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Adaptive Filtering Scheme for a Low-Capacitance StatCom

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Abstract—The use of film capacitors to substitute traditionally utilized electrolytic capacitors is a well-known trend in the power electronics industry as it significantly increases the overall reliability of the system. Control challenges arise due to the reduced capacitance of film capacitors with similar volume and weight as electrolytic capacitors. To address these control challenges, previous works have shown the good accuracy and fast dynamic performance of analytical filters to remove low-frequency capacitor voltage ripples. However, as these filters are based on an idealized mathematical model of the system, some harmonic content remains in the filtered signal due to discrepancies between the real system and utilized model, which deteriorates the overall performance of the system. In this paper, an improved adaptive filtering scheme for a low-capacitance static compensator (LC-StatCom) is proposed. The scheme mitigates both time delays and harmonic-contamination in the outer capacitor voltage control loop. Hence, the proposed solution allows the use of a high bandwidth controller and the generation of a current reference free of low-frequency harmonics. The effectiveness of the proposed approach is validated via simulation results on a seven-level 0.35-kVA single-phase LC-StatCom. The results demonstrate that the proposed solution overcomes drawbacks of previous schemes in terms of time response and filtering performance in steady-state operation.

Index Terms—Capacitor voltage filtering, cascaded H-bridge (CHB), multilevel converter, static synchronous compensator (STATCOM).

I. INTRODUCTION

In order to achieve further grid integration of distributed generation from renewable energy resources [1], [2], while enhancing voltage stability and the active power transmission capacity, the electricity network is being overhauled by adding flexible ac transmission systems (FACTS). The irregular nature of the power generation from renewable energy resources, together with the continuous fluctuation of loads, contribute to deteriorating the quality of the grid voltages. Static synchronous compensators (StatComs) are shunt-type FACTS devices based on voltage source converter principles that can support power systems with poor voltage regulation by means of dynamically injecting or absorbing the reactive power needed. Therefore, StatComs play an important role in the operation of modern transmission lines [3]–[5].

An industrially accepted implementation of the StatCom technology is based on the cascaded H-bridge (CHB) multilevel converter [6], [7], mainly due to (i) its fast dynamic response, (ii) ability to bring towards zero the tradeoff curve between switching losses and harmonic performance, (iii) its modular configuration, and (iv) the potential of direct connection to medium-voltage systems without having to necessarily increase the submodules' voltage rating. Fig. 1 shows a three-phase delta-connected CHB converter. In the CHB converter, each branch is mainly exposed to twice-fundamental-frequency variations in instantaneous power. As an approximate rule of thumb, StatCom designs limit capacitor voltage ripples to $\pm 10\%$ of the average dc-link voltage value in order to buffer these oscillations. This requires the use of high capacitance values, which increases the cost, volume, and weight of such systems. As reliability is a crucial factor, the use of film capacitors is driving the substitution of the commonly utilized electrolytic capacitors. However, a substantial increase in the converter volume and weight occurs due to the larger volume per Farad of film capacitors with respect to electrolytic capacitors.

Recently, a low capacitance StatCom (LC-StatCom) has been proposed [8]–[10], which is able to reduce the total capacitance by more than 50%. The key concept in this approach is an intentional operation with large voltage ripple on the dc-link capacitors. Significant improvements in converter efficiency and harmonic performance are also achieved when dealing with capacitive reactive power [11], [12]. This is possible due to a lower average capacitor voltage operation, and because the synthesized PWM voltage is shaped close to sinusoidal by the time-varying cluster voltage. Despite these advancements, the LC-StatCom technology is still under development and many research questions remain unanswered. For example, when dealing with large voltage ripples it is crucial to have an effective and fast filtering scheme to neither distort the current reference nor introduce significant delays in the control loop, which contributes to deteriorating the overall closed-loop performance. If the injected current into the grid presents significant harmonic distortion, the voltage at the point of common coupling (PCC) will consequently be distorted, affecting nearby customers.

In the outer control-loop of a conventional StatCom, a

simple low-pass filter or second-order bandpass filter is sufficient to remove the low magnitude ripple component of the cluster voltages. However, as the magnitude of the ripple increases, the bandwidth of the filter has to be reduced in order to obtain a more selective filter (e.g. the cutoff frequency of the low-pass filter has to be reduced), hence introducing an increased time delay in the control scheme which poses stability issues. On the other hand, the lower inertia in the capacitor voltages due to the reduced amount of energy storage requires a faster controller in the outer/cluster voltage loop to achieve similar transient performance as when deploying a conventional StatCom. Therefore, a tradeoff between filtering effectiveness and dynamic performance poses a challenging control problem. In [13], the effectiveness of an analytical filtering scheme is verified on a CHB StatCom under $\pm 30\%$ of dc-link voltage ripple. It outperforms the traditionally utilized second-order filters. The underlying idea of this filter consists of estimating the average value of the capacitor voltage at $t = t_0$, which requires the evaluation of a complete elliptic integral of the second kind due to its non-sinusoidal nature. Therefore, an increased complexity and higher computational burden constitute disadvantages of this approach. Moreover, the sensitivity of the ideal mathematical model to parameter variations becomes important as the ripple increases, leading to both phase and amplitude discrepancies between the instantaneous value of the actual ripple and its ideal estimation. These mismatches translate into undesired second-order harmonic oscillations in the filtered signal, and hence in the regulation error to be processed by the outer controller.

In this paper, an adaptive filtering scheme is proposed to solve the previous shortcomings. This filter is able to dynamically update the estimated values of the amplitude and phase of the capacitor voltage ripple so that an effective cancellation of it is achieved in steady-state operation. To achieve this functionality, the filtered signal is processed in an additional feedback loop in order to obtain the information about the differences in magnitude and phase between measurement and estimation, which lead to unwanted second-order contamination. Once the differences are determined, they are used to modify the system model parameters so that mismatches are removed. As a consequence, an almost perfectly sinusoidal output current is obtained, which implies a high-quality voltage at the PCC; and at the same time filtering requirements from the grid-side are reduced. An alternative filtering approach was presented in [14], in which a second-order generalized integrator (SOGI) estimates the peak capacitor voltage in an LC-StatCom. In this paper, the proposed adaptive filtering scheme is validated via simulations on a sevel-level 0.35-kVA single-phase CHB-based LC-StatCom and contrasted against the approaches in [13], [14].

The remaining sections of the paper are organized as follows. The viability and benefits of using low capacitance values are shown in Section II. The proposed adaptive filtering scheme is introduced in Section III. Simulation results are presented and discussed in Section IV. Some concluding remarks are given in Section V.

Fig. 1. StatCom based on a three-phase delta-connected CHB converter.

II. CAPACITANCE REDUCTION JUSTIFICATION

Due to the symmetry among phases of the converter, only a single branch is considered in this paper without loss of generality. Explicit branch/phase notation in the formulation is avoided. The voltage dynamic in the dc-link of the j^{th} H-bridge is defined as

$$C_j \frac{dv_{Cj}}{dt} = -i_{Cj} \quad (1)$$

Assuming capacitor voltage balance, an even distribution of the generated voltage, v_{out} , among the n cells per branch is achieved. In addition, if 100% efficiency is considered, the instantaneous power flowing at the dc-side of the j^{th} H-bridge can be expressed as a function of the ac-side variables as

$$p_j = v_{Cj} i_{Cj} = \frac{v_{out}}{n} i_{br} \quad (2)$$

Replacing i_{Cj} from (2) in (1) yields

$$C_j \frac{dv_{Cj}}{dt} = -\frac{v_{out} i_{br}}{n v_{Cj}} \quad (3)$$

The voltage generated by the converter and resultant current flowing through it are defined as $v_{out} = V_{out} \cos(\omega_g t + \alpha_v)$ and $i_{br} = I_{br} \cos(\omega_g t + \alpha_v + \varphi)$, respectively. If there is a sufficiently large number of submodules and/or a sufficiently high switching frequency it can be reasonably assumed that the harmonic content of the output voltage and current is almost zero. ω_g is the angular frequency of the grid voltage. V_{out} and α_v represent, respectively, the magnitude and phase difference with respect to the branch voltage to which the converter is connected, v_{br} , through the branch inductance L_{br} . It is

worth noting that in reactive power compensation applications, the angle α_v is determined by the size of the losses in the converter, which will require a finite amount of active power to maintain the capacitor voltages at their reference value. On the other hand, I_{br} and φ are the magnitude and phase difference with respect to the fundamental of the output converter voltage, v_{out} , respectively. The angle φ will ideally take the value $-\pi/2$ rad during capacitive operation, and $\pi/2$ rad during inductive mode, as the current is defined as flowing out of the converter. Solving the differential equation given by (3), a general expression for the capacitor voltages is derived:

$$v_{Cj} = \left(\left(\frac{aV_{out}}{n} \right)^2 - \frac{V_{out}I_{br}}{2n\omega_g C_j} (\sin(2\omega_g t + 2\alpha_v + \varphi) - \sin(2\alpha_v + \varphi)) - \frac{V_{out}I_{br}}{nC_j} \cos(\varphi) t \right)^{1/2} \quad (4)$$

where the initial condition is defined as $v_{Cj}(t_0 = 0) = aV_{out}/n$, a being a constant slightly higher than 1 (i.e., steady-state operation is assumed). It is worth noting that there is no circulating current flowing through the branches in the previous formulation.

Equation (4) describes the evolution of any capacitor voltage in the branch as a function of time. The amplitude of the ripple component is directly proportional to the per-module apparent power level ($S_m = \frac{V_{out}I_{br}}{2n}$), and inversely proportional to the per-module capacitance value, C_j . Fig. 2 shows that a phase alignment exists between the cluster voltage evolution, $v_{clus} \triangleq \sum_{j=1}^n v_{Cj}$, and the absolute value of the phase-to-phase voltage to which the converter branch is connected when the StatCom provides capacitive reactive power to the grid (most common operational condition). Hence, large voltage ripples will not compromise the current control (i.e., $v_{clus} \geq |v_{out}|$ for all the period of the 50-Hz-generated sine wave). Furthermore, the phase alignment allows a reduction in the average cluster voltage in comparison with a conventional StatCom and therefore, an increased ripple does not imply a larger peak voltage in the capacitors. Nevertheless, if reactive power is to be “consumed”, i.e. inductive reactive power is to be injected into the grid, this phase alignment ceases to be fulfilled. Therefore, the amount of inductive reactive power that the LC-StatCom can inject is limited due to the significant reduction in the lower limit on the instantaneous capacitor voltages [8]. The LC-StatCom proposed in [15] solves the inductive operational range constraint without increasing the voltage rating of the converter. An additional switched inductor is added to each phase of the LC-StatCom during inductive operation so that the required output converter voltage has a lower peak value due to the increased voltage drop in the inductor, thereby allowing larger capacitor voltage ripple.

A lower average capacitor voltage in the LC-StatCom technology offers a reduction in the switching power loss compared to traditional StatCom converters, enhancing the overall efficiency of the system [11]. This is due to the strong dependency between switching loss and the dc-link voltage at

Fig. 2. Simulation results illustrating the performance of the LC-StatCom during full capacitive operation (using Table I parameters). Top plot: Branch voltages; bottom plot: branch current.

the time of each switching event. Furthermore, as the semiconductor switches are exposed to lower voltage stress, increased reliability and life span, together with a cost reduction, are expected. In addition, superior quality of output voltage and current waveforms as the synthesized PWM voltage is shaped close to sinusoidal by the oscillating dc-link voltage (Fig. 2) has also been confirmed [12]. It is worth noting that all these benefits rely on the magnitude of the current, which determines the capacitor voltage ripple magnitude (i.e., the maximum ripple amplitude is achieved at rated load operation).

III. ADAPTIVE FILTERING SCHEME FORMULATION

In this section, the feedback loop responsible for adapting the ripple estimator is formulated. The control scheme of a single-phase LC-StatCom is divided in three different subsections, namely: 1) cluster voltage controller, which determines the required active power level to compensate for losses in the converter so that the cluster voltage does not deviate from its reference value; 2) current controller, which delivers the voltage reference; and 3) balancing controller, which equally distributes the cluster voltage among submodules. In this paper, the ripple compensator block is improved by means of feeding back the regulation error, $\tilde{z}$, which constitutes the input of the cluster controller as depicted in Fig. 3. The rest of the control system remains unmodified from that presented in [8].

The sum of the square of the capacitor voltages, $z_{clus} \triangleq \sum_{j=1}^n v_{Cj}^2$, is the adopted signal to be filtered due to its sinusoidal nature. The use of this measure, which is proportional to the instantaneous stored energy in the dc-link, instead of the cluster voltage allows one to both avoid the use of complex feedforward ripple estimators [8] and provides linearization of the cluster voltage control loop (easing the design of the cluster controller). This effectively decouples the cluster controller and the balancing controller [16].

By using (4), the ideal expression for the sum of the square of the capacitor voltages per phase branch, z_{clus} , is derived

measured value of the sum of the square of the capacitor voltages. The regulation error is defined as

$$\tilde{z} \triangleq Z_{dc}^* - \underbrace{(z_{clus} - z_e)}_{z_f} \quad (12)$$

with $Z_{dc}^* = nV_{C,max}^2 - \frac{V_{out}^* I_{br}^*}{2\omega_g C_m}$ during “normal operating mode” (i.e., when the StatCom operates below its rated value), with $V_{C,max}$ the desired peak value for the capacitor voltages. On the other hand, when operating in “extended operating mode”, the reference for the dc component in (5) is replaced by $Z_{dc}^* = nV_{C,min}^2 + \frac{V_{out}^* I_{br}^*}{2\omega_g C_m}$ in order to keep regulated the minimum value in the capacitor voltages, while allowing a temporary increase in their maximum value so that higher current than the rated value can be provided.

To simplify the formulation, $\psi \triangleq 2\omega_g t + \theta$ is defined. Expanding (12), the following expression for the regulation error is obtained

$$\tilde{z} \approx (Z_{dc}^* - Z_{dc}) + [A(1 - \cos(x_\theta)) + x_A \cos(x_\theta)] \sin(\psi) + [A \sin(x_\theta)] \cos(\psi) \quad (13)$$

where harmonic-components higher than the second one have not been considered.

Therefore, the regulation error can be viewed as a phasor rotating at two-times the grid voltage angular frequency (i.e. $2\pi \cdot 100 \text{ rad/s}$), defined by a direct component, $\tilde{z}^d$, a quadrature component, $\tilde{z}^q$, and a dc-term. It is noted that the d - and q -components are coupled by the difference in phase x_θ . Note that the error is expressed in rectangular form instead of polar form. This will ease the derivation of the differences in amplitude and phase provided by the ripple estimator, x_A and x_θ , respectively.

The operation of the adaptive filter is described next. A bandpass filter is deployed in the added feedback loop to obtain the predominant second-order component in the regulation error, which together with its in-quadrature signal are used to extract the dq components of $\tilde{z}$ as per (13). The required orthogonal $\alpha\beta$ components are obtained by introducing an eighth of the grid-voltage period time delay to the second-order component of $\tilde{z}$. This is because the grid angular frequency, $\omega_g = 2\pi/T_g$, is being used to obtain the in-quadrature signal of a signal of twice the grid frequency. As the information of the real amplitude and phase are unknown, the dq components in (13) have to be stated in terms of the estimated values. In addition, the Maclaurin series up to the 2^{nd} term of x_θ is utilized to simplify the model (i.e., $\sin(x_\theta) \approx x_\theta$, and $\cos(x_\theta) \approx 1 - x_\theta^2/2$).

$$\tilde{z}^d = (A_e + x_A)(1 - \cos(x_\theta)) + x_A \cos(x_\theta) \approx A_e \frac{x_\theta^2}{2} + x_A \quad (14)$$

$$\tilde{z}^q = (A_e + x_A) \sin(x_\theta) \approx A_e x_\theta \quad (15)$$

Solving the previous set of equations, the following definitions are obtained for the differences between the estimated and actual values:

$$x_A = \tilde{z}^d - 0.5x_\theta \tilde{z}^q \quad (16)$$

$$x_\theta = \tilde{z}^q / A_e \quad (17)$$

Therefore, if the filtered signal contains some second-order harmonic contamination, which is quantified by $\tilde{z}^d$ and $\tilde{z}^q$, the responsible x_A and x_θ can be determined to update the estimations and bring the second-harmonic content in z_f closer to zero.

The objective of the added feedback loop is to set the differences x_A and x_θ equal to zero, or equivalently set the dq components of the regulation error to zero. This is possible by processing x_A and x_θ through a PI controller. The bandwidth of such controllers is bounded mainly by the delay introduced by the bandpass filter, which isolates the second-harmonic from the regulation error signal, and the transport delay, which generates the quadrature component.

Remark: For three-phase systems, the controller in charge of determining the required active power level to compensate for losses (d -component of the grid current references) will not be affected by the sinusoidal ripple component as the sum of the square of the capacitor voltages are 120 deg phase shifted among phase legs, hence it cancels out when adding them together. Nevertheless, the estimation of the ripple can instead be used in the control loop responsible for distributing the capacitive stored energy evenly among the phases (e.g. to design the circulating current reference in a delta-connected StatCom, which will transfer energy from the most charged phase/s to the least charged phase/s).

IV. SIMULATION RESULTS

In this section, the effectiveness of the proposed adaptive filtering scheme is demonstrated. In addition, a comparison with previous works [13], [14] proves its superiority in terms of transient-response and filtering accuracy. A peak-to-peak ripple in the capacitor voltages of 60% is selected to demonstrate its viability in an LC-StatCom device. The ripple is defined as $r = (1 - v_{C,min}/V_{C,max})$, where $v_{C,min}$ corresponds with the minimum instantaneous value of the capacitor voltage over a fundamental period. At rated conditions the capacitor voltage ripple is maximum. Hence from (5) a general expression for the per unit ripple r is obtained as a function of the per branch nominal power $S_{br} = V_{br} I_{br}/2$, where V_{br} is the peak value of the phase-to-phase voltage to which the converter branch is connected through the branch inductance,

$$r = 1 - \left(1 - \frac{2S_{br}(1 + X_{L_{br}(p.u.)})}{n\omega_g C_m V_{C,max}^2} \right)^{1/2} \quad (18)$$

in which $X_{L_{br}(p.u.)}$ is the per unit branch filter reactance.

A sudden change in the reactive power level reference is studied. As mentioned above, a change in the reactive

TABLE I. SIMULATION PARAMETERS

Symbol	Definition	Value
V_{br}	Peak value of the branch voltage	$110\sqrt{2}$ V (1 p.u.)
S_{br}	Nominal branch power	350 VA (1 p.u.)
n	Number of H-bridges per branch	3
f_{sw}	Switching frequency per H-bridge	2 kHz
$V_{C,max}$	Peak capacitor voltage reference	60 V
C_m	Capacitance per H-bridge	0.26 mF
L_{br}	Branch inductance	5 mH
R_{br}	Parasitic resistance of the branch filter	0.2 Ω
K_P	Proportional gain of the adaptive filtering PIs	0.6
K_I	Integral gain of the adaptive filtering PIs	4
ζ_1	Damping ratio of the bandpass filter used in the adaptive loop	0.1
ζ_2	Damping ratio of the SOGI	0.707
f_r	Center frequency of the bandpass filter and SOGI	100 Hz

power will translate into a change in the reference dc/average component of $\sum_{j=1}^n v_{Cj}^2$ so that the capacitor voltages' peak remains unchanged when the ripple amplitude varies. The MATLAB/Simulink environment was used to implement the simulations. Table I presents the converter parameters that were simulated.

The transient performance of the LC-StatCom under a sudden step change in the capacitive reactive power level is illustrated in Figs. 4 and 5. In Fig. 4, the proposed adaptive filtering scheme is deployed, whereas in Fig. 5 a SOGI is used to estimate the average value of the sum of the square of the capacitor voltages [14]. The step change was from full to 33% capacitive operation at time $t = 3.0$ s, and from 33% to full load again at time $t = 3.1$ s. As can be seen, the transient performance of the adaptive filter is extremely fast. From comparing the bottom plot in Figs. 4 and 5 it can be seen that a faster dynamic in the capacitor voltages results when using the proposed adaptive filter, which is feasible due to the higher bandwidth allowable in the cluster controller. A reduction in the bandwidth from 283 rad/s to 28 rad/s was required due to stability issues when the SOGI was used as the estimator. It can be noted the correct regulation of the peak capacitor voltage values for different reactive power levels. As it can be seen, the proposed scheme was able to filter out the low-frequency ripple effectively.

Fig. 4. General performance of the LC-StatCom with fast cluster controller during a sudden reactive power change at time $t = 3.0$ s and $t = 3.1$ s, when the adaptive filtering scheme was used. Top plot: filtering performance; middle plot: branch current; bottom plot: capacitor voltages.

Fig. 5. General performance of the LC-StatCom with slower voltage controller during a sudden reactive power change at time $t = 3.0$ s and $t = 3.1$ s, when the SOGI [14] was used. Top plot: filtering performance; middle plot: branch current; bottom plot: capacitor voltages.

Fig. 6 shows how the steady-state performance is further improved when using the proposed solution in comparison with the original analytic scheme [13], achieving a filtered signal almost free of second-order harmonic. This translates into an improvement of the weighted total harmonic distortion in the output current as its third harmonic is reduced approximately 46%. It is worth mentioning that the added feedback loop in the adaptive filtering scheme does not deteriorate the fast response of the analytic filter as it only modifies the estimated values so that they become approximately equal to

Fig. 6. Performance of the analytic filtering schemes during steady-state operation at full capacitive reactive power, when the adaptive filtering scheme, and the original filter [13] were used.

Fig. 7. Filtering performance of the SOGI [14] during a sudden reactive power change at time $t = 3.0$ s and $t = 3.1$ s, when the fast and slower voltage controller were used.

the measured values in the steady-state. The time in which these discrepancies will be mitigated is dictated by the design of the added feedback loop, i.e. the quality factor of the bandpass filter and the proportional-integral gains.

Fig. 7 depicts the dynamic estimation of the average value of the sum of the square of the capacitor voltages performed by the SOGI. It is evident in the figure how the bandpass characteristic of the SOGI introduces a large delay in the cluster voltage loop, which leads to an underdamped response with high settling time when high bandwidth outer controllers are utilized. Therefore, a slower controller is required, which will slow down the transient performance of the system. However, in the proposed adaptive scheme there is no need for this bandwidth reduction.

V. CONCLUSION

This paper has proposed and verified by means of simulations an adaptive analytic-based filtering scheme to cancel out the high magnitude low-frequency ripple on the capacitor voltages of a CHB multilevel converter-based LC-StatCom. The main advantages of the proposed scheme are that it allows the use of faster voltage controllers in the outer loop, which improves the transient performance of the system; and it is much more effective in filtering than the original non-adaptive approach, which results in reference currents free of harmonics during steady-state operation.

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