A LOW CAPACITANCE CASCADED H-BRIDGE 7-LEVEL STATCOM

J.Gunasekaran¹, S.Rajesh Kumar²

¹PG Scholar, EEE, PRIST University, gunaeb@gmail.com
²Assistant Professor, EEE, P.R. Engineering college, mail2tvrsrk@gmail.com

ABSTRACT

This paper introduces a cascaded H-bridge multilevel converter (CHB-MC) based StatCom system that is able to operate with extremely low dc capacitance values. The theoretical limit is calculated for the maximum capacitor voltage ripple, and hence minimum dc capacitance values that can be used in the converter. The proposed low-capacitance StatCom (LC-StatCom) is able to operate with large capacitor voltage ripples, which are very close to the calculated theoretical maximum voltage ripple. The maximum voltage stress on the semiconductors in the LC-StatCom is lower than in a conventional StatCom system. The variable cluster voltage magnitude in the LC-StatCom system drops well below the maximum grid voltage, which allows a fixed maximum voltage on the individual capacitors. It is demonstrated that the proposed LC-StatCom has an asymmetric V-I characteristic, which is especially suited for operation as a reactive power source within the capacitive region. A high-bandwidth control system is designed for the proposed StatCom to provide control of the capacitor voltages during highly dynamic transient events. The proposed LC-StatCom system is experimentally verified on a low-voltage 7-level CHB-MC prototype. The experimental results show successful operation of the system with ripples as high as 90% of the nominal dc voltage. The required energy storage for the LC-StatCom system shows significant reduction compared to a conventional StatCom design.

Keywords: Cascaded H-Bridge, capacitor voltage filtering, StatCom, thin dc Capacitor

1. INTRODUCTION

THE cascaded H-bridge multilevel converter (CHB-MC) is a popular choice in many industrial applications due to its modularity, ability to decrease switching loss while maintaining excellent harmonic performance, and the possibility to eliminate the step-up transformer in medium voltage applications [1], [2]. An additional feature which makes this converter suitable for the StatCom application is its linear relationship between level number and component count [2], as opposed to monolithic multilevel converters where this relationship is quadratic.

Compared to monolithic multilevel converters, the requirement for isolated dc power sources is considered to be one of the main disadvantages [1]. However, in StatCom applications the isolated dc sources are floating capacitors and therefore the isolation requirement is easily met. The idea of using a CHB-MC as a StatCom was introduced in [3].
Thereafter, different aspects of this application for CHB-MC have been studied in the technical literature [4]-[24].

The three-phase CHB converter is constructed from three single-phase converters connected via a common star-point. This implies that each phase-leg must buffer the per-phase variations in instantaneous power that occur within each fundamental cycle, which is in contrast to monolithic multi-level converters which have a common dc-link. To buffer the energy variations, while still maintaining the necessary capacitor voltage to control the converter current, significant energy storage is required within each CHB phase-leg. This dictates the use of large H-bridge capacitance values, which has the following drawbacks:

- High direct cost of large dc capacitors.
- The indirect cost on reliability of the system due to the tendency of electrolytic capacitors to fail before other system components [25], [26].
- The indirect cost on cell protection due to the very large energy that is dissipated in the event of shoot-through of the dc-link. The significant weight and volume of the converter, which can make it difficult to containerise high-power StatComs.

Recently, the high reliability of film capacitors has become a major driving force in replacing electrolytic capacitors in power converters [27]-[30]. However, the relatively low capacitance values achievable with film capacitors, compared to electrolytic capacitors with the same volume, has limited the application of film capacitors in CHB-MC applications.

In typical CHB converters, the H-bridge capacitance values are chosen to limit variations in capacitor voltages to 10% of the nominal dc voltage [31]. There are two reasons why voltage variation must be limited. The first is that the peak voltage on each capacitor must be limited to avoid destruction of the associated semiconductor devices and to avoid lifetime reduction due to cosmic-ray failure rate implications [32]. The second reason is the lower limit on capacitor voltage variation, which is dictated by the need to maintain sufficient cluster voltage such that effective current control can be maintained throughout the fundamental cycle. Cluster voltage is defined as the sum of H-bridge capacitor voltages in one phase.

The main premise of the proposed approach in this paper is based on the observation that the lower limit on capacitor voltage variation can be significantly lowered when the V-I operating characteristic of the converter is somewhat restricted. It is shown that when operating in the capacitive region, the synthesized output voltage waveform has the same phase angle as the capacitor voltage ripple waveform. This implies current control can be maintained even when the cluster voltage reduces to almost zero.

Allowing larger capacitor voltage variations implies the use of significantly lower H-bridge capacitance values. The achieved reduction in the total stored capacitor energy will be shown in this paper. The required restrictions in the V-I operating characteristic will also be defined in this paper.

There are two main issues that need to be addressed to operate a CHB-MC with large H-bridge capacitor voltage ripples. Firstly, the bandwidth of the converter control system must be very high to maintain good voltage regulation on the thin-film capacitors. Secondly, the effect of high-magnitude low-order capacitor voltage harmonics on the control system and grid current needs to be minimized, while simultaneously maintaining high-bandwidth control of the capacitor voltages. This paper develops a control structure capable of achieving these goals within the proposed StatCom concept. The effect of low-order capacitor voltage harmonics on the control system is minimized by using an analytic filtering scheme which imposes negligible delay. This allows high-bandwidth control within the loop responsible for regulating the cluster voltage. Additionally, a dead-beat controller is utilized in this paper to obtain high-bandwidth current control [33], [34]. Feedforward compensation within the
PWM module is also used to mitigate any effect of capacitor voltage ripples on the grid current [35], which would otherwise be introduced from the modulation stage.

In a CHB-MC based StatCom, voltage variation on each H-bridge capacitor mainly manifests as a second order harmonic component. The ripple magnitude increases when the H-bridge capacitance decreases, which makes filtering of these voltages within the controller more challenging in the LC-StatCom. The cutoff frequency of the typically used low-pass filter for capacitor voltages is reduced while simultaneously the bandwidth of the voltage balance control loop is increased, causing difficulty in maintaining tight regulation of capacitor voltages during transients. In previous CHB-MC StatCom controllers these two requirements cannot be met simultaneously.

In [36], an analytic filtering scheme is introduced to overcome this challenge. The developed analytic filtering scheme predicts the behavior of ripple on the capacitor voltages and compensates its effect by subtracting the on-line estimate of the ripple. Therefore, it introduces no delay to the control system. This means the bandwidth of the control system is only limited by the inner loop current controller. However, no attempt has been made within this scheme to minimize the maximum voltage that semiconductors are exposed to. Furthermore, the proposed analytic formula considerably increases the computational burden.

In this paper, to complement the research done in [36], the issue of minimizing the maximum capacitor voltages is addressed. Furthermore, it has been shown previously in [37] (for typical CHB StatComs) that controlling the square of capacitor voltage results in a decoupled and linear cascaded control system. This paper utilizes the same concept to significantly reduce the computational power required to implement the analytic filtering scheme proposed in [36]. The use of complex capacitor voltage filtering is avoided as the ripple on the square of the capacitor voltages is sinusoidal (with a frequency equal to twice that of the grid frequency). Estimation of one sinusoidal waveform per-phase requires much less computational power compared to directly estimating mixed-frequency capacitor voltage signals. The rest of this paper is organized as follows. Section II provides the background on the CHB-MC based StatCom system. Analysis of the capacitor voltage ripple and the theoretical limits for reactive power exchange is provided in Section III. Experimental results are provided in Section IV. Finally, conclusions from the work are summarized in Section V.

2. LOW-CAPACITANCE STATCOM SYSTEM

In this section, a model of the CHB converter based low-capacitance StatCom (LC-StatCom) is introduced and an expression for the H-bridge capacitor voltages as a function of the converter current and grid voltage is derived. Fig. 1 shows a single-phase CHB converter LC-StatCom. A three-phase configuration is composed of three identical single-phase converters. Therefore, for the rest of this paper, without loss of generality, a single-phase system is considered.

3. CONTROL SYSTEM

The LC-StatCom control system is shown in Fig. 2, which comprises three sections, namely, (i) cluster voltage controller, which is responsible for regulating cluster voltage by controlling the active power flow, (ii) converter current controller, and (iii) individual capacitors’ voltage controller that is in charge of evenly distributing cluster voltage between sub-modules.

The individual capacitor voltage controllers use a separate PI controller to inject small ac voltage components, \( v \), in phase with the converter current to balance the capacitor voltages. The total injected components cancel each other out over the phase-leg to ensure no interference with outer control loops [37].
The current controller is based on a popular dead-beat current controller often used in variable speed drive applications [33], [34] to provide excellent dynamic current tracking performance. The dead-beat current controller uses a discretized version of (1) to calculate the appropriate voltage reference, as follows:

In (9), \( v_{\text{ref}} \) represents the total ac voltage reference of the converter, \( i_{g,\text{ref}} \) is the converter current reference value, and \( f_s \) is the sampling frequency. Superscripts \( k \) and \( k+1 \) indicate the quantity values at present and future instances, respectively. The input reference signal to the current controller, \( i_{g,\text{ref}} \), is composed of both active and reactive components. The active current reference, \( I_{d,\text{ref}} \), is generated by the cluster capacitor voltage controller, and the reactive current reference, \( I_{q,\text{ref}} \), defines the converter’s reactive current.

The cluster voltage controller uses the square of the sum of capacitor voltages to fulfill the decoupling condition with the individual voltage controllers [37]. The individual voltage controller balances the capacitor voltages by exchanging energy between the H-bridges in one phase, where the energy in each capacitor is proportional to the square of its voltage.

Therefore, the individual controller takes care of internal energy balance and the cluster voltage controller needs to act only when the total energy in the capacitors of a phase is not at the reference value. Hence, since both controllers deal with energy in the capacitors they do not interact with each other. As an example, for a simple case of a five-level converter, if the cluster voltage controller regulates the total energy in the capacitors to a value \( 2E \), then in the unbalanced condition where the energy in the first and second capacitors is \( E_1=E+dE \) and \( E_2=E-dE \), respectively, the action of the individual voltage controller in transferring \( dE \) from the first to the second capacitor will not require any action from the cluster voltage controller, which is the desired decoupled situation. This happens provided the cluster controller regulates the total energy in the phase, but not the total voltage. If the cluster controller targeted the regulation of the total voltage of the phase instead, it would try to take energy out of the leg in this example without being necessary and hence would be interacting with the internal controller.

Using the square of the voltages also linearizes the cluster voltage controller [37], which is important in the LC-StatCom system as will be discussed in the following analysis. The capacitor voltage reference in this system is not constant and varies throughout a wide range. Furthermore, the use of complex feedforward ripple compensation can be avoided because the ripple on the square of the voltages is sinusoidal:

\[
V_0^2 = V_0 \cdot \alpha \quad \text{and} \quad V_0^2_{\text{ref}} = \text{function of the reactive current reference.}
\]

In (10), \( V \) is the peak value of the generated ac voltage by the inverter and \( \alpha \) is its angle. \( V_0^2 \) is the square of the dc component in the cluster voltage, which is controlled by the cluster voltage controller. In this single-phase system, the ripple compensator block subtracts the oscillating part by estimating the ripple:

The estimated ripple is subtracted from the measured cluster voltage.

Remark: For three-phase systems the control loop responsible for regulating the sum of all the capacitor voltages inside the converter will not be affected by the sinusoidal ripple component as it will be canceled out between the phases. In the three-phase system the estimation of the ripple can instead be used in the control loop responsible for distributing capacitor voltage evenly between the phases.

In the proposed LC-StatCom system, \( V_0^2_{\text{ref}} \) is a function of the reactive current reference. The reason for having a variable...
capacitor voltage reference is to keep the maximum allowed voltage on the capacitors constant. Hence, $V_{0-ref}^2$ is generated by the capacitor voltage limiter (CVL) block to limit the maximum voltage on the capacitors. The CVL block in this paper has two operating modes, which are introduced in the following.

A. Normal Operating Mode

B. Extended Operating Mode

Converters are often thermally rated for short-term higher-power operation. It is suggested here that for a limited time the LC-StatCom can provide currents higher than the nominal current by temporarily increasing $V_{dc-max}$. The temporary increase would utilize the margin between peak capacitor voltage and maximum reverse blocking voltage of the semiconductors, typically included to minimize cosmic ray failure rates of semiconductors [38]-[40]. As the increase is temporary, the failure rate probabilities will not be greatly impacted.

In this operating mode, the CVL block will maintain the lower limit of the capacitor voltages while allowing $V_{dc-max}$ to exceed $aV_{gn}$. From (10), the total minimum voltage on the capacitors

\[
\frac{0.9 \, N \, I_{qn} \, (V_{gn}^2 \, X_L \, I_{qn})}{\sum |V_{c-j}|} \leq 0.2 \, (aV_{gn})^2 . \quad (19)
\]

With 10% ripple component, the maximum dc voltage for this system is approximately $1.1aV_{gn}$.
IV. LC-STATCOM I-V CHARACTERISTIC

LC-StatCom systems are demonstrated in Fig. 4. In this figure, the advantage of the LC-StatCom system over the conventional StatCom system can be easily seen. The figure

![Comparison between operation of LC-StatCom system and conventional StatCom system](image)

**LC-STATCOM (Capacitive)**  **Conventional STATCOM (Capacitive)**

Fig. 4. Comparison between operation of (a) LC-StatCom system and (b) conventional StatCom system.

![I-V characteristics of the proposed LC-StatCom system](image)

**Fig. 5. I-V characteristics of the proposed LC-StatCom system.**

In the inductive region on the other hand, the following inequality must be satisfied: shows that the LC-StatCom not only operates with higher ripple on each capacitor voltage, it also reduces peak capacitor voltage and hence voltage stress on each semiconductor.

The $I-V$ characteristic of the LC-StatCom is derived in the following analysis. Henceforth, to simplify the equations, the voltage drop on $X_L$ is neglected and balanced capacitor voltages are assumed. The analysis is performed for the theoretical limit of operation where $a=1$ and $b=0$. 
For the limit case ($a=1$, $b=0$, and $X_{(p.u)}=0$), from (16) $NI_{qn} = \omega CV_{gn}$. Hence, (23) is valid for the whole period ($0 < \theta \leq 2\pi$). Consequently, the $I-V$ characteristic of the LC-StatCom system is equal to the conventional StatCom system. To experimentally verify the proposed LC-StatCom system, a single-phase 7-level CHB converter was constructed. The photograph of the experimental setup is shown in Fig. 6, which parameters are given in Table I. The 240V grid voltage

![Image]

**Fig. 7. Operation of the LC-StatCom system, when delivering its nominal capacitive current.**

The next experiment studies operation under step reactive power change, where the reactive current reference is changed.
Fig. 9. Harmonics spectrum of the converter current supplied by (a) the proposed LC-StatCom system and (b) a conventional StatCom system.

Fig. 10. Filtered and unfiltered square of the capacitors’ voltage when the converter is delivering full load capacitive current.
Fi g. 14. Operatio n of the LC-StatCom under step change in the reactive current reference from capacitive to inductive at $t=t_0$.

Inductive region, the grid voltage is reduced to 80 V. Fig. 14 sh ows the resu lts when the LC-StatCom system was i tially de livering the rated capacitive current bef ore a step change to 3 A inductive current. The results demonstrate the capability of the LC-StatC om system to regulat e the maximum ca pacitor vo ltages in both inductive a nd capacitive operating re gions. Furthermore, stable operati n of the sy stem when m oving fr om inductive to capacitive region can be seen in Fig. 14. In this experiment , there is so me distortion in the current right after the transit on. This curr ent distortion is produced because the capacitor v ltages initially are too low for operation in the inductive region. Therefore, the controller priotizes reg u lating

Fi g. 16. Operatio n of the LC-StatCom when 5% fifth order harmonic is added to the grid vo ltage at $t=0.5$ s.
Fig. 17. Operation of the LC-StatCom when the grid voltage on phase $b$, $v_b$, drops to 0.2 p.u for five cycles at $t=0.5$ s.

Voltage is heavily unbalanced. The aximum capacitor voltage was maintained on each of the phases. Similar to the experimental results, while the capacitors voltage s are temporarily distorted the current does not follow the required reactive reference.

VII. CONCLUSION

A new low capacitance HB-MC based StatCom system has been introduced in this paper. Capacitor voltage ripples in the LC-StatCom system are increased to facilitate significant

REFERENCES


