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Control of Three-Phase Voltage Source PWM Rectifier

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Abstract— **Three-phase voltage source PWM rectifiers are widely used in power electronics field, they can ride out the harmonic pollution caused by the conventional ac-dc converters and also have high power factor .A mathematical model of the voltage source converter (VSC) is analyzed and a voltage based control strategy (VOC) has been implemented and simulated in MATLAB/ SIMULINK environment. The control system of the VSC has been built based on dsPACE system with DS1104 controller board and SEMIKON inverter. The simulation and experimental results are presented and theoretical study of the converter is validated.**

Keywords— three-phase PWM rectifier; VOC; feed-forward decoupling control;symmetrical optimum.

I. INTRODUCTION

Three-phase AC-DC converters are widely used in many different areas such as adjustable-speeds drive, uninterruptible power supplies, high voltage direct current systems (HVDC), battery charging for electric vehicles and battery energy storage systems, etc. Diodes and thyristors bridge rectifiers are conventionally used in power electronics field as a first stage of conversion, but due to their nonlinearity nature they are a major source of high voltage and current total harmonic distortion. So, new generation of controlled rectifiers has been investigated known as three-phase voltage source PWM rectifiers. They mainly propose three interesting features: low harmonic pollution, high power factor and bi-directional power flow [1-2]. These high frequency switching PWM converters have become recently an interesting research subject in renewable power generation systems.

Various control strategies of the PWM rectifiers have been presented in recent researches which can be classified in four groups: the voltage oriented control (VOC), the voltage-based direct power control (V-DPC), virtual flux-oriented control (VFOC) and virtual flux-based direct power control (VF-DPC). Among of them the voltage oriented vector control is considered as the most common method due to its high dynamic operation, it attempts to achieve an accurate output voltage using an outer voltage loop and fulfill the unity power factor condition using an inner current loop [3]. In this paper, a mathematical model of three–phase voltage source PWM rectifier is presented both in the three-phase coordinates and the two-phase stationary coordinates, then a study on the mentioned control strategy is carried on. Simulation model is built in MATLAB/SIMULINK environment to verify mathematical model and the chosen control method. Finally, a DSP- based control system has been built in the laboratory to validate theoretical results.

II. THE MATHEMATICAL MODEL OF PWM RECTIFIER

The three phase voltage source PWM rectifier circuit diagram is shown in Fig. 1.

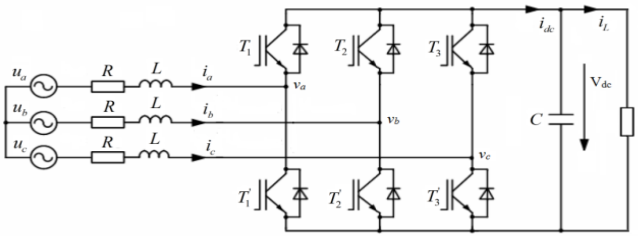


Fig. 1. PWM rectifier circuit diagram

Assuming that the three phase system is balanced and the IGBT is ideal. Where u_a , u_b and u_c present the phase voltages and i_a , i_b and i_c are the phase currents, R and L are the resistance and the inductance of the line reactor respectively , i_{dc} and i_L are the DC output current and the load current respectively and C is the dc-link capacitor. The mathematical model of three-phase PWM rectifier in the three-phase stationary coordinates is presented in (1) and (2).

To simplify the control of the PWM rectifier [4], it is necessary to convert this model into a linear model using the d-q representation.

$$\begin{cases} u_a = L\dfrac{di_a}{dt} + Ri_a + S_aV_{dc} \\ u_b = L\dfrac{di_b}{dt} + Ri_b + S_bV_{dc} \\ u_c = L\dfrac{di_c}{dt} Ri_c + S_cV_{dc} \\ C\dfrac{dV_{dc}}{dt} = i_{dc} - i_L \end{cases} \tag{1}$$

$$i_{dc} = S_ai_a + S_bi_b + S_ci_c \tag{2}$$

The mathematical model based on d-q rotating coordinate is presented as follow:

$$\begin{cases} L\dfrac{di_d}{dt} = u_d - S_dV_{dc} - Ri_d + wLi_q \\ L\dfrac{di_q}{dt} = u_q - S_qV_{dc} - Ri_q - wLi_d \\ C\dfrac{dV_{dc}}{dt} = \dfrac{3}{2}(S_di_d + S_qi_q) - i_L \end{cases} \tag{3}$$

III. THE THREE-PHASE PWM RECTIFIER CONTROL SYSTEM

As it is shown in (3), there is a mutual coupling between the two current i_q and i_d with wLi_d and wLi_q terms. So in order to control them independently it is necessary to use a decoupling feed-forward control strategy [5-6] as illustrated in Fig.2.

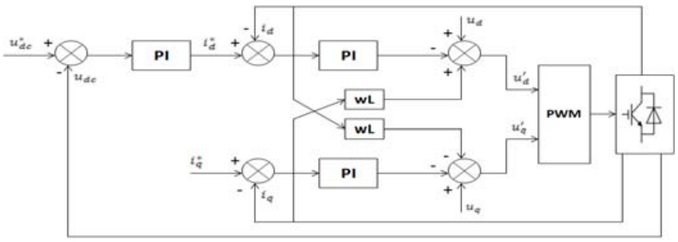


Fig. 2. The decoupling feed-forward control loop block diagram

Using $u_d^{'}=S_dV_{dc}$ and $u_q^{'}=S_qV_{dc}$, the d-q voltage commands are expressed as follow:

$$\begin{cases} u_d^{'} = u_d + wLi_q - \left(Ri_d + L\dfrac{di_d}{dt}\right) \\ u_q^{'} = u_q - wLi_d - \left(Ri_q + L\dfrac{di_q}{dt}\right) \end{cases} \tag{4}$$

A. *The inner current loop*

The inner current control loop contains two PI controllers; basically they tend to regulate the active and reactive current i_d and i_q respectively. The d-axis current loop attempts to maintain a constant DC voltage by tracing the reference current value i_d^* produced by the outer voltage loop. In order to fulfill the unity power factor condition, the q-axis current component i_q^* has to be set to zero [3].

The d-q voltage commands can be controlled as follow:

$$\begin{cases} u_d^{'} = -\left(K_{ip} + \dfrac{K_{iI}}{s}\right)\left(i_d^* - i_d\right) + wLi_q + u_d \\ u_q^{'} = -\left(K_{ip} + \dfrac{K_{iI}}{s}\right)\left(i_q^* - i_q\right) - wLi_d + u_q \end{cases} \tag{5}$$

The sample block can be presented as a first order lag, i.e. $1/(1+T_s s)$, and the PWM block is approximated also as follow: $K_{pwm}/(1+T_{pwm}s)$, where $T_{pwm}=0.5T_s$. The inner current control loop of the d-axis current is shown in Fig.3. K_{ip} and T_i are the gain and the time constant of PI regulator respectively. This current regulator can be assumed as first order system by setting $T_i=L/R$ to cancel the dominant pole of the open loop transfer function in the load [4-7].

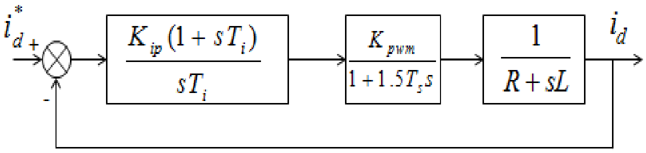


Fig. 3. The d-axis current control loop diagram

The open loop transfer function of the previous system is expressed as follow:

$$H_c(s) = \frac{k_{pwm}K_{ip}}{RT_i s(1+1.5T_s s)} \tag{6}$$

For a first order system parameter adjusting method, the damping factor is D=0.707, the proportional and the integral gain of the PI regulator are chosen in (7):

$$\begin{cases} K_{ip} = \dfrac{RT_i}{3T_s k_{pwm}} \\ K_{iI} = \dfrac{K_{ip}}{T_i} \end{cases} \tag{7}$$

B. *The outer voltage loop*

The outer voltage loop regulator is given in Fig.4.

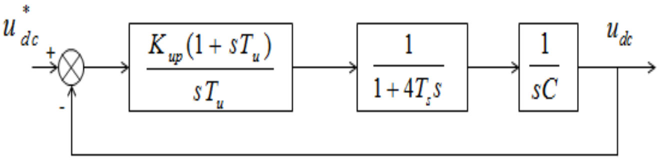


Fig. 4. The DC-voltage loop control diagram

The sample and hold block are presented by first order transfer function with time constant $T_c=T_s$ and the closed-loop transfer function of the inner current regulator has been approximated to a typical I model transfer function with time constant $T_{eq}=2*1.5T_s$ [4].

The open-loop transfer function of this voltage control loop can be calculated as follow:

$$H_v(s)=\frac{K_{up}(1+sT_u)}{sT_u(1+4T_s s)sC} \tag{8}$$

According to [4-8], it is noted that for such open loop transfer function which included a dominant time constant (T_u) and a minor time constant (T_s) the symmetrical optimum (SO) method is used for adjusting the PI regulator. The system bandwidth has been proposed as in (9). Choosing the value of 'a' is very critical for the selection of the PI parameters because low values of the chosen bandwidth could influence the system stability whereas higher values led to slow dynamic response [8].

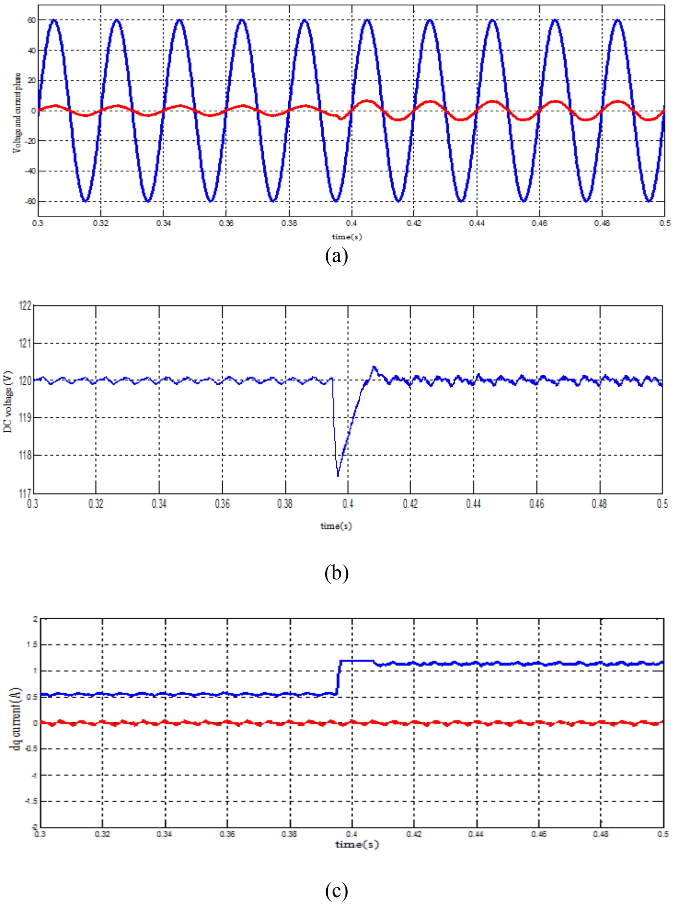
$$a^2=\frac{T_u}{4T_s} \tag{9}$$

The proportional gain of PI regulator is calculated as follow:

$$K_{up}=\frac{C}{4aT_s} \tag{10}$$

IV. SIMULATION AND EXPERIMENTAL RESULTS

A simulation model of the three-phase PWM rectifier was built in MATLAB/SIMULINK environment. The mathematical model and the control strategy studied above were implemented on the simulation. According to (7) and (10) the parameters of the inner current loop and the outer voltage loop are: K_{ip}=1.54, K_{ii}=231.33, K_{up}=26.41, K_{ui}=7330. Then a laboratory setup was built using dsPACE system with DS1104 controller board and SEMIKON inverter as it is shown in Fig.11. The system parameters are the same for both the simulation model and the experimental setup and are given in Table I.



(a)

(b)

(c)

Fig. 5. Simulation results with load variation at 0.39s (a) voltage and current phase (b) DC-link voltage (c) dq-current.

Table I. System parameters

Parameter	Symbol	Value
Nominal power	P	500 W
Grid phase voltage	V_b	60 V
Grid voltage frequency	f	50 Hz
Dc-link voltage	V_{dc}	120 V
Dc-link capacitance	C	1100 µF
Filter resistance	R	0.75 Ω
Filter inductance	L	5 mH
Switching frequency	f_s	10 kHz

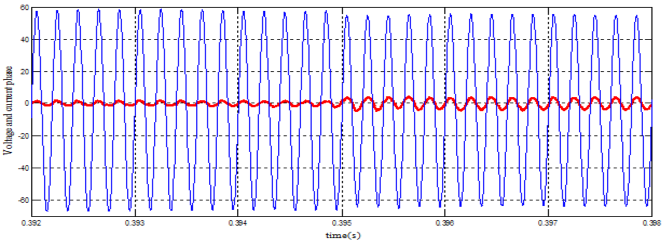


Fig. 6 Experimental results of the voltage and current phase

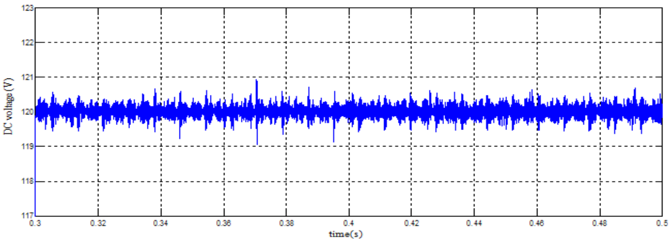


Fig. 7 Experimental result of the DC-link voltage

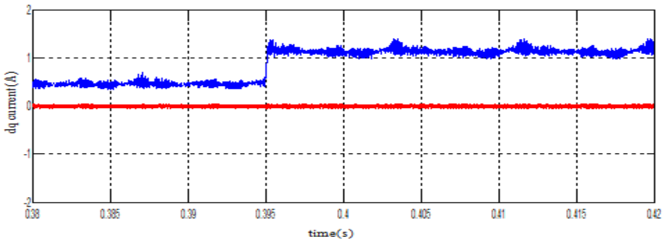


Fig. 8. Experimental results of the dq-current

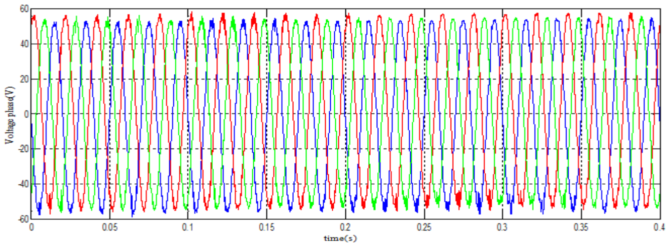
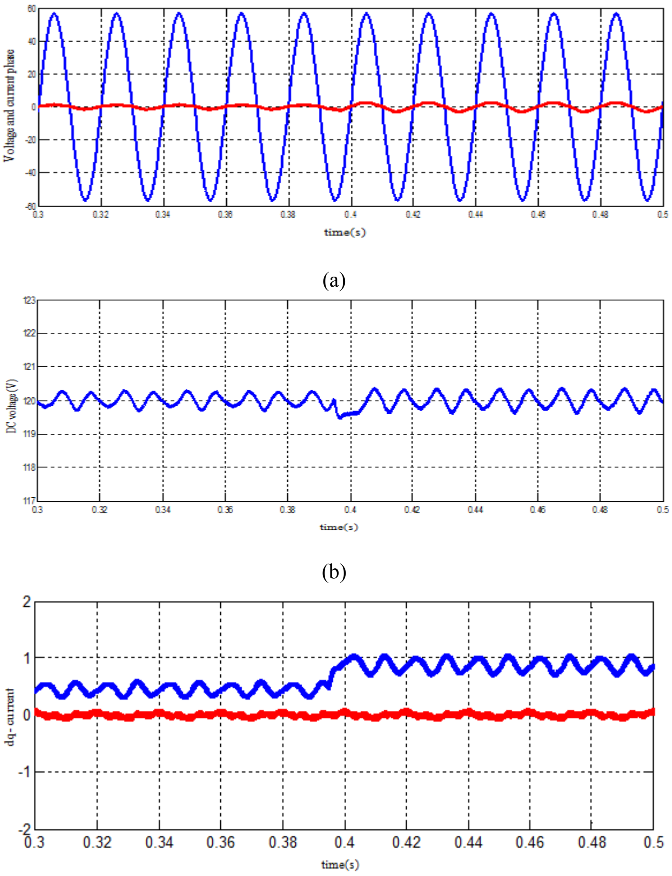


Fig. 9 The three-phase grid voltage waveforms

The simulation and experimental results demonstrate that the PWM rectifier can assure an accurate DC-link voltage, provide a sinusoidal AC current waveform and achieve unit power factor (i_q=0) as it is shown in Fig.5-8 respectively. It is clearly shown in Fig.5.a that the system has a good dynamic response to the variation load at 0.39 s. Fig.5.b shows that the current waveform is perfectly sinusoidal and has the same phase as the voltage waveforms. The reactive current continued zero even with load variation as it is shown in Fig.5.c.

Looking at the experimental results, we can see in Fig.6 that the current waveform is not perfectly sinusoidal which indicates the presence of unwanted harmonic pollution. Also in Fig.7 a slight variation of the load is shown. These defects can be explained by the unbalanced grid voltage phase as it is shown in Fig.9. Periodic voltage fluctuation has been observed in the voltage grid (8 Hz) also unbalanced voltage level between the three phases. So in order to cover all the practical aspects we need to take into account these effects in the simulation lab. The simulation results with unbalanced grid voltage phase are shown in Fig.10. We can see that the experimental results are confirmed by the simulation results which validate the effect of the integrated imperfections in the simulation model.

It must be noted also that a low-pass filter which present the overall hardware anti-aliasing filter with time constant equal to 0.0074 has been included in the control system to validate the simulation results [9].



(a)

(b)

(c)

Fig. 10. Simulation results with unbalanced grid phases (a) voltage and current phase (b) DC-link voltage (c) dq-current.

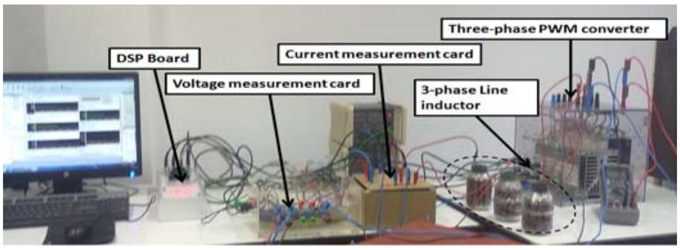


Fig. 11. Laboratory setup of the three-phase PWM rectifier

V. CONCLUSION

In this paper, a three-phase PWM rectifier model has been analyzed and simulated. The mathematical model and the decoupled feed-forward control strategy are both validated by the result of the simulation in the MATLAB/SIMULINK environment and the experimental setup. The results show that the system has a high power factor, a good dynamic response and an accurate DC-link voltage level. The defects caused by the grid are taken into account in the simulation control lab in order to get simulation results confirmed to practical results. These imperfections produce harmonic pollution in the AC current phase, so it is suggested to control the PWM rectifier with space vector modulation to ameliorate the harmonic content of the AC current waves.

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