

# Review of Control Techniques of Three phase Boost Type PWM Rectifiers

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**Abstract:** Use of uncontrolled and semi-controlled rectifiers like diode and thyristor based for obtaining DC supply makes the input current drawn from the power system non-sinusoidal due to injected harmonics. Using PWM rectifiers is one of the methods for making the input current sinusoidal and in phase with the input voltage. Different control techniques have been proposed which majorly focus on two things. First is to control the amplitude of the input current so as to meet the power requirements of the load. At the same time wave shaping the input current to make it sinusoidal and in phase with the input voltage to obtain unity power factor. Every control technique has its own advantages and disadvantages. A review of these different control schemes is presented in this paper.

**Keywords:** Pulse width modulated rectifiers, voltage oriented control, virtual flux oriented control, direct power control

## 1. Introduction

Majority of electronic equipments make use of diode or thyristor based rectifiers as the front end converters to obtain its DC supply. These converters use capacitors at their output to obtain a smooth dc voltage. The charging and discharging of these capacitors results in a peaky current at the input side. Harmonic analysis of these currents reveals the presence of low order harmonics. To improve the input power factor passive filters can be used to filter out these harmonics. But this makes the system very bulky, large in size and costly. Use of active filtering techniques provides a good solution to this. PWM rectifiers have been implemented in many such applications like vector controlled drives for control of induction motors, Traction, interfaces for renewable energy sources etc [1]-[3]. Many of these applications require bi-directional power flow to supply generated power back to the supply. The three phase current controlled voltage source boost type PWM rectifier is commonly used due to its following advantages-

Unity power factor rectification with low total harmonic distortion of the input current, regulation of output dc voltage, and bi-directional power flow. But it has certain limitations like the output DC voltage must be higher than the peak value of input line voltage in order to prevent the uncontrolled operation of the anti-parallel diodes across the switches. Also output voltage variation is not possible from zero to maximum voltage hence cannot be used as DC drives. Also higher switching losses due to increased switching frequency and more complex control as compared to the conventional converters. The control of PWM rectifiers consist of two type of controllers. One controller is used for regulating the output DC voltage while the other controller generates the switching pulses to the switches for obtaining the required unity power factor condition. E M Suhara et al have proposed a hysteresis current controlled PWM rectifier. Adaptive hysteresis technique is incorporated in the hysteresis controller to obtain nearly constant switching frequency. The hysteresis controller generates gating pulses for all the switches so that the actual current is made to follow the reference current [4]. In motor control applications the PWM inverter is used as the motor side converter while the PWM rectifiers are used as the grid

side converters. Thus the control schemes used for PWM inverters with some modifications can be applied for controlling the latter [2]. Four types of control schemes are seen. Voltage based voltage oriented control and direct power control. Virtual flux based voltage oriented and direct power control. The voltage based techniques use line voltage sensors or line voltage estimators. In VOC line voltage vector is used as reference and the d-axis in the synchronous reference frame is aligned with it. In Voltage based DPC, location of line voltage vector is used for sector selection. The virtual flux based schemes are typically sensor less schemes without the line voltage sensor. In VFOC, the virtual flux vector is used as the reference and d-axis in synchronous reference frame is aligned with it. In VF-DPC the location of the virtual flux vector is used for sector selection. These methods were applied considering balanced and sinusoidal source voltages. Recently PWM control strategies were developed for unbalanced and distorted input voltage conditions which are normally observed in practical cases [5]-[7]. A review of these different control techniques is done in this paper for their advantages and disadvantages.

## 2. Equations and model of PWM Rectifier

The basic circuit of three phase PWM Rectifier is shown in fig. 1.

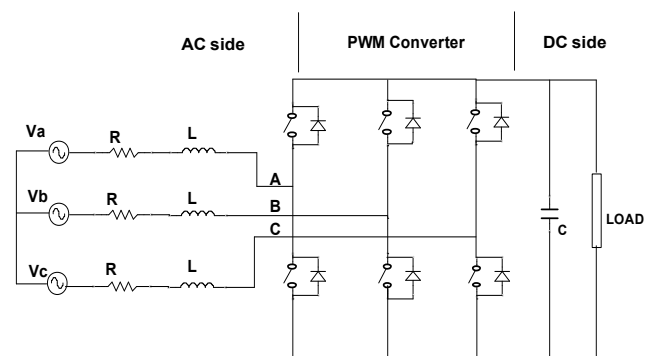
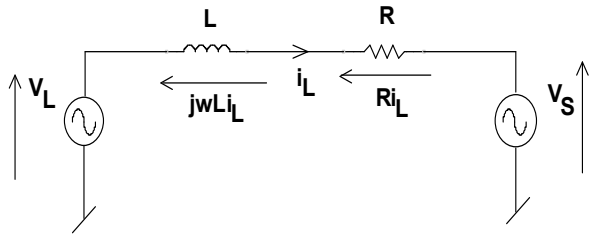


Figure 1: Three phase PWM rectifier main circuit

The input voltage  $V_L$  is three phase sinusoidal voltage obtained from the grid.  $V_s$  represent the voltage at the input of the converter bridge. The line current is denoted by  $i_L$ . At the input end the inductor gives the boost feature and helps

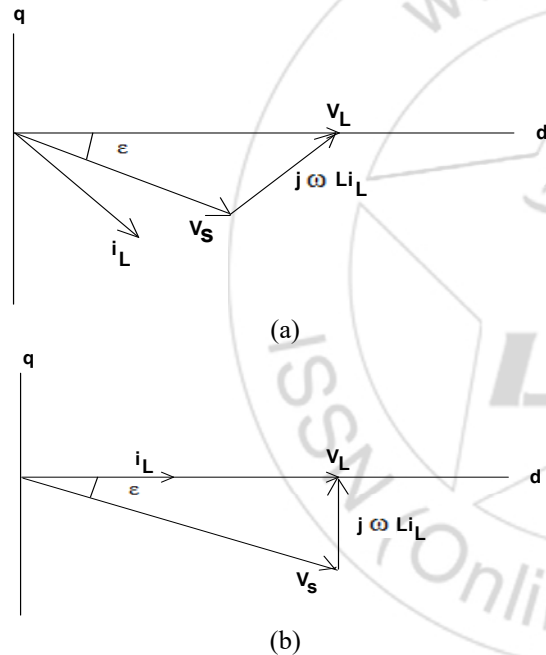
in achieving unity power factor at the input. The phase of current  $i_L$  through the inductor can be controlled by controlling the voltage drop ( $V_i$ ) across it. Its single phase equivalent circuit at the input AC side is shown in fig.2.



**Figure 2:** Single phase equivalent ckt. of PWM rectifier

From the phasor diagram shown in fig.3 it can be seen that angle ( $\epsilon$ ) between line voltage  $V_L$  and converter input voltage  $V_s$ , is responsible for the flow of current  $i_L$ . Voltage  $V_L$  and current  $i_L$  are in phase for unity power factor which can be obtained by adjusting the voltage drop across the input inductor. The voltage equation governing the mode of operation at the input side is given by equation (1), neglecting the voltage drop across the resistance.

$$V_L = V_i + V_s \quad (1)$$



**Figure 3:** AC side phasor diagram

- (a) General phasor diagram lagging power factor
- (b) Rectification at unity power factor

It is also seen that during regeneration  $V_s$  will be greater than  $V_L$ .

### 3. Equations of PWM Rectifier In Stationary and Synchronously Rotating Reference Frame [8]

Equations in three phase co-ordinate system,

$$V_L = R i_L + L \frac{di_L}{dt} + V_s \quad (2)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} V_{i\alpha} \\ V_{i\beta} \end{bmatrix} = R \begin{bmatrix} i_{i\alpha} \\ i_{i\beta} \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_{i\alpha} \\ i_{i\beta} \end{bmatrix} + \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \quad (4)$$

$$V_{id} = R i_{id} + L \frac{di_{id}}{dt} - \omega L i_{iq} + V_{sd} \quad (5)$$

$$V_{iq} = R i_{iq} + L \frac{di_{iq}}{dt} + \omega L i_{id} + V_{sq} \quad (6)$$

Active ( $p$ ) and reactive power ( $q$ ) supplied by the source is given by Eq.(7) to (10) as follows :

Complex power ,

$$S = V \cdot i^* \quad (7)$$

$$p = \text{Im}\{v \cdot i^*\} \quad (8)$$

$$q = \text{Im}\{v \cdot i^*\} \quad (9)$$

$$p = v_a i_a + v_b i_b + v_c i_c = v_{i\alpha} i_{i\alpha} + v_{i\beta} i_{i\beta} \\ = v_{id} i_{id} + v_{iq} i_{iq} \quad (10)$$

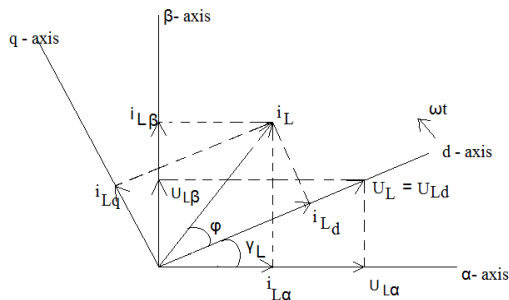
The inductor “L” between the line and the rectifier input gives the boost feature and provides the current source character of the input. The fig. 3 shows the AC input side phasor diagram which explains the control principle for PWM rectifier. For a given load, with line current  $i_L$ , the phase angle and amplitude of converter input voltage  $V_s$  and hence the voltage drop  $j\omega L i_L$  across the inductor is controlled so that current  $i_L$  is in phase with the applied line voltage  $V_L$ . Since the inductor operates at switching frequencies it is smaller in size

### 4. Control Techniques in d-q Synchronously Rotating Reference frame

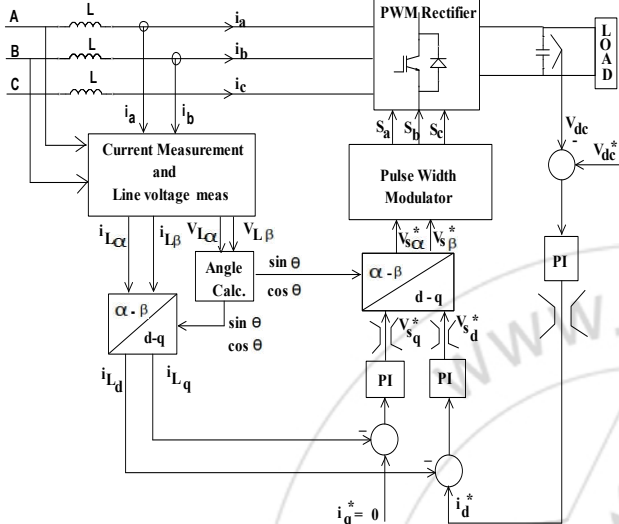
Methods applied for controlling the PWM inverters used in case of AC drives like the field oriented control is applied in a similar manner for controlling the PWM rectifiers.

#### A. Voltage Oriented Control [2]

In voltage oriented control (VOC), the line input current is oriented with respect to the line voltage vector. The line voltage vector can be obtained by measurement by using sensors or estimation. In synchronous rotating reference frame the d-axis is aligned with the line voltage vector. The d-axis component of the line current “ $i_d$ ” is proportional to the active power and its q-axis component is proportional to reactive power. To achieve unity power factor the reactive component of current reference  $i_q^*$  is set to zero. While the active component of current reference  $i_d^*$  is obtained from the PI controller, which gives the output by comparing the dc link voltage at the output with the reference voltage set as per the load requirements. The phasor diagram shown in Fig.4 depicts the control principle employed in VOC control. Fig.5 shows the main block diagram of VOC control using sensors for measuring the line voltages.



**Figure 4:** Phasor diagram of VOC control[2]



**Figure 5:** Main block diagram of VOC control using line voltage sensors [9]

Coupling occurs due to voltage drop across inductors due to orthogonal current component coming in phase with the voltage components. Decoupling is essential to have proper control.

$$V_{ld} = L \frac{di_d}{dt} - \omega L i_q + V_{sd} \quad (11)$$

$$V_{lq} = L \frac{di_q}{dt} + \omega L i_d + V_{sq} \quad (12)$$

The voltage  $V_{lq}$  is zero by aligning the line voltage vector along the d-axis and q-axis current is regulated to zero. The current controller is decoupled as,

$$V_{sd} = \omega L i_q + V_{ld} + \Delta V_d \quad (13)$$

$$V_{sq} = -\omega L i_d + \Delta V_q \quad (14)$$

where,

$$\Delta V_d = k_p (i_d^* - i_d) + k_i \int (i_d^* - i_d) dt \quad (15)$$

$$\Delta V_q = k_p (i_q^* - i_q) + k_i \int (i_q^* - i_q) dt \quad (16)$$

In VOC it is possible to calculate the voltage across the input inductor by differentiating the current flowing through it. It is then possible to estimate the line voltage by adding voltage drop across the inductor with rectifier input voltage. Though this method has a disadvantage that any noise signal present in the current signal may get gained due to differentiation.

Active and reactive power can be estimated as follows, since the sampling is done in zero vector states,

$$p = L \left( \frac{di_a}{dt} i_a + \frac{di_b}{dt} i_b + \frac{di_c}{dt} i_c \right) \quad (17)$$

$$q = 3 \frac{L}{\sqrt{3}} \left( \frac{di_a}{dt} i_c - \frac{di_c}{dt} i_a \right) \quad (18)$$

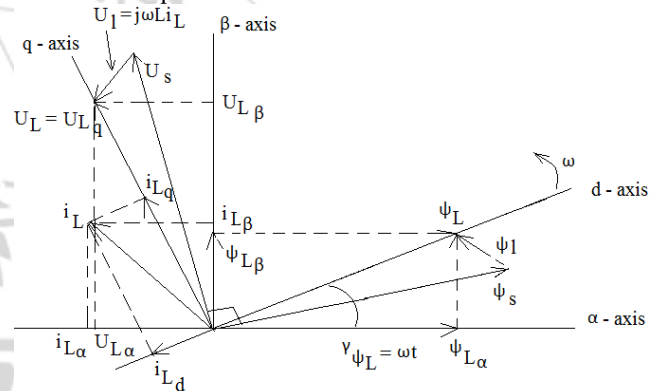
here 'p' and 'q' are DC values. The estimated voltage drop across the inductance are obtained as,

$$\begin{bmatrix} V_{l\alpha} \\ V_{l\beta} \end{bmatrix} = \frac{1}{(i_\alpha^2 + i_\beta^2)} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (19)$$

The line voltage is estimated as the sum of voltage drop across the inductor and the converter input voltage.

### B. Virtual Flux oriented control[10]

In this method it is assumed that the grid side circuit connected to the PWM converter is similar to a virtual AC motor where R and L at the input side are equivalent to the stator resistance and leakage inductance. Grid voltages  $V_a, V_b, V_c$  are similar to the induced back emfs and a virtual flux vector  $\psi_L$  is responsible for the induced voltages  $V_a, V_b, V_c$ . The VFOC phasor diagram shown in fig.6 indicates the control technique of this method.



**Figure 6:** VFOC phasor diagram[10]

The d-axis of the synchronous rotating reference frame is aligned with the Virtual flux vector  $\psi_L$ . The projection of the line current onto this rotating frame results in the separation of the line current into two orthogonal components. The instantaneous active power is given by  $i_q$ , the component in quadrature with the virtual flux vector while the  $i_d$  component gives the reactive power component. To achieve unity power factor at the input the reference  $i_d^*$  is set to zero as against in voltage based control in which  $i_q^*$  is set to zero. The rectifier input voltage is estimated from the switching states and the DC link voltage as shown in Eq. (20), (21),

$$V_{s\alpha} = \sqrt{\frac{2}{3}} V_{dc} \left[ S_a - \frac{1}{2} (S_b + S_c) \right] \quad (20)$$

$$V_{s\beta} = \frac{1}{\sqrt{2}} V_{dc} (S_b - S_c) \quad (21)$$

The virtual flux vector can be obtained by integrating the grid line voltages which in turn can be estimated by taking the sum of PWM converter input voltage and voltage drop across the inductor shown in Eq. (22) to (25).

$$V_{L\alpha} = V_{s\alpha} + L \frac{di_{L\alpha}}{dt} \quad (22)$$

$$V_{L\beta} = V_{s\beta} + L \frac{di_{L\beta}}{dt} \quad (23)$$

$$\psi_{L\alpha} = \int V_{L\alpha} dt \quad (24)$$

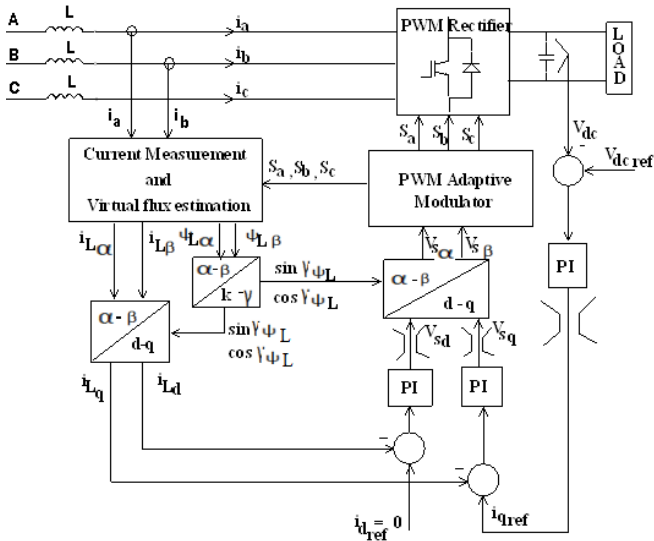


Figure 7: VFOC block diagram [10]

**C. Direct Power Control (DPC) [11]**

This method is based on instantaneous active and reactive power control loops. There is no inner current control also no PWM modulator block. The converter switching states are selected by using a switching table depending upon the instantaneous error between the commanded and estimated values of the active and reactive power. The accuracy of this method depends upon how fast and correctly the line active and reactive power is estimated. DPC schemes in which the line voltage is sensed or estimated is called as voltage based DPC. P and Q are calculated from voltage and current measured and switching vector is selected from six sectors in stationary co-ordinates. In voltage sensor-less technique P and Q are calculated from switching states, line currents measured and DC link voltage[11]. Line voltage is estimated from P, Q values calculated and line current measurements.

Power is calculated as in Eq. (26), (27) follows,

$$p = L \left( \frac{di_a}{dt} i_a + \frac{di_b}{dt} i_b + \frac{di_c}{dt} i_c \right) + V_{DC} (S_a i_a + S_b i_b + S_c i_c) \quad (26)$$

$$q = \frac{1}{\sqrt{3}} \left\{ 3L \left( \frac{di_c}{dt} i_c - \frac{di_a}{dt} i_a \right) - V_{DC} [S_a (i_b - i_c) + S_b (i_c - i_a) + S_c (i_a - i_b)] \right\} \quad (27)$$

Line voltage is further estimated as shown in Eq. (28) to (30),

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (28)$$

$$\psi_{L\beta} = \int V_{L\beta} dt \quad (25)$$

The block diagram of VFOC control scheme is shown in fig.7.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (29)$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (30)$$

Block diagram of DPC control is shown in Fig.8. The DPC with switching tables was proposed by Noguchi also known as classical DPC. Others based their improved DPC control schemes on the classical DPC. The stationary co-ordinates are divided into twelve sectors for improved control is shown in Fig. 9.

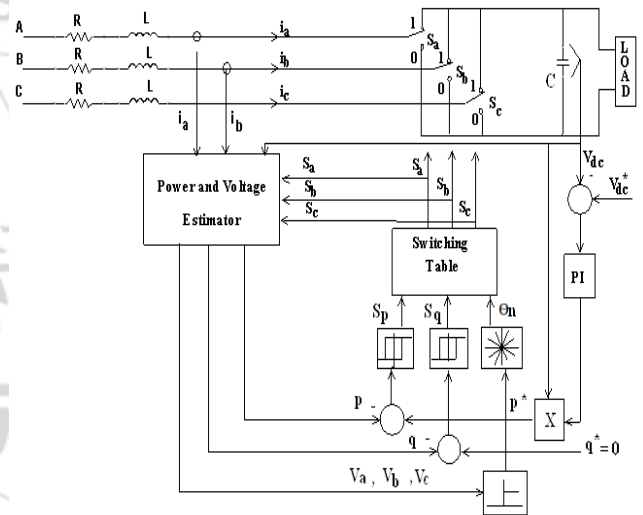


Figure 8: Block diagram showing VO-DPC control of PWM rectifier [11]

Table 1: Switching table for instantaneous direct power control [11]

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

The error between the command and the estimated power is processed by using a Hysteresis comparator which gives the output digitized signal Sp and Sq. By giving input of Sp and Sq and position theta\_n of the voltage vector, appropriate switching states are selected from the switching table. Thus the errors in P and Q are limited within the hysteresis bands by selection of correct voltage vector from the table. The switching table for direct instantaneous power control proposed by Noguchi et al [11] is shown in table 1.

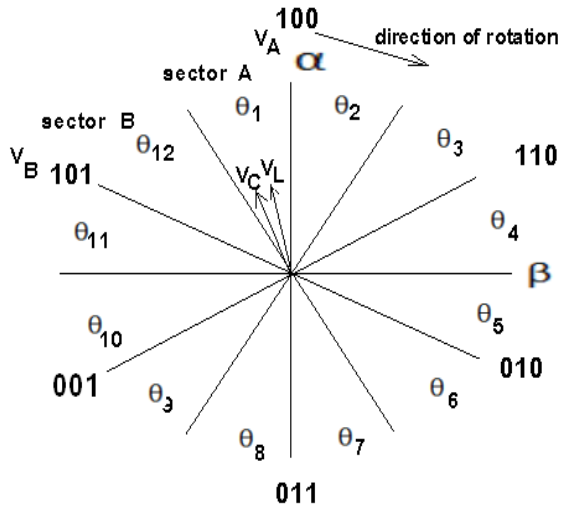


Figure 9: Twelve sectors for voltage vector selection  
 Noguchi[11]

It is required to suppress steep current ripples caused due to converter switching action. A high value of inductor can be used for the same. Calculation should be avoided at the time of switching since it may cause large errors. The line current can be controlled to be similar to the input voltage waveform. If input voltage is sinusoidal then current can be made sinusoidal for unity power factor. But if the input voltage waveform is distorted in nature then current waveform will also have the same harmonics but displacement power factor will be unity.

**D. Virtual Flux- Direct Power Control (VF-DPC) [12]**

In VF-DPC, estimated virtual flux is used for instantaneous active and reactive power estimation. Now input line voltage is given by Eq. (31)

$$V_L = \frac{d\bar{\psi}_L}{dt} = \frac{d}{dt}(\psi_L e^{j\omega t}) = \frac{d\psi_L}{dt} e^{j\omega t} + j\omega\psi_L e^{j\omega t} = \frac{d\psi_L}{dt} e^{j\omega t} + j\omega\bar{\psi}_L \quad (31)$$

where,  $\bar{\psi}_L$  is the virtual flux vector and  $\psi_L$  its amplitude.

$\bar{\psi}_L = \psi_L$ , for VF oriented in d-q co-ordinates.  $\bar{\psi}_L$  is aligned with d-axis.

Apparent power,

$$S = V_L \cdot I_L^* = \left(\frac{d\psi_L}{dt} e^{j\omega t} + j\omega\bar{\psi}_L\right)(i_{Ld} - ji_{Lq}) \quad (32)$$

Active power and reactive power are given by Eq. (33) and (34),

$$p = \frac{d\psi_{Ld}}{dt} i_{Ld} + \omega\psi_{Ld} i_{Lq} \quad (33)$$

$$q = -\frac{d\psi_{Ld}}{dt} i_{Lq} + \omega\psi_{Ld} i_{Ld} \quad (34)$$

For sinusoidal and balanced line voltages,

$$\frac{d\psi_{Ld}}{dt} = 0, p = \omega\psi_{Ld} i_{Lq}, q = \omega\psi_{Ld} i_{Ld} \quad (35)$$

Power can be estimated in  $\alpha$ - $\beta$  reference frame as shown in Eq. (36)-(39),

$$V_L = \frac{d\psi_L}{dt} |_{\alpha} + j \frac{d\psi_L}{dt} |_{\beta} + j\omega(\psi_{L\alpha} + j\psi_{L\beta}) \quad (36)$$

Apparent power ,

$$S = V_L \cdot i_L^* = \left[\frac{d\psi_L}{dt} |_{\alpha} + j \frac{d\psi_L}{dt} |_{\beta} + j\omega(\psi_{L\alpha} + j\psi_{L\beta})\right](i_{L\alpha} - ji_{L\beta}) \quad (37)$$

$$p = \left[\frac{d\psi_L}{dt} |_{\alpha} i_{L\alpha} + \frac{d\psi_L}{dt} |_{\beta} i_{L\beta} + \omega(\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha})\right] \quad (38)$$

$$q = \left[-\frac{d\psi_L}{dt} |_{\alpha} i_{L\beta} + \frac{d\psi_L}{dt} |_{\beta} i_{L\alpha} + \omega(\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta})\right] \quad (39)$$

For sinusoidal and balanced line voltages the derivatives of flux amplitudes are zero, So the instantaneous active and reactive powers are as shown in equations (40) and (41)

$$p = \omega(\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha}) \quad (40)$$

$$q = \omega(\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta}) \quad (41)$$

The procedure and equations to estimate the virtual flux  $\psi_L$  components from measured DC link voltage, converter switching states and line current is same as shown in VO-VFOC control. The flux vector position is given by ,

$$\gamma_s = \arctan(\psi_{L\alpha} / \psi_{L\beta}) \quad (42)$$

This is used for sector selection in the switching table.

There is a difference in sector numbering between DPC and VF-DPC as shown in Fig. 10(a) and 10 (b).

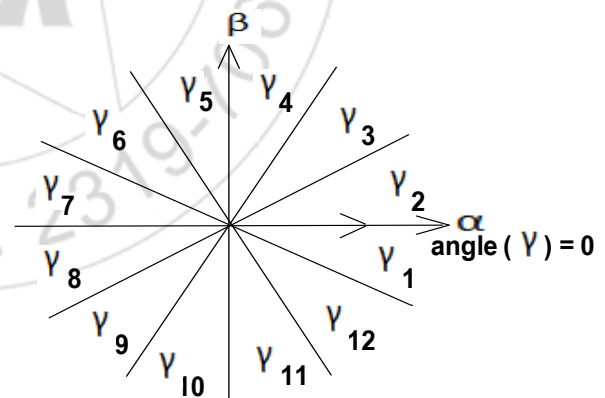
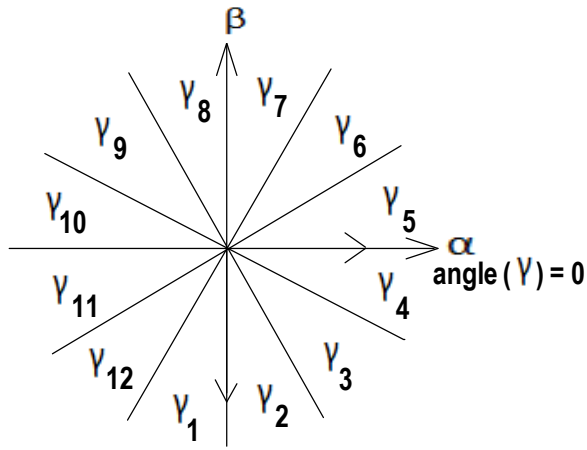


Figure 10: (a) Sector selection for DPC [8]



angle ( $\psi$ ) = -90 deg, when angle ( $Y$ ) = 0

Figure 10: (b) Sector selection for VF-DPC [8].

The block diagram of VF-DPC is shown in fig. 11.

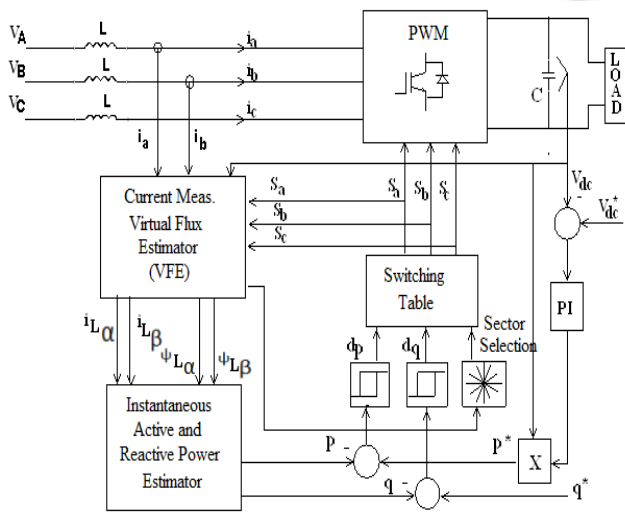


Figure 11: Block diagram of VF-DPC control of PWM rectifier [12]

### E. Virtual Flux- Direct Power Control with Space Vector Modulation (VF-DPC-SVM)[13]

VF-DPC-SVM method is a modification to achieve a constant switching frequency with the Direct Power control scheme. By Virtual flux method active and reactive power is measured in the usual way. These estimated values are compared with the reference values and errors are delivered to PI controllers. The output signals from the PI controller are converted to the  $\alpha$ - $\beta$  frame and are used as reference for generation of switching signals by space vector modulator.

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \begin{bmatrix} -\sin\gamma_{\psi L} & -\cos\gamma_{\psi L} \\ \cos\gamma_{\psi L} & -\sin\gamma_{\psi L} \end{bmatrix} \begin{bmatrix} V_{sp} \\ V_{sq} \end{bmatrix} \quad (43)$$

In VF-DPC-SVM, duty cycles of the space vector modulator are used in the calculation of the converter input voltage instead of the instantaneous switching states as in VF-DPC.

As shown in equations (44) to (48), Using DC link voltage  $V_{dc}$  and the duty cycles  $D_a$ ,  $D_b$ ,  $D_c$ , the virtual flux

components  $\psi_L$  can be calculated in the stationary reference frame.

$$V_{s\alpha} = \sqrt{\frac{2}{3}} V_{dc} (D_a - \frac{1}{2}(D_b + D_c)) \quad (44)$$

$$V_{s\beta} = \frac{1}{\sqrt{2}} V_{dc} (D_b - D_c) \quad (45)$$

$$\psi_{L\alpha(est)} = \int (V_{s\alpha} + L \frac{di_{L\alpha}}{dt}) dt \quad (46)$$

$$\psi_{L\beta(est)} = \int (V_{s\beta} + L \frac{di_{L\beta}}{dt}) dt \quad (47)$$

Block diagram of VF-DPC-SVM controller is shown in Fig. 12.

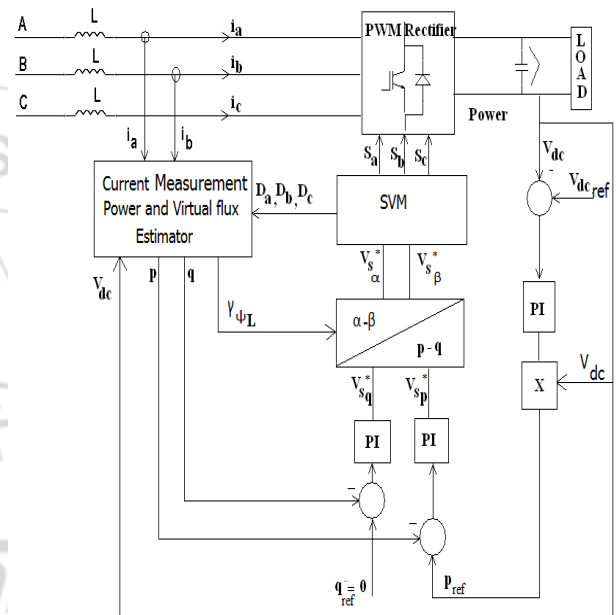


Figure 12: Block diagram of VF-DPC-SVM controller [13]

## 5. Comparative Analysis of Control Methods of Three phase boost type PWM Rectifiers

Each of the methods discussed in section III, has its own advantages and disadvantages. A comparison of these four basic methods is done by Malinowski et al [2]. Some additional points are discussed here. In VOC method we have fixed switching frequency hence smaller input filter. Advanced PWM strategies can be employed. But its drawback is it requires co-ordinate transformation and also decoupling control is required between active and reactive components. Also it has more complex control algorithm than DPC and input power factor is also less as compared to V-DPC.

Virtual Flux oriented control (VFOC) has all advantages of VOC additionally due to low pass filter effect of the integrator in flux calculations, it is less sensitive to noise than other voltage sensor less schemes. Disadvantages are similar to VOC also input power factor is better than VOC but lower than VF-DPC.

V-DPC exhibits advantages like no separate PWM voltage modulator block is required also no current regulation loops

and no co-ordinate transformations are necessary. Inherent decoupling between active and reactive power. In this method instantaneous variables with all harmonic components are estimated which leads to better power factor and efficiency. It has less complicated control algorithm than VOC. Its limitations are high value of inductance and sampling frequency is needed in order to generate smooth current waveforms for the estimator. It is more sensitive to variations in line inductance. Also it is necessary to avoid power and voltage estimation at the time of switching since it may lead to large errors in estimation. Fast processors and A/D converters required. Variable switching frequency.

Virtual flux based Direct power control (VF-DPC) has all the advantages of V-DPC. Also algorithm is simpler and noise resistant. Less sensitive to variations in line inductance. Low THD of line currents even with distorted and unbalanced line voltages. Limitations are variable switching frequency and requirement of fast A/D converters and microprocessors.

VF-DPC-SVM method has all the advantages of VF-DPC. Also it has constant switching frequency so smaller input filters. Lower sampling frequency than conventional DPC.

Less complex algorithm than VOC, VFOC due to fewer reference frame transforms. But it exhibits disadvantages like co-ordinate transformations are required as against the conventional DPC method. Also more complex control algorithm than DPC.

## 6. Conclusion

PWM rectifiers are one of the active filtering methods to eliminate the harmonics injected in the power system due to operation of diode and thyristor rectifiers. It helps in making the input current in phase with the input voltage and achieve unity power factor thus keeping with the limitations imposed by the standards. Several methods are proposed for its control but commonly employed four basic methods especially in Drives applications similar to flux control and direct torque control used for controlling PWM inverters. VOC and VFOC have good static and dynamic response and fixed switching frequency and so they are the most widely used control schemes for PWM rectifiers as reported in literature. While DPC and VF-DPC offer advantages like simpler control algorithm, the very high sampling frequency and variable switching frequency make these schemes unsuitable for practical applications. The VF-DPC-SVM control scheme has reduced switching frequency, improved noise tolerance and ability to maintain unity power factor with sinusoidal current even in the presence of unbalanced and distorted supply voltages. VF-DPC-SVM gives better performance than VOC and VFOC with less control algorithm and so can be considered as a suitable alternative.

## References

- [1] D.A.Khaburi, A.Nazempour, "Design and simulation of a PWM rectifier connected to a PM generator of micro turbine unit.", *Scientia Iranica*, Elsevier, pp. 820-828, Oct. 2010.
- [2] M.Malinowski, M. P. Kazmierkowski, and A. M. Trzynadlowski, "A comparative study of control techniques for PWM rectifiers in ac adjustable speed drives," *IEEE Trans. Power Electron.*, vol. 18, no. 6, pp. 1390–1396, Nov. 2003.
- [3] L. Grman, M. Hra'Sk , J. Kuchta, J Buday, "Single Phase PWM Rectifier in Traction Application", *Journal Of Electrical Engineering*, Vol. 62, No. 4, 2011, 206–212
- [4] E M Suhara and M Nandakumar, " Analysis of Hysteresis Current Controlled Three Phase PWM Rectifier with Reduced Switching Loss", *Inter. Sci.Press, IJCTA*, pp. 877-887, 2015
- [5] G. Abad, M. A. Rodriguez, G. Iwanski, and J. Poza, "Direct power control of doubly-fed-induction-generator-based wind turbines under unbalanced grid voltage," *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 442–452, Feb. 2010.
- [6] Z. Li et al., "Control of three-phase boost-type PWM rectifier in stationary frame under unbalanced input voltage," *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2521–2530, Oct. 2010.
- [7] Y. Zhang, and C. Qu, "Direct Power Control of a Pulse Width Modulation Rectifier Using Space Vector Modulation Under Unbalanced Grid Voltages" , *IEEE Trans. on Power Electron*, vol. 30, no.. 10, 5892- 5901, Oct. 2015
- [8] M. Malinowski, "Sensorless Control Strategies for Three - Phase PWM Rectifiers," M. Sc. thesis, Warsaw University of Technology, Warsaw, Poland - 2001
- [9] J.Rodriguez and P. Cortes, "Predictive Control of Power Converters and Electrical Drives," John Wiley and Sons, 2012
- [10] M. P. Kazmierkowski, R. Krishnan, F. Blaabjerg, "Control in Power Electronics, Selected Problems" , Elsevier Science(USA), Academic Press,
- [11] 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, pp. 473–479, May/June 1998.
- [12] 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. Ind. Appl.*, vol. 37, no. 4, pp. 1019–1027, Jul./Aug. 2001.
- [13] 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. Ind. Electron.*, vol. 51, no. 2, pp. 447–454, Apr. 2004.

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