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Low-Capacitance StatCom with Thyristor Switched Filter Inductor

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Abstract— In this paper, application of thyristor switched reactors as a filtering inductor for the cascaded H-bridge low-capacitance static compensator (LC-StatCom) is demonstrated. Replacing the fixed-value filter inductor with thyristor switched reactors reduces the overall energy storage capacity and voltage rating of the LC-StatCom. The proposed concept takes advantage of LC-StatCom's ability to synthesize high quality ac voltage to reduce the overall energy storage requirement of the filter inductance. Using modular filter inductor concept adds an additional degree of freedom to control the maximum voltage drop on the filter inductor by changing the inductance value. This additional capability decreases the overall voltage rating of the converter. The effects of adding the modular inductor unit on the I-V characteristic of the LC-StatCom are evaluated. The effectiveness of the proposed solution is demonstrated by simulation results on an 11-level 3 MVA LC-StatCom.

Keywords— Cascaded H-bridge, LC-StatCom, reactive power compensation, thyristor switched reactor.

I. INTRODUCTION

In many applications, requirement of multiple isolated dc sources is considered a disadvantage of cascaded H-bridge (CHB) multilevel converters. However, in StatComs, where the isolated dc sources are only capacitors, this drawback is eliminated. A CHB StatCom is a well-established and commercially available technology. Recent advancements in CHB StatCom technology covers a wide range of aspects including, fault tolerance and unbalanced load operation [1]-[5], voltage and current control [3]-[8], modulation based on model predictive control [9]-[11], PWM switching [1], [12], [13], and decentralized control design [14].

A CHB converter requires large capacitor banks to buffer the twice-frequency power oscillations. On the other hand, lower cost, weight, and volume along with improving reliability of the system are some of the main advantages of reducing the size of dc capacitors.

Reducing capacitance increases ripple on the capacitor voltages. This typically leads to unacceptable maximum dc voltage levels [15]. One way to limit the maximum voltage while increasing ripple on capacitor voltages is to use phase alignment of the inverter's ac side voltage and the capacitor voltage ripple [16]-[22]. However, such alignment, utilized in a so called low-capacitance StatCom (LC-StatCom), only occurs in the capacitive region.

LC-StatCom is suited for film capacitors due to the required low capacitance values and large voltage ripple. Due to the use of film capacitors, reliability of the LC-StatCom is expected to be high [23]. Furthermore, operating with low average dc capacitor voltage also results in lower switching losses [22]. In [16], the operational principal and different operation modes of StatCom with reduced capacitor size are outlined. [19] and [20] focused on improving the controller dynamics to regulate the peak capacitor voltage. In [16], the operational limit of the LC-StatCom is calculated. LC-StatCom by nature is not suitable to operate in the inductive mode, which is considered to be its main drawback. This drawback was addressed in [21], where an additional thyristor bypassed reactor was used in series with the filter inductor to provide symmetrical capacitive and inductive reactive power generation capacity.

As shown in [17], LC-StatCom uses the ripple on the capacitor voltage to generate higher quality ac voltages compared to a conventional StatCom with constant dc capacitor voltage. Hence, the size of required filter inductor could be reduced to achieve a similar current harmonic profile. However, when operating with low reactive current, the capacitor voltage ripple decreases and its positive effect on voltage total harmonic distortion (THD) diminishes, which leads to increased current total demand distortion (TDD). Therefore, LC-StatCom is unable to utilize its superior voltage quality and the filter inductance remains comparable to a conventional StatCom.

In this paper, a solution based on replacing the fixed inductor with a modular variable filter inductor is proposed. Using the proposed modular filtering inductor concept, the inductance increases as the current decreases to compensate for the adverse effect of reduced capacitor voltage ripple on the current TDD. The overall energy storage capacity of the proposed filter inductor remains significantly smaller than a fixed inductor, while maintaining current TDD lower than the allowed limit. Further, lower maximum voltage drop on the modular filter inductor results in reduced maximum voltage rating for the converter.

II. CHB LC-STATCOM

LC-StatCom's operational principle which is based on keeping the instantaneous capacitor voltage close to but higher than the absolute value of the grid voltage is shown in Fig. 1.

Fig. 1. Total capacitor voltages operating in capacitive mode. (a) LC-StatCom and (b) conventional StatCom.

Fig. 2. I - V characteristics of LC-StatCom.

In this figure, grid voltage is represented by v_g , and V_{gn} is its nominal value. V_{dc-max} and V_{dc-min} are the maximum and minimum allowed total dc voltages, respectively. v_{Cj} is the voltage across the capacitor of j th H-bridge. In the capacitive region, the main component of the capacitor voltage ripple and the absolute value of the grid voltage have an equal phase angle (neglecting losses). This allows for the ripple on the capacitors to grow without increasing the maximum capacitor voltage or going below the grid voltage.

The operational limits of LC-StatCom are shown in Fig. 2 [21]. In this figure, I_q represents the reactive current magnitude, V_g is the grid voltage magnitude, and $X_{L(p.u.)}$ is the normalized value of the filter inductance. As it can be seen in this figure, LC-StatCom cannot provide much inductive current at rated grid voltage. LC-StatCom with a symmetrical I - V characteristic requires adding additional filter inductors [21]. Therefore, for the rest of this paper only capacitive operating mode is assumed.

III. MODULAR FILTER INDUCTOR

THD of two-level PWM voltage generated by a H-bridge is defined as

Fig. 3. The proposed modular inductive filter concept.

Fig. 4. LC-StatCom's I - V characteristic using fixed and the proposed modular filter inductor.

$$THD = \frac{\sqrt{2V_{C-rms}^2 - V^2}}{V} \quad (1)$$

where, V is the peak magnitude of the generated sinusoidal ac voltage. V_{C-rms} is the rms value of the total capacitor voltage calculated as follows,

$$V_{C-rms}^2 = V_{C-max}^2 - \frac{VI_g}{2\omega C} \quad (2)$$

Therefore, at the rated current, where the capacitor voltage ripple is largest, THD is lowest. Hence, LC-StatCom can use a smaller inductor or lower switching frequency to satisfy its current quality target at its nominal load. However, when the current decreases, the capacitor voltage ripple is reduced and hence its beneficial effect on the quality of the output voltage reduces. This effect coupled with a smaller inductive filter (or lower switching frequency) pushes the current THD higher, which may exceed the regulation limits. Consequently, the filter inductor needs to be designed for the worst case scenario

Fig. 5. Operation principal of LC-StatCom with switched inductors.

of zero ripple, which means LC-StatCom cannot benefit from improved voltage quality to reduce the filter inductance.

In this section, a modular inductive filter concept based on thyristor switched reactors (TSRs) is introduced to address this problem. The proposed modular filter inductor is shown in Fig. 3. The inductance of the proposed filter inductor, L_f , is a function of the current, as follows:

$$L_f = \frac{mL_{f-n}}{[mI_{g(p.u)}]+1}, \quad I_{g(p.u)} < 1 \quad (3)$$

$$L_{f-n}, \quad I_{g(p.u)} = 1$$

L_{f-n} is the inductance value at the rated condition ($I_g=1$ p.u., $V=1$ p.u.), which is equal to L/m . From (3), the inductance reduces as the current increases. The voltage rating of the LC-StatCom with the proposed modular inductor is $1+X_{L(p.u)}/m$. Fig. 4 shows the effect of using the proposed modular filter inductor on the I - V characteristics of LC-StatCom.

Utilization of naturally commutated switches, such as thyristors to switch the inductors ensures the transition will happen at close to zero current where there is approximately zero energy stored in the magnetic field of the inductor, which would otherwise produce destructive over-voltages. Nevertheless, in high power applications a snubber circuit to control the voltage transients during thyristor turn off may be necessary. Thyristors are also relatively cheap, robust, and have very low conduction losses [24]. The current rating of these thyristors is m times lower than the rating of the semiconductors used within the LC-StatCom. The voltage rating is equal to the maximum voltage drop across the filtering inductor. Therefore, these switches have a fractional voltage and current rating compared to the converter.

The modular inductor solution will improve the current quality for light loads. Therefore, the modular filter inductor concept is also applicable to a conventional StatCom system. However, in this case the objective cannot be reducing the energy storage capacity of the inductor as the ripple on the capacitor voltages remains negligible and the synthesized ac voltage quality does not change with the current. Nevertheless, the StatCom can benefit from the modular inductor concept to

TABLE I
PARAMETERS OF THE SIMULATED LC-STATCOM SYSTEM

Symbol	Quantity	Values
V_{g-rms}	Grid voltage <i>rms</i> value	6 kV
C	H-bridge dc capacitance	9.2×10^{-3} F
L_{f-n}	Filter inductance	3.5 mH
V_{c-ref}	Capacitor reference voltage	1.9 kV
f_s	Sub-module switching frequency	500 Hz
f_g	Grid frequency	50 Hz
S	Converter nominal power	3 MVA
R_f	Filter inductor series resistance	0.2 Ω
f_v	Bandwidth of the voltage controller	10 Hz
f_i	Bandwidth of the current controller	100 Hz
N	Number of H-bridges	5

improve current quality under low currents. As the current magnitude decreases, the current THD increases. This effect can be countered by increasing the inductance value as much as m times. Here, the overall energy storage capacity of the inductor and the voltage rating of the converter remain unchanged. The proposed modular inductor concept improves current quality by increasing the filter inductance to the maximum allowed value without violating the maximum allowed voltage drop on the filter inductor. The effect of using such modular inductor on the conventional StatCom's I - V characteristic is shown in Fig. 5.

IV. SIMULATIONS

To determine the effectiveness of the proposed modular filter inductor an eleven-level single-phase CHB StatCom is simulated in MATLAB/Simulink. The parameters of this system are given in Table I.

This StatCom design can be converted into LC-StatCom by adjusting the value of capacitance to target specific maximum ripple, R , as follows,

Fig. 6. Overview of LC-StatCom system with modular filter inductor.

$$C = \frac{2I_{gn}V_n}{N\omega R(2-R)V_{C-max}^2} \quad (4)$$

where the subscript n represents the nominal parameter value. C is the capacitance of dc capacitors. Using 1900V as the maximum capacitor voltage, the capacitance of each H-bridge is 1.27 mF for reaching 70% maximum ripple ($R=0.7$). The overall diagram of the system is shown in Fig. 6.

The modular inductor controller activates or deactivates inductor branches based on reference current magnitude. For a system with m number of parallel inductors, the j th unit activates if the current reference exceeds $(j-1)/m$ p.u. Conversely, if the current goes below that threshold, the inductor goes offline. Both antiparallel thyristors share the same gate signal. When the gate signal is on, the switches start conducting (regardless of current magnitude or direction) to connect the parallel inductor. On the other hand, when the gate signal goes off, the conducting thyristor will remain conducting until the current goes below a certain value (ideally zero), after which the thyristor turns off. Operation around the threshold currents ($(j-1)/m$ p.u., $j=2, 3, \dots, (m-1)$) could cause chattering of thyristor

gate signals. This unwanted switching can easily be circumvented by introducing a hysteresis band in between the changeover of modes.

After each transition, the inductance value needs to be updated in the control system according to (3). The inductance affects mainly the operation of the voltage limiter and the current controller. The voltage limiter generates the reference signal, V_{0-ref}^2 , for the cluster voltage controller to maintain a maximum 9500V total dc voltage (1900V per capacitor) using (5).

$$V_{0-ref}^2 = \frac{V_{dc-max}^2}{N} - \frac{V_g + X_L I_{q-ref}}{2\omega C} I_{q-ref} \quad (5)$$

Therefore, after each change in the filter inductor structure, X_L needs to be updated in this block. The disturbance caused by parameter adjustment in this block is insignificant as it only causes a minor correction in the generated reference signal. The effect of changing inductance on the current controller on the other hand is substantial and could cause large disturbances if not handled properly. Therefore, for the current controller, a

Fig. 7. Capacitors voltages for LC-StatCom and StatCom systems

Fig. 8. Variation of current TDD and PWM ac voltage THD of StatCom and LC-StatCom systems.

Fig. 9. Current TDD profile using modular inductive filter.

predictive dead-beat controller is utilized where the model is updated each control period based on how many inductors are switched in during that period [21].

The cluster voltage controller and voltage balancing blocks are implemented using simple proportional integral controllers [6]. The PWM block uses a phase shifted PWM method to generate IGBT gate signals. The capacitor voltage filtering block uses a feedforward filtering technique to prevent the capacitor voltage ripple from propagating through the control system [16].

The variation of capacitors voltages at rated current for both LC-StatCom and StatCom systems are shown in Fig. 7. As it can be seen, the voltage ripple on the capacitors of LC-

StatCom is significantly larger than the capacitor voltage ripple for the conventional StatCom.

In Fig. 8, the measured current TDDs and voltage THDs are depicted for both LC-StatCom and StatCom. The maximum ripple in this LC-StatCom design reaches 70%. Both systems have the same switching frequency and inductor value. Here, the target is to keep TDD below 2.5%. Allowing for some margin of error, TDD_{max} is limited to 2.4%. TDD_{max} for both LC-StatCom and StatCom are the same, which means both systems need to utilize similar filter inductor to satisfy TDD requirement. The difference is that in a conventional StatCom TDD remains constant independent of the current, whereas, LC-StatCom's TDD decreases for higher current. Therefore, LC-StatCom can benefit from modular filter structure to lower its TDD_{max} , which then allows for utilization of lower L_{f-n} value (or lower switching frequency) to satisfy TDD requirements.

Based on the measured LC-StatCom's TDD profile, by using two parallel inductors L_{f-n} needs to be approximately 3.16 mH to keep the TDD_{max} below 2.4 threshold at 0.5 p.u current local maxima. The inductance of each inductor module is $2L_{f-n}$ which is 6.32 mH. Similarly by using three and four parallel inductor branches, L_{f-n} is 2.97 mH and 2.84 mH, respectively. The measured TDD profiles for each of these cases are shown in Fig. 9. As it can be seen the maximum TDD limit is satisfied in all of the cases. Therefore, the total energy storage capacity of the filter inductor decreases as the number of parallel branches increase ($E=0.5L_{f-n}I_{gn}^2$). However, technical limitations and complexity of the system limits the maximum feasible m value.

CONCLUSION

A modular filter inductor concept for LC-StatCom has been suggested to further reduce the energy storage capacity of the filter inductor. Furthermore, lower inductance reduces the voltage rating of the converter. The feasibility of the proposed system is verified through a detailed simulation on an eleven-level CHB LC-StatCom. The simulations show that the LC-StatCom's filter inductor's energy storage capacity using the proposed modular filter inductor can be significantly lower to satisfy a certain maximum current TDD objective.

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