Induction Furnace Compensation Using a Hybrid Active Filter

M. Salehifar,
School of Electrical Engineering
Iran University of Science and Technology
Narmak, Tehran, Iran
msalehifar@ee.iust.ac.ir

A. Shoulaie
School of Electrical Engineering
Iran University of Science and Technology
Narmak, Tehran, Iran
shoulaie@iust.ac.ir

***Abstract*- in this paper two different hybrid active filter is proposed for induction furnace compensation. Hybrid filter consists of two single tuned passive filters and a series active filter in two conditions, along power system and passive filter, respectively. A simple control method is used. The proposed configurations are simulated and simulation results are shown. On basis of obtained results, one configuration is chosen as optimal option.**

***Index Terms* - power quality, hybrid active filter, harmonic, reactive power, induction furnace.**

I. Introduction

As technology advances, the electrical loads are multiplying in numbers and complexity. This throws tremendous challenge to the quality and reliability of the power supply system. Power electronic converters are examples of such types of loads. Steel mills, which employ induction furnaces for melting scrap iron is one of the industrial areas where the use of such power converters is inevitable. The tuned filters or passive compensators are the traditional solution for harmonics issues. Since they are tuned for a fixed frequency they are not affective for load currents with varying harmonics spectrum. The induction furnace is a typical example of load, which injects harmonics in different spectrum based on the configuration of the controlled rectifier i.e., 12-pulse for heating mode or 6-pulse for sintering mode. Passive filters are also susceptible to sinking the harmonics injected by other loads in the grid. To overcome these shortcomings of passive filters various active power filter configurations have been reported. Among these configurations, shunt active filters with two-level or multilevel converter has been recognized as one of the viable solutions for harmonic compensation. The use of two-level converter is limited to medium voltage levels due to higher voltage stress on switching devices and the effective switching frequency. But multilevel converters can be used in higher voltage and power applications to obtain better harmonic performance for the given switching frequency and lower voltage stress on switching devices [1-6].

Pure active filters were proposed to mitigate passive filter disadvantages, while this is expensive method. Sometimes rate power of active filter should be 80 percent of load power. Because both pure active filters and passive are not an ideal solution, hybrid filter was introduced at 1988 and extended by many researchers. Hybrid filter is a combination of a passive filter and an active filter. In fact, active filter improve compensation characteristic of passive filter and make it a low impedance way for all load harmonics. The required power of active filter in this case is only 6 percent or less than load power. So, it is a remarkable solution and nowadays is used widely in practice as a cost effective solution for the compensation of nonlinear loads in industry [7-8].

This paper proposes two hybrid active filters with a simple control strategy. Both cases are simulated and results are demonstrated.

II. Principle operations of induction furnace

Induction heating is widely used in metal industry for melting or heating thin slabs in a continuous casting plant because of good heating efficiency, high production rate and clean working environments. A typical converter has a rectifier and an inverter. Converters are highly used in industry. Often these converters that are used as induction heating furnaces have a three phase rectifier and a single phase inverter. In these converters, load is coil of induction heating furnace that can be controlled in the form of parallel and series with a capacitor bank. Figs. 1 and 2 show two induction furnaces supplied by current source type and voltage source type inverter, respectively.

A typical parallel resonant inverter has a phase controlled rectifier that provides a constant DC current source. The H-bridge inverter consists of four Thyristors and a parallel resonant circuit comprises capacitor bank and heating coil. Thyristors are naturally commutated by the AC current flowing through the resonant circuit. The rated output power and frequency of a typical induction furnace are 250 KW and 1.2 KHz, respectively. The rated input voltage and frequency are 100 V/ac and 50Hz.

The induction furnace is a nonlinear load. A large nonlinear load such induction furnace draws heavy non-sinusoidal current. Besides the fundamental current component, this no sinusoidal current also contains undesired frequency components known as harmonics. When this distorted current is injected into distribution feeder by means of line transformer, one of the vital effects of this distorted current is the production of unavoidable distortion in voltage waveform, as this current flow through the series impedance of the distribution system. Fig. 3 shows the rectifier input currents of figs. 1 and 2 with its THD. Because input current THD in voltage source type inverter is more, this configuration is selected and compensated by a hybrid active filter.

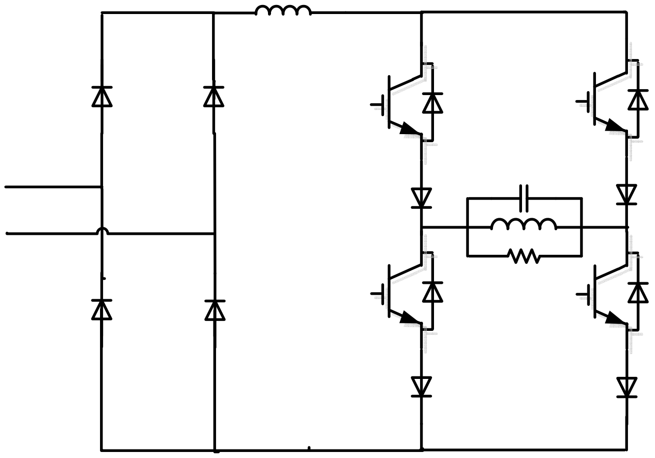

Fig. 1: induction furnace supplied with current source type inverter

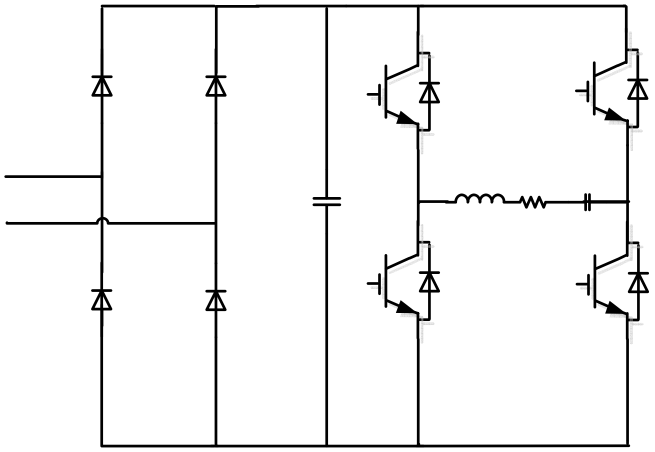

Fig. 2: induction furnace supplied with voltage source type inverter

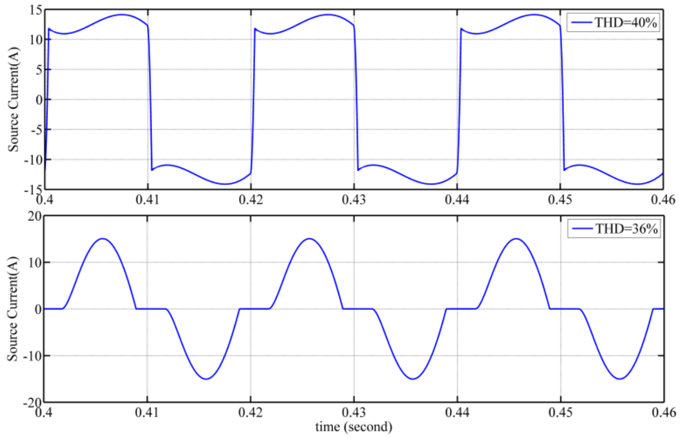

Fig. 3: Input current of induction furnace

III. Proposed Configurations for Induction Furnace Compensation

Fig. 4 and 5 shows two proposed configurations. In both configurations, two passive filters are tuned at third and fifth harmonic resonance frequency with same characteristics shown in Table 1. In Fig. 4 active filter is in series with power system through a transformer while in Fig. 5 it is along the passive filter without transformer. Control circuit detects the source harmonic current and uses it to produce switching gate signals by pulse width modulations. Also, active filter can regulate its dc capacitor voltage. Because induction furnace is mainly a variable load, it is better to supply dc capacitor voltage with a low power diode rectifier. Another point about proposed configurations is using an inductor (L_{ac}) at diode rectifier input. This can reduce source current's harmonics and in fact, it decreases the required power by active filter although increases reactive power consumption.

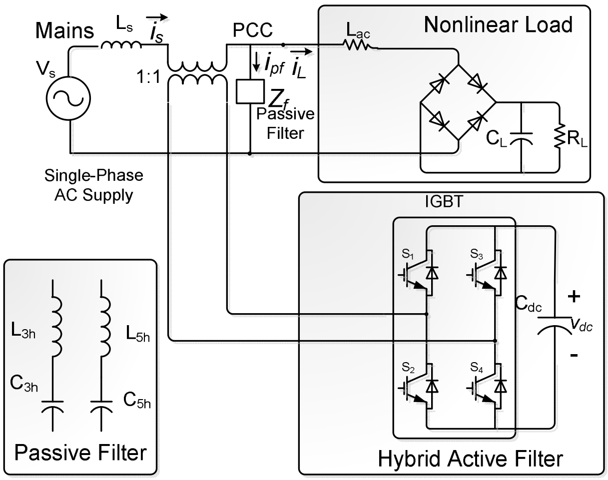

Fig 4: Hybrid active filter (first configuration)

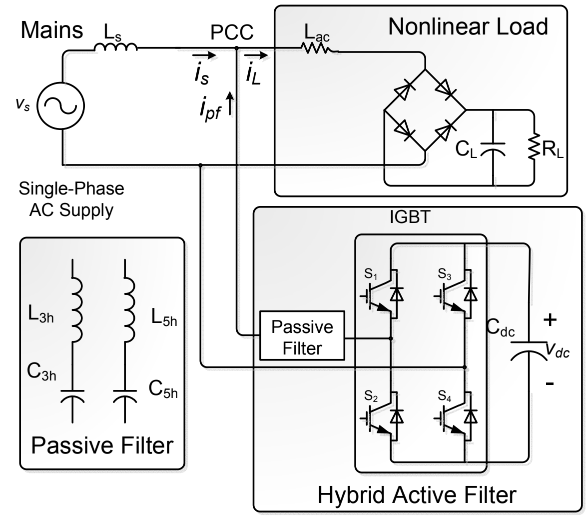

Fig 5: Hybrid active filter (second configuration)

Table 1. System parameters used in simulations

Prameter	values
System equivalent inductance:$L_s(mH)$	0.58
Load Input inductor: $L_{AC}(mH)$	3.7
Filter capacitor of 3rd: $C_{3f}(\mu f)$	80
Filter inductance of 3rd: $L_{3f}(mH)$	14.1
Filter capacitor of 5th: $C_{5f}(\mu f)$	80
Filter inductance of 5th: $L_{5f}(mH)$	5.1
Quality factor: Q	20
dc capacitor: $C_{dc}(\mu f)$	1500
Load capacitor: $C_L(\mu f)$	1500
Load resistance: $R_L(\Omega)$	20
System frequency: f (Hz)	50
Switching frequency: f_{sw} (kHz)	10

IV. Compensation Strategy

One of the key points for proper implementation of an APF is to use a reliable method for current/voltage reference generation. Currently, there is a large variety of practical implementation supported by different theories (either in time or frequency domain). However, these methods have been described for three phase active filters. The proposed method in this paper is based on transport delay. In the other words, the phase current in single phase system can be transported in one third of cycle. Consequently, the phase “b” current for the imaginary three phase system can be calculated from the current of single phase system (i.e. I_a) as follows:

$$I_b(t) = I_a\left(t - \frac{2\pi}{3}\right) \tag{1}$$

In a balanced three phase system:

$$I_a + I_b + I_c = 0 \tag{2}$$

Based on equation (2) in a balanced system, the phase "c" current can easily be calculated as:

$$I_c = -(I_a + I_b) \tag{3}$$

Now, there is an imaginary three phase system, and the reference voltage can be obtained using different transformation methods such as p-q, d-q, modified p-q, p-q-r, global, and vertical. It is noted that based on the proposed strategy the zero sequence component has no effect on transformation method because the transformation method needs only the fundamental component for reference voltage generation.

Fig. 6 shows the control circuit of APF. The APF detects the power source harmonic current, and regulates its dc bus voltage by a dc-voltage controller.

V. Control method

A. Harmonic extraction

As was aforementioned above, there are many ways to extract harmonic and reactive power in time and frequency domain. The d-q method is a useful transformation method due to selected configuration for nonlinear loads [9-10]. In d-q transformation method, the three phase quantities are transferred to synchronous reference frame at fundamental frequency by (4), as follows:

$$\begin{bmatrix} i^e_{d_1} \\ i^e_{q_1} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{4}$$

Then, 50 Hz component are extracted by a low pass filter. Afterward, the extracted quantities are transformed to initial frame by inverse transformation (5) as:

$$i_{sa1} = [\cos\theta \quad \sin\theta]\begin{bmatrix} i^e_{d_1} \\ i^e_{q_1} \end{bmatrix} \tag{5}$$

Moreover, reference harmonic components are calculated by (6):

(6)

$$i_{sah} = i_{sa} - i_{sa1}$$

Where i_{sa1} and i_{sah} are fundamental and reference harmonic component, respectively.

B. dc capacitor voltage controller

A method was proposed by Akagi [9] to control the dc voltage capacitor. Based on this method, if active filter is in series with the passive filter, an extra voltage reference should be added to q component. Fig. 2 shows this control method. It noted that a feedback, which is tuned at any harmonic component, can be added to the reference voltage to improve the response of the control method.

VI. Frequency Characteristic of Hybrid Active Filter

Single phase harmonic equivalent circuit of the power system, shown in Fig. 2, is demonstrated in Fig. 7. In this figure, the voltage source harmonics are modeled by V_{sh}, and it is in series with Thevenin impedance Z_s of the power system.

Also, nonlinear load is a diode rectifier by a resistive – capacitive load in its output. This load has usually a voltage source characteristic because an inductor is in rectifier input,

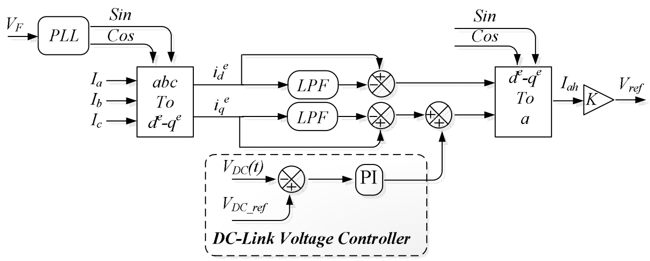

Fig. 6: Control circuit of hybrid active filter

and this makes it as a current source type load characteristic. The load is modeled by harmonic voltage V_{Lhv} in series with inductor L_{AC}. The series active filter behaves as a damping resistor that can eliminate resonance between parallel passive filter and source impedance. It also prevents flowing of harmonic currents to the power source by presenting zero impedance at the fundamental frequency and a high resistance K at the power source or load harmonics. So, the series active filter can be modeled by a resistor, K, and its output reference voltage will be as:

$$V_{af} = Ki_{sh} \tag{7}$$

Where I_{sh} is the harmonic current flowing from the power source, produced by both the load harmonic current (I_{Lh}) and the power source harmonic voltage (V_{sh}). Consequently, from model shown in Fig. 7, the harmonic current of the power source is calculated as:

$$I_{sh} = \frac{Z_{pf}}{Z_s + Z_{pf} + K} I_{Lh} + \frac{V_{sh}}{Z_s + Z_{pf} + K} \tag{8}$$

Where Z_s and Z_{pf} are power source and passive filter equivalent impedance, respectively. Based on (8), when K is large enough greater than Z_s and Z_{pf}, the power source harmonic currents will be equal to zero ($I_{sh}=0$). In fact, in this case the source impedance (Z_s) has no impact on the parallel passive filter characteristic, and the power source current harmonics will be eliminated completely. If the power source voltage harmonics (V_{sh}) is not considered, the load current will be divided between the passive filter and the power source. In this case, the ratio between the power source harmonic current and the load harmonic current is:

$$\frac{I_{sh}}{I_{Lh}} = \frac{Z_{pf}}{Z_S + Z_{pf} + K} \tag{9}$$

Fig. 8 shows the frequency response for different values of K. As seen in this figure, when the passive filter is used alone (K=0), two resonances occur between the parallel passive filter and the power source impedance at about 130 Hz and 240 Hz. Also, when the series active filter is used along with the passive filter since the series active filter behaves as a damping resistor; there is no resonance in the system.

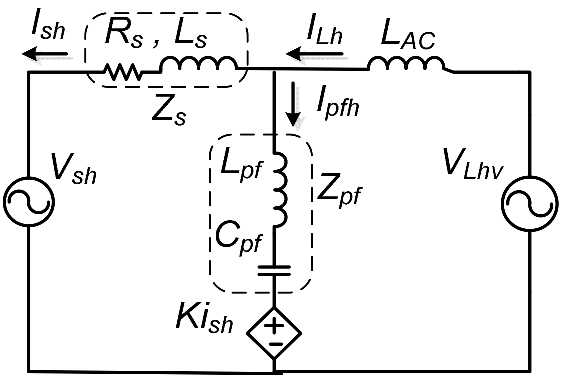

Fig. 7: Harmonic equivalent circuit of single phase system.

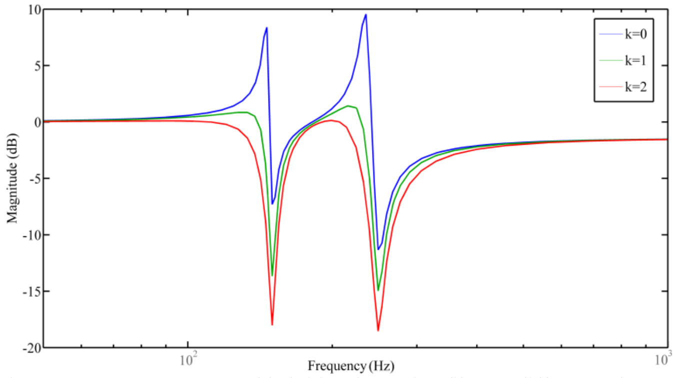

Fig. 8: Frequency response of hybrid series active filter at different values of K.

VII. Induction furnace compensation by hybrid active filter

As mentioned above, input current at induction furnace supplied with voltage source type inverter has worse THD than current source type. For convenience, a diode rectifier with resistive – capacitive load at output that has characteristic like voltage source type inverter was simulated. An inductor (i.g. L_{ac}) was put in rectifier input. This inductor improve stability margin of system and reduce THD current. Also, it brings an decrease in active filter rate power. Two hybrid active filter with the process presented above was simulated in MATLAB. In this simulation two single tuned passive filter were used with the parameters given in Table I. Fig. 9 shows simulation results without active filter. Fig 10 and 11 shows simulated systems with active filter. Fig.10 shows simulation results when active filter is along power system. Table 2 show THD and amplitude of each component for this case. THD is less than 5%. Fig. 11 shows simulation results when active filter is along passive filter. Table 2 show THD and amplitude of each component for this case. Also, THD is less than 5%. In both simulated cases dc capacitor voltage was 40 volts and only active filter was displaced. Some points are valuable about these simulations. At first, in both cases, THD level is almost same. Second, it is easy to protect second configuration in case of short circuit fault. Further more, in first case, it needs a transformer. Required power of active filter in first case is as

$$P_{af} = \frac{V_{dc}}{\sqrt{2}} \times Is \max =$$

$$\frac{40}{\sqrt{2}} \times 30 = 0.857\ kVA$$

Moreover, in second configuration it is as

$$P_{af} = \frac{V_{dc}}{\sqrt{2}} \times Ipf \max =$$

$$\frac{40}{\sqrt{2}} \times 27 = 0.771\ kVA$$

Table 2. Current THD and harmonics of the simulation results in Figs. 9, 10 and 11.

Harmonic order	3rd	5th	7th	9th	11th	13th	15th	17th	19th	THD (%)
Load current	53.03	11.04	7.14	3.18	2.59	1.74	1.23	1.08	0.78	54.85
Power source current (Fig.9)	30.2	2.58	5.27	2.47	2.11	1.52	1.03	0.92	0.64	31.5
Power source current (Fig. 10)	1.84	0.55	2.34	1.43	1.22	0.99	0.65	0.62	0.46	3.84
Power source current (Fig. 11)	1.99	0.86	2.81	1.73	1.78	1.26	1.01	0.9	0.68	4.76
Voltage at PCC	4.18	1.71	5.8	2.87	3.28	2.77	1.34	1.22	6.04	9.17

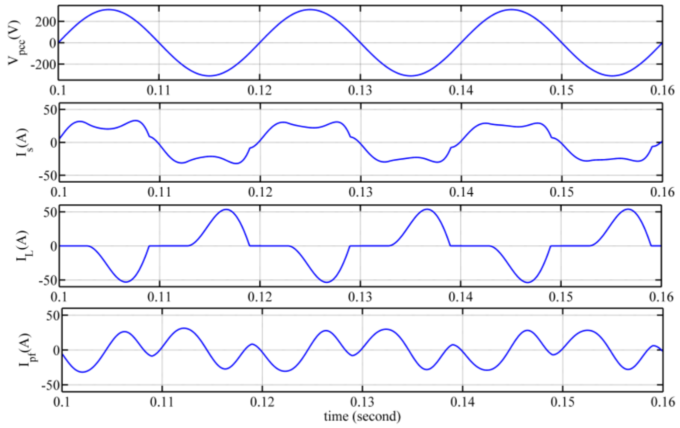

Fig. 9: Source current with passive filter only

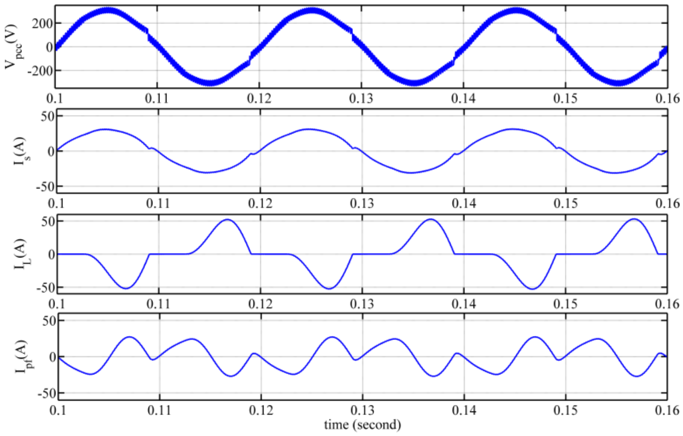

Fig. 10: Source current with first configuration

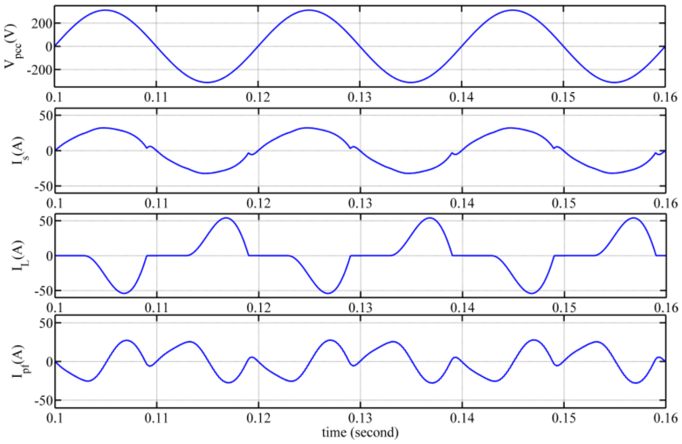

Fig. 11: Source current with second configuration

This show that required power in second configuration is less than first one and is about 6 percent of load power (i.g. 12 kW). Another drawback with first configuration is voltage waveform at point of common coupling(V_{PCC}) because active filter harmonic voltage is added to power source voltage, as a results voltage at load terminals may become different from its normal value. Subsequently, second configuration is better choice for induction furnace compensation.

VIII. Conclusion

Two induction furnaces was simulated and compensated with two different configuration of hybrid filter. Both active filters have approximately same rate power however second configuration is a better choice because of easy protection; also it doesn't need any transformer. Effectiveness of control method and hybrid active filter for harmonic and reactive power compensation was showed thorough simulation. The required power of active filter is only 6 percent of load power. The small power makes this configuration a remarkable choice in case of high power applications.

References

[1] A. K. Unnikrishnan, Aby Joseph and Subhash Joshi T.G, “Three-level Converter based Active Filter for harmonic compensation of 4MW Induction Furnace, ” *Power Elec. and Appl., 2007 European Conf.*, pp:1 – 7, Sept. 2007.

[2] M. A. Dzieniakowski, J. Fabianowski, and R. Ibach, “LCL-Load Modular Converter For Induction Heating,” *2008 13th Int. Power Elec. and Motion Control Conf. (EPE-PEMC 2008),* 2008.

[3] A. Kiyoumarsi, R. Houshmand, R. Ali-Zargar1, and M. Hassanzadeh, “Closed Loop Power Control of an Induction Furnace,” *Proc. of the 2008 Int. Conf.on Electrical Machines,* 2008.

[4] R. A. Jabbar, M. Akmal, M. Ali Masood, M. Junaid and M. Fiaz Akram, “Voltage Waveform Distortion Measurement Caused by the Current drawn by Modern Induction Furnaces,” *Harmonics and Quality of Power, 2008. ICHQP 2008. 13th Int. Conf.,* pp: 1 – 7, Sept. 2008.

[5] R. Fuentes, P. Lagos, J. Estrada, “Self-Resonant Induction Furnace with IGBT Technology,” *Ind. Elec. and Appl., 2009. ICIEA 2009. 4th IEEE Conference* , pp: 1371 – 1374, May 2009.

[6] R. C. Dugan, L. E. Conrad, “Impact of Induction Furnace Interharmonics on Distribution Systems,” *Transmission and Distribution Conf.,* Vol. 2, pp:791 – 796, Apr. 1999.

[7] B. Singh, A. Chandra and K. Al.haddad, “Hybrid Filters for Power Quality Improvement,” *IEE Proc. Gener. Transm. Distrib.*, Vol. 152, No. 3, May 2005.

[8] Fang Z. Peng, “harmonic sources and filtering approaches**,**” *IEEE Industry Applications Magazine*, July/August 2001.

[9] H. Akagi, “Active Harmonic Filters”, *Proceedings of the IEEE*, Vol. 93, No. 12, Dec. 2005

[10] S. Bhattacharya and D. M. Divan, “Synchronous frame based controller implementation for a hybrid series active filter system,” *Industry Applications Conf., 1995. Thirtieth IAS Annual Meeting, IAS '95., Conf. Record of the 1995 IEEE*, Vol. 3, pp. 2531–2540, Oct. 1995.