Model Based Predictive Control with Switcher of Redundant Vectors for a Cascade H-Bridge Multilevel STATCOM

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***Abstract*—Classical model based predictive control for cascade H-bridge multilevel STATCOM produces a different switching pattern for different cells, this generates different stresses, DC-link voltage imbalance and different active power losses among the cells. To solve the aforementioned issues, the focus of this paper is to include a switcher of redundant vectors for DC-link voltage balance on the classical predictive control method and also improve the performance in terms of total harmonic distortion and remain focus the reactive power compensation. Simulation results of the proposed control approach are analyzed to verify the effectiveness of this proposal.**

***Index Terms*—Active power filters, cascade H-bridge converter, predictive control, switcher of redundant vectors**

I. INTRODUCTION

The new generation of power electronic systems, e.g., the called static synchronous compensators (STATCOMs), which aims to improve the power quality in electrical systems, and its control, is mainly due to the evolution of power semiconductor devices joined to the advancement of digital signal processors (DSPs), with the purposes of control in power converters, their advantages are beginning to be exploited [1]. Low power factor (PF), voltage collapse, unbalance loads, excessive harmonics generated by nonlinear loads, transients and oscillations are the mainly problems which affect the power quality in distribution systems [2]-[4]. One of the main topologies of STATCOMs and active power filters (APFs) to overcome the aforementioned drawbacks are the cascaded H-bridge (CHB) multilevel converters-based [5]. The advantages of CHB converters include low harmonic distortion, reduced number of switches, suppression of switching losses, modularity and good scalability [6]-[8]. In order to provide a good trade-off among good tracking of references variables, harmonic performance, switching frequency, commutation losses and the balancing of the DC-link voltages, several control and modulation techniques can be applied to CHB converters, such as: pulse width modulation (PWM), space vector modulation (SVM), phase shift carrier - PWM (PSC-PWM) and model-based predictive control (MBPC) [9]-[11]. MBPC has recently gained the attention of the research community like a control technique in power converters and drives [1], mainly because the advantage of it focuses on its flexible feature, since it is possible to adapt to different control requirements modifying only a cost function [12].

This paper proposes a novel DC-link balance technique for a three-phase three-wire 7-level CHB converter-based STATCOM system with MBPC, using for this purpose a switcher of redundant vectors (SRV) and the equations that represent the dynamics of the system, additionally to achieve a reactive power compensation and decreased current harmonics. In order to illustrate the benefits of the proposed control a series of simulations have been carried out. The simulations results have been analyzed and compared with the obtained using a classical MBPC.

This paper is organized as follows: Section II presents the three-phase three-wire 7-level CHB multilevel STATCOM topology. In Section III is discussed the proposed model predictive control technique with SRV (MBPC-SRV) for DC-link voltage balance. Section IV discusses the simulation results and provides a comparative analysis with the classical MBPC technique. Finally, concluding remarks are presented in the last section of the paper.

II. DESCRIPTION OF THE CHB STATCOM TOPOLOGY

Fig. 1 shows the three-phase three-wire 7-level CHB converter-based STATCOM topology studied. Three cascade H-bridge modules per phase, called cells, with an independent DC-link per cell compose the STATCOM system. Since each cell contains four switching devices, four switching signals ($s\phi_{ij}$) are needed in order to achieve the desired output voltage ($v_i^{\phi} = F_i^{\phi} v_{dc}$) for each cell, where ϕ represents the phase (a, b or c), i the cell number in the corresponding phase (1, 2 or 3), j the switching device corresponding to the cell "i" (1, 2, 3 or 4), v_{dc} the voltage of the capacitor and F_i^{ϕ} the switching function. Because of there are combinations that cause a short circuit in the DC-link of the cells, only two activation signals and their complementary levels are used, i.e., if $s\phi_{11} = 1$, then $s\phi_{12} = 0$ and if $s\phi_{i1} = 0$, then $s\phi_{i2} = 1$, similarly for $s\phi_{i3}$ and $s\phi_{i4}$. One switching state ($\eta \in \{1,\ 2,\ \dots\ , \varepsilon\}$) of one phase in particular, where ε is the total of possible switching states, which depends of the number of cells per phase (n_c), is represented by a switching vector (S_{η}^{ϕ}) that contains $2n_c$ activation signals ($s\phi_{ij}$) of such phase (note that the capital "S" is related to the vector and the small "s" is related to the signal). Finally, the output voltage

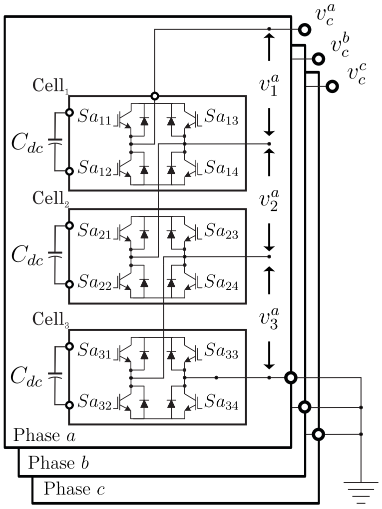


Fig. 1. Three-phase 7-level CHB converter-based STATCOM system.

for each phase of the STATCOM is $v_c^\phi = F_s^\phi v_{dc}$, where $F_s^\phi = \sum_{i=1}^{3} F_i^\phi$ denotes the switching function for each phase.

A. Continuous time-domain model

Fig. 2 shows one phase (ϕ) of the CHB converter-based STATCOM connection. The dynamic model of the circuit configuration can be obtained by using Kirchhoff's circuit laws. It is assumed, for modeling purposes, a balanced electric power grid. Applying Kirchhoff's voltage law for the AC side of the STATCOM, the following equation is obtained:

$$\frac{\mathrm{d}i_c^\phi}{\mathrm{d}t} = \frac{v_s^\phi}{L_f} - \frac{R_f}{L_f} i_c^\phi - \frac{F_s^\phi v_{dc}}{L_f} \tag{1}$$

where R_f is the parasitic (series) resistance of the inductor L_f.

B. Discrete-model for predictive control

Forward-Euler discretization method is used to obtain the predictive model from the continuous time-domain model represented by (1), which provides the following equation:

$$i_c^\phi(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^\phi(k) + \frac{T_s}{L_f}\left\{v_s^\phi(k) - v_c^\phi(k)\right\} \tag{2}$$

where k identifies the actual discrete-time sample, T_s is the sampling time, and $i_c^\phi(k+1)$ are the predictions of the STATCOM phase currents made at sample k.

III. PROPOSED MODEL BASED PREDICTIVE CONTROL WITH SWITCHER OF REDUNDANT VECTORS

Fig. 3 shows the block diagram of the proposed MBPC-SRV applied to the three-phase three-wire 7-level CHB converter-based STATCOM system. The current references are generated for reactive power compensation from the measured variables, as will be shown in the next section.

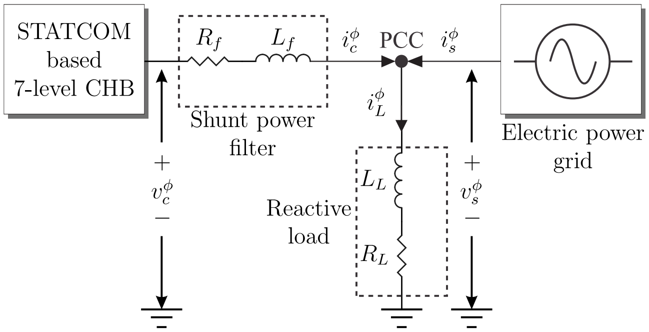


Fig. 2. STATCOM, load and electric grid connected through the PCC.

A. Reactive power compensation

The instantaneous active and reactive power references are obtained from the Clarke's transformation approach in $\alpha - \beta$ reference frame by using the following transformation matrix:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

Applying (3), the $\alpha - \beta$ current references in the AC side of the STATCOM are obtained as follows:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \tag{4}$$

where the superscript $(^*)$ denotes the reference variables and P_c^* and Q_c^* are the instantaneous active and reactive power references, respectively. In order to allow an unitary power factor at the grid side and considering which ideally the STATCOM do not absorb any active power, the instantaneous power references can be written as $P_c^* = 0$ and $Q_c^* = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha}$, being Q_L the instantaneous reactive load power to be compensate by the CHB converter-based STATCOM system. Finally, the STATCOM phase currents references used in the optimization process are:

$$[i_c^{a^*} \quad i_c^{b^*} \quad i_c^{c^*}]' = \mathbf{T}^{-1}[i_{c\alpha}^* \quad i_{c\beta}^* \quad 0]' \tag{5}$$

where the superscript (T') indicates the transposed matrix.

B. Cost function and optimization process

The cost function is defined as a quadratic measure of the predicted error, as follows:

$$g^\phi = \| e i_c^\phi(k+1) \|^2 \tag{6}$$

being $e i_c^\phi(k+1)$ the STATCOM current errors in the AC side.

The optimization is performed by search over the 7 possible levels of the control action and selects the optimal level or switching function F_s^ϕ (−3,−2,−1,0,1,2 or 3) that minimizes the defined cost function represented by (6). During the optimization process, both the cost function and the predictive model must be computed 7 times at each sampling period to guarantee optimality. Then, the first optimal vector is applied.

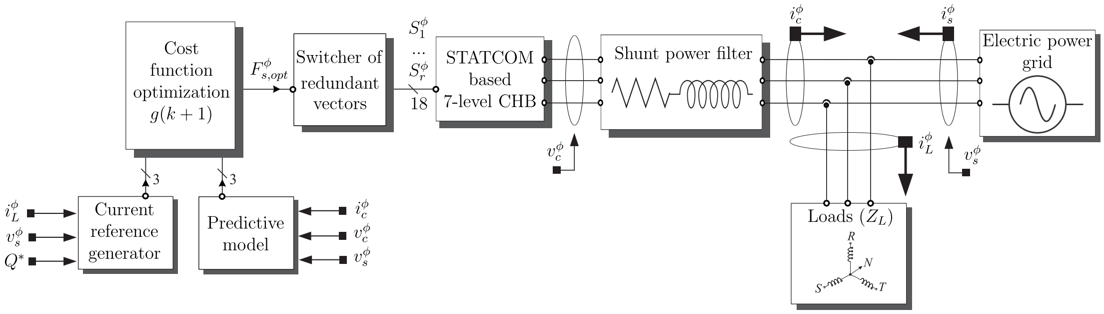


Fig. 3. Block diagram of the proposed model predictive current control with switcher of redundant vectors (MBPC-SRV).

C. *Switcher of redundant vectors*

An obvious solution to the voltage balancing problem is to commute the cells that are charging capacitors and those that are discharging capacitors [10], while maintaining the same optimal level (voltage output). Each optimal level has an amount of redundant vectors (r), which is variable depending of the level, as is shown in Table I.

TABLE I
AMOUNTS OF REDUNDANT VECTORS FOR EACH LEVEL

Voltage output ($\times v_{dc}$)	-3	-2	-1	0	1	2	3
Redundant vectors (r)	1	6	15	20	15	6	1

In order to charge and discharge all capacitors simultaneously, for one phase in particular, all redundant vectors for such phase are sequentially applied during a period until the next sampling instant, with a duty cycle given by the following equation:

$$\tau^{\phi} = \frac{T_s}{r} \tag{7}$$

To simplify the algorithm, is selected $r = 20$ for all levels, so the vectors of the levels with fewer amount of redundant vectors are reapplied until to complete a sampling period.

IV. SIMULATION RESULTS

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed MBPC-SRV technique applied to the three-phase 7-level CHB converter-based STATCOM system, considering the electrical parameters shown in Table II. The performance of the proposed MBPC-SRV technique is compared with the results obtained by a classical MBPC, in both cases considering a 20 kHz of sampling frequency and setting 114 V of the DC side.

Fig. 4 shows a simulation results of the proposed control technique under steady-state and transient conditions. Fig. 4 (upper) shows a step in the instantaneous reactive power reference where it is possible to notice the effect of reactive power compensation (from 3,000 to 1,500 VAR after 0.04 s). Moreover, Fig. 4 (bottom), shows the tracking current dynamic performance for a step change of the reactive power reference. It can be observed from the simulation results a fast dynamic response during the transient.

TABLE II
PARAMETERS DESCRIPTION

	7-Level CHB STATCOM		
PARAMETER	SYMBOL	VALUE	UNIT
Electric frequency of the grid	f_e	50	Hz
Voltage of the electric grid	v_s	310.2	V
Filter resistance	R_f	0.09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{dc}	114	V
DC-link capacitance	C_{dc}	21	mF
	Load parameters		
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
	Predictive control parameters		
Sampling time	T_s	50	μs
Active power reference	P^*_c	0	W
Ideal reactive power reference	Q^*_c	$-Q_L$	VAR

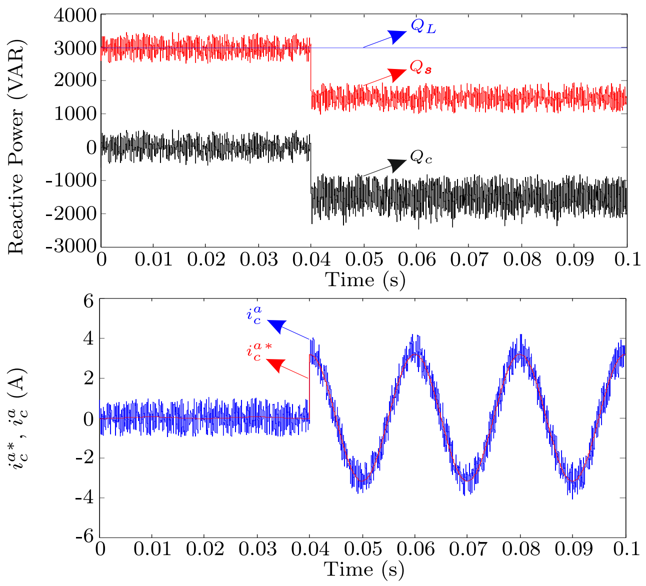
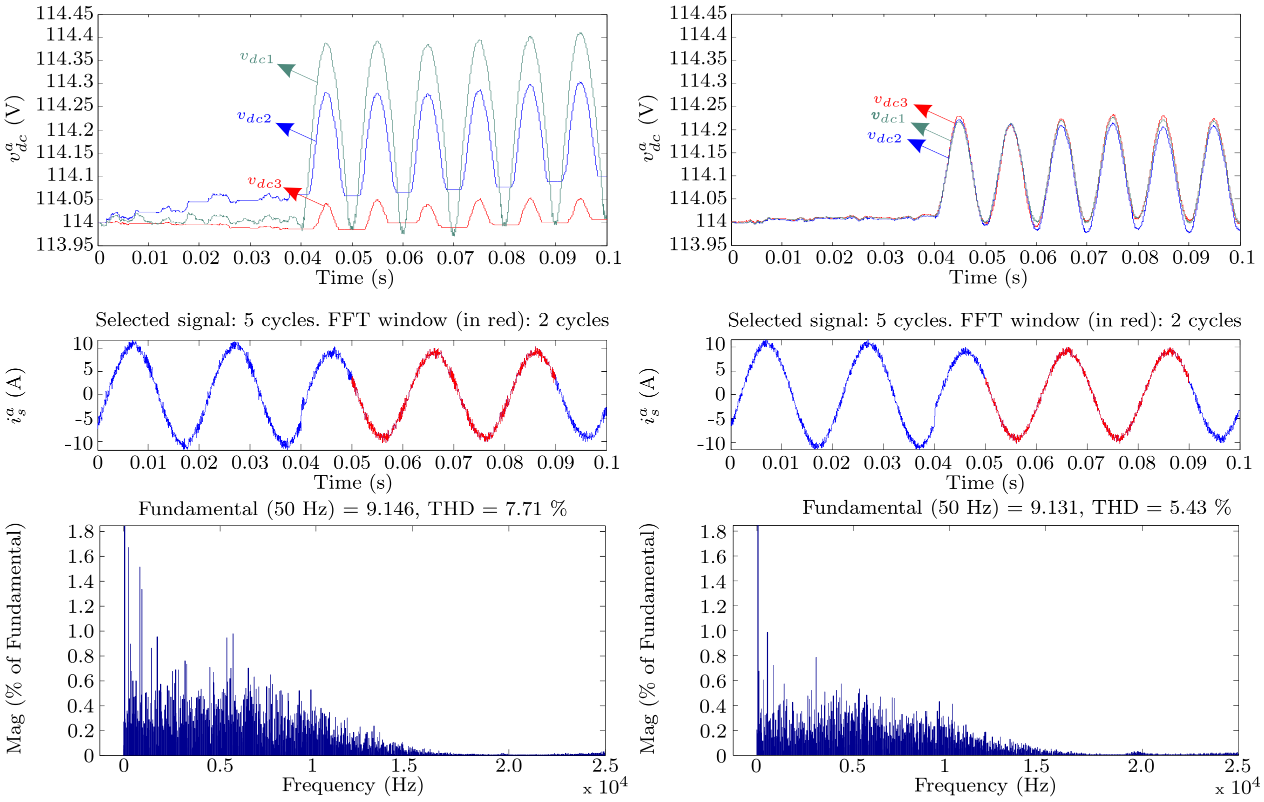


Fig. 4. CHB STATCOM steady-state and transient response: (upper) reactive power compensation, (bottom) tracking current.

Fig. 5 shows a comparison analysis between the proposed MBPC-SRV and the classical MBPC considering; (upper) the



(a) Classical model predictive control (MBPC) response

(b) Model predictive control with SRV (MBPC-SRV) response

Fig. 5. Comparison performance considering: (upper) the voltage evolution on the capacitors, (middle) the grid current and (bottom) the THD of the grid current.

voltages on the capacitors of the phase a (middle) the grid current of the phase a and (bottom) the THD of the analyzed grid current. As shown in Fig. 5 (b) a better performance is obtained in terms of voltage ripple and a simultaneous charge/discharge process on the capacitors. Furthermore, the improvement obtained in the THD performance parameter is about 30% (a drop from 7.71% to 5.43%) using the proposed method, considering the interval where the reactive power is compensated (after 0.04 s).

V. CONCLUSION

In this paper, a MBPC-SRV applied to the three-phase three-wire CHB 7-level STATCOM has been proposed. The simulation results confirm the capability of the proposed control technique to compensate the instantaneous reactive power and shows that it is possible to increase the performance in terms of THD, compared with the results obtained by the classical MBPC. A comparative simulation results performed with reference to the classical MBPC also show improvements relative to balance voltages in the DC-links.

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