

HARMONICS: GENERATION AND SUPPRESSION IN AC SYSTEM NETWORKS

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Abstract

Majority of loads such as induction motors, battery chargers, static converters, light fittings, arc furnaces, transformers, cables, transmission lines and so on draw both sinusoidal currents and currents which are multiples of the supply frequency, commonly called harmonics. These harmonics are out of phase with the supply voltage. The sinusoidal currents generate active power (kW), which is transformed into mechanical power and heat. The harmonics, on the other hand, give rise to reactive power (kVar) which enables electrical machines like transformers and motors to operate by magnetizing their cores. However, reactive power flow in electrical networks has adverse effects depending on their magnitude and the nature of the supply network. How these harmonics are generated by nonlinear loads and the means by which they can be kept low are the focus of this paper.

Keywords: non-linear loads, harmonics, reactive power, power factor

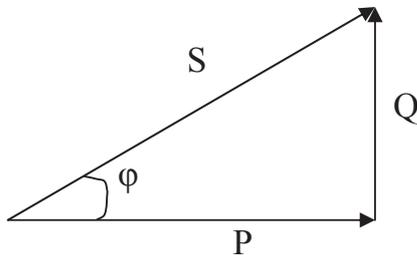


Figure 1: Power triangle for an inductive load.

1. Introduction

The total demand on the supply for a nonlinear load like induction motor is called apparent power; it is vector sum of both active and reactive components of power as shown in figure 1. The power factor is the ratio of active power to apparent power, and is given by $\cos \varphi$. When the current lags the voltage in phase rotation, the load is drawing reactive power from the source and power factor is said to be lagging. On the other hand when the current leads the voltage, the load is exporting reactive power to the source and the power factor is said to be leading.

$$P = \text{Real power} = V_{rms} \times I_{rms} \times \cos \varphi$$

$$Q = \text{Reactive power} = V_{rms} \times I_{rms} \times \sin \varphi$$

$$S = \text{Apparent power} = V_{rms} \times I_{rms}$$

$$\text{Power factor (PF)} = \cos \varphi$$

This power factor does not take into account the distortion caused by harmonics and so it is more accurately called displacement power factor (DPF). It is based on the fundamental quantities of voltage and current.

'True Power Factor' takes into consideration the effect that harmonic distortion may have on the voltage and current waveforms of a load. Figure 2 shows a solid-state converter, as nonlinear load, drawing harmonic currents from ac mains [1].

V_s = fundamental rms voltage, I_s = supply rms current and I_{s1} = fundamental rms current. φ is the angle (displacement angle) between the fundamental component of the input current, I_{s1} and voltage, V_s .

$$DPF = \frac{P}{V_s I_{s1}} \quad (1)$$

$$DPF = \frac{V_s I_{s1} \cos \varphi_1}{V_s I_{s1}} = \cos \varphi_1 \quad (2)$$

$$\text{Distortion factor, } DF = \frac{I_{s1}}{\sqrt{I_{s1}^2 + \sum_{n=3,5,7,\dots}^{\infty} I_{sn}^2}} \quad (3)$$

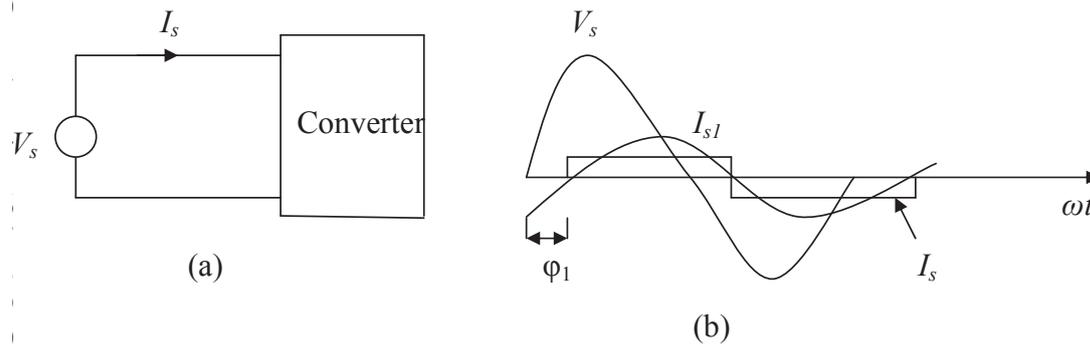


Figure 2: Line voltage and current of a converter (a) Circuit, (b) waveforms.

'True Power Factor' is defined as

$$PF = \frac{P_1}{V_s \sqrt{I_{s1}^2 + \sum_{n=3,5,7,\dots}^{\infty} I_{sn}^2}} \quad (4)$$

Combining equations (1), (2) and (3)

$$\frac{V_s I_{s1} \cos \varphi_1}{V_s \sqrt{I_{s1}^2 + \sum_{n=3,5,7,\dots}^{\infty} I_{sn}^2}} = \frac{I_{s1}}{\sqrt{I_{s1}^2 + \sum_{n=3,5,7,\dots}^{\infty} I_{sn}^2}} \cos \varphi_1$$

$$PF = \frac{I_{s1}}{I_s} \cos \varphi_1 \quad (5)$$

This power factor depends on the harmonics. Power factor can be high or low depending on the amount of harmonics injected into the system by nonlinear loads. Another important parameter used to measure the performance of a nonlinear load is the harmonic factor (HF) or total harmonic distortion (THD). It is a measure of the distortion of a waveform. It is given by the expression [2].

$$THD = \sqrt{\frac{I_s^2 - I_{s1}^2}{I_{s1}^2}} \quad (6)$$

2. Effects of Harmonics

The transport of reactive power causes low power factor, voltage sag, network losses in the form of I^2R , resulting in the reduction of available network capacity. Hence the size of generation and transmission equipment is greatly increased. In three-phase networks these harmonics cause unbalance and excessive neutral currents. Harmonics give rise to interference in nearby communication networks and disturbance to other consumers. In electric motor drives, they cause torque pulsations and cogging [3].

3. Reduction of Harmonics Injection into Utility Power Lines

3.1. Passive filter

Before the advent of modern power electronics, passive filters were extensively used to reduce the level of injected harmonics as shown in figure 3.

Conventionally, shunt passive L-C filters were used in static converters to reduce harmonics and improve power factor [4]. The filters provide low harmonic impedance to ground. Moreover, they provide part of the reactive power consumed by the converter. Suppression of current harmonics results in the reduction of the rms supply current I_s and consequently power factor improvement. Figure 4 is a single phase pulse-width modulation (PWM) voltage source inverter (VSI). Figure 5 is the output voltage waveform.

From Figure 5, the Fourier series of the output voltage, V_o is given as

$$V_o = \frac{V_s}{\pi} \left[\int_{\frac{\pi}{2} - \frac{\delta}{2}}^{\frac{\pi}{2} + \frac{\delta}{2}} \sin n\omega t d\omega t - \int_{\frac{3\pi}{2} - \frac{\delta}{2}}^{\frac{3\pi}{2} + \frac{\delta}{2}} \sin n\omega t d\omega t \right] \quad (7)$$

$$V_o = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\delta}{2} \sin \frac{n\pi}{2} \sin n\omega t \quad (8)$$

If $V_s = 295V$; $Z = (8 + j6)\Omega$ and $\delta = 2\pi/3$, the output voltage, V_o and load current, i_o are shown in figure 6.

V_o and i_o have total harmonic distortion (THD) of 31% and 7.5% respectively, Thus the output voltage of the inverter contains much harmonics. Filters can be used to smooth out the ac output voltage of the inverter. With filter inductance and capacitance added as shown in figure 7, the load voltage and filter inductor current assume the characteristics shown in figure 8. The output voltage, V_o now has THD of 4.2%, where $L = 9.55mH$ and $C = 266\mu F$.

However, in practical applications passive filters have some shortcomings. They are costly, bulky and often relatively inefficient. As a result, extensive research has developed active filters that are relatively

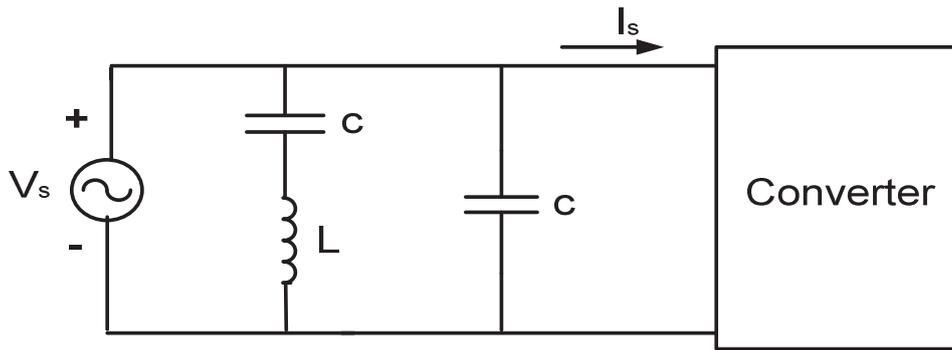


Figure 3: Passive filter.

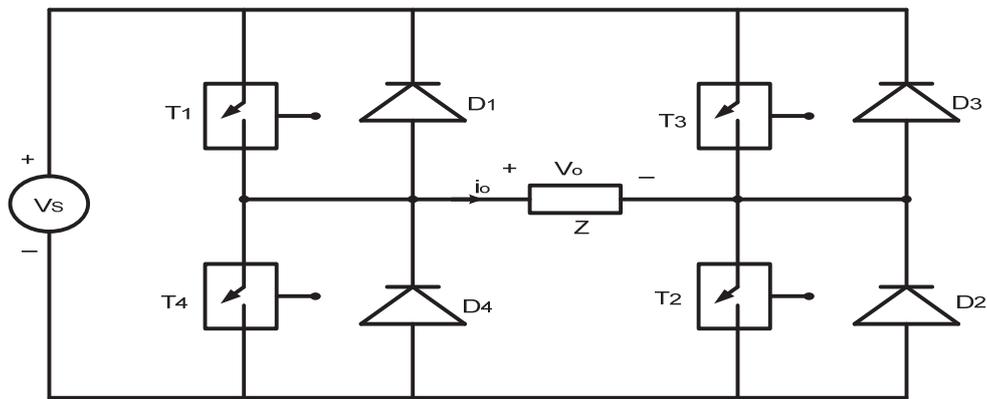


Figure 4: Single phase full bridge inverter configuration.

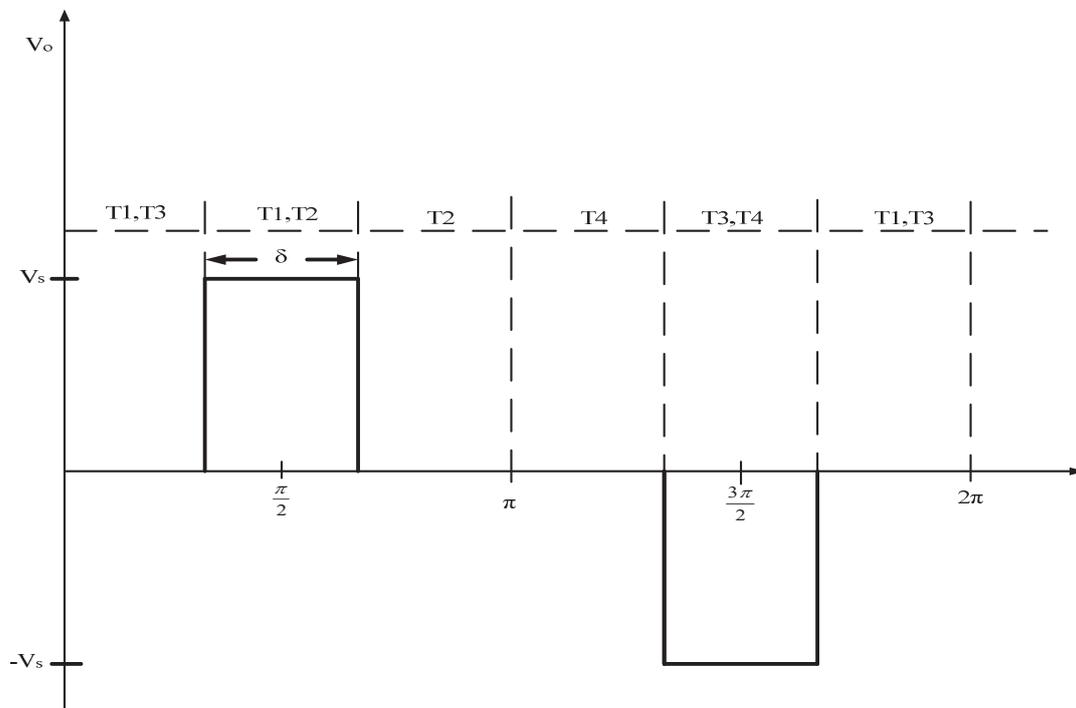


Figure 5: Output voltage waveform of the PWM voltage source inverter (VSI).

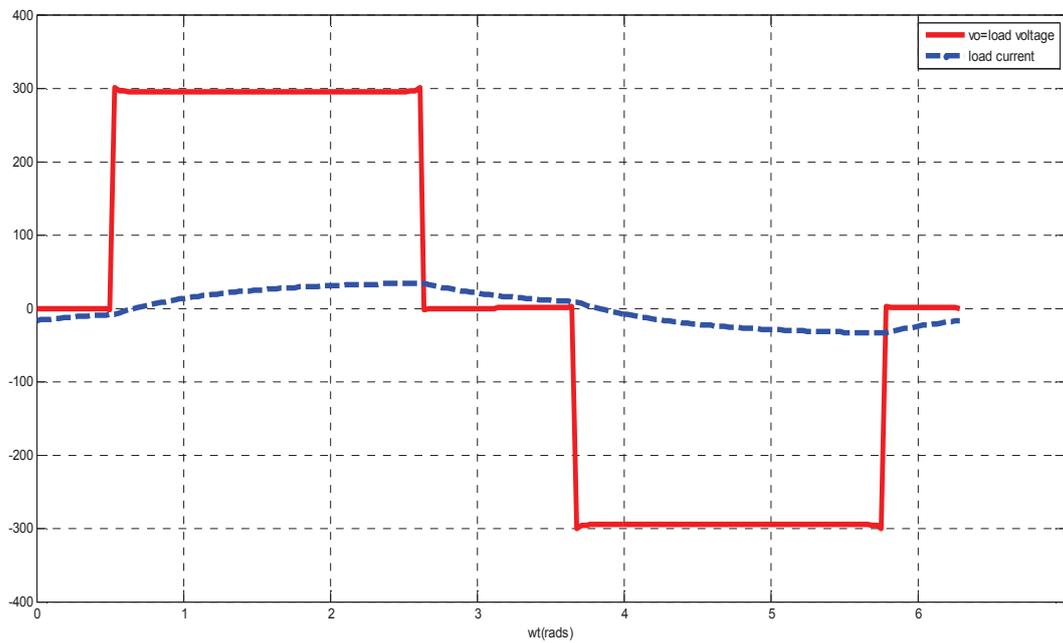


Figure 6: Output voltage V_o and load current i_o .

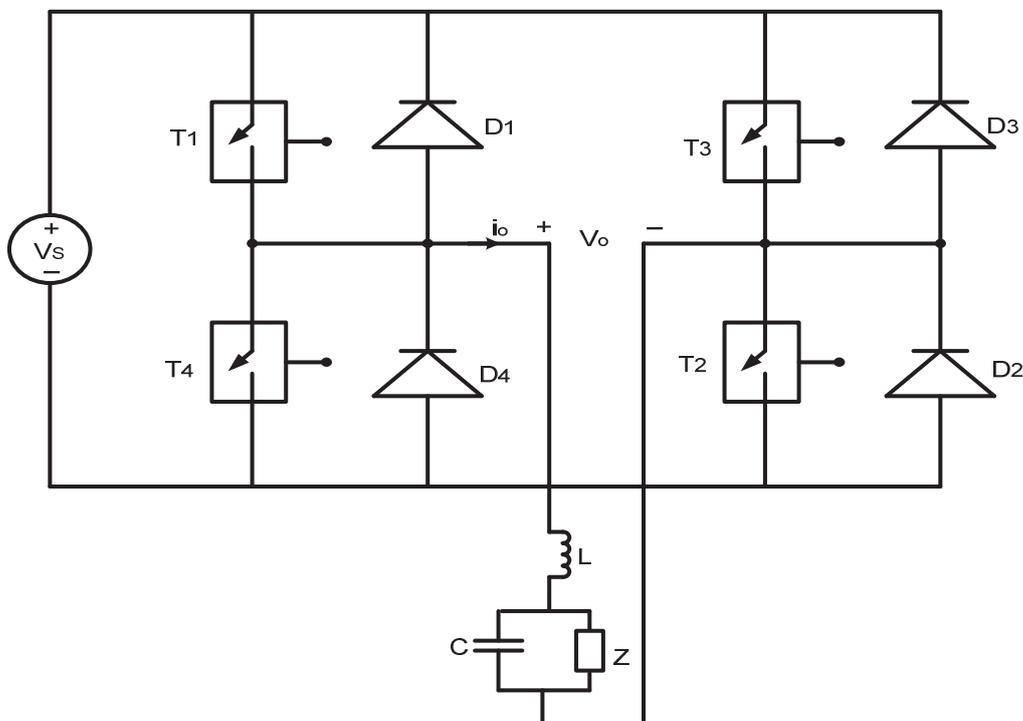


Figure 7: Single phase full bridge inverter with filter.

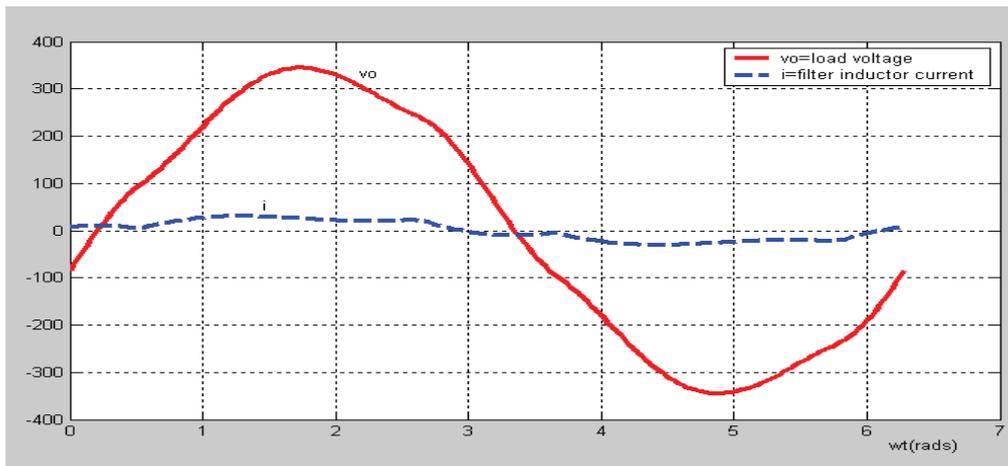


Figure 8: Output voltage V_o and filter current i_s .

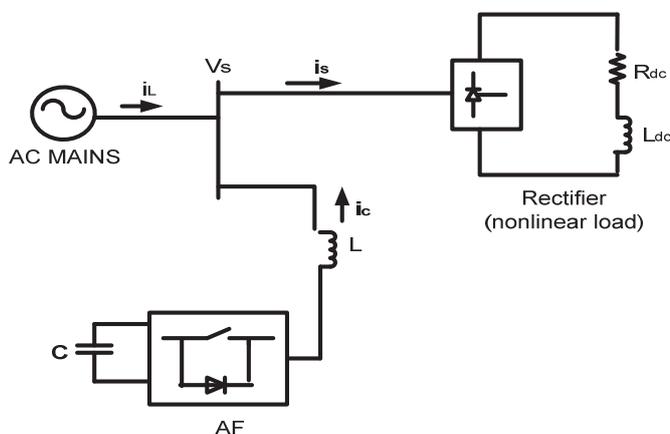


Figure 9: Voltage-fed-type AF.

lighter in weight, cheaper and more efficient [5]. The first active filters put into use were line commutated thyristors converters in combination with some reactive components. But there was the problem of reliable controlled switching. Its effective use is only when it is force-commutated, under which condition it requires costly and complex external circuits that reduce circuit reliability.

One of the major factors in the advancement of active filters technology is the advent of fast self-commutating solid-state devices such as Gate-turn-off (GTO) thyristors, bipolar junction transistors (BJT), Power MOSFETs, and Insulated-gate bipolar transistors (IGBT). Active filters (AF) are inverter circuits, comprising of these active devices that can be controlled so as to act as harmonic current or voltage generators. Different topologies and control techniques have been developed. One of the commonest topology in use is the voltage-fed pulse-width modulation (PWM) inverter as shown in Figure 9. It is used at the load end to inject compensating current, opposite in

phase to cancel harmonics or reactive components of the non-linear load current at the point of connection [6].

Let us assume a single-phase full-bridge rectifier as the nonlinear load. The load inductance is so large that the rectified current I_a is constant. The Fourier series of the load current can be shown to be [4]:

$$i_s = \sum_{n=1,3,5}^{\infty} \frac{4I_a}{n\pi} \sin n(\omega t - \alpha) \quad (9)$$

The plot is shown in figure 10, where $\alpha = 60^\circ$, $R = 0.8\Omega$, $L = 6.02\text{mH}$, $V_s = 120\text{V}$, $E = 10\text{V}$. The THD is 48.3%, and from equation (4), $PF = 0.45$.

A single-phase, single-pulse-width modulation full-bridge voltage source inverter is used as AF. From equation (8), its output current is:

$$i_o = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi Z_n} \sin \frac{n\delta}{2} \sin \frac{n\pi}{2} \sin(n\omega t - \varphi_n) \quad (10)$$

Where, $Z_n =$ load impedance; $\varphi_n =$ phase angle. The plot is shown in figure 11, where $V_s = 100\text{V}$, $R = 0.14\Omega$, $L = 0.6\text{mH}$, $\delta = 120^\circ$.

This current combines with the nonlinear load current to produce the compensated current. After compensation, the current appears as shown in figure 12. The THD is 5.7%.

The three curves are shown together in figure 13.

4. Conclusion

Nonlinear loads draw harmonic and reactive power components of current from ac mains. The effects of harmonics and reactive power flow in ac systems are quite undesirable. Hence passive $L - C$ filters were employed to reduce harmonics and capacitors were applied to improve the power factor of the ac loads.

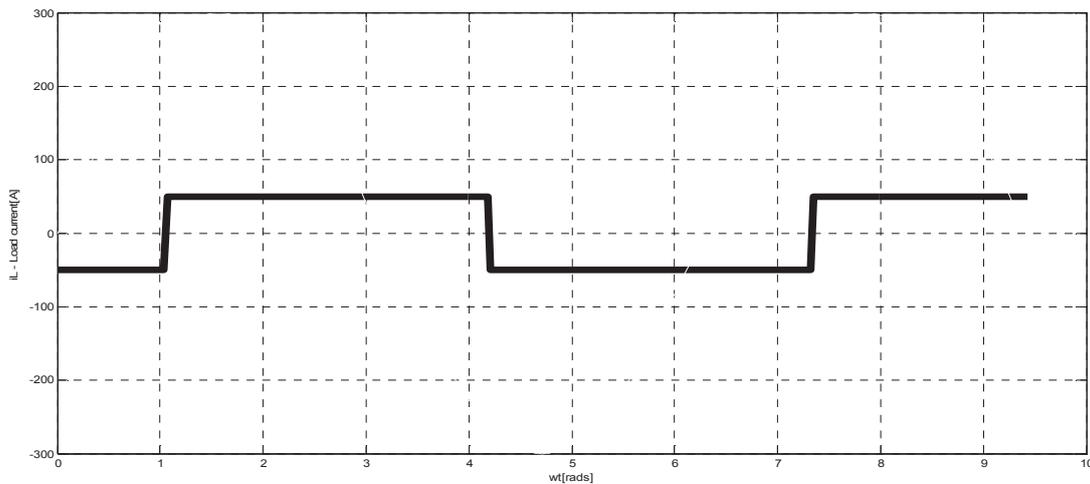


Figure 10: Non-linear load current before compensation.

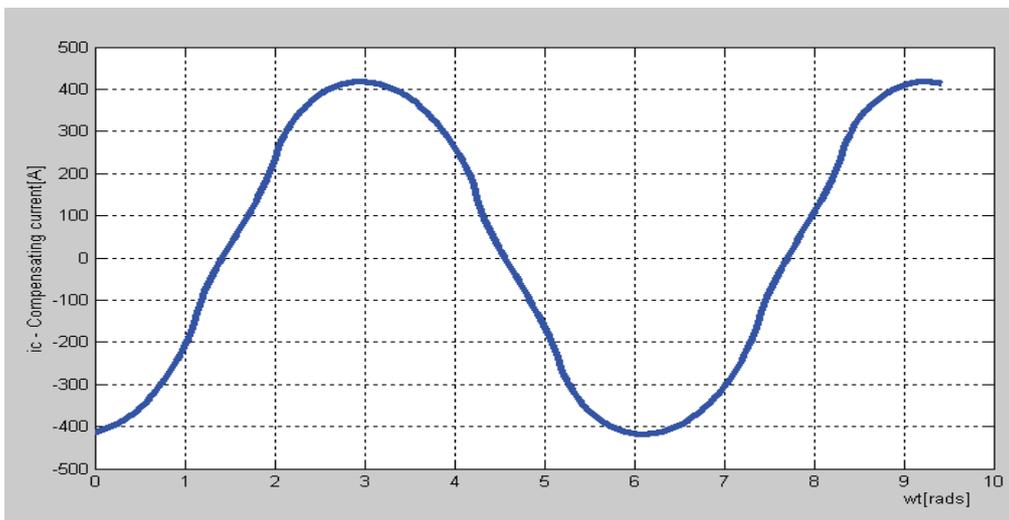
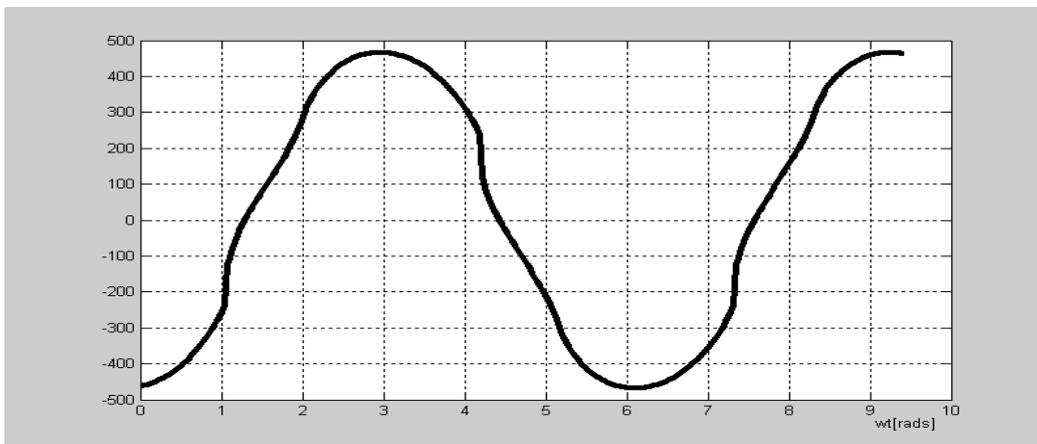


Figure 11: Output current waveform of single-phase PWM VSI.



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Figure 12: Compensated current.

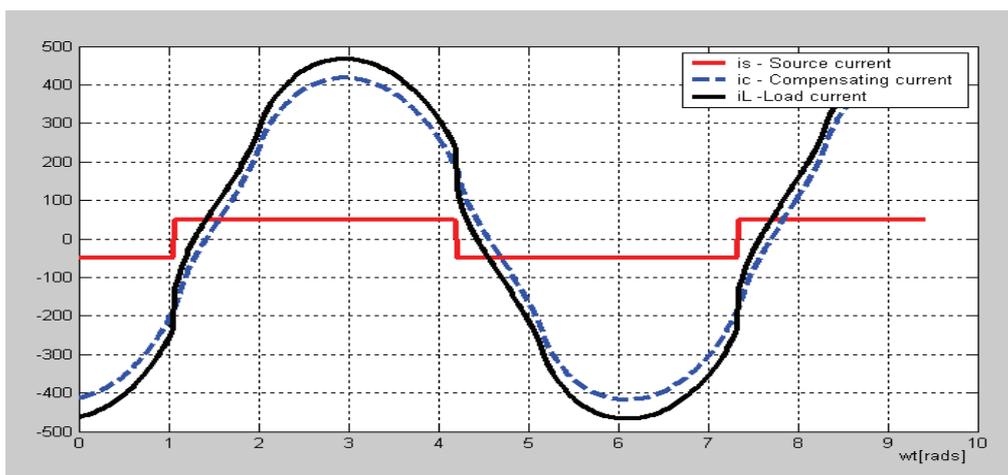


Figure 13: Source current, compensating current and compensated current.

However passive filters have the disadvantages of bulkiness, resonance and fixed compensation. Therefore, the increased severity of harmonic pollution in power networks has led to the development of the equipment known as active filters, as dynamic and adjustable solutions to the power quality problems. It has been shown in this paper that Voltage-fed PWM inverter, as an active filter, can significantly minimize harmonic pollution in ac system network. It is one of the many types of configurations of active filters applied in ac system to effectively reduce harmonic pollution.

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