Design and Simulation of Three-Phase Voltage Source Space Vector Based PWM Rectifier

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***Abstract*— Modern electrical devices are usually fed by diode or thyristor front-ends which generates higher harmonics into a grid. This paper proposes the design and simulation of three-phase voltage source (VS) space vector based PWM rectifier which is based on its model in synchronous reference frame. The mathematical model with dual close loop control strategy is applied to PWM rectifier. The goal to be reached is to get unity power factor (UPF) and to obtain nearly sinusoidal input current means lower total harmonic distortion (THD). The paper presents the MATLAB/SIMULINK simulation model and the results make sure the legitimacy of the model.**

Keywords— ***PWM rectifier, decoupled feed-forward control, SVPWM, THD, unity power factor (UPF)***

I. INTRODUCTION

The concern regarding restrictions introduced by governmental and international organizations in the harmonic content generated by the power converters framed in the standards IEEE 519 and IEC 61000-3-4, has been objective of many recently studies [1]. With developing application of power electronic devices in industry, increasing emphasis has been put on the power quality. The conventional rectifier using uncontrolled diode bridge or phase-controlled SCR bridge are extremely robust and present low cost, but draw non-sinusoidal current or reactive power from source, deteriorating the electrical power supply quality [2], [3].

Currently many power converter topologies and methods for elimination of harmonic pollution in power supply are developed and investigated, associated with the popular idea of clean power [4]. The PWM/ AFE (active front end) rectifier is a preferred choice because of its advantages as bidirectional power flow, nearly sinusoidal input current, regulation of input power factor to unity, low harmonic distortion of line current (THD below 5%) and stabilization of DC-link voltage. Therefore, the PWM rectifier is also called 'green energy converter' [5], [6].

There are many different PWM modulation techniques, such as sinusoidal PWM (SPWM), space vector PWM (SVPWM), delta modulation techniques. It has been analysed theoretically and proved in experiments that the SVPWM technique is maybe the best modulation solution on the whole [7], [8]. SVPWM has advantages like reduced harmonics, reduced switching losses and better DC bus utilization. Implementation of SVPWM becomes easy because of Digital Signal Processor (DSP) [9].

This paper presents both the design and simulation model of a three-phase voltage source space vector based PWM rectifier, rated at 22.5 kW. The dual close loop control strategy with decoupled feed-forward controller is used, providing a fast dynamic control and excellent power factor. MATLAB simulation results are provided to validate the drawn conclusions.

II. THREE-PHASE PWM RECTIFIER

A. A Basic Topology

The main circuit topology of three-phase voltage source PWM rectifier is shown in fig. 1. All advantages of PWM rectifier are valid only with assumption of balanced input supply voltage condition [10]. The AC side inputs are ideal 3-ϕ symmetrical voltage source, which are filtered by resistance R and inductance L, both are linear. It is connected to 3-ϕ rectifier consists of IGBT and diode where IGBT is ideal switch and lossless. The output load is composed of capacitor C and resistor R_L [11].

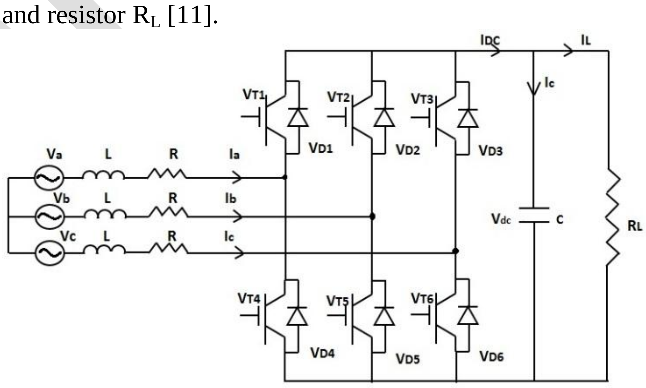

Fig. 1 Circuit diagram of 3-ϕ voltage source PWM rectifier

Here, Va, Vb and Vc are the 3-ϕ voltages of balanced voltage source. Ia, Ib and Ic are phase currents, V_{dc} the DC output voltage, C is smoothing capacitor across the DC bus. Vra, Vrb and Vrc are the input voltage of rectifier and I_L load current.

B. Mathematical Modelling

Based on the topology, the voltage equation are:

$$\begin{cases} V_a = L\frac{di_a}{dt} + Ri_a + V_{ra} \\ V_b = L\frac{di_b}{dt} + Ri_b + V_{rb} \\ V_c = L\frac{di_c}{dt} + Ri_c + V_{rc} \end{cases} \quad (1)$$

and the source phase voltage is expressed as:

$$\begin{cases} V_a = V_M \sin\theta \\ V_b = V_M \sin(\theta - 2\pi/3) \\ V_c = V_M \sin(\theta - 4\pi/3) \end{cases} \quad (2)$$

Where the input voltage of rectifier is expressed as:

$$\begin{cases} Vra = \left[Sa - \frac{1}{3}(S_a + S_b + S_c)\right] V_{dc} \\ Vrb = \left[Sb - \frac{1}{3}(S_a + S_b + S_c)\right] V_{dc} \\ Vrc = \left[Sc - \frac{1}{3}(S_a + S_b + S_c)\right] V_{dc} \end{cases} \quad (3)$$

Where, S_k (k= a, b, c) is switching functions, when S_k= 1, equals the up-arm switch is closed and the down-arm switch is open. When S_k= 0, equals an opposite result.
The current across C is:

$$C\frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_L \quad (4)$$

We can get the mathematical model in static (a, b, c) co-ordinate system shown as:

$$\begin{cases} L\frac{di_a}{dt} = V_a - Ri_a + \frac{S_b + S_c - 2S_a}{3} V_{dc} \\ L\frac{di_b}{dt} = V_b - Ri_b + \frac{S_a + S_c - 2S_b}{3} V_{dc} \\ L\frac{di_c}{dt} = V_c - Ri_c + \frac{S_a + S_b - 2S_c}{3} V_{dc} \\ C\frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - \frac{V_{dc}}{R_L} \end{cases} \quad (5)$$

The mathematical model in 3-ϕ stationary co-ordinate system (a, b, c) can be converted to the model in synchronously rotating dq coordinate system through park transformation [12]. The two phase model is shown as (6):

$$\begin{cases} L\frac{di_d}{dt} = u_d - i_d R + \omega L i_q - u_{rd} \\ L\frac{di_q}{dt} = u_q - i_q R + \omega L i_d - u_{rq} \end{cases} \quad (6)$$

Where, $u_{rd} = S_d V_{dc}$, $u_{rq} = S_q V_{dc}$
u_{rd}, u_{rq} are input voltage of rectifier and S_d, S_q are switching function in dq coordinate system. u_d, u_q and i_d, i_q are voltage source and current in dq coordinate system respectively. ω is angular frequency.
Equation (6) depicts that dq axis current is affected by cross-coupling variables ωLiq, ωLid and main voltage u_d and u_q.

$$\begin{cases} u_{rd} = -u'_{rd} + \omega L i_q + u_d \\ u_{rq} = -u'_{rq} - \omega L i_d + u_q \end{cases} \quad (7)$$

Inserting (7) into (6), we obtain:

$$\begin{cases} L\frac{di_d}{dt} = -i_d R + u'_d \\ L\frac{di_q}{dt} = -i_q R + u'_q \end{cases} \quad (8)$$

u'_{rd} and u'_{rq}, the decoupling variables are only related with i_d and i_q respectively. We can see from the equation that two axis currents (dq) are totally decoupled [11], [13]

C. Control Strategy

There are different control strategies used for VS PWM rectifier as direct power control and voltage oriented control. We have used Voltage Oriented Control (VOC) scheme which guarantees fast transient response and high static performance via internal current control loops. The dual close loop control system with decoupled feed-forward control is shown in fig. 2 [14].

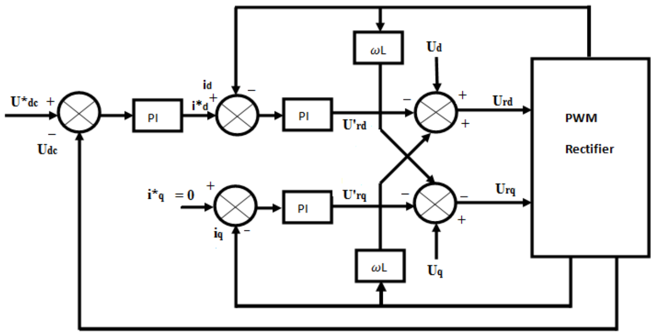

Fig. 2. Dual close-loop controller for PWM rectifier

In this reference frame, the component i_d corresponds to active power while the component i_q represents the reactive power so named active power control channel and reactive power control channel respectively. Since i_q and i_d can be regulated independently, the reactive and active power can be also controlled independently. Thus, to obtain a sinusoidal current with unity power factor in the fundamental, the i_q* is matched to zero. Active power channel stabilize the DC side voltage (outer voltage loop) and reactive power channel can regulate PF (inner current loop) [13].

The process of decoupling is a course that each of PI regulated axis current result is injected with other axis current component. When u_{rd} and u_{rq} acquired, it is transformed to d-q to α-β to apply the SVPWM method.

III. SPACE VECTOR PWM

Space Vector: Space Vector is a vector which varies with time according to its angle while magnitude remains the same.

The operating status of the switches of IGBTs in bridge can be represented by switching status, which is shown in Table I [15].

TABLE I
DEFINING SWITCHING STATES

Switching state	Leg X		
	S_{odd}	S_{even}	V_{XN}
P	ON	OFF	V_d
O	OFF	ON	0

Where, X= A, B, C
S_{odd} = 1, 3, 5, S_{even} = 2, 4, 6.

Fig. 3 shows a space voltage vector diagram for 3-ϕ PWM rectifier comprises 8 vectors. There are 8 possible combinations of switching states $S_i = (SW_a, SW_b, SW_c)$, i=0, 1,…, 7 defines 8 voltage vectors $\vec{V}_0$=[0,0,0] to $\vec{V}_7$ =[1,1,1] corresponding to switching state $\vec{S}_0$ to $\vec{S}_7$ respectively. The length of vectors $\vec{V}_1,\dots,\vec{V}_6$ are unity and are called **active vectors** and the length of $\vec{V}_0$ and $\vec{V}_7$ are zero and are called **zero vectors.** The space voltage vectors are divided up into 6 sectors [15].

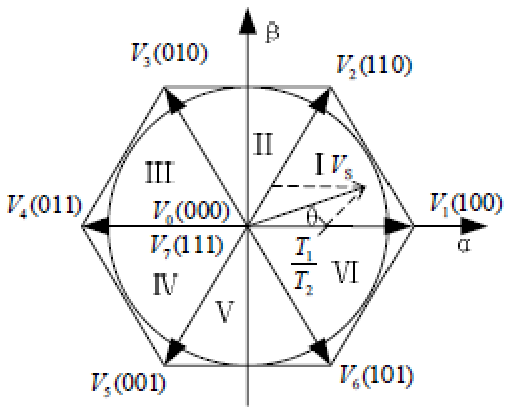

Fig. 3. Space Voltage Vectors

In one sampling interval, the output voltage vector $\vec{V}$ can be written as [16] :

$$\vec{V}(t) = \frac{t0}{Ts}\vec{V}_0 + \frac{t1}{Ts}\vec{V}_1 + \dots + \frac{t7}{Ts}\vec{V}_7 \quad (9)$$

Where, t_o, t_1,…, t_7 are the turn-on time of the vectors $\overrightarrow{V1},\dots\overrightarrow{V7}$; $t_o, t_1,\dots,t_7 \geq 0$ and $\sum_{i=0}^{7} ti = T_s$ is the sampling time.

Depending on the switching state on the circuit, the bridge rectifier leg voltages can assume 8 possible distinct states, represented as voltage vectors (V_0 to V_7) in the $\alpha-\beta$ coordinate. All the vectors are shown in the fig. 3.

There are many different methods of modulation are available to synthesize V_s according to different combinations of eight vectors. Among these methods, the two-phase modulation can minimize the switching loss, in which one switch should be always set ON or OFF in one working cycle. The desired reference vector is sampled in every sub-cycle T_s and realized by time averaging the three nearest space vectors in the space vector plane.

For example, the reference vector shown in fig. 3 with magnitude V_s and angle θ in sector 1 is realized by applying the active vector 1, the active vector 2 and the zero vector [8]. The durations T_1, T_2, and T_3 of the three space vectors, respectively is calculated as:

$$\begin{cases} T_1 = \frac{T}{2Vdc}(3V_{s\alpha} - \sqrt{3}\,V_{s\beta}) \\ T_2 = \sqrt{3}\,\frac{T}{Vdc}V_{s\beta} \\ T_0 = T_s - T_1 - T_2 \end{cases} \quad (10)$$

The vectors for other sectors can be synthesized similarly. The expressions which are developed on the universal variables X, Y, Z are shown following:

$$\begin{cases} X = \sqrt{3}\,\frac{T}{V_{dc}}V_{s\beta} \\ Y = \frac{\sqrt{3}}{2}\frac{T}{V_{dc}}V_{s\beta} + \frac{3}{2}\frac{T}{V_{dc}}V_{s\alpha} \\ Z = \frac{\sqrt{3}}{2}\frac{T}{V_{dc}}V_{s\beta} + \frac{3}{2}\frac{T}{V_{dc}}V_{s\alpha} \end{cases} \quad (11)$$

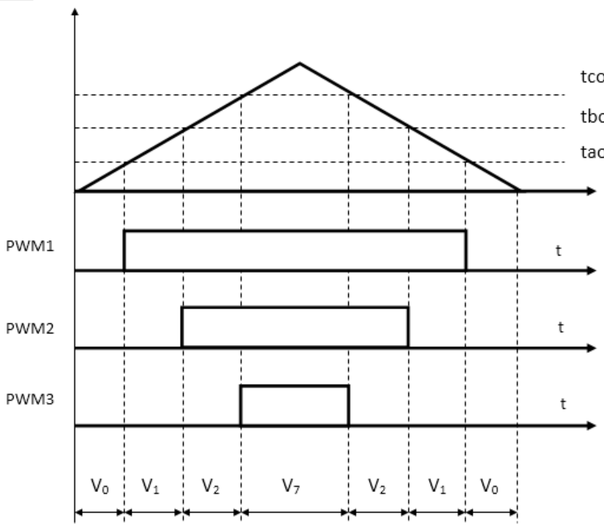

Fig. 4. SVPWM Pulse generation (sector wise)

After generation of t_a, t_b and t_c for each sector it is compared with a fixed triangular wave and SVPWM pulses are generated. To minimize the number of device switches for a given PWM period, a basic requirement is that only one switching is allowed per state transition. For this purpose, the three zero vectors are arranged in each sector as shown in fig. 4 [8].

IV. Simulation Model and Results

The simulation model is built using MATLAB/SIMULINK to test the performance of VS PWM rectifier described by the proposed model. The whole system behaviour is simulated as a discrete control system. The specification used in simulation is presented in a table II. In the circuits, the ac source is three-single phase voltage source with frequency of 50HZ and line to line voltage is 415 V.

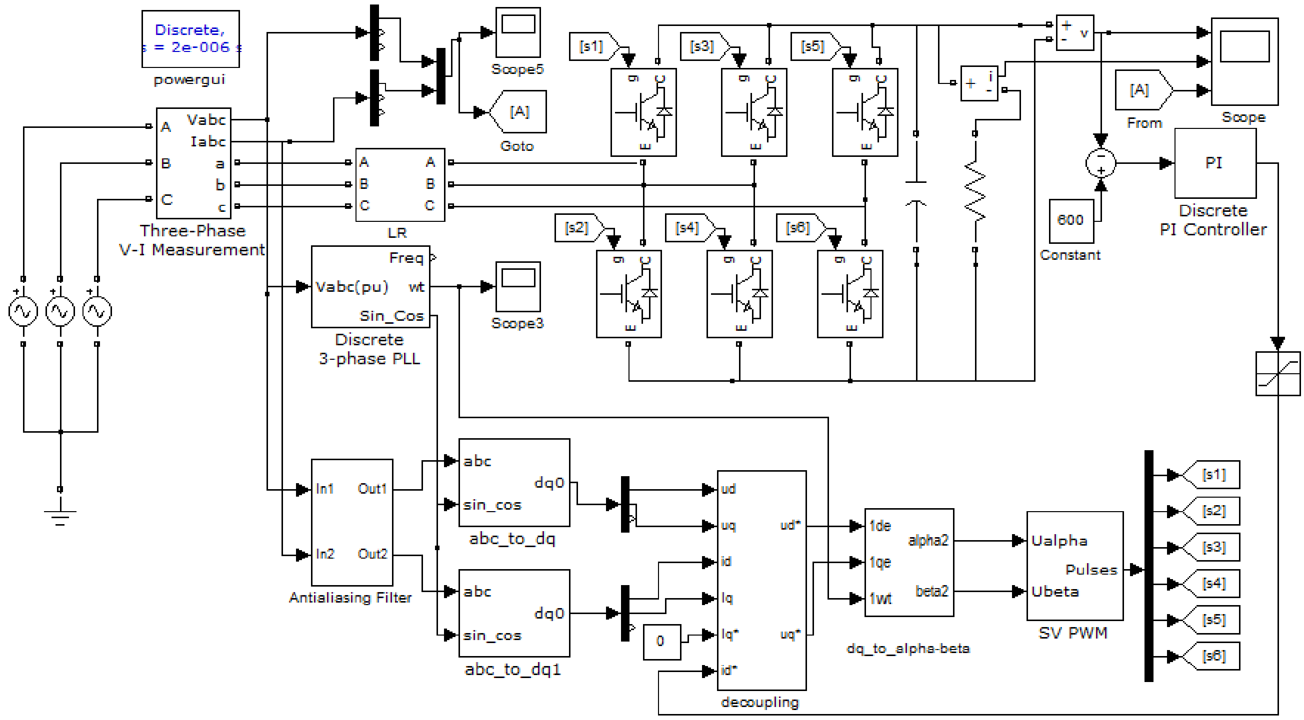

Fig. 5. Simulation model of 3-ϕ voltage source PWM rectifier in MATLAB/SIMULINK

Variable	Description	Value
V_p	Peak of line voltage	340 V
V_{in}	RMS input line voltage	240 V
V_o	Output voltage	600 V
P_o	Output power	22.5 kW
L_i	Input inductor	6 mH
C_o	Output capacitor	6300 μF
R_L	Load Resistor	16 Ω
f_s	Switching frequency	10 kHz

TABLE II
SPECIFICATION USED IN SIMULATION

The simulation model is shown in fig. 5. The waveform of output DC voltage is shown in fig. 6 and input voltage and input current are shown in fig. 7. In this results output voltage is set to 600 V DC. The current and voltage on line side are in phase with each other and it has unity power factor (UPF).

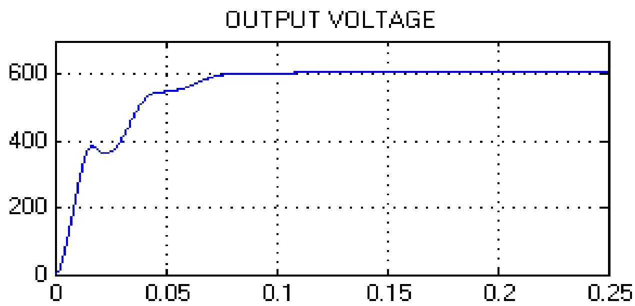

Fig. 6 Output DC link voltage

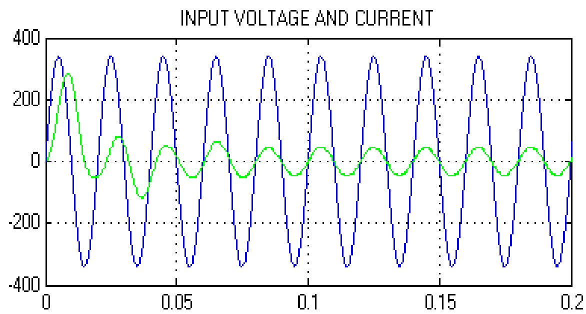

Fig. 7 Input voltage and current

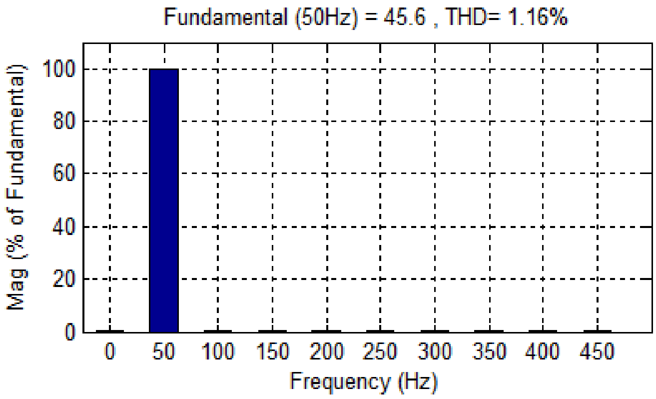

Fig. 8 FFT analysis of input current

According to IEEE 519 standards, THD should be less than 5%. In FFT analysis of input current, THD obtained is 1.16% which is nearly sinusoidal. FFT analysis of input current is shown in figure 8.

CONCLUSION

SVPWM based PWM rectifier model is presented in this paper. The voltage oriented control (VOC) strategy is used, which includes two PI controllers which are used to regulate the AC current and an outer DC voltage loop. Simulations results show that the dual closed loop strategy has good control effect providing a good regulation of dc voltage. Both the goals are achieved as input power factor is unity and the line current wave-shape is pure sinusoidal. By FFT analysis the THD obtained of input current is 1.16% which is according to IEEE 519 Standards.

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