Modulated Model Predictive Current Control for H-Bridge Two-Level Single Phase Active Power Filters STATCOM

A. Renault*, M. Rivera†, J. Rodas*, L. Comparatore*, J. Pacher and R. Gregor*
*Laboratory of Power and Control Systems, Facultad de Ingeniería, Universidad Nacional de Asunción
E-mail: {arenault, jrodas, lcomparatore, jpacher & rgregor}@ing.una.py
†Department of Electrical Engineering, Universidad de Talca
E-mail: marcoriv@utalca.cl

***Abstract*—Model predictive control techniques are characterized by a variable switching frequency which cause noise as well as large voltage and current ripple. In this paper a predictive control strategy with a fixed switching frequency for a single-phase active power filter, namely modulated model predictive control, is proposed. This technique produces modulated waveform at the output of the converter. The feasibility of this strategy is evaluated using simulation results to demonstrate the advantages of predictive control, such as fast dynamic response and the easy inclusion of nonlinearities. The constraints of the system are maintained but the performance of the system in terms of power quality is improved compared to the traditional model predictive control strategy.**

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

I. INTRODUCTION

Recently, the use of electronic-based power loads increased greatly and consequently the contamination of the distribution systems. To solve the various problems of power quality in distribution systems, active power filters (APF) and multilevel static synchronous compensators (M-STATCOM) are considered one of the best and the most popular solution [1]. The purpose of using a single phase APF, is to perform the suppression of harmonic current, reactive power compensation and power factor correction [2], [3]. This can be achieved by the injection of currents at the point of common coupling (PCC) [4]. This type of APF usually requires one H-bridge voltage source inverters (VSI) [5].

Model predictive control (MPC) technique applied to the APF can compensate downtime or nonlinearities in the system. Moreover, MPC provides a flexible control method which is easily extensible for different applications thanks to the advances of the switching devices [6], [7]. However, one of the main disadvantage of this method is its variable switching frequency nature. For instance, the MPC can choose only from a limited number of valid switching states because of the absence of a modulator. This generates noise as well as large voltage and current ripples. The variable switching frequency produces a spread spectrum, decreasing the performance of the system in terms of power quality [8], [9].

Different solutions have been proposed in the literature [10], [11] which allow the operation at fixed switching frequency. The proposed method emulates the implementation of the space vector modulation (SVM). As a consequence, the proposed predictive fixed switching frequency (PfSF) technique uses a switching pattern given through modulation scheme which minimizes the cost function using two active and the zero vectors. The simulation results were analyzed to verify the effectiveness of the proposed method.

This paper is organized as follows: Section II describes the single-phase H-bridge APF topology. Section III discusses the proposed modulated control technique model-based predictive control strategy. Section IV discusses the effectiveness of the proposed method considering the simulation results. Finally, concluding remarks are summarized in Section V.

II. SINGLE-PHASE CHB STATCOM TOPOLOGY

Fig. 1 shows the proposed single-phase two-level CHB converter-based STATCOM topology, consisting in one cascade H-bridge cell. The different H-bridge cells have an independent dc-link (C_{dc}). The cell contain four switching devices. Consequently, four switching signals ($S_{f_{ij}}$) are needed in order to control the cell, where f represents the phase (a), i the cell number in the corresponding phase (1) and j the switching device corresponding to the cell (1), 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 S_{a11} and S_{a13} Fig. 1 for the particular case of Cell_1.

A. CHB Converter-based STATCOM model

The dynamic model of the circuit configuration (Fig. 1) can be obtained by using Kirchhoff's circuit laws. For modeling purposes, it is assumed that the single-phase voltage sources are balanced and the module have the same capacitance and voltage in their dc side. The CHB converter-based STATCOM

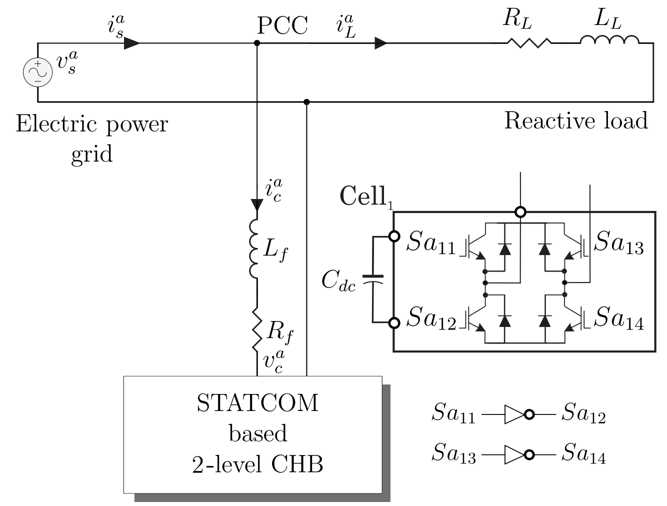


Fig. 1. Single-phase two-level CHB converter-based STATCOM system and connection.

TABLE I
ALLOWED COMBINATIONS OF ACTIVATION SIGNALS

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

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:

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

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

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. Classic Predictive Model Control

For two level STATCOMs single phase, the differential equation that models the AC side is [9]:

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

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:

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

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

Fig. 3 shows the proposed scheme applied to the single-phase 2-level CHB converter-based STATCOM system. In the proposed predictive control technique the predicted errors are computed for each possible voltage vector as:

$$ei_c^a(k+1) = i_c^{a^*}(k+1) - i_c^a(k+1) \tag{5}$$

being ei_c the APF current errors in the AC side, respectively. For each of them a cost function is evaluated. The cost function has been typically defined as a quadratic measure of the predicted error, which can be defined as [7], [8]:

$$g(k+1) = \parallel ei_c^a(k+1) \parallel^2 \tag{6}$$

C. Optimization Process

The optimization algorithm selects the optimum vector S^{opt} that minimizes the defined cost function represented by (6). Algorithm 1 summarizes the optimization process.

Algorithm 1 Optimization algorithm

1. Initialize $g_o^a := \infty, \eta := 0$
2. Compute the STATCOM reference currents. Eqn. (8).
3. **while** $\eta \leq \varepsilon$ **do**
4. $\quad S_{f_{ij}} \leftarrow S_{f_{ij}}^{\eta}\ \forall\ i = 1,\ \&\ g = 1$
5. $\quad$ Compute the STATCOM prediction currents. Eqn. (4).
7. $\quad$ Compute the errors. Eqn. (5).
8. $\quad$ Compute the cost function. Eqn. (6).
9. $\quad$ **if** $g^a < g_o^a$ **then**
10. $\quad\quad g_o^a \leftarrow g^a,\ \ S_a^{opt} \leftarrow S_{a_{ij}}$
11. $\quad$ **end if**
18. $\quad \eta := \eta + 1$
19. **end while**

D. Reference Generation

In the Fig.3 the triangle generator power with respect to the load is shown and explained as follows in points a, b and c:

a) S, Q, P and ϕ, It represents the apparent power, reactive power, active power and load power factor.

b) i_L^a, i_L^{ay} and i_L^{ax} It represents the module current with their imaginary respective components in the y-axis and x-axis real.

c) A_L^a, A_L^{ay} and A_L^{ax} It represents the modules of the amplitude, imaginary and real components.

d) Through the PLL the amplitude and phase of the measured current is obtained:

$$A_L^{ay} = A_L^a * sin(\phi_L^a) \tag{7}$$

then we apply the reference vector so as to compensate the reactive component of the measured current and therefore reactive power, as shown in Fig.3:

$$i_L^{ay*} = A_L^{ay} * sin(wt - \pi/2) \tag{8}$$

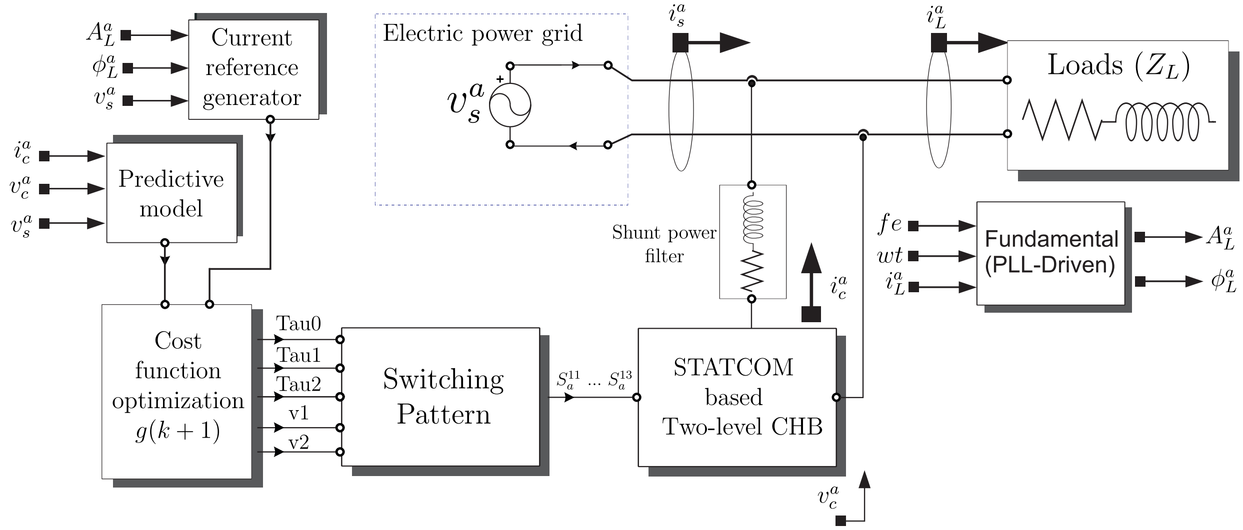


Fig. 2. Block diagram of the proposed control scheme.

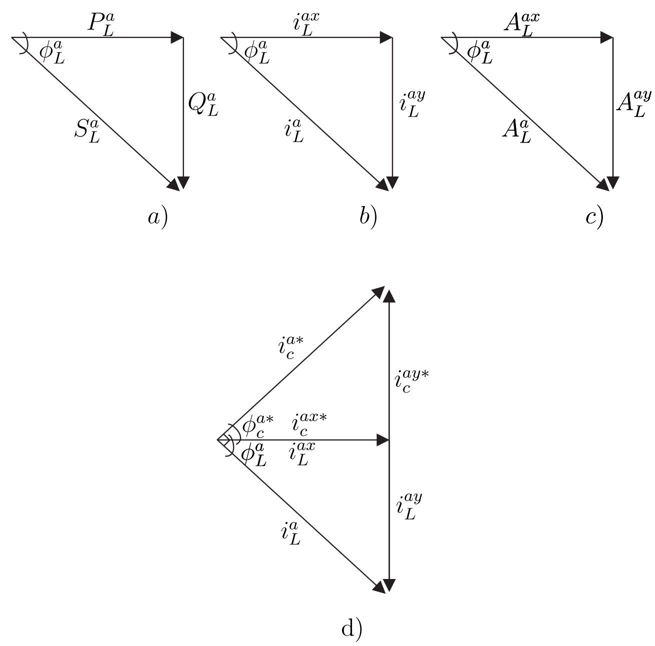


Fig. 3. Reference generation.

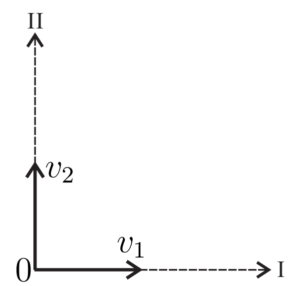


Fig. 4. Available vectors for the CHB.

III. Proposed Modulated control technique

In space vector modulation (SVM), it is possible to define each available vector for the CHB in the plane as shown in Fig.4. It is possible to define two sectors which are given by two adjacent vectors, being the first sector the one between vector v_1 and vector v_2, which correspond to the voltage generated by switching state number 1 and switching state number 2, respectively, based on Eqn. (2) and Table I. The proposed method is shown in each available vector for the CHB in the plane as shown in Fig.4. It is possible to define two vectors v_1 and v_2, with the same idea as the classical predictive control method as it uses the same prediction of the load current indicated in Eqn. (4).

Moreover the proposed technique evaluates the prediction of the two active vectors that conform each sector at every sampling time and evaluates the cost function separately for each prediction. The cost function g is evaluated for each case and is the same as the one considered for the classical predictive method. For example, for sector I, the first prediction and cost function g_1 is evaluated for vector v_1 and the second prediction and cost function g_2 is evaluated for vector v_2. Each prediction is evaluated based on Eqn. (4) and the only change is in respect to the calculation of the load voltage v_L^a. The duty cycles for the two active vectors are calculated by solving:

$$\begin{aligned} \tau_0 &= \frac{K}{g_0} \\ \tau_1 &= \frac{K}{g_1} \\ \tau_2 &= \frac{K}{g_2} \end{aligned} \tag{9}$$

$$\tau_0 + \tau_1 + \tau_2 = T_s \tag{10}$$

where τ_0 correspond to the duty cycle of a zero vector which is evaluated only one time. By solving the system of eqn. (10), is possible to obtain the expression for K and the expressions for the duty cycles for each vector are given as:

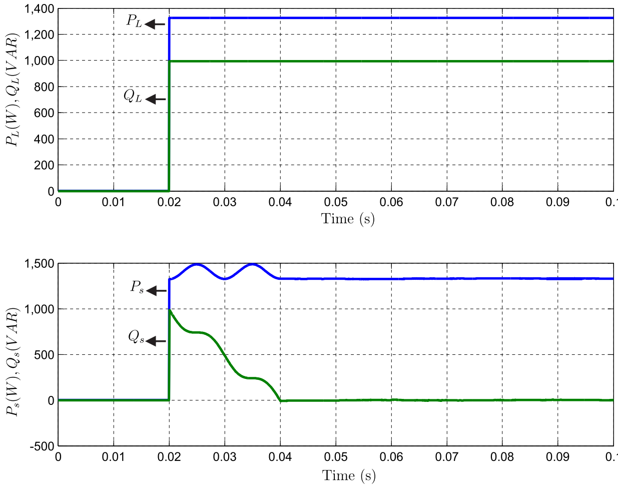


Fig. 5. Two-level H-bridge APF transient response, active and reactive power compensation (upper) in the load and (bottom) in the power grid.

$$
\begin{aligned}
\tau_1 &= \frac{g_2}{g_1+g_2} \\
\tau_2 &= \frac{g_1}{g_1+g_2} \\
\tau_0 &= T_s - d_1 - d_2
\end{aligned}
\tag{11}
$$

with these expressions, the new cost function, which is evaluated at every sampling time, is defined as

$$
g(k+1) = \tau_1 * g_1 + \tau_2 * g_2 \tag{12}
$$

The two vectors that minimize this cost function are selected and applied to the CHB at the next sampling time. After obtaining the duty cycles and selecting the optimal two vectors to be applied, a switching pattern procedure, such as the one shown in Fig.6, is adopted with the goal of applying the two active vectors and two zero vectors [12].

IV. Simulation results

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed modulated control technique applied to the single-phase two-level CHB converter-based STATCOM system, considering the electrical parameters shown in Table II. Numerical integration using Ode45 Dormand-Prince method has been applied to compute the evolution of the variables step by step in the time domain with a relative tolerance of 1e-6. The performance of the proposed method is compared with the results obtained by a conventional predictive variable control technique in both cases considering a 40 kHz of sampling frequency, setting 342 V of the dc side.

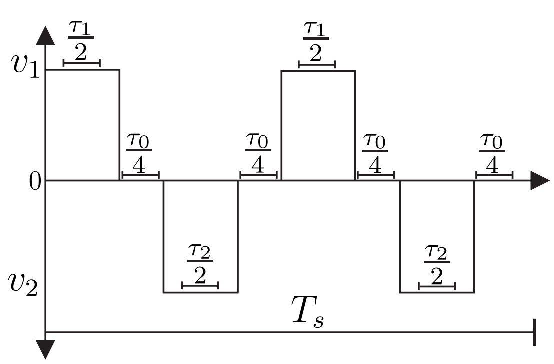


Fig. 6. Switching pattern.

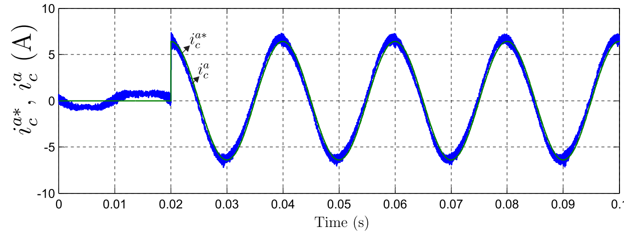


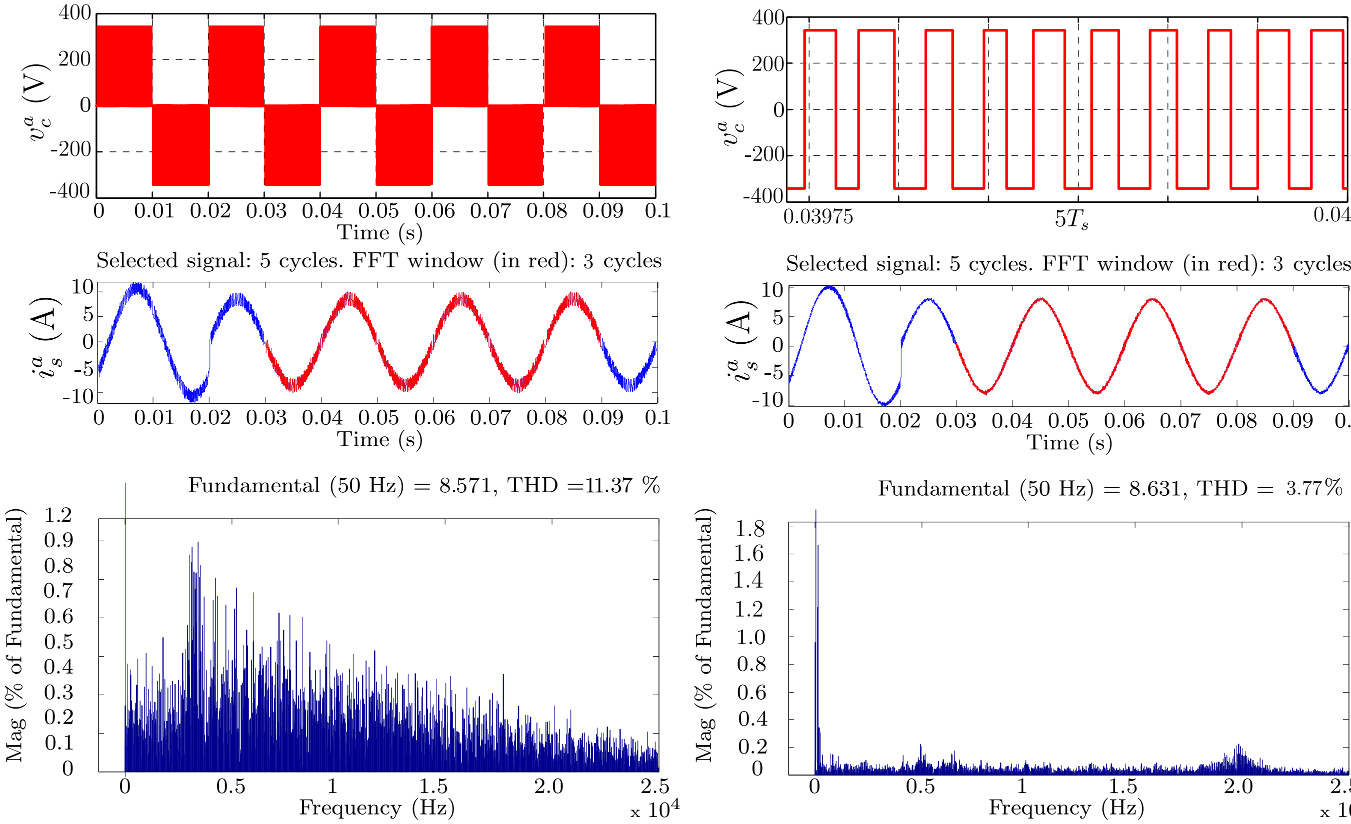
Fig. 7. Dynamic response evolution of i_c^a, i_c^a and current tracking.

TABLE II
Parameters description

PARAMETER	Two-Level CHB STATCOM 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}	342	V
	Load parameters		
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
	Predictive control parameters		
Sampling time	T_s	25	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	VAR

Fig. 5 shows a transient response when the two-level CHB STATCOM is connected in t = 0.02 s, as it is shown in active and reactive power in the load, (bottom) as it is shown in active and reactive power in the power grid. On the other hand, Fig. 7 . It can be observed from the simulation results that the phase of grid current (i_c^a) represented in blue and (bottom) the switching voltage in the active filter, suddenly changes to compensate the reactive power showing a fast dynamic response during the transient.

Fig. 8 shows a comparison analysis from each controller considering the THD of the grid current. A better performance is obtained using the proposed PfSF method mainly in terms of lower total harmonic distortion, due to the fixed switching frequency associated with the modulation process, producing a well-defined discrete current and voltage spectra in contrast to the PvSF method. The improvement obtained in the THD performance parameter is about 8% (a drop from 11.37% to 3.77%) using the PfSF method, considering the interval where the reactive power is compensated (after 0.02 s).



(a) Predictive variable switching frequency (PvSF) response

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

Fig. 8. Comparison from each controller considering: (upper) the grid current evolution at PCC point, (bottom) the THD of the grid current.

V. Conclusion

In this paper, a predictive current control technique with a modulation stage is applied to a single phase two levels CHB STATCOM converter with a fixed switching frequency while maintaining the advantages of the classical model predictive control techniques such as fast dynamic response and easy inclusion of nonlinearities. Simulation results confirm the capability of the proposed predictive-fixed switching frequency control technique in the field of instantaneous reactive power compensation.

Acknowledgment

The authors would like to acknowledge the financial support of FONDECYT Regular 1160690 project and Paraguayan Government support provided by means of a CONACYT project 14-INV-096.

References

[1] S. A. Kamran and J. Muñoz, "Study of a state-of-the art M-STATCOM," in *Proc. ICIT*, 2015, pp. 2733–2738.

[2] J. Fang, G. Xiao, X. Yang, and Y. Tang, "Parameter design of a novel series-parallel-resonant lcl filter for single-phase half-bridge active power filters," *IEEE Trans. on Power Electronics*, vol. 32, no. 1, pp. 200–217, Jan 2017.

[3] G. Brusco, A. Burgio, D. Menniti, M. Motta, A. Pinnarelli, and N. Sorrentino, "A repetitive-based control for a single-phase shunt active power filter for harmonic voltage compensation," in *Proc. EEEIC*, June 2016, pp. 1–6.

[4] K. Wada and H. Yoshida, "Improvement of power quality for three-phase grids using single-phase dg with active filter function units," in *Proc. IPEMC-ECCE Asia*, May 2016, pp. 2951–2957.

[5] Y. Xu, J. Yu, Y. Cao, J. Yu, and Y. Gu, "State variable feedback predictive control design for single phase shunt active power filter," in *Proc. IPEMC-ECCE Asia*, May 2016, pp. 2043–2046.

[6] M. G. G. Titus, "Reactive power compensation using statcom for single phase distribution system," in *Proc. ICCPCT*, March 2015, pp. 1–5.

[7] A. Valdez-Fernandez, K. Mtepele, D. Campos-Delgado, and G. Escobar, "A generalized model-based controller for the n-level chb multilevel converter used as a shunt active filter," in *Proc. ROPEC*, Nov 2015, pp. 1–6.

[8] P. Anu, R. Divya, and M. G. Nair, "Statcom based controller for a three phase system feeding single phase loads," in *Proc. TAP Energy*, June 2015, pp. 333–338.

[9] V. Ponananthi and B. R. Kumar, "Three-phase statcom controller using dq frame theory for a three-phase seig feeding single phase loads," in *Proc. (ICECS)*, Feb 2015, pp. 926–931.

[10] H. Hafezi, E. Akpinar, and A. Balikci, "Cascade pi controller for single-phase statcom," in *Proc. PEMC*, Sept 2014, pp. 88–93.

[11] P. Acuna, L. Morán, M. Rivera, J. Dixon, and J. Rodriguez, "Improved active power filter performance for renewable power generation systems," *IEEE trans. on power electronics*, vol. 29, no. 2, pp. 687–694, 2014.

[12] M. Rivera, "A new predictive control scheme for a vsi with reduced common mode voltage operating at fixed switching frequency," in *Proc. POWERENG*, May 2015, pp. 617–622.