Control Strategy of Active Power Filter Based on Modular Multilevel Converter

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Abstract. To improve the capacity, pressure resistance and the equivalent switching frequency of active power filter (APF), a control strategy of APF based on Modular Multilevel Converter (MMC) is presented. In this Control Strategy, the indirect current control method is used to achieve active current and reactive current decoupling control; Voltage Balance Control Strategy is to stabilize sub-module capacitor voltage, the predictive current control method is used to Track and control of harmonic currents. As a result, the harmonic current is restrained, and power quality is improved. Finally, the simulation model of active power filter controller based on MMC is established in Matlab/Simulink, the simulation proves that the proposed strategy is feasible and correct.

1. Introduction
The rapid increase of nonlinear loads are linked to the power grid in recent years, which increases harmonic in grid. As a result, the power quality is reduced. At present, active power filter is the most reliable and effective device to solve harmonic [1]. The traditional APF is limited by the voltage withstand ability and the equivalent switching frequency, it is difficult to meet the requirements of harmonic control in high voltage and large capacity distribution network.

To suppress the increasingly serious harmonic pollution in the high voltage distribution network, many scholars at home and abroad have done a lot of research. Literature [2] proposed a hybrid APF consisted of passive power filter and APF in series, which reduced the manufacturing cost of active power filter. Literature [3] proposed a harmonic control scheme combining hardware auxiliary clamp circuit and soft-switching control strategy, which achieve energy exchange and voltage balance between DC side capacitors, but this requires voltage balance algorithm or auxiliary capacitor voltage balance circuit, which increases the complexity and manufacturing difficulty of the system. Literature [4] proposed a Hybrid H-bridge Cascaded APF based on star structure, which has small switching loss, and it is easier to implement multilevel with the modular structure. However, when the three-phase output current is in a state of imbalances, the DC side voltage is prone to unbalance and unstable, which limits its application in the distribution system.

In recent years, the converter using MMC topology has the advantages of high efficiency, modular design, easy to cascade and small harmonic is widely used to HVDC system, but research on APF based on MMC is few. Literature [5] proposed an APF based on MMC, which used the ip-iq method to detect the harmonic current, used deadbeat control strategy to Track and control harmonic current, and used capacitance voltage balance control strategy to balance voltage among capacitors of MMC sub-modules, modularity, and flexibility of APF are greatly improved. Literature [6] proposed a kind of control method of MMC active power filter with twenty-four modules in three-phases, which used ip-
iq method, control strategy of capacitive voltage, indirect current control strategy and Carrier Phase Shift SPWM (CPS-SPWM), the capacity of APF has been increased.

Aim at it, in order to improve the capacity, withstand voltage capability and the equivalent switching frequency of APF, an active filter control strategy based on MMC is proposed, indirect current control method is used to achieve active current and reactive current decoupling control, voltage balance control strategy is used to stabilize sub-module capacitor voltage, the predictive current control method is used to track and control of harmonic. Finally, APF model based on MMC is built by Matlab/Simulink, and the simulation results show that the control strategy is correct and feasible.

2. Topological structure and mathematical model of MMC

2.1. Topological structure of MMC

Topological structure of MMC is demonstrated in Figure 1(a). Each phase composes of two identical upper and lower arms. Each bridge arm is connected with Multiple sub-module by a bridge arm reactor, topological structure of sub-module is shown in Figure 1 (b). The sub-module structure adopts half bridge structure. The sub module is composed of DC capacitor and two IGBT with anti parallel diode, which controls the on-off state of IGBT to control the charge and discharge of sub-module capacitor, the voltage outputted by sub-module is adjusted flexibly. The AC side phase voltage is drawn from the connection between the upper bridge arm reactor and lower bridge arm reactor, three-phase bridge arm is connected with the common DC bus P and N, \( e_j \) and \( i_j \) are phase current, \( u_{jn} \) and \( u_{jp} \) are the voltages of lower and upper arms, \( U_{dc} \) is the DC voltage of the converter, \( i_{jn} \) and \( i_{jp} \) are currents of lower and upper arms, \( L_0 \) is the inductance of the arm, \( L \) and \( R \) are inductance and resistance of the AC side.

2.2. the mathematical model of APF based on MMC

The sub modules on each bridge arm are in use or deactivated. When MMC works, the output voltage of sub-module can be replaced by an equivalent voltage source. Because each bridge arm is the equipotential point, is to parallel converter reactor, Then the bridge arm reactor is to parallel connection. Figure 2 is the equivalent circuit of the APF based on MMC, \( v_j \) and \( i_j \) are three-phase voltage and three-phase current of APF access AC system, \( L_s \) is a connection reactor of APF, \( L_{an} \) is the bridge arm reactance, \( v_{an} \) and \( v_{bp} \) are equivalent voltages of lower and upper arms, \( v_{cj} \) is the output voltage of converter \( j \in \{a,b,c\} \).
In Figure 2, a mathematical formula describing APF in the three-phase static coordinate can be obtained according to KVL theorem.

\[
\begin{align*}
\mathbf{v}_{ua} &= \mathbf{v}_{ua} - L \frac{\mathbf{di}_{ua}}{dt} - R\mathbf{i}_{ua} \\
\mathbf{v}_{ub} &= \mathbf{v}_{ub} - L \frac{\mathbf{di}_{ub}}{dt} - R\mathbf{i}_{ub} \\
\mathbf{v}_{uc} &= \mathbf{v}_{uc} - L \frac{\mathbf{di}_{uc}}{dt} - R\mathbf{i}_{uc}
\end{align*}
\]  

(1)

Where: \( L = L_r + L_{sa}/2 \). The control of the MMC system is implemented according to the mathematical model in formula (1).

3. Control strategy of shunt active power filter

3.1. The active and reactive current decoupling control strategy

The APF three-phase output currents \( \mathbf{i}_{ua}, \mathbf{i}_{ub}, \mathbf{i}_{uc} \) are transformed by abc/dq coordinate transformation, and the current components \( \mathbf{i}_d, \mathbf{i}_q \) are obtained. Then the AC components in \( \mathbf{i}_d \) and \( \mathbf{i}_q \) are filtered out by low pass filter (LPF), so the DC components \( \mathbf{i}_{df}, \mathbf{i}_{qf} \) corresponding to the fundamental current are obtained. Finally, the mathematical model in dq coordinate system is obtained by the dq/abc transformation of the formula (1).

\[
\begin{align*}
\mathbf{v}_d &= L \frac{\mathbf{di}_{df}}{dt} - \omega \mathbf{Li}_{qf} + \mathbf{Ri}_{df} + \mathbf{v}_{sd} \\
\mathbf{v}_q &= L \frac{\mathbf{di}_{qf}}{dt} + \omega \mathbf{Li}_{df} + \mathbf{Ri}_{qf} + \mathbf{v}_{sq}
\end{align*}
\]  

(2)

Decoupling control of the active and reactive current is achieved according to formula (2). To stabilize the DC voltage of MMC, the difference between the measuring voltage and reference voltage of DC side is coupled to \( \mathbf{i}_d \) through the PI controller. Finally, the fundamental voltage reference
value \( v_{a}, v_{b}, v_{c} \) of the active filter output is obtained by the formula (2) inverse transform. Decoupling control strategy of active power and reactive power is illustrated in Figure 3(a).

3.2. the predictive current control strategy

The compensation current instruction for transform voltage command by predictive current control algorithm because the predictive current control method is irrelevant to the number of modules, APF based on MMC can be applied in high-power and high-voltage fields, and the control algorithm does not become complicated with the increase of the number of modules.

The output voltage corresponding to harmonic current is obtained by mathematical model established by formula (1).

\[
v_{hj}(t) = v_{sj}(t) - L_{j} \frac{di_{hj}(t)}{dt} - R_{j} i_{hj}(t) \quad (3)
\]

Where, \( v_{sj}(t) \) and \( L_{j} \) are j phase voltage and connected reactance, \( R_{j} \) is line resistance.

According to derivative theory, \( di_{hj}(t) \) can be expressed as the difference between the previous two sampling points, \( di_{hj}(t) = i_{hj}(k+1) - i_{hj}(k) \), \( dt \) is a sampling period \( T_{s} \), the formula (4) is discredited.

\[
v_{hj}(k+1) = v_{sj}(k) - L_{j} \frac{i_{hj}(k+1) - i_{hj}(k)}{T_{s}} - R_{j} i_{hj}(k) \quad (4)
\]

The compensation current \( i_{hj}(k+1) \) of APF in the next time cannot be measured directly, and the frequency of digital control system is very high. Therefore, the next time sampling value can be predicted according to the current sampling value.

\[
i_{hj}(k+1) = i_{hj}(k) - i_{hj}(k) \quad (5)
\]

Where, \( i_{hj}(k) \) and \( i_{hj}(k) \) are j phase grid current value and current value.

To compensate the harmonic current, the compensation current should be equal to the harmonic current generated by the nonlinear load, and the direction is opposite.

\[
i_{hj}(k) = i_{hj}(k) - i_{hj}(k) \quad (6)
\]

Where, \( i_{hj}(k) \) is the active component of the load current.

The harmonic voltage reference of the next sampling time is obtained by plugging Formula (5) and formula (6) into formula (4).

\[
v_{hj}(k+1) = v_{sj}(k) - L_{j} \frac{i_{hj}(k) - i_{hj}(k)}{T_{s}} - R_{j} i_{hj}(k) \quad (7)
\]

Assuming the inductor voltage is \( v_{hj}(k) \), then formula (8) is obtained.

\[
v_{hj}(k) = L_{j} \frac{i_{hj}(k) - i_{hj}(k)}{T_{s}} = K \left[ i_{hj}(k) - i_{hj}(k) \right] \quad (8)
\]

where, \( K = L_{j}/T_{s} \), then formula (9) is obtained.

\[
v_{hj}(k+1) = v_{sj}(k) - v_{hj}(k) - R_{j} i_{hj}(k) \quad (9)
\]

Because line resistance \( R_{j} \) is very small, its size can be ignored.

\[
v_{hj}(k+1) = v_{sj}(k) - v_{hj}(k) \quad (10)
\]

The predictive current control strategy is illustrated in Figure 3(b).
3.3. Capacitance voltage balance control strategy
The premise of APF based on MMC working is that the voltage of each module can keep balance, and the voltage between modules does not shift. The hierarchical voltage sharing control strategy is adopted to stabilize the voltage of the DC side and suppress fluctuation of capacitor voltage of sub-modules.

The balance control strategy of the capacitance voltage is shown in figure 5, which includes the strategy of the phase-phase voltage and independent capacitor voltage. The strategy of the independent capacitor voltage makes the average value of all suspended capacitors follow a given voltage reference value, and the strategy of the phase-phase voltage makes the average value of all sub-modules capacitors follow a given voltage reference value, and the energy is equally distributed to each sub-module, as a result, all voltage capacitance is approximately equal, the circulating current is suppressed.

The average value of capacitance voltage can be calculated by the formula (11).

\[
\overline{V_{ca}} = \frac{1}{2n} \sum_{j=1}^{2n} V_{caj}
\]  
(11)

Where, \(2n\) is the number of each phase module, \(V_{caj}\) is the voltage sampling of the \(j\) module.

The deviation between the given voltage and the average value is calculated, and then the reference instruction of the circulation is obtained by the PI controller.

\[
i^*_a = K_p \left( V^*_{ca} - \overline{V_{ca}} \right) + K_i \int \left( V^*_{ca} - \overline{V_{ca}} \right) dt
\]  
(12)

Where, \(i^*_a\) is circulation reference instruction of a phase, \(V^*_{ca}\) is the given voltage.

The deviation of the circulation between the actual value and the given value is calculated, and the deviation is got into the PI controller, and the control component of the independent capacitor voltage balancing control is obtained.

\[
V_{za} = K_p \left( i_{za} - i^*_a \right) + K_i \int \left( i_{za} - i^*_a \right) dt
\]  
(13)

The deviation value is obtained by the reference value of the circulation (\(V_{caj}\)) comparing with the actual value of the circulation (\(V^*_{ca}\)), the deviation value is got into the proportional regulator, and error component of each module is obtained.

\[
i = \begin{cases} i_p, & j = 1 \sim n \\ i_n, & j = n + 1 \sim 2n \end{cases}
\]  
(14)

Where, \(u\) is the instruction signal of the current controller, \(u_p\) and \(u_n\) are voltage of upper and lower arms.

When \(i\) is greater than or equal to 0, sign is equal to 1; When \(i\) is less than 0, sign is equal to -1,

\[
\begin{align*}
V_j &= V_{za} + V_{zb} + \frac{U_{dc}}{2n} - \frac{u}{n}, \quad j = 1 \sim n \\
V_j &= V_{za} + V_{zb} + \frac{U_{dc}}{2n} + \frac{u}{n}, \quad j = n + 1 \sim 2n
\end{align*}
\]  
(15)

Where, \(V_j\) is voltage command signal of bridge arm, \(V_{za}\) and \(V_{zb}\) the voltage of phase-phase and independent capacitor. The control strategy of the capacitance voltage balance is illustrated in Figure 3(c).

4. Simulation analysis
To prove the feasible and correct of the proposed control strategy, the model of APF is established and analyzed in Matlab software. In the simulation model, DC bus capacitor is 10m F, sub-module capacitor is 3mF, arm inductor is 4mH, sub-module number of each phase is 8, AC side voltage is 35 kV, DC bus
voltage is 9kV, The reactance is 0.5mF, The triangle carrier frequency is 5 kHz, and the rated reactive power compensation capacity is 3 Mvar.

Figure 4(a) The established process of DC voltage

The established process of DC voltage is shown in Figure 3 (a), we can see that the DC voltage can get to the reference value (9000 V) within 0.1s, and there is almost no fluctuation after the steady voltage. The voltage waveforms of the sub-module capacitors are demonstrated in Figure 3(b) and Figure 3(c), the fluctuation of each sub-module voltage is not obvious, the fluctuation range is far less than 3%, and the fluctuation of capacitor voltage among sub-modules is small, which shows that the control effect of voltage sharing is better.

Waveforms of DC current and voltage with APF are demonstrated in Figure 4, waveform of DC side voltage is demonstrated in Figure 4(a), we can see that the DC side voltage is basically stable near the reference value of 9000 V, indicating that the stability of the DC-link voltage is good. The waveform of the load current is demonstrated in Figure 4(b), before APF is put into use, the load current is equal to the grid current, and the load current is distorted. The waveform of the grid current after APF is put into use is shown in Figure 4(c), grid current waveform is improved, the waveform is close to the sinusoidal wave. The waveform of harmonic compensation current is shown in Figure 4(d).

Figure 5 THD of system current

THD of the power current without APF is shown in Figure 5(a), the power current mainly includes 5/7/11/13/17/19 and other order harmonics, which are 20.33%/9.77%/7.74%/5.10%/4.38%/3.11% respectively. The total harmonic distortion rate (THD) was 25.37%.

THD of the power current with APF is shown in Figure 5(b), THD of the power current is dropped down to 2.67%, and the rate of each harmonic current is decreased obviously. The harmonics of 5/7/11/13/17/19 and other orders have been filtered out, and the harmonic is controlled within the allowable value range.

5. Conclusion
To improve the capacity, pressure resistance and the equivalent switching frequency of APF, a control strategy of APF based on MMC is presented, which utilizes MMC with high voltage resistance and high equivalent frequency. In this design, the indirect current control method is used to achieve active current and reactive current decoupling control, voltage balance control strategy is used to stabilize sub-module capacitor voltage, the predictive current control method is adopted to track and control of harmonic currents. Finally, APF model based on MMC is built by Matlab/Simulink, and the results demonstrate that the proposed strategy can stabilize the DC-side voltage, reduce voltage fluctuation.
and reduce the circulating current, the simulation also proves that APF based on MMC has faster response speed and better compensation effect.

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References
[1] Zhang M, Huang L, Yao W, et al. Circulating harmonic current elimination of a CPS-PWM based modular multilevel converter with plug-in repetitive controller[J]. IEEE Transactions on Power Electronics. 2013, 29(4): 2083-2097.
[2] WANG Jun, ZENG Guang, ZHANG Jing-gang, Research on Hybrid Active Power Filter With LC Series[J]. Power Electronics, 2016, 50(2): 48-51.
[3] GAO Congzhe, JIANG Xinjian, LI Yongdong, CHEN Junling, Cascade active power filter based on ZVS DC-link clamping circuit and hierarchical control for medium voltage applications[J], Tsinghua Univ (Sci&Tech), 2012, 52(3): 367-373.
[4] ZHANG Guorong, DAI Xinyue, A DC Voltage Stabilizing and Balancing Control Method Based on H-Bridge Cascaded APF[J]. Electrical Measurement & Instrumentation, 2014, 51(20): 70-75.
[5] LIU Shenglang, SONG Qihou, YANG Yang, DAI Gaofu, Deadbeat Control for Active Power Filter Based on Modular Multilevel Converter[J]. Power Capacitor & Reactive Power Compensation, 2016, 37(3): 15-19.
[6] LOU Xiaoqi, ZHENG Huankun, CHANG Xianrong, Control Strategy Study on MMC Active Power Filter[J]. Power Capacitor & Reactive Power Compensation, 2017, 38(1): 35-40.