A Novel Predictive-Fixed Switching Frequency Technique for a Cascade H-Bridge Multilevel STATCOM

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***Abstract*—There are several control techniques for active power filter applications. This paper presents a new alternative of predictive current control for a cascade H-bridge multilevel converter, where the optimal vector selected by the predictive controller is used for a modulation stage to obtain a fixed switching frequency. Simulation results validate the proposal where almost similar results can be obtained in comparison with the traditional methods.**

***Index Terms*—Active power filters, cascade H-bridge converter, fixed switching frequency, predictive control.**

I. Introduction

In recent years, power quality and efficiency issues have been consolidated as a scientific topic in the field of electrical engineering due to technical requirements for grid connection. Actually, power factor (PF), voltage collapse, unbalance, excessive harmonics, transients and oscillations, have been a major concern in power transmission and distribution systems. Non-linear loads normally produce disturbances in power transmission and distribution systems, causing a high-level harmonic distortion in the phase currents and voltages. Moreover, reactive loads produce a low PF, causing an excessive reactive power (VAR) restricting the maximum active power transfer, adding losses to the power transmission and distribution systems affecting its stability and reliability [1], [2]. Nowadays, several developments of flexible AC transmission system controllers, such as VAR compensators, have successfully been implemented to overcome the aforementioned drawbacks [3], [4]. Recently, multilevel converters have become a popular alternative to overcome the technological restrictions of the actual semiconductors devices that have limited power ratings [5]. Among all multilevel topologies, the cascaded H-bridge (CHB) multilevel converter is often considered as one of the most suitable configuration for high-power static synchronous compensator STATCOM, especially useful for reactive power compensation [6]. CHB converter-based STATCOM systems have been widely used in high-power applications due to its inherent advantages such as: reduced switching losses, higher conversion efficiency, modular structure, scalability to extended to more levels and higher number of redundant switching states [7]-[10]. Furthermore, in terms of control strategies, the CHB converter topology increases the degrees of freedom due to its modular feature which allows to impose an asymmetric control approach. In the mentioned control method certain cells could compensate the PF associated with the fundamental frequency and other cells could control the current harmonic distortion [11], [12].

This paper proposes a simple and efficient predictive control technique applied to the three-phase 7-level CHB converter-based STATCOM system in combination with a modulation stage. The predictive model is obtained from the dynamic equations of the compensation system. Simulation results are analyzed and compared with the obtained by using the conventional predictive control approach.

This work is organized as follows. Section II describes the three-wire CHB multilevel STATCOM topology. Section III introduces the proposed predictive control technique including the CHB STATCOM duty cycles calculation approach. A comparative analysis of the proposed control technique with a conventional predictive control approach based on variable switching frequency are discussed in Section IV. Finally, the main feature of the proposed predictive-fixed switching frequency technique are summarized in Section V.

II. CHB STATCOM topology

Fig. 1 shows the proposed three-phase 7-level CHB converter-based STATCOM topology, consisting in three cascade H-bridge cells per phase. The different H-bridge cells have an independent DC-link. Each cell contains four switching devices, resulting in a total of 36 power switches. Consequently, four switching signals ($S_{f_{ij}}$) are needed to control each cell, where f represents the phase (a, b and c), i the cell number in the corresponding phase (1, 2 or 3) and j the switching device corresponding to the cell (1, 2, 3 or 4), respectively. Table I shows the allowed combinations of activation signals and the respective output voltages corresponding to the Cell_1 of the phase "a", where C_{dc} is the voltage of the capacitor. Similar allowed combinations are defined for the other cells. Other possible combinations are not permitted because they cause a short circuit in the DC-link of the cell. To avoid this, only two activation signals and they complementary

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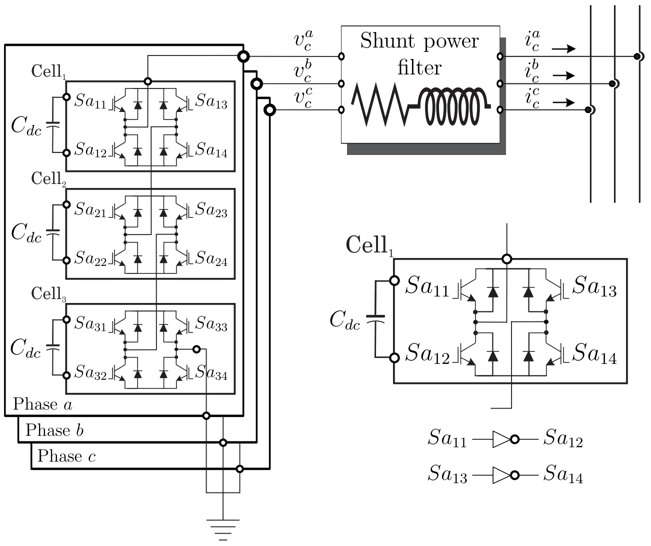


Fig. 1. Three-phase 7-level CHB converter-based STATCOM system.

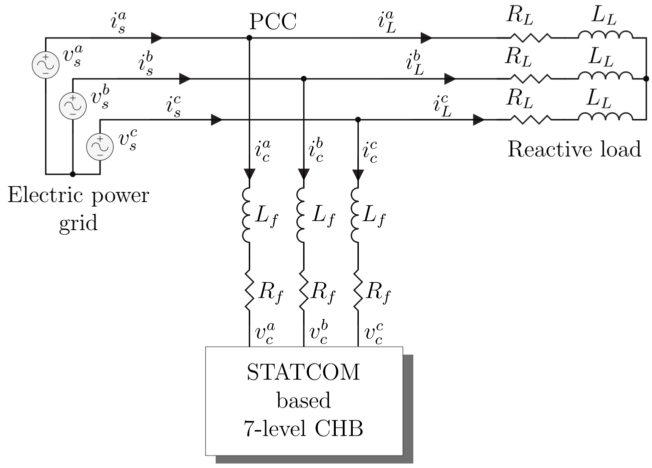


Fig. 2. CHB converter-based STATCOM connection.

TABLE I
ALLOWED COMBINATIONS OF ACTIVATION SIGNALS

Sa_{11}	Sa_{13}	Sa_{12}	Sa_{14}	v_c^a
1	0	0	1	$+C_{dc}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-C_{dc}$

levels are used as shown in Fig. 1 for the particular case of Cell_1.

A. CHB Converter-based STATCOM model

The dynamic model of the circuit configuration (Fig. 2) can be obtained by using Kirchhoff's circuit laws. For modeling purposes, it is assumed that the three-phase voltage sources are balanced and all modules have the same capacitance and voltage in their DC side. The CHB converter-based STATCOM is connected at the point of common coupling (PCC). Applying Kirchhoff's voltage law for the AC side of the STATCOM, the following equations are obtained:

$$\frac{\mathrm{d}i_c^{abc}}{\mathrm{d}t} = \frac{v_s^{abc}}{L_f} - \frac{R_f}{L_f} i_c^{abc} - \frac{n_c S_{f_{ij}} v_{dc}^{abc}}{L_f} \tag{1}$$

$$\frac{\mathrm{d}v_{dc}^{abc}}{\mathrm{d}t} = \frac{S_{f_{ij}} i_c^{abc}}{C_{dc}} - \frac{v_{dc}^{abc}}{R_{dc} C_{dc}} \tag{2}$$

where n_c is the number of cells, R_{dc} is a resistor connected in parallel to the capacitor C_{dc} that concentrates the overall losses in the DC side, $S_{f_{ij}}$ is the commutation function and the resistor R_f is the parasitic (series) resistance of the inductor L_f.

B. Predictive model

For multilevel STATCOMs, the differential equation that models the AC side is [13]:

$$\frac{\mathrm{d}i_c^{abc}}{\mathrm{d}t} = \frac{v_s^{abc}}{L_f} - \frac{v_c^{abc}}{L_f} - \frac{R_f i_c^{abc}}{L_f} \tag{3}$$

The predictive model can be obtained by using a forward-Euler discretization method from the continuous time-domain model represented by (3), which provides the following equation:

$$i_c^{abc}(k{+}1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abc}(k) {+} \frac{T_s}{L_f}\left\{v_s^{abc}(k) - v_c^{abc}(k)\right\} \tag{4}$$

being T_s the sampling time, k the actual sample and $i_c^{abc}(k+1)$ the prediction of the STATCOM phase currents made at sample k.

Moreover, the dynamics of the DC side, considering the ideal case ($R_{dc} = \infty$) can be model by the following equation:

$$v_{dc}^{abc}(k+1) = v_{dc}^{abc}(k) + \frac{T_s S_{f_{ij}}(k) i_c^{abc}(k)}{C_{dc}} \tag{5}$$

III. PROPOSED CONTROL TECHNIQUE

Fig. 3 shows the proposed scheme applied to the three-phase 7-level CHB converter-based STATCOM system. In the proposed predictive control technique the predicted errors are computed for each possible voltage vector as:

$$ei_c(k+1) = i_c^{abc^*}(k+1) - i_c^{abc}(k+1) \tag{6}$$

$$ev_{dc}(k+1) = v_{dc}^{abc^*}(k+1) - v_{dc}^{abc}(k+1) \tag{7}$$

being $ei_c(k{+}1)$ and $ev_{dc}(k{+}1)$ the STATCOM current errors in the AC side and the capacitor voltage errors in the DC side, respectively. After performing the prediction of (6) and (7), a defined cost function is computed recursively at each sampling period. The cost function provides the ability of incorporating different control objectives. This function has been typically defined as a quadratic measure of the predicted error, which can be defined as [14], [15]:

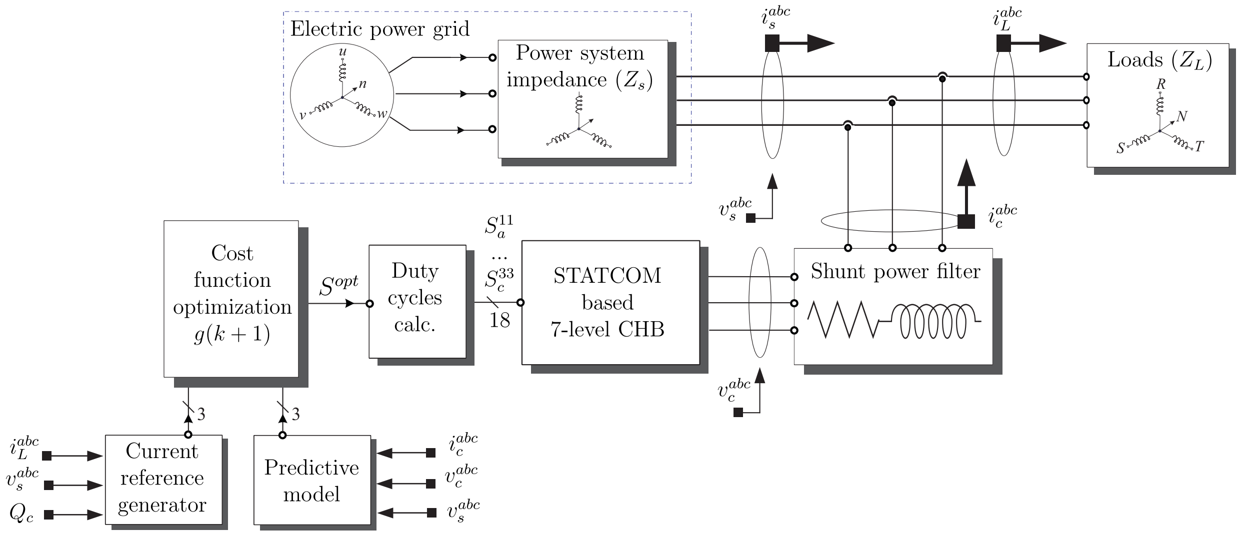


Fig. 3. Block diagram of the proposed control scheme.

$$g(k+1) = \| ei_c(k+1) \|^2 + \lambda \| ev_{dc}(k+1) \|^2 \quad (8)$$

being λ the weighting factor that gives priority to the control objectives.

A. Reference generation

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

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (9)$$

Applying (9), the $\alpha - \beta$ current references in the AC side of the STATCOM are obtained from:

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P^*_c \\ Q^*_c \end{bmatrix} \quad (10)$$

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:

$$P^*_c = 0 \quad (11)$$

$$Q^*_c = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha} \quad (12)$$

being Q_L the instantaneous reactive load power to be compensate by the H-bridge converter-based STATCOM system. The STATCOM phase currents references used in the optimization process are:

$$i_c^{abc^*} = \mathbf{T}^{-1} [i^*_{c\alpha} \quad i^*_{c\beta} \quad 0]' \quad (13)$$

where the superscript $(')$ indicates the transposed matrix.

B. Optimization process

The optimization is performed by exhaustive search over all possible switching vectors of the control action. If n is the number of H-bridge cells per phase (f), then each vector $S_{f_{ij}}$ consists in $2n$ choice signals, where $j = 1, ..., \phi$; being ϕ the number of phases. Moreover, the number of possible switching vectors per phase can be defined as $\varepsilon = 2^{2n}$. During the optimization process, both, the cost function and the predictive model must be computed 64 times at each sampling period to guarantee optimality, since there are 64 possible switching vectors for the case study. These switching vectors represent all possible output voltages of the STATCOM, v_c^a, v_c^b and v_c^c, connected at the PCC. The output voltages can be represented by the following equation:

$$\begin{bmatrix} v_c^a \\ v_c^b \\ v_c^c \end{bmatrix} = \begin{bmatrix} v_{c1} \\ v_{c2} \\ v_{c3} \end{bmatrix} v_{dc} \quad (14)$$

where v_{c1}, v_{c2} and v_{c3} are the optimal levels of the three-phase 7-level CHB converter-based STATCOM system $(-3, -2, -1, 0, 1, 2, 3)$. The first 15 switching vectors for one phase (a) are shown in Table II.

TABLE II
FIRST 15 SWITCHING VECTORS FOR A THREE-PHASE 7-LEVEL CHB CONVERTER-BASED STATCOM SYSTEM

Sa_{ij}						η	v_{c1} value
Sa_{11}	Sa_{13}	Sa_{21}	Sa_{23}	Sa_{31}	Sa_{33}		
0	0	0	0	0	0	1	0
0	0	0	0	0	1	2	-1
0	0	0	0	1	0	3	1
0	0	0	0	1	1	4	0
0	0	0	1	0	0	5	-1
0	0	0	1	0	1	6	-2
0	0	0	1	1	0	7	0
0	0	0	1	1	1	8	-1
0	0	1	0	0	0	9	1
0	0	1	0	0	1	10	0
0	0	1	0	1	0	11	2
0	0	1	0	1	1	12	1
0	0	1	1	0	0	13	0
0	0	1	1	0	1	14	-1
0	0	1	1	1	0	15	1
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.

Finally, the optimization algorithm selects the optimum vector S^{opt} that minimizes the defined cost function represented by (8). Algorithm 1 summarizes the optimization process.

Algorithm 1 Optimization algorithm

Initialize $J_o^a := \infty, J_o^b := \infty, J_o^c := \infty, \eta := 0$
Compute the STATCOM reference currents. Eqn. (13).
while $\eta \leq \varepsilon$ **do**
    $S_{f_{ij}} \leftarrow S_{f_{ij}}^{\eta} \;\; \forall \; i \;\&\; j = 1, \; 2, \; 3$
    Calculate the STATCOM prediction currents. Eqn. (4).
    Compute the dynamics of the DC side. Eqn. (5).
    Compute the errors. Eqns. (6) & (7).
    Compute the cost function. Eqn. (8).
    if $J^a < J_o^a$ **then**
        $J_o^a \leftarrow J^a, \quad S_a^{opt} \leftarrow S_{a_{ij}}$
    end if
    if $J^b < J_o^b$ **then**
        $J_o^b \leftarrow J^b, \quad S_b^{opt} \leftarrow S_{b_{ij}}$
    end if
    if $J^c < J_o^c$ **then**
        $J_o^c \leftarrow J^c, \quad S_c^{opt} \leftarrow S_{c_{ij}}$
    end if
    $\eta := \eta + 1$
end while
Compute the duty cycles. Eqn. (15).

C. CHB STATCOM duty cycles calculation

The CHB STATCOM duty cycles calculation of the proposed algorithm proceeds as follows. For a desired instantaneous active and reactive power references, the control algorithm determine the optimal vector (S_f^{opt}) that minimizes (8). The optimal vector provides the optimum voltages ($v_c^{a,opt}$, $v_c^{b,opt}$, $v_c^{c,opt}$) in terms of the CHB STATCOM current and voltage errors, respectively. Instead of applying the selected voltage vector to the CHB STATCOM during the whole switching period, which is the standard procedure in conventional predictive control schemes, the proposed algorithm uses S_f^{opt} to calculate the duty cycles by using the following equation:

$$\begin{bmatrix} \tau_a \\ \tau_b \\ \tau_c \end{bmatrix} = \frac{1}{3}(v_{dc}^{-1})[v_c^{a,opt} \;\; v_c^{b,opt} \;\; v_c^{c,opt}]' \qquad (15)$$

where τ_f is the duty cycles vector and the subscript $f = a, b, c$ are associated with the CHB STATCOM phase voltages and are normalized between -1 and 1. The calculation of the duty cycles is proposed as an optimization problem aimed to minimize the prediction error. This procedure can be considered as a systematic application in one sampling period of the optimal combination of more than one vector to minimize the CHB STATCOM current errors in the AC side and the capacitor voltage errors in the DC side, respectively.

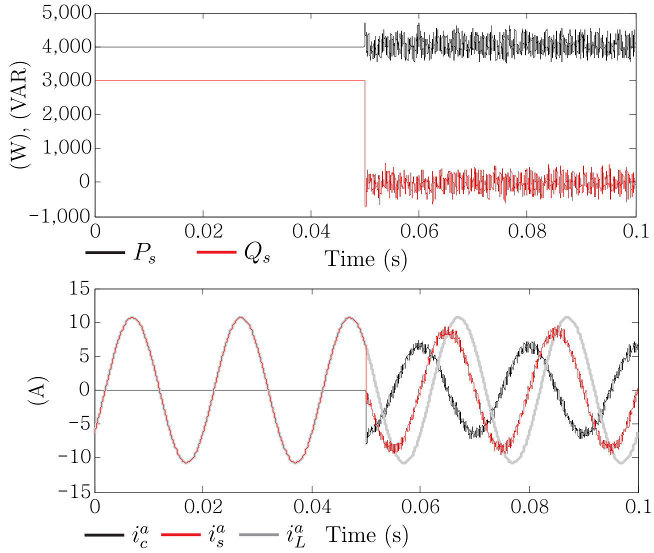
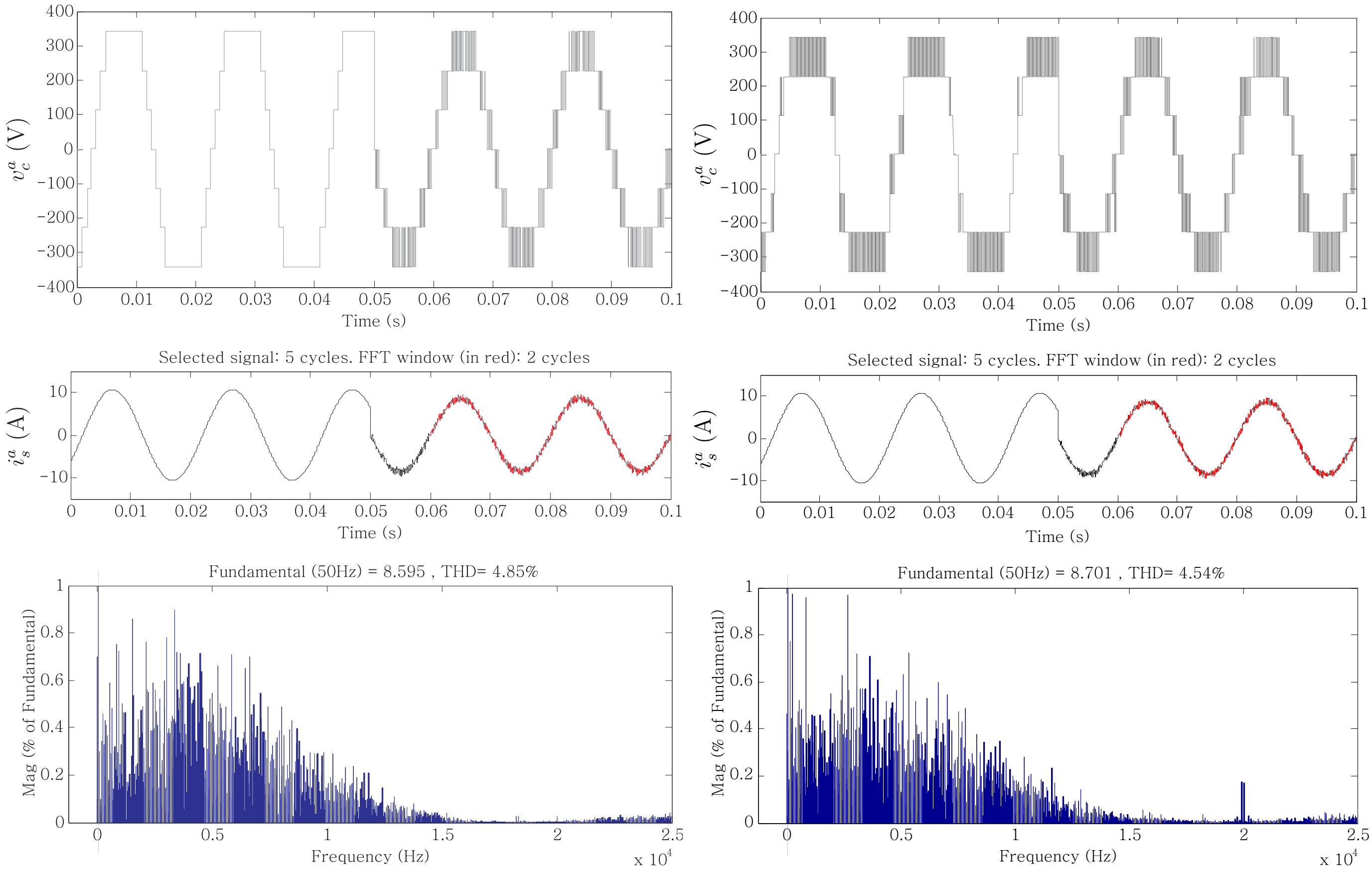


Fig. 4. CHB STATCOM transient response: (upper) reactive power compensation, (bottom) currents evolution.

IV. SIMULATION RESULTS

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed PfSF control technique applied to the three-phase 7-level CHB converter-based STATCOM system, assuming the parameters shown in Table III. Numerical integration based on Runge-Kutta method has been used to calculate the evolution of the variables step by step in the time domain. The performance of the proposed predictive-fixed switching frequency (PfSF) method is compared with the results obtained by a conventional predictive variable switching frequency (PvSF) control technique considering a 15 kHz of sampling frequency and setting 114 V of the DC side.

The cost function defined in (8) with $\lambda = 0.001$ is used to evaluate the dynamic performance of the PfSF and PvSF methods under steady-state and transient conditions.



(a) Predictive variable switching frequency (PvSF) response

(b) Predictive-fixed switching frequency (PfSF) response

Fig. 5. Comparative analysis considering: (upper) the phase voltage at PCC, (middle) the grid current and (bottom) the THD of the grid current.

TABLE III
PARAMETERS DESCRIPTION

PARAMETER	SYMBOL	VALUE	UNIT
	7-Level CHB STATCOM		
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
	Load parameters		
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
	Predictive control parameters		
Sampling time	T_s	66	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	VAR

Fig. 4 (bottom) shows a transient response when the 7-level CHB STATCOM is connected in t = 0.05 s, as it is shown in Fig. 4 (upper). It can be observed from the simulation results that the phase of grid current (i_s^a) represented in red color, suddenly changes to compensate the reactive power showing a fast dynamic response during the transient. Next, in order to compare quantitatively both controllers the mean squared error (MSE) and the total harmonic distortion (THD) are used as figures of merit. The equations are represented by (16) and (17), respectively as:

$$\mathrm{MSE}(\Psi) = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\Psi_j^2} \tag{16}$$

$$\mathrm{THD} = \sqrt{\frac{1}{i_1^2}\sum_{i=2}^{N} i_i^2} \tag{17}$$

where N is the number of vector elements, i_1 is the amplitude of the fundamental frequency of the analyzed current, and i_i are the current harmonics.

Fig. 5 shows a comparative analysis of both control systems considering (upper) the phase voltage evolution at PCC, (middle) the grid current and (bottom) the THD of the grid current. Simulation results show a better performance in terms of lower THD using the proposed PfSF method. This feature is associated to the fixed switching frequency produced by modulation process that yield a well-defined discrete current and voltage spectra in contrast to the simulation results obtained by the PvSF method. The THD improvement is quantified

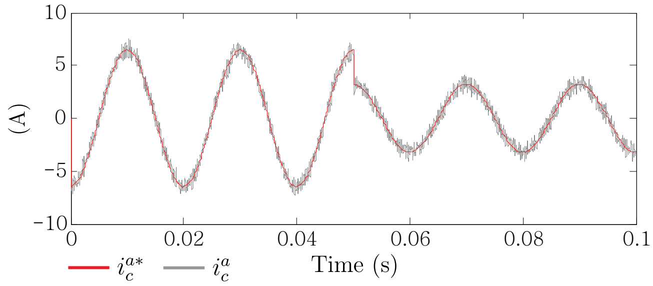


Fig. 6. Dynamic response evolution of i_c^a and current tracking considering a reactive power step.

about 8% (a drop from 4.85% to 4.54%) using the PfSF method, considering the interval where the reactive power is compensated (after 0.05 s).

Furthermore, the predictive current control loop is analyzed in detail in order to quantify the improvements obtained using the proposed control algorithm in terms of MSE. Fig. 6 shows the dynamic response obtained when a step in the reference reactive power (Q_c) from 3,000 to 1,500 VAR at t = 0.05 s is applied. Under these operating conditions the propose PfFS method introduces improvements in terms of lower MSE, from 0.3945 (PvSF) to 0.3771 (PfSF). Moreover as observed from the simulation results, the current reference tracking of the proposed PfFS method is very good, being even able to reduce the THD of the currents without affecting the dynamic response during the transient, which is however very fast.

V. Conclusion

In this paper, an alternative predictive current control technique with a modulation stage is applied to a three-wire CHB multilevel STATCOM converter. The theoretical results show that it is possible to combine the use of predictive control with modulation techniques to obtain better performance than a classic predictive control approach. Simulation results confirm that maintaining the modulation technique avoids the variable switching frequency inherent in conventional predictive controllers, easing the switch selection and providing a more adequate harmonic profile. Furthermore, the proposed technique proved to be viable in the field of instantaneous reactive power compensation.

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References

[1] M. Rivera, F. Morales, C. Baier, J. Muñoz, L. Tarisciotti, P. Zanchetta, and P. Wheeler, "A Modulated Model Predictive Control Scheme for a Two-Level Voltage Source Inverter," in *Proc. IEEE ICIT*, Seville, Spain, pp. 2224–2229, 2015.

[2] L.K. Haw, M.S.A. Dahidah, and H.A.F. Almurib, "A New Reactive Current Reference Algorithm for the STATCOM System Based on Cascaded Multilevel Inverters," *IEEE Trans. Power Electron.*, vol. 30, no. 7, pp. 3577–3588, Jul. 2015.

[3] Y. Neyshabouri, H. Iman-Eini, and M. Miranbeigi, "State Feedback Control Strategy and Voltage Balancing Scheme for a Transformer-Less STATic Synchronous COMpensator Based on Cascaded H-Bridge Converter," *IET Power Electron.*, vol. 8, no. 6, pp. 906–917, Jun. 2015.

[4] A. Renault, L. Comparatore, J. Pacher, R. Gregor, and J. Rodas, "Model Predictive Current Control with Neutral Current Elimination for H-Bridge Two-Level Active Power Filters," in *Proc. IEEE ETCM*, Guayaquil, Ecuador, 2016.

[5] J. Muñoz, P. Melín, and J. Espinoza, "Static Compensators (STATCOMs) in Power Systems," *Control of Multilevel STATCOMs*, ISBN:978-981-287-281-4, pp. 265–311, 2015.

[6] A. Marzoughi, Y. Neyshabouri, and H. Imaneini, "Control Scheme for Cascaded H-Bridge Converter-Based Distribution Network Static Compensator," *IET Power Electron.*, vol. 7, no. 11, pp. 2837–2845, Nov. 2014.

[7] C.D. Townsend, T.J. Summers, and R.E. Betz, "Phase-Shifted Carrier Modulation Techniques for Cascaded H-Bridge Multilevel Converters," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 6684–6696, Nov. 2015.

[8] Y. Yu, G. Konstantinou, B. Hredzak and V. G. Agelidis, "Operation of Cascaded H-Bridge Multilevel Converters for Large-Scale Photovoltaic Power Plants Under Bridge Failures," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7228–7236, Nov. 2015.

[9] G. Farivar, B. Hredzak, and V.G. Agelidis, "Decoupled Control System for Cascaded H-Bridge Multilevel Converter Based STATCOM," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 322–331, Jan. 2016.

[10] L. Comparatore, A. Renault, J. Pacher, R. Gregor, and J. Rodas, "Model Predictive Current Control with Switcher of Redundant Vectors for a Cascade H-Bridge Multilevel STATCOM," in *Proc. IEEE ANDESCON*, Arequipa, Peru, 2016.

[11] M. Norambuena, H. Hang, S. Dieckerhoff, and J. Rodriguez, "Improved Finite Control Set Model Predictive Control with Fixed Switching Frequency for Three Phase NPC Converter," in *Proc. PCIM Europe*, Nuremberg, Germany, 2016.

[12] L. Sun, Z. Wu, F. Xiao, X. Cai, and S. Wang, "Suppression of Real Power Back Flow of Nonregenerative Cascaded H-Bridge Inverters Operating Under Faulty Conditions," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 5161–5175, Jul. 2016.

[13] R.P. Aguilera, R. Baidya, P. Acuna, S. Vazquez, T. Mouton, and V.G. Agelidis, "Model Predictive Control of Cascaded H-Bridge Inverters based on a Fast-Optimization Algorithm," in *Proc. IEEE IECON*, Yokohama, Japan, 2015, pp. 4003–4008.

[14] R.P. Aguilera, P. Lezana, G. Konstantinou, P. Acuna, B. Wu, S. Bernet, and V.G. Agelidis, "Closed-Loop SHE-PWM Technique for Power Converters Through Model Predictive Control," in *Proc. IEEE IECON*, Yokohama, Japan, 2015, pp. 5261–5266.

[15] R.P. Aguilera, Y. Yu, P. Acuna, G. Konstantinou, C.D. Townsend, B. Wu, and V. G. Agelidis, "Predictive Control Algorithm to Achieve Power Balance of Cascaded H-Bridge Converter," in *Proc. IEEE PRECEDE*, Valparaiso, Chile, 2015, pp. 49–54.