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A new topology of the distributed power flow controller and its electromagnetic transient characteristics

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ABSTRACT

In this paper, the modular multilevel converter (MMC) is introduced into the shunt side of the distributed power flow controller (DPFC), and a new topology of distributed power flow controller is constructed. The mathematical models are developed, in these models the internal energy relationship between the MMC module and the single-phase converter in the shunt side, as well as between the shunt-side single-phase converter and series-side single-phase converter are considered, and the corresponding control strategies are proposed based on the mathematical models. The internal electromagnetic transient characteristics of the MMC based DPFC are studied in PSCAD/EMTDC. The simulation results show that the MMC based DPFC is able to adjust the control variables such as voltage amplitude, phase angle and line reactance of the power system individually or simultaneously, and also the DPFC is able to respond to the power flow regulation demand effectively.

1. Introduction

The principle topology of the distributed power flow controller (DPFC) is shown in Fig. 1. The DPFC consists of two parts, the shunt side converters and the series side converter. The shunt side converters are installed in the transmission substation, consisting of a three-phase voltage source converter, VSC1, and a single-phase voltage source converter, VSC2. VSC1 has two functions. One is to inject reactive power into the system to maintain the system bus voltage, $\dot{V}_s$, at the setting value. The other is to absorb the active power from the system to maintain the shunt side converter DC capacitor voltage, V_{dcsh}, at a constant value, and to inject the 3rd harmonic currents, $\dot{I}_{sh3}$, into transmission line via VSC2 [1]. The series side adopts distributed synchronic series converter (DSSC) that includes several single-phase voltage source converters [1–4]. The series and shunt side DC capacitors enable energy exchange through the 3rd harmonic current of the transmission line, $\dot{I}_{sh3}$.

DPFC has all the functions of unified power flow controller (UPFC). By adopting the single-phase distributed compensator at the series side, DPFC is able to address power quality issues such as voltage dip, frequency variation, harmonics and asymmetry currents and to inhibit a variety of transient fluctuations and interferences [5–10]. DPFC series side compensators adopt small capacity and low cost power electronic devices, which are convenient for mass production, cost saving, disassembling and reloading, initial investment and occupied area reducing. The application of DPFC can fully improve the control activeness, flexibility and reliability of the power grid for the flexible AC power flow control in transmission/distribution network. It can effectively advance the robustness of power grid, increase power transmission capacity and reduce operational costs. The DPFC also can provide alternative means for power flow control to ensure economical, efficient and safe operation of power grid. This technology is key for smart grid development in China, and has a wide application prospect and commercialized potential.

At present, the research works on DPFC such as model establishment, characteristic analysis, simulation and model verification are based on the principle shown in Fig. 1. The cases in distribution networks or in single infinity systems are selected for model validation.

The modular multilevel converter (MMC) applies low voltage rating devices to construct high voltage applications by a cascading topology. The MMCs gain the popularity with the merits of low harmonics in input/output voltage, no use of AC filtering inductance, easy modularization and high reliability, and are gradually applied in the flexible DC transmission system [11] and power flow control equipment [12].

In this paper, a novel topology with the MMC introduced into the shunt side of DPFC is proposed. The proposed MMC based DPFC, namely MMC-DPFC, is suitable for high power transmission networks and provide an alternative way for power flow control. The detailed switch model, the control strategy, the internal electromagnetic transient characteristics of MMC-DPFC are analyzed in the following

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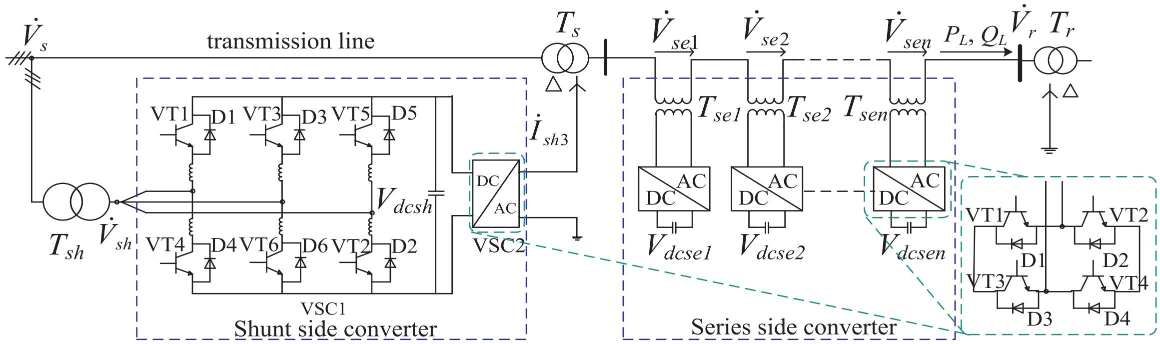

Fig. 1. The topology of DPFC.

sections and simulations are conducted in the PSCAD/EMTDC.

2. MMC-DPFC topology

To date, the highest power rating of IGBT has reached to 6500 V/650 A and 3300 V/2000 A, and the laboratory level has reached to 8000 V/3800 A [13]. In Fig. 1, the VSC2 only needs to provide the 3rd harmonic active component to maintain the DC capacitor voltage of the series side converter constant. Since the 3rd harmonic value is small, the commercialized IGBT can be directly adopted to build up single-phase full bridge converter. The DPFC series side converter consists of as many as hundred single phase converters with the capacity no less than 10 MVA, based on the IGBT voltage and current ratings of 3300 V/2000 A. This scheme could satisfy the capacity requirements of the system power flow control. Therefore, the single phase converters can be used in the series and the shunt side to construct VSC2 in Fig. 2, which are the same as shown in Fig. 1. As for the three-phase multilevel VSC1 connected by multiple IGBT in Fig. 1, the voltage balancing and the voltage rating of the devices is required to be higher. In this paper, a MMC based distributed power flow controller (DPFC) is constructed and the MMC topology is constructed by IGBT chip based on low state loss. The topology of the circuit is shown in Fig. 2.

3. MMC-DPFC controller design

3.1. Shunt side controller design

3.1.1. Design of MMC three-phase converter controller

The details of shunt side is shown in Fig. 3.

For the MMC module, the AC side current $\dot{I}_{sh,i}$ can be expressed as:

$$\dot{I}_{sh,i} = \dot{I}_{down,i} - \dot{I}_{up,i}, \tag{1}$$

where $i = a,b,c$, $\dot{I}_{down,i}$ denotes the single-phase lower bridge arm current and $\dot{I}_{up,i}$ is the single phase upper bridge arm current.

Based on the relation between the current and the voltage of the capacitor in Eqs. (2) and (3):

$$\dot{I}_{up,i} = C_{sh,sm}\, dV_{sh,sm,up}/dt, \tag{2}$$

$$\dot{I}_{down,i} = C_{sh,sm}\, dV_{sh,sm,down}/dt, \tag{3}$$

where $C_{sh,sm}$ denotes the capacitor value of the sub module, $V_{sh,sm,up}$ is the capacitor voltage of the sub module input by the upper bridge arm, $V_{sh,sm,down}$ is the capacitor voltage of the sub module input by the lower bridge arm.

Substituting Eqs. (2) and (3) into (1):

$$\dot{I}_{sh,i} = C_{sh,sm}(dV_{sh,sm,down}/dt - dV_{sh,sm,up}/dt), \tag{4}$$

For the N + 1 level:

$$V_{dcsh} = \sum_{i=1}^{N/2} K_i V_{sh,sm,i} + \sum_{j=1}^{N/2} K_j V_{sh,sm,j}, \tag{5}$$

where, V_{dcsh} represents the DC side voltage. K_i is the state of the ith sub modules of the upper bridge arm, the submodule is OFF if $K_i = 0$, $K_i = 1$, the submodule is ON. K_j is the state of the jth sub modules of the lower bridge arm, the submodule is OFF if $K_j = 0$, the submodule is ON if $K_j = 1$. $V_{sh,sm,i}$ represents the capacitive voltage of the upper bridge arm, $i = 1,2\ldots N/2$. $V_{sh,sm,j}$ represents the capacitive voltage of the lower bridge arm, $j = 1,2\ldots N/2$.

Eq. (5) can also be expressed as:

$$V_{dcsh} = \frac{1}{C_{sh,sm}}\left(\sum_{i=1}^{N/2} K_i \int \dot{I}_{up,i}dt + \sum_{j=1}^{N/2} K_j \int \dot{I}_{down,i}dt\right), \tag{6}$$

Similarly, the relationship between the bus terminal voltage $\dot{V}_s$ and the AC voltage at the three-phase converter side $\dot{V}_{sh}$ is,

$$\dot{V}_s = K_{Tsh}\dot{V}_{sh}, \tag{7}$$

where, K_{Tsh} is turns ratio of the transformer T_{sh} in Fig. 2.

A single bridge arm of MMC is drawn in Fig. 4.

From Fig. 4, the voltage relationship can be expressed as,

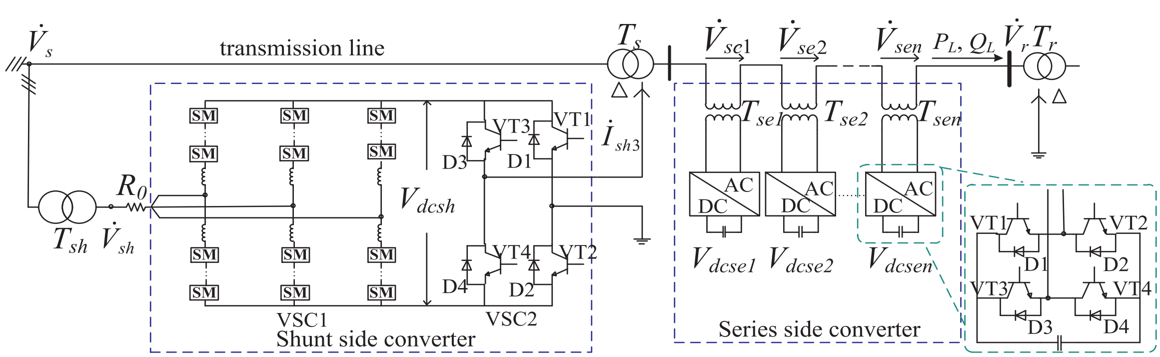

Fig. 2. The topology of MMC-based DPFC.