Independent positive- and negative-sequence control for MMC-SAPF with unbalanced PCC voltage

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***Abstract*—This paper presents a harmonic suppression control strategy under unbalanced point of common coupling (PCC) voltage for modular multilevel converter based shunt active power filter (MMC-SAPF). Harmonics are extracted by multiple synchronous reference frame (MSRF) algorithm to generate the compensation current references of positive- and negative-sequence control for MMC-SAPF. The proposed independent positive- and negative-sequence control loop ensures precise tracking of the compensation currents to the acquired independent current references in the positive- and negative-sequence control respectively. Simulation tests validate the effectiveness of the proposed control scheme on a downscaled 64V/2kVA apparatus.**

Keywords—Modular multilevel converter; active power filter; unbalanced PCC voltage; nonlinear load; multiple synchronous reference frame

I. Introduction

In the last decades, with sharply increasing nonlinear electronic equipment operates in manufacturing, there comes the serious ordeal for medium-voltage transmission and distribution power system, especially those supplying the sensitive loads with strict requirements. Hence, various devices are proposed to provide effective solutions for improving the power quality [1]. Among which, passive power filter (PPF) still dominates in the field of medium-voltage distribution power system for easy implement and cheap price. However, shunt active power filter (SAPF) which combines the three-phase half-bridge structure and control theory gradually takes the place of PPF for superior performance. It is successfully applied in low-voltage power system for harmonic compensation. However, it lacks sufficient capacity or voltage rate for medium-voltage and large capacity application. To extend its application field, diverse tentative improvements are carried out including topology, control method and so on.

As for the topology development, three-level diode neutral clamped converter (NPC) and flying capacitor converter (FCC) are examples of available multilevel converter topologies for application in medium voltage system [2]. They are challenged by the increasing complex control strategy and performance degradation while using for SAPF with more voltage level generating. Static synchronous compensator (STATCOM) based on cascaded H-bridge converter (CHB) topology is widely used, however as for SAPF application, the essential problem lies in the capacitor voltage balance as well as the stress of semiconductor devices [2].

Many researches are carried out on improving SAPF both on the harmonic extraction and control method. One cycle control, predictive control and dead-beat control are some new approaches to mitigate the compensation performance. Several intelligent control methods have been proposed for SAPF with balanced PCC voltage, such as fuzzy control, artificial neural network (ANN). Additionally, some improved methods are issued to simplify the harmonic extraction, such as using the adaptive notch filter (ANF) or self-tuning filter (STF)[3], [4]. However, all of those control methods are under research and the most widely used methods in the market product now are based on the instantaneous reactive power theory or on synchronous reference frame method demonstrated in II.C.

Modular multilevel converter (MMC) is a recently proposed multilevel topology. Compared with aforementioned multilevel converters, its advantages include higher modularity, lower output THD, and higher voltage scalability [5]. Especially, this topology is attractive in high voltage direct current transmission (HVDC) and flexible alternative current transmission systems (FACTS) application because of easy expansion of serial submodule and elimination of the transformer while connecting directly to the grid. Traditional SAPF control strategy based on the synchronous transform could be easily embedded in the MMC control strategy to achieve superior harmonic compensation. Due to the hierarchical voltage control applied in MMC-SAPF, capacitor voltage of each module keep balanced under normal operation.

Although MMC-SAPF can effectively compensate most of the harmonics for diode rectifier when applying traditional positive-sequence control with synchronous frame transform under balanced PCC voltage. Additional dual harmonics would occur when the PCC voltage varies from balanced to unbalanced condition [6], [7]. This change happens when large capacity single-phase load (e.g. rail transport) cuts in and distributes not uniformly among three phase. It brings great challenges for MMC-SAPF to maintain superior compensation performance when PCC voltage is unbalanced.

This work is a part of the project "Multimode Resonance Mechanism and Corresponding Multifunction Active Damping Control Technique for Power Electronic Hybrid Systems" (51277086), sponsored by National Natural Science Foundation of China.

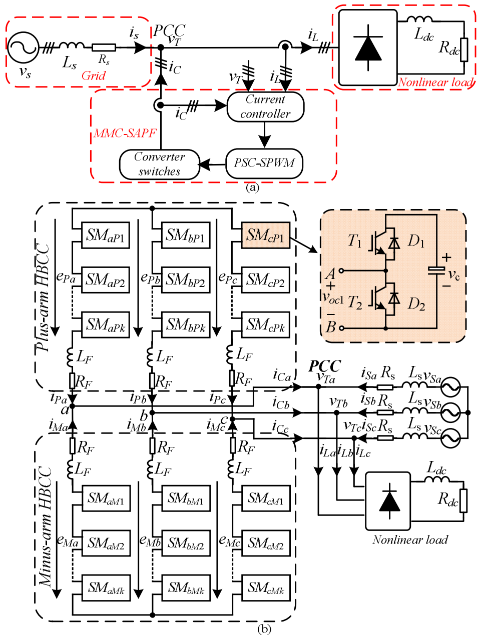

Fig. 1. Configuration and operation principal of MMC-SAPF system (a)Operation principal (b)Equivalent circuit

To solve this problem, reference [1] proposed a control strategy for SAPF based on the instantaneous reactive power theory and utilizing the STF to extract the DC component of nonlinear-load current. However, all the harmonics are suppressed together leading to the lack of flexibility on the choice of special compensation currents. Control strategy of MMC under different unbalanced PCC voltage conditions for HVDC application is investigated in [5]. Research on energy balance of MMC-SAPF are carried out in order to make sure its normal operation [8]. A novel mutually independent positive- and negative-sequence control is proposed by [9] for MMC in medium-voltage STATCOM application aiming to cancel out the negative-sequence component of unbalanced PCC voltage completely.

Based on these researches, an independent positive- and negative-sequence control for MMC-SAPF based on MSRF is proposed in this paper. Then details on embedding the proposed control into the employed MMC control diagram is explicated. Finally, some static and dynamic simulation results are carried out to verify the effectiveness of the proposed control strategy on suppressing specified harmonics caused by nonlinear load with unbalanced PCC voltage.

II. OPERATION PRINCIPAL FOR MMC-SAPF

A. System configuration of MMC-SAPF system

Fig. 1(a) shows the operation principle of MMC-SAPF. Firstly, compensation current reference (i_{C_ref}) is generated by extracting desired component of the measured nonlinear-load current (i_L). Then precise compensation current tracking could be achieved with the help of proper current control loop. Finally, switch driven signal is generated by phase-shifted carrier modulation (PSC-PWM) thus the control signal could fulfill the current compensation.

TABLE I SYSTEM PARAMETERS

Subsystem	Parameter		Value
AC Grid	PCC voltage (rms)	v_{Tab}	63.6V
		v_{Tbc}	53.1V
		v_{Tca}	64.5V
	Grid frequency f_S		50 Hz
	Grid inductance L_S		300 μH
	Grid resistance R_S		0.01 Ω
MMC-SAPF	Rated capacity S_n		2 kVA
	Carrier frequency f_c		1 kHz
	Switching frequency f_{sw}		4 kHz
	Capacitor voltage v_c		70 V
Nonlinear load	DC-link inductance L_{dc}		0.2 mH
	DC-link resistance R_{dc}		3.25Ω

Fig. 1(b) shows the equivalent circuit of distribution system composed by grid, nonlinear load and MMC-SAPF subsystem. Two star-type three-phase half-bridge cascaded converters (HBCC) connect in parallel to form the MMC-SAPF. Each plus- or minus-arm has k sub-modules with single-phase half bridge converter shown in the Fig. 1(b).

Tab. I gives the detailed parameters of the aforementioned MMC-SAPF system corresponding to the real laboratory. It can be seen that the phase-to-phase PCC voltage is unbalanced (the rms value of v_{Tab} and v_{Tca} is higher than that of v_{Tbc}). %*VUF* is given to evaluate the voltage unbalance degree (as shown in (1)) if the PCC voltage is unbalanced. According to PCC voltage given in Tab. I, the voltage unbalance degree equals to 10%, which is much higher than the limit in the IEEE Std. 1547.2-2008 (%*VUF* keeps below 2.0% ~ 3.0%).

$$\%VUF = \left(V_{\mathrm{T}}^{-} / V_{\mathrm{T}}^{+}\right) \times 100\% \tag{1}$$

B. Operation principal of MMC-SAPF under unbalanced PCC voltage

Three-phase diode rectifier load is the dominate harmonic source deteriorating the grid current. Unbalanced PCC voltage would make grid current become much worse. To compensate the nonlinear-load harmonic precisely, it is indispensable to analyze the harmonic of nonlinear-load current and operation principal of the MMC-SAPF under unbalanced PCC voltage in order to adapt to the changed voltage.

According to the symmetrical component theory, as shown in Fig. 2, unbalanced PCC voltage vector (v_{Ta}, v_{Tb}, v_{Tc}) can be decomposed into separate balanced positive-, negative- and zero-sequence voltage vector (v^{+}_{Ta} v^{+}_{Tb} v^{+}_{Tc}, v^{-}_{Ta} v^{-}_{Tb} v^{-}_{Tc} and v^{0}_{Ta} v^{0}_{Tb} v^{0}_{Tc}). Despite the amplitude of each phase synthesized voltage vector (v_{Ta}, v_{Tb}, v_{Tc}) is unequal, decoupled sequence component of three phase voltage vector (e.g. v^{+}_{Ta}, v^{+}_{Tb}, v^{+}_{Tc}) are with same amplitude. Then, the MMC-SAPF system can be analyzed independently with balanced positive- and negative-sequence PCC voltage, while zero-sequence component is neglected in three-phase three-wire power system.