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Sliding mode active and reactive power decoupled control for Distributed Power Flow Controllers

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ABSTRACT

Unified Power Flow Controllers (UPFC) are one of the most useful Flexible AC Transmission Systems (FACTS). They can be used for power flow control in AC transmission grids, allowing simultaneous control of the bus voltage and line active and reactive power. However, due to high costs and reliability concerns, UPFCs have experimented limited use in such applications. Recently, the concepts of Distributed FACTS (DFACTS) and Distributed Power Flow Controller (DPFC) have been introduced as a low cost, high reliability alternative for power flow control. However, DPFCs present cross-coupled (interdependent) and limited regulation of active and reactive power. Therefore, this paper contributions include: (1) a third-harmonic output voltage controller for a full-bridge converter, able to extract active power from third-harmonic currents, to maintain the converter DC voltage constant; (2) DPFC sliding-mode controllers to simultaneously inject active and reactive power at the fundamental frequency, to achieve cross-decoupled (independent) control of active and reactive power flow; (3) applying the sliding mode controlled DPFC to a part of the Portuguese distributed generation and transmission network under study. To provide the required active power to each DPFC device, a PI controlled full-bridge converter acting as a virtual resistance is proposed to extract active power from zero-sequence harmonic frequency currents injected into the line. DPFC models including semiconductor switching, together with line transmission models, were simulated in Matlab/Simulink environment and in PSCAD for comparison purposes. Simulations results show the effectiveness of the full-bridge converter sliding mode controllers in decoupling P and Q control while simultaneously extracting active power from the injected zero-sequence injected currents.

1. Introduction

Nowadays it is essential to improve the performance of power lines and the optimization of power flow on existing lines. Flexible AC Transmission Systems (FACTS) offer the possibility of power flow control both in static and dynamic conditions, improving transmissions systems [1]. FACTS devices can be inserted in existing transmission lines to achieve control functions, including enhancement of power transfer capacity, decrease line losses and generation costs, and increase the stability and security of the power system [2,3].

The most powerful and versatile FACTS device is the Unified Power Flow Controller (UPFC), proposed by L. Gyugyi in 1992 [4,5]. It uses solid-state power semiconductors and can be used for power flow control, improvement of transient stability and damping oscillations or active filtering [6,7]. With a UPFC it is possible to control a local bus voltage and active and reactive power flows of a transmission line. The UPFC series converter may have also other control modes such as direct voltage injection, phase angle shifting and impedance control modes [5].

A UPFC consist of two AC–DC converters, a Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC), connected back to back via a common DC link allowing active power exchange between them. Both converters AC sides are connected to the transmission line through coupling transformers. The line series converter performs as a synchronous AC-voltage source, providing the main function of the UPFC, by injecting a controllable voltage vector, while the shunt converter acts as a synchronous source, controlling the voltage of the DC capacitor (U_{dc}). Fig. 1 illustrates the simplified diagram of UPFC.

Although FACTS devices offer several benefits, they have not seen widespread commercial acceptance due to a number of

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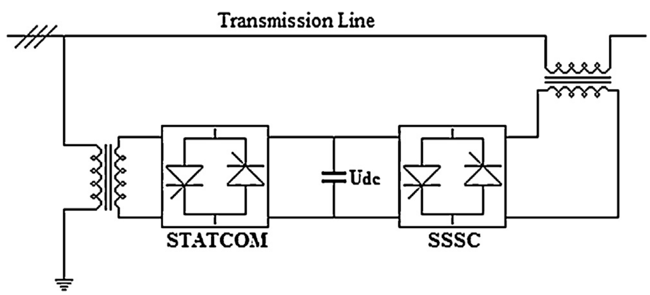

Fig. 1. Simplified diagram of UPFC.

reasons [8]: (i) high system power ratings require the use of custom high power devices; (ii) high fault currents and basic insulation requirements stress the power electronics system; (iii) utilities require higher reliability levels than they have experienced with FACTS devices so far; (iv) required skilled work force in the field to maintain and operate the system; (v) High total cost of ownership.

Recently, the concept of distributed FACTS devices (DFACTS) has been proposed as an alternative approach for realizing the functionality of FACTS devices [8,9]. Although being a lower cost and higher reliability solution, the Distributed Static Series Compensator (DSSC), presented in Fig. 2, can only adjust the line impedance and is not as powerful as UPFC, since it has no power source to inject active power and therefore cannot decouple the control of active and reactive power.

To achieve the same functionality as the UPFC, a new concept of Distributed Power Flow Controller (DPFC), that combines conventional FACTS and DFACTS, has been proposed [10,11]. The DPFC is derived from the UPFC but eliminates the common DC link between the shunt and series converters. As UPFCs, DPFC devices give the possibility to control system parameters, such as line impedance and power angle.

In [12] a controller for a DPFC able to control active and reactive power flow in static and dynamic conditions was presented and a DPFC converter topology was proposed using three single-phase half-bridge legs sharing a common DC bus subdivided by two capacitors.

In contrast to [12], this paper uses just a single phase full-bridge converter as a simpler DPFC series converter, thus reducing the number of semiconductors, and proposes new sliding-mode controllers allowing cross-decoupled control of active and reactive power flow. To provide the required active power to all DPFC devices, third-harmonic currents are injected into the line and a PI controlled virtual resistance is proposed for the DPFC full-bridge converter to extract active power from the third harmonic currents. Switched state-space models suited for control design are obtained

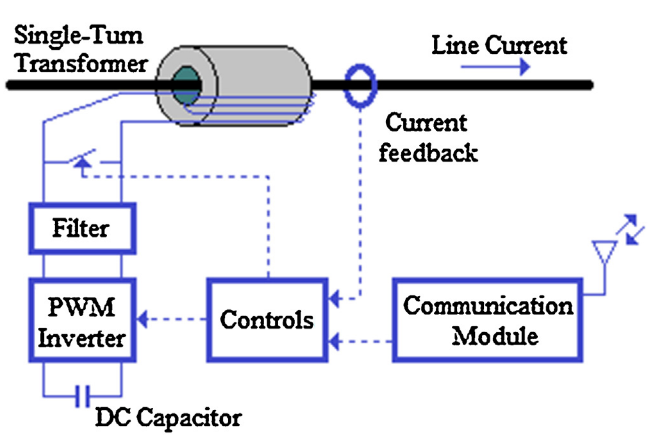

Fig. 2. Circuit schematic of a DSSC module.

in Section 2. The designed controllers (Section 3) are tested (Section 4) using the DPFC switched state-space models including semiconductor switching and line transmission models implemented with SimPowerSystems blockset and validated in PSCAD. Simulations results show the ability of the full-bridge converter sliding mode controllers to decouple P and Q power flow while simultaneously extracting active power from the injected zero-sequence injected currents.

2. Distributed Power Flow Controller

As UPFC, DPFC devices can be inserted in existing transmission lines to achieve power flow control. The DPFC uses multiple small-size single-phase converters, distributed in series with the transmission line, cooperating together to allow cross-decoupled control of active and reactive power flow. Each DPFC device injects a relatively small controllable voltage vector to vary the transmission angle and line impedance and consequently control the power flow through the line. The use of a large number of DPFC devices provides increased system reliability due to high number and redundancy of the series converters. Each converter within the DPFC is independent and has its own DC capacitor to provide the required DC voltage for the bridge AC converter. Fig. 3 illustrates the configuration of a transmission line with DPFC devices.

To provide independent control of active and reactive power (as in the UPFC) it is necessary to supply active power to all DPFC devices, ensuring the steadiness of the DC capacitor (U_{dc}) voltage. So, in order to eliminate the common DC link of UPFC, in this paper it is proposed that the required active power is transmitted to all devices through the line by injecting a zero-sequence third-harmonic current. Since active power at different frequencies is isolated from each other and zero-sequence line currents can be canceled in a transformer, it is possible to DPFC devices to absorb active power at third-harmonic frequency and release it at the fundamental frequency. Fig. 3 illustrates the power flow diagram in a transmission line with DPFC devices, where each DPFC device handles active and reactive power at fundamental frequency and active power at third-harmonic frequency. The required active power needed by DPFC devices can be supplied by a conventional controlled voltage source shunt converter, as described in [10], represented in Fig. 3 as a third-harmonic current source (I_{3h}).

As illustrated in Fig. 3, the transmission line carries both the current at fundamental and third-harmonic frequency. In order to block the harmonic which carries the active power transmitted to DPFC devices, zero sequence harmonic is selected, since the most widely used transformer in power systems is Y-Delta transformer, which has the capability to block the zero-sequence component naturally, preventing the harmonic leakage to the rest of the network.

2.1. DPFC converter model

The proposed DPFC series converter topology, consisting of a single-phase full-bridge converter, is presented in Fig. 4. Each of the two legs of the converter shares the common DC bus provided by the DC capacitor voltage v_C ($v_C \approx U_{dc}$), allowing the converter to deliver one of three possible voltages levels U_{dc}, 0 or $-U_{dc}$.

2.2. Switching variables

Assuming power semiconductors as ideal switches, each converter leg can be represented by the switching variable γ_k ($k \in \{1,2\}$), and each switch represented by the control variable S_{ki}. While each switch has two possible states, *ON* ($S_{ki} = 1$) or *OFF* ($S_{ki} = 0$), to guarantee the topological constraints of this converter, for each leg the switching strategy must ensure complementary