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Performance Analysis of Control Techniques for PWM Rectifiers

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Abstract— **This paper contains the performance evaluation and comparison of two typical control strategies for rectifier with pulse width modulation (PWM). These are voltage oriented control (VOC) and direct power control (DPC). The theoretical background is described, and the advantages and disadvantages of each scheme are studied through theoretical analyses and a series of experiments. A comprehensive comparison and evaluation are implemented for the two methods from several aspects such as algorithm complexity, steady state and dynamic performances, , and startup current which are important for the high power applications. The simulation and experimental results show that all the two schemes can provide good abilities; and VOC possess better steady state performance while DPC is provided with best dynamic performance.**

Keywords: **direct power control DPC, voltage oriented control VOC, PWM converter, power factor, DSP**

I. INTRODUCTION

AS power electronic systems are extensively used, not only in industrial fields, but also in consumer products, several problems with regard to their diode rectifiers, which are employed mainly in the dc power supplies, have arisen in recent years. One of the problems is a low input power factor, and another problem is caused by harmonics in the input currents. The use of direct power control is increasing in the recent past years due to the advantages, such as a very fast dynamic response and simplicity over other methods. On the other hand, the variable switching frequency and resulting spread spectrum are the disadvantages of the traditional direct power control. A constant switching frequency DPC without losing its advantages can be achieved based on direct torque control (DTC) methods described in [2]. In DPC, there are no internal current control loops and no PWM modulator block, because the converter switching states are appropriately selected by a switching table based on the instantaneous errors between the commanded and measured values of the active and reactive powers. In state of the art systems cascaded voltage oriented control (VOC) is often implemented in order to control the line side converter of a renewable energy source. The currents of the converter are controlled directly by means of the inner control loops. The outer control loops control the active power, or dc link voltage and reactive power [5], Voltage oriented control (VOC) is widely employed which provides a good dynamic and steady-state response by its internal current control loops. One main drawback of such a system is that the performance is highly dependent on the applied current control strategy and the connected AC network conditions [7].

II. CONTROL STRUCTURE

A. *Direct power control _main concept*

The basic principle of the Direct Power Control (DPC) was proposed by Noguchi [4] and is based on the well know Direct Torque Control (DTC) for induction machines. In the DPC, the active and reactive powers replace the torque and flux amplitude used as the controlled output in the DTC. The basic concept consists in appropriately selecting the switching errors present in the active and reactive powers, which are limited by a hysteresis band as presented In Fig 1.

-Two important aspects must be considered to guarantee the correct operation of the system:

- Correct selection of the switching states.
- Accurate and fast estimation of the active and reactive power.

TABLE I :INDEX GENERATED BY HYSTERESIS CONTROLLER

index	desired effect on active power	desired effect on reactive power
0	↓(decrease)	↓(decrease)
1	↓(decrease)	↑(increase)
2	↑(increase)	↓(decrease)
3	↑(increase)	↑(increase)

Fig. 1 shows the configuration of the direct instantaneous active and reactive power controller for the PWM Converter in which the symbols are as follows:

$\overline{V}_{abc}$ Three - phase power-source voltages.

$\overline{I}_{abc}$ Three - phase line currents.

S_{abc} Switching states of the converter.

$\overline{V}_{dc}$ dc -link voltage.

L inductance of interconnecting reactors.

R resistance of interconnecting reactors.

C smoothing capacitor across the dc link.

R_L load resistance.

The controller features relay control of the active and reactive power by using hysteresis comparators and a switching table. In this configuration, the dc-bus voltage is regulated by controlling the active power, and the unity power factor operation is achieved by controlling the reactive power to be zero. As shown in Fig .1 , the active power command p* is provided from a DC-link voltage control block, while the reactive power command q* is directly given from the outside of the controller. Errors between the commands and the estimated feedback power are input to the hysteresis comparators and digitized to the signals Sp and Sq Also, the phase of the power-source voltage vector is converted to the digitized signal θn fig.2

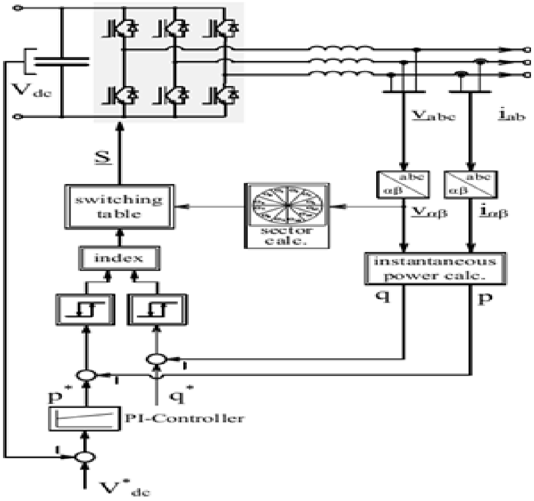


Fig. 1. Control structure of the basic direct power control method

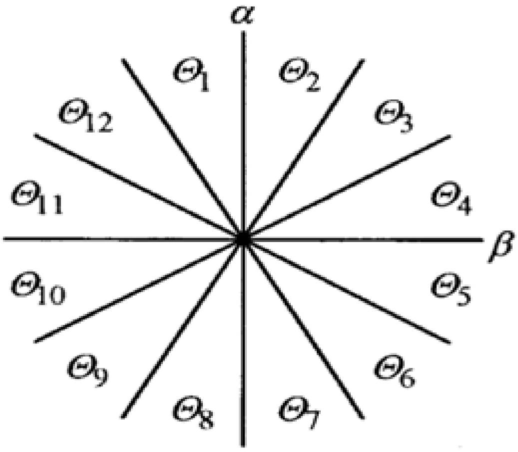
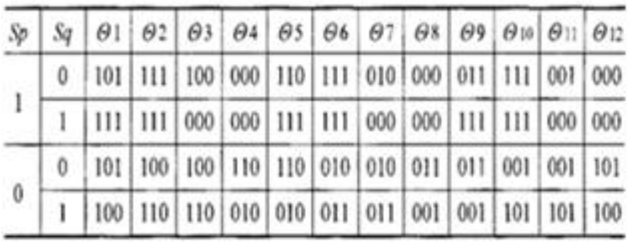


Fig.2. Twelve sectors on stationary coordinates to specify voltage vector phase. [4]

TABLE II

Switching table for direct instantaneous power control [4]



Sp	Sq	θ1	θ2	θ3	θ4	θ5	θ6	θ7	θ8	θ9	θ10	θ11	θ12
1	0	101	111	100	000	110	111	010	000	011	111	001	000
	1	111	111	000	000	111	111	000	000	111	111	000	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
	1	100	110	110	010	010	011	011	001	001	101	101	100

For this purpose, the stationary coordinates are divided into 12 sectors, as shown in Fig. 2, and the sectors can be numerically expressed as:

$$(n-2)*\frac{\pi}{6} \le \theta_n \le (n-1)*\frac{\pi}{6} \text{ ; n=1,2,3,……12} \qquad (1)$$

By using several comparators, it is possible to specify the sector where the voltage vector exists .The digitized error signals Sp and Sq and digitized voltage phase θn are input to the switching table in which every switching state Sa , Sb , and Sc , of the converter is stored. By using switching table II, the optimum switching state of the converter can be selected uniquely in every specific moment according to the combination of the digitized input signals. The selection of the optimum switching state is performed so that the power errors can be restricted within the hysteresis bands.

B. *voltage oriented control-main concept*

Similarly as in FOC of an induction motor, the Voltage Oriented Control (VOC) for line side PWM rectifier is based on coordinate transformation between stationary α,β and synchronous rotating d-q reference system. This strategy guarantee fast transient response and high static performance via an internal current control loops. Consequently, the final configuration and performance of system largely depends on the quality of applied current control strategy [6]. The easiest solution is hysteresis current control that provides a fast dynamic response, good accuracy, no DC offset and high robustness. However the major problem of hysteresis control is that its average switching frequency varies with the load current, which makes the switching pattern uneven and random, thus, resulting in additional stress on switching devices and difficulties of LC input filter design. Therefore, several strategies are reported in literature to improve performance of current control [2]. Among presented regulators the widely used scheme for high performance current control is the d-q synchronous controller, where the currents being regulated are DC quantities what eliminates steady state error. [1]

bloc diagram of the voltage oriented control (VOC)

The conventional control system uses closed-loop current control in rotating reference frame, the Voltage Oriented Control (VOC) scheme is shown in Fig 3.

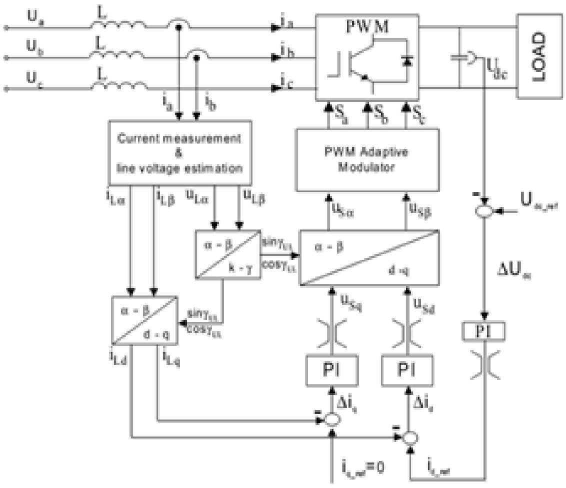


Fig.3. Block scheme of a conventional VOC

A characteristic feature for this current controller is processing of signals in two coordinate systems. The first is stationary α-β and the second is synchronously rotating d-q coordinate system. Three phase measured values are converted to equivalent two-phase system α-β and then are transformed to rotating coordinate system in a block αβ/dq

$$\begin{bmatrix} K_d \\ K_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} * \begin{bmatrix} K_\alpha \\ K_\beta \end{bmatrix} \qquad (2)$$

Thanks to this type of transformation the control values are DC signals. An inverse transformation dq/αβ is achieved on the output of control system and it gives a result the rectifier reference signals in stationary coordinate:

$$\begin{bmatrix} K_\alpha \\ K_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} * \begin{bmatrix} K_d \\ K_q \end{bmatrix} \qquad (3)$$

For both coordinate transformation the angle of the voltage vector θ (VL) is defined as:

$$\sin(\theta) = \bar{V}_{L\beta} \Big/ \sqrt{\left(\bar{V}_{L\alpha}\right)^2 + \left(\bar{V}_{L\beta}\right)^2} \qquad (4)$$

$$\cos(\theta) = \bar{V}_{L\alpha} \Big/ \sqrt{\left(\bar{V}_{L\alpha}\right)^2 + \left(\bar{V}_{L\beta}\right)^2} \qquad (5)$$

In voltage oriented coordinates, the AC line current vector is split into two rectangular components $\bar{i}_L = \left[\bar{i}_{Ld}, \bar{i}_{Lq}\right]$ fig.4 the component i_{Lq} determinates reactive power, whereas decides about active power flow. Thus the reactive and the active power can be controlled independently. The unity power factor (UPF) condition is met when the line current vector i_L is aligned with the line voltage vector, V_L (Fig .4) By placing the d-axis of the rotating coordinates on the line voltage vector a simplified dynamic model can be obtained.

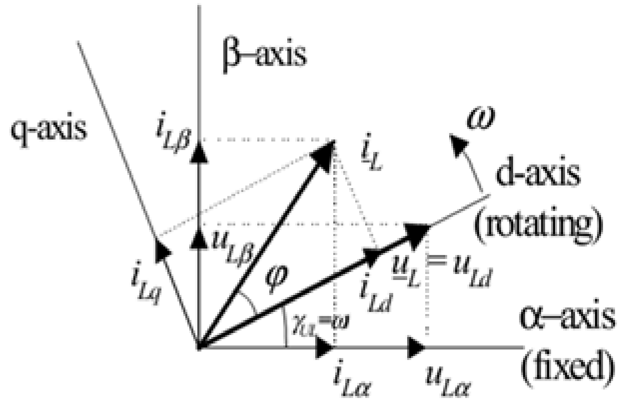


Fig.4. Vector diagram of VOC. [6]

The voltage equations in the d-q synchronous reference frame:

$$\bar{V}_{Ld} = R.i_{Ld} + \frac{Ldi_{Ld}}{dt} + \bar{V}_{sd} - w.L.i_{Lq} \qquad (6)$$

$$\bar{V}_{Lq} = R.i_{Lq} + \frac{Ldi_{Lq}}{dt} + \bar{V}_{sq} - w.L.i_{Ld} \qquad (7)$$

Regarding to Fig.4 the q-axis current is set to zero in all condition for unity power factor control while the reference current is set by the DC-link voltage controller and controls the active power flow between the supply and the DC-link. For R $\approx$0 equations (8), (9) can be reduced to:

$$\overline{V}_{Ld} = \frac{L di_{Ld}}{dt} + \overline{V}_{sd} \tag{8}$$

$$0 = \overline{V}_{sq} - w.L.i_{Ld} \tag{9}$$

The output signals from PI controllers after transformation (Eq. (8)) are used for switching signals generation by a Space Vector Modulator.

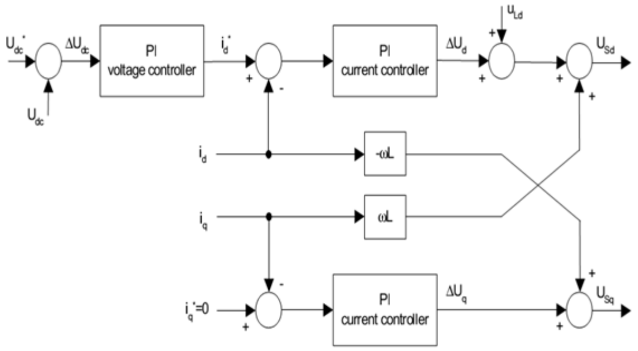
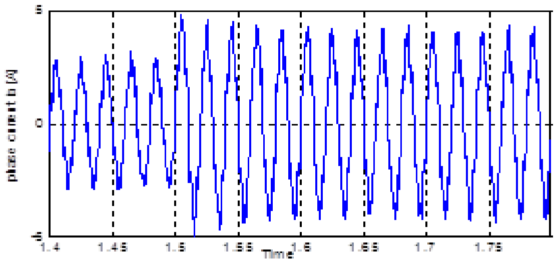


Fig .5 Decoupled current control of PWM rectifier [6]

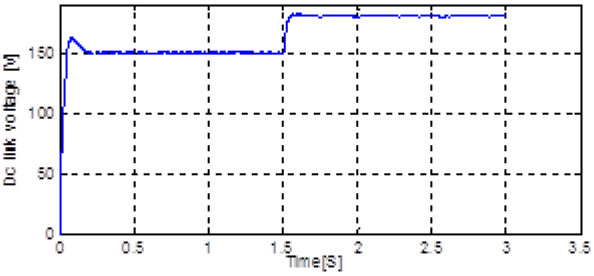
III. SIMULATION AND EXPERIMENTAL RESULTS

A. *Experimental results*

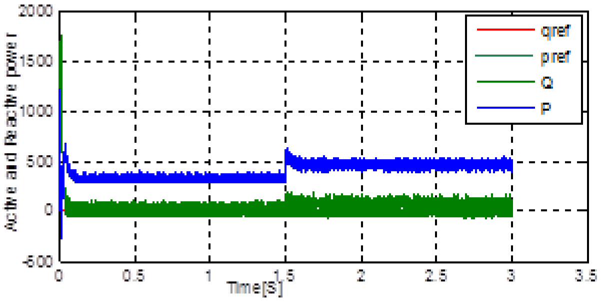
An experimental prototype has been developed to examine operating characteristics of the proposed technique. The power circuit of the PWM converter (SEMIKRON) is constituted by an insulated gate bipolar transistor (IGBT)-based full-bridge circuit. Five Hall-effect CT's and an isolation amplifier are employed to detect the line currents and voltages and the dc-bus voltage, respectively. The estimation of the instantaneous power and the voltages is proceeded by a DSP (DS1104), and the estimation program is executed in every a control period which is regularly initiated by an internal timer of the DSP. It is essential to make the control period as short as possible, because the estimating equations have to be changed every time the switching state of the converter is changed. The interface circuits which deal with detection of the line currents are specially designed to attain a fast data acquisition corresponding to the control period of the DSP. For this Sampling rate and high resolution analog to digital converters (ADC's) (DAC's) are employed in the system [4].



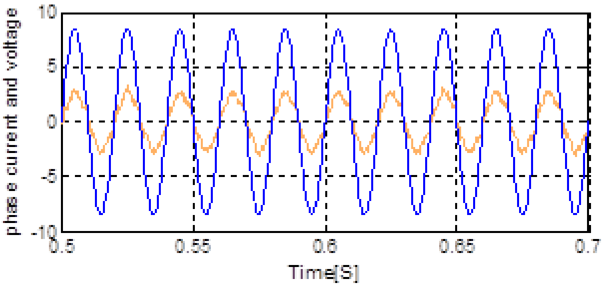
(A1)



(B1)



(C1)

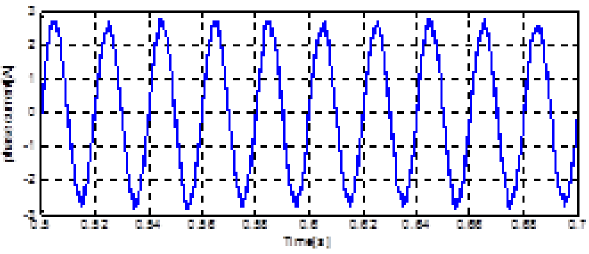


(D1)

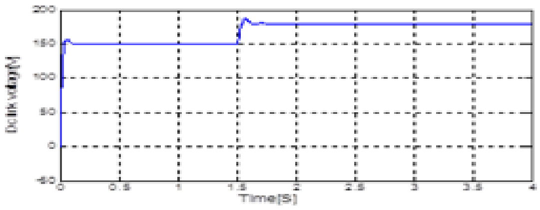
Fig 5. Simulation results of direct power control (DPC)

(A1) phase current [A] ; (B1) Dc link voltage [V]

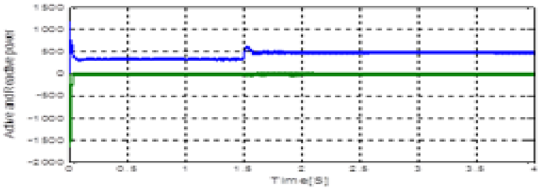
(C1) Active and Reactive power (D1) phase current and voltage



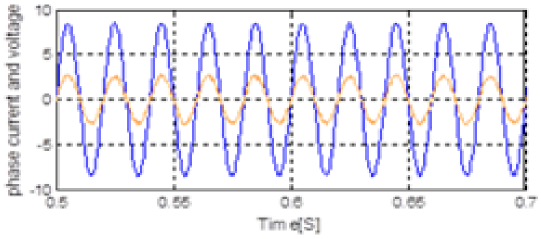
(A2)



(B2)



(C2)

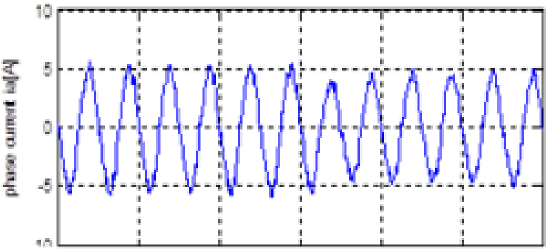


(D2)

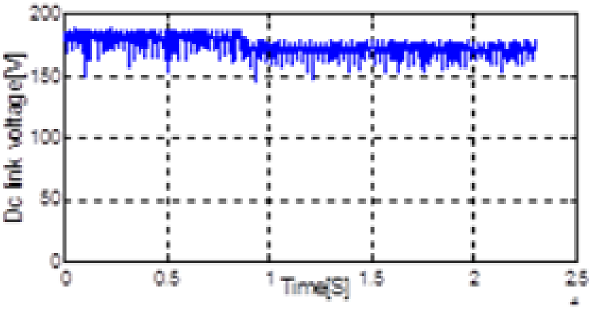
Fig 6. simulation results of voltage oriented control (VOC)

(A2) phase current [A] ; (B2) Dc link voltage [V]

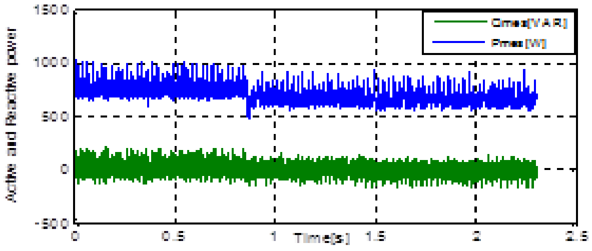
(C2) Active and Reactive power ; (D2) phase current and voltage



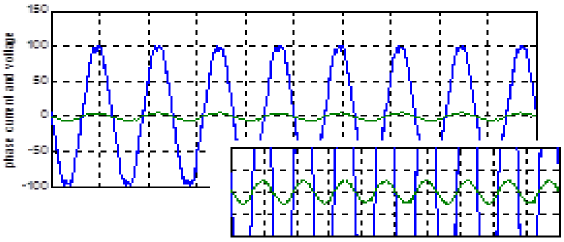
(A3)



(B3)



(C3)

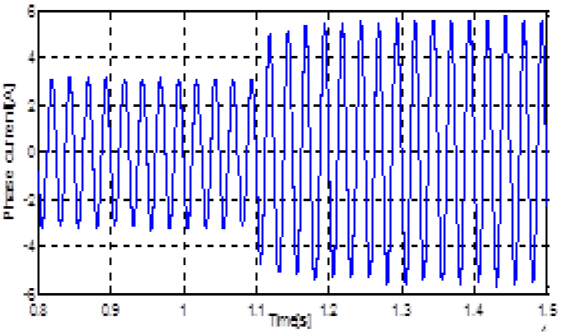


(D3)

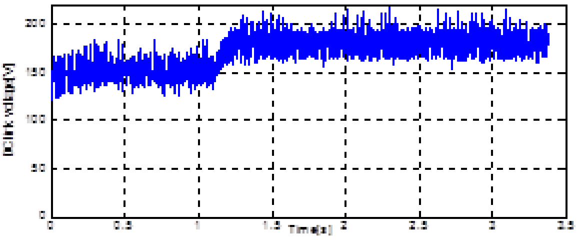
Fig 7. Experimental results of direct power control (DPC)

(A3) phase current [A] ; (B3) Dc link voltage [V]

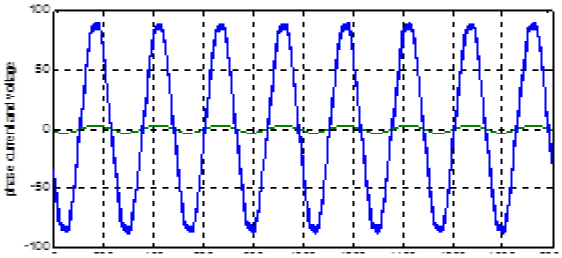
(C3) Active and Reactive power ; (D3) phase current and voltage



(A4)



(B4)



(C4)

Fig 8. Experimental results of voltage oriented control (VOC)

(A4) phase current [A] ; (B4) Dc link voltage [V]

(C4) phase current and voltage

As we see in fig .5 (B1) and fig .6 (B2) the behavior of regulation for dc link voltage it prove a good tracking of variations happened in system. From the same figures we can see also the start up behavior for the two algorithms of control (DPC and VOC) , we see that DPC (0.10 s) has better time response than VOC (0.16 s). the form of main current in source prove that the use of VOC generate a current include less harmonics than DPC algorithm.

Through fig .5 (D1) and fig .6 (D2) we see that main current and voltage have the same phase, this mean that the power factor is 1 and this is a important aspect for the quality of generated energy .

As shown in fig .7 and fig .8 the experimental validation of the two algorithms DPC and VOC respectively.

TABLE III:

Technique	Stability	Harmonic Content	Dynamic Response	Simplicity
DPC	Robust	Spread harmonics	Extremely Fast	Simple
VOC	Dependent on load parameters	Well defined harmonics	Slow	Complex

IV .CONCLUSION

Two techniques for control of PWM rectifiers have been de-scribed and compared. In the voltage oriented control scheme, the unity power factor is obtained by aligning the direct component of the line voltage vector with the current vector. In the direct power control schemes associated with the voltage control technique, bang-bang controllers of the real and reactive power are employed for selection of the next state of the rectifier. the direct power control schemes are similar to the direct torque control of ac motors. These similarities allow extending some of the expertise gained in the area of adjustable-speed ac drives on the field of PWM rectifier control. Based on the comparative investigation, the direct power control appears to be superior to the other control technique for PWM rectifiers. Simple algorithm with low sensitivity to non-ideal supply voltage, and lack of the pulse width modulator, are the most prominent advantages of that method. On the other hand, the variable switching frequency and fast sampling required for digital implementation of hysteresis controllers are disadvantageous. These drawbacks can be eliminated by replacing hysteresis comparators with a switching table and employing PI current controllers providing a reference voltage vector to a space vector modulator. This leads to use VOC control scheme, which have good advantages.

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