Control Strategy for Three Phase Voltage Source PWM Rectifier Based on the Space Vector Modulation

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***Abstract*— This paper proposes the space vector pulse width modulation (SVPWM) control scheme for three-phase voltage source PWM rectifier. The control system based on SVPWM includes two PI controllers which are used to regulate the AC currents and DC-link voltage. The proposed control can stabilize the minimum of the systems storage function at the desired equilibrium point determined by unity power factor and sinusoidal current on the AC side, and constant output voltage on the DC side. So the stable state performance and robustness against the load's disturbance of PWM rectifiers are both improved. The simulation result shows feasibility of this strategy.**

INDEX TERMS— ***PWM rectifier, SV-PWM, power factor.***

I. INTRODUCTION

Recently, the three phase switch-mode rectifier with six switches has gained increasing interest among researches. Each switch requires an individual 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 pulse with modulation technology (PWM) which allows to obtain sinusoidal three-phase input current. Other advantages of this structure are [1]-[2]:

- improvement of the supply current harmonic content in the presence of multiple nonlinear loads;
- improvement of the displacement power factor in presence of multiple loads with a leading or lagging power factor;
- improvement of the supply current balance;
- The power flow is bilateral, allowing a four-quadrant active rectifier operation.
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Thus, 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 the power quality on the power-distribution system.

There are many different PWM modulation techniques, such as sinusoidal PWM, space vector PWM, delta modulation techniques. It has been analysed theoretically and proved that the SVPWM technique may be the best modulation solution on the whole [3].

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 dq decoupling and control, similar to the field orientation (vector) control of AC machines, provide excellent performance both in voltage response and is low harmonic distortion [4]-[5].

In this approach, dq currents are controlled, providing a fast dynamic control and excellent power factor. An outer DC voltage loop is composed by an IP regulator with anti-windup strategy. Simulation results are presented for load variations.

II. MATHEMATICAL MODEL OF PWM RECTIFIER

The circuit diagram of the three-phase voltage source rectifier structure is shown in Figure 1. In order to set up math model, it is assumed that the AC voltage is a balanced three phase supply, the filter reactor is linear, IGBT is ideal switch and lossless [6]-[8]. Where v_a, v_b and v_c are the three phase voltages of three phase balanced voltage source, and i_a, i_b and i_c are phase currents, v_{dc} is the DC output voltage, R and L mean resistance and inductance of the filter reactor respectively, C is smoothing capacitor across the DC bus, R_L is the DC side load, v_{ra}, v_{rb} and v_{rc}, are the input voltages of rectifier, and i_L is load current.

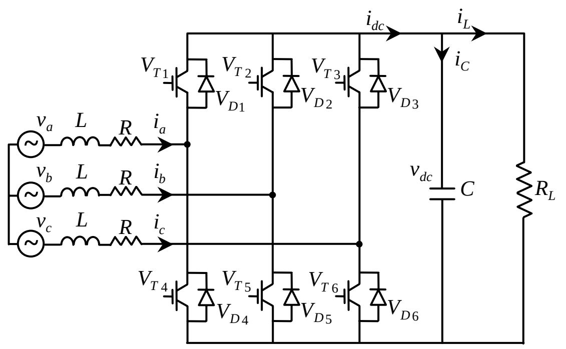

Figure 1. Circuit schematic of three-phase voltage-source PWM rectifier.

The voltage equations are given by:

$$\begin{cases} v_a = L\dfrac{di_a}{dt} + Ri_a + v_{ra} \\ v_b = L\dfrac{di_b}{dt} + Ri_b + v_{rb} \\ v_c = L\dfrac{di_c}{dt} + Ri_c + v_{rc} \end{cases} \tag{1}$$

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and the source phase voltage is expressed as

$$\begin{cases} v_a = V_M \sin\theta \\ v_b = V_M \sin(\theta - 2\pi/3) \\ v_c = V_M \sin(\theta - 4\pi/3) \end{cases} \tag{2}$$

Where the input rectifier voltage v is expressed as:

$$\begin{cases} v_{ra} = \left[S_a - \frac{1}{3}(S_a + S_b + S_c) \right] v_{dc} \\ v_{rb} = \left[S_b - \frac{1}{3}(S_a + S_b + S_c) \right] v_{dc} \\ v_{rc} = \left[S_c - \frac{1}{3}(S_a + S_b + S_c) \right] v_{dc} \end{cases} \tag{3}$$

Where S_k $(k = a,b,c)$ is the switching functions.

The current across C is :

$$C\frac{dv_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_L \tag{4}$$

We can acquire the mathematical mode of the three-phase rectifier in static abc coordinate system, shown as (5) :

$$\begin{cases} L\frac{di_a}{dt} = v_a - Ri_a + \frac{S_b + S_c - 2S_a}{3} v_{dc} \\ L\frac{di_a}{dt} = v_b - Ri_b + \frac{S_a + S_c - 2S_b}{3} v_{dc} \\ L\frac{di_c}{dt} = v_c - Ri_c + \frac{S_a + S_b - 2S_c}{3} v_{dc} \\ C\frac{dv_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - \frac{v_{dc}}{R_L} \end{cases} \tag{5}$$

Using the Park coordinate transform,

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{6}$$

Equation (5) can be rewritten as following

$$\begin{cases} L\frac{di_d}{dt} = u_d - Ri_d + \omega L i_q - u_{rd} \\ L\frac{di_q}{dt} = u_q - Ri_q - \omega L i_d - u_{rq} \\ C\frac{dv_{dc}}{dt} = \frac{3}{2}\left(S_d i_d + S_q i_q\right) - \frac{v_{dc}}{R_L} \end{cases} \tag{7}$$

Where,

$$\begin{cases} u_{rd} = S_d . v_{dc} \\ u_{rq} = S_q . v_{dc} \end{cases} \tag{8}$$

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, ω is angular frequency.

Equation (7) shows that $d-q$ current is related with both coupling voltages $\omega L i_q$ and $\omega L i_d$ and main voltage u_d and u_q. besides the influence of u_{rd} and u_{rq}. In the equation (7) u_{rd} and u_{rq} can be regulated to ensure the correctness of equation (9).

$$\begin{cases} u_{rd} = -u_{rd}^{'} + \omega L i_q + u_d \\ u_{rq} = -u_{rq}^{'} - \omega L i_d + u_q \end{cases} \tag{9}$$

Insering equation (9) into equation (7), we obtain :

$$\begin{cases} L\frac{di_d}{dt} = -Ri_d + u_{rd}^{'} \\ L\frac{di_q}{dt} = -Ri_q + u_{rq}^{'} \end{cases} \tag{10}$$

We notice that the two axis currents are totally decoupled. $u_{rd}^{'}$ and $u_{rq}^{'}$ are only related with i_d and i_q respectively. The simple proportional-integral (PI) and IP controllers are adopted in the current and voltage regulation. Figure 2 displays the dual closed-loop control system, which fulfils the current decoupling of the PWM rectifier [9].

In this reference frame, the component i_d corresponds to active power while the component i_q represents the reactive power. Since i_d and i_q can be controlled 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 reference i_q^* is matched to zero.

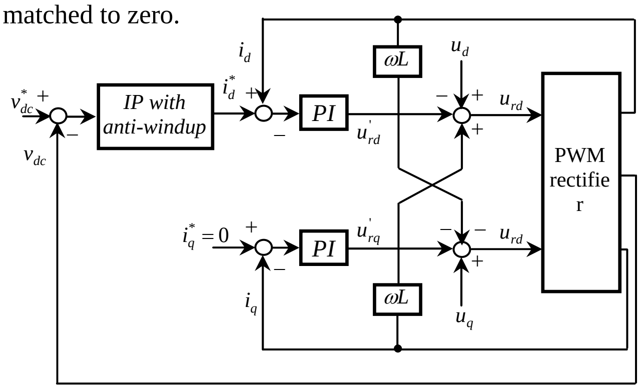


Figure 2. Control block diagram of $d-q$ dual-close-loop controller of the rectifier.

From Figure 2, the input voltages u_{rd} and u_{rq} of the rectifier are transformed to $V_{r\alpha}$ and $V_{r\beta}$ to apply the SVPWM method. To regulate the DC voltage, an input power must be injected to the capacitor to compensate the power delivered to the load. The control of input power can be accomplished through the regulation of input current in coordination with line voltage. An IP controller with anti-windup strategy is used for the voltage loop regulation to obtain the reference current i_d^* [10]. Figure 3 shows the block diagram for the DC voltage regulation of PWM rectifier.

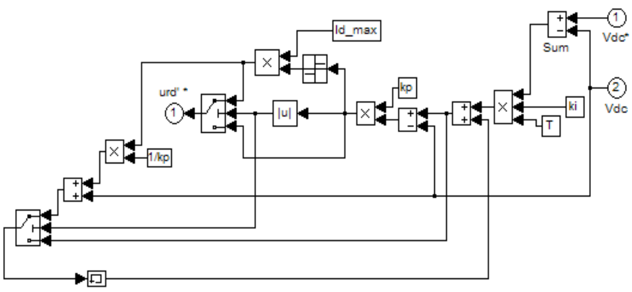


Figure 3. Control block diagram of $d-q$ dual-close-loop controller of the rectifier.

III. SVPWM RECTIFIER

Different methods for DC voltage control nearly sinusoidal input current are well known. Classical methods are based on hysteresis control of rectifiers legs following the sinusoidal reference or optional PWM pattern for harmonic elimination. Basic tasks for SVPWM controlled rectifier are [11]-[13]:

- to provide a constant and adjustable DC link voltage with respect to the load changes and supply network imperfection;
- to ensure possibility of energy regeneration;
- to minimize line side harmonics injected by the rectifier switching;
- to provide unity power factor at the point of common coupling.

Figure 4 shows a space voltage vector diagram for three-phase PWM rectifier. Depending on the switching state on the circuit Figure 1, the bridge rectifier leg voltage 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.4. V_1 to V_6 are six fixed nonzero vectors, (V_0 and V_7) are two zero vectors. The nonzero vectors are all of the same magnitude, equal the DC bus voltage V_{dc}. Three-phase voltage can be treated as a voltage vector V_r, Table I.

For example, the reference vector shown in Figure 4 with magnitude V_r and angle θ in sector I, is realized by applying the active vector 1, the active vector 2 and the zero vector.

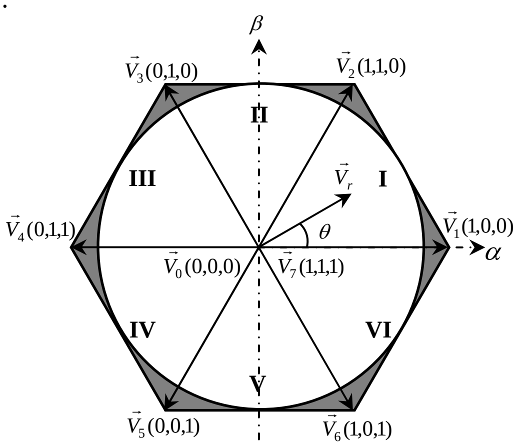


Figure 4. Space voltage vectors.

IV. SIMULATION RESULTS

Based on the analysis, the simulation of the whole is built using MATLAB/SIMULINK to test the performance model of the SVPWM rectifier described by the proposed model. The simulation model is shown in Figure 5. The main parameters of the simulation circuit are given in Table II.

TABLE II. RECTIFIER PARAMETER

The input phase voltage :	$V = 125V$ / $f = 50Hz$
The input inductance :	$L = 37mH$
The input resistance :	$R = 0{,}3\Omega$
The output capacitor :	$C_{dc} = 1100\mu F$
The output voltage :	$V_{dc} = 250V$

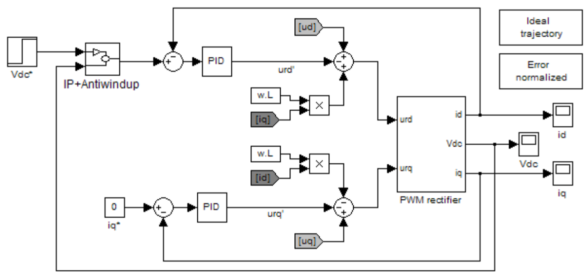
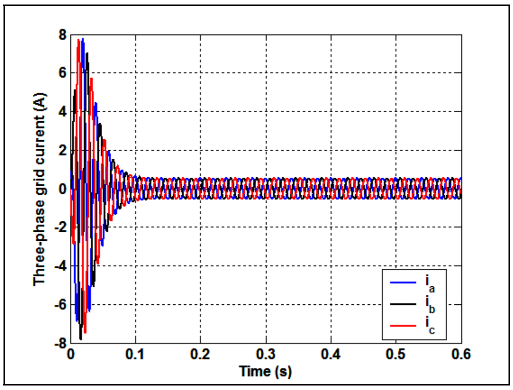


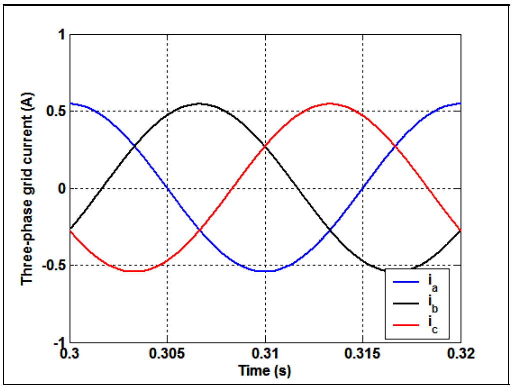
Figure 5. Three-phase voltage source SVPWM rectifier system model



(a)

TABLE I. SVM DURY SWITCHING VECTORS AND DUTY CYCLES

Sector $i=1$	Sector $i=2$	Sector $i=3$
$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{1}{2E}\begin{bmatrix} \sqrt{6} & -\sqrt{2} \\ 0 & 2\sqrt{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$	$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{1}{2E}\begin{bmatrix} -\sqrt{6} & \sqrt{2} \\ \sqrt{6} & \sqrt{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$	$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{1}{2E}\begin{bmatrix} 0 & 2\sqrt{2} \\ -\sqrt{6} & -\sqrt{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$
$SV_1 = V_1 = (1 \quad 0 \quad 0)$	$SV_1 = V_3 = (0 \quad 1 \quad 0)$	$SV_1 = V_3 = (0 \quad 1 \quad 0)$
$SV_2 = V_2 = (1 \quad 1 \quad 0)$	$SV_2 = V_2 = (1 \quad 1 \quad 0)$	$SV_2 = V_4 = (0 \quad 1 \quad 1)$
Sector $i=4$	Sector $i=5$	Sector $i=6$
$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{1}{2E}\begin{bmatrix} 0 & -2\sqrt{2} \\ -\sqrt{6} & \sqrt{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$	$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{1}{2E}\begin{bmatrix} -\sqrt{6} & -\sqrt{2} \\ \sqrt{6} & -\sqrt{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$	$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{1}{2E}\begin{bmatrix} \sqrt{6} & \sqrt{2} \\ 0 & -2\sqrt{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$
$SV_1 = V_5 = (0 \quad 0 \quad 1)$	$SV_1 = V_5 = (0 \quad 0 \quad 1)$	$SV_1 = V_1 = (1 \quad 0 \quad 0)$
$SV_2 = V_4 = (0 \quad 1 \quad 1)$	$SV_2 = V_6 = (1 \quad 0 \quad 1)$	$SV_2 = V_6 = (1 \quad 0 \quad 1)$



(b)

Figure 6. The waveform of three phase grid voltage.

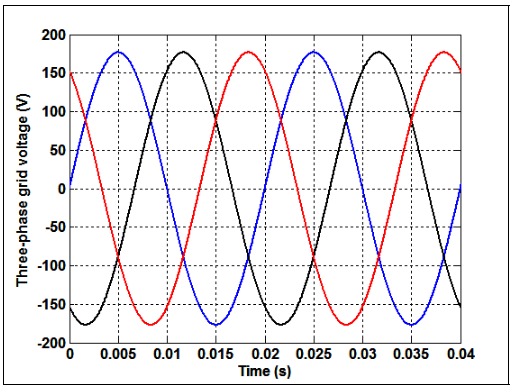
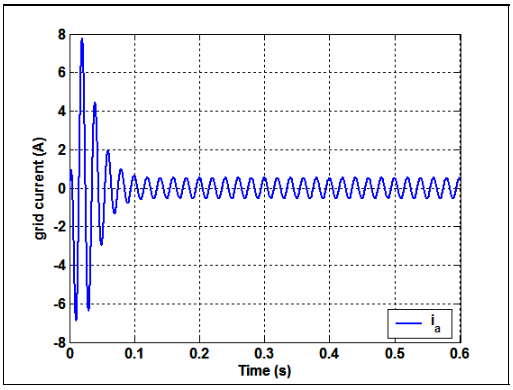
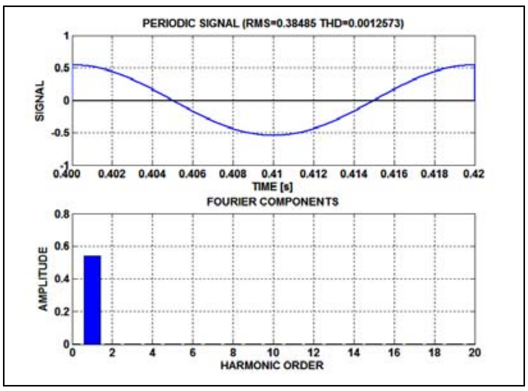


Figure 7. The waveform of three phase grid current.



(a)

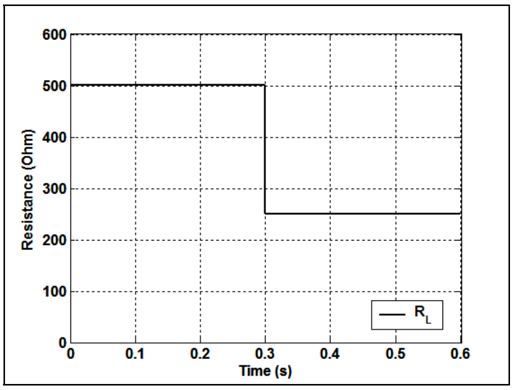


(b)

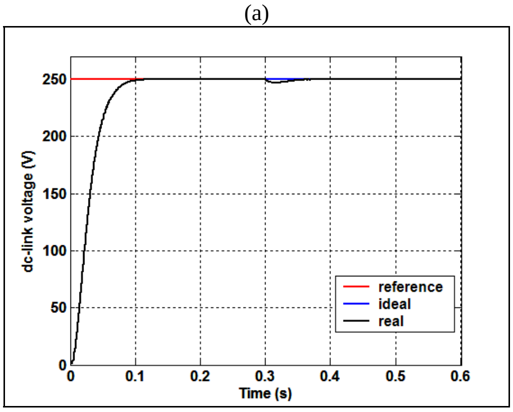
Figure 8. Simulated phase current and its harmonic content.

In order to test the robustness of the controller presented in this paper, we introduce some changes into the DC load. The rectifier was submitted to load variation. Figure 12 respectively show simulation waveform that the load varieties from 500Ω to 250Ω at $0{,}3s$, Figure 9 (a). It is observed that direct voltage has a small drop and the rectifier remains operating at unitary power factor in spite of load variation. The behaviour of rectifier is shown in Figure 9 (b) and (c). Figure 9 (d) is the normalized error of the output DC voltage. Obviously, the i_d component increases aiming to compensate the increase of load current, Figure 9 (e). With rectifier operating at unity power factor, the i_q component current remains equal to zero. The steady state grid voltages and currents at $0{,}25s$ are given in Figure 9 (f) and (g).

The simulation results show that the rectifier has good character such as constant DC output voltage, sinusoidal input currents and unity power factor.



(a)



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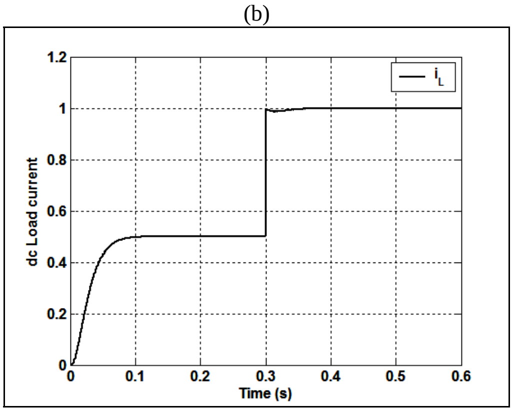

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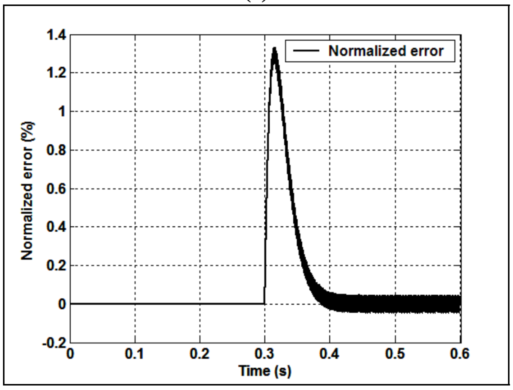

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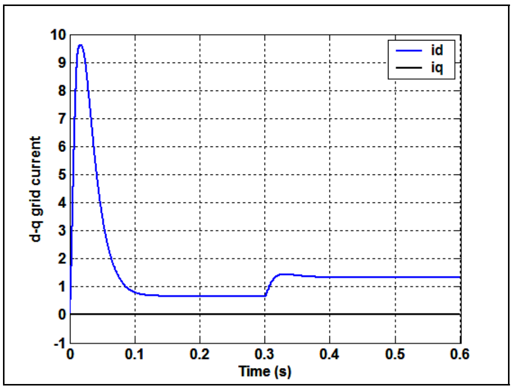
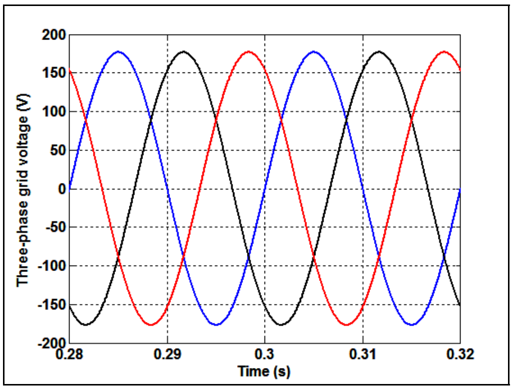
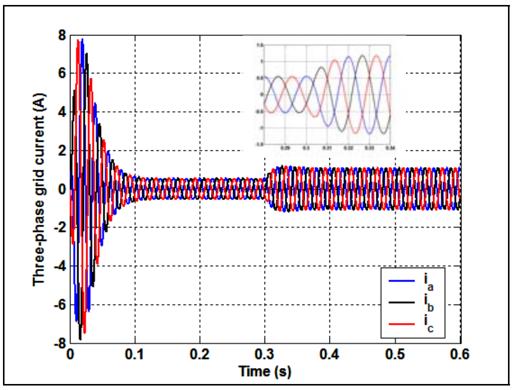


(e)



(f)



(g)

Figure 9. Simulation result of the PWM rectifier with under load disturbance (50% variation of resistance at $0,3s$).

V. CONCLUSION

In this paper, a control strategy of the three phase voltage source PWM rectifier based on the space vector modulation is proposed. The control system based on SVPWM includes two PI controllers which are used to regulate the AC current and an outer DC voltage loop is composed by IP controller with anti-windup strategy. The simulation results shows a good performance of proposed strategy method at start-up and during load variations, providing a good regulation of output DC voltage, sinusoidal input AC current and unitary power factor.

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