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Passivity Control in Multilevel Cascaded H-Bridge Converters: A Variable Gain Approach

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Abstract—This paper proposes a multi-input linear time-variant control law based on the incremental passivity theory for cascaded H-bridge (CHB) low-capacitance static compensators (LC-StatComs). The proposed control law guarantees global asymptotic stability of the system and controls the capacitor voltages and inductor current without assuming fast dynamics in the current and slow dynamics in voltages. This is particularly important for LC-StatCom applications as the control of the inductor current and capacitor voltages are inherently coupled due to the reduced capacitance. After introducing the incremental model of the converter, a passivity-based control that ensures the global stability is derived. Simulation results on a seven-level 1-kVA CHB LC-StatCom are shown to corroborate its excellent performance in steady-state and during transients.

Index Terms—Bilinear system control, cascaded H-bridge (CHB), incremental passivity, multi-input global tracking, multilevel converter, static synchronous compensator (STATCOM)

I. INTRODUCTION

The recently proposed low-capacitance static compensator (LC-StatCom), based on the cascaded H-bridge (CHB) multilevel converter [1]–[8], represents an efficient and low-cost solution for reactive power compensation in power grids. However, the existent coupling between voltage and current dynamics in the LC-StatCom, poses several control challenges. For instance, it limits the application of the classical cascaded control schemes [9]–[13], where the bandwidths associated with the nested control loops of the inductor current and the capacitor voltage are designed to be comparatively different in order to avoid interactions between them. The circuit diagram of the CHB power converter arm and its cascade control block diagram are depicted in Figs. 1(a) and (b), respectively.

In a cascade control scheme, the outer capacitor voltage loop regulates the dc component of the square-sum-capacitor-voltages (denoted as $z_{clus} = \sum_{j=1}^n v_{C_j}^2$, where v_{C_j} is the capacitor voltage in the j^{th} H-bridge, and $j \in \{1, 2, \dots, n\}$ is the H-bridge index in the converter arm) to the reference z_{clus}^* . This aim is effectively achieved by calculating the required active power component of the arm current $\hat{I}_d^*$, which together with its reactive counterpart $\hat{I}_q^*$, constitute the current reference for the inner current loop.

In order to avoid the imposition of ensuring different bandwidths that is inherent in the cascade control schemes, this paper proposes a multi-input time-varying control law based on the incremental passivity theory for the LC-StatCom [14]–[16]. This robust nonlinear approach provides fast and damped

Fig. 1. CHB power converter arm. (a) Circuit diagram and (b) control block diagram.

transient responses while controlling the capacitor voltages and inductor current with similar bandwidth. Furthermore, unlike the conventional cascade control schemes, the global asymptotic stability is guaranteed even if the averaged control inputs of the modulator are saturated.

Another important feature of the proposed control approach is that it does not assume a perfect balancing in capacitor voltages [17], [18]. Thus, as the proposed control drives each switching signal with a different control law, voltage balancing is a consequence of the tracking objectives. This control approach also differs from the classical current regulation problem in the dq frame [19]–[21], since the tracking variables are the measurable ones. Consequently, the proposed control law in this paper is multi-input and time-varying, which avoids the use of a voltage balancing strategy in addition to the control stage, and the utilisation of reference frame transformations.

In addition, losses of the system are also considered in the model, which improves the accuracy of the model and hence, the control performance. Linearity is an additional important feature of the proposed control law, which is achieved in spite of inherently bilinear nature of the system. Having a linear

control law is especially important in practice, as it makes the implementation straightforward. Once the global asymptotic stability is ensured, a small-signal analysis is carried out in order to determine the value of the control parameter that ensures a satisfactory behaviour of the system in the neighborhoods of the equilibrium path.

The rest of this paper is organised as follows. First, it reviews the CHB converter model in Section II. The control law, which is adapted to the multilevel nature of the CHB converter, is derived in Section III. Section IV reports simulation results, which show excellent steady-state performance, very fast and robust transient responses under large-signal perturbations, and effective capacitor voltage balancing capability. Finally, Section V summarizes and concludes the main ideas in the paper.

II. CASCADED H-BRIDGE CONVERTER DYNAMICS

This section reviews the CHB converter topology, its state variables, and its exact piecewise continuous dynamics. Then, the averaged dynamics of the converter are derived, which allows formulating its incremental representation (i.e., its transient behaviour) given a coherent reference trajectory.

The converter topology, shown in Fig. 1(a), represents a power converter arm of the CHB converter. A smoothing inductor L is interfacing the power converter with the grid. The power converter arm consists of n series-connected H-bridges. Each H-bridge is made up of a floating capacitor C_j at the dc-side, and four semiconductor power switches that determine the pulse-width modulated (PWM) output voltage of the H-bridge.

The inductor current i_L and the n capacitor voltages $v_{C_1}, v_{C_2}, \dots, v_{C_n}$ are the state variables for describing the dynamic behaviour of the CHB converter. The variable v_g stands for the grid voltage, which is a noncontrollable input. The set of switching positions of each H-bridge S_j are taken as the control inputs. The state variables are grouped in the state vector $\mathbf{x} \in \mathbb{R}^{n+1}$ as:

$$\mathbf{x}(t) = [i_L(t) \ v_{C_1}(t) \ v_{C_2}(t) \ \dots \ v_{C_n}(t)]^T. \quad (1)$$

The losses of each H-bridge are modelled with a resistance R_{SM_j} in parallel with the capacitor C_j , whereas the parasitic resistance of the inductor L and semiconductor conduction losses are modelled with the series resistance R_L , as depicted in Fig. 1(a).

The dynamic model of the converter, considering independent switching of each H-bridge, corresponds to the following $n+1$ differential equations:

$$L \dot{i}_L(t) = -R_L i_L(t) + \sum_{j=1}^n v_{C_j}(t) S_j(t) - v_g(t) \quad (2)$$

$$C_j \dot{v}_{C_j}(t) = -i_L(t) S_j(t) - \frac{v_{C_j}(t)}{R_{SM_j}}, \quad (3)$$

where $\forall j \in \{1, 2, \dots, n\}$, and the discrete term S_j that drives the j^{th} H-bridge belongs to the set $S_j \in \{-1, 0, 1\}$.

It is noted that the control inputs (S_j) multiply the state variables (i_L and v_{C_j}), hence state model results in a bilinear dynamics [22]. Thus, the proposed CHB converter model is nonlinear, with dimension of $n+1$ and with n control inputs. In addition, model variables are time-varying and piecewise continuous due to the switching nature of the converter.

The exact model in (2)-(3) can be approximated by an averaged one with the continuous state variables,

$$L \dot{\bar{i}}_L(t) = -R_L \bar{i}_L(t) + \sum_{j=1}^n \bar{v}_{C_j}(t) \delta_j(t) - v_g(t) \quad (4)$$

$$C_j \dot{\bar{v}}_{C_j}(t) = -\bar{i}_L(t) \delta_j(t) - \frac{\bar{v}_{C_j}(t)}{R_{SM_j}}, \quad (5)$$

where $\forall j \in \{1, 2, \dots, n\}$, and $\bar{\mathbf{x}} = [\bar{i}_L \ \bar{v}_{C_1} \ \bar{v}_{C_2} \ \dots \ \bar{v}_{C_n}]^T$ stands for the averaged current and voltage state variables. The averaged control input of the modulator δ_j is determined by the proposed controller in order to track the state reference. The switching period is assumed much faster than the converter time-constants, and much faster than $2\pi/\omega_{r_j}$, where $\omega_{r_j} = 1/\sqrt{LC_j}$ is the j^{th} resonant frequency of the converter.

The incremental state variables $\tilde{\mathbf{x}}$ and the incremental control input $\tilde{\delta}_j$, or error signals with respect to their references $\bar{\mathbf{x}}^*$ and δ^* , respectively, can be defined as follows:

$$\tilde{\mathbf{x}}(t) = \bar{\mathbf{x}}(t) - \bar{\mathbf{x}}^*(t) \quad (6)$$

$$\tilde{\delta}_j(t) = \delta_j(t) - \delta^*(t), \quad (7)$$

where $\forall j \in \{1, 2, \dots, n\}$. Thus, the incremental averaged dynamics of (4)-(5), given that the reference signals are coherent, correspond to:

$$\begin{aligned} L \dot{\tilde{i}}_L(t) = & -R_L \tilde{i}_L(t) + \delta^*(t) \sum_{j=1}^n \tilde{v}_{C_j}(t) \\ & + \bar{v}_C^*(t) \sum_{j=1}^n \tilde{\delta}_j(t) + \sum_{j=1}^n \tilde{v}_{C_j}(t) \tilde{\delta}_j(t) \end{aligned} \quad (8)$$

$$\begin{aligned} C_j \dot{\tilde{v}}_{C_j}(t) = & -\frac{\tilde{v}_{C_j}(t)}{R_{SM_j}} - \delta^*(t) \tilde{i}_L(t) \\ & - \bar{i}_L^*(t) \tilde{\delta}_j(t) - \tilde{i}_L(t) \tilde{\delta}_j(t), \end{aligned} \quad (9)$$

where $\forall j \in \{1, 2, \dots, n\}$. It is noted that the dynamic of the incremental system in (8)-(9) is bilinear periodically time-varying [23].

This section has stated the notations of the incremental model, which will be used in the following section to derive the proposed control law for the CHB converter that guarantees the global tracking of the desired current and voltage references.

Fig. 2. Block diagram of the proposed incremental passivity-based control.

III. PROPOSED MULTI-INPUT LINEAR TIME-VARYING CONTROL LAWS FOR LARGE-SIGNAL STABILITY IN CHB CONVERTERS

In this section, the proposed control law, which tracks the desired LC-StatCom references, is described. It is based on passivity concepts. The control law considers n inputs and n outputs, where parameters are periodically time-varying. Each control input corresponds to an H-bridge within the converter arm. Despite the bilinear time-varying nature of the incremental dynamics, the resulting control law is linear, and ensures large-signal stability and provides a fast and damped response.

Fig. 2 depicts the scheme of the proposed incremental passivity-based control, applied to the CHB converter. The converter is synchronized with the grid by using a phase-locked loop (PLL) to provide $\omega_g t$. Subsequently, the reference signals $\bar{i}_L^*$, $\bar{v}_{clus}^*$ and δ^* are calculated using the steady-state reference generation algorithm. Finally, the passivity control-based multi-input block is developed to generate the averaged control inputs, which are fed to the phase-shifted carrier PWM (PSC-PWM) [24], [25] block to generate the switching signals.

The analysis of the proposed control law is derived multi-plying (8) by the incremental current $\tilde{i}_L$, and multiplying (9) by the incremental voltage $\tilde{v}_{C_j}$, yielding,

$$L\tilde{i}_L\dot{\tilde{i}}_L = -R_L\tilde{i}_L^2 + \delta^*\tilde{i}_L \sum_{j=1}^n \tilde{v}_{C_j} + \bar{v}_C^*\tilde{i}_L \sum_{j=1}^n \tilde{\delta}_j + \tilde{i}_L \sum_{j=1}^n \tilde{v}_{C_j}\tilde{\delta}_j \quad (10)$$

$$C_j\tilde{v}_{C_j}\dot{\tilde{v}}_{C_j} = -\frac{\tilde{v}_{C_j}^2}{R_{SM_j}} - \delta^*\tilde{i}_L\tilde{v}_{C_j} - \bar{i}_L^*\tilde{v}_{C_j}\tilde{\delta}_j - \tilde{i}_L\tilde{v}_{C_j}\tilde{\delta}_j, \quad (11)$$

where $\forall j \in \{1, 2, \dots, n\}$.

Adding the $n+1$ differential equations in (10)-(11), the following expression can be obtained:

$$\left(L\tilde{i}_L\dot{\tilde{i}}_L + \sum_{j=1}^n C_j\tilde{v}_{C_j}\dot{\tilde{v}}_{C_j} \right) = - \left(R_L\tilde{i}_L^2 + \sum_{j=1}^n \frac{\tilde{v}_{C_j}^2}{R_{SM_j}} \right) + \sum_{j=1}^n (\bar{v}_C^*\tilde{i}_L - \bar{i}_L^*\tilde{v}_{C_j})\tilde{\delta}_j. \quad (12)$$

It is noted that the left-hand-side of (12) corresponds to the incremental power in the inductor and n capacitors, and the first term at the right-hand-side is the incremental power dissipated in the system losses/parasitics, which only adds dissipativity to the system. The n feedback outputs can be defined as:

$$y_j = \bar{v}_C^*\tilde{i}_L - \bar{i}_L^*\tilde{v}_{C_j}, \quad (13)$$

where $\forall j \in \{1, 2, \dots, n\}$. Therefore, (12) can be rewritten as:

$$\dot{V}(\tilde{x}) < \sum_{j=1}^n y_j\tilde{\delta}_j, \quad (14)$$

where

$$V(\tilde{x}) = \frac{1}{2} \left(L\tilde{i}_L^2 + \sum_{j=1}^n C_j\tilde{v}_{C_j}^2 \right), \quad (15)$$

represents a storage function of the incremental model (8)-(9), which is globally positive defined and radially unbounded.

From (14), it can be concluded that the incremental system has a passive relationship between the output feedback y_j and the control input $\tilde{\delta}_j$ [26], [27]. Thus, by feeding back the j^{th} output y_j times a positive gain $\alpha \geq 0$, which means that the feedback control law is

$$\tilde{\delta}_j(t) = -\alpha y_j(t), \quad (16)$$

where $\forall j \in \{1, 2, \dots, n\}$, the time derivative of the storage function becomes globally negative defined, i.e., $\dot{V}(\tilde{x}) < 0$. This proves that the incremental dynamics tend to zero. Consequently, the equilibrium is globally asymptotically stable, and the system tends towards the references from any initial condition. It can be noted that even though the nonlinear nature of the LC-StatCom is considered in the derivations, the calculated control law in (16) is linear.

Once global asymptotic stability has been guaranteed, a small-signal analysis can be performed in order to determine the value for the control parameter α around the equilibrium point. A small-signal analysis implies that both bilinear terms in the incremental dynamics (8)-(9), and the saturation of the control input (16), are neglected. In addition, neglecting losses, the small-signal model of the CHB converter is obtained, which is linear periodically time-varying,

$$L\dot{\tilde{i}}_L(t) = \delta^*(t) \sum_{j=1}^n \tilde{v}_{C_j}(t) + \bar{v}_C^*(t) \sum_{j=1}^n \tilde{\delta}_j(t) \quad (17)$$

$$C_j \dot{\tilde{v}}_{C_j}(t) = -\delta^*(t) \tilde{i}_L(t) - \tilde{i}_L^*(t) \tilde{\delta}_j(t), \quad (18)$$

where $\forall j \in \{1, 2, \dots, n\}$. The following transfer function from the output of the j^{th} subsystem y_j (variable to be controlled) to its corresponding incremental input $\tilde{\delta}_j$, can be derived as

$$\frac{y_j(s)}{\tilde{\delta}_j(s)} = \bar{v}_C^* \frac{\tilde{i}_L(s)}{\tilde{\delta}_j(s)} - \tilde{i}_L^* \frac{\tilde{v}_{C_j}(s)}{\tilde{\delta}_j(s)}, \quad (19)$$

where $\forall j \in \{1, 2, \dots, n\}$, s being the Laplace transform complex variable. Using (17)-(18), (19) is rewritten as

$$\frac{y_j(s)}{\tilde{\delta}_j(s)} = \frac{1}{LC} (C \bar{v}_C^{*2} + L \tilde{i}_L^{*2}) \frac{s}{s^2 + \frac{\delta^{*2}}{LC}}, \quad (20)$$

where the capacitance value C_j in each H-bridge is assumed to be equal to C . It is noted that for every operating point along the output sinusoid, there will be both a different location of the system poles and a different value of the gain.

Once the control law is applied to the system, the loop gain is defined as $T(s) = \alpha \frac{y_j(s)}{\tilde{\delta}_j(s)}$, and the closed-loop poles are obtained as the solution for $1 + T(s) = 0$ as

$$s_{1,2} = \frac{\beta}{2} \left(-1 \pm \sqrt{1 - 4 \frac{\delta^{*2}}{\beta^2 LC}} \right), \quad (21)$$

with

$$\beta = \frac{\alpha}{LC} (C \bar{v}_C^{*2} + L \tilde{i}_L^{*2}) \geq 0. \quad (22)$$

In order to avoid oscillations and achieve the fastest possible transient response, regardless of the operation point (i.e., critically damped response, with double real roots at $s_{1,2} = -\frac{\beta}{2}$), the discriminant of $1 + T(s)$ has to be equal to zero, which is true if

$$\alpha = \frac{|\delta^*| \sqrt{LC}}{\frac{1}{2} (C \bar{v}_C^{*2} + L \tilde{i}_L^{*2})} \geq 0. \quad (23)$$

Choosing this value for α implies that the gain of the feedback loop depends on the operating point. This means that the control gain is adjusted according to the variable operating point. It is noted that the lower the energy, the higher the value of the gain α that contributes to dissipate (together with the system losses) the incremental energy that arises during transient events. Having a time-varying feedback gain allows to have a constant damping ratio regardless of the operation point. However, the settling time differs depending on the operation point. This is because the repeated real closed-loop poles depend on the operating point as $s_{1,2} = -\frac{|\delta^*|}{\sqrt{LC}}$.

IV. SIMULATION RESULTS

Simulation results, shown in this section, have been carried out on a 1-kVA CHB power converter arm with three H-bridges. The parameters of the simulated LC-StatCom device are shown in Table I. The size of the capacitors C is relatively small, which results in approximately 80% (of the nominal

TABLE I
PARAMETERS OF THE EXPERIMENTAL SETUP

Symbol	Definition	Value
$\hat{V}_g$	Grid Voltage Nominal Amplitude	$200\sqrt{2}$ V (1 p.u.)
S_g	Nominal Power	1 kVA (1 p.u.)
n	Number of H-Bridges per Arm	3
f_g	Grid Frequency	50 Hz
$V_{C,\max}^*$	Peak Capacitor Voltage Reference	113 V
C	Capacitance per H-Bridge	0.18 mF (0.442 p.u.)
L	Interface Filter Inductance	5 mH (0.039 p.u.)
R_L	Parasitic Parameter	0.2 Ω
f_c	Carrier Frequency	1 kHz

dc component) low-frequency voltage ripple magnitude at the rated power. The control law depicted in Fig. 2 is implemented in MATLAB/Simulink environment. The reference signals are given by:

$$v_g(t) = \hat{V}_g \sin(\omega_g t) \quad (24)$$

$$\tilde{i}_L^*(t) = \hat{I}_L^* \sin\left(\omega_g t \pm \frac{\pi}{2} + \alpha_v^*\right) \quad (25)$$

$$\bar{v}_C^*(t) = V_{C,\max}^* \sqrt{1 - \frac{\hat{I}_L^* \hat{V}_{out}^*}{2\omega_g n C V_{C,\max}^{*2}} (1 \mp \cos(2\omega_g t + 2\alpha_v^*))} \quad (26)$$

$$\delta^*(t) = \frac{L \dot{\tilde{i}}_L^*(t) + R_L \tilde{i}_L^*(t) + v_g(t)}{n \bar{v}_C^*(t)}. \quad (27)$$

Variable $\omega_g = 2\pi f_g$ is the grid angular frequency. $\hat{V}_g$, $\hat{V}_{out}^*$ and $\hat{I}_L^*$ represent the amplitude of the grid voltage, amplitude of the converter voltage reference, and amplitude of the desired load current, respectively; and α_v^* is the phase shift between converter output voltage reference and grid voltage, which is determined by the losses. During capacitive operation, the injected current into the grid is lagging the grid voltage, whereas it is leading it during inductive operation. The proposed capacitor voltage reference effectively maintains the maximum limit on capacitor voltages $V_{C,\max}^*$, as required by the LC-StatCom operating principle [1].

The various features of the proposed control algorithm are evaluated on the LC-StatCom CHB converter with three different test cases: *Case I*: Start-up response, *Case II*: Transient response, and *Case III*: Balancing capability considering an initial unbalanced capacitor voltage state.

Case I: Converter start-up considering an initial condition equal to zero in the capacitor voltages and inductor current, i.e., $v_{C_1}(0) = v_{C_2}(0) = v_{C_3}(0) = 0$, and $i_L(0) = 0$.

Fig. 3. **Case I:** Simulation waveforms showing the (a) inductor current and (b) converter arm voltages during start-up, when operating the LC-StatCom at 100% capacitive operation.

Fig. 3 shows simulation results depicting the start-up when the converter draws 100% rated capacitive power. It can be appreciated that, despite the large-signal perturbation applied to the converter, the proposed control law brings the state variables to their references in less than 5 ms under this test condition. Once the steady-state is reached, the capacitor voltage waveforms exhibit 80% peak-to-peak low-frequency ripple, and the total harmonic distortion of the injected current into the grid is equal to 3.8%.

Case II: Transient performance of the proposed control algorithm is illustrated in Fig. 4, which depicts the simulation waveforms under sudden change of the reactive power level reference from full-rated power capacitive-mode to 33%-rated power inductive-mode, which, in fact, represents a large-signal perturbation. It can be noted that the transient response is very fast, while obtaining a proper peak capacitor voltage regulation and a minimum saturation of the control input. The proposed control is able to reach, robustly, a perfect tracking of the time-varying reference signals in less than 5 ms.

Case III: Balancing capability considering an initial unbalanced capacitor voltage state, specifically, $v_{C_1}(0) = 1.5\hat{V}_g/n$, $v_{C_2}(0) = 0.5\hat{V}_g/n$, and $v_{C_3}(0) = \hat{V}_g/n$. Fig. 5 shows the simulated balancing behaviour when the converter draws 100% rated capacitive power. It can be appreciated that the control reestablishes a balanced situation in less than 10 ms under this test condition, which represents a highly unbalanced initial situation. The proposed multi-input control strategy carries out accurate and fast balancing of the capacitor voltages.

Consequently, this paper has verified that global asymptotic

Fig. 4. **Case II:** Simulation waveforms showing the (a) inductor current and (b) converter arm voltages during a sudden reactive power change from 100% capacitive operation to 33% inductive operation.

Fig. 5. **Case III:** Simulation waveforms showing the balancing capability when operating the LC-StatCom at 100% capacitive operation.

stability and global tracking of the desired trajectories in an LC-Statcom multilevel converter is possible with a multi-input linear time-varying control law.

V. CONCLUSION

A multi-input incremental passivity control law has been analyzed and described for the LC-StatCom in the paper. It guarantees global tracking of the time-varying references while it balances the capacitor voltages. It has been shown that the resulting multi-input linear time-varying control law is an effective solution for controlling LC-StatComs. This is because it does not require the use of nested control loops designed with very different bandwidths.

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