Electrical Power Quality and Utilisation, Magazine *Vol. II, No. 1, 2006*

Analysis of a TSC Failure in a Steel Mill Industry

Hossein MOKHTARI [1], Abolfazl ZEBARDAST [2], Mostafa PARNIANI [1]

[1] *Sharif University of Technology, Iran;* [2] *Islamic Azad University of Qazvin Branch, Iran*

***Summary*: This paper presents the results of a thorough analysis of failure of TSC modules in a steel mill plant. The TSCs are used to reduce the flicker level caused by the arc furnace loads used in the plant. The plant is modeled and Harmonic analysis is carried out. Statistical analysis is performed and the results are compared with IEEE standard limits. The system is analyzed and the resonance modes are extracted. Site measurements are carried out, and the results, which verify those obtained by the simulations are also presented.**

Key words:
harmonic analysis, power quality, resonance conditions, steel mill

1. INTRODUCTION

Arc furnace loads are nonlinear time-varying loads which are widely used in steel mill plants. These loads cause several power quality problems such as generating current/voltage harmonics, voltage imbalance and fluctuation. The voltage fluctuation, which results in flicker, is due to the highly varying nature of furnace currents, specially in the early phase of the melting process. To compensate for the voltage fluctuation and to reduce the flicker level, fast reactive compensating devices are employed. One of these devices is a Thyristor Switched Capacitor (TSC) which is used in Khouzestan steel mill plant located in south of Iran. The main characteristic of arc furnace loads is the highly varying and randomly nature of the arc. This nature results in generation of wide range of current/voltage harmonics and interharmonics in the system. To mitigate the effects of harmonics in the system, harmonic filters are used in parallel with other power quality enhancement devices.

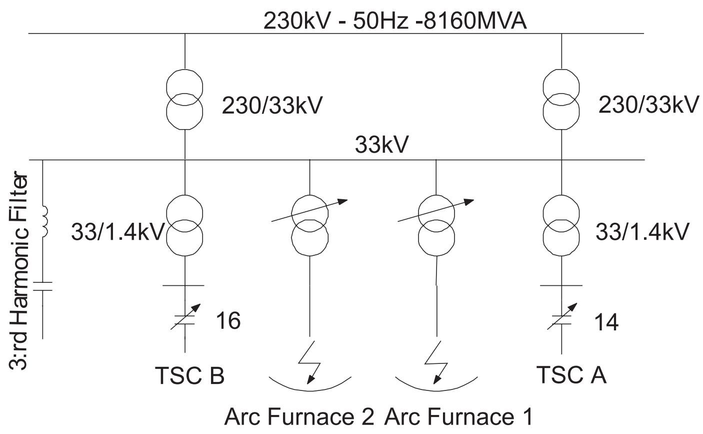
Operators in Khouzestan steel mill plant have been reporting the failure of the TSC modules installed at site. The reports indicated the explosion of the capacitor banks. This paper summarizes the results of a thorough study on this case. The results include analytical harmonic analysis of the plant as well as examining of the site measurement records. The paper is organized as follows. Following the introduction, khouzestan steel mill plant structure is described. Then, the TSC control strategy is explained. To map the research approach and determine the cause of the TSC failures, behavior of capacitor banks in harmonic environments is studied. Harmonic analysis for the site is performed and resonance conditions are determined. Experimental results are presented to verify the theoretical analysis.

2. PLANT CONFIGURATION

Khouzestan steel mill plant is composed of three similar sections. Each section consists of two arc furnace loads. The plant is supplied from a 230kV system through 230kV/33kV transformers. Fig. 1 depicts the schematic diagram of one of the sections which includes main transformers, furnace transformers, TSC transformers, arc furnaces, TSCs and harmonic filters.

Furnace loads are supplied via 33kV/1.4kV transformers which are connected in delta at primary. The secondary windings of the furnace transformers are also connected in delta with two half sections each of which rated at 1.4kV. Arc furnaces are rated at 120MVA and 78MVA. Each section employs a TSC module. One module is equipped with 16 capacitor banks, while the other one has 14 capacitor banks as shown in Figure 1. Harmonic filters are also tuned at the 3 rd harmonic and are rated at 20MVAr. System parameters are given in the appendix.

Fig. 1. Schematic diagram of the plant



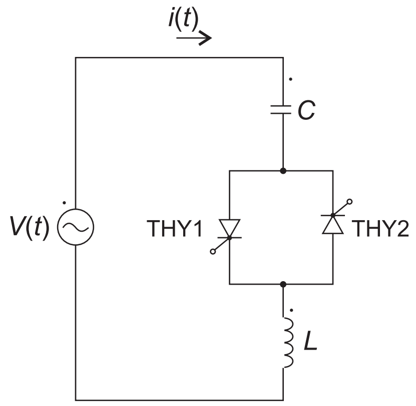


Fig. 2. Basic Thyristor Switched Capacitor (TSC)

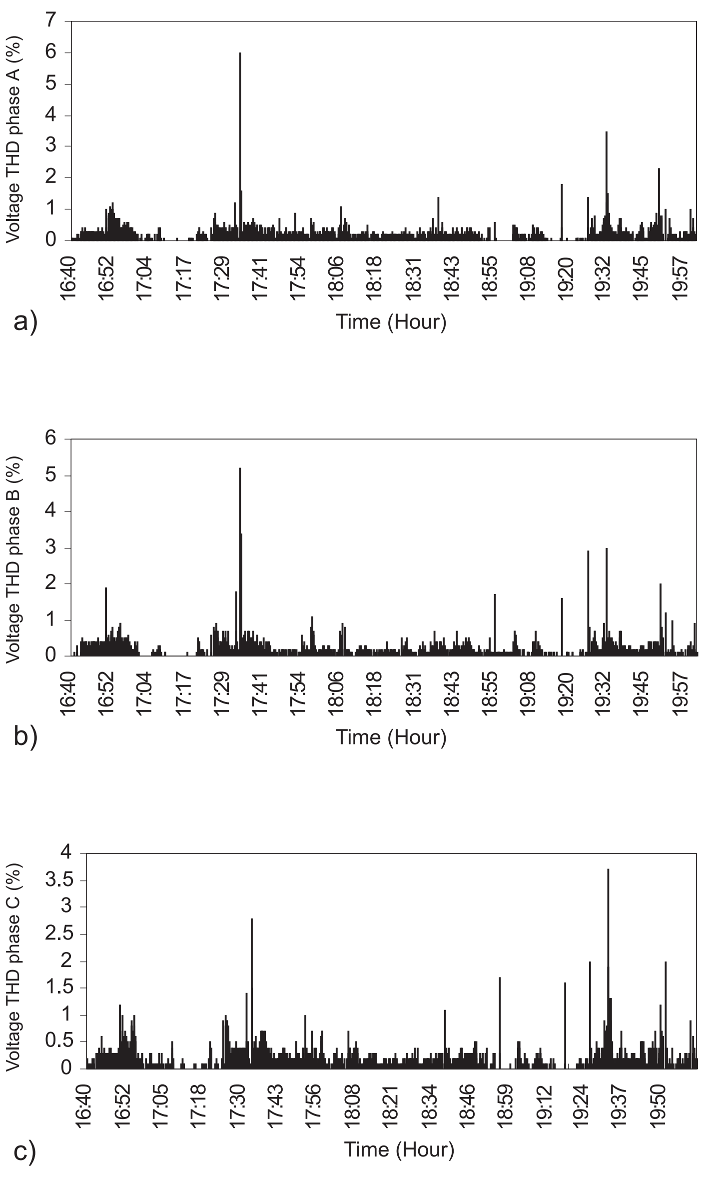


Fig. 3. Voltage THD measurement results: (a) phase-A (b) phase-b (c) phase C

3. TSC CONTROL STRATEGY

A TSC control strategy may use one or a combination of the following parameters as the control variable; load reactive power, voltage and power factor. In Khouzestan plant, load reactive power is measured and depending on system requirement, TSC blocks are entered or taken out from the system. The control circuit is composed of three different sections; reactive power measurement, step control and a gating unit. The step control unit determines the amount of required reactive power and commands the gating unit to generate suitable gating pulses for the thyristors.

The capacitors are remained charged by the control strategy when they are not in the system. Fig. 2 depicts the TSC circuit which is equipped with a series reactance. The reactance limits the inrush current of the capacitor. When a TSC module is connected to the network, the capacitor draws a current. If the system voltage is assumed sinusoidal; i.e.:

$$V(t) = V \sin\omega t \tag{1}$$

then, capacitor current is:

$$i(t) = V \frac{n^2}{n^2 - 1} \omega C \cos\omega t \tag{2}$$

where:

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}} \tag{3}$$

When a capacitor is taken off the circuit at the zero crossing of line current, its voltage is its maximum, i.e.:

$$V_m = V \frac{n^2}{n^2 - 1} \tag{4}$$

If the capacitor voltage remains unchanged, firing thyristors at peak voltage of supply voltage results in no transient current. However, capacitors discharge due to being non-ideal. Therefore, to keep the voltage constant, the control circuit triggers the thyristors such that the voltage across the capacitors remains at maximum.

4. HARMONIC EFFECTS ON CAPACITORS

Harmonics have different effects on capacitors. Due to the internal resistance, capacitors waste power as heat when they are subjected to current flow. Harmonics superimposed on a capacitor current result in an increase in the rms current, and thus, increase the losses in a capacitor bank. The peak value of a capacitor voltage/current can also be affected by harmonics, which may in turn result in capacitor failure. IEEE 18 specifies standard limits for capacitors operating in a harmonic environment.

The other effect of harmonics on capacitors is related to the resonance phenomena. The parallel connection of TSC capacitors with the inductance of the system forms a resonance condition which occurs at ω_r, i.e.:

$$\omega_r = \omega\sqrt{\frac{X_c}{X_{SC}}} = \omega\sqrt{\frac{S_{SC}}{Q}} \qquad (5)$$

Where X_C and Q are the reactance and the reactive power of the capacitor bank, and X_{SC} and S_{SC} are the short circuit impedance and power of the system to which the TSC is connected.

If ω_r is close to the frequency of a harmonic generated by a nonlinear load, it will produce strong harmonic voltages on the low voltage bus and over currents in the transformer and the capacitor bank.

5. STUDY OF THE TSC PROBLEM

To study the failure of the TSCs, site measurements were performed in order to check IEEE18 and IEEE519 compliance. Measurements were conducted at different locations in the steel mill plant. Figure 3 depicts a THD graph of the capacitor voltage measured over 3.5 hours.

In order to check the IEEE18 compliance, statistical analysis is performed, and a THD level is found below which 95% of THD measurements lie. To find this level, the cumulative distribution of THD measurements is drawn. The results are shown in Figure 4. Similar calculations are performed for the capacitors currents. The results show that voltage and current limits are within IEEE standard limits. Based on IEEE519 standard limits, for a system with rated voltage below 69 kV, THD level must not exceed 5%. Each individual harmonic must also be limited to 3%. Therefore, the failure of the TSC modules could not be attributed to the high level of stationary harmonics.

The other scenario is the improper design or malfunction of the TSC control system. If the control logic fails to fire the thyristors at system peak voltages, high level of inrush current may damage the capacitor banks.

Several transient measurements are captured. All results indicate that the control system is working properly, and therefore, switch misfiring cannot be a major reason in TSC failures. Figures 5 and 6 show typical voltage and current waveforms of the TSC modules during turn on.

The next step is to study possible resonance conditions in the system. Figure 7 is a simplified single-line equivalent diagram of Khouzestan steel-mill plant viewed from the 33kV side. In this figure, Lf and Cf represent the 3rd harmonic filter; LTA, KACA, LTB and KBCB represent the two TSC modules, and Lt is the equivalent inductance of the plant and the network. The driving point impedance at PCC can be found as:

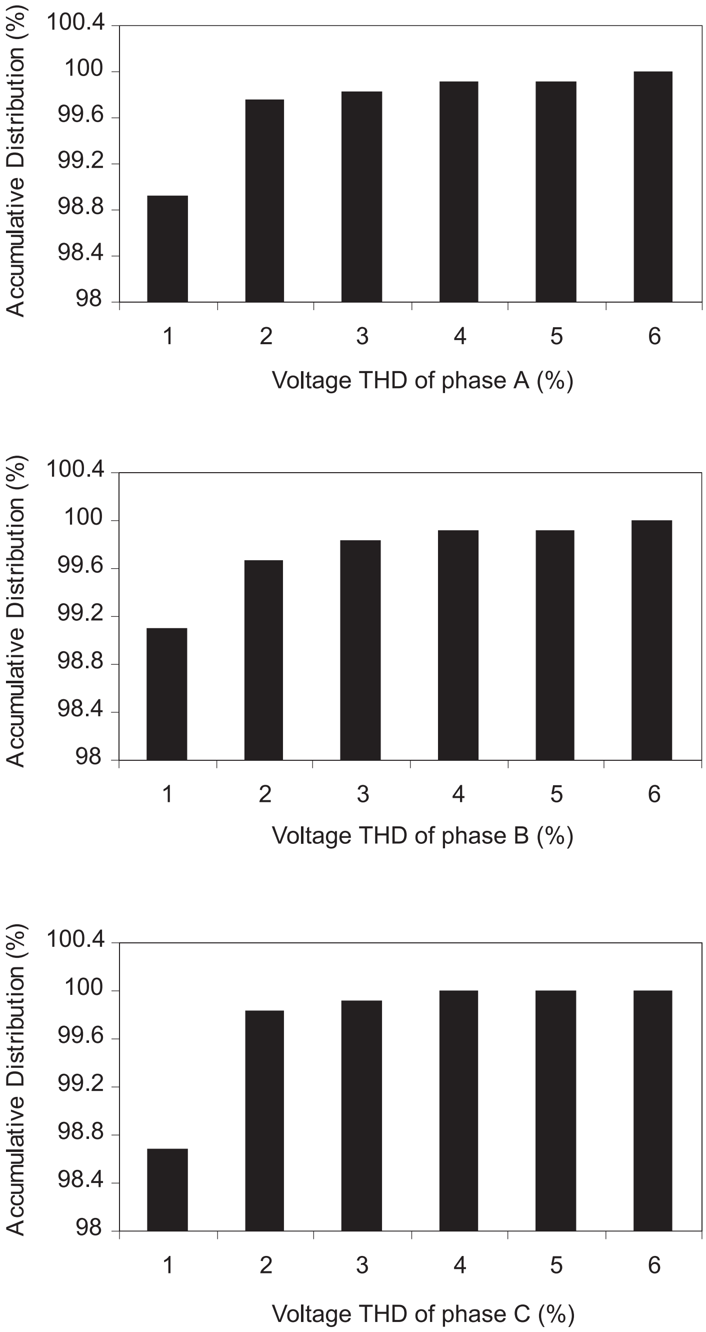


Fig. 4. Cumulative distribution of voltage THD

$$|Z_{PCC}| = \frac{f(n_A)f(n_B)}{f(n_A)+f(n_B)} \qquad (6)$$

Where:

$$f(n_A) = j\frac{X_{LT}(n_A X_{LTA} - X_{CA})}{n_A(X_{LT}+X_{LTA}) - X_{CA}}$$

$$(7)$$

$$f(n_B) = j\frac{(X_{Lf}-X_{Cf})(n_B X_{LTB} - X_{CB})}{n_B(X_{Lf}-X_{Cf}+X_{LTB}) - X_{CB}}$$

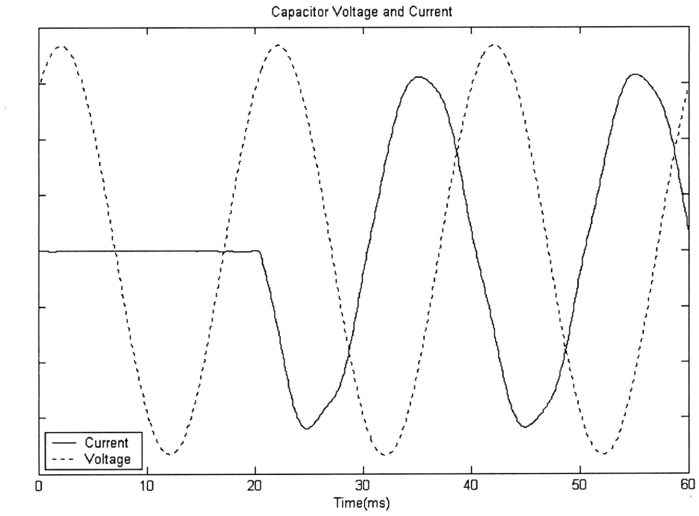


Fig. 5. Measured waveforms of a TSC module—case 1

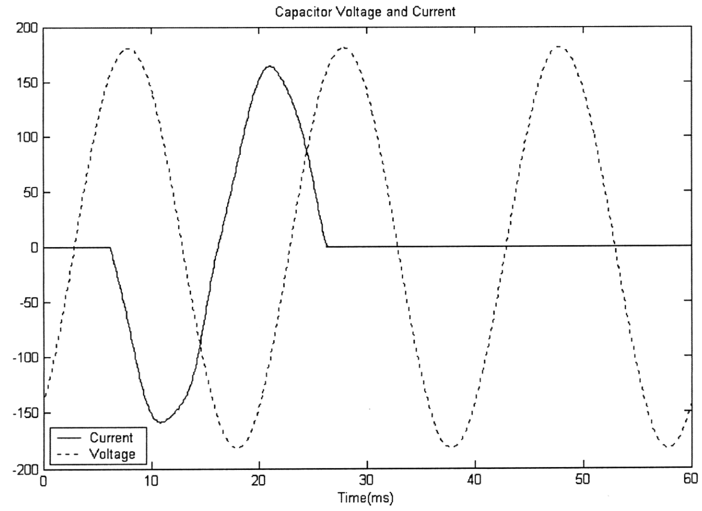


Fig. 6. Measured waveforms of a TSC module—case 2

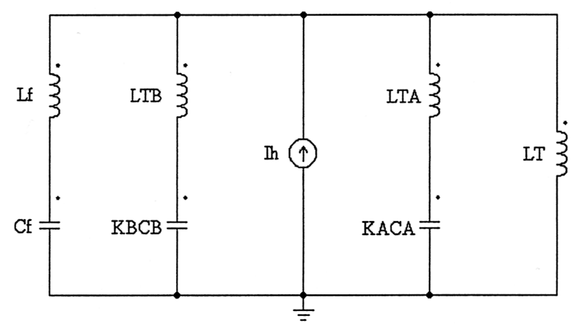


Fig. 7: Simplified single-line equivalent diagram of Khouzestan steel-mill plant

and h_A and h_B indicate the number of TSC modules which are connected to the system and $1 \leq n_A \leq 14$ and $1 \leq n_B \leq 16$.

System parameters in Figure 7 are:

$Lf = 21.64\,mH$ $Cf = 51.987\,\mu F$

$LTA = LTB = 3.467\,mH$ $LT = 2.1275\,mH$

$CA = CB = 14.63\,\mu F$

As it can be seen, changing n_A or n_B changes the roots of the denominator in Eq. (6). Therefore, a total number of 14 x 16 = 224 resonance conditions may occur depending on TSCs configuration. Accordingly, 224 frequency responses of the system can be found. Figures 8, 9, and 10 present three frequency responses of the system for three different TSC configurations. Figure 8 shows the results when $[n_A = 8, n_B = 1]$. Figures 9 and 10 correspond to $[n_A = 7, n_B = 5]$ and $[n_A = 2, n_B = 8]$ respectively. These figures indicate that the third harmonic is effectively attenuated, and therefore, the existing harmonic filter works properly. Close observation of the figures also reveals that a resonance frequency exists at 200Hz, i.e. the 4th harmonic. Therefore, if this harmonic exists in load currents, a resonance condition may occur.

Site measurements are conducted in order to determine the frequency spectrum of the current harmonics. Figures 11-a and 12-a show the line current of one of the furnace loads at two different times. Fourier transform of these signals are shown in Figures 11-b and 12-b respectively. It can be seen that the 4th harmonic is present in the line currents. Comparing these experimental results with the aforementioned frequency response of the system verifies the resonance condition at the 4th harmonic.

6. CONCLUSION

In this paper, a thorough study is conducted to find the reason for the failure of TSC modules in a steel-mill plant. Harmonic analysis is performed for the system, the TSC control strategy is tested, and the frequency response of the plant is also found. Experimental results show that the THD level is below IEEE519 standard limits. The recorded data also indicate no sign of control system malfunctioning. By modeling the plant, the frequency response of the system is found for different operating conditions. Since the number of capacitors in the system changes, the frequency response also changes. The study showed resonant conditions for particular arrangements of TSC modules at the 4th harmonic. Close observation of line currents also verifies a resonance near the 4th harmonic.

ACKNOWLEDGEMENTS

The authors would like to appreciate the financial support of Khouzestan Steel Mill plant. The efforts of Mr. M. Hejri and A. Banitalebi Dehkordi in performing the measurements are also appreciated.

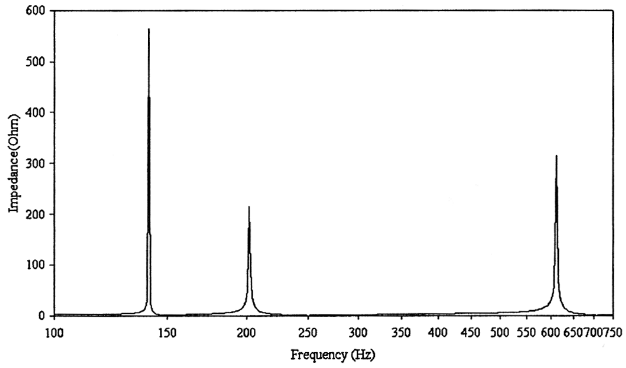


Fig. 8. Frequency response for $n_A = 8$ and $n_B = 1$

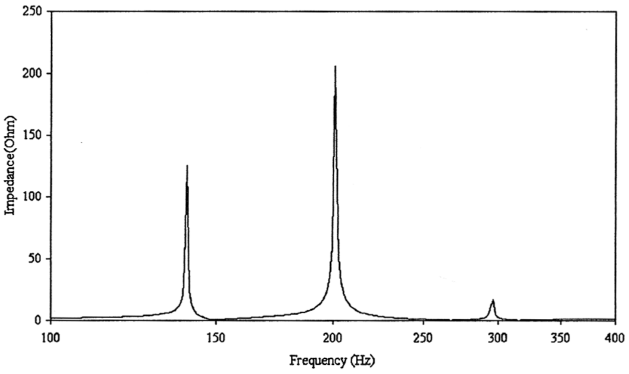


Fig. 9. Frequency response for $n_A = 7$ and $n_B = 5$

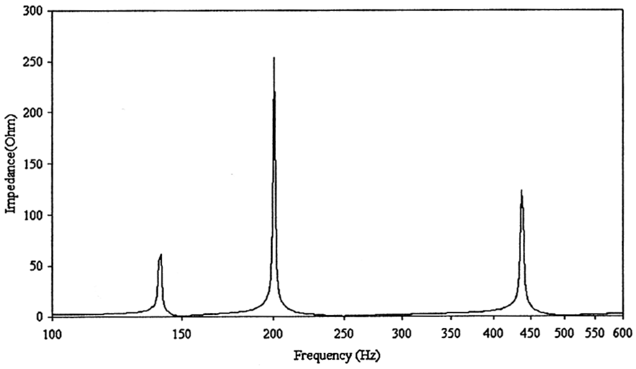


Fig. 10. Frequency response for $n_A = 2$ and $n_B = 8$

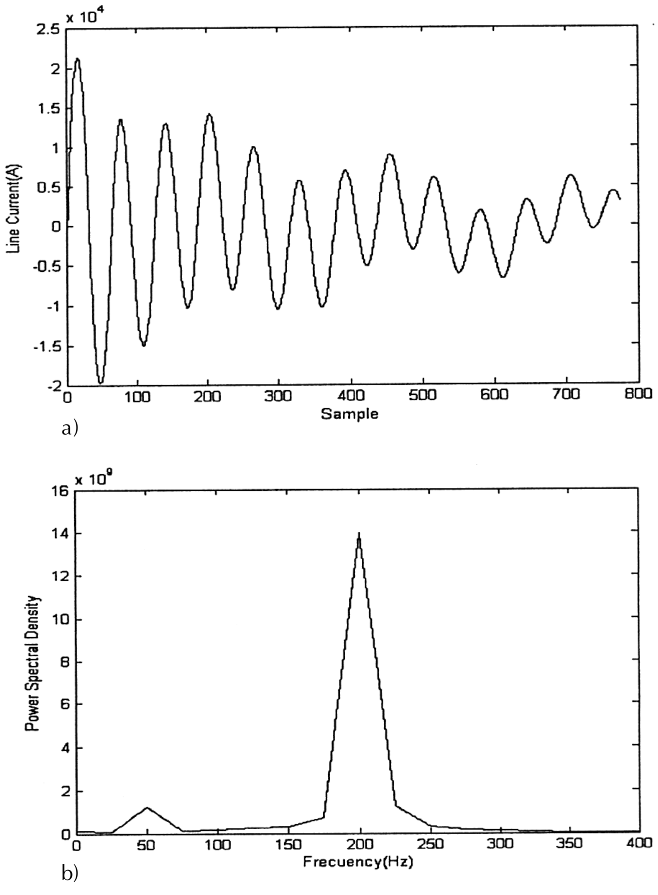


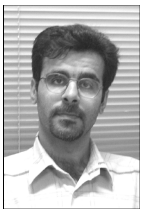
Fig. 11. Measured furnace line current (a) waveform (b) Fourier Transform—case 1

REFRENCES

1. Heydt G.T.: *Electric power quality.* 2nd Edition, Stars in a Circle Publications, Scottsdale, 1991.
2. Vakileh G.J.: *Power systems harmonics, fundamentals, analysis and filter design.* Springer, 2001.
3. Medis S.R., Bishop M.T., and Witte J.F.: *Investigation of Voltage Flicker in Electric Arc Furnace Power Systems.* IEEE Industry Application Magazine, Jan./Feb. 1996, 28–34.
4. Miller T.J.: *Reactive power control in electric systems.* John Wiley, New York 1982.
5. Hingorani N.G. and Gyugyi L.: *Understanding FACTS.* IEEE Press New York, 2000.
6. Song Y.H. and Johns A.T.: *Flexible transmission systems (FACTS).* IEE Press, London, 1999.
7. Ghosh A. and Ledwich G.: *Power quality enhancement using custom power devices.* Kluwer Academic Publishers, Boston, 2002.

APPENDIX

Main Transformer:
230kV/33kV Y/Y/Δ 73MVA X=8.96%
Arc Furnace1 Transformer:
33kV/653-1820V 90.3-120MVA X=10%
Arc Furnace2 Transformer:
33kV/58-400V 70-78.4MVA X=7%
TSCs Transformer:
33kV/1.4kV Δ/ 50MVA X=5%
230kV Short-Circuit Capability 8160MVA
3rd Harmonic Filter 20MVAr
TSCA 14x5MVAr TSCB 16x5MVAr



Hossein Mokhtari was born in Tehran, Iran. He received his B.Sc. degree in Electrical Engineering from Tehran University, Tehran, Iran in 1989. He worked as a consultant engineer for Electric Power Research Center (EPRC) in Tehran in dispatching projects for 3 years. In 1994, he received his M.A.Sc. degree from University of New Brunswick, Fredericton, Canada and his Ph.D. degree in Electrical Engineering from the University of Toronto in 1998. He is currently an associate professor in the Electrical Engineering Department at Sharif University of Technology, Tehran, Iran. His research interests includes power quality and power electronics.

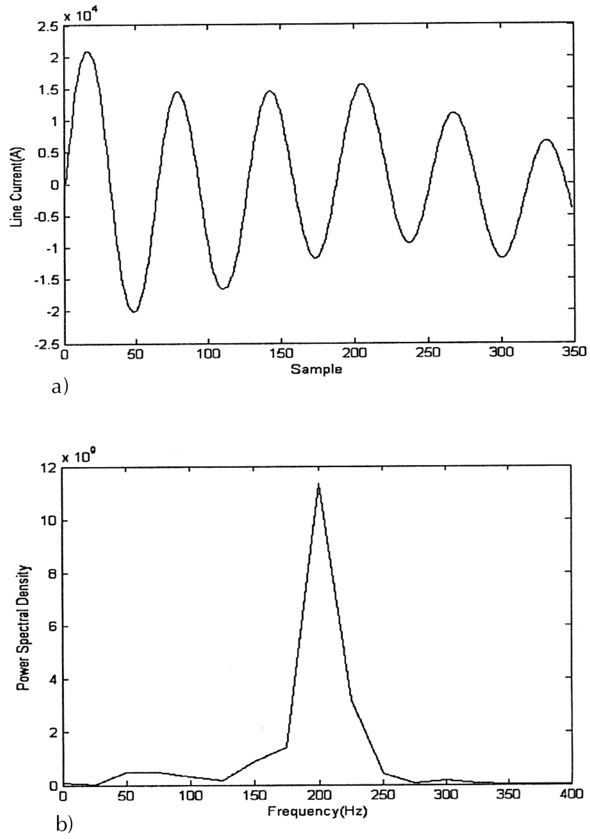


Fig. 12. Measured furnace line current (a) waveform (b) Fourier Transform—case 2

Abolfazl Zebardast was born in Qazvin, Iran, in 1974. He received his B.Sc. degree in Electronic Engineering from Razi University, Iran in 1998. In 2001, he received his M.S.c. degree from the University of Mazandaran, Iran. He is currently working as a lecturer at Qazvin Azad University.

Mostafa Parniani was born in Tehran, Iran in 1963. He received his B.Sc. degree in Electrical Engineering from Amirkabir University, Tehran, Iran in 1987. He worked as a consultant engineer for Electric Power Research Center (EPRC) and Ghods Niroo Co. in Tehran. He obtained his Ph.D. degree in Electrical Engineering from the University of Toronto in 1995. He is currently an assistant professor in the Electrical Engineering department of Sharif University of Technology. His research interest includes power system dynamics and control and Flexible AC Transmission Systems (FACTS).