

# Active AC/DC Voltage Source Converter with Function of Reactive Power Compensation for Neighboring Inductive Loads

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**Abstract-** Reactive power compensation is presented in this paper as an additional function to the three phase active ac/dc voltage source converter for neighboring inductive loads. The main function of this converter is to operate as controlled DC power supply with harmonic free ac-line current. The second function is to compensate for reactive power absorbed by neighboring loads. These two functions improve the system power factor and decrease the additional cost of compensating equipment. The proposed control strategy is based on instantaneous active and reactive power (p-q) theory. The p-q calculations are applied to inductive load current to compensate for reactive power, and to the converter current to compensate for harmonics. The experimental prototype uses a low cost Intel 80C196KC microcontroller to realize the proposed control algorithm. The simulation and experimental results are presented to prove the effectiveness and reliability of the proposed system.

**Key Words:** Active ac/dc voltage source converter, instantaneous active and reactive power, harmonics, reactive power, power factor

## 1. INTRODUCTION

Recently, the active ac/dc voltage source converters are widely used in ac-dc conversion because of their distinct advantages, such as sinusoidal line currents, controlled input displacement factor, bi-directional power flow and stabilization of DC link voltage [1-2].

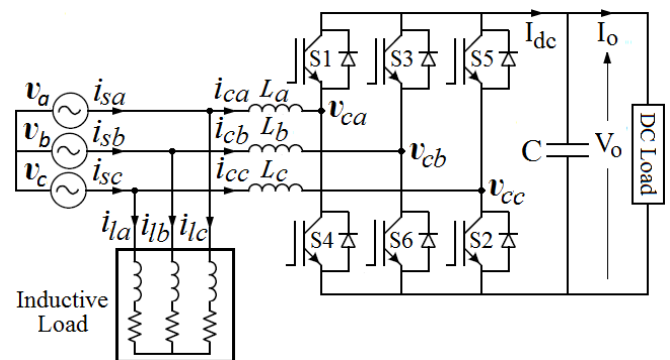
The power circuit of active ac/dc voltage source converter, shown in figure 1, consists of six-switch VSI linked with the AC network through line inductors and its DC side connected to a smoothing capacitor. According to this topology, the active ac/dc converter can absorb (or generate) reactive power beside its main function of harmonic elimination from line current.

Different control strategies based on direct power control (DPC) and synchronous reference frame (d-q) frame are proposed for reactive power compensation of active ac/dc converter [3-8].

In this paper, the instantaneous active and reactive power theory [9] is applied to the inductive load current and converter line current to extract the reactive power component of the load as well as the harmonic component

of the line current. Then the reference current of the active ac/dc converter must include both reactive and harmonic components.

The switching scheme of the power circuit is based on hysteresis current control that provides simple control algorithm for controllable power factor and good spectral performance of the line current [10]. Moreover, the proposed control scheme is implemented with a low-cost fixed-point microcontroller (Intel 80C196KC).



**Fig -1:** Three phase active ac/dc voltage source converter Neighboring inductive load

## 2. THEORY AND OPERATION

Figure 1 shows the power circuit of three-phase active ac/dc voltage source converter in bridge connection. In this topology; to maintain linear PWM operation and sinusoidal line current, the dc-bus voltage  $V_o$  must be maintained such that [11]:

$$V_o \geq \frac{2\sqrt{2}}{\sqrt{3}} V_{LL} \tag{1}$$

Where;  $V_{LL}$  is the line to line supply voltage.

This equation is used to select the minimum value of the output dc voltage.

The basic operation of the active ac/dc converter can be easily explained using Figure 2. Where Fig.2.a shows a single phase equivalent circuit of Fig.1, while Fig.2.b represents the general phasor diagram of the system. The ac line current ( $I_a$ ) vector can be controlled in its phase ( $\theta$ ) by adjusting the converter voltage vector ( $V_{ca}$ ).

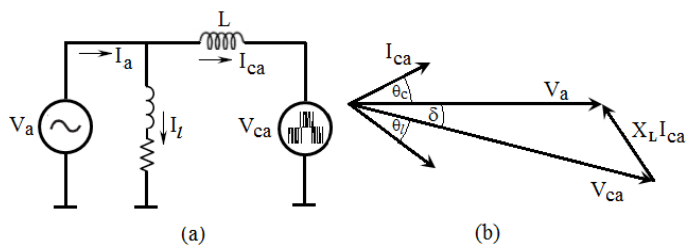


Fig -2: a) Single line diagram, b) Phasor diagram

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. Figure 3 shows a particular switching state for the active ac/dc converter.

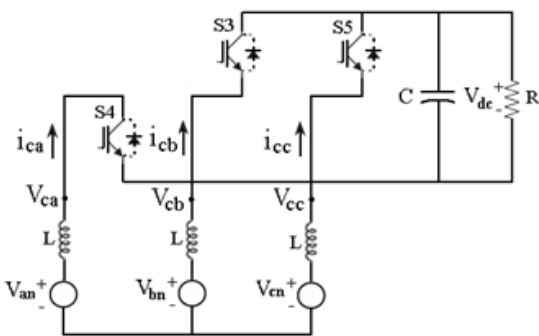


Fig -3: A particular switching state for active ac/dc converter.

Assuming negligible conduction drops across the participating switches, the equations representing the switching states of the active ac/dc converter are:

$$\begin{bmatrix} L \frac{d}{dt} i_{ca} \\ L \frac{d}{dt} i_{cb} \\ L \frac{d}{dt} i_{cc} \end{bmatrix} = V_{dc} \begin{bmatrix} -\frac{2}{3} & 1 & 1 \\ 1 & -\frac{2}{3} & 1 \\ 1 & 1 & -\frac{2}{3} \end{bmatrix} \begin{bmatrix} S_1 \\ S_3 \\ S_5 \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C} (I_{dc} - I_o) \quad (3)$$

$$I_{dc} = S_1 I_{ca} + S_3 I_{cb} + S_5 I_{cc} \quad (4)$$

where S1, S3, S5 are the high-side switches of the ac/dc converter and S=0 means that the switch is open whereas S=1 means that it is closed.

### 3. PROPOSED CONTROL SCHEME

The application of p-q theory requires transformation of “three-phase source voltages ( $v_{abc}$ ), load currents ( $i_{Labc}$ ), and converter line currents ( $i_{cabc}$ )” into  $\alpha$ - $\beta$  stationary reference frame as;

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

Using p-q theory, the reactive power component ( $q_l$ ) of the inductive load can be calculated as;

$$\begin{bmatrix} p_l \\ q_l \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \quad (7)$$

Similarly, the instantaneous active and reactive powers ( $p_c, q_c$ ) of the active ac/dc converter are;

$$\begin{bmatrix} p_c \\ q_c \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad (8)$$

$p_c$  and  $q_c$  are divided into two components;

$$p_c = \bar{p}_c + \tilde{p}_c \quad (9)$$

$$q_c = \bar{q}_c + \tilde{q}_c \quad (10)$$

where  $\bar{p}_c$  and  $\bar{q}_c$  are the dc and ac components of the instantaneous active power,  $\tilde{q}_c$  and  $\tilde{p}_c$  are the dc and ac components of the instantaneous imaginary power. The dc components  $\bar{p}_c$  and  $\bar{q}_c$  correspond to the conventional active and reactive powers of the fundamental component of the active ac/dc converter, respectively. Whereas, the ac components  $\tilde{p}_c$  and  $\tilde{q}_c$  correspond to the harmonic component of the active ac/dc converter.

In order to compensate the reactive power of inductive load and current harmonics of the active ac/dc converter, the reference currents of the active ac/dc converter must include the values of  $q_l, \bar{p}_c, \bar{q}_c$  and  $\tilde{q}_c$  with suitable sign. The dc components  $\bar{p}_c$  is extracted from instantaneous active power  $p_c$  using a low pass filter. In this case the reference currents required by the active ac/dc converter are expressed as;

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p}_c \\ -q_l - q_c \end{bmatrix} \quad (11)$$

Finally, reference converter currents in *abc* reference frame are calculated as;

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \quad (12)$$

The block diagram of the proposed control system is shown in Fig.4.

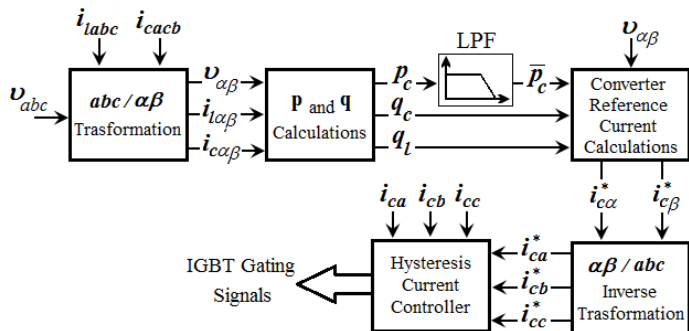


Fig -4: Proposed control system block diagram.

The regulation of dc-link voltage ( $V_o$ ) is accomplished by adjusting the reference voltage according to equation (1). A conventional PI controller is used to regulate the dc voltage, and the resulting signal added to dc component  $\bar{p}_c$  of the converter active power.

#### 4. SIMULATION RESULTS

A simulation platform is built using SIMULINK and Power System Blockset under MATLAB to evaluate the performance under different operating conditions. The line to line voltage is 380V and according to equation (1) the reference dc output voltage is chosen to be 700V. The system parameters are chosen as in Table 1.

Table 1. System Parameters.

Parameter	Value
AC line voltage	380V
Ref. DC Link voltage	700V
Line inductance	4mH
DC Load resistance	40Ω
DC link capacitor	1000μF
Inductive Load	$P_L=4.84KW$ $Q_L=4.84KVAR$ $PF=0.707$ lag.

Figure 5 presents the inductive load current and its associated active and reactive powers.

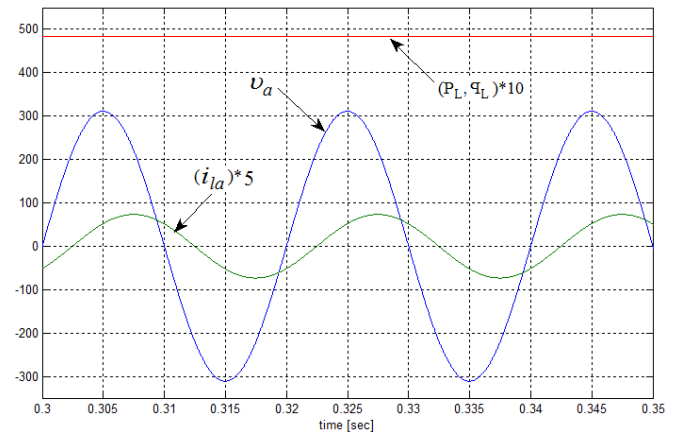


Fig -5: Inductive load current and its associated powers.

The performance of active ac/dc voltage source converter under proposed control scheme is shown in Fig. 6. It is seen that the source current  $i_{sa}$  is near sinusoidal and with the same phase of the source voltage  $v_a$  (i.e. unity power factor). Also the dc output voltage is regulated at its reference value of 700V.

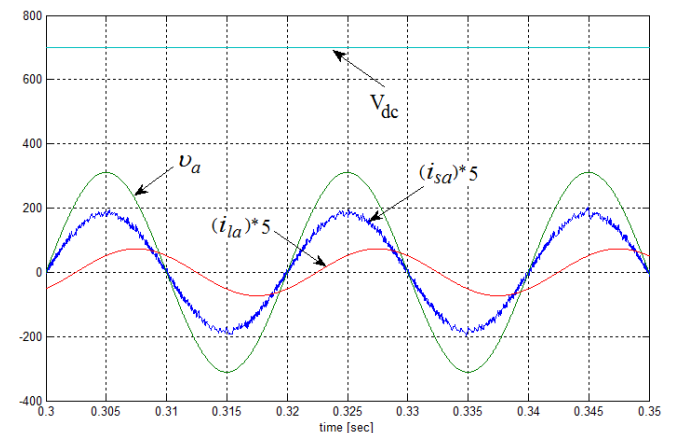


Fig -6: Performance of active ac/dc voltage source converter.

Figure 7 presents the harmonic spectrum of the supply current as a percent of the fundamental component. It is seen that the total harmonic distortion of the current has a very low value of 1.38%

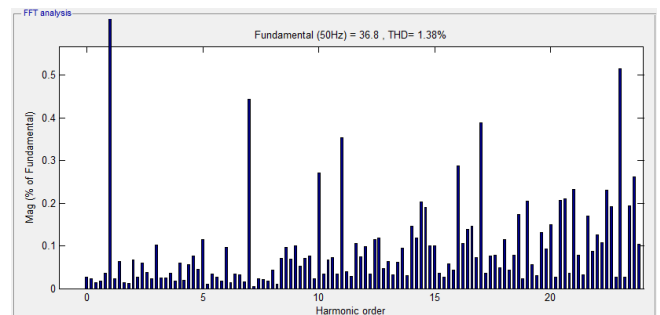


Fig -7: Harmonic spectrum of the supply current

Figure 8 shows the converter active power  $p_c$ , converter reactive power  $q_c$ , source reactive power  $q_s$ , and load reactive power  $q_l$ . It is seen that the reactive power absorbed by the inductive load is generated by the active ac/dc converter rather than the source, thus the source reactive power equals zero.

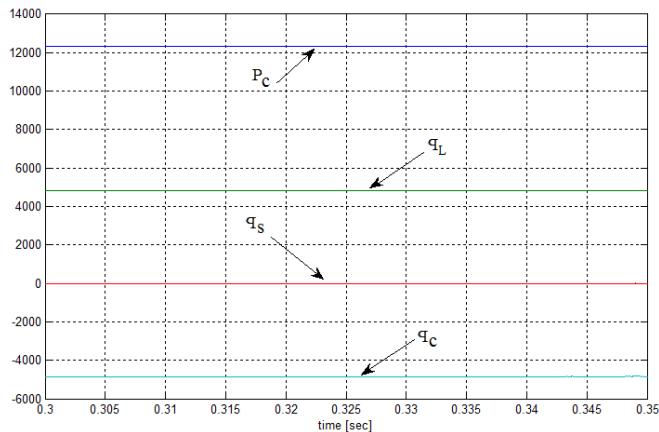


Fig -8: System reactive powers.

Figure 9 shows the source line currents  $i_{sa}$ , converter line current  $i_{ca}$ , and load line current  $i_{la}$ . The converter line current is operating at leading displacement angle to compensate for the reactive current of the inductive load.

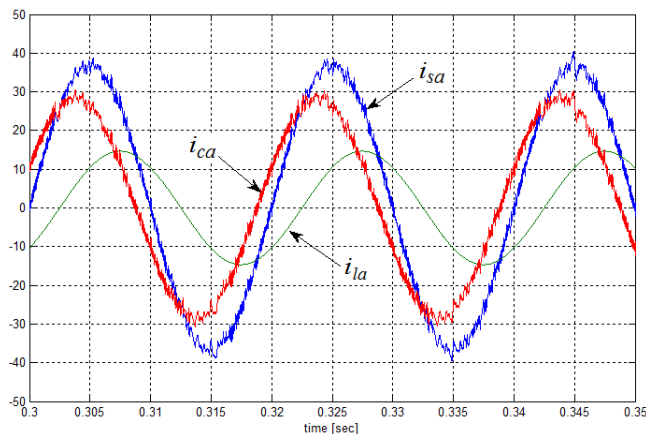


Fig -9: System line currents.

Figure 10 presents the transient response of active ac/dc converter according to step changes in dc output voltage. It is seen that the regulation of dc output voltage has a fast response and doesn't affect the system function.

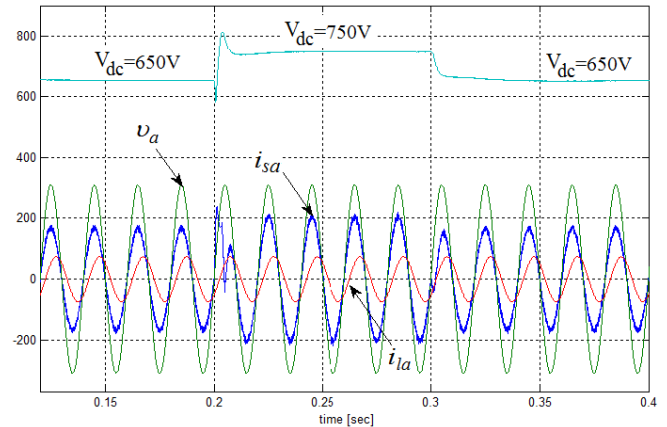


Fig -10: Transient response of active ac/dc voltage source converter according to step changes in dc output voltage.

### 5. EXPERIMENTAL SETUP AND RESULTS

The block diagram of the proposed experimental setup is shown in Fig.11. The software algorithm is implemented using an Intel 80C196KC microcontroller, which provides an eight A/D converter channels used for the various A/D operations required by the control algorithm. The output ports are used to provide the switching signals required by IGBT's drive circuit. A synchronizing circuit is used to generate a square wave at the power frequency every zero-crossing transition of the source voltage waveform. A built-in high-speed input unit (HSI) is used to capture the positive rising edge of the synchronizing signal. This combination enables a PLL at the power frequency and synchronized with the source voltage.

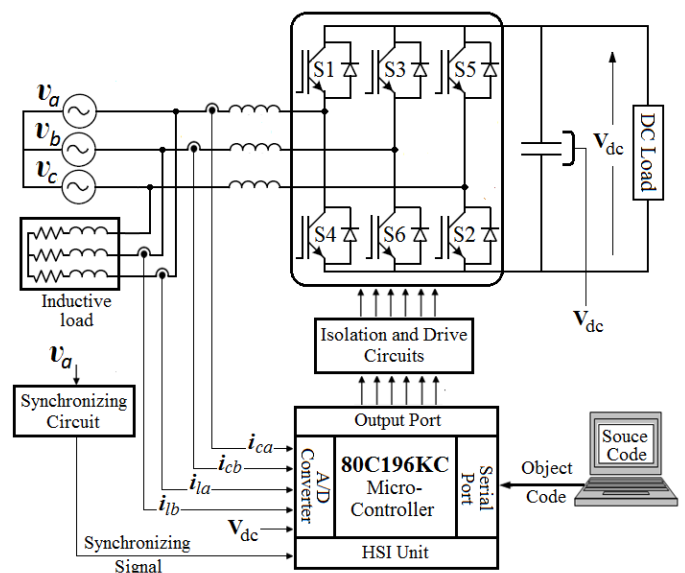
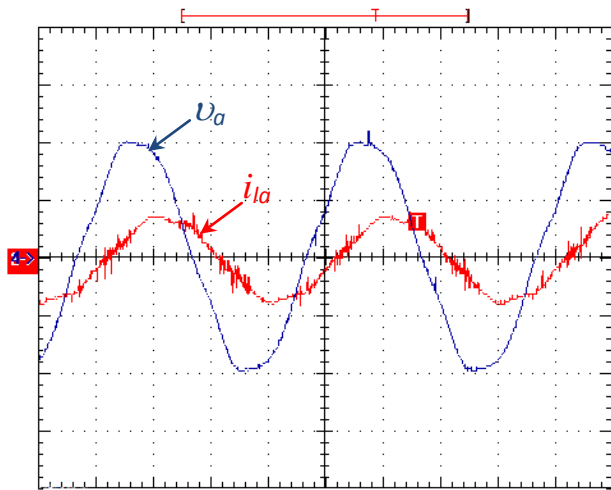


Fig -11: Experimental Setup

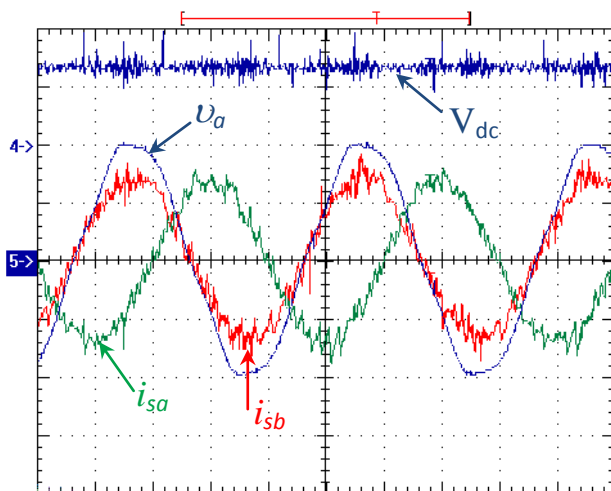
Practically, a three-phase induction motor of 1hp is used as inductive load. Figure 12 presents the motor line current with respect to source voltage.



I [4A/div.], V [50V/div.], t [5ms/div.]

Fig -12: Inductive line current with respect to source voltage.

Figure 13 shows the performance of the active voltage source converter with function of reactive power compensation. It is seen that the source current  $i_{sa}$  is near sinusoidal at unity displacement power factor. Thus, the reactive power required by the induction motor is generated by the active ac/dc converter rather than the mains.



I [4A/div.], V [50V/div.], t [5ms/div.]

Fig -13: Performance of active voltage source converter for harmonics and reactive power compensations.

Figures 14 and 15 present the harmonic spectrum of mains voltage and current. It is seen that the mains voltage is already has a large value of 5<sup>th</sup> harmonic, which in turns affects the supply current waveform. Although the supply

voltage has THD=3.71%, the supply current after compensation has a low THD value of 4.53%.

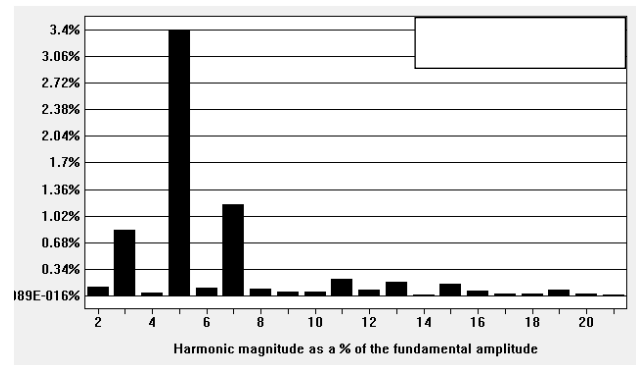


Fig -14: Harmonic Spectrum of mains voltage.

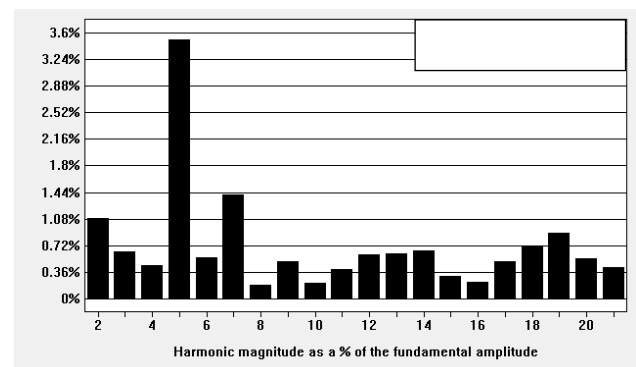


Fig -15: Harmonic Spectrum of mains current.

## 6. CONCLUSION

In this paper reactive power compensation for neighboring inductive loads is presented as an additional function to the active ac/dc voltage source converter. In the proposed control scheme, which is based on instantaneous active and reactive power theory, the reactive power required by the inductive load is calculated and generated by the active ac/dc converter rather than ac supply. The control algorithm is implemented using a single chip Intel microcontroller 80C196KC. The simulation and experimental results prove that the supply current after compensation is near sinusoidal, THD=4.53%, and in-phase with supply voltage.

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#### BIOGRAPHIES



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