A. Bouafia
J.P. Gaubert
A. Chaoui

J. Electrical Systems 8-4 (2012): 367-383

Regular paper

Direct Power Control Scheme Based on Disturbance Rejection Principle for Three-Phase PWM AC/DC Converter under Different Input Voltage Conditions

Journal of Electrical Systems

Conventional direct power control (DPC) technique is a simple and efficient control strategy for three-phase PWM rectifier. However, its performance is deteriorated when the converter is supplied by unbalanced or distorted grid voltages. This paper describes the design and implementation of a new configuration of DPC based on disturbance rejection principle to achieve near-sinusoidal input current waveforms of the converter under different input voltage conditions. In the proposed DPC scheme, instantaneous active and reactive powers provided by harmonic component of input currents are directly controlled using a predefined switching table. In order to achieve full rejection of the effect of any disturbance on the quality of input currents, the reference of both controlled powers are directly given from the outside of the controller and are equal to zero. Moreover, prior knowledge of disturbance's nature, calculation of positive and negative sequences of unbalanced input voltages and content harmonic extraction are not required for the proposed DPC. Compared to the conventional DPC, the proposed one uses a PLL block to extract the fundamental of input currents and defining the position of the grid voltage vector in α-β plane without any passive filters. Finally, the simulation results have verified the validity of the proposed DPC and have proven an excellent performance under different input voltage conditions. Full disturbance rejection and good robustness towards supply voltage disturbances are the main advantages of the proposed DPC compared to the conventional one.

Keywords: Three-phase PWM rectifiers, instantaneous powers, direct power control (DPC), switching table, voltage distortion, disturbance rejection principle.

1. INTRODUCTION

Traditionally, diode or thyristor bridge rectifiers are extensively employed in industrial fields and consumer products to obtain dc voltage from ac main. This has the advantages of being simple, robust, and inexpensive. However, these rectifiers result in only unidirectional power flow and pollute the utility with low-order harmonics, which are difficult to filter. Apart from application of active and passive filters, a pulse width-modulated (PWM) rectifier is used to overcome this problem. It offers several advanced features such as low harmonic distortion of input currents, bidirectional power delivery capability, high power factor (usually, near unity), and high-quality dc-bus voltage with small filter circuit. Moreover, it represents an interesting solution for equipment which frequently works in regeneration operation, like adjustable speed drives (ASDs) and for the integration of renewable energy applications [1-4]. As a result, this type of PWM rectifier has become the new alternative for ac to dc power conversion which draws a near sinusoidal input current that fulfils the new standards for the electric grid, IEEE-519 for USA and IEC 61000-3-2 and 61000-3-4 for Europe. Over the past few years, considerable research work has been carried out on the control of three-phase PWM rectifiers. Although the proposed control strategies can achieve the same main goals, such as near-sinusoidal input current waveforms at a required power factor and a nearly constant dc output voltage, their principles differ. They can be classified for their use of current loop controllers or active/reactive power controllers [5].

Corresponding author : bouafia_aou@yahoo.fr
Université de Sétif 1, Laboratoire d'électronique de puissance et commande industrielle (LEPCI), Sétif, Algérie.

Firstly, a voltage-oriented control (VOC) which resembles the field-oriented control, used for vector-controlled ac motors, has been developed [6-10]. It is the most commonly used control technique of indirect active and reactive power control. Its principle is based on the two axis method for current vector orientation with respect to the voltage vector. For this control system, unity power factor (UPF) operation on the ac side is achieved when the line current vector is aligned with the phase voltage vector of the power line supplying the PWM rectifier. This control scheme guarantees excellent dynamics and static performance via internal current control loops. However, the final configuration and performance of the VOC system largely depend on the quality of the applied current control strategy.

Secondly, over the last few years, an interesting emerging control technique has been direct power control (DPC) developed analogously with the well-known direct torque control (DTC) used for adjustable speed drives [11-25]. In fact, various DPC schemes without any current control loops have been developed to control the three-phase PWM rectifier. In the developed DPC schemes, instantaneous active and reactive powers are directly controlled in a manner analogous to torque and flux control in an induction motor via internal power control loops. Initially, the developed DPC scheme directly controls active and reactive power by selecting voltage vectors (switching states) from a predefined lookup table (LUT) based on the tracking errors of active and reactive power and the power-source voltage vector position [11-12, 14-17] or virtual-flux (VF) vector position in the stationary reference frame [13,18,20]. The performance of this DPC scheme depends on the choice of the switching table. In references [11] and [13], a switching table similar to the one used in DTC is employed. Next, in [15] and [16] a new switching table allowing smooth and simultaneous control of active and reactive power compared to the first one is proposed. Next, other DPC schemes with space-vector modulation have been proposed in [18]. They join important advantages of SVM with DPC features such as simple and robust structure, good dynamics and lack of internal current control loops. Over the last years, several predictive control approaches combined with DPC have also been proposed in order to enhance control performance [26-30]. All the above mentioned control schemes, including LUT-DPC, SVM-DPC and DPC combined with predictive approaches, are based on the control of the total instantaneous active and reactive powers provided by power-source supplying the PWM rectifier and deal with the case of balanced input voltages with only fundamental harmonic content. As a result, when these DPC strategies are applied under unbalanced or distorted input voltages, the performance of the system is highly deteriorated and low order harmonic contents appear in input currents. Works that deal with the problem of DPC under unbalanced or distorted input voltages are minor and the proposed controls require much computation as in [31-36].

This paper proposes a new DPC scheme to achieve near-sinusoidal input current waveforms of three-phase PWM rectifier under different input voltage conditions. For this purpose, it employs the principle of disturbance rejection to compensate the effect of any grid disturbance on input current waveforms, such as unbalanced and/or distorted voltages. In the proposed DPC, instantaneous active and reactive powers provided by the harmonic component of input currents are chosen as controlled variables. According to the disturbance rejection principle, the references of controlled powers in the proposed control scheme are maintained to zero to reject any input voltages disturbance without having knowledge of its nature. Moreover, calculation of positive and negative sequences of input voltages, exploited in [31-35], and content harmonic extraction, commonly used for unbalanced and distorted input voltages respectively, are not taken into account in the controller design for the proposed DPC. As a result, components transformation and passive filters are not required. Compared to the conventional DPC, the proposed one requires a PLL block to extract the fundamental of input currents and defining the position of the grid voltage vector in α-β plane. Finally, the developed DPC strategy was tested in simulation for different input voltage conditions. Simulation results are shown to demonstrate the effectiveness and the robustness of the proposed DPC controller which is compared with the conventional one.

2. DPC BASED ON DISTURBANCE REJECTION PRINCIPLE

2.1 System Configuration

Mainly, direct control techniques of static converters establish a direct relation between the behavior of the controlled variables and the state of the converter's switches. Recently, direct power control (DPC) has become one of the most popular direct control techniques of grid-connected PWM converters. This technique is derived from the first and original direct torque control (DTC) of induction motors.

In conventional DPC scheme, showed in Fig. 1, controlled variables are total instantaneous active and reactive powers provided by the grid supplying the PWM rectifier. The basic concept consists of selecting the appropriate converter switching states from a lookup table based on the tracking errors, which are limited by a hysteresis band, present in the active and reactive powers and the position θ_n of the power-source voltage vector in α-β plane. For this purpose, this stationary plane is divided into twelve sectors as illustrated in Fig. 3. Therefore, it does not require any internal control loop, any modulator block and any coordinates transformation to avoid coupling effects between transformed variables. In this DPC scheme, the active power command P^* is provided from a dc-bus voltage control block. While the reactive power command q^* is directly given from the outside of the controller.

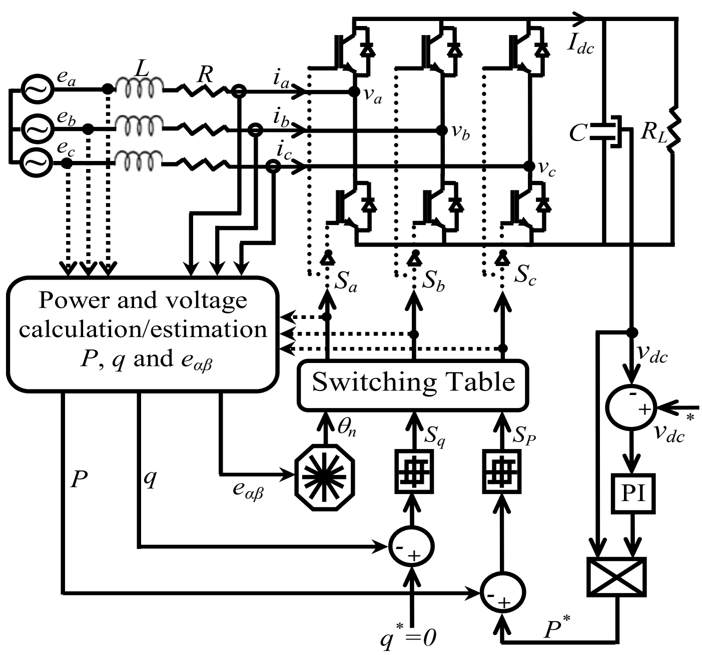

Fig 1: Block diagram of the conventional DPC.

Fig. 2 shows the configuration of the proposed DPC for three-phase PWM rectifier. Its concept is based on disturbance rejection principle to achieve near-sinusoidal input current waveforms and constant dc-bus voltage simultaneously under different input voltage conditions. For this purpose, active and reactive power provided by the harmonic component of input currents, P_h and q_h respectively, are chosen as controlled variables. As shown in Fig. 2, both power commands P_h^* and q_h^* are given from the outside of the controller and are set to zero for full rejection of grid disturbances. Moreover, the dc-bus voltage is regulated by adjusting the magnitude of fundamental term of input current I_{max}, delivered from the outer proportional-integral dc-bus voltage controller. As in conventional DPC, the converter switching states are selected from a lookup table based on the digitized signals S_{Ph} and S_{qh} of power tracking errors, provided by fixed band hysteresis comparators, according to the position θ_n of the fundamental term of input voltage vector $e_{\alpha\beta 1}$ in α-β plane via PLL block.

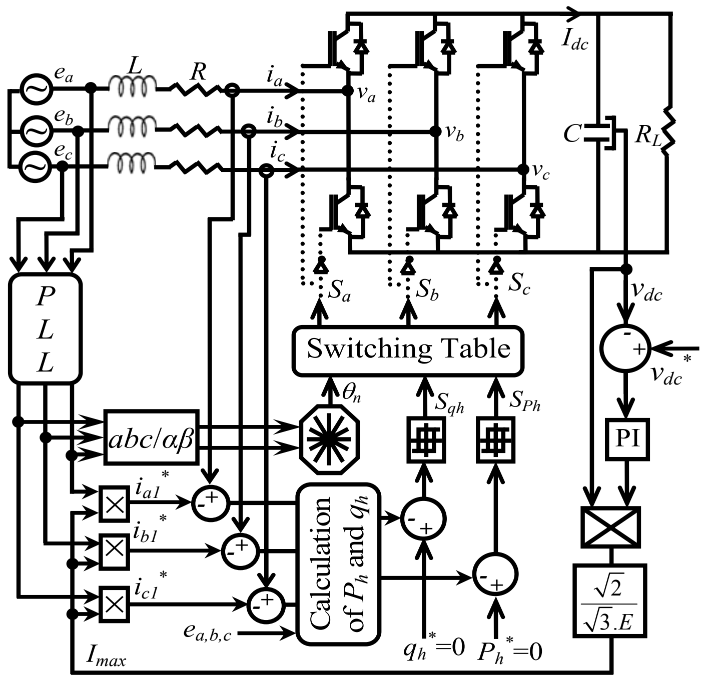

Fig 2: Block diagram of the proposed DPC.

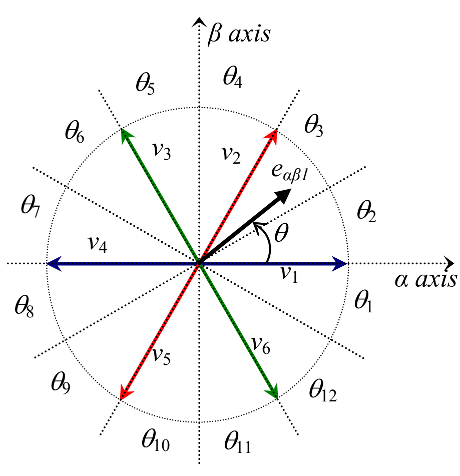

Fig 3: Sectors on stationary frame to specify fundamental power-source voltage vector position, and rectifier voltage vectors.

Table. I: Switching table of DPC

S_p	S_q	θ_1	θ_2	θ_3	θ_4	θ_5	Θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
1	0	v_5	v_6	v_6	v_1	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5
	1	v_3	v_4	v_4	v_5	v_5	v_6	v_6	v_1	v_1	v_2	v_2	v_3
0	0	v_6	v_1	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5	v_5	v_6
	1	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5	v_5	v_6	v_6	v_1

v_1(100), v_2(110), v_3(010), v_4(011), v_5(001), v_6(101), v_0(000), v_7(111).

2.2 Control principle

The instantaneous input active and reactive powers of three-phase PWM rectifier are generally defined as:

$$P = e_a i_a + e_b i_b + e_c i_c \tag{1}$$

$$q = \frac{1}{\sqrt{3}}\left[\left(e_b - e_c\right)i_a + \left(e_c - e_a\right)i_b + \left(e_a - e_b\right)i_c\right] \tag{2}$$

On the one hand, harmonic component of input currents of three-phase PWM rectifier are estimated as follows:

$$\begin{bmatrix} i_{a_h} \\ i_{b_h} \\ i_{c_h} \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_{a_1}^{\ *} \\ i_{b_1}^{\ *} \\ i_{c_1}^{\ *} \end{bmatrix} \tag{3}$$

In the proposed DPC scheme, magnitude of fundamental input currents is delivered from the outer proportional-integral (PI) dc-bus voltage controller, as shown in Fig. 2. So, fundamental terms of these currents are given via PLL block and are in phase with respect to the fundamental line voltages to achieve unity power factor operation (UPF).

$$\begin{bmatrix} i_{a_1}^{\ *} \\ i_{b_1}^{\ *} \\ i_{c_1}^{\ *} \end{bmatrix} = \begin{bmatrix} I_{\max}\sin\left(\omega t\right) \\ I_{\max}\sin\left(\omega t - 2\pi/3\right) \\ I_{\max}\sin\left(\omega t + 2\pi/3\right) \end{bmatrix} \tag{4}$$

Substitution of (4) in (3) gives:

$$\begin{bmatrix} i_{a_h} \\ i_{b_h} \\ i_{c_h} \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} I_{\max}\sin\left(\omega t\right) \\ I_{\max}\sin\left(\omega t - 2\pi/3\right) \\ I_{\max}\sin\left(\omega t + 2\pi/3\right) \end{bmatrix} \tag{5}$$

Instantaneous active and reactive powers provided by the harmonic component of input currents are given as follows:

$$P_h = e_a.i_{a_h} + e_b.i_{b_h} + e_c.i_{c_h} \tag{6}$$

$$q_h = \frac{1}{\sqrt{3}}\left[\left(e_b - e_c\right).i_{a_h} + \left(e_c - e_a\right).i_{b_h} + \left(e_a - e_b\right).i_{c_h}\right] \tag{7}$$

In the proposed controller, P_h and q_h are directly controlled to be zero to ensure full rejection of grid disturbances and to achieve balanced sinusoidal input currents. For this purpose, both commands P_h^* and q_h^* are given from the outside of the controller and are set to zero. Tracking errors between the commands and computed powers P_h and q_h are input to the hysteresis comparators and digitized to the signals S_{Ph} and S_{qh} according to the bandwidths B_P and B_q respectively. Where:

$$\begin{cases} if\ P_h^* - P_h \geq B_P \ \Rightarrow S_{P_h} = 1,\ \ if\ P_h^* - P_h \leq -B_P \ \Rightarrow S_{P_h} = 0 \\ if\ q_h^* - q_h \geq B_q \ \Rightarrow S_{q_h} = 1,\ \ if\ q_h^* - q_h \leq -B_q \ \Rightarrow S_{q_h} = 0 \end{cases}$$

Next, the digitized error signals S_{Ph} and S_{qh} and the position θ_n of fundamental input voltage vector $e_{\alpha\beta 1}$ are inputs to the switching table in which every switching state (S_a, S_b, S_c) of the converter is stored, as shown in Table I. By using our own switching table, proposed in [15-16], the appropriate switching state of the converter can be selected in every specific moment according to the combination of the digitized input signals. The selected switching state allows the best restriction of both power tracking errors to achieve simultaneous control of P_h and q_h with good accuracy.

3. Simulation Results

In order to confirm the effectiveness of the proposed DPC scheme and evaluate its performance under different input voltage conditions, a model of three-phase PWM rectifier, including the control system, has been simulated in Matlab/Simulink™ environment. Simulations have been carried out using the main electrical parameters of power circuit and control data showed in Table II. Several tests were conducted to verify feasibility and performance of the new DPC scheme compared to the conventional one, always with our own switching table. In fact, the following cases of input voltages are investigated in simulation study: balanced sinusoidal voltages, unbalanced sinusoidal voltages, balanced distorted voltages and unbalanced distorted voltages.

Table. II: Electrical parameters of power circuit

Switching period T_s	65 µS
Resistance of reactors R	0.56 [Ω]
Inductance of reactors L	19.5 [mH]
dc-bus capacitor C	1100 µF
Load resistance R_L	68.6 [Ω]
Line to line ac voltage E and frequency f	85 V rms, 50 Hz
dc-bus voltage v_{dc}	180 V

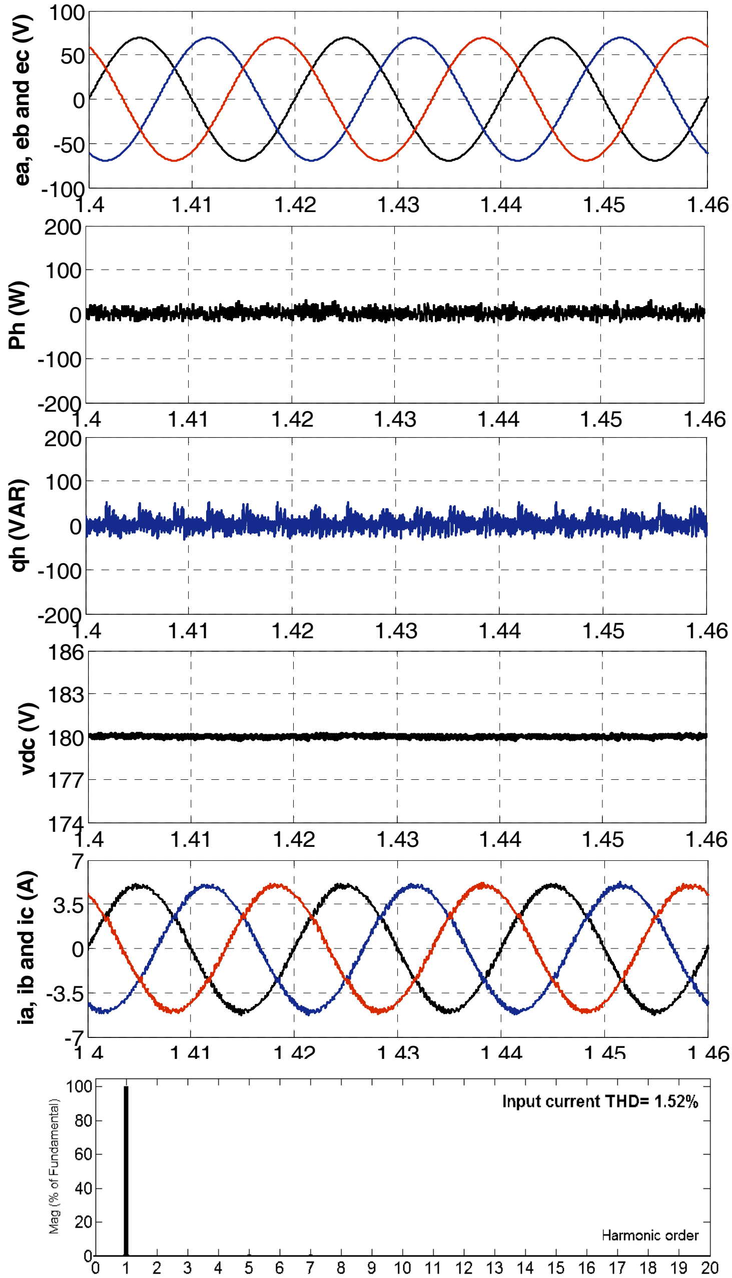

Fig 4: Simulation results for the proposed DPC of PWM rectifier under balanced sinusoidal input voltages for v_{dc}^{*}=180V.

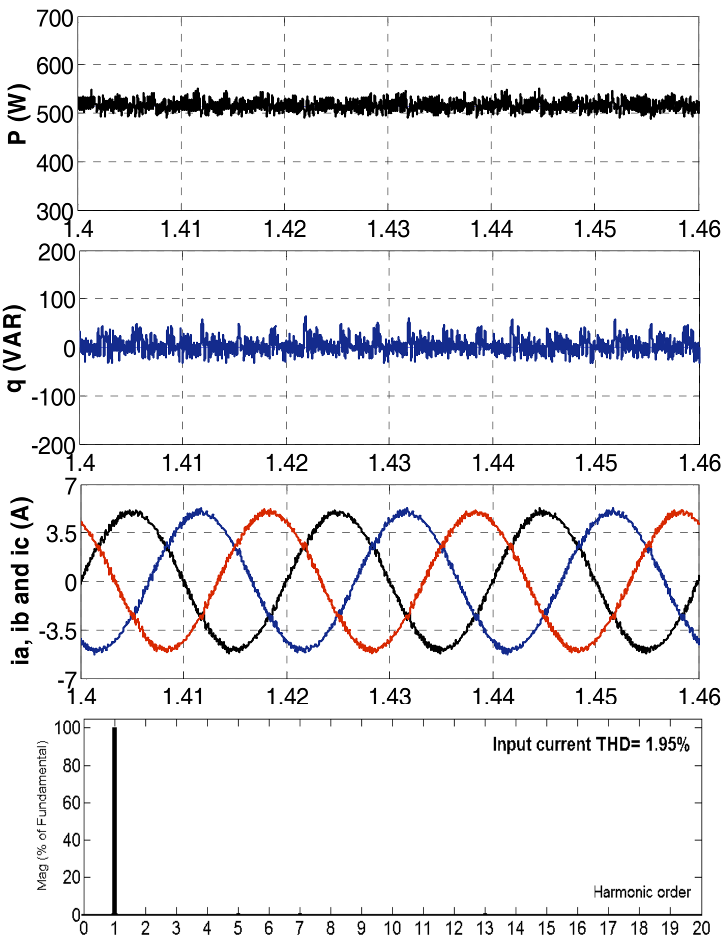

Fig 5: Simulation results for the conventional DPC of PWM rectifier under balanced sinusoidal input voltages for v_{dc}^{*}=180V.

Fig. 4 and Fig. 5 show simulation results of the three-phase PWM rectifier operation under balanced sinusoidal input voltages for the proposed DPC scheme and conventional one respectively. It can be clearly seen that controlled powers and the dc-bus voltage track their references with good accuracy and stability for both control strategies. Therefore, input currents are very close to sinusoidal waveforms and are in phase with their corresponding line supply voltages, thus guaranteeing operation with a power factor very close to unity. Moreover, the proposed DPC is better than conventional one in this case.

The behavior of the proposed DPC and conventional one under unbalanced sinusoidal input voltages (e_a=+25% and e_b=-18% with respect to e_c) are shown in Fig. 6 and Fig. 7 respectively. The input currents for the proposed DPC have nearly sinusoidal waveforms (THD=1.86%) and are balanced, unlike those of conventional DPC which are distorted (THD=11.88%) due to the presence of the 3rd harmonic as shown in current spectrum. Controlled powers and dc-bus voltage are maintained very close to their references. The proposed DPC is much better than the conventional one in this case.

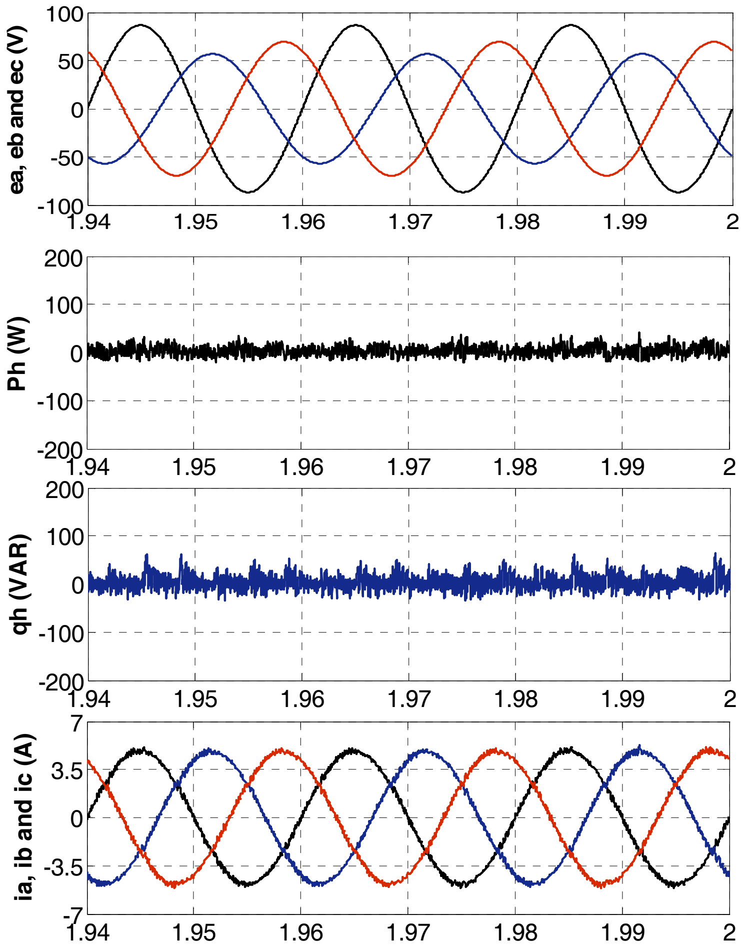

Fig 6: Simulation results for the proposed DPC of PWM rectifier under unbalanced sinusoidal input voltages for v_{dc}^{*}=180V.

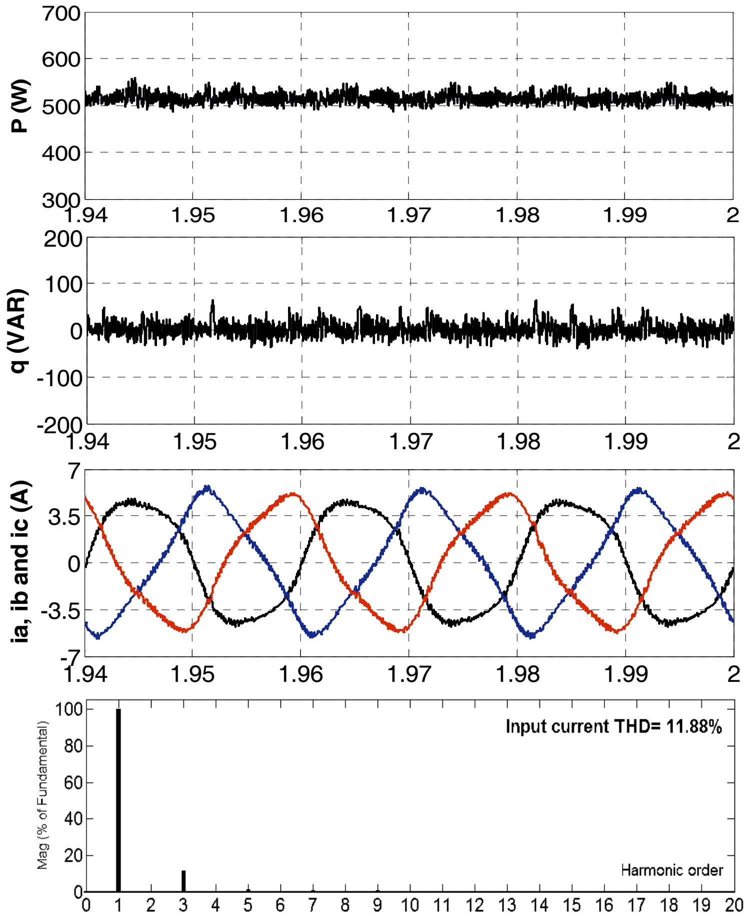

Fig 7: Simulation results for conventional DPC of PWM rectifier under unbalanced sinusoidal input voltages for v_{dc}^{*}=180V.

Fig. 8 and Fig. 9 show simulation results of the three-phase PWM rectifier operation under balanced and distorted input voltages for the proposed DPC and conventional one. In the first test, a fifth harmonic voltage component of 10% is superposed on the fundamental of input voltages (THD=11.11%). In the second test, a seventh harmonic voltage component of 10% is superposed on the fundamental of input voltages (THD=11.11%). It can be clearly seen that the proposed DPC guarantees near-sinusoidal input current waveforms in both tests (THD=1.78 and THD=1.88), by maintaining controlled powers P_h and q_h very close to their references to ensure full rejection of grid disturbance.

However, the distortion of input currents for conventional DPC, showed in Fig. 9, is mainly caused by the presence of 7th harmonic current component for the first test (THD=11.43%) and 5th harmonic current component for the second test (THD=11.42%) to keep controlled powers close to their references. These results confirm that the performance of conventional DPC is highly deteriorated when the converter is supplied by distorted grid voltages.

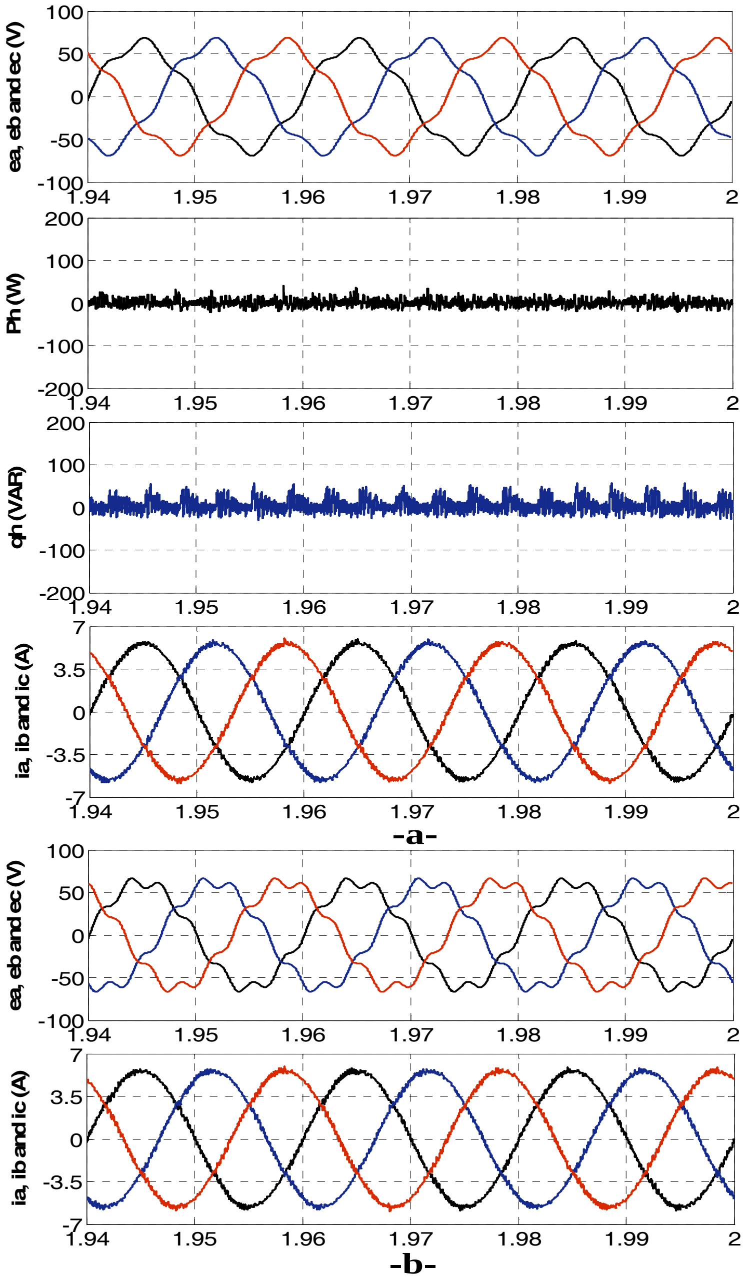

Fig 8: Simulation results for the proposed DPC of PWM rectifier under balanced and distorted input voltages for v_{dc}^{*}=180V: (a) Input voltages with 5th harmonic, (b) Input voltages with 7th harmonic.

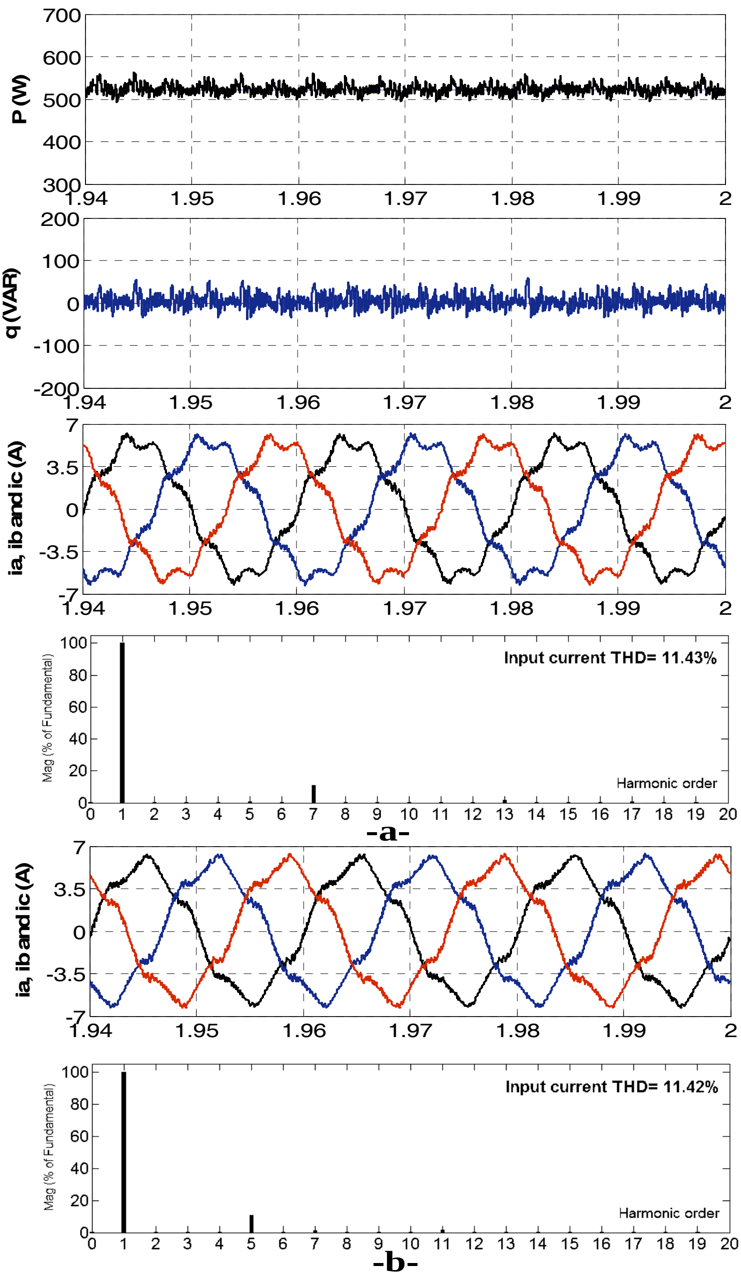

Fig 9: Simulation results for conventional DPC of PWM rectifier under balanced and distorted input voltages for v_{dc}^{*}=180V: (a) Input voltages with 5th harmonic, (b) Input voltages with 7th harmonic.

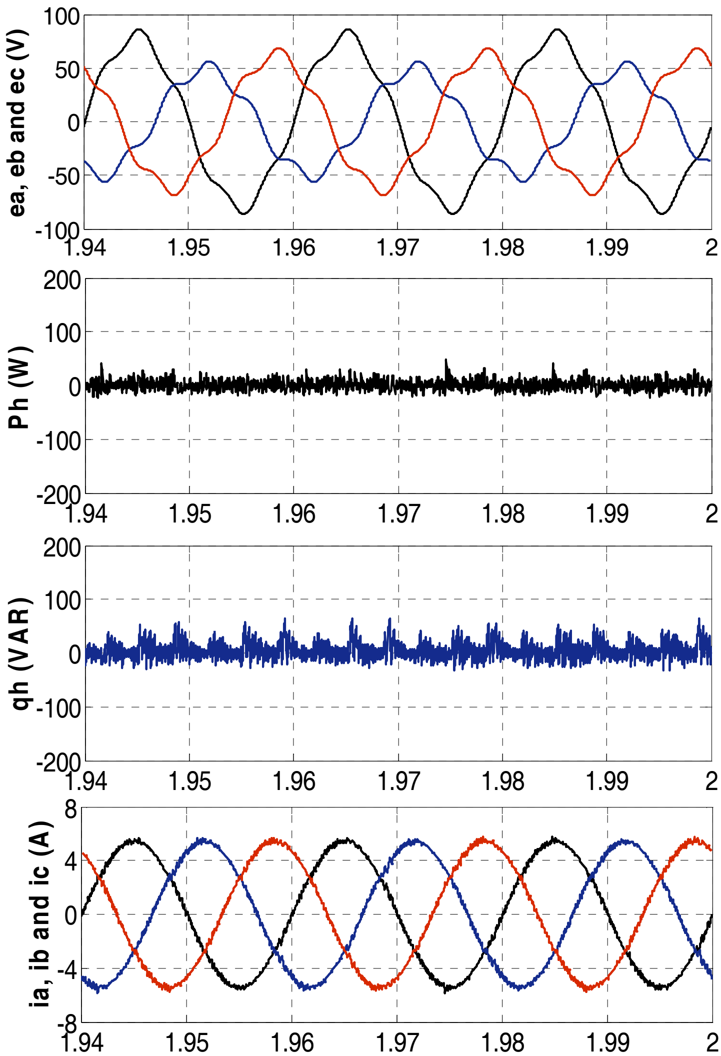

Fig 10: Simulation results for the proposed DPC of PWM rectifier under unbalanced and distorted input voltages for v_{dc}^{*}=180V.

Simulation results of the three-phase PWM rectifier operation under unbalanced and distorted input voltages for the proposed DPC and conventional one are presented in Fig. 10 and Fig. 11 respectively. In this test, the fifth harmonic voltage component of 10% is superposed on unbalanced sinusoidal input voltages (e_a=+25% and e_b=-18% with respect to e_c). The proposed DPC also guarantees near-sinusoidal input current waveforms (THD=1.87%) by maintaining controlled powers very close to zero to ensure full rejection of grid disturbance. However, input currents for conventional DPC are highly distorted due to the presence of the 3rd harmonic, caused by the voltage unbalances, and the presence of the 7th harmonic, caused by the 5th harmonics voltage component as shown in current spectrum.

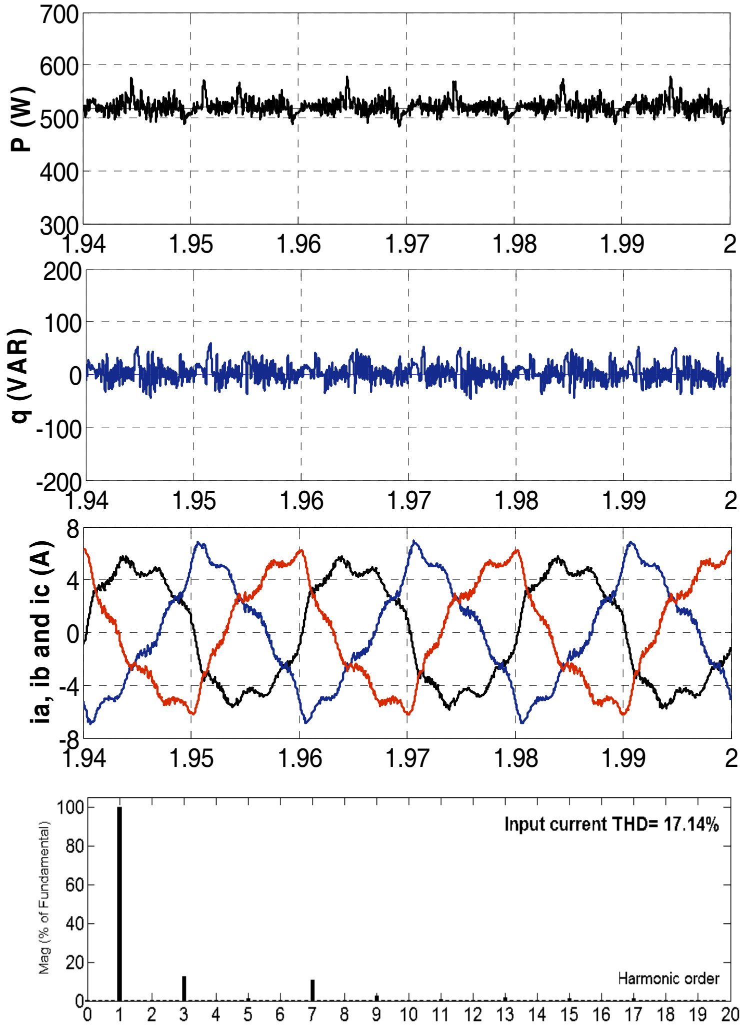

Fig 11: Simulation results for conventional DPC of PWM rectifier under unbalanced and distorted input voltages for v_{dc}^{*}=180V.

4. CONCLUSIONS

This paper has presented the development and the implementation of a new direct power control (DPC) scheme for three-phase PWM rectifier. The main goal of the proposed control strategy is to achieve near-sinusoidal input current waveforms of the converter under different input voltage conditions and maintaining the dc-bus voltage at the required level. The proposed DPC is based on disturbance rejection principle. In fact, instantaneous active and reactive powers provided by harmonic component of input currents are directly controlled via a switching table. Simulation results have proven excellent performance of the proposed DPC scheme which is much better than conventional DPC, even in both transient and steady states. Nearly sinusoidal waveforms of input currents are successfully achieved under different input voltage conditions. The presented simulation results confirm that the proposed DPC is capable to ensure full rejection of disturbance affecting input voltages (unbalance and/or distortion), unlike the conventional DPC which is very sensitive to such disturbances.

LIST OF SYMBOLS

- e_a, e_b and e_c: input voltages
- i_a, i_b and i_c: input currents
- v_a, v_b and v_c: ac terminal voltages of the PWM rectifier
- P, q: total instantaneous active and reactive powers
- P_h, q_h: powers provided by harmonic component of input currents
- S_a, S_b, S_c: switching states of the converter;
- L, R: inductance and resistance of smoothing inductor;
- C, R_L: dc-link capacitor and load resistance.

REFERENCES

[1] J. R. Rodriguez, J. W .Dixon, J. R. Espinoza, and J. Pontt, P. Lezana, PWM regenerative rectifiers: state of the art, *IEEE Trans. Industrial Electronics*, vol. 52, No. 1, pp. 5-22, February 2005.

[2] B. Singh, B. N. Singh, A. Chandra, K. Al-haddad and all, A review of three-phase improved power quality AC-DC converters, *IEEE Trans. Industrial Electronics*, vol. 51, No. 3, pp. 641-660, June 2004.

[3] B. Yin, R. Oruganti, S. K. Panda, and K. S. Bhat, A simple single-input-single-output (SISO) model for a three-phase PWM rectifier, *IEEE Trans. Power Electronics*, vol. 24, No. 3, pp. 620-631, March 2009.

[4] R. Ghosh and G. Narayanan, Control of three-phase, four-wire PWM rectifier, *IEEE Trans. Power Electronics*, vol. 23, No. 1, pp. 96-106, January 2008.

[5] M. Malinowski, M. P. Kazmierkowski, and A. Trzynadlowski, Review and comparative study of control techniques for three-phase PWM rectifiers, *ELSEVIER, Mathematics and computers in simulations*, vol. 63, pp. 349-361, 2003.

[6] B. H. Kwon, J. H. Youm, and J.W. Lim, A line voltage-sensorless synchronous rectifier, *IEEE Trans. Power Electronics*, vol. 14, No. 5, pp. 966-972, September 1999.

[7] M. Liserre, A. Dell'Aquila, and F. Baabjeerg, Genetic algorithm-based design of the active damping for an LCL-filter three-phase active rectifier, *IEEE Trans. Power Electronics*, vol.19, No. 1, pp. 76-86, January 2004.

[8] M. Malinowski and S. Bernet, A simple voltage sensorless active damping scheme for three-phase PWM converters with LCL filter, *IEEE Trans. Industrial Electronics*, vol. 55, No. 4, pp. 1871-1880, April 2008.

[9] B. Yin, R. Oruganti, S. K. Panda, and A. K. S. Bhat, An output-power-control strategy for a three-phase PWM rectifier under unbalanced supply conditions, *IEEE Trans. Industrial Electronics*, vol. 55, No. 5, pp. 2140-2150, May 2008.

[10] J. Dannelh, C. Wessels, and F. W. Fuchs, Limitations of voltage-oriented PI current control of grid-connected PWM rectifiers with LCL filters, *IEEE Trans. Industrial Electronics*, vol. 56, No. 2, pp. 380-388, February 2009.

[11] T. Noguchi, H. Tomiki, S. Kondo, and I. Takahashi, Direct power control of PWM converter without power-source voltage sensors, *IEEE Trans. Industry Applications*, vol. 34, No. 3, pp. 473-479, May 1998.

[12] G. Escobar, A. M. Stankovic, J. M. Carrasco, E. Galvan, and R. Ortega, Analysis and design of direct power control (DPC) for a three phase synchronous rectifier via output regulation subspaces, *IEEE Trans. Power Electronics*, vol. 18, No. 3, pp. 823-830, May 2003.

[13] M. Malinowski, M. P. Kazmierkowski, S. Hansen, f. Blaabjerg, and G. D. Maeques, Virtual flux based direct power control of three phase PWM rectifiers, *IEEE Trans. Industry Applications*, vol. 37, No. 4, pp. 1019-1027, July/August 2001.

[14] L. A. Serpa, S. Ponnaluri, P .M. Barbosa, and J. W. Kolar, A modified direct power control strategy allowing the connection of three-phase inverters to the grid through LCL filters, *IEEE Trans. Industry Applications*, vol. 43, No.5, pp. 1388-1400, September/October 2007.

[15] A. Bouafia, J. P. Gaubert, and F. Krim, Analysis and design of new switching table for direct power control of three-phase PWM rectifier, *13th International Power Electronics and Motion Control Conference (EPE-PEMC 2008)*, pp. 703-709, 2008.

[16] A. Bouafia, F. Krim, and J. P. Gaubert, Design and implementation of high performance direct power control of three-phase PWM rectifier, via fuzzy and PI controller for output voltage regulation, *ELSEVIER*, *Energy Conversion and Management*, vol. 50, No. 1, pp. 6-13, Jan. 2009.

[17] A. Bouafia, F. Krim, and J. P. Gaubert, Fuzzy-logic-based switching state selection for direct power control of three-phase PWM rectifier, *IEEE Trans. Industrial Electronics*, vol. 56, No. 6, pp. 1984-1992, June 2009.

[18] M. Malinowski, M. Jasinski, and M. P. Kazmierkowski, Simple Direct power control of three phase PWM rectifier using space vector modulation (DPC-SVM), *IEEE Trans. Industrial Electronics*, vol. 51, No. 2, pp. 447-454, April 2004.

[19] S. Vazquez, J. A. Sanchez, J. M. Carrasco, J. I. Leon, and E. Galvan, A model-based direct power control for three-phase power converters, *IEEE Trans. Industrial Electronics*, vol. 55, No. 4, pp. 1647-11657, April. 2008.

[20] D. Zhi, L. Xu, and B. W. Williams, Improved direct power control of grid-connected DC/AC converters, *IEEE Trans. Power Electronics*, vol. 24, No. 5, pp. 1280-1292, May 2009.

[21] J. A. Restrepo, J. M. Aller, J. C. Viola, A. Bueno, and T. G. Habetler, Optimum space vector computation technique for direct power control, *IEEE Trans. Power Electronics*, vol. 24, No. 6, pp. 1637-1645, June 2009.

[22] J. Hu, L. Shang, Y. He, and Z. Q. Zhu, Direct active and reactive power regulation of grid-connected DC/AC converters using sliding mode control approach, *IEEE Trans. Power Electronics*, vol. 26, No. 1, pp. 210-222, Jan 2011.

[23] J. A. Restrepo, J. M. Aller, A. Bueno, J. C. Viola, A. Berzoy, R. Harley, and T. G. Habetler, Direct power control of dual converter operating as a synchronous rectifier, *IEEE Trans. Power Electronics*, vol. 26, No. 5, pp. 1410-1417, May 2011.

[24] J. A. Martinez, J. E. G. Carrasco, and S. Arnaltes, Table-based direct power control: a critical review for microgrid applications, *IEEE Trans. Power Electronics*, vol. 25, No. 12, pp. 2949-2961, December 2010.

[25] A. Sato and T. Noguchi, Voltage-source PWM rectifier-inverter based on direct power control and its operation characteristics, *IEEE Trans. Power Electronics*, vol. 26, No. 5, pp. 1559-1567, May 2011.

[26] P. Cortés, M. P. Kazmierkowski, R. M. Kennel, D. E. Quevedo, and J. Rodríguez, Predictive control in power electronics and drives, *IEEE Trans. Industrial Electronics*, vol. 55, No. 12, pp. 4312-4324, December 2008.

[27] A. Bouafia, J. P. Gaubert, and F. Krim, Predictive direct power control of three-phase pulsewidth modulation (PWM) rectifier using space-vector modulation (SVM), *IEEE Trans. Power Electronics*, vol. 25, No. 1, pp. 228-236, January 2010.

[28] S. A. Larrinaga, M. A. R. Vidal, E. Oyarbide, and J. R. T. Apraiz, Predictive control strategy of DC/AC converters based on direct power control, *IEEE Trans. Industrial Electronics*,vol. 54, No. 3, pp. 1261-1271, June 2007.

[29] P. Antoniewicz and M. P. Kazmierkowski, Virtual-flux-based predictive direct power control of AC/DC converters with online inductance estimation, *IEEE Trans. Industrial Electronics*, vol. 55, No. 12, pp. 4381-4390, December 2008.

[30] P. Cortés, J. Rodríguez, P. Antoniewicz, and M. P. Kazmierkowski, Direct power control of an AFE using predictive control, *IEEE Trans. Power Electronics*, vol. 23, No. 5, pp. 2516-2523, September 2008.

[31] S. C. Ahn and D. S. Hyun, New control scheme of three-phase PWM AC/DC converter without phase angle detection under the unbalanced input voltage conditions, *IEEE Trans. Power Electronics*, vol. 17, No. 5, pp. 616-622, September 20002.

[32] M. Cichowlas, M. Malinowski, M. P. Kazmierkowski, D. L. Sobczuk, and J. Pou, Active filtering function of three-phase PWM boost rectifier under different line voltage conditions, *IEEE Trans. Industrial Electronics*, vol. 52, No. 2, pp. 410-419, April 2005.

[33] H. Nian, Y. Song, P. Zhou, and Y. He, Improved direct power control of wind turbine driven doubly fed induction generator during transient grid voltage unbalance, *IEEE Trans. Energy Conversion*, vol. 6, No. 3, pp. 976-986, September 2011.

[34] X. H. Wu, S. K. Panda, and J. X. Xu, Analysis of the instantaneous power flow for three-phase PWM boost rectifier under unbalanced supply voltage conditions, *IEEE Trans. Power Electronics*, vol. 23, No. 4, pp. 1679-1691, July 2008.

[35] J. Hu and Y. He, Modeling and control of grid-connected voltage-sourced converters under generalized unbalanced operation conditions, *IEEE Trans. Energy Conversion*, vol. 23, No. 3, pp. 903-913, September 2008.

[36] S. Vazquez, J. A. Sanchez, J. M. Carrasco, E. Galvan, J. I. Leon, E. Dominguez, and O. Martinez, Direct power control of three-phase power converters under distorted input voltages, *International Conference on Industrial Technology (ICIT 2009)*, pp. 1-6, 2009.