High Power Factor AC/DC Converter

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ABSTRACT

A single phase boost rectifier circuit is studied with and without feedforward techniques. The circuit is implemented and tested experimentally. It can be operated at high power factor (greater than 0.99), and at line current total harmonic distortion (THD) (less than 0.06), by selecting suitable control parameters at the desired output power.

Key words: AC-DC converter, Power factor improvement

List of Symbols

\[ \begin{align*}
C_0 & : \text{Snubber circuit capacitor (F).} \\
I_a & : \text{Load current (A).} \\
I_l & : \text{Line current (A).} \\
L & : \text{Rectifier inductance (H).} \\
L_s & : \text{Snubber circuit inductance (H).} \\
M & : \text{Modulation index.} \\
P_F & : \text{Power factor.} \\
R & : \text{Inductor resistance (Ohm).} \\
R_L & : \text{Load resistance (Ohm).} \\
\text{THD} & : \text{Total harmonic distortion.} \\
V_o & : \text{Output voltage (V).} \\
V_{ac} & : \text{AC input voltage (V).}
\end{align*} \]
1. Introduction

It is well known that conventional ac-dc power supplies are characterized by high input current total harmonic distortion (THD) and low power factor (PF) [1]. Several techniques have been proposed and demonstrated to overcome these drawbacks, and they have essentially been based on pulse width modulation (PWM) scheme [2]. For example, the input current THD of a boost rectifier has been reduced by intentionally introducing a lagging power factor current command [3]. The goal has been achieved in a single phase rectifier by using current mode control technique [4-6]. Different control circuits employing either compensator, current control, and multiplier, or nonlinear carrier control scheme have been proposed to overcome the problem [7-9].

In this paper, a single phase boost rectifier circuit supported by a simple feedforward control circuit is proposed to achieve high power factor and low THD. The rectifier circuit can be used with different ranges of output power by changing the control circuit parameters. The proposed circuit is implemented and tested experimentally. The experimental results are found in good agreement with theoretical predictions, and with the results obtained in [3, 10], and [11].

2. The Proposed Circuit

2.1. Circuit Operation

The proposed circuit is shown in Fig. (1). It consists of four diodes (D1 to D4), two switches MOSFET transistors (S1 and S5), two inductors (L), and a smoothing capacitor (C1). The switching operation of the main diodes and switches can be described by two modes of operation for each half cycle as follows:

During positive half cycle of the input supply voltage, the transistor S1 is switching on and off repeatedly according to the switching frequency signal. So the operation of the rectifier circuit during this cycle is consists of two modes.

Mode 1

In this mode of operation, the switching transistor S1 is on, and the
supply current flows through $S_1$, $D_s$, and $L$, while the capacitor ($C_a$) discharging through the load as shown in Fig.(2). The following two equations describe the operation of this mode.

$$V_{ac} = L \frac{di}{dt} + r i$$  \hspace{1cm} (1)

$$i_o = C_o \frac{dV_{ac}}{dt}$$  \hspace{1cm} (2)

Mode 2

When the transistor $S_1$ is switched off, the operation is transferred from mode 1 to mode 2. In this mode, the input line current flows through the inductor $L$, the two diodes $D_1$ and $D_s$, then the load and the smoothing capacitor, $C_a$ as shown in Fig.(3). The operation of this mode can be described by the following two equations:

$$V_{ac} = L \frac{di}{dt} + r i + V_{ac}$$  \hspace{1cm} (3)

$$i_s = i_o + C_o \frac{dV_{ac}}{dt}$$  \hspace{1cm} (4)

At the negative half cycle of the supply, mode 1 and mode 2 are repeated with transistor $S_2$ and the two diodes $D_1$ and $D_s$.

2.2. The Control Circuit

Different PWM techniques have been used to improve the power factor and THD of a rectifier circuit [2,12]. These techniques are used in the case of open loop control, but the improvement is not significant. For that reason, a feedforward control technique has been used to get high input power factor and low THD [5,7 and 10] and this technique is adopted here.

A simple control circuit is suggested and implemented, Fig.(4) show the complete diagram of the power circuit as well as the suggested control circuit. The control circuit consists of integrator, adder, and subtractor circuits, and has the benefit that it is not requiring any multiplier or divider circuits. The output voltage of the rectifier is sensed with gain of $K_o$, which is compared with a reference voltage, $V_{ref}$. The result of comparison is injected through an appropriate voltage controller. The current $I_s$ is sensed with gain $K_i$, and subtracted from the voltage controller output. The rectifier input AC voltage is rectified by two diodes, sensed with gain $K_o$, and then added to the subtractor output. The output of the adder is fed into a PWM circuit with a high frequency triangular waveform to produce the switching transistors.
3. Simulation Results

The open loop operation of the proposed boost rectifier is analyzed using sine pulse width modulation (SPWM) technique. The feedforward operation is analyzed by simulating the function of the control circuit shown in Fig. 6. In both cases, equations 1-4 are solved numerically using fourth-order Runge-Kutta method [13].

The operation parameters of the rectifier circuit are:

- \( V_{cc} = 30 \text{ V (rms)} \)
- \( L = 1 \text{ mH} \)
- \( r = 0.1 \text{ Ohm} \)
- \( C_0 = 4700 \text{ uF} \)
- \( S_1 \) and \( S_2 : IRF840 \)
- \( D_1, D_4, D_7 : BYX71 \)
- \( D_2, D_6 : 251-536 \)

The snubber circuit parameters are: \( L_s = 7 \text{ uH} \), and \( C_s = 47 \text{ nF} \). The feedforward control circuit has three parameters, \( K_a, K_s, \) and \( K_v, K_o \) is kept constant (\( K_o = 0.1 \)), while \( K_a \) and \( K_v \) are varied according to the output load power.

3.1. Open Loop Operation

Fig. (5) shows the simulated output voltage of the rectifier as a function of the modulation index (M) of the SPWM and for different values of load resistance at open loop operation. The variations of the input power factor and the line current THD against modulation index are depicted in Figs. (6) and (7) respectively. Note that, the variations of power factor and THD with modulation index are very small when the modulation index is less than one and they are have poor values when modulation index is greater than one. Fig. (8) presents the power factor and THD of the circuit against output power when the output voltage is kept constant (\( V_o = 60 \text{ V} \)). Fig. (8) reveals that both power factor and THD are almost constant during the large variation of the output power, and they also have a reasonable values.

3.2. Feedforward Operation

The feedforward technique is simulated using different values of gain parameters, \( K_a \) and \( K_s \). The power factor and THD are
The proposed single phase boost rectifier circuit is implemented and tested at both open loop mode and with feedback technique. In Figs.(14-17), we compare the experimental data with theoretical results to assess the performance of the practical circuit. Fig.(14) illustrates the variation of output voltage with modulation index at open loop operation with SPWM technique and assuming R_L=100 Ohm. Fig.(15) shows the dependence of the power factor on the output power when the output voltage is kept constant equal to 60V and at open loop operation. Data related to the variation of power factor and rectifier efficiency under feedback operation are plotted in Figs.(16) and (17), respectively. These results indicate clearly that the experiment results are in agreement with theoretical data. Note that the practical circuit is able to deliver an output power up to 135W with power factor greater than 0.94 and efficiency greater than 86%. The theoretical calculated efficiency is greater than the experimental results, because

4. Experimental Results


the switches and diodes are assumed to be ideal devices in the theoretical calculation. The experimental oscillograph of the line current and voltage are shown in Fig. (18), while the output waveform voltage is shown in Fig. (19). Fig. (20) illustrates that the transistor voltage of the rectifier does not exceed the output voltage value.

5. Conclusion

In this paper a single phase boost rectifier circuit is proposed and implemented with and without feedforward technique. A simple control circuit is used to improve the power factor and THD of the input supply. The operation of the circuit is analyzed and then simulated using Runge-Kutta fourth order method. The operating power of the rectifier can be increased by selecting suitable control parameters. The analytical and experimental results show a good agreement.

References


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Fig. (4) The complete studyed circuit with feedforward control circuit.

Fig. (5) Output voltage against modulation index for different load resistors (R L = 100, 40, 20, 10, and 5 (Ohm)) from top to down.

(37)
Fig. (1) The studied system.

Fig. (2) Mode 1 of operation.

Fig. (3) Mode 2 of operation.
Figure 6: Power factor against modulation index for different load resistances (45, 15, 40, and 100Ω) from top to bottom.

Figure 7: Total harmonic distortion against modulation index for different load resistances (45, 15, 40, and 100Ω) from top to bottom.

Figure 8: Power factor and total harmonic distortion factor against output power at open loop and for k = 250.

Figure 9: Power factor against output power for k = 250, and for k = 0 to 2.5 with 0.2 steps right to left.

(39)
Fig (a): TD factor against output power for VA=0.2 and for cell 1 to 4, step 0.2 (from right to left).

Fig (b): Current gain (k1) against output power for k1=0.2, k2=0.1, k3=0.01, and k4=0.001.

Fig (c): Line current and voltage at the converter for k1=0.2, k2=0.1, k3=0.01, and output = 50V.

Fig (d): Output voltage of the converter for k1=0.2, k2=0.1, k3=0.01, and input = 20V.
Fig. 2a) Experimental line voltage and current of the diode for $k=0.2, n=0.3$ and $N=200$ [rpm].

Fig. 2b) Experimental output voltage of the motor for $k=0.2$, $N=20$, and $R=15$ [ohm].

Fig. 2c) Experimental transistor voltage.