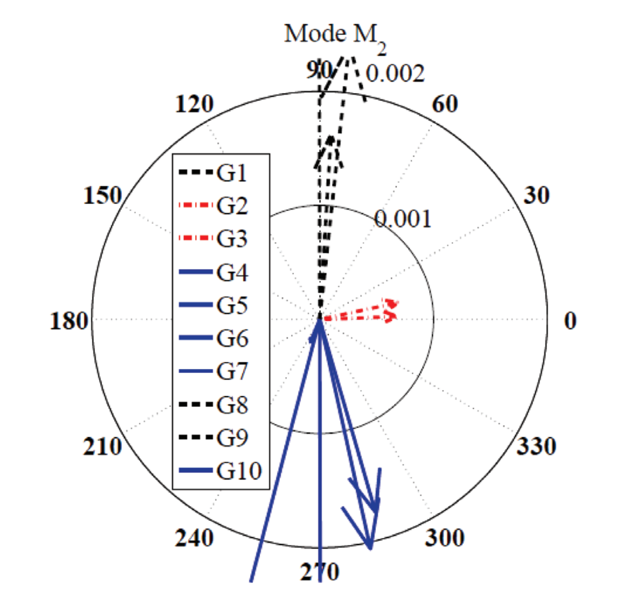

FIG. 7 MODE-2 INTER AREA MODE

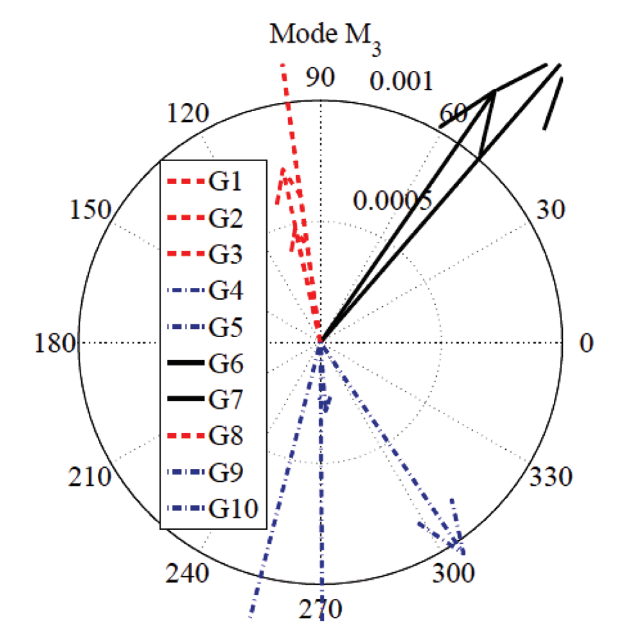

FIG. 8 MODE-3 INTER AREA MODE

5.4.1 Results - Plot of Rotor Angle Terms of Inter-Area Mode Eigen Vector

The above three modes of the table are shown in radial plots for better understanding as Figure 6, Figure 7 and Figure 8 respectively. Here Mode -2 and Mode -3 have low damping as Mode -1 but have relatively larger frequency compared to Mode -1 so these modes will get settled in few cycles. Hence, the critical mode in this case is Mode -1 with eigen valus of $-0.2777 \pm j3.9129$.

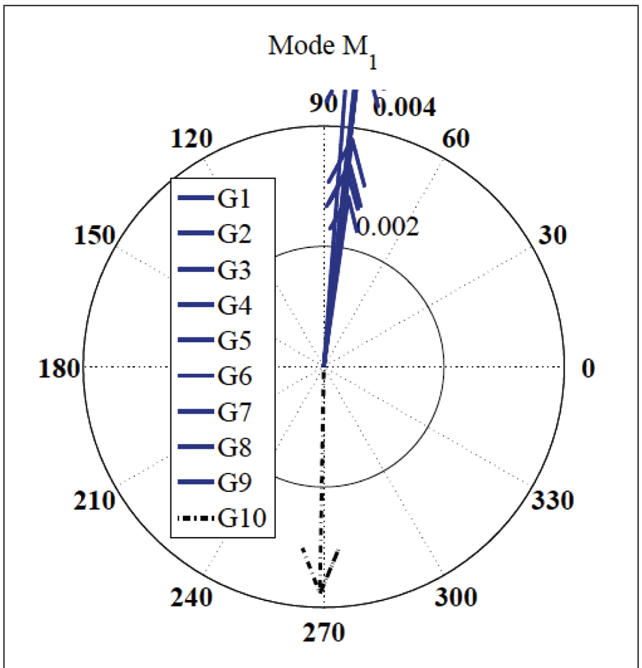

FIG. 6 MODE-1 INTER AREA MODE

6.0 CONCLUSIONS AND FUTURE SCOPE

The case study on two-area, four machine and eleven buses power system [1] has been carried out and it is also observed that mode identification problem has been solved using normalized eigen vector method. The optimal design of the synchronous generator involves a deep understanding of two-area power system. Created power system model is linearized in Matlab.

State space model of two-area, four machine and eleven bus power system has been obtained. The effect of various critical parameters like damping ratios, frequencies are verified on power system. All the simulation results are found to be closed accordance with theoretical results.

In this thesis work we have verified local and inter-area modes of oscillation.

The same work could be extended for more area systems or for a larger systems. Also using these mode identification, we can design a wide-area controller to damp inter-area mode of oscillations.

ACKNOWLEDGEMENT

The authors wish to thank the management of CPRI for giving an opportunity to publish this technical paper in the field of Power System Stability.

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