International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2014): 5.611

Critical Review on Power Oscillation Damping Controllers

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Abstract: ***This paper presents a complete overview of power frequencyoscillations in power system and the root causes of their generation and how they can be damped. Various methods are been presented to tackle with these oscillations can be damped efficiently and the importance of selection of stabilizing input signal for FACTS devices to damp oscillations and how they can be choosen .***

Keywords: PSS, AVR, POD, FACTS, WAM, Electrochemical Capacitors (ECs), EMTP.

1. Introduction

Large power systems typically exhibit multiple dominant interarea swing modes on the order of 0.1–1.0 Hz. This type of oscillations limits the amount of power transfer on the tie-lines between the regions containing coherent generator groups. Today, oscillatory stability control has become more important because these low-frequency interarea oscillations are often poorly damped with the increase of energy interchanges across the power grids. Hence, fast exciter or Automatic Voltage Regulators (AVR) was introduced in the system as one of the remedial measures to solve the problem. The introduction of **fast AVR was able to give the ―coarse adjustment" to keep** electrical speed of synchronous generators within the limits and successful in maintaining synchronism by controlling the first **swing. However, the fast AVR could not do the ―fine adjustment" to control oscillation in the speed. Then, Power** System Stabilizer (PSS) was introduced in generator to give that fine adjustment to damp out power oscillations that are referred to as electromechanical or low frequency oscillations.

Method of wide area damping controllers is been described for damping power oscillations in section (II) proposed by Yang Zhang and Anjan Bose. Reference [1] discussed a systematic design procedure of wide-area damping control systems by combining stabilizing signal selection and LMI based robust control design together ,with particular attention to several issues. One such issue is the selection of input stabilizing signals. The number of input signals and the effect of different types of signals on control performance are important design considerations. For example, generator speed deviations have often been used as controller inputs but these are not easily obtained and need to be synchronized, which often increases time delays. The recently developed robust control theory and wide-area control system technologies offer a great potential to overcome the shortcomings of conventional local controllers. Robust control techniques have been applied to design controllers that formally guarantee the system stability with an acceptable performance for a wide range of operating conditions. With the technology of phasor measurement units (PMU), synchronized dynamic data of power systems can be transferred across the whole power system [5] . The availability of wide-area measurements enables the real time detection and control of small signal instability in large scale power systems.

In section (III) a novel approach for damping interarea oscillations proposed by MahyarZarghami et al in a bulk power network using multiple unified power flow controllers (UPFCs) utilizing ultracapacitors, also known more generally as electrochemical capacitors (ECs). In reference [2], a new control is introduced to mitigate interarea oscillations by **directly controlling the UPFCs' sending and receiving bus** voltages that better utilizes the stored energy in the ECs. The results of this controller are compared with and without ECs. In addition to steady-state power flow control, damping oscillations in a power network is one of the primary applications of a unified power flow controller (UPFC). As high-voltage power electronics become less expensive, flexible ac transmission systems (FACTS) devices will become more prevalent in the bulk transmission system to control active power flow across congested corridors and ensure voltage security.

Sections (IV) describes the power oscillation damping using facts devices, specially using unified power flow controller. Section (V) describes about the most suitable input signal for the controllers such as facts controllers proposed by M. M. Farsangi, Y. H. Song, Kwang Y Lee which would result maximum in damping power oscillations and maintaining stability, the location and input signal play an important role in the ability of control devices to stabilize the interarea oscillations. In a practical power system, allocation of the devices depends on a comprehensive analysis of the steady-state stability, the transient stability, the small-signal stability and the voltage stability. Moreover, other practical factors, such as cost and installation conditions, also need to be considered.In reference [4] a method is proposed to select the input signals for both single and multiple flexible ac transmission system

(FACTS) devices in small and large power systems. Different input output controllability analyses are used to assess the most appropriate input signals (stabilizing signal) for the static var compensator (SVC), the static synchronous compensator (SSSC), and the unified power-flow controller (UPFC) for achieving good damping of interarea oscillations.

a) Wide Area Damping Controllers for Damping Power Oscillations

The traditional approach to damp out interarea oscillations is to install power system stabilizers (PSS) that provide supplementary control action through the generator excitation systems. In recent years, supplementary modulation controllers (SMC) are added to FACTS devices to damp the interarea oscillations. These controllers usually use local inputs and cannot always be effective in easing the problem due to two main shortcomings. First, based on a linearization of the system model in a nominal operating point, conventional local controllers designed by the classical control techniques have their validity restricted to a neighborhood of this point. But power systems constantly experience changes in operating conditions due to variations in generation and load patterns and changes in transmission networks. In addition, some uncertainty is introduced into the power system model due to inaccurate approximation of the power system parameters, neglected high frequency dynamics and invalid assumptions made in the modeling process. Second, local controllers lack global observation of interarea modes. It has been proved that under certain operating conditions an interarea mode may be controllable from one area and be observable from another. In such cases, local controllers are not effective for the damping of that mode.

In most power systems, local oscillation modes are often well damped due to the installation of local PSSs, while interarea modes are often lightly damped because the control inputs used by those PSSs are local signals and often lack good observation of some significant interarea modes. This suggests that a wide area controller using wide-area measurements as its inputs to create control signals supplement to local PSSs may help to damp interarea oscillations out. A centralized controller structure is thus proposed and shown in Fig. (1).

In the proposed wide-area damping control system, selected Stabilizing signals are measured by PMUs and sent to the controller through dedicated communication links. The wide-area damping controller calculates modulation signals and sends Them to the selected generator exciters. Normally, all the local PSSs are still conventional controllers designed by classical methods. In this design, they are modeled in the open loop state-space representation, on which the design of the WADC is based. The whole damping system includes two levels. The first level is fully decentralized and consists of conventional PSSs. The second level is centralized and provides supplemental damping actions in addition to the first level for the lightly damped interarea oscillations.

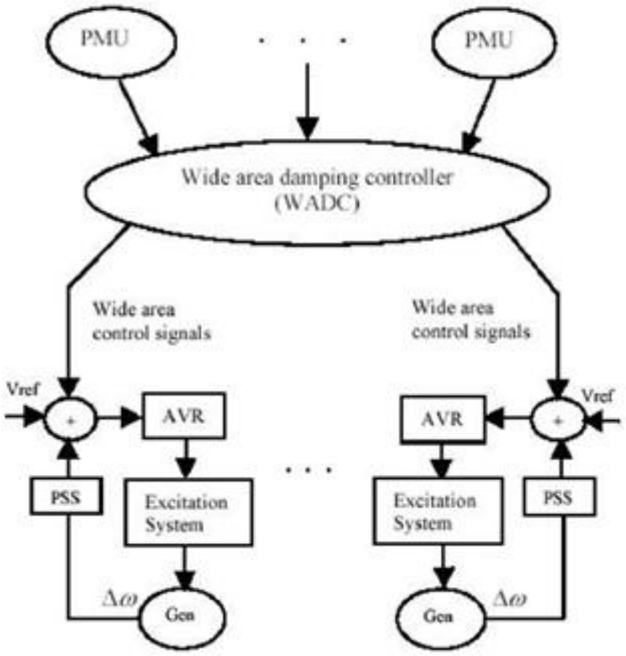

Figure 1: general structure of wide area damping control system

b) LMI-Based Mixed H2/H∞ Output-Feedback Control With Regional Pole Placements

LMI provides a natural framework to formulate the multi objective control problems without additional conservatism [6] . In reference [1] given that LMI offers more flexibility for combining several constraints on the closed-loop system or objectives in a numerically tractable manner. The resulting controllers do not in general suffer from the problem of pole-zero cancellation.

Good transient response can be achieved by placing all closed loop poles in a prescribed region in the left half plane. Pole constraints are also useful to avoid fast dynamics and high frequency gain in the controller, which in turn facilitate its digital implementation. Excessively large controller gains should be avoided because they could lead to controller output saturation and a poor large disturbance response of the system. To avoid large feedback gains, the system poles should not be shifted too far into the left half plane. Restricting the real parts of the closed loop poles to be greater than a suitable negative number inhibits such excessive shifting. One LMI region for all pole placement objectives discussed is shown in Fig. 2. When the closed-loop poles are in this region, it ensures minimum damping ratio $\zeta=\cos\theta$ minimum rate of decay σ and acceptable controller gains.

c) Wide-Area Damping Controller Design Procedure

1) System model and small signal analysis: The full-order nonlinear model of the studied system is calculated using MATLAB All generators are represented by detailed models, i.e., the two-axis model with exciter, governor and conventional PSS with two lead-lag compensation blocks. The nonlinear model is linearized around a chosen operating point. Then, small signal analysis is conducted with this linear model to get the frequencies, shapes and damping ratios of critical interarea modes.

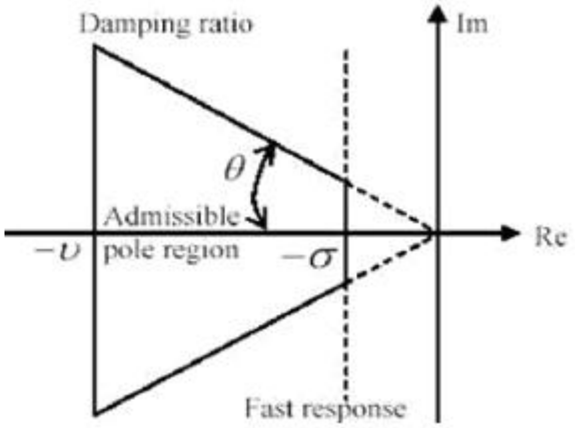

Figure 2: LMI region for pole placement

2) **Selection of measurements and control device locations:** Measurements that can be easily obtained and synchronized and have the highest observability of critical interarea modes are good candidates for input signals. Geometric measures of modal controllability/observability are used to evaluate the comparative strength of candidate signals and the performance of controllers at different locations with respect to a given interarea mode. The most often used input signals are voltage magnitudes, voltage phase angle, line power or current, frequency and generator rotor speeds.

3) **Linear model reduction:** The controller obtained by the LMI approach is of full order, that is, the same size as the design model including weighting functions. A middle size system usually has several hundreds of states. To design a controller with such a high order model is neither practical nor necessary. Therefore, model reduction is often applied to obtain a lower order model for controller design. The reduced order model should be assured to have the same global characteristics as the original system . In this research, the balanced model reduction via the Schur method provided by the robust control toolbox in Matlab is used for the model reduction task.

4) **Controller synthesis:** An LMI approach to the mixed output-feedback control with regional pole placement is applied to design a wide-area damping controller for interarea oscillations. The designed controller should meet the requirements of robust stability, robust performance and acceptable transient response. Sometimes the order of the obtained controller still needs to be reduced for easy implementation. In this case, the balanced model reduction is applied again.

5) **Closed-loop verification and nonlinear time domain simulation:** The performance of the controller is evaluated in the closed-loop system with the full-order linear model by using Matlab. The controller is then tuned and its performance in the actual nonlinear power system is evaluated by time domain simulation using TSAT. The robustness of the designed controller is verified for different operating conditions and fault scenarios.

2. A Novel Approach to Interarea Oscillation Damping by UPFC Utilizing Ultracapacitors

An added benefit of UPFCs deployed in the transmission system is that they can also effectively control active power oscillations that can damage generators, increase line losses, and increase wear and tear on network components. Therefore, developing suitable control strategies is a requirement before UPFCs can be confidently utilized in the power system. Mitigating power oscillations can be accomplished by rapidly changing the power flow through the series part of the UPFC. By controlling the amplitude and angle of the series-injected voltage, the active and reactive power flow in the transmission line can be altered. Upfc controller performs the control by controlling the modulation index and angels of series and shunt inserted voltage.

Furthermore mitigation control can be achieved by inclusion of independent high-power-density energy storage. Ultracapacitors [Electrochemical capacitors (ECs)] can be used as rapid discharge energy storage for power applications. ECs have been Used extensively in pulsed power applications for high-energy physics and weapons applications. Ideal power system applications for ECs are short-duration storage applications such as power stabilization, power quality ridethrough applications, and voltage flicker mitigation among other applications that require high power density and rapid recharge. The major difference between an EC compared to a conventional capacitor is that the liquid electrolyte structure and porous electrodes give the EC a high effective area that minimizes the distance between the two plates. Additionally, unlike batteries, ECs have cells that can be connected in series and parallel to obtain the desired voltage level and capacitance [7] . The dc-link capacitor of the UPFC voltage-source converter provides the ideal interface for an EC. In steady-state, the dc-link capacitor serves as a dc voltage from which the sinusoidal voltage waveform is constructed through pulsewidth modulation. The voltage of this capacitor is tightly controlled so that there is no degradation in the staircase waveform. During small transients, the dc-link capacitor will charge or discharge to compensate for converter losses in the UPFC. During large transients, however, the ability to exchange active power with the external power system is desirable to aid in damping oscillations. In this situation, the energy stored in the dc-link capacitor is inadequate to accomplish significant damping without severe dc voltage degradation. By utilizing a bidirectional dc-dc converter, the EC can be fully discharged without significantly impacting the voltage across the dc-link capacitor. For this reason, an EC is an attractive solution for providing large amounts of short-term active power.

In this a new control methodology, specifically designed to take advantage of the EC, is introduced for damping interarea oscillations in which the sending and receiving end voltages are controlled instead of the active and reactive powers. This is based on a two-stage control scheme in which the controlling UPFC voltages are first determined, and then the desired sending and receiving end conditions are imposed upon the UPFC dynamics to derive the controlling modulation amplitudes and angles. This approach effectively utilizes the energy stored in the EC by discharging (or charging) the EC by the amount required to achieve the desired bus voltages and angles.

a) UPFC Model

The UPFC is the most versatile FACTS device. It consists of a combination of a shunt and series branches connected through a dc capacitor, as shown in Fig. 3. The series-connected inverter injects a voltage with controllable magnitude and phase angle in series with the transmission line, thus providing real and reactive power to the transmission line. The shunt-connected inverter provides the active power drawn by the series branch plus the losses, and can independently provide reactive compensation to the system. The dc-link capacitor is connected to the EC through a bidirectional dc-dc converter. The UPFC model is a combination of the static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC) models presented in reference [2], where the parameters are as shown in Fig.(3).The currents id1,iq1 are the d,q components of shunt current and id2,iq2 are the series inserted d,q component of current, **V1<θ1 and V2<θ**2 are the sending and receiving end voltages.

W, ws are synchronous angular frequency,Rs1 and Ls1 are shunt resistance and inductance, Rs2, Ls2 are series resistance and inductance, Vdc is dc link voltage ,Cdc , Rdc are dc link capacitance and resistance,VdcEC is ECdc voltage, CEC, CResr are EC capacitance and resistance.

The UPFC is controlled by varying the phase angles **(α1,α2)** and magnitudes(k1,k2) of the converter shunt and series output voltage(e1 and e2)s , respectively. The EC is connected to the dc-link capacitor of the UPFC through a bidirectional dc-dc converter such as the SEPIC/Zeta converter. The steady-state dc-link capacitor voltage and the EC voltage are related through the duty cycle ratio D.

$$Vdc=D/1-D*VdcEC$$

The duty cycle 0<D<1 is the percent of a switching cycle in which the EC discharges. For example, if ,D=0.5 then the EC is in steady state and discharges (and charges) for half of each cycle, and Vdc=VdcEC. If, D>0.5then the EC discharges for a greater portion of the switching cycle and VdcEC drops (and vice versa charges for D<0.5 , power balance equations are given in reference [2].

b) Controller Design

If the original system were linear, this feedback control would result in the optimal values of voltage magnitudes and angles at both the sending and receiving buses of the UPFC to damp the interarea oscillations. The second stage of the control is to convert the control inputs into the modulation gain, and phase angles k and **α** for each UPFC. The first step in this stage is to find the values of currents, id1, iq1, id2, iq2 and from the UPFC active and reactive power balance equations at the sending and receiving end buses given in reference [2].

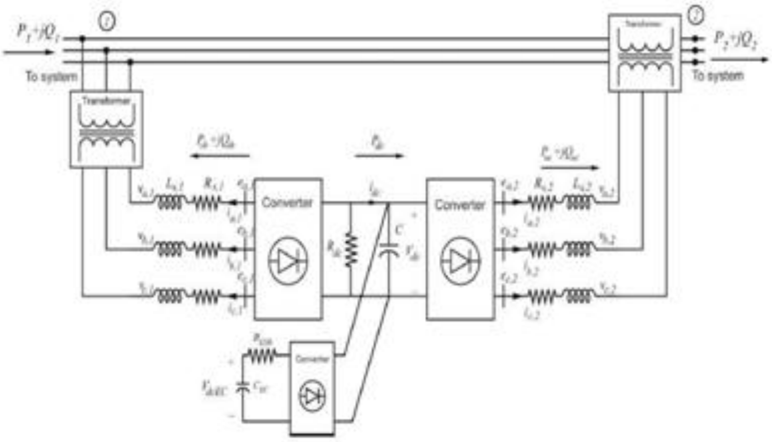

Figure 3: UPFC with EC

c) Basic Operation of UPFC

The UPFC is made out of two voltage-source inverters; one inverter is connected to the power system through a shunt transformer, whereas the other inverter is inserted into the transmission line through a series transformer. These two voltage-source inverters are coupled on their dc sides through a common dc capacitor link. From the control perspective, the UPFC can be decoupled into two branches; the parallel branch formed by the shunt transformer, voltage source inverter and dc capacitor operating as a STATCOM, and the series branch composed of the series transformer, a voltage source inverter and the dc capacitor which behaves as a SSSC. The basic UPFC Structure is shown in Fig (4).The main objective of series inverter is to produce an ac voltage of controllable magnitude and phase angle, and inject this voltage of fundamental frequency into the transmission line through the series transformer. The series inverter exchanges real and reactive power at its ac terminals, while the shunt inverter provides the required real power at the dc terminals, so that real power flows freely between the controller shunt and series ac terminals through the common dc link [9]. The reactive power is generated/absorbed independently by each inverter and does not flow through the dc link. Due to the inherent and unique characteristics of the UPFC to independently control the real and reactive power, the control strategies of the controller can vary widely. However, in most cases, it is anticipated that the UPFC will be used to control its bus voltage by locally generating or absorbing reactive power, as well as control power flows on the transmission line by regulating the magnitude and phase shift of the series injected synchronous voltage. This control mode is referred as Automatic Voltage Control Mode for the shunt inverter, and Automatic Power Flow Control Mode for the series inverter. Since the UPFC is able to force a desired power flow through the transmission line in steady state as well as in dynamic conditions, the Automatic Power Flow Control Mode feature can be enhanced to damp power oscillation in power networks.

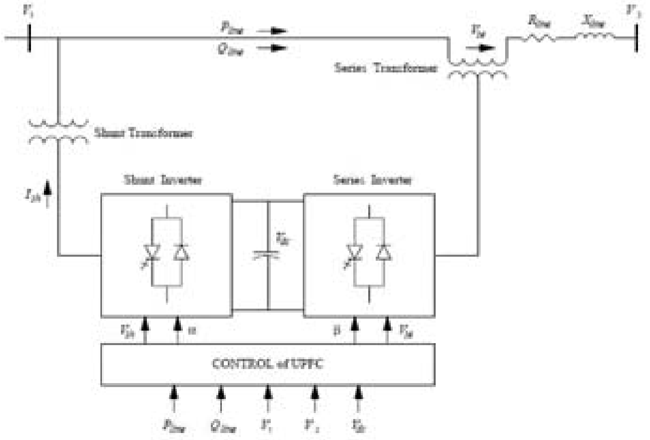

Figure 4: Functional model of UPFC

d) Power Oscillation Damping

The stability of a machine depends on the existence of two torque components; a synchronizing torque Ts that is in phase with the power **(torque) angle perturbations Δδ**, and a damping torque Td that is in phase with the speed **deviations Δw**. Thus, the change in electrical torque of a **synchronous machinate** following a perturbation can be represented by [8] Te = Ts**Δδ** + Td**Δw**

For a machine to remain in synchronism after the perturbation, both torque components Td and Ts have to be positive and sufficiently large. Lack of sufficient damping leads to oscillatory behavior of machine output quantities, and sometimes even to instability. Since the UPFC is able to act almost instantaneously to changes in power, it is possible to improve damping and transient stability of a power system by coordinated control actions of the UPFC. Thus, power oscillations resulting from swings in rotor angles can be readily damped by using the series branch voltage of the UPFC to control the system power flow.

3. Choice of Most Suitable Control Inputs for FACTS Devices

A new method is proposed to select the most responsive input signals (stabilizing signals) to the modes of oscillation for supplementary control of both single and multiple FACTS devices (or in general, for any power system damping control). The method is applicable in damping out both a single interarea oscillation mode in a small power system and multiple interarea oscillation modes in an extensively interconnected power system.

This method uses the minimum singular values (MSV), the right-half plane zeros (RHP-zeros), the relative gain array (RGA), and the Hankel singular values (HSV) [4] , as indicators to find stabilizing signals in the single-input single-output (SISO) and multi-input multi-output (MIMO) systems. In the SISO system with one FACTS device, only the criterion of RHP-zeros is used as the indicator for limiting the performance of the closed-loop system and the HSV as the indicator for controllability-observability. This is because the MSV and the RGA are useful indicators to quantify the degree of directionality and the level of interaction in the MIMO systems. In the MIMO system, using multiple FACTS devices, all four Indicators are utilized.

a) Procedure of Selection of Stabilizing Signal For Facts Device

The procedure to select stabilizing signals for supplementary controller of the FACTS devices using the MSV, the RHP zeros, the RGA-number, and the HSV can be described as follows.

In a SISO system, using only one FACTS device, the RHPzeros and the HSV are used as indicators to select the most responsive signal to a mode of the interarea oscillation. The procedure to carry out the selection of a proper stabilizing signal is summarized in the following steps:

Step 1) After placing a FACTS device, choose the stabilizing signal candidates for supplementary control.

Step 2) For each candidate, calculate the RHP-zeros. If any RHP-zeros is encountered in the frequency range of 0.1–2 Hz that is undesirable, then the corresponding candidate should be discarded.

Step 3) Check the observability and controllability of the remaining candidates using the HSV. The candidate with the largest HSV is more preferred, which shows that the corresponding signal is more responsive to the mode of oscillation and is the final choice.

For a MIMO system using multiple FACTS devices, in addition to using the HSV and the RHP-zeros, the MSV and the RGA-number are also used to find the most responsive signals to modes of the interarea oscillation. The procedure can be described as follows:

Step 1) Place the FACTS devices in the system. Choose the possible stabilizing signal candidate sets for supplementary control.

Step 2) Calculate the MSV for the candidate sets in step 1. In the case of having a large number of candidate sets, a range of candidate sets with larger values of the MSV should be selected for a more detailed input output controllability analysis.

Step 3) Calculate the RHP-zeros for the selected candidate sets considered in step 2. Those candidate sets, which encounter the RHP-zeros, will be discarded.

Step 4) Calculate the RGA-number for the remaining candidate sets from step 3. Candidate sets with smaller RGA-number are preferred. Few candidate sets with the RGA-number close to the achieved smallest RGA-number will be selected for the next step.

Step 5) The observability and controllability of the selected candidate sets from step 4 will be checked using the HSV. The candidate set with the largest HSV is preferred and known as the final choice for the stabilizing signals for the supplementary controllers [10].

4. Conclusion

In this paper, a systematic design procedure for wide-area damping control systems is described. A centralized structure is proposed for such systems. Active powers and current magnitudes on tie-lines are good choices for stabilizing signals with respect to critical interarea oscillation modes. For the small size system considered, one stabilizing signal is enough for the input of a Wide area damping controller. Multiple inputs improve the control performance only slightly for such small systems but are expected to be necessary for acceptable control performance in large systems.

Another method introduced a novel approach for damping interarea oscillations in a bulk power network using UPFCs with ECs . A new multistage control had been proposed that specifies the bus voltages (phase and magnitude) at the sending and receiving ends of the UPFCs to damp the oscillations. These desired voltages are then converted into the required switching commands that directly control the UPFCs. Furthermore, the proposed control is shown to be especially effective for UPFCs that are interfaced with ECs through a dc-dc converter.

The power oscillation damping capability of UPFC is shown by EMTP study.

The importance of identifying effective stabilizing signals for the FACTS devices in a power system is highlighted. It is concluded that the method of controllability and observability alone as an analytical tool is not adequate to identify the most effective feedback signals.

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