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Capacitor Voltage Shaper for Cascaded H-Bridge StatCom

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Abstract— In this paper, an active shaping method of the capacitor voltage for a cascaded H-bridge (CHB) low-capacitance static synchronous compensator (LC-StatCom) is introduced. The traditional LC-StatCom is able to operate with large capacitor voltage ripples when it is operating with rated current. However, as the current is reduced below rated current, voltage ripple on the capacitors decreases. Decreasing the current therefore removes the advantages of the LC-StatCom such as better current quality and reduced switching losses. The active shaping method aims to keep consistent large voltage ripple on the capacitor using a simple boost converter cell to inject an appropriate auxiliary capacitor current. Simulation results are provided to confirm the performance of the proposed CHB-StatCom system.

Keywords—Cascaded H-Bridge, Multilevel converter, StatCom, Low capacitance, Large ripple.

I. INTRODUCTION

A cascaded H-bridge multilevel converter (CHB-MC) is one of the most popular converter systems in many industrial applications thanks to its modularity, possibility to remove the transformer in medium voltage applications and ability to decrease switching loss [1]. Although the CHB-MC has these advantages, a requirement for isolated DC power sources, which make the system heavy, complex and adds cost to each HB cell is a disadvantage to be considered [2]. However, in the static synchronous compensator (StatCom) application, the requirement for isolated DC power sources is no longer a critical disadvantage because floating capacitors on the HB cells are able to replace the isolated dc sources. The idea of utilizing a CHB-MC as a StatCom was introduced in [3]. After that for many years, considerable studies of StatCom based on the CHB-MC have been conducted in the technical literature [4]-[15].

In the conventional StatCom systems implemented with CHB-MC circuits, dc voltage ripples on the capacitors are minimized as much as possible [4]-[15]. Therefore, a large

capacitance value is necessary to reduce the low frequency ripple magnitude. In typical CHB-MC, the dc capacitor size is chosen to limit voltage ripple on the capacitor to less than 10% of the nominal dc voltage, which dictates the use of large capacitance values and physical capacitor sizes [16], [17]. In typical CHB-MC, large voltage ripple increases the maximum voltage stress on the semiconductor devices, reduces total quality of the current, increases losses, and requires complex filtering methods to control the dc voltages [18].

Recently, a low-capacitance StatCom (LC-StatCom) system has been developed. In this concept, voltage ripple is considered as a positive aspect of the converter operation, which enhances performance [19]-[26]. As opposed to conventional StatCom, a large ripple improves quality of the current, reduces losses, and decreases voltage stress on the semiconductor devices [19], [22], [25], [26]. The LC-StatCom's operational principle is depicted in Fig.2 and Fig.3. As shown in Fig.2 the LC-StatCom is able to operate with large capacitor voltage ripples when the system operates with rated capacitive current. However, as the current reduces below the rated current, the magnitude of voltage ripple on the capacitors decreases. This removes the advantages of the LC-StatCom mentioned above.

In several previous papers, it has been proposed that a H-bridge dc-capacitor voltage can be maintained with a desired constant dc value by using a simple buck or boost cell in parallel with each dc-capacitor [27]-[29]. These previous power-decoupling approaches aimed to eliminate oscillation on each dc-capacitor. In contrast, this paper proposes intentionally increasing the capacitor voltage ripples, using the same circuit topology as previously utilized and shown in Fig.4, to maintain the performance benefits of LC-StatCom at less than rated current.

The rest of this paper is organized as follows: Section II provides a brief introduction of the LC-StatCom, Section III introduces the proposed active capacitor voltage shaping concept, and Section IV provides simulation results for the

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proposed CHB-StatCom. Finally, conclusions and future works are summarized in Sections V.

Fig. 1. Single-phase cascaded H-bridge LC-StatCom.

II. CASCADED H-BRIDGE LC-STATCOM

The single phase CHB StatCom is shown in Fig.1. Each H-bridge cell has a floating dc capacitor. The capacitor voltage of CHB LC-StatCom is a function of the ac side current and voltage. An expression for the capacitor voltage can be derived by assuming the ac side voltage is $v = V \sin(\omega t + \alpha)$ and the current is harmonic free and purely reactive, $i_g = I_g \sin(\omega t \pm 90 + \alpha)$. The expression can be represented as below [20]

$$v_c(t) = \sqrt{A_o \pm \frac{VI_g}{2\omega C} \cos(2\omega t + \alpha)} \quad (1)$$

where A_o is a constant defining the capacitor's initial charge, V is the peak value of the generated ac voltage by the inverter and α is its angle and ω is the angular frequency of the grid voltage. C is the H-bridge capacitance and v_c represents the capacitor voltage.

Fig. 2 and Fig. 3 demonstrate that the second order ripple component of capacitor voltage has the same phase angle with the absolute value of the grid voltage. As shown in Fig. 2, the maximum operating voltage of the capacitor is controlled to be fixed independent of the voltage ripple magnitude.

Fig. 3 shows a comparison between LC-StatCom and conventional StatCom operating in capacitive mode. As it can be seen from Fig. 3, the maximum operation voltage of cluster voltage in the LC-StatCom is the same value of the minimum

voltage of the cluster voltage in the conventional StatCom where cluster voltage is defined as the sum of each capacitor voltage in a phase-leg. Therefore, the voltage stress on semiconductors is lower in the LC-StatCom [20].

Fig. 2. Operating principle of LC-StatCom with fixed V_{C-max} .

Fig. 3. Operation comparison between LC-StatCom and conventional StatCom, (a) LC-StatCom, (b) StatCom.

Fig. 4. Proposed active shaper circuit, which consists of an active shaping boost converter cell in each H-bridge module.

III. PROPOSED CHB-STATCOM

A. Basic concept

The LC-StatCom has the maximum capacitor voltage ripple when it is operating with rated current. It can take full advantage of the large ripple to improve performance such as a better quality of a synthesized ac voltage that has an improved THD [24], [26]. However, in practice, the LC-StatCom will often work with lower currents, where it will not be able to take benefits from large voltage ripple [24] - [26].

The proposed active shaping circuit solution is shown in Fig. 4. It aims to overcome this issue by making the CHB-StatCom more adaptable to the light loading condition. As it can be seen from Fig. 4, using Kirchhoff's current law on the capacitor, equivalent capacitor voltage value can be expressed by

$$v_c = \frac{1}{C} \int i_c dt = \frac{1}{C} \int i_1 - i_b dt \quad (3)$$

where i_b is the harmonic current of the boost cell, i_1 is the equivalent current on the capacitor from the LC-StatCom, i_c is the capacitor current. As can be seen from (3), the voltage ripple of the dc capacitor can be adjusted by controlling the magnitude of the current and/or the phase angle of the harmonic current injected by the boost cell. Assuming that the losses are negligible, the input power of the HB cell is equal to its output power. Hence,

$$-v_c i_1 = v i_g \quad (4)$$

from (3) the capacitor current i_c becomes

$$i_c = C \frac{dv_c}{dt} = i_1 - i_b \quad (5)$$

A desired capacitor voltage with rated current is given by

$$v_c(t) = \sqrt{A_o \pm \frac{VI_{g-rated}}{2\omega C} \cos(2\omega t + \alpha)} \quad (6)$$

Substituting (4) into (5), then subsequently substituting (6) into (7), the boost cell's reference current can be expressed by

$$i_b^* = -C \frac{dv_c}{dt} - \frac{vi_g}{v_c} \quad (7)$$

$$i_b^* = -C \frac{d}{dt} \sqrt{A_o \pm \frac{VI_{g-rated}}{2\omega C} \cos(2\omega t + \alpha)} - \frac{vi_g}{\sqrt{A_o \pm \frac{VI_{g-rated}}{2\omega C} \cos(2\omega t + \alpha)}} \quad (8)$$

The expression for the reference current of boost cell shown in (8) can be solved numerically to shape the capacitor voltage ripple.

B. Control

The total capacitor stored energy of the previous LC-StatCom was controlled by using a cluster voltage controller and an individual balancing controller that balances energy among the HB cells [20], however, in this work, an additional controller which is a proportional-resonant (PR) controller has been added to control the second order harmonic component of the capacitor voltage. The active shaping control scheme which is the PR controller for boost converter adjusts the

current of the capacitor by controlling both magnitude and phase on the boost cell current to maintain the large ripple as though CHB-StatCom operates with rated current. A simple circuit diagram of proposed solution and control scheme are shown in Fig. 5.

Fig. 5. Simple control scheme of the proposed active shaping boost cell.

The transfer function of the PR controller is shown in (9) [30].

$$H_{PR} = K_p + \frac{2K_i\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (9)$$

where K_p is a proportional gain, K_i is an integral gain, ω_c is a cut-off angular frequency, and ω_0 is a resonant angular frequency of the controller. Each parameter is chosen by $K_p = 10$, $K_i = 10$, $\omega_c = 62.8$ rad/s, and $\omega_0 = 628$ rad/s so that controller achieves a high gain at resonant frequency 100 Hz that is given by the second order harmonic frequency of the boost cell's reference current.

IV. SIMULATION

The operation of the CHB-StatCom equipped with the proposed active shaping circuit is demonstrated by simulations on a seven-level single-phase CHB-StatCom. The simulations are carried out using MATLAB/Simulink. The parameters of the simulation are given in Table I and the circuit diagram of the simulation is shown in Fig. 6. The operation of the proposed active shaping system in the steady state is simulated, and some of the results are shown. Fig. 7 shows a simulation result of the proposed CHB-StatCom operating with large cluster voltage ripple at the full capacitive mode. For this operational condition there is no auxiliary current required from the boost cell to achieve large voltage ripple.

Fig.8 shows results when the StatCom is delivering 0.2 p.u. capacitive current. As it can be seen, each boost cell is injecting an auxiliary current to shape the capacitor voltage to achieve the same ripple magnitude as with 1.0 p.u. capacitive current.

The simulation of ripple comparisons has been carried out to see the difference between proposed system and conventional LC-StatCom system. Fig. 9 and Fig. 10 present the comparison. As it can be seen from these figures, the ripples of the cluster voltages remained large in the proposed approach when system operates both at 0.5 p.u. and 0.2 p.u. This confirms that in the proposed approach the capacitor voltage ripple can be controlled to be independent of the injected grid current, and can therefore produce superior current quality at all operational conditions.

TABLE I. PARAMETERS OF THE SIMULATION OF THE PROPOSED CHB-StatCom

Symbol	Quantity	Values
V_{gn-rms}	Grid voltage rms value	110 V
C, C_b	Capacitor-H-bridge, Boost cell	130 μ F
L	Filter inductor	5 mH
L_b	Boost converter Inductor	0.5 mH
R	Series parasitic resistor	0.2 Ω
f_s	Switching frequency (for each H-bridge)	2 kHz
f_b	Switching frequency (for each Boost converter)	10 kHz
f_g	Grid frequency	50 Hz
S	Converter nominal power	350 VA
N	Number of H-bridges	3

Fig. 6. Circuit diagram of the simulation of the proposed CHB-StatCom with the voltage shaper boost cell.

Fig. 7. Operation of the proposed CHB-StatCom system, when delivering its nominal (1 p.u.) capacitive current.

Fig. 8. Operation of the proposed CHB-StatCom, when delivering its 0.2 p.u. capacitive current. (a) H-bridge currents of each cell (i_1, i_2, i_3), (b) Currents of each boost cell (i_{b1}, i_{b2}, i_{b3}), (c) Currents of each dc-link capacitor (i_{c1}, i_{c2}, i_{c3}), (d) Voltages of each dc-link capacitor (v_{c1}, v_{c2}, v_{c3}) and cluster voltage ($v_{c1}+v_{c2}+v_{c3}$)

Fig. 9. Operation of the proposed CHB-StatCom system and conventional LC-StatCom, when delivering its 0.5 p.u. capacitive current. (a) Proposed CHB-StatCom, (b) Conventional LC-StatCom.

Fig. 10. Operation of the proposed CHB-StatCom system and conventional LC-StatCom, when delivering its 0.2 p.u. capacitive current. (a) Proposed CHB-StatCom, (b) Conventional LC-StatCom.

THD analysis under 0.2 p.u. capacitive current has also been performed, with Fig. 11 showing THD of the output voltage of the converter without boost cell operation. On the other hand, Fig. 12 shows THD of the output voltage of the converter with voltage shaping operation of boost cell. As it

can be seen these simulation results, better THD value can be obtained due to large ripple on the dc capacitor, which is able to make the output voltage of the converter closer to a sinusoidal waveform.

Fig. 11. THD analysis of the conventional StatCom, when delivering its 0.2 p.u. capacitive current.

Fig. 12. THD analysis of the proposed CHB-StatCom, when delivering its 0.2 p.u. capacitive current.

V. CONCLUSION

The simulation results presented in this paper on a 350VA single-phase seven-level CHB-StatCom prototype confirmed viability of using an active shaping solution. The simulation results confirmed the effectiveness of the proposed CHB-StatCom to keep voltage ripple on the capacitors large to retain low losses in the H-bridge semiconductors and high quality output currents.

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