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Research Article

Application of polynomial control to design a robust oscillation-damping controller in a multimachine power system

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ABSTRACT

This paper addresses the application of a static Var compensator (SVC) to improve the damping of interarea oscillations. Optimal location and size of SVC are defined using bifurcation and modal analysis to satisfy its primary application. Furthermore, the best-input signal for damping controller is selected using Hankel singular values and right half plane-zeros. The proposed approach is aimed to design a robust PI controller based on interval plants and Kharitonov's theorem. The objective here is to determine the stability region to attain robust stability, the desired phase margin, gain margin, and bandwidth. The intersection of the resulting stability regions yields the set of k_p–k_i parameters. In addition, optimal multiobjective design of PI controller using particle swarm optimization (PSO) algorithm is presented. The effectiveness of the suggested controllers in damping of local and interarea oscillation modes of a multimachine power system, over a wide range of loading conditions and system configurations, is confirmed through eigenvalue analysis and nonlinear time domain simulation.

1. Introduction

Low frequency oscillations have been observed in the interconnected power systems and impede the purposes of maximum power transmission and optimal power system security. These oscillations may result in serious consequences, such as tripping of the generators and initiating major system blackouts. One of the most important oscillations in the frequency range of 0.1–2 Hz involves many generators in the interconnected system, commonly known as inter-area oscillations [1]. The stability of a power system can be improved by applying an additional feedback control loop in the automatic voltage regulator (AVR) system of selected generating units. This additional controller is called a power system stabilizer (PSS). During the recent years, the fast progresses in the field of power electronics have opened new opportunities for the application of the Flexible AC Transmission System (FACTS) devices as one of the most effective ways to improve both power system controllability and power transfer limits. Shunt FACTS controllers are used in transmission network so as to provide dynamic voltage control and to improve power flow control [2]. As a promising FACTS device, static Var compensator (SVC) is applied to control voltage at the point of connection to the grid, and to maintain bus voltage approximately near to a constant level. In addition to voltage control, if a supplementary damping controller (SDC) is implemented, the SVC could be utilized for damping of electromechanical oscillations. As known, the SDC input signal must be opted accurately to be effective in damping of oscillations. A Residue method is widely exploited based on controllability/observability indices to select the input signal and location of FACTS devices [3]. A technique based on Hankel singular value (HSV) and right half plane zeros (RHP-zeros) for input signal selection has been presented in [4,5]. The RHP-zeros technique investigates various input-output combinations of transfer function zeros in both pre-fault and post-fault conditions whereas the HSV method uses the concept of joint controllability and observability indices. In [6], the relative residue error covariance matrix is calculated for each signal, and then the best stabilization signal associated with the smallest relative residue error covariance matrix is opted. In the present paper, the proper stabilization input signal for the SDC is selected using the HSV and RHP-zeros.

The main problem encountered in the SDC design is that power systems undergo frequent changes in operating conditions. These changes results from variations in the power consumption, generation and transmission device structure, network configuration, and the number of operating generation units. The continuous variation in operating points is the source of structured

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uncertainties in power systems [7]. Robust control theory is a powerful tool that is applied to cope with the uncertainties into account at the controller design process, because such uncertainties are not systemically considered by conventional control methods [8,9]. A multi-objective mixed H_2/H_∞ output feedback control with the regional pole placement to design a wide area robust damping controller has been represented in [3,10]. Application of interval polynomials and Kharitonov's theorem in design of a robust PSS to mitigate low frequency oscillations in the single machine infinite bus and 4-machine-2-area test systems has been presented in [7,11,12]. Soliman (2014) [13] has presented a simple analytical method for computing the set of robust PID and lead–lag controllers based on three-term stabilizing PSSs for a single machine infinite bus test system. Although the results are reliable and the designed PSS can stabilize the power system under a wide range of parametric uncertainties, the test systems are generally easy. In [14–16], application of Kharitonov's theorem has been reported for designing the FACTS devices based on SDC. In [15], Kharitonov's theorem and linear matrix inequality (LMI) approach are applied to characterize a fixed order robust controller for satisfying desired damping. The results in the aforementioned paper demonstrate that the Kharitonov's polynomial method is useful in synthesizing robust and simple power oscillation damping control. In [16], authors use Kharitonov's theorem for designing a robust SVC-SDC that would be able to mitigate electromechanical oscillations in 4-machine-2-area test system. The system under test is very simple and only the load variation is considered as a source of uncertainty. In this paper a robust PI controller considering robust stability and robust performance (desired Gm, Pm, and bandwidth) by illustrating the boundary locus of k_p–k_i plane has been designed. The proposed method is simple and straightforward for the PI controller design. The effectiveness of the proposed controller in damping of interarea oscillations has been tested by the eigenvalue analysis and nonlinear time-domain simulation for a large-scale power system.

2. Kharitonov's stability theory

During the recent decades, remarkable results regarding the stability analysis of uncertain systems have been presented [17,18]. The Kharitonov's theorem provides a necessary and sufficient analysis test for determining the robust stability of polynomials with the perturbed coefficients [19]. The characteristic equation of uncertain system is as follows:

$$P(s)=\sum_{x=0}^{n} a_x\, s^x \quad ,\underline{a_x}\le a_x\le \overline{a_x} \tag{1}$$

where the "_" and "–" show the minimum and maximum bounds of the polynomial coefficients, respectively. The overall system is stable, if and only if the four following Kharitonov's polynomials are Hurwitz.

$$\begin{aligned}
P_1(s)&=\underline{a_0}+\underline{a_1}s+\overline{a_2}s^2+\overline{a_3}s^3+\underline{a_4}s^4+\underline{a_5}s^5+\cdots\\
P_2(s)&=\underline{a_0}+\overline{a_1}s+\overline{a_2}s^2+\underline{a_3}s^3+\underline{a_4}s^4+\overline{a_5}s^5+\cdots\\
P_3(s)&=\overline{a_0}+\underline{a_1}s+\underline{a_2}s^2+\overline{a_3}s^3+\overline{a_4}s^4+\underline{a_5}s^5+\cdots\\
P_4(s)&=\overline{a_0}+\overline{a_1}s+\underline{a_2}s^2+\underline{a_3}s^3+\overline{a_4}s^4+\overline{a_5}s^5+\cdots
\end{aligned} \tag{2}$$

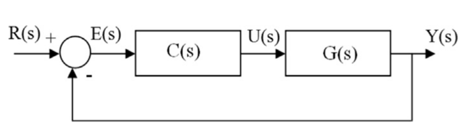

Fig. 1. Uncertain plant with controller.

Fig. 1 shows a single-input single-output (SISO) control system. The plant is represented using transfer function $G(s)=N(s)/D(s)$, which the numerator and denominator are presented by:

$$N(s)=\sum_{x=0}^{m} n_x s^x, \underline{n_x}\le n_x\le \overline{n_x}, \quad D(s)=\sum_{y=0}^{n} d_y s^y, \underline{d_y}\le d_y\le \overline{d_y} \tag{3}$$

A set of sixteen Kharitonov transfer functions can be expressed based on the four Kharitonov polynomials as follows:

$$G_{xy}(s)=\frac{N_x(s)}{D_y(s)}, \quad x,y=1,\ 2,\ 3,\ 4 \tag{4}$$

The fixed parameter PI controller can be assumed to be as : $C(s)=k_p+(k_i/s)=(k_ps+k_i)/s$. The closed loop system presented in Fig. 1 with the PI controller is robustly stable if only if the sixteen characteristic polynomials of the following set are stable [16]:

$$F_{xy}=D_y(s)s+(k_ps+k_i)N_x(s), \quad x,y=1,\ 2,\ 3,\ 4 \tag{5}$$

3. Problem statement

Fig. 2 shows the 68-bus interconnected New York power system and New England test system (NYPS-NETS) [8]. The first eight machines have slow excitation system whereas the ninth one has a fast excitation system equipped with a conventional PSS. All system generators are considered using six-order model. Loads are constant power (CP) loads. The system equations and data are presented in [20] and [8].

3.1. Optimal location and size of SVC

Voltage stability is the capability of a power system to maintain the voltages at all system buses within an acceptable range under normal operating condition and following a disturbance [5]. In this paper, a technique based on modal analysis associated with bifurcation theory is used for analysis of voltage stability. In this technique, using continuation power flow (CPF) method [1,5], the system loads are gradually increased in order to reach the voltage collapse point because of the lack of steady-state solutions arises from system controls reaching limits (e.g., generator reactive power limits). This case is known as limit-induced bifurcations. Then, near this point, the modal analysis is carried out and the weakest system bus according to the eigenvalues of the reduced Jacobian matrix is defined [5]. The main conclusion from this method is that power system cannot support any combination of reactive power demand [5]. Based on QV analysis, the system is voltage stable if all the eigenvalues of Jacobian matrix are positive, and voltage unstable if at least one of the eigenvalues is negative. The smaller the magnitude of the eigenvalue, the closer the corresponding modal voltage is to being voltage unstable [1]. If the eigenvalue is zero the system is on the verge of voltage instability. Therefore, the most associated bus to the worst eigenvalue (smallest eigenvalue) is the best candidate for compensation. Table 1 shows the worst eigenvalues and associated buses of the test system. As can be seen in Table 1, since the eigenvalue associated with bus 64 (λ=1.7209) is the smallest eigenvalue, therefore, bus 64 is the best location for installing SVC to the grid. After determining the best location of SVC, its optimal size will be calculated through minimizing the defined objective function $\sum_{n=1}^{nbus} abs\ (V_n-1)^3$ using PSO algorithm. The main objective is to bring the voltage of all buses approximately near 1 pu. The V_n is voltage of the nth bus and $nbus$ is total number of the system buses. In the proposed objective function, the small voltage deviation becomes negligible while large deviations become relatively larger [5]. Therefore, this objective function will check the improvement of the voltage, only at critical buses resulting from the placement of