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Enhancing small signal power system stability by coordinating unified power flow controller with power system stabilizer

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Abstract

Advancement of power electronic technologies makes ac systems to be more adaptive and flexible as new forms of power controller emerges in recent years. Though not yet well developed, underpinned research suggests that unified power flow controller (UPFC) is a promising power system controller. This paper proposes a method to coordinate UPFC with power system stabilizer (PSS) so as to damp down oscillations caused by small signal disturbance. It starts by deriving a mathematical model of UPFC, with which its linearized differential equations are integrated to design an overall control strategy for enhancing small signal stability of the so connected power systems. The approach is to identify the eigenvalue of the largest real part and then minimize it as a nonlinear optimization problem. In order to ensure the robustness of the control system, different operating conditions are simultaneously considered in the parameter optimization process. Results of a case study on the New England test system show that the model is correct and the method is promising for coordinating the model parameters to enhance the small signal stability of the complex power system.

Keywords: Flexible AC transmission system; Unified power flow controller; Power system stabilizer; Small signal stability; Eigenvalue analysis; Parameter optimization

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1. Introduction

The loadability of large interconnected power systems is often degraded due to their poor damping ability especially on low frequency oscillations. It is, therefore, desirable for the systems to achieve higher operational margin and to enhance power control capability by using the state-of-art power electronic technologies [1–9], such as Static Var Compensation and Thyristor Controlled Series Capacitor. These can be regarded as early forms of devices for realizing the flexible AC transmission systems (FACTS) concept, which can most, be generalized in the form of unified power flow controller (UPFC) [9]. Though not yet well developed, effects of using UPFC for improving transient stability are presented in [10–12] and it has also been proved to be effective for damping power system oscillation by employing UPFC's three independent dimensions of control, namely, in-phase voltage control, quadrature voltage control and shunt compensation. However, extension of the study to a highly nonlinear multi-machine system is still constrained by its need to reduce the power system as a single-machine to infinite-bus model. A case to mitigate the torsion mode of power system oscillation is reported in [13]. The instantaneous active and reactive power flown through the UPFC embedded transmission line and the voltage amplitude of the UPFC connected busbar are introduced as three differential state variables for small signal analysis in [14] and a case study for a seventh-order autonomous system consisting of three generators and one UPFC is performed as well. Research result for finding damping function of UPFC for single-machine-to-infinite-bus power system is reported in [15] and that for multi-machine power systems by the same author is reported in [16]. It is found that basic control of the UPFC, through its voltage control of the DC link capacitor,

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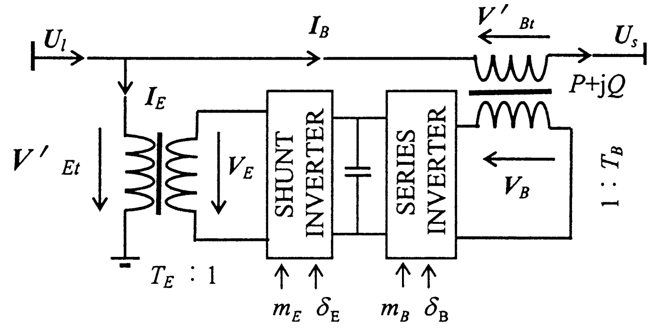

Fig. 1. Schematic diagram of UPFC.

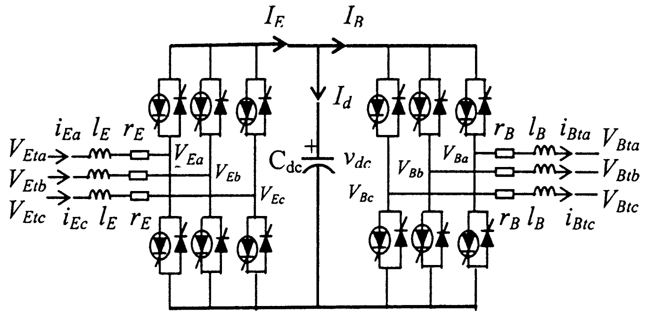

Fig. 2. The three-phase equivalent circuit of UPFC refered to converter side.

interacts negatively with the power system stabilizer (PSS) installed in the system.

Functionally, the method proposed in this paper intermingles the traditional linear optimal control with the sensitivity analysis techniques making it possible for determining both the feedback matrix and the control parameters at the same time. Based on the Lyapunov's asymptotic stability theory, all eigenvalues of the system should be positioned as far away to the left hand half complex-plan as possible for having higher stability margin. It leads to the following optimization problem:

$$\text{Objective:}\quad \sigma^* = \min_{T}\left\{\max_{i,j}[\sigma_{ij}(\mathbf{T})]\right\} \quad i = 1, 2, \ldots, n_Z;$$
$$j = 1, 2, \ldots, n_c$$

$$\text{Subject to:}\quad c_L \leqslant \mathbf{T} \leqslant c_U \tag{1}$$

where the vector $\mathbf{T} \in \mathbf{R}^{n_t}$comprises all the controllable parameters with the constant vector c_L and c_U as lower and upper limits of $\mathbf{T}$ respectively and n_Z is the order of the system matrix.

In order to ensure the robustness of the control parameters, a set of operating conditions, n_c, is properly selected and taken into consideration simultaneously in the optimization problem (Eq. (1)). σ_{ij} is the real part of the ith eigenvalue at the jth operating condition. Hence, it can be seen that the optimal solution, $\mathbf{T}^*$, minimizes the real part of the eigenvalue whose real part is the largest one among all $n_Z \times n_C$ eigenvalues. In other words, the minimization process will force all eigenvalues to move toward the left hand half of the complex-plan and as far away from the imaginary axis as possible at any operating condition, j, and thus it makes the system perform better when having small signal disturbance. A dynamic UPFC controlled power system model and its control functions are also derived in Sections 2–4. The approach of finding the solution of the problem (Eq. (1)) is discussed in Section 3 and the application case study is given in Section 6.

2. Mathematical model of UPFC

Fig. 1 and Fig. 2 show respectively a schematic and a three-phase single line diagram of the UPFC developed in [9] and [13].

When the sinusoidal pulse width modulation (SPWM) scheme is adopted and only fundamental frequency components under balanced operating conditions are considered, output voltages of the two converters of UPFC can be equivalented by two ideal three-phase voltage sources [13], V_{Ea}, V_{Eb}, V_{Ec}, V_{Ba}, V_{Bb}, and V_{Bc}, which can be represented by two phasors:

$$V_E = \frac{1}{2\sqrt{2}} m_E v_{dc} \angle \delta_E \quad m_E \in [0, 1] \tag{2}$$

$$V_B = \frac{1}{2\sqrt{2}} m_B v_{dc} \angle \delta_B \quad m_B \in [0, 1] \tag{3}$$

where m_E and m_B denote the modulation index of the shunt and series converter respectively and δ_E and δ_B are the phase angles of the control wave.

In a quasi-steady-state condition, the relationship of the voltages and currents in the exciting transformer (ET), the boosting transformer (BT) and the two sides of the converter valves can be represented by algebraic functions, whereas the equation on the DC side of the converters is differential. The algebraic equations can be directly written in single phase equivalent since the quasi-static state condition is assumed and UPFC is a static element rather than a rotating one. With reference to Fig. 2, the equations of the UPFC can be written as

$$(r_E + j\omega l_E) I_E = V_{Et} - V_E \tag{4}$$

$$(r_B + j\omega l_B) I_B = V_B - V_{Bt} \tag{5}$$

$$C_{dc} v_{dc} \frac{dv_{dc}}{dt} = 3\, Re[V_E I_E^* - V_B I_B^*] \tag{6}$$

where r_E and r_B are the equivalent resistance of the transformer and the switch-on state valve conduction losses in the exciting and boosting sides respectively, while ωl_E and ωl_B are the respective equivalent leakage reactance of the ET and BT.