A Survey Paper on Power System Stabilizer to Damped Out the Inter-Area Oscillations

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Abstract— Power system oscillation damping remains as one of the major concerns for secure and reliable operation of large power systems, and is of great current interest to both industry and academia. The principal reason for this is that the inception of poorly-damped low-frequency inter-area oscillations (LFIOs) when power systems are operating under stringent conditions may lead to system-wide breakups or considerably reduce the power transfers over critical corridors. With the availability of high-sampling rate phasor measurement units (PMUs), there is an increasing interest for effectively exploiting conventional damping control devices, such as power system stabilizers (PSSs), by using these measurements as control input signals. In this paper, we provide a comprehensive overview of distinct elements (or ‘‘building blocks’’) necessary for wide-area power system damping using synchrophasors and PSSs. These building blocks together shape a tentative methodical framework, and are disposed as follows: (1) fundamental understanding of the main characteristics of inter-area oscillations, (2) wide-area measurement and control systems (WAMS and WACS) and wide-area damping control (WADC), (3) methods for model-based small-signal analysis, (4) control input signals selection, and (5) methods for PSS control design. We also describe the latest developments in the implementation of synchrophasors measurements in WAMS. In this paper research read many papers related to signal selection approach for WADC designed which is based on two different approaches namely: Residue approach and Geometric approach.

Key words: Geometric Approach, Inter-area oscillations, Power System Stabilizer

I. INTRODUCTION

NOWDAYS, the continuous inter-connection of regional electric grid is the developing trend of modern power system in India and rest of the world. The main reason for interconnection of electric grids is that it can efficiently utilize various power resources distributed in different areas and achieve the optimal allocation of energy resources. This also optimizes the economic dispatch of power and gets relatively cheaper power, which implies that decrease of system installed capacity and the investment. Moreover, in case of fault or disturbance in operating condition, it can also provide additional supporting power of each area of interconnected grids which can increase the reliability of generation, transmission and distribution system.

With the growing electricity demand and the aging utility infrastructure, the present-day power systems are operating close to their maximum transmission capacity and stability limit. In the past few decades, the angular instability, caused by small signal oscillations, has been observed in the power systems under certain system conditions, such as during the transmission of a large amount of power over long distance through relatively weak tie lines and under use of high gain exciters. These conditions introduce inter-area oscillations [0.1-1.0 Hz][1] in the power system and which may cause a black out of the whole power system.

The inter area oscillations inherent to the large inter connected grid becomes more dangerous to the systems security and the quality of the supply during transient situation. Hence it can be said that the low frequency oscillations put limitations on operation of the power system and networks control security. The increased interconnected network of power system carries out heavyinter change of electrical energy which invokes such poorly damped low frequency oscillation that the system stability becomes major concern. The following are some example where large disturbances in power system network tends to produce low frequency inter area oscillations in the grid through the world [2]

– Detroit Edison (DE-Ortario Hydro-Hydro Quebec-1960s, 1985s)
– Finland-Sweden-Norway-Denmark (1960s)
– Western Elctric Coordinating Council (1964,1996)
– South East Australia (1975)
– Scotland-England (1978)
– Western Australia (1982, 1983)
– Ghana-Ivory Coast (1985)
– Southern Brazil (1975,1984)
– India (2012)

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. 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 traditional approach to damp out the inter-area oscillations by using Conventional Power System Stabilizer (CPSS). The basic function of PSS is to add damping to the generator rotor oscillation by controlling its excitation using auxiliary stabilizing signal. These controllers use local signals as an input signal and may not always be able to damp out inert-area oscillations, main cause behind this, the design of CPSS based on system components linearization around one operating point. Also local controller have not global observation and may does not be effectively damped out the inter-area oscillation[3] It is observed that the remote signals from different locations of power system are more effective to damp inter area oscillations[4] The effective damping 2 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 initial development of PMU based WAMS was introduced by Electric Power Research of Institute (EPRI) in 1990. The real time information of synchronous phasor and sending the control signal to major control device (e.g. PSSs, HVDC controllers, FACTs based controllers) at high speed have nowbecome easier due to the use [5]

The PMU can provide wide area measurementsignals. The signals can be used to enhance the wide area damping characteristics of a power system. The global signals or wide area measurement signal are then sent to the controllers through communication channel. It is found that if remote signals comes from one or more distant location of power system are used as a controller input then, the system dynamics performance can be improved in terms of better damping of inter-area oscillation.

The signals obtained from PMUs or remote signals contain information about overall network dynamics whereas local control signals has lack adequate observability with regard to some of the significant inter-area mode.

The wide area signals or the global signals are nothing but the remote stabilizing signals or the global signals. For the local mode of oscillations the most controllable and observable signals are the local signals. Such as generator speed deviation. But for inter area modes the local signals may not have maximum observability to damp these modes. Rather this can be effectively damped by the use of remote signals from a distant location or combination of several locations. Another important advantage of use of wide area signals is that it needs very small gain for the controller compared to the local controllers in order to achieve the same amount of damping. [6]

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 systems inter area mode. So the signal which allow maximum observability and controllability of systems mode has to be selected as the most effective stabilizing signal for the controllers.

In this paper, the two different approaches are applied to the Kundur's two area four machines system in order to select the most effective signals to damped out the inter-area oscillations.

II. INTER-AREA OSCILLATIONS

A. *Characteristics*

Inter-area oscillations are a part of the nature of interconnected power systems. Large power systems being connected by weak ties transmitting heavy power flows tend to exhibit such modes. These oscillations are a result of the swing between groups of machines in one area against groups of machines in another area, interacting via the transmission system. They may be caused by small disturbances such as changes in loads or may occur as an aftermath of large disturbances. This type of instability (small-signal rotor-angle instability) in interconnected power systems is mostly dominated by low frequency inter-area oscillations (LFIO). LFIOs maybe result in small disturbances, if this is the case, their effects might not be instantaneously noticed. However, over a period of time, they may grow in amplitude and cause the system to collapse [6].Incidents of inter-area oscillations have been reported for many decades. One of the most prominent cases is the WECC breakup in 1996 [7]. Mode properties of LFIO in large interconnected systems depend on the network configuration, types of generator excitation systems and their locations, while load characteristics largely affect the stability of inter-area modes [1]. In addition, the natural frequency and damping of inter-area modes depend on the weakness of inter-area ties and on the power transferred through them. Characteristics of inter-area oscillations are analyzed in Ref. [8,9] using modal analysis of network variables such as voltage magnitude and angle; these are quantities that can be measured directly by PMUs. The study gives a deeper understanding of how inter-area oscillations propagate in the power system network and proposes an alternative for system oscillatory mode analysis and mode tracing by focusing on network variables.

B. *Damping of inter-area oscillations*

Power system oscillation damping has always been a major concern for the reliable operation of power systems. To increase damping, several approaches have been proposed; the most common ones being excitation control through PSS and/or supplementary damping control of HVDC, SVCs, and other FACTS devices. In this paper, we focus on PSS excitation control using control input signals derived from PMU data.

III. WIDE-AREA DAMPING CONTROLLER DESIGN STRUCTURE

For the designing of damping controller, decentralized and centralized structure is mostly used. In decentralized structure, there is no need of additional telecommunication equipment because it uses local signal as a control signal and also in this, all generators have local controller which increases the cost of the system. As days go by, more and more electrical networks are interconnected, as a result electrical networks are highly stressed. Decentralized or say local control alone may not be enough to fulfill the damping needs of future electrical networks [7]. Centralized wide area damping control provides more efficient solution due to the availability of large amount of system wide dynamic data and better observation of inter area mode. Wide area controls include any control that requires some communication link to either gather the input or to send out the control signal [8]. If remote signals are applied to the controller, then it is found that, system dynamic performance can be enhanced with respect to inter area oscillation[9], for this an additional telecommunication equipment is required for the realization of centralized wide area control system, still it is cost effective as compared to installing a new control device.

In a power system local oscillation modes are well damped out due to installation of local PSSs, but inter area modes are lightly damped out because of less observability of some significant inter area mode. A centralized controller structure is shown in Fig.1. In the wide area damping control system selected stabilizing signals are measured by PMUs and send through dedicated communication links to the controller. This signal is modulated and sent them to selected generator exciters.

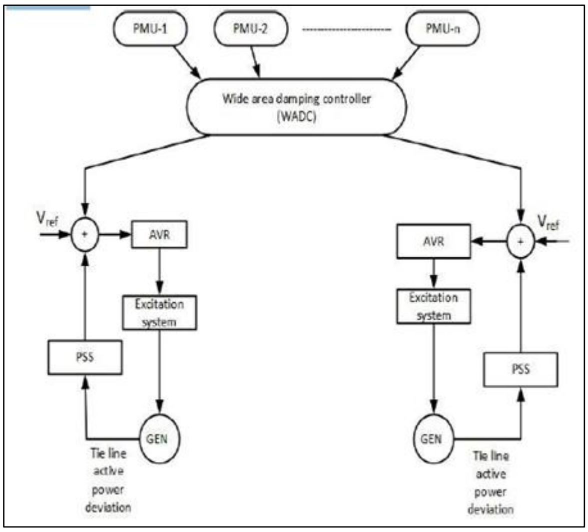

Fig. 1: General structure of wide area damping controller

IV. SMALL SIGNAL STABILITY ANALYSIS OF POWER SYSTEM BY MODAL ANALYSIS

Small perturbation continuously occurs in any power system due to small changes in load and generation. For analysing 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 pointcan be developed. A set of non-linear differential and algebraic (DAE) equations are used for the study of multi-machine power system dynamic behaviour. The algebraic equations are derived from the network power balance and generator stator current equations. The high frequency network and stator transients are usually ignored when the analysis is focused on small signal stability analysis, because small signal stability analysis deals with low frequency oscillations. The initial operating state of the algebraic variables such as bus voltages and angles are obtained through a standard power flow solution. The initial values of the dynamic variables are obtained by solving the differential equations through simple substitution of algebraic variables into the set of differential equations. The set of DAE are then linearized around the equilibrium point and a set of linear DAE are obtained as follows: [Martins, 1999]

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

Where, ‘f’ and ‘g’ are vectors of differential and algebraic equations and ‘h’ is a vector of output equations. The notation$x \in R^n, z \in R^m$, $u \in R^p$and $y \in R^q$ are the state, algebraic, input, output vectors respectively. ‘n’ is the dimension of system, ‘p’ is the no. of inputs, ‘q’ is the no. of outputs. The inputs are normally reference values such as speed and voltage at individual units and can be voltage, reactance and power flow as set in FACTS devices. The output can be unit power output, bus frequency, bus voltage, line power or current etc. After linearizing, around the equilibrium point $\{x_o, z_o, u_o\}$,the above mentioned non-linear equations can be linearized in terms of the following equations

$$\Delta\dot{x} = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial z}\Delta z + \frac{\partial f}{\partial u}\Delta u$$
$$0 = \frac{\partial g}{\partial x}\Delta x + \frac{\partial g}{\partial z}\Delta z + \frac{\partial g}{\partial u}\Delta u$$
$$\Delta y = \frac{\partial h}{\partial x}\Delta x + \frac{\partial h}{\partial z}\Delta z + \frac{\partial h}{\partial u}\Delta u$$

Elimination of the vector algebraic variable Δz from above equation provides

$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u$$

Power system state space representation is normally linearized around an operating point (hence the term small signal). The symbol Δ can be omitted so as to follow the standard state space representation by referring ‘x’ and ‘u’ (instead of Δx andΔu) as the incremental values

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

V. SIGNAL SELECTION

Let us consider the idendified linear model of network given by equation (1)

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

where$x \in R^{n\times n}$, $u \in R^{n\times m}$ and $y \in R^{p\times n}$ are the state, inputs and output vectors respectively. $A \in R^{n\times n}$, $B \in R^{n\times m}$ and $C \in R^{p\times n}$ are state, input and output matrices, respectively.

An eigenanalysis of matrix A produces the distinct eigenvalues$\lambda_i (i = 1,2,3, \dots \dots n)$and corresponding matrices of right and left eigenvectors ϕ and ψ, respectively.

Modal analysis of linear model (1) is applied to find out the low-frequency oscillation modes and then identify the critcal inter-area mode. Modal observability have been used to select a sutaible feedback signal for WADC, such as residue measures [10]and geometric measures [11]

A. *Geometric Approach*

The geometric measure of controllability $gm_{ci}(k)$ and observability $gm_{oj}(k)$associated with the mode k^{th} are given by[11]:

$$gm_{ci}(k) = cos\big(\alpha(\psi_k, b_i)\big) = \frac{|\psi_i b_i|}{\|\psi_k\|\|b_i\|}$$
$$gm_{oj}(k) = cos\left(\theta\left(\phi_k, c_j^T\right)\right) = \frac{|c_j\phi_k|}{\|\phi_k\|\|c_j\|}$$

In above equation, b_i is the i^{th} column of matrix B corresponding to i^{th} input, c_j is the j^{th} row of output matrix C corresponding to j^{th} output. $|z| and \|z\|$ is the modulus and Euclidean norm of z respectively. $\alpha(\psi_k, b_i)$ is geometrical angle between input vector i and k^{th} left eigenvector and $\theta\left(\phi_k, c_j^T\right)$ geometric angle between the output vector j and k^{th} right eigenvector.The joint controllability and observability index of geometric approach is defined by:

$$\boldsymbol{C = gm_{ci}(k) * gm_{oj}(k)}$$

In the geometric approach it can prove that the higher the value of joint controllability and observability index more the stability of signal selected.

B. Residues Approach

The transfer function of an interconnected power system associated with the state equations (1) can be expressed by:

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

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

$$R_i = C\phi_i\psi_i B$$

For $j = 1,2, \ldots \ldots, q$ and $k = 1,2, \ldots \ldots, p$ the elements of the residue matrixR_i can be expressed as

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

In fact the residue can be represented as the product of the mode's controllability and observability. Thecontrollability for the mode i at k^{th}generator can be represented as

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

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

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

From eq. it is concluded that

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

In[13] it has been proved that the PSS is installed at that generator where largest residue for the i^{th} mode is found.

VI. PSS CONTROLLER DESIGN

Power System Stabilizers are supplementary control devices which are installed in generator excitationsystems. Their main function is to improve stability by adding an additional stabilizing signal to compensate for undamped oscillations. In addition, it has become more common to use thesupplementary damping control available in flexible alternating current transmission systems. (FACTS). Conceptually, this supplementary damping control is similar to PSSs. Recently, Thyristor controlled series capacitors (TCSC) along with PSSs have been used to enhance the power system dynamic performance. A generic PSS block diagram is shown in Figure 1. It consists of three blocks: a gain block, a washout block and a phase compensation block. An additional filter may be needed in the presence of torsional modes. Depending on the availability of input signals, PSS can use single or multiple inputs. General procedures for the selection of PSS parameters are also described.

Recent studies on controller design have focused on using multi-objective control. adaptive coordinated multi-controllers. and a hierarchical/decentralized approach [32,37], A significant advantage of the decentralized hierarchical approach is that several measurements are used for feedback in the controllers. In addition, this approach is reliable and more flexible than the centralized approach because it is able to operate under certain stringent conditions such as loss of remote signal [32]. It is also important to mention that, as shown in. , centralized controllers require much smaller gain than in the decentralized approach to achieve a similar damping effect. On the other hand, the ability to reject disturbances is lower for centralized control. Because of these tradeoff between the two design methods, an alternative is to use mixed centralized/decentralized control scheme to effectively yield both global and local damping. .

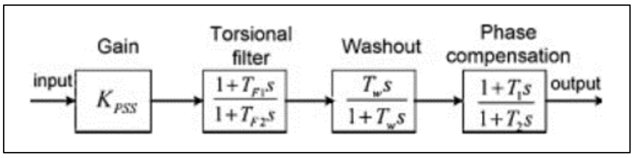

Fig. 2: An example of PSS block diagram

VII. CONCLUSION

A review of the necessary building blocks for PMU-based control of PSSs has been presented in this paper. The importance of PMUs and their implementation in WAMS and WACS for inter-area mode monitoring and damping in large interconnected systems has been highlighted. The main Characteristics of inter-area oscillations have been summarized. It has been suggested in several studies that the information obtained from PMUs is valuable for damping control, and with properly tuned controllers, global control may yield better performance than local control. The most important open question is if the current design methods can properly deal with new signals available from PMUs and how to adequately implement those signals in closed-loop feedback. PSSs should be designed to cover damping over a wide range of modes with high robustness and, in addition, the effect of time delays needs to be taken into account. The number of PMU installations and the signals used for wide area damping feedback control will be contingent upon the number of inter-area modes present in the system and the degree of Observability for closed-loop control available in the selected control input signals. Further research is necessary to determine the specific number of PMU sittings and optimal closed-loop feedback control input signal selection.

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