HARMONIC REDUCTION AND POWER FACTOR REGULATION FOR THREE-PHASE PWM BOOST RECTIFIER

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ABSTRACT

Due to the enhancement in high-speed switching semiconductor devices, the employ of three-phase PWM boost rectifier (BR) has grown to be more common in the past decade. The PWM rectifier can provide input currents without distortion and with unity power factor at the supply terminals. The description and modeling of the three-phase PWM rectifier have been analyzed using the voltage source inverter (VSI) with resistive load. The proposed control scheme in this paper has two closed loops to compute the three-phase reference currents of PWM rectifier. The first, namely dc load current loop, and the second, using dc bus voltage loop. The unity power factor and reduction of pollution harmonic is completely fulfilled with current controller that is applied linear current controller. The Simulation and experimental results verify the operational characteristics of the PWM rectifier.

يعتبر التقدم الهائل فى صناعة المفاتيح الالكترونية من أشباه الموصلات السريعة الفتح والغلق من أسباب ازدياد استخدام موحد معزز الجهد بكثرة فى الآونة الأخيرة. يستخدم موحد معزز الجهد للحد من مشاكل تيار التوافقيات وفى نفس الوقت يعمل على تحسين معامل القدرة عند المصدر. تم وصف وعمل نموذج لموحد معزز الجهد باستخدام مبدل جهد المصدر مع استخدام مقاومة كحمل. اقترح فى هذا البحث مسارين تحكم لموحد معزز الجهد للحصول على التيارات المرجعية للمصدر: المسار الأول باستخدام تيار الحمل المستمر والمسار الثانى باستخدام جهد المكثف المستمر. استخدمت طريقة تحكم التيار الخطى للحصول على نبضات فتح وغلق المفاتيح الالكترونية لموحد معزز الجهد لإتمام عملية تقليل التوافقيات وتحسين معامل القدرة. وأوضحت النتائج النظرية والعملية قدرة موحد معزز الجهد على تقليل التوافقيات وفى نفس الوقت يحسن من معامل القدرة عند المصدر.

Keywords: Boost rectifier, voltage source inverter (VSI), dc load current loop, harmonic reduction

1. INTRODUCTION

As it has been observed for recent decades, an increasing part of the generated electric energy is converted through rectifiers, before it is used at the final load. In power electronic systems, especially, diode and thyristor rectifiers are commonly applied in the front end of DC-link power converters. The rectifiers are nonlinear in nature and, consequently, generate harmonic currents in to the AC line power. The high harmonic content of the line current and the resulting low power factor of the load, causes a number of problems in the power distribution system [1] like:

1-Voltage distortion and electromagnetic interface (EMI) affecting other users of the power system.

2-Increasing voltampere ratings of the power system equipment (generators, transformers, transmission lines, etc.).

These problems have become a major concern nowadays, and the research and developed effects are thus being concentrated on the solutions by which distortion influences can be eliminated or reduced significantly. The passive filters used for input current shaping provide a limited range of harmonic compensation with varying load [2]. One of the potential solutions to cancel the harmonics from the entering of power system is by three-phase PWM rectifier. The most interesting feature of this PWM rectifier, however, is not the unity power factor or the boost output voltage, but the bi-directional energy flow capability [3]. To control this system, many control strategies have been proposed recently [1-11]. The conventional algorithm (i.e.PI) to control these systems suffer from the problem, in that they are tuned if any of the system parameters change, [4]. Moreover, conventional control methods for PWM rectifier, which depending on *PI* regulators for the output voltage, still are dependent on the load and the switching frequency. Also these types of conventional control give rise times and damping factors depending on the rectifier operating point [5]. So, in this paper, a new control strategy, which based on two closed loops; dc load current loop, beside, dc bus voltage loop with PI controller has been proposed to reduce the harmonics and power factor regulation of the PWM rectifier. The current controller technique, which discussed in this paper, is based on linear current regulator. In this controller the feedback of current always follows its reference.

2. DESCRIPTION, OPERATION AND MODELING OF THE THREE-PHASE PWM RECTIFIER

2.1 Description of the Three-Phase PWM Rectifier

The main circuit of the three-phase PWM rectifier is shown in Fig.1. It basically consists of six switches (IGBT anti-parallel with diodes); three boost inductors (L_s), the output capacitor (C) and variable resistance (R) as a resistive load. The supply voltage supplies power to the load through the full-bridge converter. This construction of the three-phase PWM rectifier as a voltage source inverter VSI, combination with the load, consider as a nonlinear load in respect to the AC supply. The line inductors (L_s) decouple the supply voltage from the converter's ac terminals, while providing the input current source characteristic and limiting the input current distortion [7]. The capacitor (C) provides the output voltage characteristic, and stores the energy required to satisfied purpose of reducing the supply current harmonic and improve the power factor.
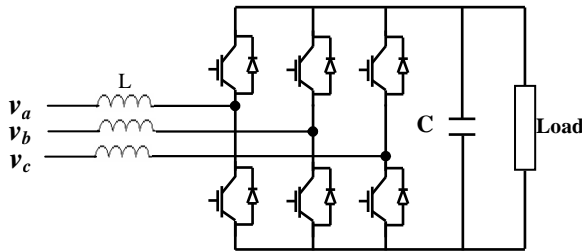

Fig.1 Main circuit of the Three-Phase PWM Rectifier

2.2 Operation Principle

The basic operation principle of the PWM rectifier is analogous to that of the boost dc chopper, that is, during the AC side by-pass of the current source rectifier, the source energy is accumulated in the inductor, and then, by switching of the current source rectifier, this energy is expelled to the DC side resulting in boost effect. But the PWM rectifier has another control object; the unity power factor, harmonic reduction at input AC side, besides the boost output voltage.

2.3 Modeling of the Three-Phase PWM Rectifier

The principal simulation model of three-phase PWM rectifier that illustrated in Fig.2 can be represented as a state (1 or 0) of bi-directional switches (IGBTs), by introducing the converter functions *NA, NB* and *NC* for the three legs of PWM rectifier.
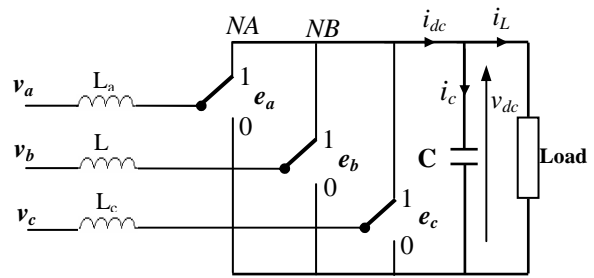

Fig.2 Three-Phase PWM Rectifier modeling

The equations, which are coupled the three- phase AC side with DC side of PWM rectifier as shown in Fig.2, are deduced as follows:

The voltages (e_a, e_b, e_c) as a function in dc side voltage and the converter functions can be written as Eq. (1):

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} V_{dc} \tag{1}$$

Where

$$f_1 = \frac{2NA - NB - NC}{3}$$

$$f_2 = \frac{2NB - NC - NA}{3}$$

$$f_3 = \frac{2NC - NA - NB}{3}$$

The dc current i_{dc} as a function with line currents (i_a, i_b, i_c) is defined as: Eq. (2):

$$i_{dc} = \begin{bmatrix} NA & NB & NC \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

The output dc bus voltage equal as Eq.(3):

$$V_{dc} = -\frac{1}{C} \int i_c \, dt$$
$$= -\frac{1}{C} \int (i_{dc} - i_L) \, dt \tag{3}$$

The line current in ac side can be deduced from the Eqs. (4) as follows:

$$v_a - e_a = L_a \frac{di_a}{dt}$$
$$v_b - e_b = L_b \frac{di_b}{dt} \tag{4}$$
$$v_c - e_c = L_c \frac{di_c}{dt}$$

3. LAYOUT CONTROL OF THE PWM RECTIFIER

The layout of control of PWM rectifier that shown in Fig.3 is contain two units. This control techniques are combined and has two-closed loop namely, dc load current loop and dc bus voltage loop.

3.1 DC Load Current Loop

As shown in Fig.3, the dc load current loop maintains a proper balance in power flow from input port to output port of the PWM rectifier. During the load change on PWM rectifier from one value to another, the dc load current loop provides instantaneous information to control structure of the PWM rectifier. With the knowledge output load conditions the dc load current loop makes the one component of computation the three-phase reference currents at the input of PWM rectifier. To implement dc load current loop, the dc load current (i_L) is sensed and passed through a low pass filter to get rid off high frequency ripples in the load current. The output of the low pass filter (I_{P1}) is considered a first component of the magnitude of three-phase reference currents at the input port of the PWM rectifier.

3.2 DC Bus Voltage Loop

The second loop as illustrated in Fig.3 is dc bus voltage loop with *PI* controller. The output dc voltage V_{dc} is compared with its reference voltage $V_{dc}*$, and the error is fed to a *PI* regulator to reduce the steady state error and keeps the dc output voltage

constant. The output of *PI* controller is input to a limiter and output of limiter (I_{P2}) is considered as second component (magnitude) of computation the three-phase reference currents at the input of PWM rectifier. The component (I_{p2}) keeps the dc bus voltage of PWM rectifier close to the set values V_{dc}^*.

3.3 Reference Current Determination

To compute the three-phase reference currents at the input of the PWM rectifier, the dc load current loops and the output of the dc bus voltage are used. Therefore, the magnitude (I_P) of three-phase reference currents is expressed as;

$$I_P = I_{P1} + I_{P2} \tag{5}$$

Where I_{P2} regulates the dc load voltage close to its set value (V^*_{dc}). Whereas, I_{P1} balances the power flow from input port to output port of the PWM rectifier and this is according to the need of load power at output port of PWM rectifier. On the other side, the phases of three-phase reference currents are computed from the supply voltages and the amplitude of rms supply voltages (V_P), which is calculated from the source phase voltages v_a, v_b and v_c as expressed in (6).

$$V_P = \sqrt{\frac{2(v_a^2 + v_b^2 + v_c^2)}{3}} \tag{6}$$
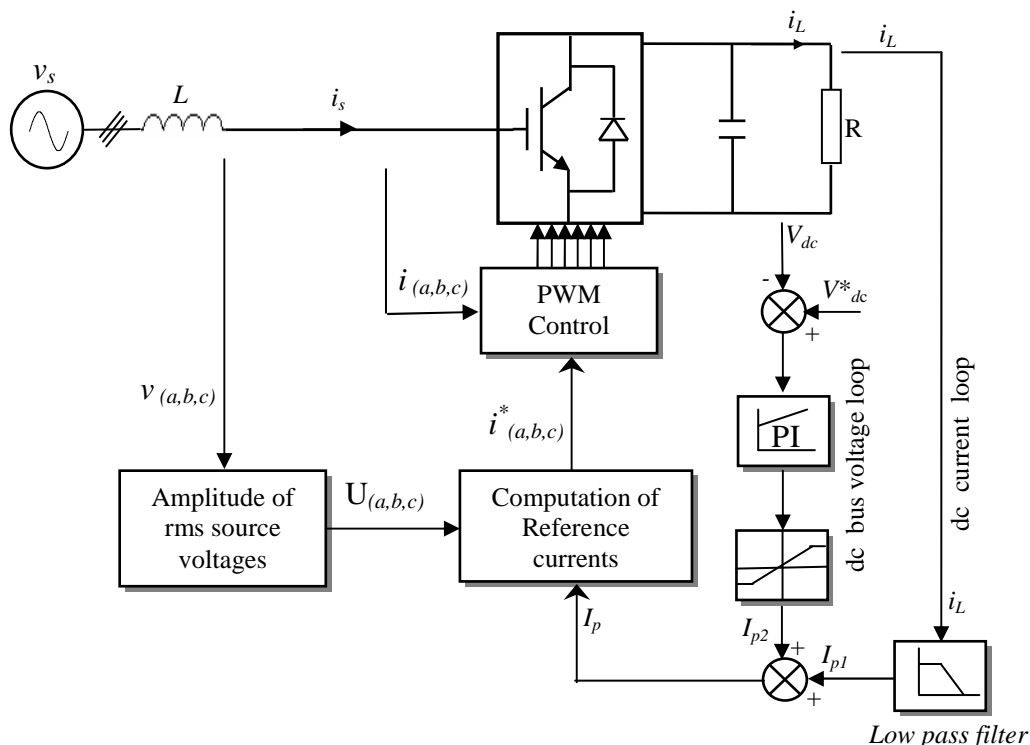

Fig.3 The layout of control of PWM Boost Rectifier

Then, the *phase*s of three-phase reference currents (U_a, U_b and U_c) is obtained as:

$U_a = V_a / V_P$
$U_b = V_b / V_P$
$U_a = V_c / V_P$

The three-phase reference currents are then computed as follows:

$i^*_a = U_a I_P$
$i^*_b = U_b I_P$
$i^*_c = U_c I_P$

3.4 Modulation Technique

In the modulation stage (Fig.4), comparison of three-phase reference currents (i^*_a, i^*_b, i^*_c) with sensed current (i_a, i_b, i_c), obtaining a current error adapted according to the amplitude of the triangular carrier. The purpose of introducing the triangular waveform is to stabilize the converter switching frequency by forcing it to be constant and equal to the frequency of the triangular reference signal. Since the current error signal is always kept within in the negative and positive peaks of the triangular waveform, the system has an inherent over current protection [9]. The PWM output is completed with the introduction of an appropriate dead time to the control signals of the inverter switches.
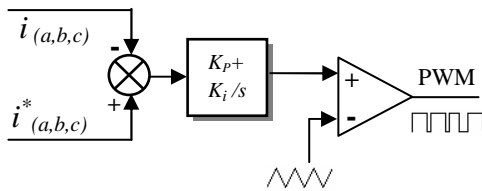
Fig.4 Linear current control technique

4. THE SIMULATION RESULTS

The simulation results were carried out under the parameter shown in appendix (A). The simulation is studies in two cases of operation of the PWM rectifier and its control circuit, steady state and transient operation.

4.1 Steady State Operation

In these figures, the waveform of ac line phase current i_a and respective voltage v_a is shown in Fig. (5-a). Also Fig.(5-b) shows the three-phase line currents. The ac line phase current and its reference are depicted in Fig.(5-c). Harmonic spectrum of ac line current is shown in Fig.(5-d) then, the total harmonic distortion has been calculated. Fig.(5-e) shows the dc bus voltage V_{dc} with its reference $V_{dc}*$ where the reference output dc bus is set to 560 v. It is observed from these figures that the ac line current is in phase with the supply voltage and make sure the unity power factor at the supply with good result of *THD*, where it was found 1.4313%. The feedback line current i_s follows its reference, also the dc bus voltage V_{dc} is regulated at its reference of set value.
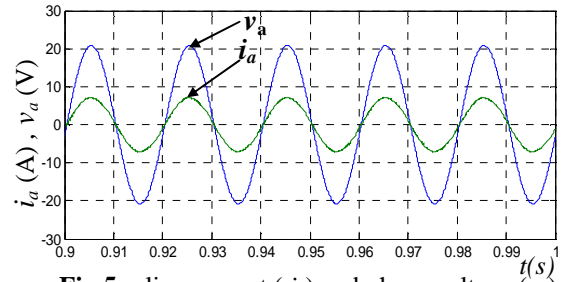
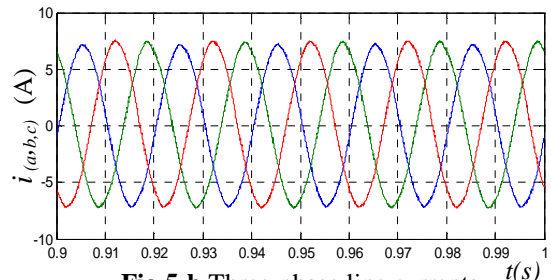**Fig.5-a** line current (i_a) and phase voltage (v_a)

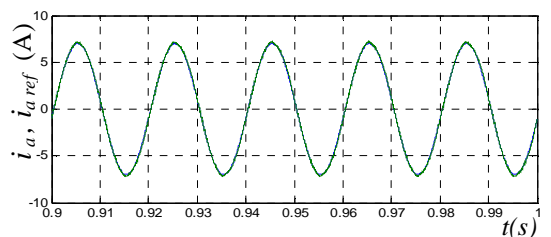**Fig.5-b** Three-phase line currents

Fig.5-c Actual line current and its reference
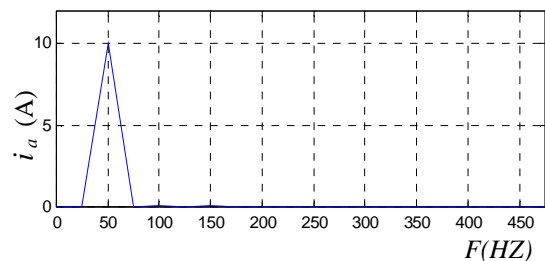
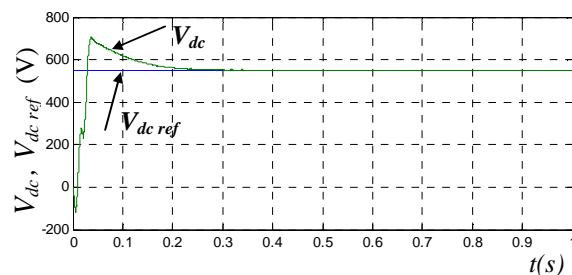**Fig. 5-d** Harmonic spectrum of ac line current

Fig.5-e Actual dc voltage (capacitor voltage) and its reference

Fig.5 Simulation result in case steady state operation

4.2 Transient Operation

In transient operation of PWM rectifier, change of both the resistive load and dc output bus voltage are considered.

4.2.1 Change the load (R)

Figure 6 shows responses to step changes   in the resistive load. The load resistance *R* was changed from 45 Ω at time 0.9 sec. to 25 Ω. Fig.(6-a) shows the line phase current i_a and the supply voltage v_a while the suddenly changing of R load. The dc bus output voltage V_{dc} and its reference also is shown in Fig.(6-b). From these figures, its notice that the line phase current i_a almost in phase with respective voltage v_a even with changing of R load. Also the dc bus output voltage is arrival to the target value after finishing the transient period of suddenly change of R load.
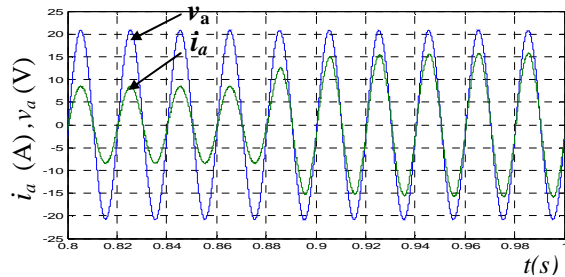

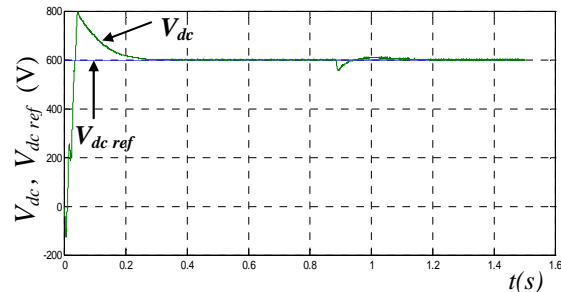**Fig. 6-a** The line current i_a and the supply voltage v_a

Fig. 6-b The dc bus output voltage V_{dc} and its reference

Fig.6 Simulation result in case step change of resistive load
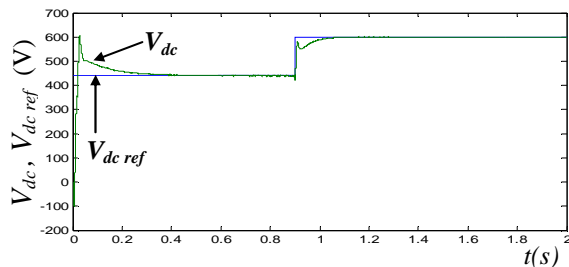

Fig.7-a   Step change in dc output voltage V_{dc} and its reference
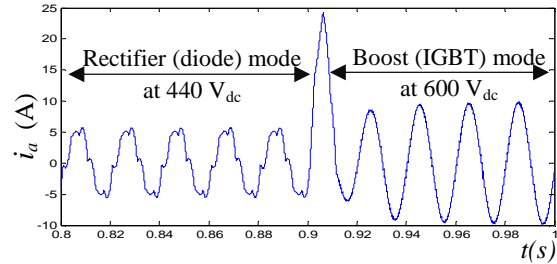

Fig.7-b The line current while step change in dc output voltage
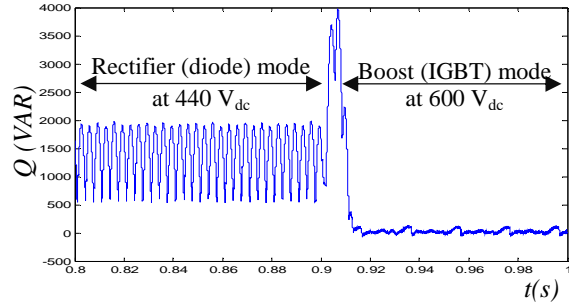

Fig.7-c The reactive power (Q) while step change in dc output voltage

Fig.7 Simulation result in case change of dc output voltage

4.2.2 Change of DC output voltage

The reference of dc bus output voltage is changed from 440 V to 600 V and the results are shown in Fig.(7). The feedback dc bus output voltage V_{dc} and its set value $V_{dc}*$ is shown in Fig.(7-a) Also the behavior of line current i_a and its respective supply voltage v_a in case changing of dc bus output voltage reference is shown in Fig. (7-b). The reactive power (*Q*) is obtained (Fig.7-c) while changing from 440 v to 600 v (reverse power flow direction). From this figures, it can be remarked that; when the output dc voltage is 440 v (power flow direction from source to load) the line current is non sinusoidal and the reactive power (Q) is arrival around to 1500 VAR. Otherwise the   line current is sinusoidal and   the reactive power (Q) is arrival around to zero when the output dc voltage is 600 v (reverse power flow direction).

5. EXPERIMENTAL TESTS

Prototype of the PWM rectifier was build and tested in the laboratory. Simplified diagram of the test circuit is depicted in Fig. 8. The power circuit is constructed IGBT's. The necessary feedback signals from the power circuit are obtained by using the hall-effect voltage and current sensors. (only two of the three-phase quantities are sensed). Also the voltage and the current isolators sense the DC capacitor voltage and load current respectively. This system is fully controlled by using Digital Signal Processor

(DSP) and developed under the integrated development environment of MATLAB – SIMULINK provided by the MATHWORK. The control algorithm of experimental setup generates switching functions, which are the output of DSP and the resulting pulses are gating the IGBT's of the PWM rectifier. Figure (9) shows experimental results for the resistive load condition. Figure (9-a) shows

the ac line current (ia) composite with its phase voltage (va). The three-phase line currents is depicted in Figure (9-b). Fig.(9-c) shows the dc capacitor voltage Vdc and its reference Vdc* . From these figures, it is clear that the line current almost sinusoidal and in phase with supply voltage, and the actual capacitor voltage follow its reference.
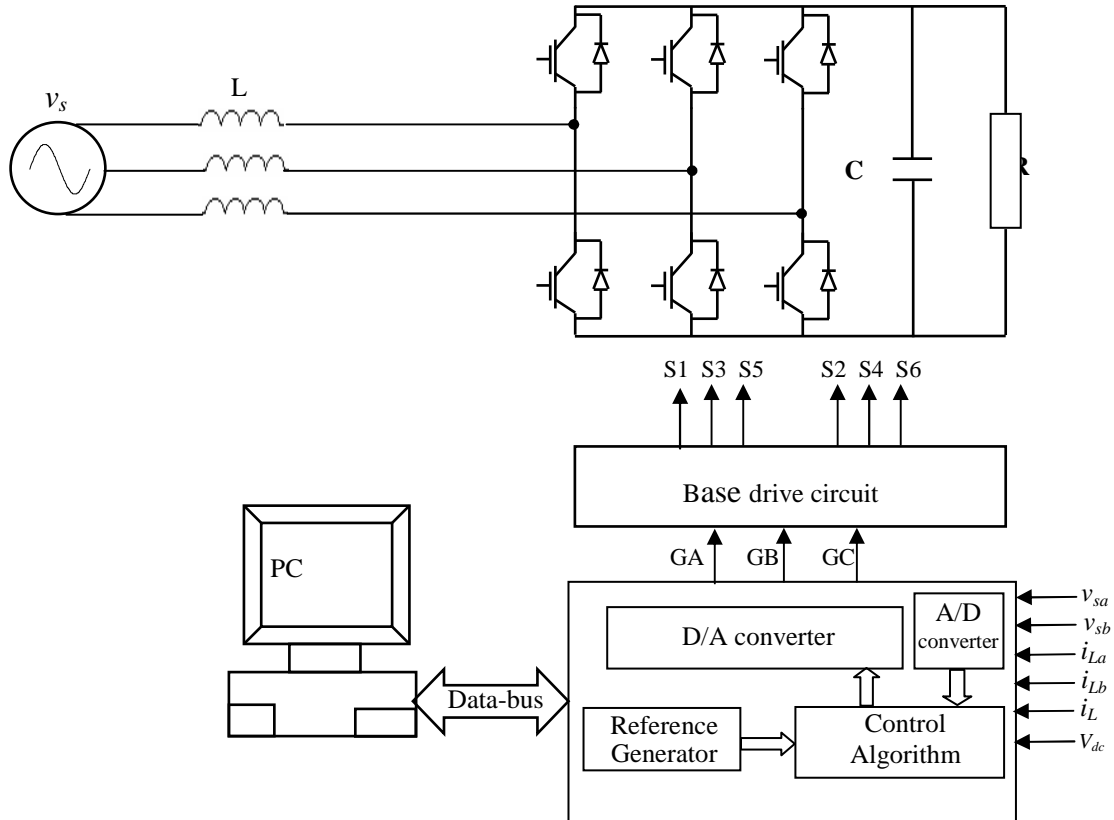

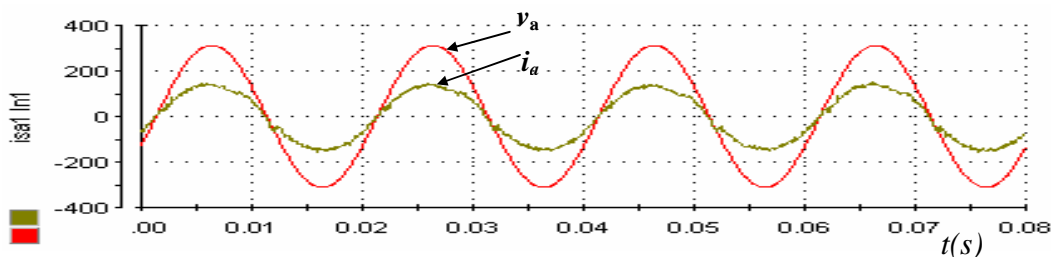**Fig.8** Digital Signal Processing (DSP) system hardware.

Fig. 9-a Experimental tests; The actual line current i_a and with supply voltage v_a
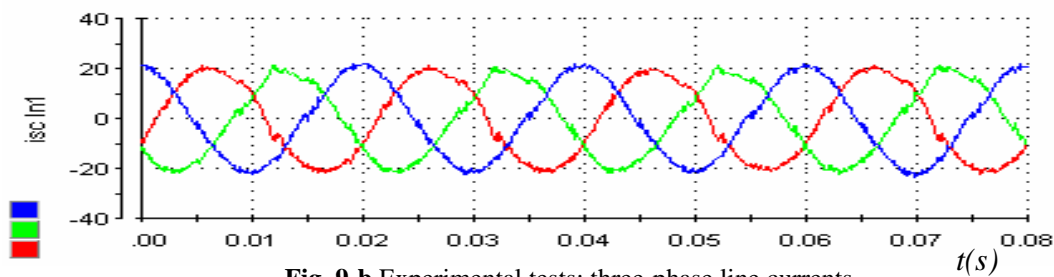

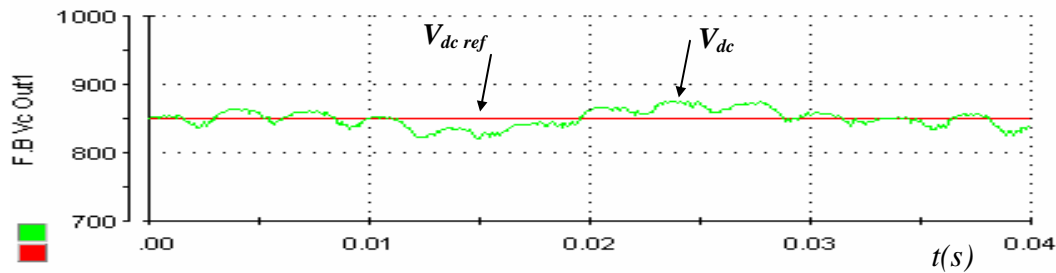**Fig. 9-b** Experimental tests; three-phase line currents

Fig. 9-c Experimental tests; The dc bus output voltage V_{dc} and its reference

6. CONCLUSION

In this paper, a three-phase PWM rectifier with control method based on two closed loops has been presented and analyzed. The first loop was dc bus voltage with PI controller, and the second was Dc load current feed-forward loop. The summing output for two loops of control was employed to generate the reference line current of PWM rectifier. The simulation results proved the validity of the proposed control method and feasibility of PWM rectifier. The actual current tracks the desired value without delay; it is robust to the variations of resistance R This paper verified that PWM rectifier and its proposed control scheme have ability to obtain sinusoidal shaped ac input current, which in phase with corresponding voltage. Then the harmonics in the ac line current has been reduced also the power factor was improved. The paper prove that the three-phase PWM rectifier has a series of advantages, such as low input current distortion, high quality dc voltage, controllable power factor, reduced size-filtering components, which besides are not subjected to power system resonance [4]. An experimental PWM rectifier has been carried out on DSP to explore the advantages and practical implementation with the proposed control strategy. The experimental and simulation results showed that the proposed system has a good performance in the harmonic mitigation and improving the input power factor.

7. APPENDIX (A)

The parameters of the three-phase PWM boost rectifier (BR).

Input voltages v_s *= 380 volt*
BR load resistance R *= 45 Ω*
BR input inductor L_s *= 10 mH*
BR capacitor C *= 750 μF*
SAF inductor L_f *= 30 mH*

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