Design and Control Strategy of LCL-FILTER Based on MMC-STATCOM

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Abstract: A new shunt STATCOM based on modular multilevel converter (MMC) was researched, but the performance of modular multilevel converters (MMC) was affected directly by higher harmonic and the circulating current. The paper presents a new topology of modular multilevel converter (MMC), which is based on LCL filter. MMC-STATCOM by combination of LCL was researched based on mathematical model of MMC-STATCOM. Based on it, the values of the leg inductance and filter inductance were redefined. And a parallel filter capacitor has been designed between them. Therefore, a new topology of MMC-STATCOM has been composed which is conducive to output characteristics and the circulating current suppression. The paper researched on the influence of elements on the system, and the algorithm of elements were given. Moreover, a new control strategy based on filter capacitor feed-forward was put forward .The effectiveness and feasibility of the proposed control strategy have been verified by the simulation performed based on MATLAB.

Keywords: The center point, Matlab, Tilt, Bending, Distortion, Converter.

1. INTRODUCTION

With the development of power and electronic technology, multilevel converter research has become a hot topic in the field of high voltage and high power. The unique structural characteristics of Modular Multilevel Converters (MMC), especially the superiority of MMC in treating reactive power gradually, make it a hot topic of research. In 2001, a German scholar A.L esnicar *et al.* put forward a new type of Modular Multilevel Converter (MMC). Each phase consisted of two legs. In existing studies, Literature [1] emphasized the structural characteristics and control strategy of MMC. Literature [1, 2] expounded that MMC can be applied to the field of offset. But as MMC-STATCOM is mostly operated under high voltage and high power conditions, the requirements for the output offset current of MMC-STATCOM are high. Therefore, it is of great research value to improve the output properties of MMC-STATCOM and reduce higher harmonic, especially switching subharmonic. But the existing literature seldom studies in this aspect.

Since there exists energy exchange between interphase and DC side, MMC-STATCOM produces interphase circulating current [3-5]. Harmonic component in interphase circulating current will increase the power consumption of equipment and pose hidden threats to the stable operation of equipment. Literature presented a Circulating Current Suppressing Controller (CCSC) under a Second Harmonic Generation (SHG) negative sequence rotating coordinate system. It required SHG negative sequence coordinate transformation and interphase decoupling. Literature [6-10] set up a MMC internal dynamic mathematical model, analyzed the internal dynamic characteristics of MMC and proposed an energy balance control strategy based on MMC leg energy estimates. This strategy suppressed the size of harmonic circulating current to a certain extent, without the need of coordinate transformation. Literature [11] achieved the effect of circulating current suppression by analyzing the internal mechanism of circulating current and increasing leg inductance.

M. Lindgren and J. Svensson proposed solving the above problems with LCL filter on two-level STATCOM. The impedance value of LCL filter is inversely proportional to the flowing current frequency. The higher the frequency is, the smaller the impedance will be. High frequency harmonic can be filtered out. In moderate and high power applications, the advantage is even more obvious [12-14]. So, in view of the existing problems, this article, based on the existing MMC-STATCOM topology, adds filter capacitor between leg inductance and filter inductance and builds a LCL filter, allowing MMC-STATCOM to reduce higher harmonic and suppress interphase circulating current effectively. This article redesigns the parameters of LCL filter inductance and presents a current feed-forward control strategy to add capacitance based on a leg inductive closed loop current. Through simulation experiment, the validity of the proposed topology and the effectiveness of the control strategy are verified.

2. ESTABLISHMENT OF A LCL-FILTER-BASED MMC-STATCOM TOPOLOGY

Assuming Fig. (**1**) shows a LCL-filter-based MMC-STATCOM topology. Each leg is composed of 1 leg inductance and n sub modules in series. The upper and lower legs of each phase form a unit. In theory, the upper and lower legs of each phase in MMC-STATCOM are equivalent to one controlled voltage source respectively. The port voltages of upper and lower legs are defined as:

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1874-4443/15 2015 Bentham Open

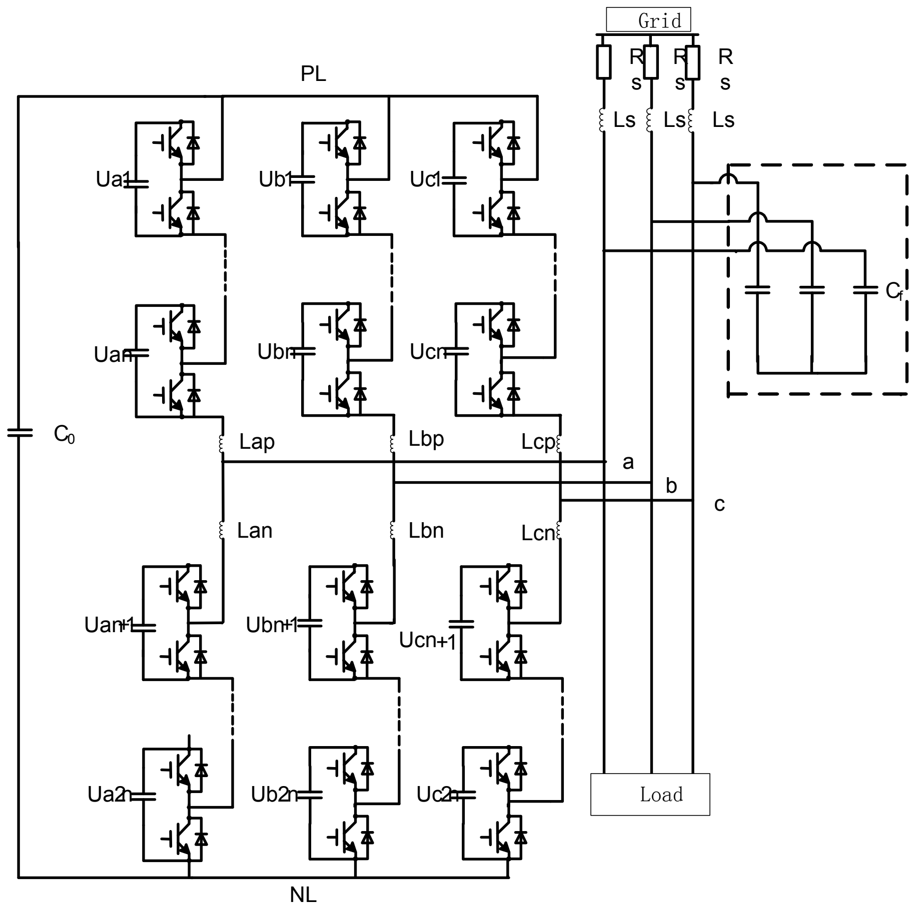

Fig. (1). Basic Structure of MMC-STATCOM.

$$V_{pj} = \sum_{k=1}^{n} s_{jk}E \tag{1}$$

$$V_{nj} = \sum_{k=n}^{2n} s_{jk}E \tag{2}$$

Where s_{jk} is the switching function of module, E is the stable value of modular voltage. As the three-phase legs of MMC-STATCOM are independent and their working principles are exactly the same, j-phase is taken as an example for analysis, thus,

$$V_{jo} = \frac{1}{2}\left(V_{nj} - V_{pj}\right) + \frac{L_a}{2}\frac{d(i_{nj}-i_{pj})}{dt} \tag{3}$$

Where i_{pj} and i_{nj} are the upper and lower leg currents of *j*-phase respectively. Again, as the leg currents of *j*-phase,$i_{sj}=i_{nj}-i_{pj}$, the formula above can be summed up as follows:

$$V_{j\text{`}o} = \frac{1}{2}\left(V_{nj} - V_{pj}\right) + L'a\frac{di_{sj}}{dt} \tag{4}$$

Where $L'_a=L_a/2+L_s$, *i.e.*, an equivalent circuit of A-phase MMC-STATCOM can be derived, as shown in Fig. (**2a**).

Take L'_a in the equivalent circuit as the inverter side inductance in the new topology, build a LCL filter on this basis and derive an equivalent circuit as shown in Fig. (**2b**). In this figure, L_1 is the new equivalent leg inductance of MMC-STATCOM, L_2 is the filter inductance of new MMC-STATCOM, C_f is the filer inductance. A LCL-filter-based MMC-STATCOM is thus established. For LCL filter, the addition of damping resistance can reduce the resonance peak of the system and increase the stability of the system. But the addition of damping resistance also increases the damping loss of the system. Damping loss of the system is determined by many factors simultaneously. For MMC-STATCOM system with LCL filter, reactive fundamental current can't get through the filter capacitor. While after adding damping resistance, the effect of resonance current can be ignored. Therefore, the damping loss of the system is mainly caused by switching subharmonic [15].

3. EFFECT OF LCL FILTER ON MMC-STATCOM PERFORMANCE AND PARAMETER DESIGN

3.1. Inverter Side Inductance

(1) As the three-phase units in MMC are independent, as if connected to both ends of the DC side in parallel, the DC voltage of each phase can't be completely equal. So there will always be interphase circulating current. Through analysis, it can be confirmed that MMC interphase circulating current not only contains DC components, but also duplation circulating current and negative sequence circulating current. The peak value of this circulating current is:

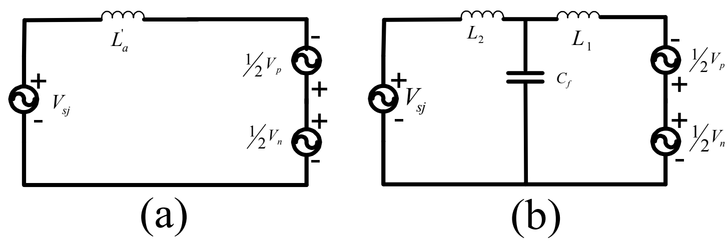

Fig. (2). Equivalent Circuit of A-phase MMC-STATCOM.

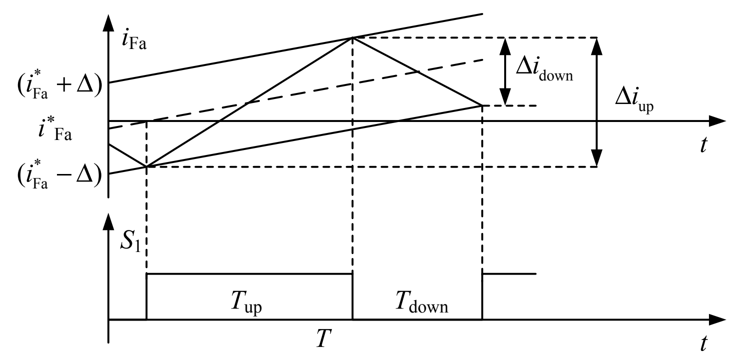

Fig. (3). Maximum Variation Rate.

$$I_{2f} = \frac{S}{3}\frac{1}{8\omega^2 CsmL1\overline{U}_{sm} - U_{dc}} \tag{5}$$

Where S is the output apparent power, ω is the angular frequency of modulated wave and $\overline{U}_{sm}$ is the average voltage of Module C_{sm}. It can be observed from the above formula that increasing L_1 will be beneficial to the suppression of duplation circulating current.

$$L1 \geq \frac{1}{8\omega^2\overline{U}_{sm}}\left(\frac{S}{3I_{2f}} + U_{dc}\right) \tag{6}$$

(2) The tracking requirement for command current. From the variation rate of sine wave, fundamental current produces the maximum variation rate at Zero Crossing Point (ZCP). At this point, inductance should be the lower limit within the effective range, in order to meet the tracking requirement.

As shown in Fig. (**3**), at this point, A-phase current is located at ZCP. The positive direction of current is toward the system side. The up and down directions of current is corresponding to the on and off of switch tube.

(3) The suppression requirement for harmonic at switching frequency. When current reaches the peak, the variation rate of current is the minimum. But at this point, the current fluctuation will reach the peak. Only when induction is the maximum within the effective range will the suppression requirement for harmonic at switching frequency be satisfied. At this point, the value range of induction required by the suppression of harmonic at switching frequency is analyzed, as in Fig. (**4**).

Take two circumstances (2) and (3) into consideration. The derived range of leg inductance is

$$\frac{U_{dc}^2 - 4u_a^2}{4U_{dc}\Delta i_{max} f_{sw}} \leq L1 \leq \frac{U_{dc}2u_a}{2n\omega I_a} \tag{7}$$

Where u_a and I_a are the A-phase voltage and current. f_{sw} is the switching frequency of power component.

To sum up, the inductance value should not only satisfy the requirement for command current, but also be able to suppress interphase circulating current effectively. But if the value of inverter side inductance is too large, it may increase the volume and engineering costs. Thus, inductance just needs to be the minimum of value range [16-18].

3.2. Grid Side Inductance

Both the harmonic attenuation ratio σ and resonance frequency ω_{res} of LCL system may affect the value of grid side inductance, so their effect must be taken into full consideration when designing grid side inductance.

The resonance frequency of LCL system is defined as follows:

$$\omega_{res} = \sqrt{\frac{L_1+L_2}{L_1L_2C_f}} \tag{8}$$

For high frequency harmonic, grid side inductance presents high impedance. While as filter capacitor can filter out higher harmonic, it presents low impedance, so the switching

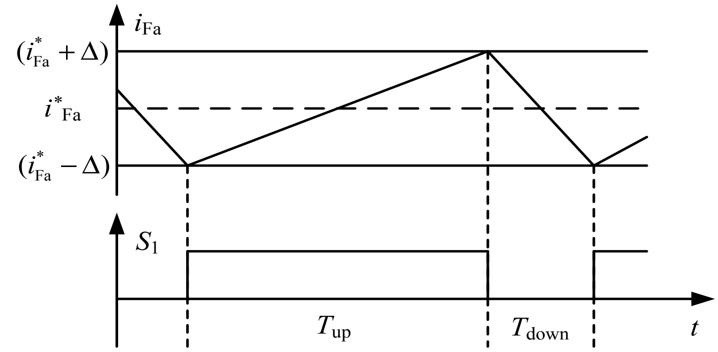

Fig. (4). Maximum Fluctuation of Current.

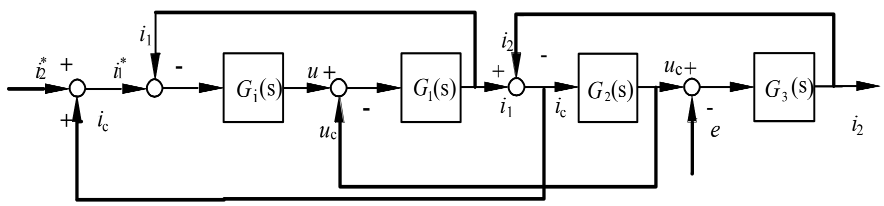

Fig. (5). Active Damping Strategy Based on Filter Capacitor Current.

frequency subharmonic content in the final reactive current output by the system is very little.

The attenuation ratio of switching subharmonic of MMC-STATCOM can be obtained by calculation, as shown in Formula 9:

$$\frac{i2(hsw)}{i1(hsw)} = \frac{1}{1-\omega_{sw}^2 L_g C_f} \quad (9)$$

Where $i_2(h_{sw})$ is the switching subharmonic in output current (A);

$i_1(h_{sw})$ is the switching subharmonic in inverter side current (A);

ω_{sw} is the angular frequency of switching subharmonic (rad/s).

$L_2/L_1<1$, the resonance frequency of the system can be simplified to get $\omega^2_{res}\approx 1/L_g C_f$, it means $1\approx\omega^2_{res}L_g C_f$. Thus, Formula (8) can be rewritten as the following approximate form:

$$\frac{i2(hsw)}{i1(hsw)} = \frac{1}{L_g C_f |\omega_{res}^2-\omega_{sw}^2|} \quad (10)$$

When calculating the value of grid side inductance, first of all, determine $i_2(h_{sw})/ i_1(h_{sw})$, which is the attenuation ratio of switching subharmonic, and then select an appropriate resonance frequency ω_{res}. After that, the value of grid side inductance can be determined.

It is worthy that to ensure that LCL filter filters out higher harmonic, resonance frequency can't be too large. When the value of inverter side inductance and grid side inductance is determined, on the premise that filter capacitor C_f meets the requirement of the system for reactive power, C_f should be as large as possible. As the reactive current output by MMC-STATCOM must inject load smoothly, so resonance frequency ω_{res} should choose half of the switching frequency as far as possible and avoid harmonic amplification.

3.2. Filter Capacitor

Reactive current presents high impedance to filter capacitor, while switching sub harmonic is just the opposite. Besides, it may produce reactive power when passing through the filter capacitor bypass. And the capacitance is proportional to the injected reactive current. The attenuation ratio of harmonic is inversely proportional to capacitance, but the increase of capacitance will cause a lot of negative effect to the system. The attenuation ratio of harmonic can be reduced by adjusting the selection of other parameters. Therefore, the value of filter capacitor should be as small as possible and suppress the effect of filter capacitor on the system as far as possible. Thus, the value of filter capacitor is related to the rated power of the system. Generally, it is defined as five percent of the rated power of the system.

$$C \le 0.05\times\frac{P}{2\pi f E_{line}^2} \quad (11)$$

Where f is the fundamental frequency of grid(Hz);

P is the rated power of MMC-STATCOM (KVA);

E_{line} is the effective value of grid line voltage (V).

4. ADDITION OF CAPACITIVE CURRENT FEED-FORWARD CONTROL TO THE LEG INDUCTANCE CURRENT CLOSED LOOP

For MMC-STATCOM structure, it has leg inductance and filter inductance, so the current control in present study

Table 1. The Parameters of Circuit.

Parameters	Symbols	LCL+MMC	MMC
DC bus voltage/V	U_{dc}	200	200
Phase voltage amplitude/V	U_m	170	170
Leg inductance/mH	L_1	4.2	2
Submodular capacitor/μF	C_{SM}	2200	2200
Carrier frequency/kHz	f_s	1.2	1.2
Filter capacitor/μF	C_f	1.5	3.5
Filter inductance/ mH	L	0.5	0.5

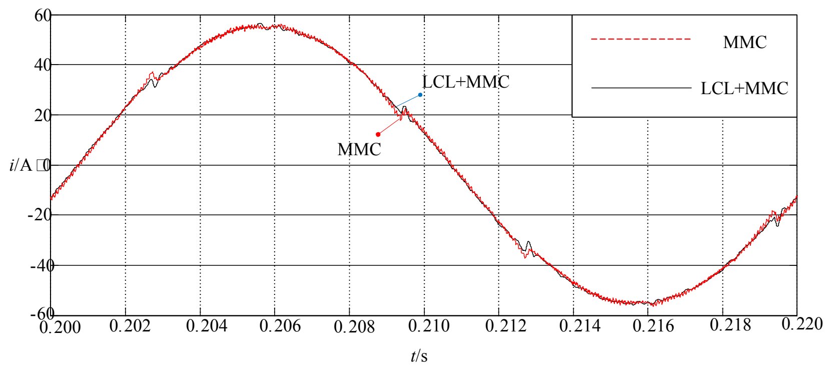

Fig. (6). Comparison of Output Current.

is based on leg current, which is inverter side inductance current. While for LCL structure, due to the introduction of filter capacitor, the system changes from first-order to third-order. If not controlled, no matter how small the open loop gain is, a pole will always appear in the right half plane of the complex plane and make the system instable. For the above problems, this article presents an improved filter capacitor feed-forward control strategy. In traditional capacitive current feed-forward control, the characteristics of capacitor per se causes phase shifting between the sampled feed-forward current and the grid side current, which makes phase inaccurate and affects the offset accuracy. Therefore, the improvement made in this article is to introduce a low-pass filter to the current feed-forward link. After passing through low-pass filtering, feed-forward current only reserves low frequency components. In this way, the current loop phase difference in the original control can be made up and the offset accuracy can be improved effectively.

The steady-state error is:

$$\begin{aligned} e(s) &= i_2^*(s) - i_2(s) \\ &= i_2^*(s)\times\left(1-\frac{G_i(s)G_1(s)G_2(s)G_3(s)}{1+G_1(s)G_2(s)+G_2(s)G_3(s)+G_i(s)G_1(s)G_2(s)G_3(s)}\right) \end{aligned}$$

Inverter side current i_1, offset current i_2 and attenuation ratio of harmonic current are inferred as follows:

$$i_1 = i_2^*\frac{G_i(s)G_1(s)+G_i(s)G_1(s)G_2(s)G_3(s)}{1+G_1(s)G_2(s)+G_2(s)G_3(s)+G_i(s)G_1(s)G_2(s)G_3(s)}$$

$$i_2 = i_2^*\frac{G_i(s)G_1(s)G_2(s)G_3(s)}{1+G_1(s)G_2(s)+G_2(s)G_3(s)+G_i(s)G_1(s)G_2(s)G_3(s)}$$

$$\sigma = \frac{I_g(s)}{I_c(s)} = \frac{i_2}{i_1} = \frac{G_2(s)G_3(s)}{1+G_2(s)G_3(s)} = \frac{1}{s^2 L_g C_f + 1}$$

5. SIMULATION VERIFICATION

In order to verify the effectiveness of the proposed MMC circulating current suppressor, this article carries out a simulation experiment. Under Matlab/Simulink platform, the parameters of MMC-STATCOM system are set up as in Table **1**. The modulation strategy adopts dual modulation carrier phase-shifting PWM modulation technology, with 180 degrees phase deviation. Table **1** shows the MMC-STATCOM experimental parameters of the added LCL-filter. MMC is the experimental parameter of the original topology.

Fig. (**6**) shows the comparison between traditional MMC-STATCOM and MMC-STATCOM with LCL filter in output

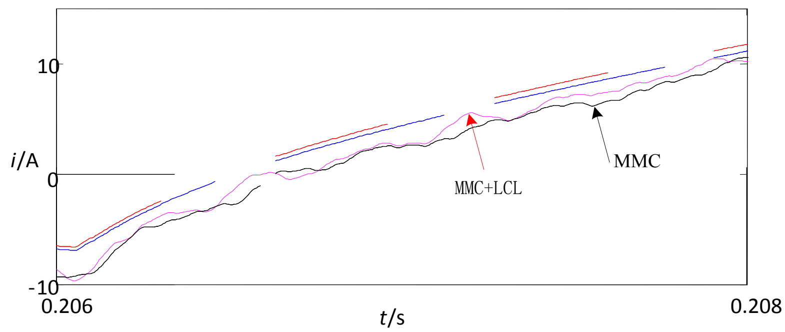

Fig. (7). Local Amplification of Command and Offset Current.

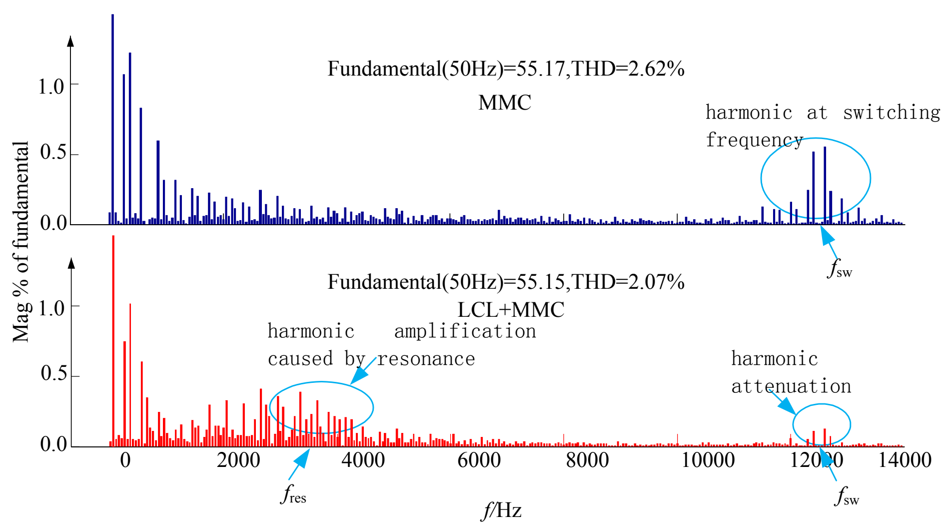

Fig. (8). FFT Analysis of Output Current.

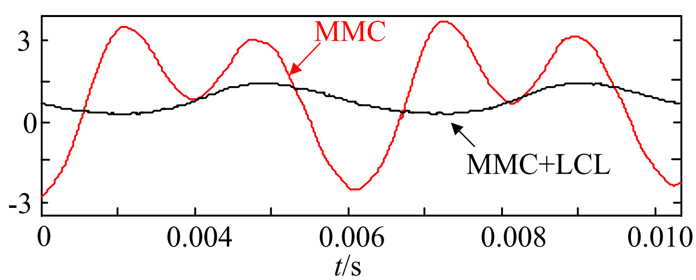

Fig. (9). Effect of Circulating Current Suppressor.

current. As the original topology cannot suppress high frequency harmonic quite well, there is a large amount of switching subharmonic in output current, leading to too many offset current glitches. While after adding LCL filter, it can be seen that switching subharmonic is significantly reduced. The current becomes smoother.

Fig. (**7**) shows a local amplification of command and offset current/A represents the command current, if represents the offset current. From the figure, if the variation of command current can be ignored, after adding an improved control strategy, the offset current accuracy will be improved and errors will be reduced.

Fig. (**8**) shows a harmonic analysis diagram of both currents. From the diagram, their performance in low frequency is basically the same. But the attenuation capacity of MMC-STATCOM with LCL-filter at switching frequency is far better than the traditional topology. The proportion of switching harmonic is significantly reduced. But it can also be seen that the harmonic in the middle of new topology to the nearby of frequency has been amplified. The addition of damping resistance can attenuate resonance and suppress resonance peak effectively.

Fig. (**9**) shows a comparison between both currents in the suppression effect of circulating current. The circulating current of MMC-STATCOM fluctuates between -3A and 3A. While after reconfiguring LCL parameters, the peak value of circulating current is not more than 0.35A, only about 5% of the original. Thus, the suppression effect on the internal circulating current of MMC-STATCOM is very distinct.

6. CONCLUSION

For the switching subharmonic and interphase circulating current existing in the output current of MMC-STATCOM, this article designs a MMC-STATCOM based on LCL-filter, adds filter capacitor to the hardware topology and redefines the value range of leg inductance and filter inductance. In control strategy, based on the original control, an improved filter capacitor current feed-forward control is introduced, to make up the phase difference of the original control. The content of switching subharmonic is reduced, interphase circulating current is suppressed and the waveform of leg current is greatly improved. The simulation results prove that this topology is easy to implement, in favor of the stable operation of MMC-STATCOM and is of certain value in engineering application.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

This work is supported by the the International Technology Cooperation Plan (2010RR0002);

REFERENCES

[1] M. Hagiwara, and H. Akagi, "PWM control and experiment of modular multilevel converters," *Power Electronics Specialists Conference*, Rhodes, pp. 154-161, 2008.

[2] M. Hagiwara, K. Nishimura, H.A. Akagi, "Medium-voltage motor drive with a modular multilevel PWM inverter," *IEEE Transactions on Power Electronics*, vol. 25, no. 7, pp. 1786-1799, 2010.

[3] Q.R. Tu, Z. Xu, and X. Zheng, "Mechanism analysis on the circulating current in modular multilevel converter based HVDC," *High Voltage Engineering*, vol. 36, no. 2, pp. 547-552, 2010.

[4] Q.R. Tu, Z. Xu, X. Zheng, and M.Y. Guan, "Design of circulating current suppressing controllers for modular" multilevel converter *Automation of Electric Power Systems*, vol. 34, no. 18, pp. 57-61, 2010.

[5] A. Antonopoulos, L. Angquist, and H. P. Nee, "On dynamics and control of the modular multilevel converter," In: *Proceedings of Power Electronics and Applications, EPE*, vol. 13, no. 7, pp. 11-10, 2009.

[6] Y. Wang, F. Wu, L. Sun, and S. Sun, "Optimized design of LCL

[7] Filter for minimal damping power loss," In: *Proceedings of the CSEE*, vol. 30, no. 27, pp. 90-95, 2010.

[8] X. Yang, Z. Lin, T. Q. Zheng, and X. You, "A review of modular multilevel converters," In: *Proceedings of CSEE*, vol. 33, no. 6, pp. 1-14, 2013.

[9] S.S. Wang, X.X. Zhou, and G.F. Tang, "Modeling of modular multi-level voltage source converter," In: *Proceedings of CSEE*, vol. 31, no. 24, pp. 1-8, 2011.

[10] X. Peng, Q. Song, and W.H. Liu, "Mathematical model and control method of new modular multilevel converters," The 26th Annual Meeting of Chinese Higher Institutions of Power System and Automation and Specialized Power System Committee of Chinese, *Society Electrical Engineering*, Shanghai, 2010.

[11] A. Lesnicar, R. Marquardt, "An innovative modular multilevel converter topology suitable. for a wide power range," In: *IEEE Transactions on Power Electronics*, vol. 19, no. 1, pp. 76-86, 2004.

[12] Z.Q. Liu, Q. Song, and W.H. Liu, "VSC-HVDC system based on modular multilevel converters," *Automation of Electric Power Systems*, vol. 34, no. 2, pp. 53-58, 2010.

[13] M. Liserre, A. Dell'Aquila, and F. Blaabjerg, "Stability improvements of an LCL-filter based three-phase active rectifier" *IEEE Annual Power Electronics Specialists Conference*, Cairns, vol. 3, pp. 1195-1201, 2002.

[14] Z.L. Qiu, E.X. Yang, J. Kong, and G. Chen, "Current loop control approach for LCL-based shunt active power filter," In: *Proceedings of the CSEE*, vol. 29, no. 18, pp. 15-20, 2009.

[15] Y.Q. Huang, X.J. Jiang, and A.R. Qiu, "A novel active damping control scheme for a three-phase active rectifier with LCL-filter," *Transactions of China Electro Technical Society*, vol. 23, no. 9, pp. 86-91, 2008.

[16] Y. Xie, B.C. Chen, Y.J. Chen, and Y.S. Zeng, "Function analysis and parameter selection for series reactor of modular multilevel converter," *Electric Power Automation Equipment*, vol. 32, no. 9, pp. 55-59, 2012.

[17] G.J. Ding, G.F. Tang, M. Ding, and Z. Y. He, "Topology mechanism and modulation scheme of a new multilevel voltage source converter modular" In: *Proceedings of the CSEE*, vol. 29, no. 36, pp. 1- 8, 2009.

[18] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an LCL-filter based three-phase active rectifie," In: *IEEE Trans. on Industry Applications*, vol. 41, no. 5, pp. 1281-1291, 2005.

Received: June 16, 2015 Revised: August 10, 2015 Accepted: September 19, 2015