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Optimal Signal Selection techniques for Damping Low Frequency Oscillations in Multimachine Power System

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ABSTRACT: This paper presents identification of a best selection process for selecting the most effective stabilizing signal to improve damping of inter area oscillations in a multimachine power system.It is shown in this paper that how different signal selection techniques provides different control loop for damping of a particular inter area mode of oscillations [1]. In spite of these the controller locations were obtained for optimum placement of phasor measurement units for wide area measurement systems.Wide Area Measurement Systems (WAMS) uses Phasor Measurement Units or PMUs and the amount of data collected by PMUs is large and they need to be transferred to regional and global data centers where real-time state estimation, and protection. It is resulted from the two area 4 machine system that the geometric measure of joint controllability and observability approach performs excellent in small disturbance for the test system compared to residue approach. Non-linear simulations are carried out in order to evaluate the performance of different approaches of signal selection under study.

Key Words: Inter-area oscillations, residue approach, geometric measures, power system stabilizer (PSS), Phasor Measurement Unit (PMU)

I. INTRODUCTION

Power system stability has been recognized as an important problem for secure system operation. As power systems have evolved through continuing growth in interconnections, use of new technologies and controls, and the increased operation in highly stressed conditions,different forms of system instability haveemerged. For the satisfactory design and operation of power systems, a clear understanding of different types of instability and relationship between them is necessary.Some of the major oscillations attributed to system collapse are local mode, intra-plant mode, inter-area mode, control mode and torsional mode of oscillations. From all of these modes inter area mode of oscillations are very severe and observed over a large region of the network. To make the system stable, it is very necessary that the inter-area modes of oscillations are effectively damped. In order to damp inter area oscillation, the conventional approach is to provide the supplementary control signal to the excitation system by installing Power System Stabilizer (PSS) at the generator location [2].

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 [3]. 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. 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. 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.PMUs measure the positive sequence voltage, current, at different location of the grid [5]. The GPS technology provides proper time synchronisation among several global signals. The global signals are then sent to the controllers through communication channel. The PMUs are very useful device to provide a coherent picture of the entire network at real time. PMUs are major part of the smart grid technology.

These PMUs can deliver synchronous phasors and control signals at high speed. PMUs are located remote to the controllers and the signals from PMU are referred as remote stabilizing signals. PMUs are deployed at strategic locations on the grid at the buses and obtain a coherent picture of the entire network in real time. The basic function of PMU is to measure the positive sequence voltages and currents at different locations of the grid. It is important to know that the phasor technology was not developed to replace the SCADA system, but to complement it.

II. ELECTROMECHANICAL MODES:

(I) Intraplant mode: These types of oscillations are observed in machines located 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.

(II) Local plant mode: The impact of the local modes of oscillations are noticed when one generator swings against the rest of the system at 1.0 to 2.0 Hz. The oscillations are localized to the generator and the line connecting it to the grid.

(III) Inter-area mode oscillations: Inter-area mode involves two coherent group groups of generators swinging against each other at 1 Hz or less. The oscillation frequency is about 0.3 Hz.This phenomenon is observed over a large part of the network.

(IV) Control mode oscillations: These are colligated with generators and poorly tuned exciters, governors, HVDC converters and SVC controls. Loads and excitation systems can interact through control modes.

(V) Torsional mode oscillations: These modes of oscillations arecolligated with a turbine generator shaft system in the frequency range of 10-46 Hz. Whenever a multi-stage turbine generator is connected to the grid system through a series compensated line, these modes are initiated.

III. SYNCHROPHASOR

A phasor is a complex number that represents both the magnitude and phase angle of voltage and current sinusoidal waveforms (60 Hz) at a specific point in time. Synchrophasor are precise time-synchronized measurements of certain parameters on the electricity grid, now available from grid monitoring devices called phasor measurement units (PMUs). In order to understand how Synchrophasor can enhance grid operations and planning, it is useful to understand phasor technology. PMUs measure voltage, current and frequency and calculate phasors, and this suite of time synchronized grid condition data is called phasor data. Each phasor measurement is time stamped against Global Positioning System universal time; when a phasor measurement is time stamped, it is called a Synchrophasor.

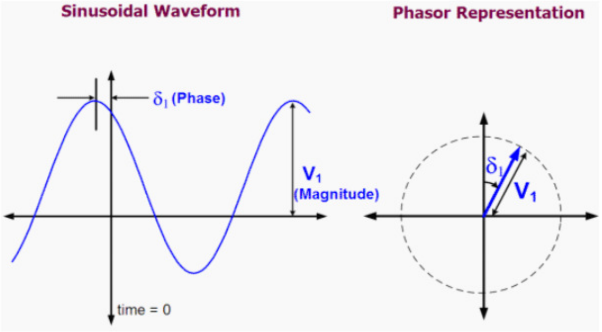

Fig. 1. Sinusoidal Waveform and Phasor Representation.

This allows measurements taken by PMUs in different locations or by different owners to be synchronized and time-aligned, then combined to provide a precise, comprehensive view of an entire region or interconnection. [5] PMUs sample at speeds of 30 observations per second, compared to conventional monitoring technologies (such as SCADA) that measure once every two to four seconds.

IV. EIGEN VALUE ANALYSIS:

For analyzing the small signal stability of any system, the system model can be linearized around an operating point i.e. the disturbances are considered to be so small or incremental in nature so that a linear model of the system around an operating point can be developed. The state space representation of the power system can be written as

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

Once the state space model of a power system is obtained the small signal stability of the system can be calculated and analysed and the eigenvalues λ_i are calculated for the A matrix. They are the non-trivial solutions of the equation:

$$\det(A - \lambda I) = 0$$

The solutions of characteristic equation are the eigenvalues of the $n \times n$ matrix A.

These eigenvalues are of the form $\sigma \pm j\omega$.The stability of the operating point may be analyzed by studying the eigenvalues.

The conjugate-pair complex eigenvalues ($\sigma \pm j\omega$) each corresponds to an oscillatory mode. A pair with a positive σ represents an unstable oscillatory mode since these eigenvalues yield an unstable time response of the system. However, a pair with a negative σ represents a desired stable oscillatory mode. Eigenvalues associated with an unstable or poorly damped oscillatory mode are also called dominant modes since their contribution dominates the time response of the system. It is quite obvious that the desired state of the system is for all of the eigenvalues to be in the left-hand side of the complex plane.

The damped frequency of the oscillation in Hertz and damping ratio are given by:

$$f = \frac{\omega}{2\pi}$$

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

The operating point is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable.

V. SIGNAL SELECTION AND CONTROLLER LOCATIONS

In order to damp the inter area oscillations; wide area controller employing signals from remote locations are very much necessary because they are more controllable and observable compared to local signals. The remote stabilizing signals are often considered to as "global signals". In the selection of stabilizing signals and control location the effort should be to use as few measurement and control device as possible to achieve acceptable damping effect.

The controllability and observability methods are often used to select controller location and stabilizing signals. There are three different approaches are used for measurement and control signal selection such as

(I)Residue approach:

The transfer function of an interconnected power system associated with the state equations can be expressed by

$$\mathbf{G(s) = C(sI - A)^{-1}B} = \sum_{i=1}^{n} \frac{\mathbf{R_i}}{(\mathbf{s} - \lambda_i)}$$

Where $\boldsymbol{R_i}$ is known as residue matrix of size $\mathbf{q \times p}$ associated with$\boldsymbol{\lambda_i}$

$$\mathbf{R_i = C\phi_i\psi_i B}$$

For $\mathbf{j = 1, 2, \ldots\ldots, q}$ and $\mathbf{k = 1, 2, \ldots\ldots, p}$ the elements of the residue matrix$\boldsymbol{R_i}$ can be expressed as

$$\mathbf{R_i(j, k) = C_j\phi_i\psi_i B_k}$$

In fact the residue can be represented as the product of the mode's controllability and observability.

The controllability for the mode **i** at $\mathbf{k^{th}}$generator can be represented as

$$\mathbf{cont_{j,k} = |\psi_i B_k|}$$

The observability of the mode **i** from $\mathbf{j^{th}}$ output is defined by

$$\mathbf{obj_{j,k} = |C_j\phi_i|}$$

From above equations, it is concluded that

$$\mathbf{|R_i| = |C_j\phi_i\psi_i B_k| = obj_{j,k} * cont_{j,k}}$$

It has been proved that the PSS is installed at that generator where largest residue for the $\mathbf{i^{th}}$ mode is found.

The limitation of the residue approach is that the approach is only valid for signals of the same type. However signals of widely varying physical significance such as tie-line power flow (MW), bus frequency (Hz), shaft speed (rad/s), angle shift (deg.), etc. will be involved in the output matrix simultaneously, then residue approach suffers a lot from scaling problem. To overcome this problem geometric approach is used.

(II) Geometric approach:

Optimal selection of measured signal and control site location is performed with the geometric measures of joint controllability and observability approach. The indices for controllability and observability $\mathrm{COI_k}$ and $\mathrm{OBI_j}$ for a particular$\boldsymbol{i^{th}}$ mode of oscillations are defined by:

$$\mathbf{COI_k = \cos(\theta(\psi_i, B_k)) = \frac{|\psi_i B_k|}{\|\psi_i\|\|B_k\|}}$$

$$\mathbf{OBI_j = \cos\left(\theta(\phi_i, C_j)\right) = \frac{|C_j\phi_i|}{\|C_j\|\|\phi_i\|}}$$

where, b_k is the $\mathbf{k^{th}}$ column of input matrix B (corresponding to the ith input), $\boldsymbol{\psi_i}$ is the left eigenvector of $\mathbf{i^{th}}$ mode of oscillation and c_j is the $\mathbf{j^{th}}$ row of output matrix C (corresponding to the $\mathbf{j^{th}}$ output). $\boldsymbol{\phi_i}$is right eigenvector of $\mathbf{i^{th}}$ mode of oscillations. The symbol| | and || || are the absolute value of a scalar and standard-2 norm respectively. The joint controllability and observability index of geometric approach is defined by

Joint-index k,j= $\mathbf{COI_k * OBI_j}$

If $\mathrm{COI_k} = 0$, then the mode k is uncontrollable from input i and If$\mathrm{OBI_j} = 0$, then the mode k is unobservable from the output j.

VI. TEST SYSTEM

Despite the high level of activity in recent years on wide-area control, there are many aspects remain poorly understood due to the complexity in large power system. Therefore a small Kundur's two area 4 machine power system has been set up to deal with the most of the issues/challenges faced by wide-area control. In the test system all the generators are equipped with governor, AVR, and IEEE ST1A type static exciter. The loads taken here are constant impendence type and connected to bus no. 7 and 9. The structure of the case study power system is given in Fig.2

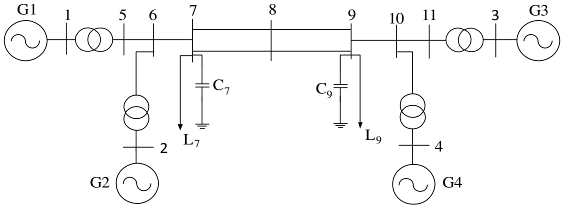

Fig. 2. Kundur's two area four machine system.

It is assumed that the Local signal based PSSs (LPSSs) are assumed to be connected with the chosen generators, that are determined as suitable control location, for damping of local area oscillations. After the calculation of most suitable stabilizing signal and control location a Global signal based PSS (GPSS) is employed supplement to the input of AVR along with LPSS for the damping of inter area oscillations. The exporting Power Ptie from area 1 to area 2 through tie line is 413 MW and chosen as nominal operating point.

VII. SMALL SIGNAL STABILITY ANALYSIS

Power system dynamic components of the studied system are modelled 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($\boldsymbol{P_{tie} = 413MW}$). After performing modal analysis with Power System Toolbox (PST), 44 modes with their eigenvalues, damping ratio and frequency are obtained which are tabulated in table 1.

There is only one inter-area mode having frequency of 0.6648 Hz, presented in thesystem. This mode is referred to lightly damp inter-area mode 15 with eigenvalue (0.0543 - 4.2113i) and damping ratio of - 0.021.

The objective of the proposed WADC is aimed at achieving adequate acceptable damping for this mode.

Table 1: Two Area System Modes of Oscillations.

Mode No.	Eigen Value	Damping Ratio	Frequency (Hz)
5	- 0.2522 - 0.6536i	0.3601	0.1040
15	0.0543 - 4.2113i	- 0.021	0.6648

Modal analysis was also performed for coherent machine identificationin accession to the critical mode identification where the one group of generators forms one area and oscillating with another group of generators. The coherent areas in the studied system are shown in Compass plot as shown in figure 3.

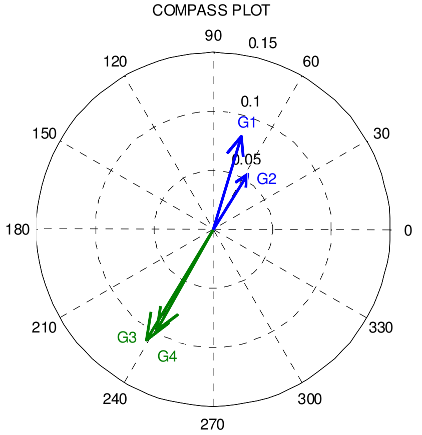

Fig. 3. Coherent Area Identification using Compass Plot.

There are four arrows representing the four 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. In 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.

VIII. OPTIMAL SIGNAL SELECTION AND CONTROL SITE LOCATION

The tie-line active power flow at various lines of the system has been taken for signal selection. The signal selection is carried out by residue approach and geometric measure of controllability/observability approach.

Table 2 and Table 3 shows results obtained from Residue approach and Geometric approach respectively.

Table 2: Normalized values of the Residue approach for the 4 machine two area system.

Signals	Generators			
	G-1	G-2	G-3	G-4
P6-7	0.5298	0.6849	0.5206	0.6686
P7-8	0.3545	0.4584	0.3484	0.4475
P8-9	0.3224	0.4169	0.3168	0.4070
P9-10	0.7735	1	0.7601	0.9763

Table 3: Normalized values of the geometric measure of controllability/observability approach for 4 machine 11 bus system.

Generators	Signals			
	P_{6-7}	P_{7-8}	P_{8-9}	P_{9-10}
G-1	0.3528	0.7735	0.7655	0.4179
G-2	0.4560	1	0.9897	0.5402
G-3	0.3466	0.7601	0.7522	0.4106
G-4	0.4452	0.9763	0.9662	0.5274

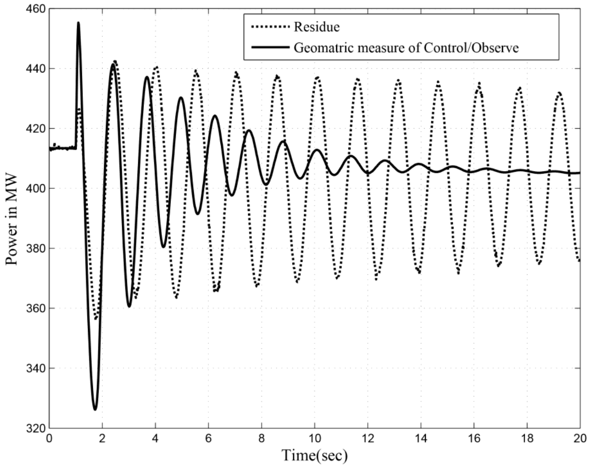

Fig. 5. Tie-line active power flow after stepping up voltage reference at Generator-1.

The responses of the line active power flow connecting the tie-line from area 1 to area 2, positive sequence voltage at Bus 9 and Speed response at Generator2 in both the cases of signal selection by approach based on residue and geometric measure.

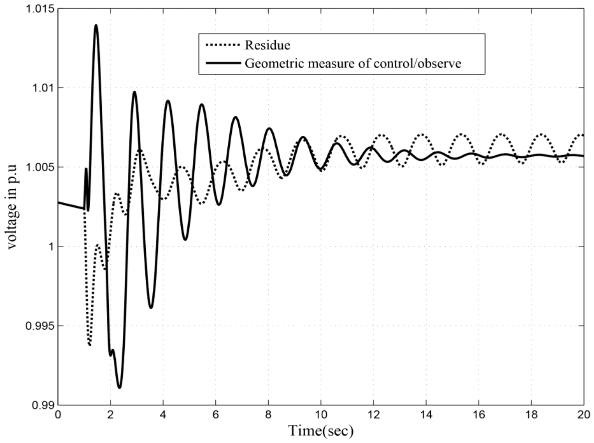

Fig. 6. Positive sequence voltage at Bus 9 for step change at Generator no. 1.

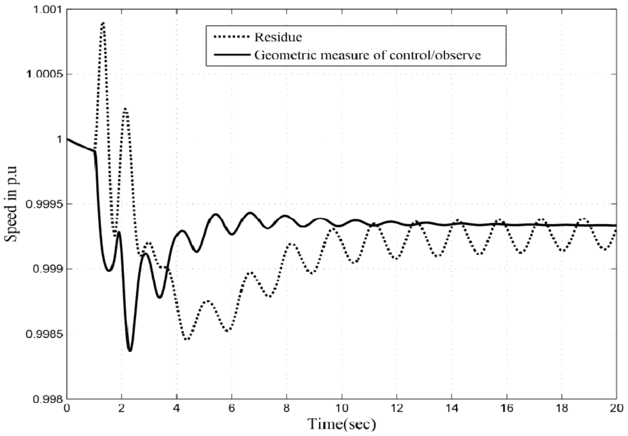

Fig. 7. Speed response at Generator2 for step change at Generator no. 1.

The plots have been taken by perturbing the voltage reference of Generator 1 AVR input. It can be observed that the signal selected by geometric approach gives better response as compared to the stabilizing signal selected by residue approach.

IX. CONCLUSION

The selection of control loop for a given inter area mode by two different method of signal selection approaches are obtained. In order to validate the result of two different methods, the Kundur's two area four machine system has been used for the case study example. The responses of Tie line active power flow,Positive sequence voltage and speed response are investigated for two methods i.e Residue and Geometrical measure of controllability & observability are observed. The controller locations for the optimum placement of PMU for wide area measurement system are obtained

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