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Dynamic control of unified power flow controller under unbalanced network conditions

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ABSTRACT

The effective and reliable use of existing transmission lines are critically important because high-voltage transmission networks met enormous power demands are very expensive investments in terms of their costs. Flexible Alternating Current Transmission Systems (FACTS) are quite efficient to control the power flow of the transmission lines and increase the current capacity of system. Unified Power Flow Controller (UPFC) is the more efficient among FACTS equipments which have the potential to increase the power flow and stability of the transmission line. This paper develops new control approaches for both series and shunt inverters of UPFC. The proposed controller algorithms of shunt and series inverters are based on fuzzy logic controller and rotating orthogonal-coordinate method, respectively. Dynamic control of power flow using proposed UPFC is analyzed as mathematically. Power System Computer-Aided Design (PSCAD) is used to simulate the system and test UPFC in the simulation environment. The test results are presented to show the increased stability of the system and improved dynamic response of UPFC during faults occurred in the transmission line.

1. Introduction

The construction of new generating units and transmission networks become more difficult because of economic and environmental reasons. Power utilities are compelled to benefit from existing generating units and to bring closer existing transmission lines to their thermal limits. The stability of the power system has to be maintained permanent even in the case of contingency conditions such as loss of transmission lines or generating units [1]. Novel control strategies are needed to be implemented in order to operate the power system effectively without reduction in security of the system and quality of supply. In the late 1980s, a new technology program known as Flexible Alternating Current Transmission System (FACTS) was presented by Electric Power Research Institute [2]. The idea of FACTS technology is to increase controllability and to optimize the utilization of the existing power system capacities using the reliable and high-speed power electronic devices instead of mechanical controllers. FACTS technology opens up new opportunities for controlling the power and enhancing the usable capacity of the present transmission systems. The opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems, which includes the series/shunt impedances, current angle, phase angle and damping of oscillations at various frequencies below the rated frequency. These constraints cannot be overcome otherwise, while maintaining the required system stability, by mechanical means without decreasing the transmission capacity. By proving added flexibility, FACTS controllers can enable a line to carry power closer to its ratings [1].

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The basic system parameters affecting the active/reactive power flows in the transmission line (i.e. line voltage (*V*), line current (*I*), line impedance (*V*/*I*) and phase angle (between *V* and *I*)) have been controlled separately by using mechanical devices such as Static VAR Compensator (SVC), Thyristor Controlled Reactor (TCR), etc., until UPFC was introduced.

UPFC is a combination of Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC), which is coupled via a common DC link and controllable phase shifting transformer [3]. This arrangement functions as an ideal AC to AC power inverter in which the active power can freely flow in either direction between the AC terminals of two inverters and each inverter can independently generate or absorb reactive power at its own AC output terminal. UPFC is able to control concurrently or selectively the transmission line voltage, line impedance, phase angle and alternatively active/reactive power flows in the line by means of angularly unconstrained series-injected voltage [4]. UPFC can provide simultaneous, fast and independent control of these system parameters.

Unbalanced faults, motor starting, overhead lines/cables and transformer faults, causing to the increasing large level of current in a short time in the power systems, result in the unbalanced network conditions [5]. The unbalanced network conditions such as voltage drop, high inrush current, a low lagging power factor, voltage sag/swell and unbalanced voltage are defined by standards of IEEE 1149. A three-phase fault leads to an equal drop in voltage in all three phases. Nonsymmetrical faults lead to drops in one, two or three phases, with not all phases having the same drop. The resulting voltage drops and phase-angle shifts depend on a number of factors. A short duration increase in the current somewhere of a system, for instance, during faults, motor starting and power transformer energizing, causes the voltage sag. Voltage swell is not as common as voltage sag and its main causes are the switching-off of large loads, energizing a capacitor bank, voltage increase of unfaulted phases during a single line-to-ground fault and reversed power somewhere in the distribution systems [6].

The modeling and controlling of UPFC have come into intensive investigation in recent years due to its attractive features. Several references in the literature focused on development of steady state, dynamic and linearized models of UPFC. In [7–9], steady state model, which is necessary to analyze the power flow operation of device embedded in a power system, is preferred. In [4], Ann based direct control algorithm method is used. The used UPFC model is simple and helpful to understand the impact of UPFC in the power system. However, the amplitude modulation and phase-angle control signals of the series voltage source inverter (VSI) have to be adjusted manually in order to find the desired load-flow solution. In [10], vector-control method proposed by Schauder and Mehta [11] is used. The decoupled control of the active/reactive powers can be applied easily in this method and it is suitable for UPFC applications. The decoupled control can be achieved by changing the three-phase balanced system into a synchronously rotating orthogonal system (*DQ* transform). *D*-axis current component coincides with instantaneous active power and *Q*-axis current coincides with reactive power in this coordinate system. This control scheme can be applied to control the series and shunt inverters as in [12–14]. Proportional-Integral (PI) controller is used to obtain the parameters of system dynamics that are close to their reference values. The bus voltage of sending-end and DC link voltage are measured to generate reference system currents in [11,12,15,16]. Another approach is automatic power flow method based on *DQ* transform in [17]. DC link and sending-end voltage are measured and taken as reference value for shunt inverter. Active/reactive powers of the line are measured and taken as reference value for series inverter as in [17–19]. The reference value of system dynamics should be pre-specified (i.e. reference value of active/reactive powers, reference value of DC link voltage, etc.) to obtain the desired result. The linearized model of UPFC applications are examined in [20,21]. It is practical for small-signal analysis and damping-controller design. The effect of UPFC on transient stability enhancement of a longitudinal system is analyzed in [3]. To utilize UPFC possibilities fully, the three controllable UPFC parameters were determined during the digital simulation process performed.

Refs. [22–24] has proposed to linearize the differential–algebraic equation network and eliminate the algebraic equations through reduction methods. Then, linear control methods are applied to the linearized power system in [25]. This approach, however, tacitly assumes that the network variables remain in the neighborhood of the desired operating point. A single-machine infinite bus model is used to apply nonlinear control schemes in [26–28]. However, the infinite bus assumption required for this approach is not valid for large multi-machine systems when the fault affects the power system [25]. FACTS devices have been considered in [29,30] via utilizing energy functions to develop the controllers and estimate the critical clearing time. This approach is not practical to develop the controllers because it requires the calculation of bus voltage and phase angle derivatives and also requires numerical differentiators and approximations. Several authors have investigated utilizing the UPFC to damp interarea oscillations utilizing a variety of control approaches. Some of this research is based on a linear control analysis of the UPFC and power system, whereas other authors consider nonlinear control systems theory and Lyapunov energy functions [31].

As another approach, Fuzzy Logic Controller (FLC) and Neural Network (NN) based controller are used with several control methods in control of UPFC [32–36]. FLC does not require the mathematical model of the system under transient and steady-state conditions. It can cover wide range of operating conditions and is simple to implement. PI and FLC are used together in the current injection model in [33,34].

In general, control strategy of UPFC should have preferably the following attributes:

- New reference extraction method based on *DQ* algorithm is proposed for series inverter of UPFC.
- Both DC link and sending-end voltages are controlled with FLC separately in the shunt inverter. Assignment of the optimum control rules in the error-phase plane is presented.
- The improvement of dynamic stability using appropriate controller references is achieved and tested with case studies.