A Simple and Efficient Control Strategy for Four-Switch Three-Phase Power Converters

Mohammad MONFARED[1], Hasan RASTEGAR[1], Hossein M. KOJABADI[2]
[1]*Dept. of Electrical Eng., Amirkabir University of Technology, Tehran, Iran*
[2]*Dept. of Electrical Eng., Sahand University of Technology, Tabriz, Iran*
m.monfared@aut.ac.ir

***Abstract*—In this paper a simple and high performance power control strategy for four-switch three-phase converters is developed. Compared to already available control schemes, the proposed controller is very simple to derive and implement; however, it is established on a strong mathematical approach based on the knowledge of the system model. The required converter voltage in each sampling period is directly calculated based on reference and measured values of reactive and active powers, system parameters, and the measured voltage of AC source. Then, the reference voltage is synthesized by a PWM block. Simulation results confirm the effectiveness of the proposed method in providing precise power control with minimum distortion and harmonic noises (THD*i*), and at the same time, low distortion in active and reactive powers.**

***Index Terms*—control, four-switch three-phase power converter**

I. INTRODUCTION

Semiconductor switches mainly determine the overall price of the power converter devices. So, there has always been a desire to develop new topologies with reduced number of semiconductor devices aiming at reduced costs. Above all, in the range of a few ten kilowatts and above, this may cause considerable savings. Therefore, several AC/DC/AC converter topologies have been introduced so far [1-12]. Among various three-phase component minimized converter topologies, the four-switch converter has shown the best performance thanks to the reduced number of semiconductor devices, minimized conduction and switching losses, regeneration capability, higher DC link voltage utilization, etc. [1]. This converter topology, shown in Figure 1, is often called a voltage-doubler. As it can be seen, the DC link voltage is twice with respect to the conventional six-switch converter. This topology is widely employed in industrial applications. The circuit of Fig. 1 has two converter legs and the third phase is connected to the middle point of the DC link capacitor bank.

As compared to the conventional six-switch converter, the four-switch converter has a lot of advantages such as [1-12]; the number of power semiconductor switches and the fly-wheel diodes are reduced, this resulting in cost and space savings. Besides, associated control and drive circuits are also eliminated, which itself brings more savings. On the other hand, due to a reduced number of switches, the conduction and switching losses in the semiconductor devices will also be decreased. What's more, eliminating some semiconductor devices from the topology brings more reliability. Last but not least, DC link voltage is as twice as compared to a six-switch converter; although it is an advantage in rectifying operation, this may not be desired in some inverter applications. This topology has also some drawbacks; the third phase current flows through the DC link capacitors. So they are exposed to low frequency harmonics which calls for bigger DC link capacitors. Besides, the four-switch converter does not eliminate the third-order harmonics automatically, so higher switching frequencies are expected.

During the two last decades, many works regarding the control and modulation strategies [6, 7], design and adaption in AC/DC/AC applications, especially AC motor drives [8, 9] are reported. Some other works successfully employed this converter in the grid connection of distributed generation systems such as wind energy conversion systems [10, 11, 12]. The same as conventional six-switch converters, these converters also require sophisticated control of active and reactive power flows between the power supply and the electric grid or local loads.

This paper is focused on the control of active and reactive power flows of a four-switch three-phase voltage-source converter. After a brief description of commonly used control strategies, a new control approach is presented. The proposed technique besides having a very simple algorithm, also shows superior performance. The effectiveness of the presented method in providing fast and accurate control is validated by extensive simulations.

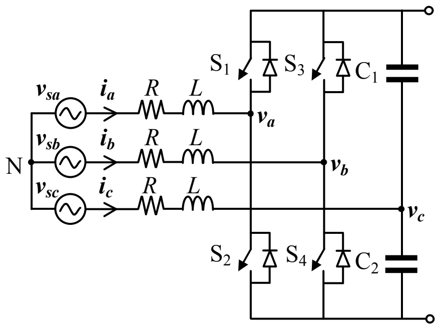

Figure 1. Four-switch voltage source converter.

II. INDIRECT AND DIRECT POWER CONTROL TECHNIQUES

The control schemes commonly used for voltage source converters can be divided into direct or indirect control strategies. Although these control strategies can achieve the same main goals, such as accurate and fast power control and near-sinusoidal currents, their principles differ. The indirect control is characterized by a voltage modulator which computes the on/off times of converter switches along a switching period through the evaluation of the voltage reference. This reference is produced by the current controllers, which idealizes the converter as a continuous

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voltage source. On the other hand, the direct control technique is aimed to control the instantaneous active and reactive powers and establishes a direct relation between the behavior of the controlled variable and the state of the converter switches.

A. Indirect power control

A well-known method of indirect active and reactive power control is based on the current vector orientation with respect to the line voltage vector called voltage-oriented control or VOC. VOC guarantees high dynamics and static performance via internal current control loops. As it can be seen in Figure 2, the scheme decouples the converter currents into active and reactive power components. Control of the active and reactive powers is then achieved by controlling the decoupled converter currents using current controllers. The PWM signals can be generated according to a scalar pulse-width modulation (SPWM) or space vector modulation (SVM) strategy [5, 13, 14]. These well-known modulation techniques for the four-switch converter topology are comprehensively addressed by the authors in another work [1]. The VOC scheme, except for the PWM generation block, is exactly the same for both four-switch and conventional six-switch converter topologies. The virtual flux oriented control (VFOC), which is an adaptation of VOC to a virtual flux reference frame is recently developed and seems to be less sensitive against line voltage variations [14].

Indirect control technique provides good transient behavior and PI current controller ensures zero steady-state error. Besides its complex algorithm, one main drawback of the control strategy depicted in Fig. 2 is that the performance is highly dependent on the applied current control strategy and the connected AC network conditions. The implementation of the rotating reference frame controller allows an improved reference tracking capability of the PI regulator; however, this involves coordinate transformation and a decoupling feed-forward path between d and q components of reference currents [5, 13, 14].

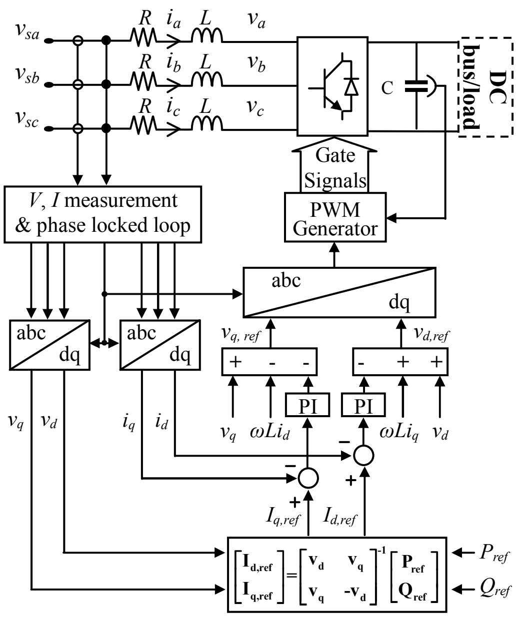


Figure 2. Voltage oriented control (VOC) of three-phase six-switch and four-switch converters.

B. Direct power control

Another control strategy called direct power control (DPC) is based on the instantaneous active and reactive power control. As it is shown in Figure 3, in DPC, there are no internal current control loops and no PWM modulator block, because the converter switching states are appropriately selected by a look-up table based on the instantaneous errors between the commanded and measured values of the active and reactive powers. Compared to VOC, there is a simpler algorithm, no current control loops, no coordinate transformation and separate PWM voltage modulator, no need for decoupling between the control of the active and reactive components, and better dynamics performance. On the other hand, the variable switching frequency and some problems due to the high gain of the hysteresis controllers are the well-known disadvantages of the DPC scheme [14-19].

In the case of four-switch converters, some essential requirements of DPC principle cannot be achieved. Mainly, due to an unsymmetrical voltage vector space and reduced realizable switching states, as depicted in Figure 4, it is impossible to develop an efficient switching table which is the heart of DPC scheme. So, the conventional switching table based DPC cannot be applied to the four-switch converter topology.

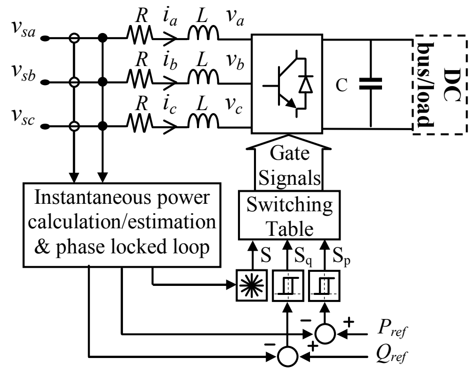


Figure 3. Direct power control (DPC) of three phase six-switch converters.

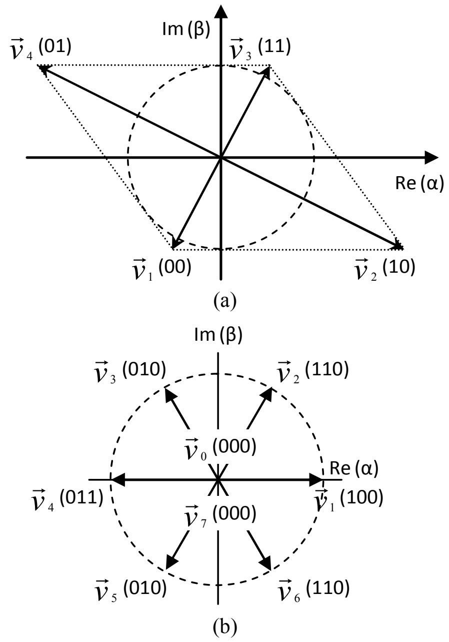


Figure 4. Switching vectors for (a) four-switch and (b) conventional six-switch converter.

III. Proposed Instantaneous Power Control Method

In this research work, a novel control method for four-switch three-phase pulse-width-modulated converters is presented. Compared to VOC, the proposed technique has a simple algorithm and current control loops are omitted, in addition, there is no need for decoupling between the control of active and reactive components. These advantages are achieved for the conventional six-switch converters by DPC technique. The proposed strategy for the four-switch converters, besides having the conventional DPC method advantages, offers many unique features such as fixed switching frequency and no need for hysteresis controllers.

Figure 5 shows the block diagram of the proposed method. In this method, the required converter voltage in each sampling period is directly calculated based only on reference and measured values of active and reactive powers, system parameters, and the measured voltage of the AC source through simple mathematical operations. Then, a PWM generator synthesizes the reference voltage and generates the switching pulses for the voltage source converter.

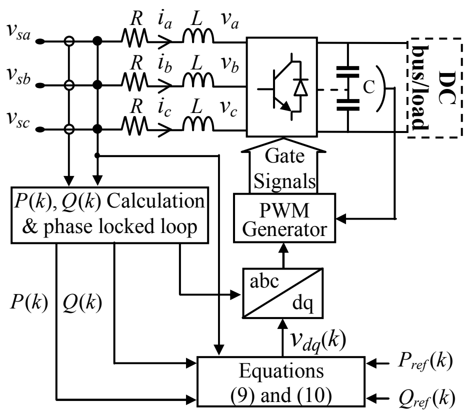


Figure 5. Proposed power control scheme.

A. Proposed controller equations

The following equations can be obtained from the circuit in Fig. 1:

$$L\frac{d}{dt}\vec{i}_{abc} = -R\vec{i}_{abc} + \vec{v}_{sabc} - \vec{v}_{abc} \tag{1}$$

where v is the converter voltage, v_s is the AC source voltage, i is the line current, R, and L are equivalent resistance and inductance between the source and the converter, respectively. Equation (1) can be expressed in the rotating reference frame:

$$\frac{d}{dt}\vec{i}_{dq} = (-\frac{R}{L} - j\,\omega)\vec{i}_{dq} + \frac{1}{L}\vec{v}_{sdq} - \frac{1}{L}\vec{v}_{dq} \tag{2}$$

Equation (2) is separated in each small sampling period (T_{sp}) and decoupled to d and q components as shown by equations (3) and (4).

$$i_d(k+1) = \left(1 - \frac{T_{sp}R}{L}\right)i_d(k) + T_{sp}\omega i_q(k) + \frac{T_{sp}}{L}\left(v_{sd}(k) - v_d(k)\right) \tag{3}$$

$$i_q(k+1) = \left(1 - \frac{T_{sp}R}{L}\right)i_q(k) - T_{sp}\omega i_d(k) + \frac{T_{sp}}{L}\left(v_{sq}(k) - v_q(k)\right) \tag{4}$$

On the other hand, the active and reactive powers in the rotating reference frame are:

$$P(k+1) = v_{sd}(k+1)i_d(k+1) + v_{sq}(k+1)i_q(k+1) \tag{5}$$

$$Q(k+1) = v_{sq}(k+1)i_d(k+1) - v_{sd}(k+1)i_q(k+1) \tag{6}$$

By substituting (3) and (4) in (5) and (6) and assuming that by using a PLL, the control system will be synchronized with the AC source voltage and during a small sampling period, the AC source voltage is constant, i.e. $v_{sd}(k+1) \cong v_{sd}(k)$ and $v_{sq}(k+1) \cong v_{sq}(k) = 0$, then we will obtain the following equations for the instantaneous powers:

$$P(k+1) = \left(1 - \frac{T_{sp}R}{L}\right)P(k) - T_{sp}\omega Q(k) + \frac{T_{sp}}{L}\left(v_{sd}^2(k) - v_{sd}(k)v_d(k)\right) \tag{7}$$

$$Q(k+1) = \left(1 - \frac{T_{sp}R}{L}\right)Q(k) + T_{sp}\omega P(k) + \frac{T_{sp}}{L}v_{sd}(k)v_q(k) \tag{8}$$

The target of the control is to make the load active and reactive powers at the sampling point ($k+1$), equal to the reference active and reactive power values currently available at the sampling point (k), i.e. $P(k+1) = P_{ref}(k)$ and $Q(k+1) = Q_{ref}(k)$. These two control rules are substituted in (7) and (8). By rearranging the results we will have the following equations for $v_d(k)$ and $v_q(k)$:

$$v_d(k) = v_{sd}(k) + \left(\frac{L}{T_{sp}} - R\right)\frac{P(k)}{v_{sd}(k)} - \frac{L}{T_{sp}}\frac{P_{ref}(k)}{v_{sd}(k)} - L\omega\frac{Q(k)}{v_{sd}(k)} \tag{9}$$

$$v_q(k) = -\left(\frac{L}{T_{sp}} - R\right)\frac{Q(k)}{v_{sd}(k)} + \frac{L}{T_{sp}}\frac{Q_{ref}(k)}{v_{sd}(k)} - L\omega\frac{P(k)}{v_{sd}(k)} \tag{10}$$

The above equations are the d and q components of the converter voltage in the rotating reference frame which will satisfy the control criteria. The gating signals of the four-switch PWM converter will then be produced according to these d and q voltage components using one of the well-known modulation techniques mentioned in [1] in order to achieve high efficiency and good harmonics performance.

B. Limitation of Vd and Vq Voltages

The maximum injected voltage of a voltage source PWM converter is limited by its DC link voltage. Equations (9) and (10) show that during transients, large variations of active and/or reactive power references can result in voltages higher than feasible values. Thus, v_d and v_q must be limited properly. So, within a sampling period, if calculated $v_d(k)$ and $v_q(k)$ exceed the voltage limit, then they must be scaled proportionally as: [5]

$$v'_d(k) = v_d(k)\frac{V_{\max}}{\sqrt{v_d^{\,2}(k)+v_q^{\,2}(k)}} \tag{11}$$

$$v'_q(k) = v_q(k)\frac{V_{\max}}{\sqrt{v_d^{\,2}(k)+v_q^{\,2}(k)}} \tag{12}$$

where V_{max} is the maximum available voltage in the converter AC side.

IV. PERFORMANCE EVALUATION

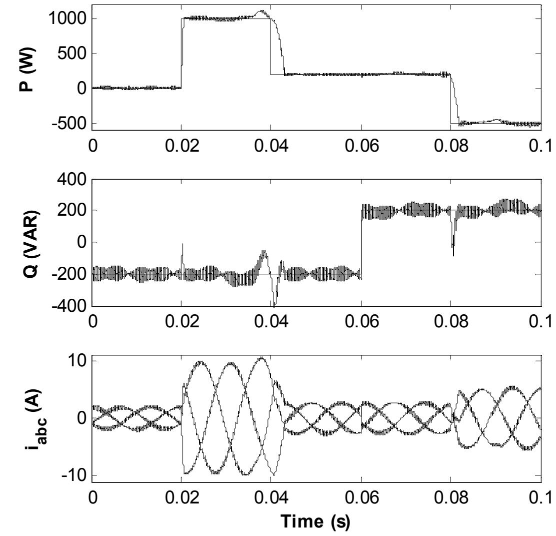
In order to verify the effectiveness of the proposed configuration and its control strategy, a digital computer simulation model has been developed in MATLAB/SIMULINK platform. The system parameters are summarized in Table 1. The performance of the proposed system will be verified by simulation results and will be compared with the results of the well-known indirect control method, such as VOC. To assure a valid comparison, both the proposed method and VOC utilize Sinusoidal PWM (SPWM) with 5 kHz switching frequency to generate gate signals, and for both techniques the sampling frequency is chosen to be 10 kHz. Figure 6 shows the response of the proposed controller and VOC schemes to various changes in commanded active and reactive powers. These waveforms confirm the proper operation of the proposed method in comparison with VOC. Both controllers provide precise current control with low distortion and harmonic noises (THD*i*) and at the same time, accurate regulation of output active and reactive powers. Indeed, the reference tracking capability as well as the steady-state performance of the proposed controller is as good as a properly designed VOC. The harmonic spectrum of the phase current i_a is shown in Figure 7. As it was expected, the proposed method and the VOC produce a similar harmonic spectrum.

TABLE I. ELECTRICAL PARAMETERS OF SIMULATED SYSTEM

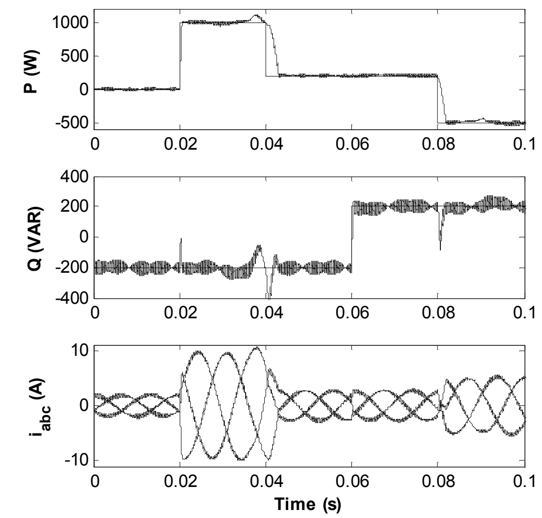
Sampling frequency (kHz)	10
Switching frequency (kHz)	5
Resistance of reactors (Ω)	0.2
Inductance of reactors (mH)	10
DC Link capacitor (μF)	1000
Line to ground AC voltage (V rms)	50
AC Voltage frequency (Hz)	50
DC Link voltage (V)	300

V. CONCLUSION

A novel method for control of four-switch three-phase power converters is presented. The control method is very simple to design and implement; however it is established on a strong mathematical approach based on the knowledge of the system model. Simulation results confirm the effectiveness of the proposed method in providing precise power control with minimum distortion and harmonic noises (THD*i*), and at the same time, low distortion in active and reactive powers. The proposed strategy, besides having the VOC's advantages, offers many unique features such as: no hysteresis or linear PI controller are required and reference values in each sampling period are directly computed on the basis of measurements and system parameters through simple mathematical operations;

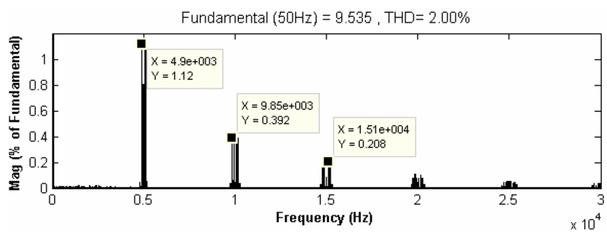


(a)

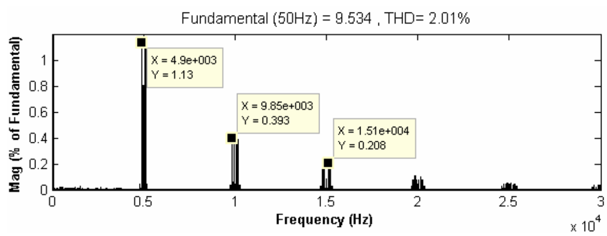


(b)

Figure 6. Simulated waveforms with various active and reactive power steps: (a) VOC (b) Proposed controller.



(a)



(b)

Figure 7. Simulated line current harmonic spectrum (P_{ref} = 1000 W, Q_{ref} = 0): (a) VOC (b) Proposed controller.

- decoupled control of active and reactive powers;

- no need for evaluation of any quality function or any other optimization which are time consuming calculations;

- simple algorithm in addition to strong theoretical background;

- finally, it operates at constant switching frequency thanks to the PWM generator, which makes the use of advanced modulation techniques possible.

REFERENCES

[1] M. Monfared, H. Rastegar, and H. M. Kojabadi, “Overview of modulation techniques for the four-switch converter topology,” Proc. of IEEE PECON, 2008, pp. 803-807.

[2] R. Matinez, and P. N. Enjeti, “A high performance single phase ac to dc rectifier with input power factor correction,” IEEE Trans. Power Electron., vol. 11, no. 2, Mar. 1996, pp. 311-317.

[3] R. Madorell, and J. Pou, “Modulation techniques for a low-cost single-phase to three-phase converter,” Proc. of IEEE ISIE, 2004, pp. 1279-1284.

[4] R. Madorell, J. Pou, J. Zaragoza, P. Rodriquez, and R. Pinado, “Modulation strategies for a low-cost motor drive,” Proc. of IEEE ISIE, 2006, pp. 1492-1497.

[5] D. O. Neacsu, Power Switching Converter Medium and High Power. Florida: CRC, 2006.

[6] G. T. Kim, and T. A. Lipo, “VSI-PWM rectifier/inverter system with a reduced switch count,” IEEE Trans. Ind. Applicat., vol. 23, no. 6, Nov./Dec. 1996, pp. 1331-1337.

[7] F. Blaabjerg, S. Freysson, H. H. Hansen, and S. Hansen, “A new optimized space-vector modulation strategy for a component-minimized voltage source inverter,” IEEE Trans. Power Electron., vol. 12, no. 4, July 1997, pp. 704-714.

[8] C. B. Jacobina, M. B. de R. Correa, A. M. N. Lima, and E. R. C. da Silva, “AC motor drive systems with a reduced-switch-count converter,” IEEE Trans. Ind. Applicat., vol. 39, no. 5, Sept./Oct. 2003, pp. 1333-1342.

[9] C. B. Jacobina, I. S. de Freitas, and A. M. N. Lima, “DC-link three-phase-to-three-phase four-leg converters,” IEEE Trans. Ind. Electron., vol. 54, no. 4, Aug. 2007, pp. 1953-1961.

[10] A. M. El-Tamaly, H. H. El-Tamaly, E. Cengelci, P. N. Enjeti, and E. Muljadi, “Low cost PWM converter for utility interface of variable speed wind turbine generators,” Proc. of IEEE APEC, 1999, pp. 889-895.

[11] A. B. Raju, K. Chatterjee, and B. G. Fernandes, “A simple maximum power point tracker for grid connected variable speed wind energy conversion system with reduced switch count power converters,” Proc. of IEEE PESC, 2003, pp. 748-753.

[12] J. A. Baroudi, V. Dinavahi, and A. M. Knight, “A review of power converter topologies for wind generators,” Renewable Energy, vol. 32, Jan. 2007, pp. 2369-2385.

[13] G. Giglia, M. Pucci, C. Serporta, and G. Vitale, “Experimental comparison of three-phase distributed generation systems based on VOC and DPC control techniques,” Proc. of European Conference on Power Electronics and Applications, 2007, pp. 1-12.

[14] M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, Control in Power Electronics, New York: Academic, 2002.

[15] T. Ohnishi, “Three phase PWM converter/inverter by means of instantaneous active and reactive power control,” Proc. of IEEE IECON, 1991, pp. 819-824.

[16] T. Noguchi, H. Tomiki, S. Kondo, and I. Takahashi, “Direct power control of PWM converter without power-source voltage sensors,” IEEE Trans. Ind. Applicat., vol. 34, no. 3, 1998, pp. 473-479.

[17] M. Cichowlas, M. Malinowski, M.P. Kazmierkowski, D.L. Sobczuk, P. Rodriguez, and J. Pou, “Active filtering function of three-phase PWM boost rectifier under different line voltage conditions,” IEEE Trans. Ind. Electron., vol. 52, no. 2, 2005, pp. 410-419.

[18] 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,” Energy Conversion and Management, vol. 50, no. 1, 2009, pp. 6-13.

[19] A. Chaoui, F. Krim, J.P. Gaubert, and L. Rambault, “DPC controlled three-phase active filter for power quality improvement,” International Journal of Electrical Power & Energy Systems, vol. 30, no. 8, 2008, pp. 476-485.