論文の内容の要旨

論文題目　Application of Interline Power Flow Controller (IPFC) to Optimal Power Flow Control and Stability Enhancement in Power Systems
（送電線間潮流制御装置（IPFC）による電力系統最適潮流制御と安定度向上制御）

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The recent request for better utilization of existing transmission networks and the constant demand of modern society for more flexible, controllable, and stable power systems have afforded great opportunities for the application of the Flexible AC Transmission System (FACTS) devices. With the availability of the fully controlled semiconductors such as the gate turn-off thyristor (GTO) and the insulated gate bipolar transistor (IGBT) etc getting more and more economical, the voltage-sourced converter (VSC)-based FACTS devices have become more realistic choices for the power industries than ever before. The VSC-based interline power flow controller (IPFC) was first proposed in 1998, as the latest component of FACTS device family. Its unique capability of simultaneously compensating multiple transmission lines at a given substation has since aroused great interest of researchers and power industries around the world. This dissertation presents a study on the application of IPFC to optimal power flow (OPF) control and stability enhancement in deregulated power systems.

Like Unified Power Flow Controller (UPFC), the IPFC is a kind of combined compensators, in which at least two Static Synchronous Series Compensators (SSSCs) are combined via a common DC voltage link. If there is no energy storage system installed in the apparatus, this DC voltage link is usually modeled as a DC capacitor. It is this link that provides the IPFC with the path through which different transmission lines can exchange active and reactive power. In both steady-state analysis and rotor angle stability analysis, the VSC of IPFC can be modeled as a series voltage source injecting an almost sinusoidal voltage with controllable magnitude and angle. In order to study the effect of inclusion of the IPFC in power systems by numerical simulation, proper mathematical modeling of IPFC is necessary and very important. Based on the equivalent circuit of IPFC, various power injection models have been developed by the author, in which the voltage sources are removed and the impact of IPFC is represented by active and reactive power injections at the buses connecting to IPFC series transformers. These power injections can be expressed by system variables and IPFC variables. According to different purposes of IPFC application, different control strategies are adopted, and accordingly, the VSCs are represented by different sets of variables, such as controllable magnitudes and angles of injected voltages, and controllable injected voltage components perpendicular to each other, etc. In the dissertation, power injection models of IPFC in steady state analysis, transient stability analysis, and small-signal stability analysis are proposed respectively. Here the IPFC is assumed to generate or absorb no active power.

First, investigation of IPFC steady state operation and some comparison with the performance of UPFC in steady state is carried out. Three possible applications of IPFC to optimal OPF control have been explored, namely congestion management, power flow regulation, and available transfer capability (ATC) enhancement. By using the IPFC power injection model in steady state analysis, we can know that IPFC is a powerful tool for congestion management. It is shown that based on the multi-objective OPF control method, congestion can be resolved by the application of IPFC without generation redispatching, while the simultaneous optimization of both the total active power loss and IPFC capacity is achieved. It is also shown in numerical examples that both the UPFC and the IPFC are powerful tools for power flow regulation. Combined with generating bus voltage adjustment, the OPF incorporating either FACTS device can effectively minimize the overall generating cost without active power generation redispatching.

Due to the necessity of a relatively large shunt VSC, the capacity of the UPFC is usually significantly larger than that of the IPFC to achieve a similar or the same effect of the same goal, even when the series VSCs and their corresponding constraints are exactly same. The IPFC also demonstrates its superiority over UPFC in efficiency in its application to ATC enhancement. All the OPF control problems in this dissertation are solved by the sequential quadratic programming (SQP) method.

Based on the energy function analysis, the operation of IPFC should guarantee that the time derivative of the global energy of the system is not greater than zero in order to damp the electromechanical oscillations. Accordingly, control laws of IPFC are proposed for its application to the single-machine infinite-bus (SMIB) system and the multimachine systems, respectively. By using the IPFC power injection model in transient stability analysis, numerical simulations on the corresponding model power systems are presented to demonstrate their effectiveness in improving power system transient stability.

This dissertation also evaluates the damping effect of the PI controller, which is originally for constant power flow control, and modal analysis of the power system is carried out. Then the pole shifting technique is adopted to stabilize the oscillatory mode having insufficient damping ratio by use of a PSS-type supplementary damping controller. The design process of the supplementary damping controller and the selection of input signal according to the mode observability are presented. By using the IPFC power injection model in small-signal stability analysis, numerical simulations demonstrate that the IPFC with the above control system is an effective tool to damp power oscillations. In the comparison between IPFC and UPFC in this part, the IPFC demonstrates its superiority over UPFC in both efficiency and effectiveness in damping of power flow oscillation and rotor swing. Numerical results are in line with the respective characteristics of series and shunt VSCs.

Finally this dissertation develops a detailed dynamic model of IPFC suitable for power system electromechanical stability analysis. The dynamic equation of the DC capacitor is derived and the effect of a PI-type DC voltage regulator on small-signal stability enhancement is analyzed. Quantitative analysis demonstrates that with proper control of the DC capacitor voltage and a large enough DC capacitor, variation of the DC capacitor voltage is very small during power oscillations. Therefore active power exchange between IPFC and the rest of power systems is very little. Thus the proposed power injection models are verified. In this part, eigenvalue sensitivity based parameter optimization technique has bee adopted for PI controller parameter tuning.

Thus, modeling, simulation and application of IPFC in power networks have been fully explored.