Implementation of Microcontroller-Based Three Phase PWM Rectifier without Measuring the Supply Voltage

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ABSTRACT: A simplified control strategy for three-phase PWM rectifier without measuring the supply voltage is presented. Beside simplicity, the proposed control algorithm is robust, inexpensive, and can be used for unity or variable power factor operation. This paper describes the proposed control strategy and its implementation with the help of a low cost Intel 80C196KC microcontroller and three-phase bridge inverter using IGBT transistors. The experimental results are presented to prove the near sinusoidal and low harmonic content of the ac-line current.

Keywords: *Three Phase PWM rectifier; unity power factor; hysteresis current controller; dc-voltage controller*

I. INTRODUCTION

As the amount of equipment using conventional diode rectifiers increases, harmonic input currents are becoming a problem. Harmonic current limits are recommended by the IEC 555 and IEEE 519 standards. These guidelines necessitate the use of bulky expensive filters at the input of these classical rectifiers. These filters are optimized for certain cut-off frequencies and operating conditions. Also, the filters have a negative impact on the system dynamic performance. Recently, the PWM rectifier, shown in Fig.(1), has been more and more widely used for its distinct advantages, such as sinusoidal line currents, unity input power factor, bi-directional power flow and stabilization of DC link voltage. Many of controlling methods have been proposed [1-5]. The controller presented in this paper is based on hysteresis current control that provides simple control algorithm for controllable power factor and good spectral performance of the line current. Moreover, it has been implemented in a single low-cost fixed-point microcontroller (Intel 80C196KC).

The normal operation basically requires three kinds of sensors for detecting ac voltages, ac currents and dc voltage. A dc voltage sensor is needed for the dc voltage feedback control and excessive voltage protection. The two ac voltage sensors are needed to detect the phase angle of the source voltage, which is taken as a reference frame of the controller, and thus to control the input power factor.

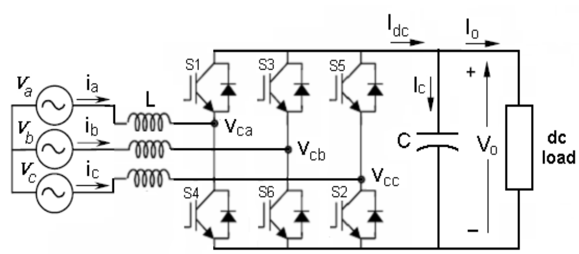


Fig.1. Three phase PWM rectifier.

The two line current sensors are required for the input current control for boosting action and excessive current protection. Using all of these sensors makes the system bulky and expensive. In addition, the sensed signals are usually subjected to noise and furthermore incidental missing of any signal may deteriorate the system reliability. Therefore, it is desirable to reduce the number of sensors as far as possible [6-8]. In this paper, a method to eliminate the ac supply voltage measurement is proposed, which uses only two current sensors and dc-side voltage sensor.

II. THEORY AND OPERATION

Figure (1) shows the power circuit of three-phase PWM boost rectifier in bridge connection, which uses six IGBT transistors with antiparallel diodes to produce a controlled dc voltage V_{dc}.

In this topology; to maintain linear PWM operation and sinusoidal input currents, the dc-bus voltage must be maintained such that [9]:

$$V_{dc} \geq \frac{2\sqrt{2}}{\sqrt{3}} V_{LL} \qquad (1)$$

where; V_{LL} is the line to line supply voltages. This equation is used to select the minimum value of the output dc voltage. The PWM rectifier operates with the dc-link voltage kept at a desired reference value, using a feedback control loop. To accomplish this task, the dc-link voltage is measured and compared with the desired value V_{ref}. The error signal is applied to PI controller then multiplied by a unity sine-wave synchronized with the phase voltage. The resulting signal is considered to be the reference current , which is compared with the actual line current and producing the switching pattern through a hysteresis controller as shown in Fig.(2).

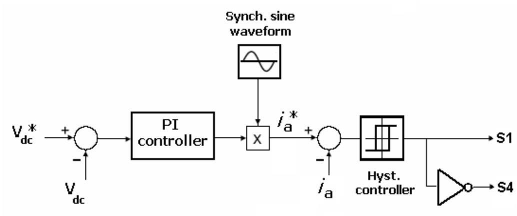


Fig.2. Block diagram of the proposed control strategy.

The signal generated from this comparison is used to ON and OFF the six switches of the rectifier. In this way, power can come or return to the ac source according to dc link voltage requirements.

Figure (3) shows the single line diagram, waveforms, and phasor diagrams of the PWM rectifier operations according to unity, leading and lagging power factor.

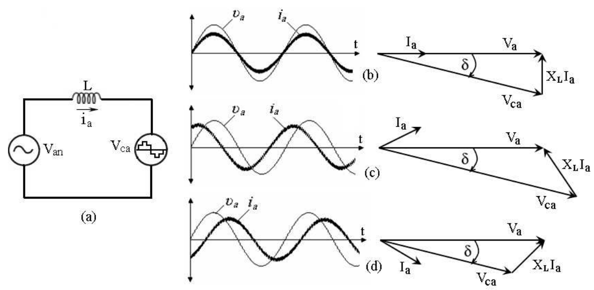


Fig.3. a) Single line diagram, b) Unity power factor operation, c) Leading power factor operation, d) Lagging power factor operation.

The six IGBT-diode combination switches can be classified into the high-side and the low-side switches, forming a conjugate pair per phase. The simultaneous operation of a conjugate pair is not allowed to prevent short circuit faults. At any instant of time, only three of the six switches participate in current conduction. A valid switching state consists of the participation of two switches of the same category with the third participating switch from the other category. This switch combination is based upon the possible current errors. Assuming negligible conduction drops across the participating switches, the equations representing the switching states shown in Fig.(4) are:

$$V_{an} = L\frac{di_a}{dt} + V_{ca} \qquad (2)$$

The converter voltage V_{ca} takes values of $(\pm\frac{2}{3}V_{dc})$ or $(\pm\frac{1}{3}V_{dc})$ depending on the switching state, thus,

$$\frac{di_a}{dt} = \frac{1}{L}(V_{an} + \frac{2}{3}V_{dc}) \qquad (3)$$

$$\frac{di_b}{dt} = \frac{1}{L}(V_{bn} - \frac{1}{3}V_{dc}) \qquad (4)$$

$$\frac{di_c}{dt} = \frac{1}{L}(V_{cn} - \frac{1}{3}V_{dc}) \qquad (5)$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C}(I_{dc} - I_o) \qquad (6)$$

Similarly, equations can be generated for the remaining valid switching states.

Currents and voltages can be represented as function of switching states as follows:

$$I_{dc} = S_1 I_a + S_3 I_b + S_5 I_c \qquad (7)$$

$$V_{ca} = (V_{dc}/3)\,(2S_1 - S_3 - S_5) \qquad (8)$$

$$V_{cb} = (V_{dc}/3)\,(-S_1 + 2S_3 - S_5) \qquad (9)$$

$$V_{cc} = (V_{dc}/3)\,(-S_1 - S_3 + 2\,S_5) \qquad (10)$$

Where S_1, S_3, S_5 are the high-side switches of the rectifier and S=0 means that the switch is open whereas S=1 means that it is closed. Equations (3-10) are used to develop the model of PWM rectifier under any switching techniques.

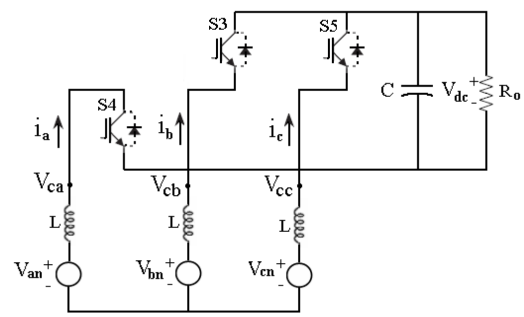


Fig.4. A particular switching state for PWM rectifier.

III. SIMULATION RESULTS

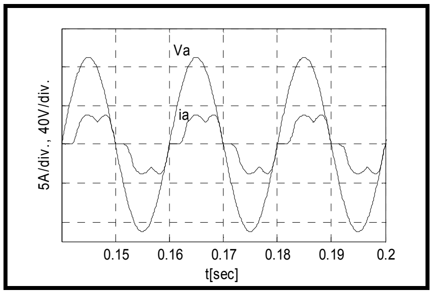
A simulation platform using SIMULINK and Power System Blockset under MATLAB is built to evaluate the performance under different operating conditions. The system parameters are chosen in Table 1.

Table 1. System Parameters.

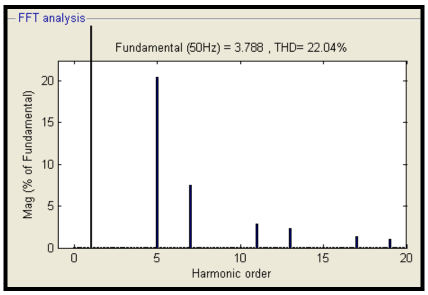
Parameter	Value
AC line voltage	110V
Ref. DC output voltage	180V
Line inductance	10mH
Load resistance	45Ω
DC link capacitor	1000µF
Hysteresis band	5%

The line to line voltage is 110V and according to equation (1) the reference dc output voltage is chosen to be 180V. The step time is 100µsec, which is equivalent to 10KHz sampling rate.

Figure (5) presents the ac line current of the classical diode rectifier and its harmonic spectrum; the line current waveform is highly distorted with THD=22%.



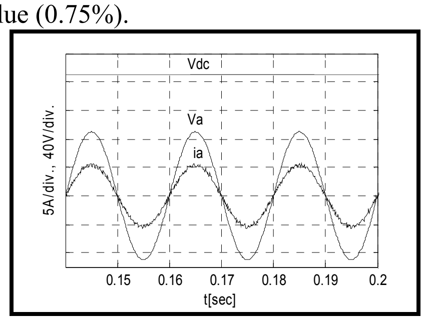
(a)



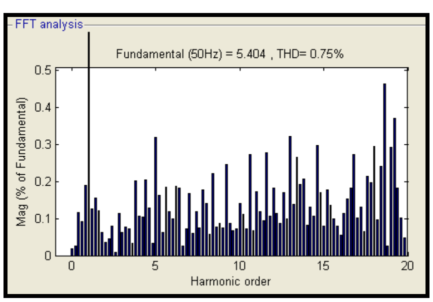
(b)

Fig.5. Steady state performance of the classical diode rectifier.
a) Phase voltage and line current waveforms, b) Harmonic spectrum of the line current.

Figure (6) presents the steady state performance of the PWM rectifier at unity power factor operation; the ac line current has a near sinusoidal waveform with low THD value (0.75%).



(a)



(b)

Fig.6. Steady state performance of PWM rectifier, a) Phase voltage and line current, b) Harmonic spectrum of the line current.

Figure (7) shows the transient response according to lead-lag power factor operation with angle of 30^o.
Figure (8) shows the transient response according to 15% step change in reference dc voltage.

Figure (9) shows the transient response according to 20% step change in load resistance. The reference dc load voltage is regulated at 180V. Figure (10) shows the phase to neutral and phase to phase converter voltages.

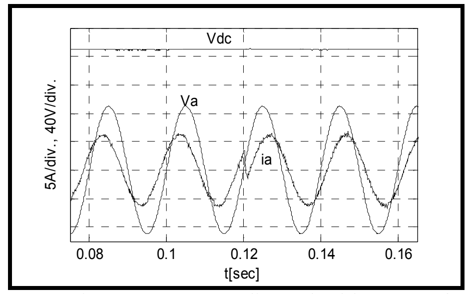


Fig.7. Transient response according to lead-lag power factor.

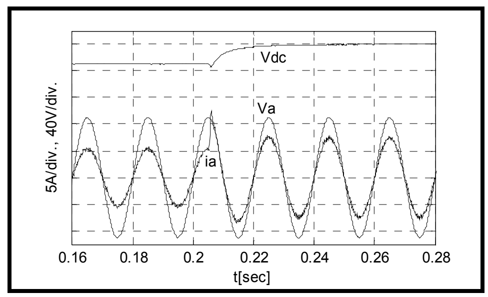


Fig.8. Transient response according to 15% step change in reference load voltage.

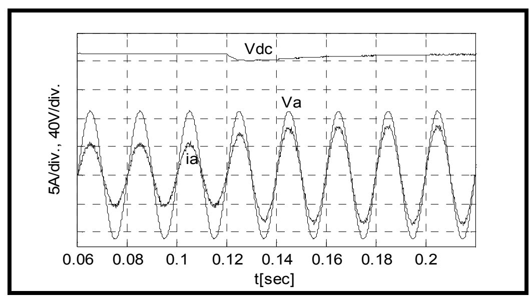


Fig.9. Transient response according to 20% step change in load resistance.

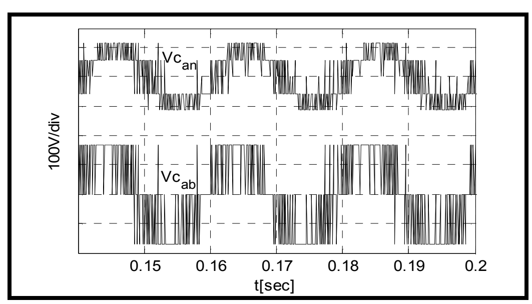


Fig.10. Converter voltages, a) phase to neutral b) phase to phase.

From these simulation results it is observed that the proposed control scheme provides a good regulation of the output voltage with a controlled input power factor (unity, leading, and lagging) and low THD values (0.75%) of the ac line current.

IV. EXPERIMENTAL SETUP

The block diagram of the experimental setup of proposed system is shown in Fig.(11). Principle connections between the different elements in the complete system are indicated. The software algorithm is implemented using Intel 80C196KC 16-bit embedded microcontroller. This microcontroller provides an A/D converter with multiplexed eight-input channels, which is used for the various A/D operations required by the controller algorithm. The output ports provided by the 80196 microcontroller are used for interfacing the switching signals to the IGBT drivers. The high-speed input port is used for phase voltage zero-crossing detection measurement.

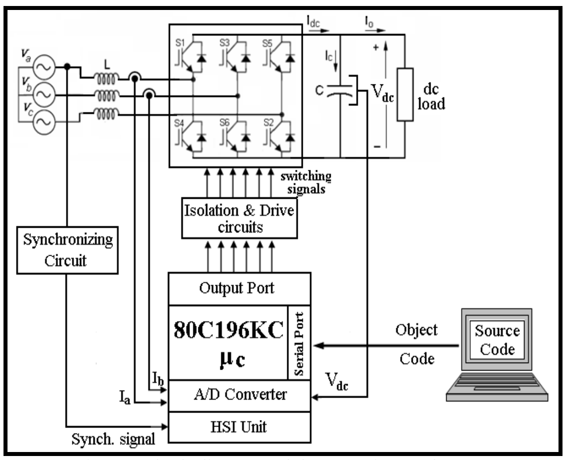


Fig.11. Block diagram of the experimental setup.

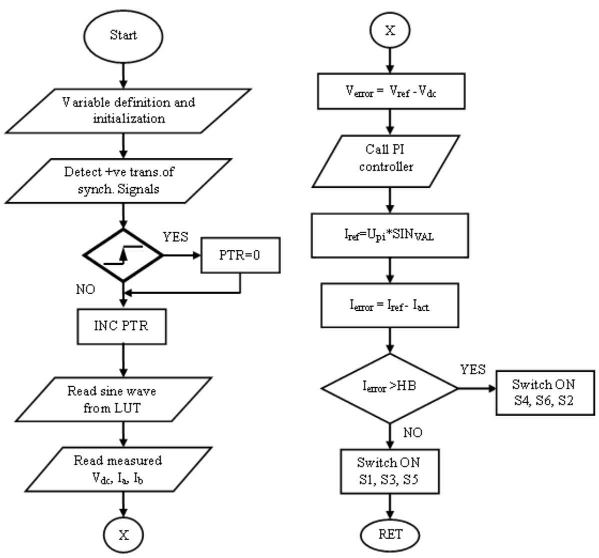
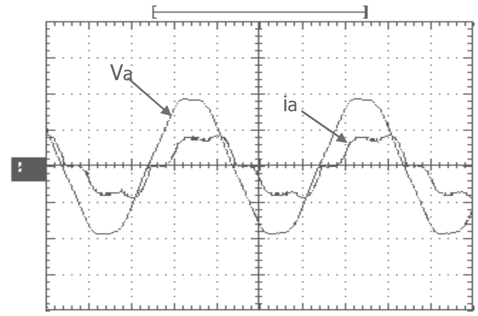


Fig.12. Flowchart of the software algorithm.

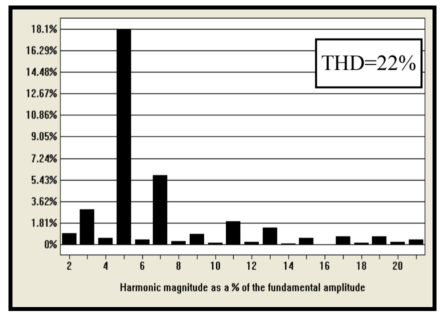
A unity sine wave is stored in a lookup table (LUT) in the microcontroller memory. The pointer of the LUT starts with zero every zero-crossings and then incremented every sampling period. These enable the formation of a phase-locked loop (PLL) for the current controller, which, thus, tracks the grid frequency.

Figure (13) shows the waveform of the ac line current with the phase voltage and its harmonic spectrum in case of three-phase classical diode rectifier. As shown in the figure the source current has a low quality waveform.



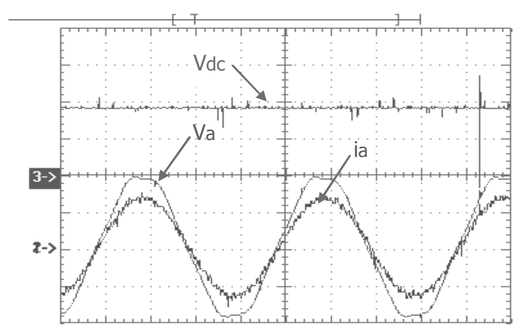
Ia [4A/div.], Va [50V/div.], 5ms/div.

(a)



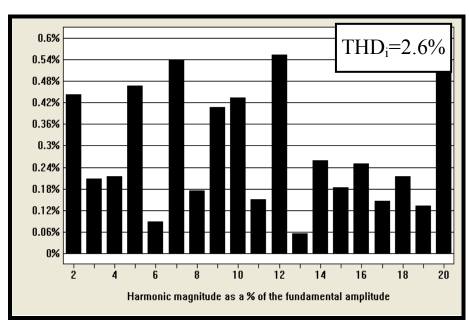
(b)

Fig.13. Steady state performance of classical diode rectifier. a) Phase voltage and line current waveforms, b) Harmonic spectrum of the line current.



Ia [4A/div.], Va [50V/div.], Vdc [100V/div.], 5ms/div.

(a)

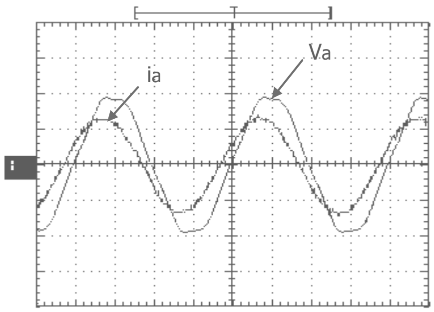


(b)

Fig.14. Steady state performance of PWM rectifier, a) Phase voltage and line current waveforms, b) Harmonic spectrum of the line current.

Figure (14.a) shows the steady state performance of the PWM rectifier according to unity power factor operation. The line current is sinusoidal with a low THD value of 2.6%, as shown in Fig.14.b, and the dc voltage is regulated at its reference value of 180V.

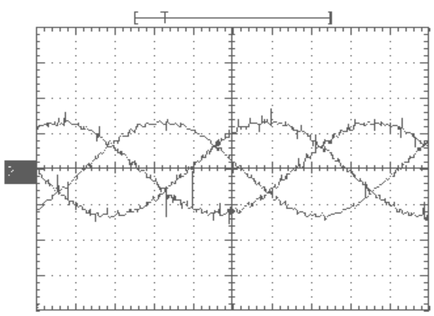
Figure (15) shows the leading power factor operation at angle of 30^o.



Ia [4A/div.], Va [50V/div.], 5ms/div.

Fig.15. Performance according to leading power factor operation.

Finally the three phase line currents at unity power factor operation are shown in fig.(16).



Ia [4A/div.], 5ms/div.

Fig.16. Three phase line currents.

V. CONCLUSION

In this paper a high performance three phase PWM rectifier with minimum number of sensors has been implemented using IGBT transistors as a power switches. The control algorithm of experimental prototype is implemented using a single chip Intel microcontroller 80C196KC. The experimental results prove that the converter draws a near sinusoidal current waveform with low THD values. Moreover, the converter can operate at any desired power factor. The dc load voltage is regulated against load disturbance and ac supply variation. The maximum obtainable sampling frequency is 4.5KHz, which resulted in an average switching frequency of about 2.6KHz.

VI. REFERENCES

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