Deadbeat Direct Power Control for Grid Connected Inverters using a Full-Order Observer

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Abstract—**this paper presents an improved deadbeat direct power control (DPC) for grid connected voltage source converters (VSCs). The proposed deadbeat-DPC combines a deadbeat control law with a full order Luenberger observer to predict the converter behavior. The deadbeat control law is chosen to cancel out the power error and the Luenberger observer is adopted to compensate for the control delay and simultaneously to eliminate the grid voltage sensors. Finally, the excellent steady-state and dynamic performance of the proposed method is confirmed through extensive simulations.**

Keywords-DC/AC PWM converter; Predictive Direct power control; grid volateg sensorless control

I. INTRODUCTION

In recent years, renewables such as solar and wind have become among most important energy sources due to their social and environmental benefits as well as economic considerations. However, these sources produce electrical energy inconsistent with the power grid characteristics. Consequently, a power electronic converter is required to successfully transfer the electricity generated from these energy sources to the power grid.

Pulse-width modulated (PWM) voltage source converters (VSCs) are most widely used solution for the grid connected renewable energy sources [1, 2]. In order to regulate the power exchange between the VSC and the grid and simultaneously provide sinusoidal currents, various control strategies such as voltage oriented control (VOC) [1-3], proportional-resonant (PR) control [1-3] and direct power control (DPC) [4, 6-21] are already presented. Recently, methods based on the predictive direct power control (P-DPC) have attracted great interests due to various advantages they offer [6-21], the main being superior dynamic performance, simpler structure and concepts, ease of implementation, ability to be used in various applications and conformity with the inherent discrete nature of power converters. In general, P-DPC can be classified into two main categories: model predictive control (MPC) and deadbeat control.

The MPC method utilizes maximum benefits of limited number of switching states and discrete nature of the power converter. In this method a cost function is defined to evaluate the error between the reference and the output powers for all possible switching states. Optimal switching action that minimizes the error is selected and is directly applied to the power converter without requiring any voltage modulator. The MPC has several advantages such as suitability for multivariable and nonlinear systems and straightforward inclusion of nonlinearities and constraints in the control law and system variables. Main shortcoming of this method is the variable switching frequency, which leads to a spread current spectrum in a wide range of frequencies [5-14].

Another approach is the deadbeat control that calculates the required VSC voltage reference vector to achieve a zero active and reactive power error at the end of the control step by using the discrete model of the system. The switching times of the converter switches are later computed via a modulation block [15-21].

In general, the P-DPC uses the measured grid voltage in its structure to achieve a proper disturbance rejection and performance. In order to reduce the size and cost of the converter system, it is desired to eliminate the grid voltage sensors. So, the sensorless P-DPC based on the virtual flux (VF) is presented in [17, 19]. The VF is an open loop estimator and needs the initial conditions of the grid voltages to perform correctly. Also implementation of a perfect VF estimator is based on an ideal integrator and is not possible, because noises and the DC offset causes saturation of such ideal integrators.

This work presents an improved deadbeat-DPC scheme for the grid connected PWM VSC which utilizes the Luenberger full-order observer in its structure. In this study and in order to compensate for the control delays introduced by the digital implementation of the predictive controller, a two-step deadbeat-DPC based on the Luenberger Observer (LO) is presented. In the first step, states are estimated by using a full order observer for one step in advance and then based on the deadbeat control theory, the converter reference voltage is calculated such that the power errors become zero in the next sampling period. Eventually, the optimal converter voltage is saved and applied in the start of the next sampling period. Another important advantage of using the LO in the proposed

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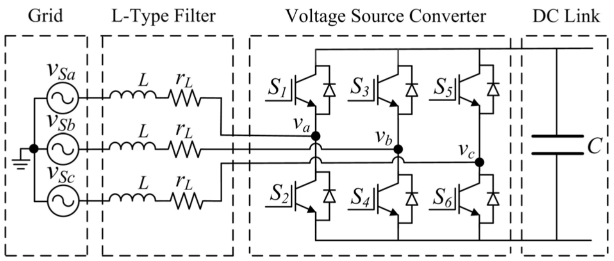

Figure 1. Three-phase grid connected PWM VSC

control scheme is that it provides the sensorless operation of the converter by eliminating the grid voltage sensors.

In the following sections the system equations are presented and a discrete state space model is achieved. In addition, based on the state space model of the system, a full order Luenberger observer is designed. Afterwards, the control law based on the deadbeat theory is derived by using the discrete system model and the outputs of the observer. Finally, the performance of the proposed method is confirmed through extensive simulation tests. Simulation results approve the excellent performance of the proposed method in steady state and dynamic conditions.

II. SYSTEM MODEL

A. State-space model of the grid connected VSC

The simplified structure of the grid connected three-phase PWM VSC considered in this study is shown in Fig. 1, which includes the power grid, the L-type filter, the six IGBT switches and the DC link capacitors.

In the stationary reference frame, the two coordinate mathematical model can be readily represented as:

$$v_{S\alpha\beta} = r_L i_{\alpha\beta} + L\frac{d}{dt}(i_{\alpha\beta}) + v_{\alpha\beta} \tag{1}$$

where, $v_{\alpha\beta}$, $v_{S\alpha\beta}$, and $i_{\alpha\beta}$ are the converter voltages, grid voltages and grid currents in the αβ reference frame, respectively. Also, L and r_L are filter inductance and equivalent series resistance, respectively.

Under the assumption of a balanced and sinusoidal three-phase system, the grid voltage components in the αβ reference frame can be expressed as:

$$\begin{cases} v_{S\alpha} = V_m \sin(\omega t) \\ v_{S\beta} = V_m \cos(\omega t) \end{cases}. \tag{2}$$

Differentiating (2) with respect to time results in the instantaneous variations of the grid voltage components:

$$\begin{cases} \dfrac{dv_{S\alpha}}{dt} = \omega V_m \cos(\omega t) \\ \dfrac{dv_{S\beta}}{dt} = -\omega V_m \sin(\omega t) \end{cases}. \tag{3}$$

Thus, the system state-space model can be obtained from (1) and (3) as:

$$\frac{dx}{dt} = Ax(t) + Bu(t) \tag{4}$$

where

$x=[i_{\alpha\beta}, v_{S\alpha\beta}]$, $u=[v_{\alpha\beta}]$, $A = \begin{bmatrix} \frac{-r_L}{L}I & \frac{1}{L}J \\ 0 & \omega J \end{bmatrix}$, $B = \begin{bmatrix} \frac{1}{L}I \\ O \end{bmatrix}$,

$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $O = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$ and $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

Discretizing (4) with the sampling period T_S, yields the following discrete state-space equations:

$$\begin{cases} x(k+1) = A_d x(k) + B_d u(k) \\ A_d = L^{-1}[(sI - A)^{-1}] \approx I + AT_S \\ B_d = \int_0^{T_S} A_d(T_S - \tau)Bd\tau \approx BT_S \end{cases} \tag{5}$$

where s is the Laplace operator and $L^{-1}[.]$ is the inverse Laplace transform.

B. Luenberger observer

In this paper to achieve a closed-loop estimator, a full order LO is employed. The LO is a deterministic closed-loop estimator that uses the state-space model to predict the states of the system from the measured inputs and outputs based on the minimization of the difference between the measured and the estimated outputs [22-23]. The observer allows reducing the influence of disturbance variables and to predict the desired quantities in advance and therefore helps to compensate for delays introduced by digital implementation of the P-DPC. Using the observer, the grid voltage sensors are eliminated from the control scheme. High accuracy and reliability, cost and size reduction and noise immunity are the most important advantages of estimating the signals by the LO.

The observer equations are given by:

$$\begin{cases} \hat{x}(k+1) = A_d\hat{x}(k) + B_d u(k) + k(y(k) - \hat{y}(k)) \\ \hat{y} = C_d\hat{x}(k), C_d = \begin{bmatrix} I & O \\ O & O \end{bmatrix} \end{cases} \tag{6}$$

where y and $\hat{y}$ are the measured and estimated outputs and k is the observer gain. Matrices A_d and B_d in the observer equations (6) are determined by the plant equations (5).

Equations (6) can be rewritten as:

$$\begin{cases} \hat{x}(k+1) = A_O\hat{x}(k) + B_d u(k) + ky(k) \\ A_O = A_d - kC_d \end{cases}. \tag{7}$$

With respect to (7), by using the pole placement technique, k must be selected such that the two following conditions are fulfilled [22-23]:

1. all eigenvalues of A_O lie inside the unit circle;

2. to make the observer dynamically faster than the plant, the observer eigenvalues should be selected proportional to the system eigenvalues (the proportionality constant is less than unity).

III. PROPOSED P-DPC

The developed P-DPC scheme is based on the deadbeat control as shown in Fig 2. In the proposed method, in each sampling period, the required converter voltage for the next control period is computed from the predicted values by the LO, the reference powers and the model of the converter system. The optimal converter voltage is saved and applied in the start of the next sampling period. Consequently, a whole sampling period is available to perform all calculations and control delays due to computations are compensated.

The proposed deadbeat-DPC is based on the two-step ahead predicted powers that can be expressed as:

$$\begin{aligned} S(k+2) &= p(k+2) + jq(k+2) = \\ &\hat{v}_S(k+2)\hat{i}(k+2)^* (* = \text{conjugate}) \end{aligned} \tag{8}$$

where $\hat{v}_S(k+2)$ and $\hat{i}(k+2)$ are predicted grid voltage and current vectors that can be calculated from (5) as follows:

$$\begin{cases} \hat{i}(k+2) = (1 - \dfrac{r_L}{L}T_S)\hat{i}(k+1) + \dfrac{1}{L}T_S(\hat{v}_S(k+1) - v(k+1)) \\ \hat{v}_S(k+2) = (1 + j\omega T_S)\hat{v}_S(k+1) \end{cases}. \tag{9}$$

In the above equations, $\hat{v}_S(k+1)$ and $\hat{i}(k+1)$ are observed signals via the LO.

Finally, by substituting (9) into (8) and replacing $S(k+2)$ with the reference powers at sampling instant k ($S_{ref}(k)$) and performing some manipulations, the required converter voltage can be obtained as:

$$\begin{cases} v_{ref}(k+1) = \hat{v}_S(k+1) - (\dfrac{P_1}{P_2})^* \\ P_1 = S_{ref}(k) - (1 + j\omega T_S)(1 - \dfrac{r_L}{L}T_S)S(k+1) \\ P_2 = \dfrac{T_S}{L}(1 + j\omega T_S)\hat{v}_S(k+1) \end{cases} \tag{10}$$

where $S(k+1)$ is calculated from the LO outputs:

$$S(k+1) = \hat{v}_S(k+1)\hat{i}(k+1)^*. \tag{11}$$

IV. PERFORMANCE EVALUATION

In order to examine the performance of the proposed deadbeat-DPC with the LO, several simulation tests were carried out using MATLAB/Simulink. The main system and control parameters are listed in Table. I.

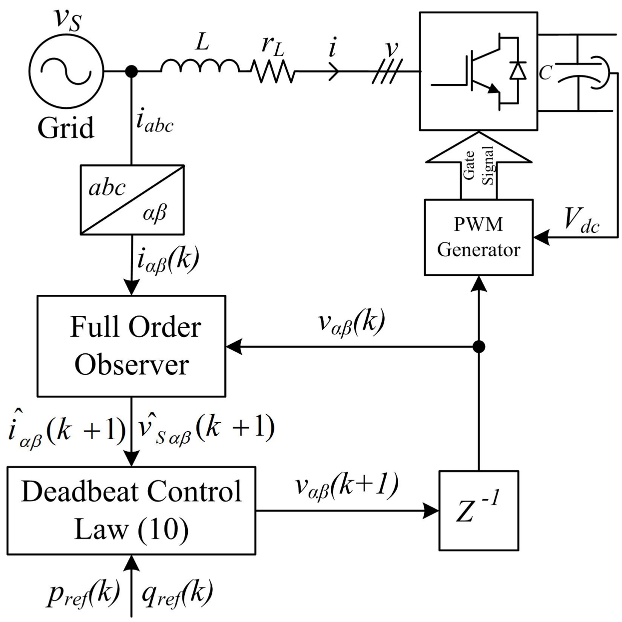

Figure 2. Three-phase grid connected PWM VSC in presence of P-DPC and LO.

TABLE I. SIMULATION PARAMETERS

Grid Voltage	70 Vrms
DC Link Voltage	140 V
Filter Inductance	2mH
Filter Resistance	0.6 Ω
Grid Frequency	50 Hz
Sampling and Switching Frequency	5 kHz

The steady-state waveforms are presented in Figs. 3 and 4. The waveforms confirm accurate regulation and minimum distortion in the output active and reactive powers and at the same time, low total harmonic distortion (THD=3.6%) of the grid currents.

Moreover, the transient performance of the proposed sensorless control scheme under various step changes in active and reactive powers is presented in Fig. 5. It can be seen, a fast and decoupled power control is achieved.

Finally, as shown in these figures, LO can successfully estimate the grid voltages and currents with minimum distortions and noises in both steady-state and transient conditions.

V. CONCLUSION

This paper attempts to improve the performance of deadbeat-DPC by combining the deadbeat control theory with the full order Luenberger observer. The most important advantages of the proposed control method are:

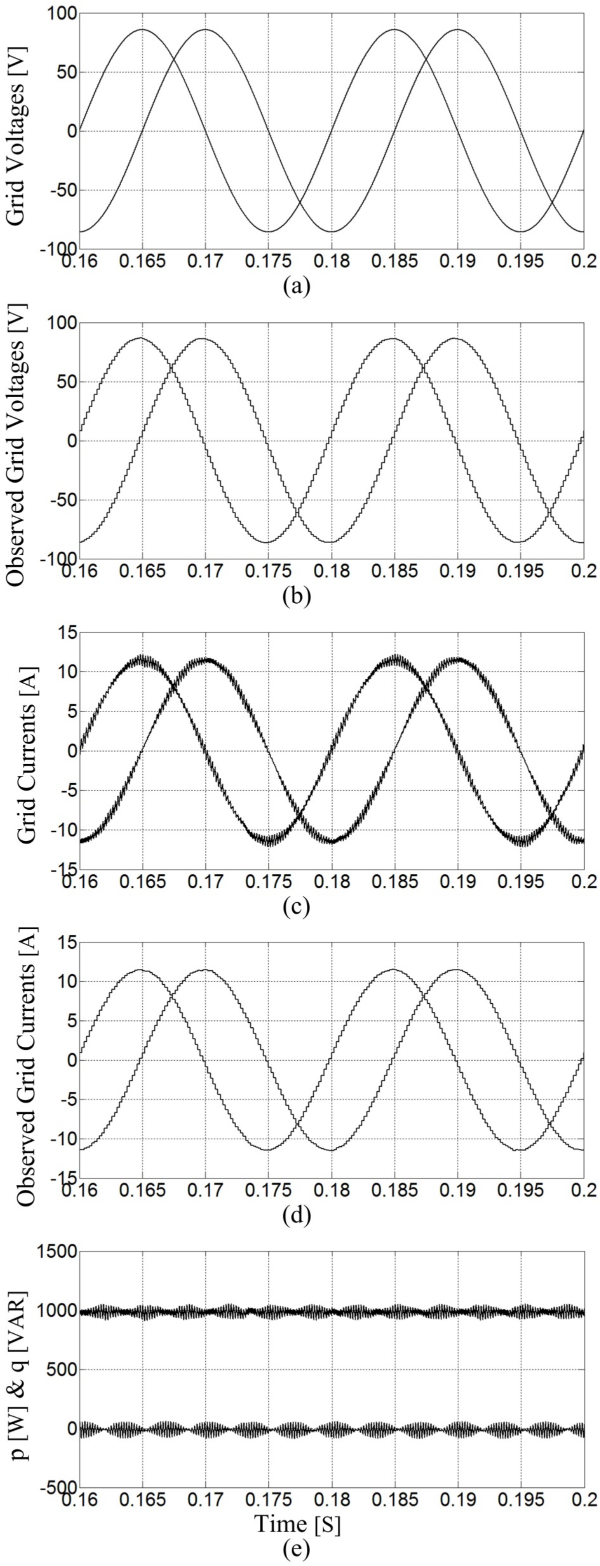

Figure 3. Steady-state performance of the proposed method

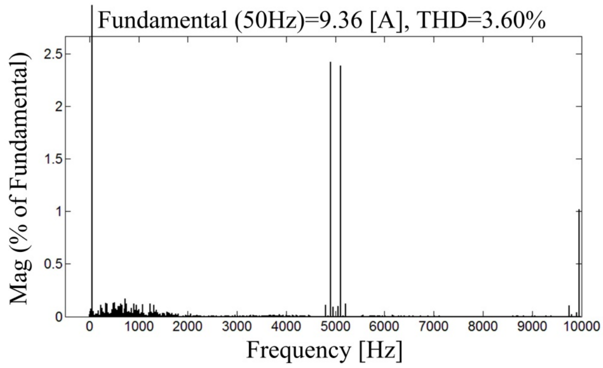

Figure 4. Grid current harmonic spectrum

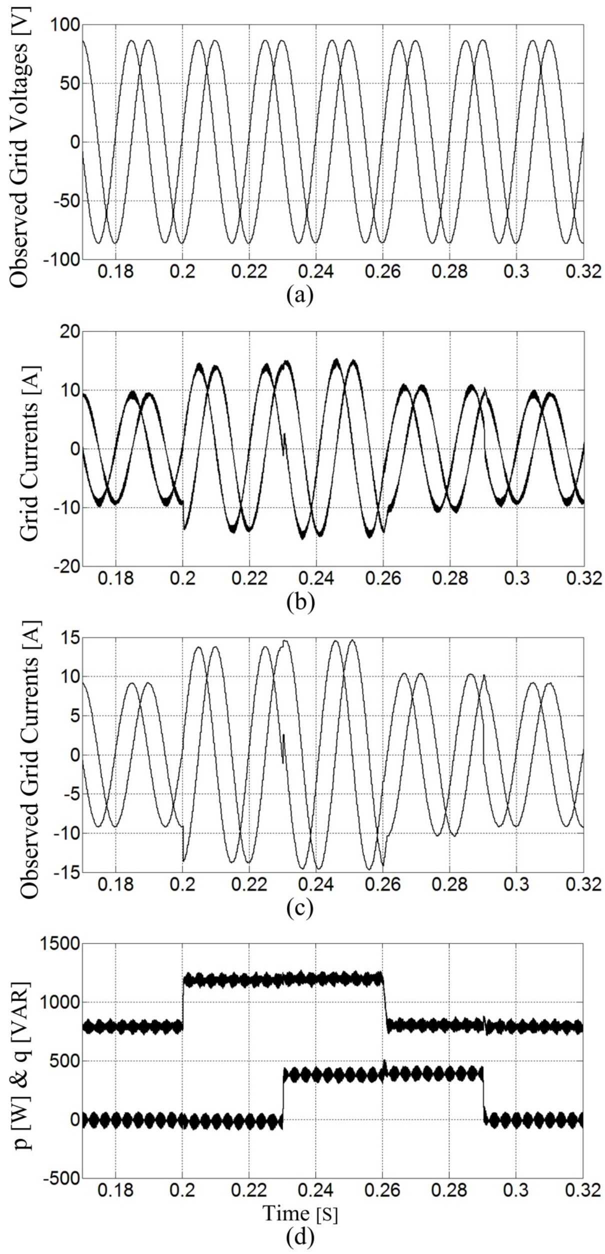

Figure 5. Transient performance of the proposed method

• good dynamic and steady-state performance;

• decoupled active and reactive power control;

• simple structure and concepts and ease to digital implementation;

• proper compensation for delays of digital implementation;

• constant switching frequency;

• no need for coordinate transformations and a PLL;

• reduced cost, size and improved reliability of the system, which are consequences of eliminating the voltage sensors.

REFERENCES

[1] A. Yazdani and R. Iravani, *Voltage-sourced converters in power systems*. IEEE/Wiley, 2010.

[2] R. Teodorescu, M. Liserre, P. Rodríguez, *Grid converters for photovoltaic and wind power systems*. Wiley/IEEE, 2011.

[3] F. Blaabjerg, R. Teodorescu, M. Liserre and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron*., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[4] T. Noguchi, H. Tomiki, S. Kondo and I. Takahashi, "Direct power control of PWM converter without power-source Voltage sensors," *IEEE Trans. Ind. Appl.*, vol. 34, no. 3, pp. 473–479, May/Jun. 1998.

[5] P. Cortes, M. Kazmierkowski, R. Kennel, D. Quevedo, and J. Rodriguez, "Predictive control in power electronics and drives," *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4312–4324, Dec. 2008.

[6] S. Kouro, P. Cortes, R. Vargas, U. Ammann, and J. Rodriguez, "Model predictive control–A simple and powerful method to control power converters," *IEEE Trans. Ind. Electron.*, vol. 56, no. 6, pp. 1826–1838, Jun. 2009.

[7] P. Cortes, J. Rodriguez, P. Antoniewicz, and M. Kazmierkowski, "Direct power control of an AFE using predictive control," *IEEE Trans. Power Electron.*, vol. 23, no. 5, pp. 2516–2523, Sep. 2008.

[8] P. Antoniewicz, M. P. Kazmierkowski, P. Cortes, J. Rodriguez, A. Sikorski, "Predictive direct power control algorithm for three phase AC/DC converter," *in Proc. IEEE Eurocon Conf., Warsaw, Poland*, Sep. 2007, pp. 1530–1534.

[9] S. Kwak; J. Park, "Model-predictive direct power control with vector preselection technique for highly efficient active rectifiers," *IEEE Trans. Ind. Informatics,* vol. 11, no. 1, Mar. 2015

[10] P. Antoniewicz, M. P. Kazmierkowski, S. Aurtenechea, M. A. Rodriguez, "Comparative study of two predictive direct power control algorithms for three-phase AC/DC converters," *in Proc. EPE, Aalborg, Denmark*, Sep. 2007, pp. 1–10.

[11] Y. Zhang, W. Xie, Z. Li and Y. Zhang, "Model predictive direct power control of a PWM rectifier with duty cycle optimization," *IEEE Trans. Power Electron*, vol. 28, no. 11, Nov. 2013.

[12] Y. Zhang; C. Qu, "Model predictive direct power control of PWM rectifiers under unbalanced network," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, Jul. 2015.

[13] D. Choi; K. Lee, "Dynamic performance improvement of AC/DC converter using model predictive direct power control with finite control set," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, Feb. 2015.

[14] Z. Song; W. Chen; C. Xia, "Predictive direct power control for three-phase grid-connected converters without sector information and voltage vector selection," *IEEE Trans. Power Electron*., vol. 29, no. 10, Oct. 2014.

[15] A. Bouafia, J. Gaubert, and F. Krim, "Predictive direct power control of three-phase pulsewidth modulation (PWM) rectifier using space-vector modulation (SVM)," *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 228– 236, Jan. 2010.

[16] M. Monfared, H. Rastegar, H. M. Kojabadi, "High performance direct instantaneous power control of PWM rectifiers," *Energy Conversion and Management,* vol. 51, pp. 947–954, 2010.

[17] D. Zhi, L. Xu and B. W. Williams, "Improved direct power control of grid-connected DC/AC converters," *IEEE Trans. Power Electron.,* vol. 24, no. 5, May. 2009.

[18] S. A. Larrinaga,M. A. R. Vidal, E. Oyarbide, and J. R. T. Apraiz, "Predictive control strategy for dc/ac converters based on direct power control," *IEEE Trans. Ind. Electron.*, vol. 54, no. 3, pp. 1261–1271, Jun. 2007.

[19] P. Antoniewicz and M. Kazmierkowski, "Virtual-flux-based predictive direct power control of ac/dc converters with online inductance estimation," *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4381–4390, Dec. 2008.

[20] J. Hu and Z. Q. Zhu, "Improved voltage-vector sequences on dead-beat predictive direct power control of reversible three-phase grid-connected voltage-source converters," *IEEE Trans. Power Electron.,* vol. 28, no. 1, Jan. 2013.

[21] J. Hu, "Improved dead-beat predictive DPC strategy of grid-connected DC–AC converters with switching loss minimization and delay compensations," *IEEE Trans. Ind. Informatics,* vol. 9, no. 2, May. 2013.

[22] J. M. Huerta, J. C. Moreno, J. R. Fischer and Rafael G. Gila, "Synchronous reference Frame robust predictive current control for three-phase grid-connected inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, Mar. 2010.

[23] P. Vas**,** *Sensorless vector and direct torque control*, Oxford University Press, 1998.