HARMONIC REDUCTION IN THREE-PHASE SINGLE-SWITCH POWER FACTOR CORRECTION CIRCUIT

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ABSTRACT: Diode rectifiers are commonly used at the front end of a power converter as an interface with the electric utility. The rectifiers are nonlinear and generate harmonic currents into the ac power source. A harmonic injection technique, which reduces the line frequency harmonics of single switch three-phase boost rectifier, was developed in this study. In this method, a periodic voltage was injected into the control circuit to vary the duty cycle of the rectifier switch within a line cycle so that the fifth-order harmonic of the input current is reduced to meet the total harmonic distortion (THD) requirement. As the injected voltage signal that is proportional to the inverted ac component of the rectified three-phase line-to-line input voltage is employed; the injected duty cycle variations are inherently synchronized with the three-phase line-to-neutral input voltage.

KEYWORDS: Discontinuous conduction mode, harmonic injection, boost converter, power factor correction
INTRODUCTION

In most power electronics applications, diode rectifiers are used as an interface with the electric utility. Rectifiers are nonlinear in nature and consequently, generate harmonic currents into the ac power source. The nonlinear operation of the diode rectifiers causes highly distorted input current. The non-sinusoidal shape of the input current drawn by the rectifiers causes a number of problems in sensitive electronic equipment and power distribution network. The distorted input current flowing through the system produces distorted voltages at the input of the common coupling. The increased harmonic currents result in increasing volt-ampere ratings of utility equipment such as generators, transmission lines, and transformers. In addition to the inefficient use of electric energy, the discontinuous conduction of the bridge rectifier results in high total harmonic distortion (THD) in the input lines. Figure 1 shows the three phase rectifier circuit used in this study as a harmonics generator.

One approach is to use three single-phase power factor corrected rectifiers in cascade (Kocher and Steigerwald, 1983). The main advantage of this configuration is that a well-established single-phase power factor correction (PFC) technique can be used for three-phase applications. However, this approach suffers from several disadvantages. Cascading three single-phase PFC circuits requires the use of additional diodes, increases component count, and complicates the input synchronization logic. Therefore, it is clear that lower cost three-phase PFC circuits are required for high power processing.

![Figure 1. Circuit implementation of a harmonic generator](image-url)
Amongst the three-phase ac-to-dc rectifiers, boost type topologies are frequently used because of their ability to withstand continuous input currents and generate high output voltages. Basically, two topologies are most popular: a six-switch full-bridge boost rectifier and a single switch boost rectifier. The first one uses six switches to achieve sinusoidal input current control and share the output power, resulting in features which include continuous input current, excellent power factor, and low switch current rating (Jiang et al., 1994; Chattopadhyay and Ramanarayanan, 2001). However, this circuit is very complicated in power stage and control, making it too expensive for medium power level (5kw-10kw) applications. The second type uses six diodes and one switch to control input currents and output power as depicted in Figure 2 (Sedigly and Dawson, 1995). Since these rectifiers have a single switch and perform input current wave-shaping naturally without the need for complex control circuitry, they are very suitable for low cost power three-phase ac-dc applications. In addition, they can achieve high efficiencies because the reverse-recovery-related losses of the boost diode are eliminated. However, when a discontinuous conduction mode (DCM) PWM boost rectifier is implemented with the conventional constant frequency low bandwidth output voltage feedback control, the rectifier input current exhibits a relatively large fifth-order harmonic. As previous studies have shown, the distortion level depends on the ratio of the output voltage to the input line voltage.

Different modulation techniques have been proposed to reduce the harmonic distortion of the input currents without increasing the output voltage beyond practical levels. The first approach involved operating the single switch boost rectifier in the critical mode (Simonetti et al., 1993; Kolar and Zach, 1993). To do this, the power switch must be turned on at the instant at which the boost diode current reaches zero. As a result, the switching frequency becomes variable and the effective duty cycle modulation over the line cycle results in reduced THD of the input currents. The drawback of operating the discontinuous conduction mode (DCM) boost rectifier in the critical mode is the wide variation of the switching frequency that depends upon both load and input voltage limits.

![Diagram of a three-phase bridge rectifier with an EMI filter, PWM compensator, and modulation index](Figure 2. Implementation of an Injection (Jang and Jovanovic, 2000))
Another approach for improving the THD of the input currents involves controlling the average current in the boost diode to a constant level. In order to keep the average current constant through the boost diode, the duty cycle must be modulated over the line cycle, resulting in an improved input current waveform. The drawback of this method is the extra current sensor required to control the average boost diode current.

The simple technique of harmonic injection has been used by Sun (1996) and Jang and Jovanovic (2000), to reduce the harmonic distortion of input current. The principles for achieving optimal harmonic injection have been described by Sun (1996). The injected signal modifies the duty cycle of the rectifier switch so that the fifth-order harmonic of the input current and the overall THD are reduced to meet the IEC1000-3 requirement. If the phase of the injected signal is not well synchronized with the fifth-order harmonic of the input current, the expected reduction of the fifth-order harmonic and the improvement of the THD's will not be achieved.

A low cost harmonic injection method for a single switch three-phase DCM boost rectifier and its implementation is presented. Therefore, to reduce the fifth-order harmonic and improve THD of the rectifier input currents, a periodic voltage signal, that utilizes the voltage ripple of the rectifier output voltage is injected to modify the duty cycle of the rectifier within line cycle. The injected voltage signal is proportional to the ac component of the rectified three-phase line-to-line input voltages. As a result, the injected signal is naturally synchronised with the three-phase line-to-neutral input voltages. Moreover, the closed loop feedback control of the DCM boost rectifier is not affected by the proposed open loop harmonic injection method.

CONVERTER OPERATION

The principle of converter circuit shown in Figure 3 can be easily understood by firstly assuming that the rectifier operates in DCM, and the IGBT switch is operated at constant switching frequency ($f_s$), with a fixed duty ratio. Since the boost rectifier is operated in DCM with constant frequency and constant duty cycle, all three-phase currents $i_a$, $i_b$, $i_c$ become zero immediately at the end of a switching period. Four operating stages can be identified in a switching period as shown in Figure 3b. In the first operating stage, the power switch is turned on to linearly charge the input inductors according to the phase voltage that is applied. In the second operating stage, the power switch is turned off to reset the inductors, the inductor with the lowest peak current resets first. In the third operating stage, the two remaining inductor currents are reset to zero at the same rate. Once the reset interval has finished, the output load is supplied by the energy stored in the output capacitor until the next switching period restarts.

The average line current during a switching period of a constant frequency, constant duty cycle DCM boost rectifier has been derived (Simonetti et al, 1993). The derivations assume that switching frequency ($f_s$) is much higher than line frequency $f_L$; the well-balanced and
undistorted three-phase input voltages could be constant within each switching cycle. By averaging the input current in a switching period, its higher-order harmonics are filtered out. The shape of the resulting input current $i_a$ for some $M$ values ($M$ is the ratio output voltage / input peak voltage) is shown in Figure 4. It can be observed that the current shape is completely determined by the voltage conversion ratio $M$: the higher the value of $M$, the lower the distortions.

\[ d(t) = D \left[ 1 - m \cos 6wt \right] \]  

(1)

where $d(t)$ is the modulated duty cycle, $D$ is the duty cycle in the absence of the modulation, and $m$ is the modulation index.
RESULTS

Figure 5 shows the block diagram of the control circuit for the converter. A three-phase bridge rectifier followed by band-pass filter was used to generate the sixth-order, and a multiplier, harmonic whose amplitude was modified by the modulating index. The modulated signal was applied as the control input to a pulse width modulator. In this control scheme, the PWM signal is obtained by monitoring the rectified input voltage and the dc output voltage of the control circuit. There was no necessity to monitor the current as in the case of the continuous mode operation. Since the boost circuit works in discontinuous conduction mode (DCM), stability was not a problem.

The following parameters were used:

- Input: \(3 \times 110\text{V} / 50\text{Hz}\)
- Switching frequency: 45kHz
- Control bandwidth: 200Hz
- Output capacitor: 220 \(\mu\text{F}\)
- Output: 250V / 1.1 kW
- Modulation index \(m\): 4.6
- Input inductor: 50 \(\mu\text{H}\)

IGBT was used as the main switch in the experimental prototype. Figure 6 shows the pre-filtered line current of phase A, which contains high frequency components. It can be seen that the current always starts at zero during each switching period and its peak value takes the envelope of the phase voltage and in phase with it. Therefore, it is clear the boost converter operates well in DCM mode with the designed values of the boost inductors. Figures 7 and 8 show the waveforms of input current and phase voltage with and without injection respectively. Figures 9 and 10 show the harmonic spectrum of the converter input current before and after injection. From the spectrum it can be seen the fifth-order harmonic is the dominant order. By using the injection approach the fifth-order harmonic is reduced and the total harmonic distortion (THD) is improved, although the seventh-order increased due to some resonance of the additional circuit parameters with the original. Figures 11 and 12 show the three-phase currents and voltages together, before and after injection.

![Block diagram of control circuit](Image)

**Figure 5.** Block diagram of control circuit
Figure 6. Experimental results of input current passing through the inductor

Figure 7. Input current of phase A and its phase voltage before injection

Figure 8. Input current of phase A and its phase voltage after injection

Figure 9. Measured harmonics contents of input current before injection

Figure 10. Measured harmonics contents of input current after injection
CONCLUSION

A low cost harmonic injection method for single switch three-phase discontinuous conduction current mode boost rectifiers was developed. In this method, a periodic voltage, which is proportional to the inverted ac component of the rectified three-phase input voltages, is injected into the control circuit to vary the duty cycle of the rectifier switch within a line cycle. This is done so that the fifth-order harmonic is reduced and the total harmonics in the single switch rectifier improved. The injected duty cycle variations could be naturally synchronised with the three-phase line-to-neutral input voltages without using expensive phase-detecting and phase-looking circuits. The results obtained from the experimental prototype showed that to meet the THD<10% requirement, the rectifier voltage gain M can be reduced to 1.45 instead of 1.65 without injection.

REFERENCES


