PERFORMANCE EVALUATION OF THREE PHASE SCALAR CONTROLLED PWM RECTIFIER USING DIFFERENT CARRIER AND MODULATING SIGNAL

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Abstract

Power quality problems caused by significant increase of non-linear loads initiated intensive research in high power factor converters. Most of the modern power electronic systems like variable speed drives, DC power supplies and battery charging systems uses uncontrolled diode bridge rectifier. The uncontrolled rectifier system injects lot of harmonics in to the AC supply system there by reducing the power factor to less than unity. Single stage PWM rectifier is the novel solution to eliminate the harmonics and to improve the input power factor. In this paper, a scalar controlled PWM rectifier is modeled and the system is compared with the conventional bridge rectifier with and without filter.The major advantages of using this technique are less intensive computational control and sensor less input voltage operation. The PWM rectifier system is investigated using the different carrier and modulating signal. The scalar control technique is used to control the boost rectifier output voltage and input power factor. The performance of the rectifier with different carrier and modulating techniques were compared with respect to the Total Harmonic Distortion (THD) in source current. Simulation results demonstrate the effectiveness of the modified modulating signal and triangular carrier signal for effectively reducing the source current THD.

Keywords: Scalar control, PWM rectifier, Power quality, Power system harmonics, Pulse width modulation converters.

Nomenclatures	
C	Output filter capacitance, F
dt	Duty ratio of the power switch
$i_R{}^*$, $i_Y{}^*$, $i_B{}^*$	Three-phase reference current signal
i_s	Source current, A
i_{sR}, i_{sY}, i_{sB}	Three-phase input current, A
L_B, L_R, L_Y,	Three-phase line inductances, H
R_e	Emulated resistance
R_L	Load resistance, Ω
V_B, V_R, V_Y	Three-phase phase voltages, V
V_C	Capacitor voltage, V
V_{Cref}	Reference DC link voltage V
V_m	Controller output voltage signal
V_{ref}	Reference voltage signal
v_s	Source voltage, V

1. Introduction

Power quality has emerged as a major area of electrical power engineering. The predominant reason for this emergence is the wide spread use of sophisticated end-use equipment. Until very recently, AC-DC rectification was done using peak-charging circuits and thyristor based phase-controlled rectifiers. These systems operate at low power factor and inject significant amount of lower order harmonics into the power system. The adverse effects of low power factor operation and harmonics on the utility are well understood. The amount of current and voltage harmonics injected by the consumers in to the systems are well studied and the standards are given in IEEE 519.With advances in device technology, MOSFETs and IGBTs started replacing GTOs and thyristors as preferred power devices at low and medium power levels. These developments led to the growth of active Power Factor Correction (PFC) techniques using IGBTs and MOSFETs. The major advantages of active power factor correction technique are low THD input current and close to unity power factor operation. The proposed method offers the advantages of control simplicity and sensor less input voltage operation.

Three-phase boost rectifiers are widely used in industry as power factor correction converters due to their high efficiency and low EMI emissions. Various aspects of these converters have been studied in many papers. However, there is no comprehensive study on the various carrier and PWM techniques of the boost PWM converter. In this paper, a concise description of activities regarding the power quality problems and active correction techniques to be implemented for PWM rectifiers are presented. Figure 1 shows the power circuit of a typical three-phase boost rectifier. The two most widely used PWM schemes for inverters are the carrier-based sine-triangle PWM technique, and the space vector PWM technique. These modulation techniques have been extensively studied and compared for the performance parameters with two level inverters [1]. Several generic PWM techniques employed for inverter operation have been compared [2]. The inverter leg switching times are calculated directly from the sampled amplitudes of the reference three-phase voltages with considerable reduction in the computation time [3, 4]. In this paper the improved performance

of the rectifier in terms of source current THD, due to the modifications carried out on the reference wave has been presented.
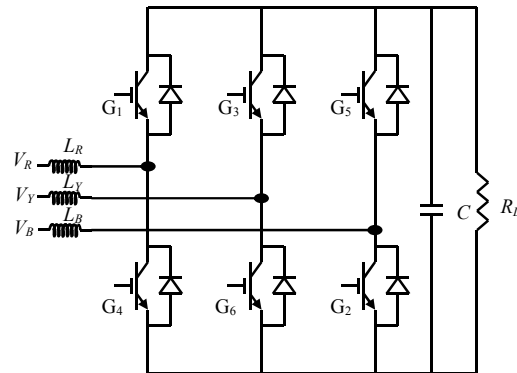
Fig. 1. Power circuit of three phase boost rectifier.

Most control techniques discussed in the literature [5-8] are based on d-q transformation of the control signals and digital implementation and cannot be directly applied to analog controlled system, which is preferred in many applications. This paper presents a design-oriented analysis for analog controlled three-phase boost rectifiers. The analog controller based boost rectifier can be implemented for end user applications.

Energy conversion systems such as wind energy conversion, switched mode power conversion and Variable Frequency drives typically employ two stage of power conversion namely AC-to-DC and DC-to-AC. The conventional first stage AC to DC converter in the system is an uncontrolled diode bridge rectifier. The uncontrolled diode bridge rectifier inject harmonics in to the supply system, consequently the input power factor is low. To eliminate this problem one more power conversion stage is required. The single stage PWM rectifier is the novel solution to eliminate the harmonics and to improve the input power factor. In the proposed system, there is only one stage of controlled conversion, which reduces the harmonics and improves the power factor on the supply side. So in this paper, to understand the effectiveness and importance of the PWM control based rectifier,the harmonics content in the input current waveform of the proposed scalar control based PWM rectifier is compared with the conventional three-phase bridge rectifier. Further, the PWM rectifier system performance is analyzed using the various carrier and modulating signal.

2. Scalar Control

The scalar control based three-phase power factor correction and harmonic mitigation is proposed in this paper. The main advantages of the scalar control technique are simple control algorithm and sensor less input voltage operation. Conventional three-phase H-bridge configuration is used to derive the necessary control equations. The DC link voltage is maintained at a desired reference voltage by using a feedback control loop. The DC link voltage is measured and

compared with a reference voltage V_{ref}. The error signal is used to generate the switching pulses to turn on and off the six switching devices of the rectifier. The power flow from and to the AC source can be controlled according to the DC link voltage requirements. The three reference current waveforms are generated using the three input source current waveform and the capacitor voltage [9, 10]. The current reference waveforms are compared with the high frequency carrier to generate the command pulses. The generated three command pulses are given to the top of the switch gates G_1, G_3 and G_5. The complimentary signal is given to the other switches G_2, G_4 and G_6. The control objectives of the scalar control based converter are:

- Sinusoidal input current at Unity Power Factor (UPF).
- Regulation of DC bus voltage and low harmonic content in input current.

The first control objective is achieved by implementing a current modulator, in the rectifier control circuit. The second control objective of maintaining constant DC bus voltage, V_c, is achieved by introducing an outer voltage loop controller. The voltage controller is responsible to maintain the power balance between the AC and DC side of the converter. The output of the voltage controller V_m, commands a particular current from the AC source to meet the load demand on the DC side. The current modulator does the function of maintaining sinusoidal input current in phase with the voltage. The output of the voltage controller, V_c, controls the depth of the modulation. The modulation technique is based on the concept of resistance emulation [11].

3. Mathematical Model

The single-phase equivalent circuit of the converter is shown in Fig. 2. On applying volt-second balance equation on the line inductance, L, the relation between the input voltage, $V_S(t)$ and the DC bus voltage, V_C is given in Eq. (1).
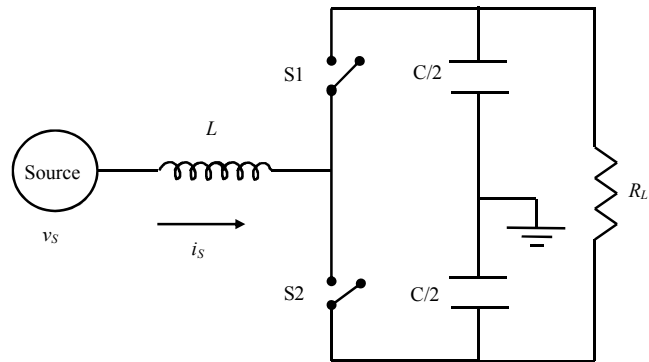

Fig. 2. Single phase equivalent circuit of PWM boost rectifier.

$$V_S(t) = \frac{V_C}{2}\left[1 - 2d(t)\right] \tag{1}$$

where, $d(t)$ is the duty ratio of the S2 device shown in Fig. 2. The control desires that the input current, $i_s(t)$ to be in phase with the input voltage, $V_s(t)$ and emulate

a resistance. The emulated resistance R_e, indicates the amount of power drawn from the source.

$$V_S(t) = i_S(t)R_e \tag{2}$$

From Eqs. (1) and (2), the duty ratio is obtained as,

$$d(t) = \frac{1}{2} - \frac{i_S(t)R_e}{V_c} \tag{3}$$

Equation (3) can be modified in terms of the control level variables. It can be rewritten as

$$d(t) = \frac{1}{2} - \frac{i_S(t)R_e}{V_m} \tag{4}$$

where, R_e is the current sense resistor and V_m is the output of the voltage controller. By varying the duty ratio of the switches as per the modulation law given in Eq. (4), sinusoidal input current at UPF can be achieved. In boost rectifier circuit, to reduce the harmonics in input current waveform, synchronous reference frame theory based vector control is being normally employed. In the proposed scalar control, the modulation law is implemented without transformation, resulting in minimum computation.

The current waveform follows the voltage waveform as per the principle of resistor emulation law and responds to frequency components present in the voltage. In general, the input voltage has negligible harmonics and hence the current contains negligible harmonics. The control block diagram of the scalar control based three-phase boost rectifier is shown in Fig. 3. The output of the voltage controller is given to the input of current modulator, the output from the current modulator is used as a current reference and the pulses are generated by comparing with high frequency carrier.
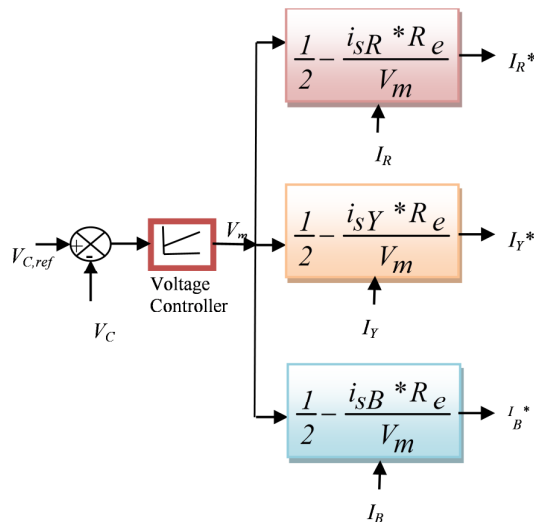
**Fig. 3. Block diagram of control structure
for scalar controlled PWM boost rectifier.**

4. Generation of Switching Signal

The signals associated with generalized switching pulse generator are shown in Fig. 4. To investigate the performance of the three phase boost rectifier using various carriers; here the carrier is considered as high frequency triangular and sawtooth. The effectiveness of the different carrier and modulating signal is tested in the boost PWM rectifier. Further, to improve the performance of the converter the current reference is modified using the Sampled Amplitude PWM (SAPWM) technique. The flowchart of SAPWM pulse generation is shown in Fig. 5.

This method takes the instantaneous average of the maximum and minimum of three reference currents and subtracts this value from each of the individual reference currents. The addition of this offset current continuously centers all of the three reference waveforms in the carrier band, which is similar to the space vector PWM with the zero voltage state divided evenly at the beginning and end of each half carrier interval.

$$i_{offset} = \frac{max\left(i_R^*, i_Y^*, i_B^*\right) + min\left(i_R^*, i_Y^*, i_B^*\right)}{2} \tag{5}$$

$$i_{R\,ref} = i_R^* - i_{offset} \tag{6}$$

$$i_{Y\,ref} = i_Y^* - i_{offset} \tag{7}$$

$$i_{B\,ref} = i_B^* - i_{offset} \tag{8}$$

The offset reference current is calculated from Eq. (5) and is subtracted from each of the reference signals, with respect to their previous values. The reference waveforms obtained by using sampled amplitude PWM is shown in Fig. 6.
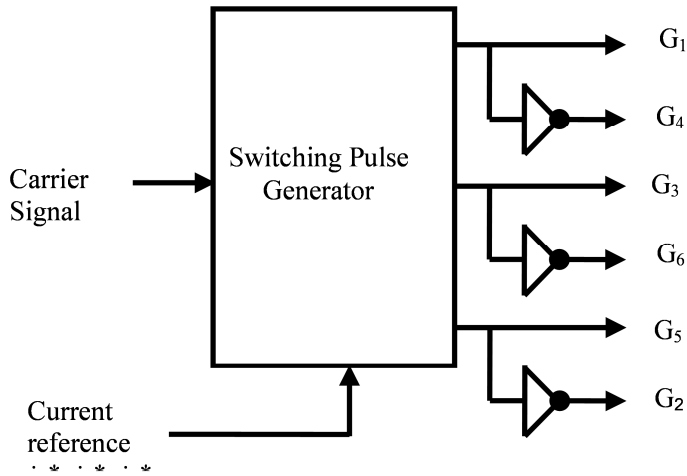
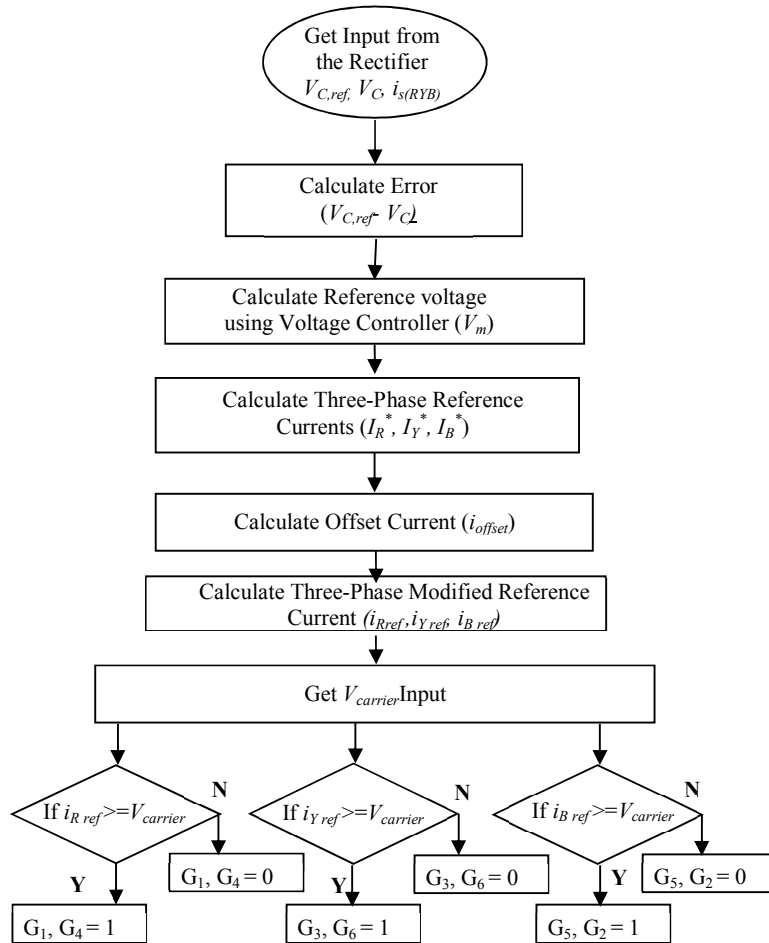**Fig. 4. Block diagram of generalized PWM pulse generator.**

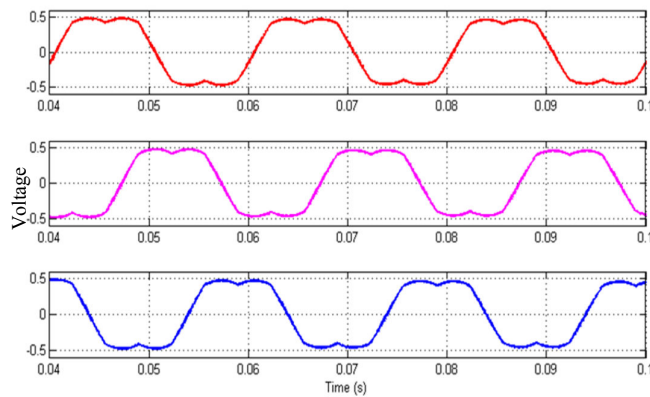**Fig. 5. Flowchart for generation of the SAPWM pulses.**

Fig. 6. Three-phase modified reference current waveforms.

5. Simulation Results and Discussions

In order to verify the performance of the single stage three-phase boost PWM rectifier with scalar control technique, the test system is simulated using MATLAB/Simulink.

Simulation studies are carried out using the system parameters given in Table 1. The implementation of scalar control technique for boost PWM rectifier using MATLAB/ Simulink schematic is shown in Fig. 7. Using the scalar control technique, reference current waveforms are generated and compared with carrier to generate PWM pulses for the IGBTs in the PWM rectifier circuit. The subsystem for reference wave generation for R phase is shown in Fig. 8. The reference wave generation is done using the scalar control technique using Eq. (4). The resistance emulation based scalar control technique requires only the output capacitor voltage V_c and the three input currents I_R, I_Y and I_B as feedback signals.

The PI controller maintains the output voltage at a desired value and the inner current loop is used to maintain the power factor and low harmonic content in the input current. In this scalar control technique, current loop is present implicitly in the control law. The reference signal is compared with the high frequency carrier to generate the pulses for the six switches. The reference signal can be either used directly or modified using the SAPWM algorithm.

Firstly, to understand the effect of harmonic pollution due to rectifier circuits, the diode based three-phase rectifier is simulated with and without output filter and the corresponding source current waveforms are plotted, as shown in Fig. 9. Figure 9(a) shows the three non-linear source currents and output voltage waveforms. Figure 9(b) shows that the R phase current THD spectrum contains significant amount of lower order harmonics.

Table 1. System parameters.

Parameters	Value
Input Voltage (line-to-neutral)	230 V (rms)
System Frequency	50 Hz
DC link Capacitor	1650 μF
Boost Inductor	15 mH
Load Resistor	60 Ω
Carrier Frequency	10 kHz
$V_{DC,ref}$	700 V

Figures 10(a) and (b) demonstrate the effect of filter capacitor in the conventional diode bridge rectifier; it shows the high non-linearity of three source currents. The effectiveness of the proposed three-phase boost PWM rectifier is compared with the conventional diode bridge rectifier with and without filter.
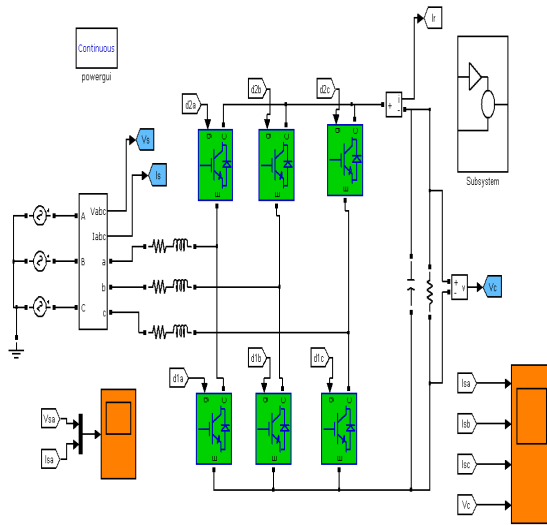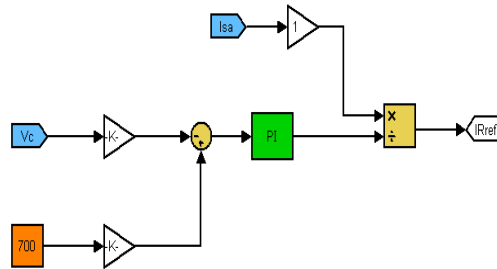
Fig. 7. Simulink model of three-phase boost PWM rectifier.

Fig. 8. Simulink schematic of referencewave generation.
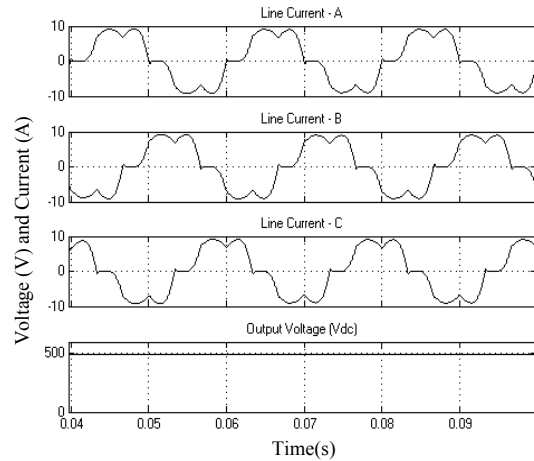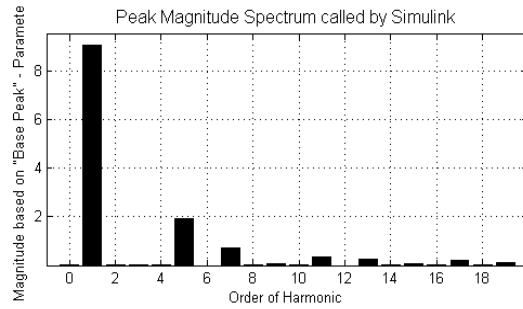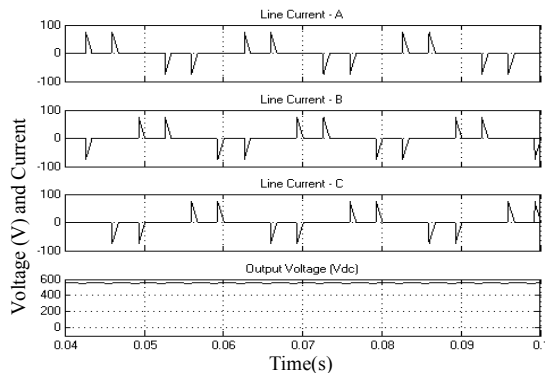

**Fig. 9(a). Source current and output voltage
waveform of diode bridge rectifier without output filter.**

**Fig. 9(b). THD spectrum of line current (I_R)
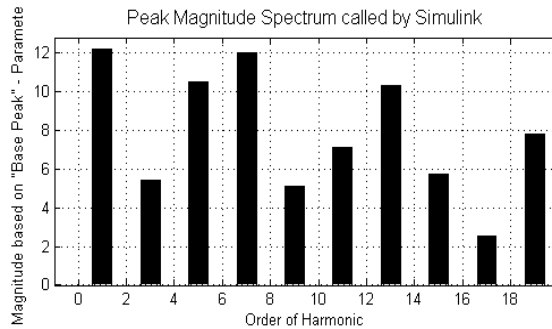of diode bridge rectifier without output filter.**

**Fig. 10(a). Source current and output voltage
waveform of diode bridge rectifier with output filter.**

**Fig. 10(b). THD Spectrum of line current (I_R)
of diode bridge rectifier with output filter.**

6. Performance Comparison

An attempt is also made here to examine the performance aspect of reducing the source current THD using various carriers. For this purpose, triangular and sawtooth carriers are considered. For the given load and source, firstly the source current THD with sawtooth carrier scheme is computed. Secondly, the THD in

source current with triangular carrier is computed for the same load. In each case, the source current waveform for R phase and the corresponding THD is plotted. Figure 11(a) shows the three sinusoidal source current waveforms and output voltage after correction with sawtooth carrier. This result shows the effective reduction of source current THD and the improved power factor. Figure 11(b) shows the R phase voltage and the R phase source current, the corresponding R phase source current THD is shown in Fig. 11(c).

Further, the system has been tested using triangular carrier, and the corresponding THD is shown in Table 2. The results shows that the source current THD is improved. Similarly, the second case is using SAPWM technique, the effect of source current THD is analyzed for the two carriers with the same load. In the earlier literature, there is no comprehensive study on the various carrier and PWM techniques of the boost PWM converter. Similarly, the same system with SAPWM for triangular carrier is tested and the results are tabulated in Table 2. However, the present results show that using triangular carrier with SAPWM has less THD compared to other methods. Simulation results demonstrate the effectiveness of the modified modulating signal and triangular carrier on effectively reducing the source current THD. The comparative results of the two cases are tabulated in Table 2.

Unity power factor rectifier using scalar control technique was presented in [11], the source current THD was given in this paper is 12%. A passive interconnected star/delta transformer based in put power factor correction was given in [12], but the total harmonic content was around 15%. The two stage AC-DC and DC-DC converter based high power factor boost rectifier for power quality solution was presented in [13, 14], the source current THD value was given in this paper is 5.9%, but the proposed system has only one stage conversion to improve the power quality. In this paper, computationally less intensive control algorithm has been presented and it is suitable for low power cost effective solution for the PWM rectifiers. There is no comprehensive analysis was done for the various carrier and modulating signal based analysis for scalar controlled PWM boost rectifier. In the proposed scalar controlled rectifier with modified modulating signal using triangular carrier, the source current THD is less than 1%.

Table 2. THD performance comparison.

Scheme	Current (I_R) THD in %	Current(I_Y) THD in %	Current(I_B) THD in %
Boost PWM Rectifier with Sawtooth Carrier	1.316	1.346	1.367
Boost PWM Rectifier with Triangle Carrier	0.9481	0.9515	0.9481
Boost SAPWM Rectifier with Sawtooth Carrier	1.579	1.813	1.723
Boost SAPWM Rectifier with Triangle Carrier	0.8557	0.8642	0.8524
Diode Bridge Rectifier without Output Filter	22.87	22.87	22.87
Diode Bridge Rectifier with Output Filter	208.9	208.9	208.9
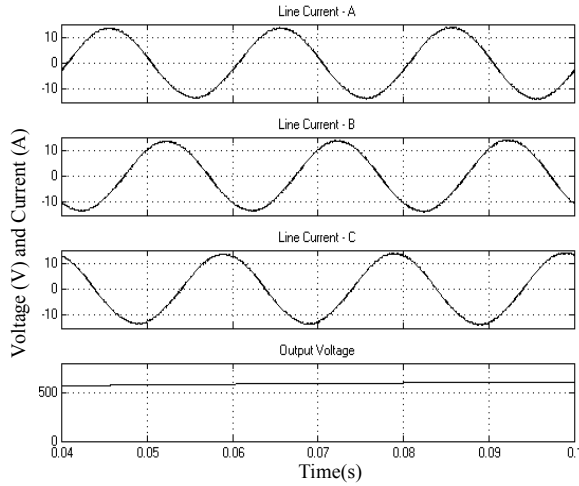
**Fig. 11(a). Source current and output voltage
waveform of diode bridge rectifier with output filter.**
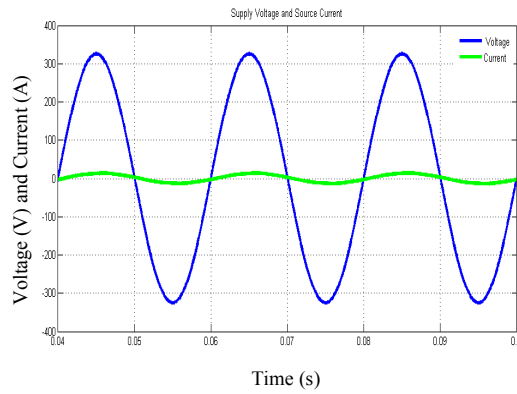
**Fig. 11(b). Source voltage (V_R) and current (I_R)
waveform of boost PWM rectifier with sawtooth carrier.**
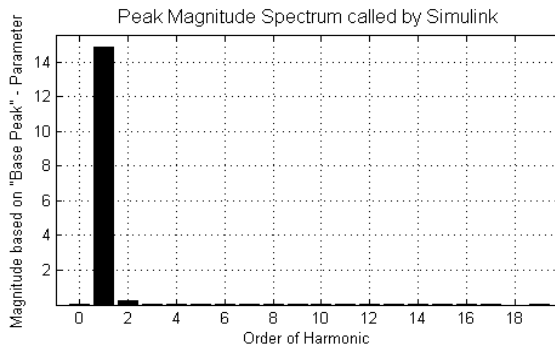
**Fig. 11(c). THD spectrum of source current (I_R)
of boost PWM rectifier with sawtooth carrier.**

7. Conclusion

The mathematical modeling and simulation of the scalar controlled boost PWM rectifier has been presented in this paper. To show the effectiveness of the PWM rectifier the source current of the conventional uncontrolled rectifier is compared with source current of Scalar controlled PWM rectifier. The test result shows that using the scalar controlled PWM rectifier THD value is drastically reduced to less than 2 %, which is well below the IEEE 519 standard. The proposed boost PWM rectifier model is investigated with different carrier and PWM modulation techniques. Using the triangular carrier waveform has shown reduction in input current THD than using the sawtooth carrier. Further, the test system is compared with the conventional modulating signal generation with the SAPWM based modulating signal. The proposed scalar controlled rectifier with modified modulated current reference controller is tested with two different carriers. The SAPWM based boost PWM rectifier using triangular carrier, the source current THD is effectively reduced below 0.8%. The given simulation results are an excellent agreement to establish the viability of the proposed scheme. The proposed method offers the advantages of control simplicity and input voltage sensor less operation and hence it is easy to implement in the analog-based controllers. The proposed single stage scalar controlled boost PWM rectifier is suitable for the micro-wind energy conversion system and front-end drive system.

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