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DESIGN OF HVDC DAMPING CONTROLLER USING PMU DATA

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ABSTRACT

This paper describes a novel method to design a supplementary HVDC damping controller for damping the power oscillations in the electrical network. The electrical network of Karnataka and Tamil Nadu is the system under consideration and the Raigarh-Pugalur HVDC linkis taken for integrating the supplementary controller. PSSNETOMAC is used for Eigenvalue analysis to identify the oscillatory modes. The test signal method and pole placement method are used for designing and tuning the parameters of the supplementary controller. RTDS^{TM} is utilized for the controller design and implementation. Dynamic analysis has been performed to validate the effectiveness of the designed controller.

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INTRODUCTION

Grid stability issues are the norm in modern power systems. The increase in coupling and interconnections in the power system to cater to the increase in power demand may lead to inter area and local oscillation problems during transients. The ability to withstand small disturbances in the power system determines the small signal stability of that system. Inevitably, power systems are always subjected to small disturbances, which leads to power system oscillations and any system which is unstable to these small disturbances cannot operate in practice. Addressing these small signaloscillations, in an appropriate manner becomes an integral part of maintaining grid stability. When the power system was less complex in earlier times, Automatic Voltage Regulators (AVRs) were mainly used to damp the local oscillations [1]. But as the system size kept increasing, the adjustment of the excitation of AVRs were unable to damp out oscillations. Power System Stabilizers (PSS) were then used in conjunction with generators which participated heavily towards the power system oscillations [2]. Hence, local modes of oscillations are traditionally damped using PSS. Interarea oscillations have become prevalent as the system interconnections increase, with coherent groups of generators swinging against each other (at a frequency typically less than 2 Hz). Classical PSSs are generally incapable of damping interarea oscillations due to a limited bandwidth of the filter in the design [3]. More recent technologies like FACTS and HVDC [4] are now being used to damp inter area oscillations. With the advent of a rapidly developing Phasor Measurement Unit (PMU) technology, the Wide-area Monitoring and Control (WAMPAC) concept is being thoroughly researched for utilizing this concept in the damping of oscillations in the network. Traditionally, the oscillation damping was achieved through local signals as inputs to controllers such as PSS, FACTS, HVDC, etc. [5]. Advancement in communication infrastructure helped in bringing to light the advantages of wide-area signals over local signals [6]. Several control designs have been proposed for the PSS, FACTS and HVDC controllers regarding the Wide-area control structures [6-9]. In case of PSS controllers, the co-ordination of different PSS control structures may present a challenge for implementing the overall control architecture in large scale power systems. For FACTS controllers, consideration and allocation of the FACTS devices is essential in determining damping controller performance [10]. In contrast to these potential limitations, HVDC controllers would be better feasible choice fordamping controller as HVDC systems generally interconnect two regional grids, hence effectively influencing the operating characteristics of the electrical system [11]. Also, dynamic adjustments in the power system are more feasible due to the fast response characteristics of HVDC system. In an interconnected AC/DC system, adding a supplementary controller to the existing primary control of the HVDC system can damp low frequency oscillations [12]. This paper proposes a novel HVDC controller design that utilizes Phasor measurements as input to the controller to effectively damp the small signal oscillations in power system. This paper analyses the small signal stability of a representative system, namely the reduced South Indian grid system. The supplementary controller is then designed from the results obtained from the stability analysis, using pole placement method.

The performance of the controller is checked under dynamic conditions and found thatit is satisfactory. The paper is organized as follows: Section II describes the system considered and the small signal stability analysis of the said system using PSS NETOMAC software. Section III describes the supplementary controller design and the method of tuning the parameters of the controller. Section IV gives the results of the dynamic simulations performed to test the robustness of the controller. Section V presents the conclusion.

Small signal stability analysis of the system considered

Description of the system: The system considered for the study is the reduced south Indian grid system, which is obtained from the all India grid system by the method of network reduction [13] in PSS/E software. The system consists of Karnataka and Tamil Nadu states electrical network with 88 buses. All buses of 400 kV and 765 kV are considered. Raigarh-Pugalur HVDC line is considered. This is a bipolar HVDC link between the Western Region (Raigarh, Chhattisgarh) and Southern Region (Pugalur, Tamil Nadu) rated at ±800 kV and has a capacity of 6000 MW, of which only half the rated capacity, i.e. 3000 MW is considered in this study, as the link is not fully operational at present. The length of theline is about 1800 km. The South Indian grid map is as shown in Fig. 1.

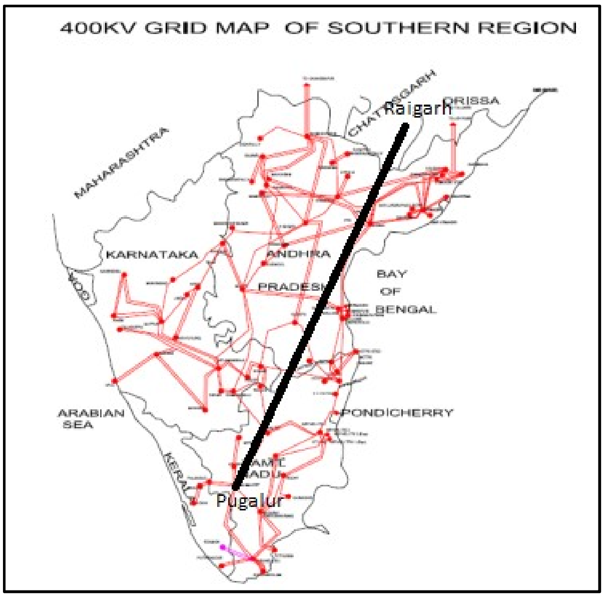

Figure 1. Power Map of Southern region (CEA Power Maps)

Eigenvalue Analysis: Load flow analysis is carried out for the chosen system and then small signal stability (eigenvalue) analysis is carried out. This analysis is performed using PSS NETOMAC software. The eigenvalue distribution of the system in s-plane is shown in Fig. 2.

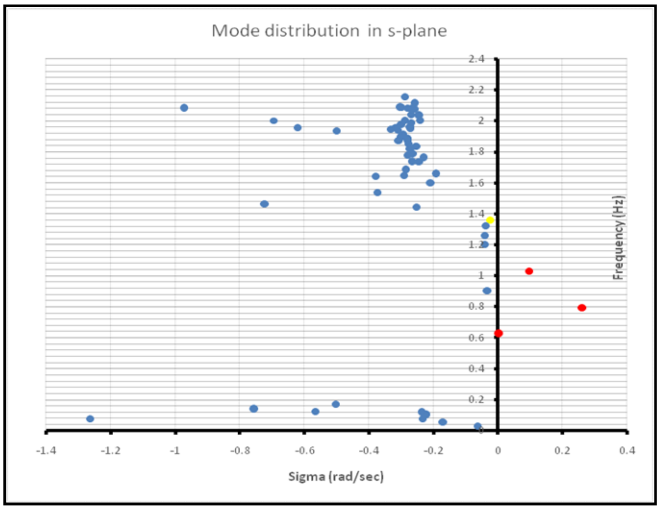

Figure 2. Mode distribution in complex s-plane

From the s-plane distribution the four least damped modes are identified as Mode 1, Mode 2, Mode 3 (red marks as shown in Fig. 2) and Mode 4 (yellow mark as shown in Fig. 2). The frequency and relative damping of these four modes are given in Table I. It is observed that the participating machines in the first three modes are all due to the interactions of equivalent machines, which do not practically exist in the electrical grid. Hence, Mode 4 is taken as the decisive mode for which asupplementary controller is designed to damp out this frequency of oscillations. From the eigenvalue analysis and results obtained, the least damped mode of oscillation is mode 4, with a mode frequency of 1.359 Hz and a damping percentage of 0.283 %. Table II shows the network elements which principally participate in this mode of oscillation. Once the least damped mode of oscillation and its corresponding participating elements have been identified, Residue analysis [14] is performed to determine the most favorable entity that can be utilized as input to the supplementary controller. From the residue analysis, it is determined that voltage phase angle difference between the buses of Tuticorin and Checkanurani is the most favorable input to the controller. Previous literature [15] also indicate that voltage phase angle difference can effectively reflect the characteristics of power oscillations. Hence, the HVDC supplementary controller is designed using the angle difference between the buses as input.

Table 1. Least damped modes of selected system

Mode	Frequency (f) (Hz)	Relative damping (ζ) (%)	Omega (ω = 2πf) (rad. /sec.)	Sigma (σ) (rad. /sec.)
1	0.793	-5.258	4.980	0.262
2	1.032	-1.490	6.486	0.097
3	0.625	-0.112	3.363	0.004
4	1.359	0.283	8.539	-0.024

Table 2. Participating network elements in mode 4

Mode of oscillation	4
Frequency (Hz)	1.359
Damping (%)	0.283
Participating machines	Coastal Energen (600 MW) and Tuticorin (500 MW)
Participating branch	400 kV Tuticorin – Checkanurani line

Figure 3 shows the analytical outline of the proposed controller in conjunction with the HVDC controller.

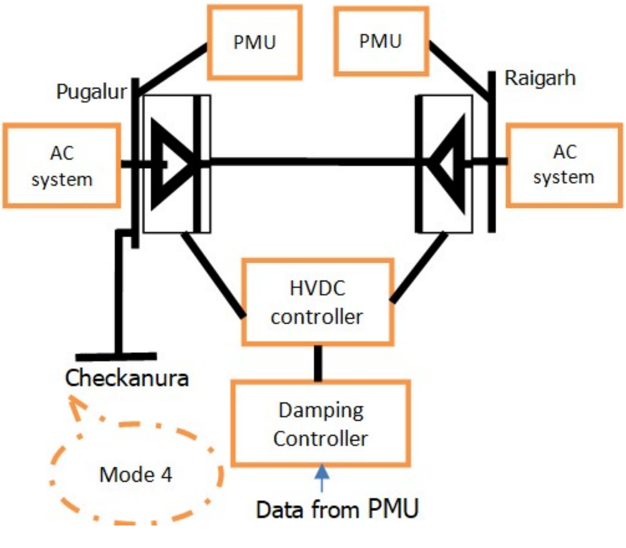

Figure 3. SLD of HVDC control structure

HVDC supplementary controller based on pmu data

The control structure adopted for the HVDC supplementary controller is shown in Fig. 4.

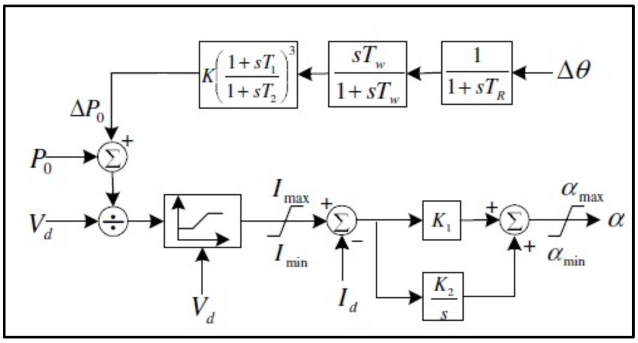

Figure 4. Transfer function diagram of HVDC supplementary controller using PMU data

To design the proposed controller, the pole placement technique is adopted. It uses the root locus rule to shift a pair or pairs of dominant poles, which determine the system dynamic stability to a pre-determined location in the s-plane. An open loop transfer function is defined taking two variables. The first variable chosen is the deviation of the power order, ΔP_0 of the HVDC link. This variable is the control variable and is the input to the open loop transfer function. The second variable chosen is the voltage phase angle difference between the buses of Tuticorin and Checkanurani, $\Delta\theta$ which is the controlled variable. The variable $\Delta\theta$ can be obtained from the Phasor output data of PMUs placed at Tuticorin and Checkanurani. PMUs placed at Tuticorin and Checkanurani buses provide time synchronized voltage (and/or current) phasors, from which the voltage magnitude and the phase angle of the phasor is known. Since the signals are time stamped, the phase difference between the two buses are accurately determined at every time instant. Let the open loop transfer function from ΔP_0 to $\Delta\theta$ be defined as T(s). With $\Delta\theta$ as the feedback variable, the feedback controller transfer function is defined as C(s). The block diagram of the closed loop transfer function of the proposed HVDC supplementary controller is shown in Fig. 5.

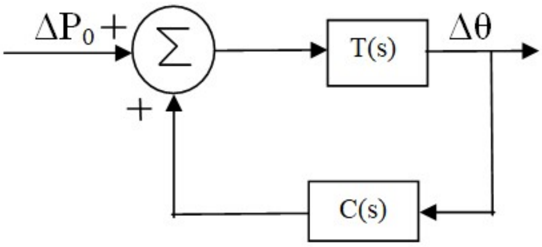

Figure 5. Block diagram of closed loop transfer function with the supplementary HVDC controller C(s)

The closed loop transfer function equation is given by

$$T_c(s) = \frac{T(s)}{1-T(s)C(s)} \tag{1}$$

Assume that a dominant real pole or a pair of dominant complex conjugate poles is to be shifted to a new location in the s-plane. Let that pole be λ_d. As $\lambda_d$must satisfy the characteristic equation of (1), then the following hold true.

$$C(\lambda_d) = \frac{1}{T(\lambda_d)} \tag{2}$$

Equation (2) can be spilt into magnitude and phase components

$$|C(\lambda_d)| = \frac{1}{|T(\lambda_d)|} \tag{3}$$

$$\arg[C(\lambda_d)] = -arg[T(\lambda_d)] \tag{4}$$

Hence, the magnitude and phase of the feedback or supplementary controller C(s) at a pole placement location $\lambda_d$can be calculated from the open loop transfer function T(s).

Obtaining the open loop transfer function T(s) is extremely difficult for a practical AC/DC system with large number of interconnections. A method known as the test signal method, whose basis lies in the background of mechanical admittance and mode identification [16], is utilized to obtain the open loop transfer function. Here it is assumed that the power system islinearized about an operating point for small signal stability analysis.

Test Signal Method

The steps for performing the test signal method in time domain simulation is as follows:

Step 1) A series of small oscillating power signals are added to the power reference set point of the HVDC controller.

$$\Delta P_0 = \sum_k P_k \cos(k\omega_0 + \phi)$$

where $k\omega_0$ = 0.1 ~ 3 Hz, P_k and ϕ are amplitude and phase of the oscillating power signal whose frequency is $k\omega_0$. The value ΔP_0 should be taken in such a way that the linearization condition of the system is not violated.

Step 2) Simulate the system to steady state after adding the power oscillations and obtain $\Delta\theta$ (from the PMU) and ΔP_0.

Step 3) Phasor values $\widehat{\Delta\theta}$ and $\widehat{\Delta P_0}$ are obtained from Fourier decomposition of $\Delta\theta$ and ΔP_0 at different frequencies.

Step 4) The open loop transfer function at different frequencies is calculated as follows:

$$T(k\omega_0) = \frac{\Delta\theta\widehat{(k\omega_0)}}{\Delta P\widehat{(k\omega_0)}} \tag{5}$$

Step 5) Once the transfer function values are obtained at different frequencies, the approximate expression of T(s) is obtained by curve fitting technique, which is explained in the next section.

Identification of T(s) by curve fitting method: The data points obtained for T(s) at different frequencies can be utilized to form the approximate expression for T(s) using curve fitting method. The System identification Application toolbox in MATLAB is utilized for this purpose. The toolbox accepts frequency data obtained from equation (5) as inputs, estimates the approximate fit to the data points based on the number of poles and zeroes or the order of the transfer function that is selected by the user. Table III shows the order of T(s) that was considered and their respective fit to estimation data and errors.

Table 3. Order of T(s) considered

Order of T(s) [No. of poles in T(s)]	Percentage fit to estimation data (%)	Final Prediction Error (FPE)	Mean Square Error (MSE)
3	42.64	1.653000	1.102000
4	87.54	0.025500	0.009340
5	96.53	0.007507	0.004042

From Table III, a transfer function of fifth order must be chosen as the percentage fit to the estimated data is the highest and it also has the lowest FPE and MSE. Hence, the estimated open loop transfer function T(s) is given by

$$T(s) = \frac{1.823s^3+47.97s^2-371.4s-86.05}{s^5-9.403s^4+74..73s^3-619.4s^2+1336s-944} \tag{6}$$

From T(s) we can use Eq. (2) to (4) to determine C(s), the supplementary controller by pole placement technique [17].

Hence the controller transfer function C(s) is given by

$$C(s) = \left(\frac{s+5.2992}{s+9.6452}\right)^2 \left(\frac{9.0763s}{s^2+5.7691s+14.223}\right) \left(\frac{114.04}{s-0.98198}\right) \tag{7}$$

Dynamic simulation to test the controller performance: After adding the supplementary controller to the HVDC system, cases of dynamic simulation are simulated to check the performance of the controller. Fig. 6 shows the interconnections of the HVDC Pugalur station with its adjacent substations.

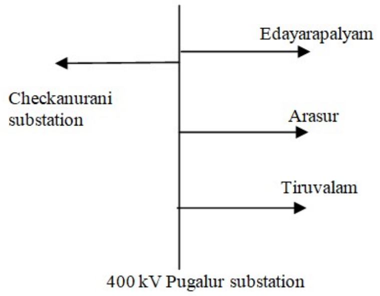

Figure 6. Interconnections between Pugalur and surrounding substations

In each of the following fault cases, the power flow on the 400kVCheckanurani-Tuticorin line is plotted for scenarios with and without the supplementary controller. In each case, the plots clearly indicate that the oscillations have been considerably damped when the supplementary controller is in place, validating its performance.

PSG fault on Pugalur bus and opening of Pugalur - Arasur line: A 3-phase to ground fault is simulated at Pugalur bus for 100 ms. The fault is cleared by disconnecting the Pugalur – Arasur 400 kV line. Without the controller, it is seen from Fig. 7 that the power flow oscillates about 780 MW. The oscillations are slowly getting damped and are present well beyond 10 seconds. It can be concluded that the system is poorly damped. With the controller, it is seen from Fig. 7 that the oscillations are damped, and the system reaches an equilibrium point at about 10 seconds. The supplementary controller provides adequate damping to the system.

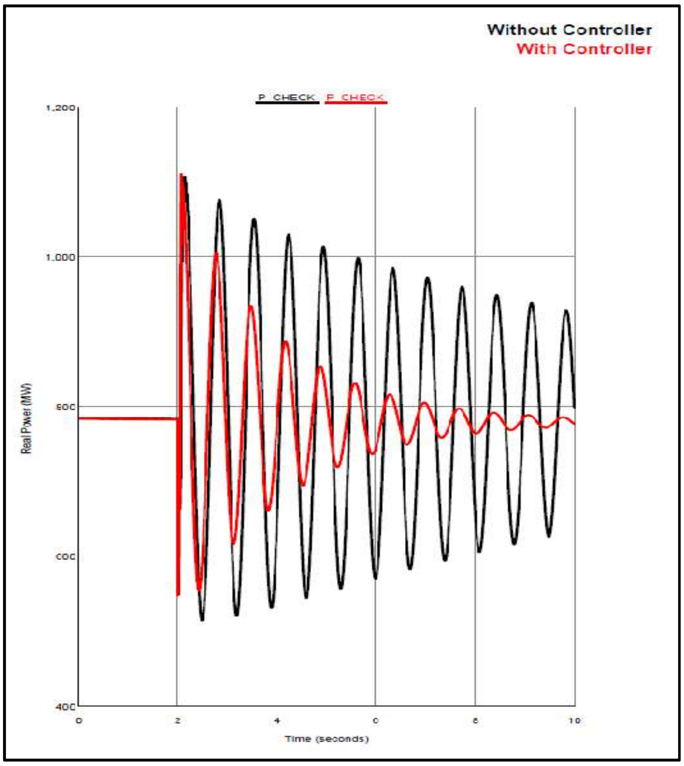

Figure 7. Power flow over Checkanurani-Tuticorin with and without the supplementary controller for Case 1

PSG fault on Pugalur bus and opening of Pugalur - Edayarapalyam line: A 3-phase to ground fault is simulated at Pugalur bus for 100 ms. The fault is cleared by disconnecting the Pugalur – Edayarapalyam 400 kV line. Without the controller, it is seen in Fig. 8 that the power flow oscillates about 780 MW. The damping of the oscillations appears to be negligible. Although the oscillations are stable, any further transients would result in the system losing the oscillatory stability. With the controller, it is seen from Fig. 8 that the oscillations are almost completely damped out and the system reaches an equilibrium point at about 10 seconds. The designed supplementary controller provides excellent damping to the system in this scenario.

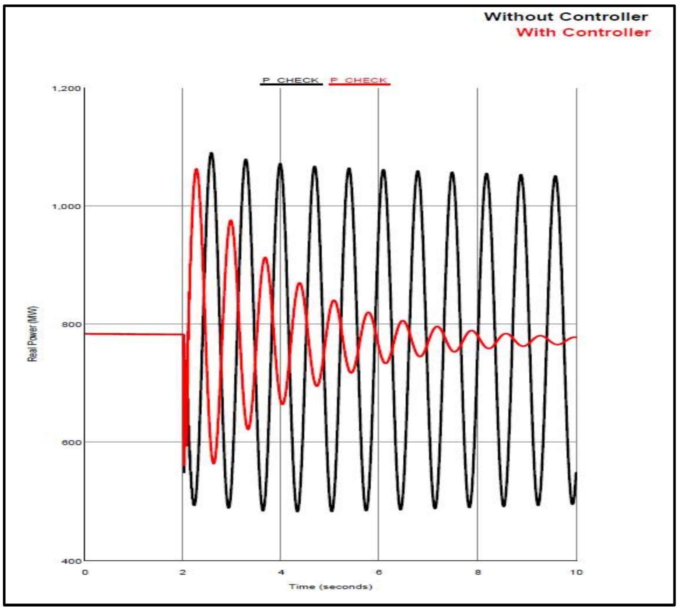

Figure 8. Power flow over Checkanurani-Tuticorin with and without the supplementary controller for Case 2

PSG fault on Pugalur bus and opening of Pugalur – Tiruvalam line: A 3-phase to ground fault is simulated at Pugalur bus for 100 ms. The fault is cleared by disconnecting the Pugalur – Tiruvalam 400 kV line. Without the controller. it is seen in Fig. 9 that the power flow oscillates about 780 MW. The oscillations are slowly getting damped but are present well beyond 10 seconds. It can be concluded that the system is poorly damped. With the controller, it is seen from Fig. 9 that the oscillations are damped, and the system reaches an equilibrium point at about 10 seconds. The supplementary controller provides adequate damping to the system.

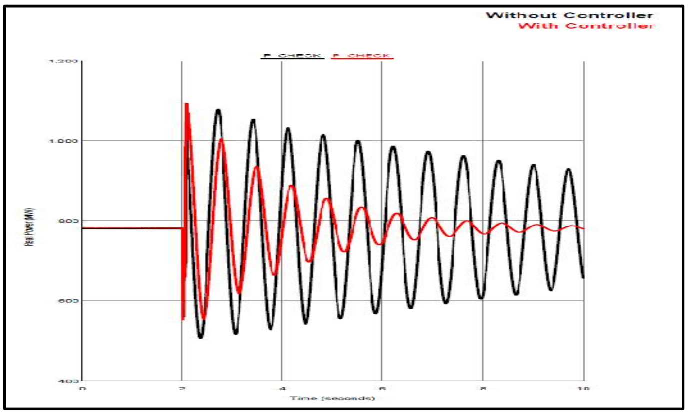

Fig. 9. Power flow over Checkanurani-Tuticorin with and without the supplementary controller for Case 3

CONCLUSION

A novel HVDC supplementary controller using PMU data is proposed in this paper, for damping the power oscillations in the system. The voltage phase angle difference between the two buses (Tuticorin and

Checkanurani) derived from the PMU data is chosen as an input to the controller. Small signal stability analysis is used to determine the low frequency oscillatory modes in the system. The test signal method and the pole placement technique are utilized in designing the parameters for the proposed damping controller. Dynamic simulations in the time domain show that the controller acts in satisfactory manner under fault conditions, validating the controller design.

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