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Multi-objective evolutionary algorithm for SSSC-based controller design

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ABSTRACT

In this paper, an evolutionary multi-objective optimization approach is employed to design a static synchronous series compensator (SSSC)-based controller. The design objective is to improve the transient performance of a power system subjected to a severe disturbance by damping the multi-modal oscillations namely; local mode, inter-area mode and inter-plant mode. A genetic algorithm (GA)-based solution technique is applied to generate a Pareto set of global optimal solutions to the given multi-objective optimization problem. Further, a fuzzy-based membership value assignment method is employed to choose the best compromise solution from the obtained Pareto solution set. Simulation results are presented and compared with a PI controller under various disturbances namely; three-phase fault, line outage, loss of load and unbalanced faults to show the effectiveness and robustness of the proposed approach.

1. Introduction

When large power systems are interconnected by relatively weak tie lines, low frequency oscillations are observed. These oscillations may sustain and grow to cause system separation if no adequate damping is available. The frequency of the multi-mode oscillations is commonly classified in the following three main modes; local mode 0.8–1.5 Hz, inter-area mode 0.2–0.8 Hz, and inter-plant mode 1.5–2.5 Hz [1]. The main purpose of designing an optimal controller should be to damp out all these three kinds of oscillation modes. Design of such kind of controller is essentially a multi-objective optimization problem (MOP).

Recent development of power electronics introduces the use of flexible ac transmission systems (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system [2]. The voltage sourced converter-based series compensator, called static synchronous series compensator (SSSC) provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the system [3]. An auxiliary stabilizing signal can also be superimposed on the power flow control function of the SSSC so as to improve power system oscillation stability [4]. Applications of SSSC for power oscillation damping, stability enhancement and frequency stabilization can be found in several references [5–8]. The influence of degree of compensation and mode of operation of SSSC on small disturbance and transient stability is also reported in the literature [9,10]. Most of these proposals are based on small disturbance analysis that required linearization of the system involved. However, linear methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for tuning the FACTS-based controllers in that the controllers tuned to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances. Further, unbalanced fault analysis cannot be performed using the single-phase models. To overcome the above, three-phase model have been used in the present study and the controller is tuned for large disturbance.

Owing to the diverse frequency ranges and multiple objectives, an optimal controller that simultaneously minimizes all the three modes of oscillations is usually not attainable. One approach to design the optimal controllers is the classical weighted-sum approach where the objective function is formulated as a weighted sum of the objectives. But the problem lies in the correct selection of the weights to characterise the decision-makers preferences. In recent years, the multi-objective problems are solved to find non-inferior (Pareto-optimal, non-dominated) solutions. The most widely used methods for generating such non-inferior solutions are the weighting method, ε-constraint method and weighed min–max method. The decision maker has to choose the best compromise solution from the obtained solution set.

In this paper, genetic algorithm (GA)-based method is adapted for generating Pareto solutions for designing a SSSC-based con-

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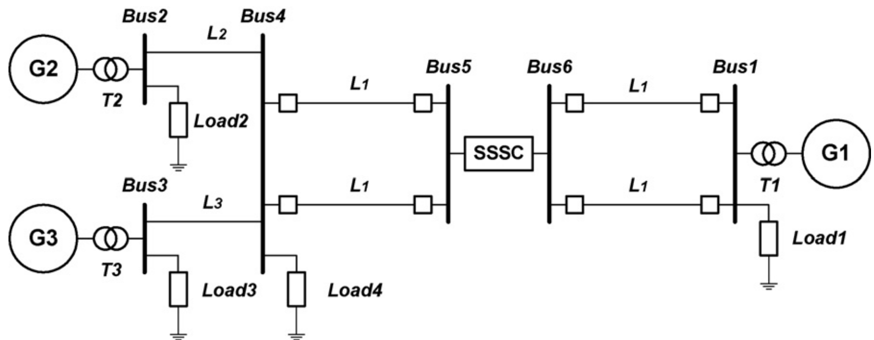

Fig. 1. Three-machine power system with SSSC.

troller. The design objective is to improve the transient performance of a power system subjected to a severe disturbance by minimizing all the modal oscillations with respect to a post-contingency equilibrium point for a power system installed with a SSSC. The main motivation for using GA is for the reason that it deals simultaneously with a set of possible solutions (the so-called population) which allows the user to find several members of the population. Additionally, GAs are less susceptible to the shape or continuity of the Pareto front as they can easily deal with discontinuous and concave Pareto fronts, whereas these two issues are known problems with mathematical programming [11]. A fuzzy-based approach is applied to select the best compromise solution from the obtained Pareto set. Simulation results are presented and compared with a PI controller under various disturbances to show the effectiveness and robustness of the proposed approach.

2. System under study

The multi-machine power system with SSSC shown in Fig. 1 is considered in this study. It is similar to the power system used in references [12,13]. The system consists of three generators divided in to two subsystems and are connected through an inter-tie. The generators are equipped with hydraulic turbine and governor (HTG) and excitation system. The HTG represents a nonlinear hydraulic turbine model, a PID governor system, and a servomotor. The excitation system consists of a voltage regulator and DC exciter, without the exciter's saturation function. Following a disturbance, the two subsystems swing against each other resulting in instability. To improve the stability the line is sectionalized and a SSSC is assumed on the mid-point of the tie-line. In Fig. 1, G_1, G_2 and G_3 represent the generators; T_1, T_1 and T_3 represent the transformers and L_1, L_2 and L_3 represent the line sections respectively. The relevant data for the system is given in Appendix A.

A SSSC is a solid-state voltage sourced converter (VSC), which generates a controllable AC voltage, and connected in series to power transmission lines in a power system. SSSC provides the virtual compensation of transmission line impedance by injecting the controllable voltage (V_q) in series with the transmission line. V_q is in quadrature with the line current, and emulates an inductive or a capacitive reactance so as to influence the power flow in the transmission lines. The virtual reactance inserted by V_q influences electric power flow in the transmission lines independent of the magnitude of the line current [2]. The variation of V_q is performed by means of a VSC connected on the secondary side of a coupling transformer. The compensation level can be controlled dynamically by changing the magnitude and polarity of V_q and the device can be operated both in capacitive and inductive mode [14,15]. The VSC uses forced-commutated power electronic devices to produce an AC voltage from a DC voltage source. A capacitor connected on the DC side of the VSC acts as a DC voltage source. To keep the capacitor charged and to provide transformer and VSC losses, a small active power is drawn from the line.

VSC using IGBT-based PWM inverters is used in the present study. However, as details of the inverter and harmonics are not represented in power system stability studies, the same model can be used to represent a GTO-based model.

3. The proposed approach

3.1. Structure of SSSC-based damping controller

The commonly used lead–lag structure shown in Fig. 2 is chosen in this study as a SSSC-based controller to modulate the SSSC injected voltage V_q. The lead–lag structure is preferred by the power system utilities because of the ease of on-line tuning and also lack of assurance of the stability by some adaptive or variable structure techniques. The structure consists of a gain block with gain K_S, a signal washout block and two-stage phase compensation block. The signal washout block serves as a high-pass filter, with the time constant T_W, high enough to allow signals associated with oscillations in input signal to pass unchanged. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range of 1 to 20 s [1]. The phase compensation blocks (time constants T_{1S}, T_{2S} and T_{3S}, T_{4S}) provide the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. In Fig. 2, V_{qref} represents the reference injected voltage as desired by the steady state power flow control loop. The steady state power flow loop acts quite slowly in practice and hence, in the present study V_{qref} is assumed to be constant during the disturbance period. The desired value of compensation is obtained according to the change in the SSSC injected voltage ΔV_q which is added to V_{qref}.

3.2. Problem formulation

The transfer function of the SSSC-based controller is:

$$U_{SSSC} = K_S \left(\frac{sT_W}{1+sT_W} \right) \left(\frac{1+sT_{1S}}{1+sT_{2S}} \right) \left(\frac{1+sT_{3S}}{1+sT_{4S}} \right) y \quad (1)$$

where U_{SSSC} and y are the output and input signals of the SSSC-based controller respectively.

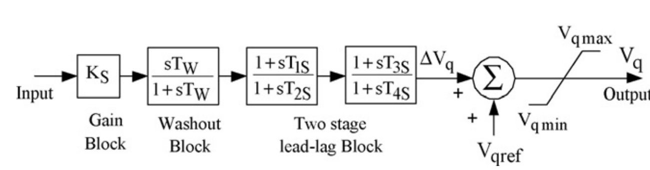

Fig. 2. Structure of SSSC-based controller.