ISSN (online): 2349-6010

Vector Control of Three-Phase Active Front End Rectifier

Heema Shukla
Department of Electrical Engineering
The Maharaja Sayajirao University, Baroda

Abstract

This paper talks about the vector control of three phase active front end rectifier employed using space vector pulse width modulation (svpwm) scheme. The major problems that tend to deteriorate the power quality mains are the current harmonics injected in the utility due to non-linear loads and resulting low power factor of load. Using the instantaneous reactive power theory and voltage oriented vector control idea; a dual channel closed-loop control strategy is built, which in turn mitigates the major problems mentioned above. The proposed control can stabilize the minimum of the system storage function at the desired equilibrium point determined by unity power factor, sinusoidal current on ac side and constant output voltage on dc side. A simulation of three phase active front end rectifier is verified under different loads. The simulation results show that the system has a characteristic of good anti-interference performance and fast dynamic response.
Keywords: Space Vector Pwm; Unity Power Factor; Decoupled Controller; Active Front End Rectifier; Reactive Power

---

I. INTRODUCTION

A nonlinear load is a source of current harmonics, which produce increase of reactive power and power losses in transmission lines. The harmonics also cause electromagnetic interference and, sometimes, dangerous resonances. Moreover, nonlinear loads and non-sinusoidal currents produce non-sinusoidal voltage drops across the network impedances, so that a non-sinusoidal voltage appears at several points of the mains.

According to the international standards such as IEC1000-3-2, EN61000-3-2, and IEEE519, the modern rectifiers are required to limit the current harmonics and to implement the power factor correction. In literatures, several algorithms of three-phase PWM rectifier have been proposed to accomplish such requirements. In [2], the modified hysteresis current control was proposed to reduce the current ripples and the number of switching's per cycle, comparing with the conventional hysteresis current control. However, this modified hysteresis current control may require the fast analog to digital conversion and high frequency digital controller when it is implemented digitally. Secondly, the one-cycle current control technique was proposed in [3]. Although the technique is simple to implement, the duty cycles of switches are directly calculated based on the measured currents in the open-loop fashion. Thus, the sensitivity of control strategy is highly dependent to the quality of current measurement, comparing with other current closed loop techniques. In [4], the overall power factor control system implements the instantaneous active and reactive power controls rather than the current controls (so called direct power control). The powers are computed by using the virtual estimated flux and line currents. However, this virtual flux estimator ignores the line resistor and requires the precise value of line inductor. In [5], the repetitive current controller was designed to take care of the parameter uncertainties used in the deadbeat controller (fast one-sampling controller). However, most parameters are still necessary to be known in order to check the system stability.

Many different PWM methods have been developed to achieve the following aims: wide linear modulation range; less switching loss; less total harmonic distortion (THD) in the spectrum of switching waveform; and easy implementation and less computation time. For a long period, carrier-based PWM methods [6] were widely used in most applications. The earliest modulation signals for carrier-based PWM are sinusoidal. The use of an injected zero-sequence signal for a three-phase inverter initiated the research on non-sinusoidal carrier-based PWM. Different zero-sequence signals lead to different non-sinusoidal PWM modulators. Compared with sinusoidal three-phase PWM, non-sinusoidal three-phase PWM can extend the linear modulation range for line-to-line voltages. With the development of microprocessors, space-vector modulation has become one of the most important PWM methods for three-phase converters [7]. It uses the space-vector concept to compute the duty cycle of the switches. It is simply the digital implementation of PWM modulators. An aptitude for easy digital implementation and wide linear modulation range for output line-to-line voltages are the noticeable features of space vector modulation. It has been analysed theoretically and proved that the Space Vector Pulse Width Modulation (SVPWM) technique may be the best modulation solution on the whole [8].

Since the DC load varies, the robustness must be a very important characteristic for rectifier controllers. So far PI regulators have been used for rectifier control. However, the controlled variables are coupled with each other and the PI regulators design requires empirical knowledge. Several methods for de-coupling and control, similar to the field orientation (vector) control of AC machines, provide excellent performance both in voltage response and is low harmonic distortion. In this approach, dq currents are controlled, providing a fast dynamic control and excellent power factor.

For convertor, PWM rectifier has many advantages which non-controlled rectifier does not have. For example, the power factor can be controlled, network side current has no harmonic and the power can flow in both directions.

Here, an Active Front-End Rectifier (AFE) for reactive power compensation is analyzed. It presents the dq-axis current closed loop controls based on space-vector PWM, providing a constant switching frequency operation (predictable switching losses). The vector control method is used; so that better line current (sinusoidal) at the input side with unity power factor and DC output voltage is obtained for any type of load (e.g. induction motor Drive). To achieve better dynamic performance the decoupled control is also used in the line-side using PI controllers. The SVPWM scheme is used to control Insulated Gate Bipolar Transistor (IGBT) switches in rectifier bridges. Thus, we are able to have complete control of harmonics, reactive power, DC busbar voltage and complete energy reversibility using it.

II. THEORETICAL BACKGROUND

As discussed in introduction, an Active Front-End Rectifier for reactive power compensation is analyzed. The vector control method is used for high performance control of any type of load (e.g. induction motor Drive). To achieve better dynamic performance, the decoupled control is also used in the line-side. The system model is obtained using d-q rotating frame theory. The line currents are decomposed into iq and id components. The iq component is used to control the reactive power. The id component is used to control the DC-link voltage and also to supply active power required by the motor. A high gain feedback with input-output linearization control is presented to remove coupling between iq and id currents. A load power feed-forward loop is added to the DC-link voltage controller for fast dynamic response.

Using dynamic d-q model, the Drive performance is analyzed to define system specifications. The simulation model is built in a MATLAB/SIMULINK. The complete system hardware comprising of switches, line inductors, DC- link capacitor bank and the load is implemented in a MATLAB/SIMULINK.

The term Active Front End (AFE) Rectifier refers to the power converter system consisting of the line-side converter with active switches such as IGBTs, the DC-link capacitor bank and the load. This converter, during regeneration it can also be operated as an inverter, feeding power back to the line. AFE Rectifier is popularly referred to as a PWM rectifier. This is due to fact that, with active switches, the rectifier can be switched using suitable pulse width modulation technique. The PWM rectifier basically operates as a boost chopper with AC voltage at the input, But the DC voltage at the output.

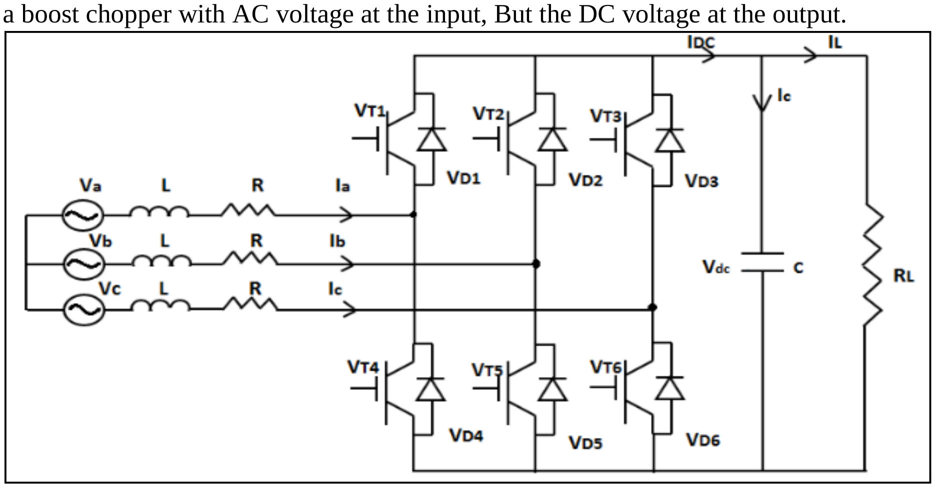

Fig. 1: Active Front End System

The intermediate voltage should be higher than the peak of supply voltage [1]. This is required to avoid saturation of the PWM controller due to insufficient DC link voltage, resulting in line side harmonics. The required DC-link voltage needs to be maintained constant during operation. The ripple in DC-link voltage can be reduced using an appropriately sized capacitor bank. The Active Front-End Rectifier for any type of load is shown in Figure 1. The configuration uses 6 controllable switches. The inductor is needed for boost operation of the line side converter.

For a constant DC-link voltage, the IGBTs are switched to produce three-phase PWM voltages at a, b, and c input terminals. The PWM voltages, generated in this way, control the line currents to the desired value. When DC-link voltage drops below the reference value, the feedback diodes carry the capacitor charging currents, and bring the DC-link voltage back to reference value.

An Active Front End Rectifier can categorically be classified in different ways as follows: converter based, supply system based and topology based. Out of which, here it describes one of the topology i.e. PWM Reversible Rectifier (two level converter).

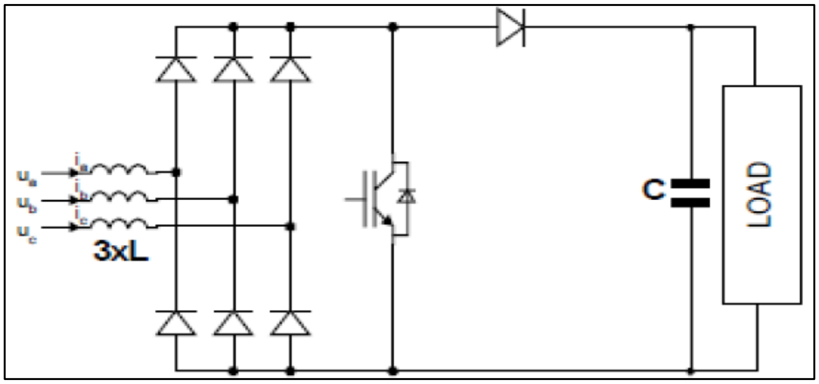

Fig. 2: PWM Reversible Rectifier (2-level converter)

The circuit of PWM Reversible Rectifier (2-Level Converter) is shown in Figure 2. This topology presents the most popular topology used in UPS and more recently as a PWM rectifier. This universal topology has the advantage of using a low-cost three-phase module with a bidirectional energy flow capability. The line side converter is popularly referred to as a PWM rectifier. This is due to fact that, the rectifier can be switched using suitable pulse width modulation technique. This PWM rectifier basically operates as a boost chopper with AC voltage at the input, but DC voltage at the output.

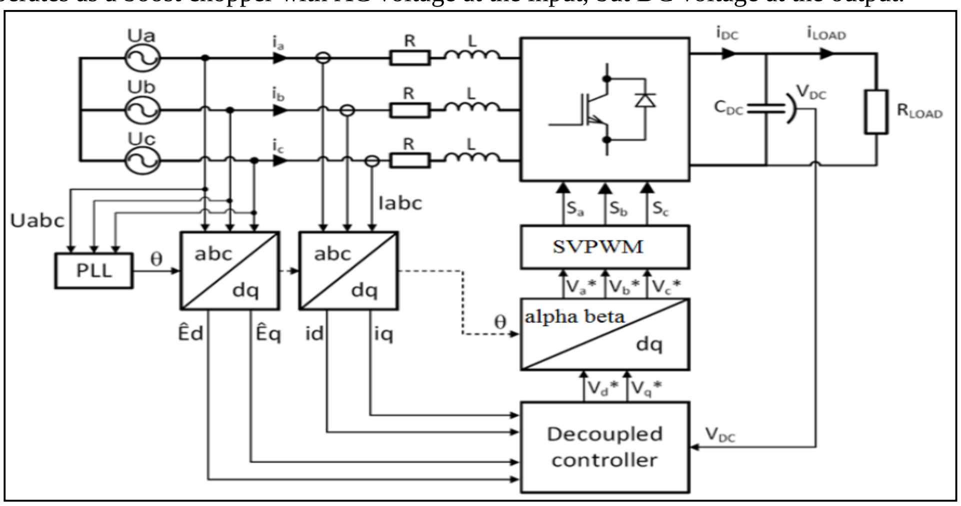

Fig. 3: Block diagram representation of active front end rectifier

Block diagram representation of three phase active front end rectifier is shown in Figure 3. The overall system consists of a i) Forward path, ii) Feed-forward path and iii) Feedback path; hence it is a Dual Closed loop system.

Forward path goes from source to load through input resistor and inductor, 6 IGBT Bridge and output capacitor. Feed-Forward path starts from sensing of three phase input voltage and current to decoupled controller via abc to dq transformation. Feedback path senses output DC link voltage and compare that with desired reference voltage and transfers error to Decoupling Block.

From the supply mains, the AC power feed to the active fronted rectifier which produces the DC output with the help of SPWM signal generation block. Here, three phase to two phase transformation is done with the help of Clarke and Park transformation. The output voltage is compared with the reference voltage produce an error. This error and dq components of input voltage is given to decoupling controller. Output of decoupling controller is transformed into alpha-beta components via dq to alpha-beta transformation. These alpha-beta components are given to Space Vector PWM generation (SVPWM) block and generate gating pulses for 6 Switches (IGBT). This gating pulses controls switching of IGBTs and gives unity power factor as well as sinusoidal input current.

III. MATHEMATICAL DESCRIPTION OF ACTIVE FRONT END RECTIFIER

The basic relationship between vectors of the Active Front End Rectifier is presented in Figure 4 below.

A. Description of Line Voltage and Line Current

Three phase line voltage and the fundamental line current is: where, E_m (I_m) and ω are amplitude of the phase voltage (current) and angular frequency, respectively, with assumption

$$i_a + i_b + i_c = 0 \tag{1}$$

B. Description of Input Voltage in Active Front End Rectifier

Line to line input voltages of PWM rectifier can be described as [8]:

$$U_a = L\frac{di_a}{dt} + R\,i_a + U_{ra} \tag{2}$$

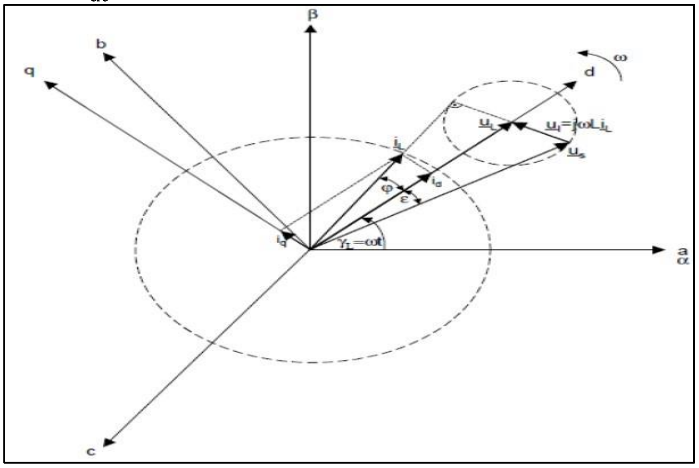

Fig. 4: Relationship between the vectors of Active Front End Rectifier

$$U_b = L\frac{di_b}{dt} + R\,i_b + U_{rb} \tag{3}$$

$$U_c = L\frac{di_c}{dt} + R\,i_c + U_{rc} \tag{4}$$

Line to line input voltages of PWM rectifier can be described as:

$$U_{ra} = \left[S_a - \frac{1}{3}(S_a + S_b + S_c)\right]U_{dc} \tag{5}$$

$$U_{rb} = \left[S_b - \frac{1}{3}(S_a + S_b + S_c)\right]U_{dc} \tag{6}$$

$$U_{rc} = \left[S_c - \frac{1}{3}(S_a + S_b + S_c)\right]U_{dc} \tag{7}$$

Model of three-phase PWM rectifier:

The voltage equations for balanced three-phase system without the neutral connection can be written as:

$$u_L = u_I + u_S \tag{8}$$

$$U_L = R\,i_L + L\frac{di}{dt} + U_S \tag{9}$$

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = R\begin{bmatrix} \mathbf{i_a} \\ \mathbf{i_b} \\ \mathbf{i_c} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} \mathbf{i_a} \\ \mathbf{i_b} \\ \mathbf{i_c} \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \tag{10}$$

Additionally for currents:

$$C\frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_L \tag{11}$$

C. Model of Active Front-End rectifier in synchronous rotating co-ordinates (d-q)

The equations in the synchronous d-q coordinates are obtained using the Park coordinate transformation [12].

$$P = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{12}$$

$$L\frac{di_d}{dt} = u_d - R\,i_d + \omega L\,i_q - u_{rd} \tag{13}$$

$$L\frac{di_q}{dt} = u_q - R\,i_q + \omega L\,i_d - u_{rq} \tag{14}$$

$$C\frac{dV_{dc}}{dt} = \frac{3}{2}\left(S_d i_d + S_q i_q\right) - \frac{V_{dc}}{R_L} \tag{15}$$

; where

$$S_d = S_\alpha \cos\omega t + S_\beta \sin\omega t \tag{16}$$

$$S_q = S_\beta \cos\omega t + S_\alpha \sin\omega t \tag{17}$$

$$u_{rd} = S_d V_{dc} \tag{18}$$

$$u_{rq} = S_q V_{dc} \tag{19}$$

u_{rd}, u_{rq}, and S_d, S_q are input voltage of rectifier, switch function in synchronous rotating d-q coordinate, respectively. u_d, u_q and i_d, i_q are voltage source, current in synchronous rotating d-q coordinate, respectively and ω is angular frequency [13].

IV. CONTROL STRATEGIES FOR PWM RECTIFIER

Various control strategies have been proposed in recent works on this type of PWM converter. Although these control strategies can achieve the same main goals, such as the high power factor and near-sinusoidal current waveforms, their principles differ. Particularly, the Voltage Oriented Control (VOC) which guarantees high dynamic and static performance via an internal current control loops, has become very popular and has constantly been developed and improved. Consequently, the final configuration and performance of the VOC system largely depends on the quality of the applied current control strategy [10].

Another control strategy called Direct Power Control (DPC) is based on the instantaneous active and reactive power control loops. The main advantages of VOC over DPC is low sampling frequency for good performance, cheaper A/D converter and fixed switching frequency so design of input inductor is easier. There are some disadvantages of VOC like coupling occurs between active and reactive component but it can be resolved by a decoupling controller.

The control techniques for PWM rectifier can be generally classified as voltage based and virtual flux based, as shown in Figure 5.

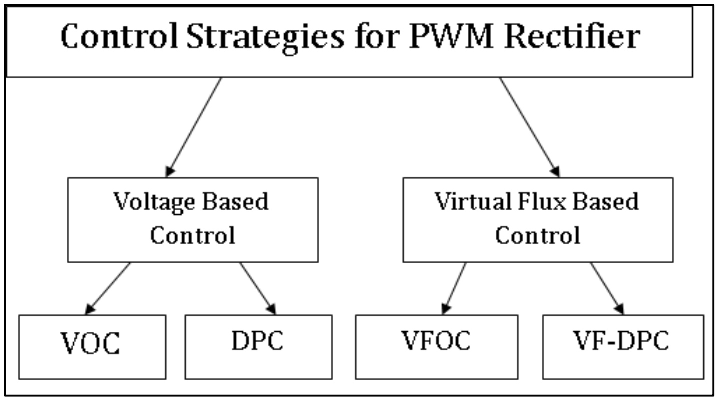

Fig. 5: Types of Control techniques for PWM Rectifier

Similarly to Field Oriented Control of an induction motor, voltage oriented control (VOC) for line side PWM rectifier is based on coordinated transformation between stationary α - β and synchronous rotating d-q reference systems. This strategy guarantees fast transient response and high static performance via internal current control loops [1]. The conventional control system uses closed loop current control in a rotating reference frame. A characteristic feature for this current controller is the processing of the signals in two coordinated systems. The first is the α-β and the second is the synchronously rotating d-q coordinate system. Three-phase measured values are converted into stationary two phase system (α-β) and then into rotating coordinate system (d-q).

In voltage oriented d-q coordinates, the ac line current vector i_L is split into two rectangular components $i_L = [i_{Ld}, i_{Lq}]$ as shown in Figure 6. The component i_{Lq} determines reactive power, whereas i_{Ld} decides active power flow. Thus the reactive and the active power can be controlled independently [13].

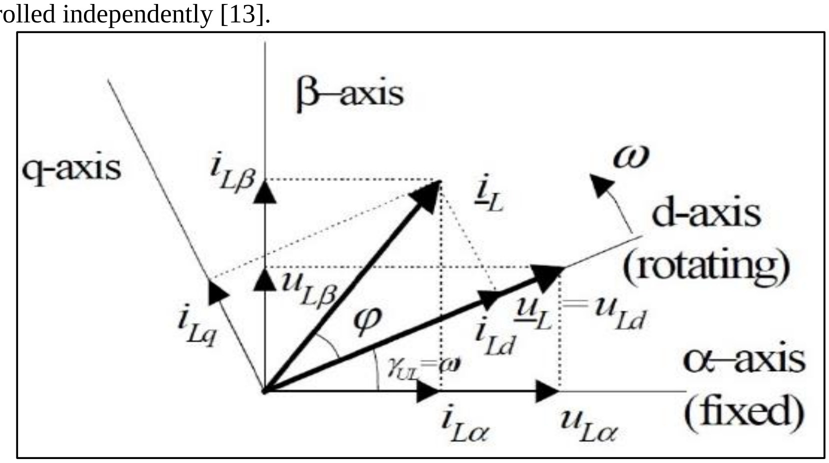

Fig. 6: Vector diagram of VOC transformation from α-β to d-q co-ordinates

The UPF condition is met when the line current vector i_L is aligned with the line voltage vector v_L. By replacing the d-axis of the rotating coordinates on the line voltage vector a simplified dynamic model can be obtained. The voltage equations in the d-q synchronous reference frame are as follows,

$$u_{Ld} = R\, i_{Ld} + L\frac{di_{Ld}}{dt} + u_{sd} - \omega L\, i_{Lq} \quad (1)$$

$$u_{Lq} = R\, i_{Lq} + L\frac{di_{Lq}}{dt} + u_{sq} - \omega L\, i_{Ld} \quad (2)$$

;the q-axis current is set to zero in all condition for unity power factor control while the reference current iLd is set by the DC link voltage controller and controls the active power flow between the supply and DC link. For R = 0 the above equation can be reduced to:

$$u_{Ld} = L\frac{di_{Ld}}{dt} + u_{sd} - \omega L i_{Lq} \quad (3)$$

$$0 = L\frac{di_{Lq}}{dt} + u_{sq} - \omega L i_{Ld} \quad (4)$$

As the current controller, the PI-type can be used. However, the PI current controller has no satisfactory tracing performance especially for the coupled system described by above equations. For a high performance application with accuracy current tracking at a dynamic state the decoupled controller diagram for the PWM rectifier should be applied, as shown in Figure 7.

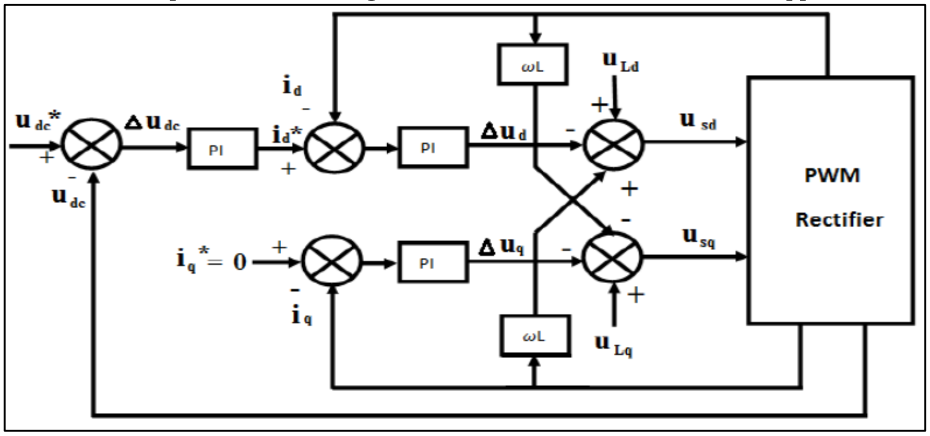

Fig. 7: Decoupled Current Control for PWM rectifier

In the reference frame, the component id corresponds to active power while the component iq represents the reactive power so named active power control channel and reactive power control channel respectively. Active power channel stabilize the DC side voltage (outer voltage loop) and reactive power channel can regulate power factor (inner current loop) [14].

$$u_{sd} = \omega L i_{Lq} + u_{Ld} + \Delta u_d \quad (5)$$

$$u_{sq} = \omega L i_{Ld} + \Delta u_q \quad (6)$$

; where, Δ are the output signals of the current controllers:

$$\Delta u_d = k_p(i_d^* - i_d) + k_i \int (i_d^* - i_d)dt \quad (7)$$

$$\Delta u_q = k_p\left(i_q^* - i_q\right) + k_i \int \left(i_q^* - i_q\right)dt \quad (8)$$

The output signals from PI controllers after d-q transformation are used for switching signal generation by a space vector modulator (SVM).

V. PWM TECHNIQUES

The three-phase switch-mode rectifier with six switches has gained increasing interest among researches. Each switch requires an additional driving circuit for its control, which makes the control scheme more complicated. However, the switch-mode rectifier is a promising solution because the use of PWM technology which allows obtaining sinusoidal three-phase input current. A PWM rectifier can operate as a static VAR compensator, adjusting
the power factor of any loads, filtering harmonic contents on power lines and improving significantly power quality on the power-distribution system. There are many different PWM modulation techniques, such as sinusoidal PWM
(SPWM), space vector PWM (SVPWM), delta modulation techniques [15].

Space vector is a vector which varies with time according to its angle while magnitude remains the same. Space vector modulation is one of the preferred real time modulation techniques and is widely used for digital control of PWM converters. Basic tasks for SVPWM controlled rectifier are given below [8],

1) To provide a constant and adjustable DC link voltage with respect to the load changes and supply network imperfection
2) To ensure possibility of regeneration
3) To minimize line side harmonics injected by the rectifier switching
4) To provide UPF at the point of common coupling

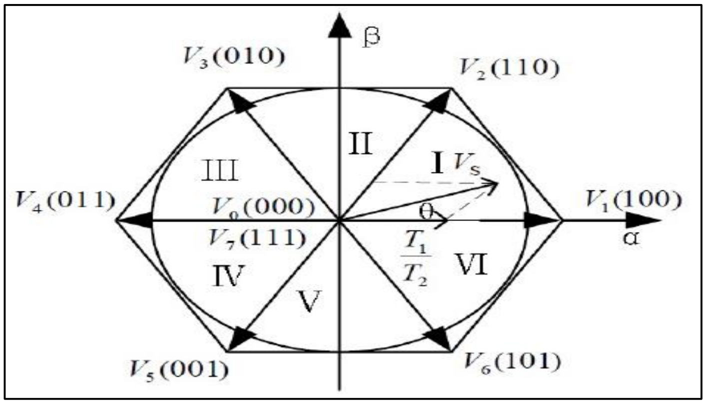

Fig. 8: Space Voltage vector representation for SVPWM technique

Figure 8 shows a space voltage diagram for three-phase PWM rectifier. Depending on the switching state on the circuit, the bridge rectifier leg voltage can assume 8 possible distinct states, represented as voltage vectors (V_0 to V_7) in the α-β coordinates. V_1 to V_6 are six fixed non-zero voltage vectors and V_0, V_7 are two zero voltage vectors. The non-zero vectors are all of the same magnitude, equal the DC bus voltage. Three phase voltage can be treated as a voltage vector V_r. For example, the reference vector shown in Figure 8 with magnitude V_r and angle Θ in sector I, is realized by applying the active vector 1(V_1) , the active vector 2 (V_2) and the zero vector (V_0).

SVPWM scheme gives more fundamental voltage and better harmonic performance compared to SPWM scheme. Very low switching losses because only one switch change its state from sector to other and higher values of output voltage can be obtained by an additional over-modulation range. But it requires sector identification and lookup tables to determine the timing for various switching vectors in all the sectors. This makes the implementation of SVPWM scheme quite complicated and increase the computational time. SVPWM (space vector PWM) technique is used to get the required waveforms for active front end topology.

VI. RESULTS & CONCLUSION

Based on the performance analysis, parameters were designed. The Simulink model has been built using MATLAB/SIMULINK model. The block diagram for the same is as shown in Figure 9. In the circuit, an a.c. source is an ideal balanced three-phase voltage source with supply frequency of 50 Hz. The three-phase r.m.s. input voltage is 415 V. The output capacitor is 6300 µF. The line inductance of each phase has the value of 6 mH. In steady state DC output voltage is taken 600 V. The switching frequency is 10 kHz.

Figure 9 shows simulation results shows the transient response of output voltage. Figure 10 shows the transient response of output current and Figure 11 shows the transient response of input current. With reference to this model, found that initially the dc bus voltage behaves as a diode rectifier with load resistor 16 Ω. Gradually, when the control action is applied, keeping the load resistance and the output voltage increases to the desired dc value.

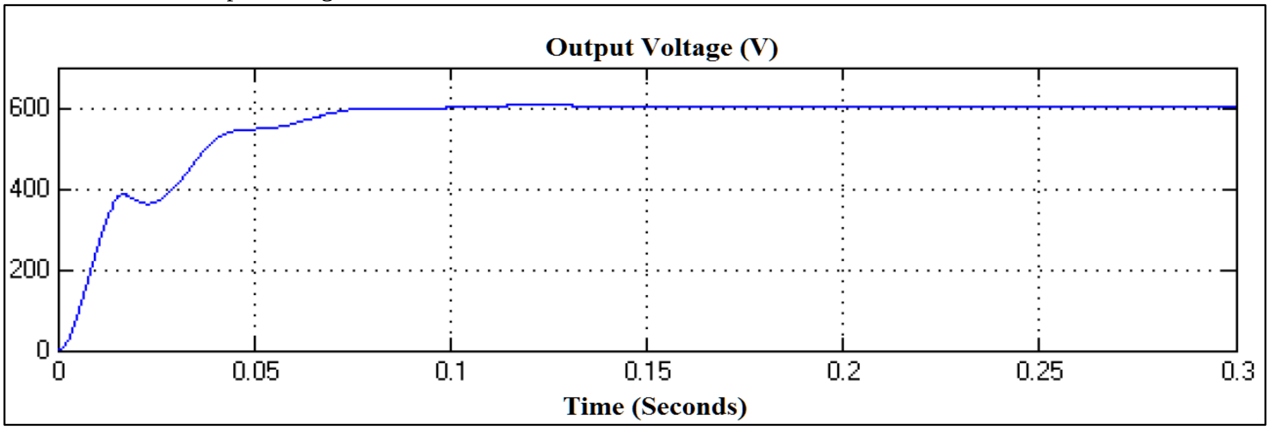

Fig. 9: Simulation result of output DC voltage

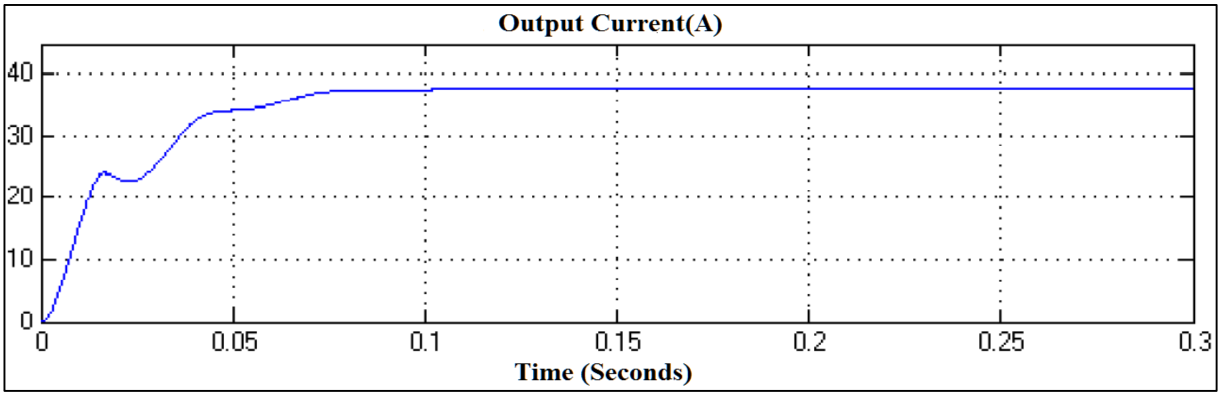

Fig. 10: Simulation result of output current

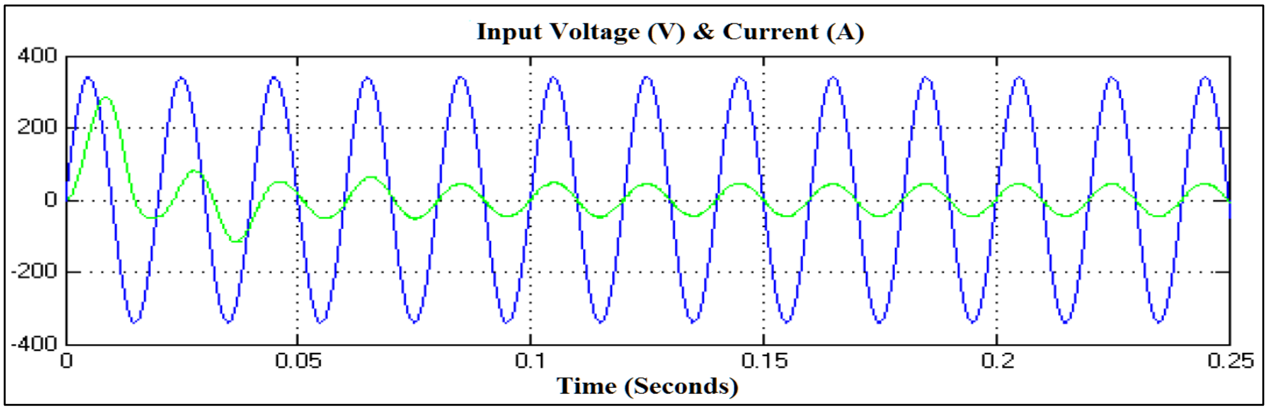

Fig. 11: Simulation result of input current

A three phase active front end rectifier using space vector modulation for a unity power factor in presented in this paper. The major amendments have been made in the rectifier model. By doing so, found that the conventional non-linear models can be improved to linear models using non-linear transformation. The decoupled controller has been designed due to which reactive power analysis became easier. This model can generate the voltage for resistive as well as resistive-inductive load. Thus, the result shows that a very fast and dynamic response can be obtained in both the dc and reactive power quantities.

REFERENCES

[1] Marius Malinowski, Marian P. Kazmierkowski, "Sensorless control strategies of three-phase PWM rectifiers," PhD thesis, IEEE Press, 2001.
[2] A.N. Tiwari, P. Agarwal, and S.P.Srivastava, ""Modified hysteresis controlled PWM rectifier"," IEEE Proceedings - Electrical Power Application, vol. 150, no. 4, pp. 389-396, July 2003.
[3] G.Chen and K.M.Smedley, "Steady-State and Dynamic Study of One-Cycle-Controlled Three-Phase Power-Factor Correction," IEEE Transaction on Industrial Electronics, vol. 52, no. 02, pp. 355-362, April 2005.
[4] 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. on Industrial Electronics, vol. 51, no. 2, pp. 447-454, April 2004.
[5] D.Wan and K.Zhou , "Digital Repetitive Controlled Three-Phase PWM Rectifier," IEEE Trans. on Power Electronics, vol. 18, no. 1, pp. 309-316, January 2003.
[6] S.R.Bowes, "New Sinusoidal Pulse Width Modulated Inverter," Proc. Inst. Elect. Eng., vol. 122, pp. 1279-1285, 1975.
[7] Keliang Zhou and Danwei Wang, "Relationship between Space vector modulation and Three Phase carrier based PWM: Comprehensive Analysis," IEEE Trans. on Industrial Electronics, vol. 49, no. 1, pp. 186-196, February 2002.
[8] Kada Hartani, Yahia Miloud, "Control Strategy for Three Phase Voltage Source PWM Rectifier based on the Space Vector Modulation," Advances in Electrical and Computer Engineering, vol. 10, no. 3, 2003.
[9] Hui Wang , Hui Qi, "Study of Control Strategies for Voltage Source PWM Rectifier," Proceedings of the 2nd International Conference on Computer Science and Electronics Engineering, 2013.
[10] Ricardo Luiz Alves, Ivo Barbi, "A New Hybrid High Power Factor Three Phase Unidirectional Rectifier," IEEE International Symposium on Industrial Electronics, vol. 2, pp. 1046-1051, July 2006.
[11] Joable Andrade Alves, Gilberto da Cunha and Paulo Turri, "Medium voltage industrial variable speed drives".
[12] B.K.Bose, Modern Power Electronics and AC Drives, PHI Publication, 2002.
[13] Wang Xu, Huang Kaizheng, Yan Shijie, Xu Bin, "Simulation of Three-Phase Voltage Source PWM Rectifier based on the Space Vector Modulation," IEEE Chinese Control and Decision Conference, pp. 1881-1884, 2008.
[14] V.Ramnarayanan, "Unity power factor front end rectifier for three phase input," Switch Mode Power Conversion, IISc, no. 11, pp. 185-195.
[15] M.H.Rashid, Power Electronics: Circuits, Devices and Application, Pearson Publication, 2007.