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Control of Harmonics Generated by Alternating Current Electric Arc Furance and Laddle Furnace

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An arc of an electric arc furnace as a virtual short circuit is purely resistive load but the reactor connected in series with primary of furnace transformer to smoothen the arc makes the total combination as an inductive load, with its fluctuating active and reactive power requirements, it leads to power quality issues such as poor power factor, harmonic generation, etc. This paper presents measurement and analysis of harmonics generated by alternate current electric arc furnace (AC EAF) and laddle furnace (LF) loads and also defines terms like harmonics, total harmonic distortion etc. Harmonic Filter Banks (HFB) of static Var compensator (SVC) are tuned to particular order of frequency to provide least resistance path to that order of harmonics for elimination. This paper also describes design criteria for harmonic filter banks of 100 Hz, 150 Hz and 200 Hz and presents the SVC as a solution for control of harmonics. The final results are compared with allowable limits set by international standards.

Keywords: *Alternate current electric arc furnace (AC EAF), Laddle furnace (LF), Harmonics, Total harmonic distortion, Harmonic filter banks (HFB) and Static Var compensators (SVC).*

1.0 INTRODUCTION

India produces about 70 million tonne of steel per annum from its installed capacity of 80 million tonne. India's per capita steel consumption of steel has gone up by around 25% in the last five years to 57 kg/person year in 2011 [1]. The specific energy consumption of an integrated steel plant is around 1000 kWh/tonne of finished steel. The electric arc furnace is heart of any integrated steel plant used for melting of steel [2]. The specific energy consumption of an alternate current electric arc furnace (AC EAF) is about 200 kWh/tonne and of a direct current electric arc furnace (DC EAF) is about 400 kWh/tonne for charged hot iron as raw material. Nonlinear, chaotic and short time varying loads like alternating current electric arc furnace (AC EAF) with their almost instantaneous fluctuations in both active and reactive power requirements leads to power quality issues like harmonic generation, poor power factor, current and voltage unbalances, voltage flickers, voltage dip and swells.

The direct smelting of iron containing materials, mainly scrap, is usually performed in electric arc furnaces. An electric arc furnace is a large refractory lined steel pot, fitted with a refractory roof through which three vertical graphite electrodes are inserted, as shown in Figure 1. The metal charge is melted with resistive heating generated by electrical current flowing among the electrodes and through the charge [3].

This study had considered CONARC alternating current electric arc furnace of 200 tonne capacity with transformer rating of 165 MVA, 33/1.45 kV and Laddle Furnace of 200 tonne capacity with

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transformer rating of 25 MVA, 33/1.45 kV. Figure 2 gives the single line diagram of furnace and the SVC. Reactor is connected in series with furnace transformer primary to smoothen the electric arc.

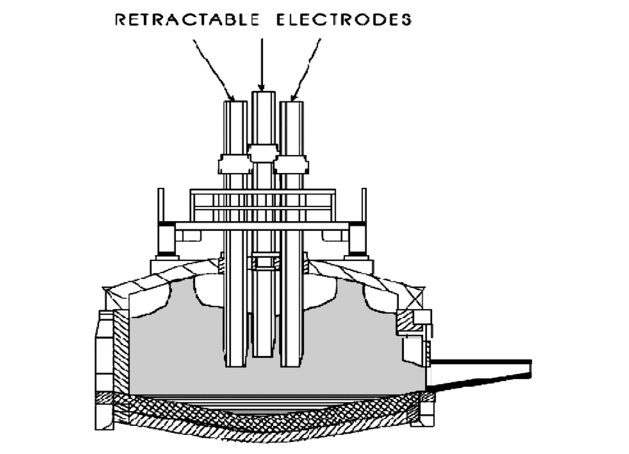

FIG. 1 SCHEMATIC OF ELECTRIC ARC FURNACE.

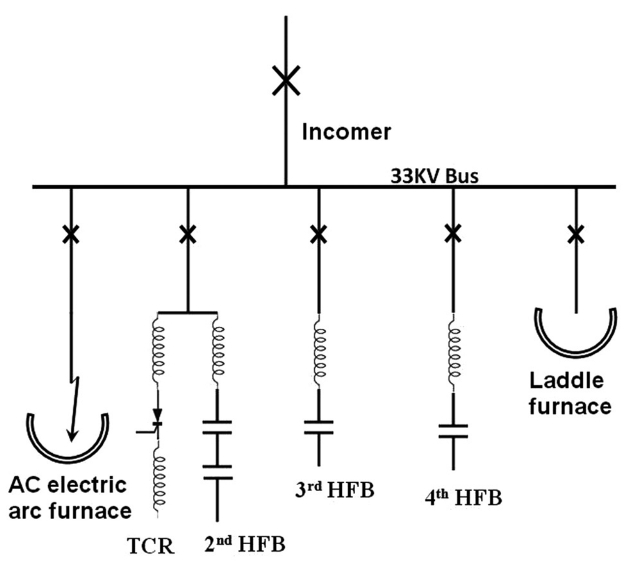

FIG. 2 SINGLE LINE DIAGRAM OF AC EAF AND SVC.

Shunt connected SVC for harmonic control consists of harmonic filter banks of 100 Hz, 150 Hz and 200 Hz.

Harmonics can be defined as sinusoidal voltage and current having frequencies that are integer multiple of fundamental supply frequency [4]. Any signal component having a frequency which is not an integer multiple of the fundamental frequency can be designated as inter harmonic component or referred to more simply as an inter harmonic. Harmonic disturbances are generally caused by loads like AC EAFs with nonlinear voltage/current characteristic and are mainly the result in use of modern power electronic components. The harmonic current from different sources produces harmonics voltage drops across the impedance of network. The result of all the single harmonics coming from different sources is obtained by the vector addition of the single elements [5–6].

Total harmonic distortion (THD) of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency [7–8]. THD is used to characterize the linearity of audio systems and the power quality of electric power systems. Generally the current values are described as demand factors and thereby the total current harmonics are described as Total demand distortion (TDD). The TDD is defined as the harmonic current distortion express as a percentage of maximum demand load current using 15 or 30 min demand period. The crest factor or peak-to-average ratio is a measurement of a waveform, calculated from the peak amplitude of the waveform divided by the root mean square value of the waveform [9].

$$\mathrm{THD} = \sqrt{\frac{\text{Sum of squares of amplitudes of harmonics}}{\text{Square of amplitude of fundamental}}} \times 100\% \quad ..(1)$$

$$\mathrm{THD(voltage)} = \sqrt{\frac{(V_2)^2 + (V_3)^2 + (V_4)^2 + (V_5)^2 + ... + (V_n)^2}{(V_1)^2}} \times 100\% \quad ...(2)$$

$$\mathrm{TDD(current)} = \sqrt{\frac{(I_2)^2 + (I_3)^2 + (I_4)^2 + (I_5)^2 + ... + (I_n)^2}{(I_1)^2}} \times 100\% \quad ...(3)$$

2.0 CONARC FURNACE PROCESS

In conventional DC electric arc furnace raw material (hot briquetted iron and direct reduced iron (DRI)) is first charged in furnace shell and then electric arc is initiated for melting [10].

Sometimes due to topography of shells it is difficult to charge directly the hot iron metal into shell. The specific energy consumption (SEC) for CONARC EAF is about 200 kWh/tonne of steel and is much lower compared to similar capacity of conventional DC EAF of 400 kWh/tonne of steel [11].

The CONARC concept combines the conventional Converter process with electric ARC steel making in a furnace having two identical shells. The furnace is equipped with common one set of electrodes which are connected to a transformer and can be lowered and raised alternatively over each of two shells. The oxygen is injected through a water cooled top lance.

The AC CONARC furnace is split into two stages. During converter process, the liquid iron is decarburised by injection of oxygen through the top lance and during the electric arc process, electrical energy is used for melting of cold charge (DRI or scrap) and for the super heating of the bath to tapping temperature.

The process starts with the charging of hot metal into a small part of the previous melt kept in the furnace. After top lance is brought into position, the oxygen blow is initiated. During the converter phase, the contents of carbon, silicon, manganese and phosphorus in the bath are reduced. These reactions are exothermic, i.e. they generate heat. Cold material like DRI or scrap is added to the furnace to utilise this energy and to avoid overheating of the bath.

After completion of the decarburisation process, the top lance is slewed away and electrodes are bought into operating position. In the arcing phase, the remaining solid charge material like scrap or sponge iron is fed into the bath until the desired tapping weight is reached. The temperature of the bath is then increased to the required value, where upon the heat is tapped into a Laddle.

Flexibility regarding the raw material input composition is another feature of the CONARC technology. This enables the operator to minimize the production costs by selecting a mix according to quality requirements as well as the availability and price of the raw materials and of the energy sources (primary: coal, oil and oxygen and secondary: electrical power).

The CONARC has proven that a production in the range of 100% direct reduced iron and also 100% scrap is possible. It is also demonstrated that the tap to tap time could be constantly adjusted in the range of less than 60 minutes with the same productivity.

3.0 MODELLING OF AC ELECTRIC ARC FURNACE

Kirchhoff's Current Law (KCL) can be used to equate voltages and currents for analysis of electrical circuit of EAF [12].

Figure 3 shows four nodes, one for each of the electrodes and the fourth representing the virtual ground at the matte (V_m).

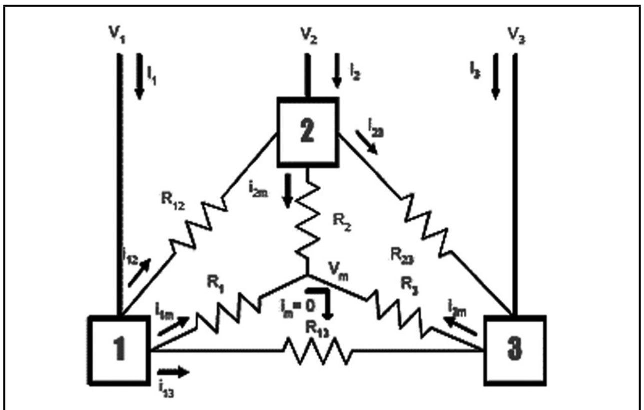

FIG. 3 ELECTRIC ARC MODEL OF THREE PHASE AC EAF.

Using these nodes, it is possible to determine the current in each electrode with respect to each voltage and the conductance coefficients, using its position as the input [13].

The following sets of equations can be obtained by applying KCL to each of the four nodes.

The Current Matrix Model can be represented as:

$$[I_i] = [G_{ij}][x_i] + [B_i]$$

Where

I_i is current matrix for electrode currents,

G_{ij} is conductance matrix and

B_i is a constant matrix.

The currents at nodes 1, 2 and 3 are modeled as:

$$I_1 = G_{12}(V_1 - V_2) + G_1(V_1 - V_m) + G_{13}(V_1 - V_3) \quad \ldots (4)$$

$$I_2 = -G_{12}(V_1 - V_2) + G_2(V_2 - V_m) + G_{23}(V_2 - V_3) \ldots (5)$$

$$I_3 = G_3(V_3 - V_m) - G_{13}(V_1 - V_3) + G_{23}(V_2 - V_3) \quad \ldots (6)$$

$$G_1(V_1 - V_m) + G_2(V_2 - V_m) + G_3(V_3 - V_m) = 0 \quad \ldots (7)$$

The voltage (V_m) can be computed as:

$$V_m = \frac{G_1V_1 + G_2V_2 + G_3V_3}{G_1 + G_2 + G_3} \quad \ldots (8)$$

These three currents represent three electrodes of AC EAF. The total current (I_1) flowing through electrode 1 is modelled as:

$$I_1 = \frac{1}{G_T}\begin{bmatrix} x_1\begin{pmatrix} 2V_1c_1(G_s+G) - V_2c_1(G_s+G) - V_3c_1(G_s+G) \\ + c_1c_2x_2(V_1 - V_2) + c_1c_3x_3(V_1 - V_3) \end{pmatrix} \\ + x_2\left(V_1c_2(G_s+2G) - V_2c_2(G_s+G) - V_3c_2G\right) \\ + x_3\left(V_1c_3(G_s+2G) - V_2c_3G - V_3c_3(G_s+G)\right) \\ + (2V_1 - V_2 - V_3)(G_s^2 + 3GG_s) \end{bmatrix} \quad \ldots (9)$$

Similarly, the total currents $I_2$and $I_3$are computed as:

$$I_2 = \frac{1}{G_T}\begin{bmatrix} x_1\left(-V_1c_1(G_s+G) + V_2c_1(G_s+2G) - V_3c_1G\right) \\ + x_2\begin{pmatrix} -V_1c_2(G_s+G) + 2V_2c_2(G_s+G) - V_3c_3(G_s+G) \\ + c_2c_3x_3(V_2 - V_3) + c_1c_2x_1(V_2 - V_1) \end{pmatrix} \\ + x_3\left(-V_1c_3G - V_2c_3(G_s+2G) - V_3c_3(G_s+G)\right) \\ + (-V_1 + 2V_2 - V_3)(G_s^2 + 3GG_s) \end{bmatrix} \quad \ldots (10)$$

The electrode current of EAF are:

$$I_3 = \frac{1}{G_T}\begin{bmatrix} x_1\left(-V_1c_1(G_s+G) - V_2c_1G - V_3c_1(G_s+2G)\right) \\ + x_2\left(-V_1c_2G - V_2c_2(G_s+G) + V_3c_2(G_s+2G)\right) \\ + x_3\begin{pmatrix} -V_1c_3(G_s+G) - 2V_2c_3(G_s+G) + 2V_3c_3(G_s+G) \\ + c_1c_3x_1(V_3 - V_1) + c_2c_3x_2(V_3 - V_2) \end{pmatrix} \\ + (-V_1 - V_2 - +2V_3)(G_s^2 + 3GG_s) \end{bmatrix} \quad \ldots (11)$$

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \frac{1}{G_T}\begin{bmatrix} \begin{pmatrix} 2V_1c_1(G_s+G) \\ -V_2c_1(G_s+G) \\ -V_3c_1(G_s+G) \\ +c_1c_2x_2(V_1-V_2) \\ +c_1c_3x_3(V_1-V_3) \end{pmatrix} & \begin{pmatrix} V_1c_2(G_s+2G) \\ -V_2c_2(G_s+G) \\ -V_3c_2G \end{pmatrix} & \begin{pmatrix} V_1c_3G \\ -V_2c_3(G_s+2G) \\ -V_3c_3(G_s+G) \end{pmatrix} \\ \begin{pmatrix} -V_1c_1(G_s+G) \\ +V_2c_1(G_s+2G) \\ -V_3c_1G \end{pmatrix} & \begin{pmatrix} -V_1c_2(G_s+G) \\ +2V_2c_2(G_s+G) \\ -V_3c_3(G_s+G) \\ +c_2c_3x_3(V_2-V_3) \\ +c_1c_2x_1(V_2-V_1) \end{pmatrix} & \begin{pmatrix} -V_1c_3G \\ -V_2c_3(G_s+2G) \\ -V_3c_3(G_s+G) \end{pmatrix} \\ \begin{pmatrix} -V_1c_1(G_s+G) \\ -V_2c_1G \\ -V_3c_1(G_s+2G) \end{pmatrix} & \begin{pmatrix} -V_1c_2G \\ -V_2c_2(G_s+G) \\ +V_3c_2(G_s+2G) \end{pmatrix} & \begin{pmatrix} -V_1c_3(G_s+G) \\ -V_2c_3(G_s+2G) \\ +2V_3c_3(G_s+G) \\ +c_1c_3x_1(V_3-V_1) \\ +c_2c_3x_2(V_3-V_2) \end{pmatrix} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \frac{(G_s^2 + 3GG_s)}{G_T}\begin{bmatrix} 2V_1 - V_2 - V_3 \\ -V_1 + 2V_2 - V_3 \\ -V_1 - V_2 + 2V_3 \end{bmatrix} \quad \ldots (12)$$

The conductance matrix is nonlinear. Therefore this system cannot be controlled as a linear state space model. Therefore, linearization of the G_{ij} conductance matrix will be necessary to control this system with state feedback.

Another observation is that when the electrodes are positioned flush on the slag (i.e. x_1=x_2= x_3= 0), there is still a constant current passing through them. This constant value is represented by the second term in above Equation 12. It arises from the presence of G_s in the slagtomatte conductance.

4.0 RESULTS AND DISCUSSIONS

The power quality parameters of Electric arc furnace (CONARC) of 120 MW (33 kV) and Laddle furnace of 25 MW (33 kV) are measured by using power quality analyser as per IEEE 519 standard [14–15]. The results of the measured parameters are discussed below:

4.1 Electric Arc Furnace (EAF)

Figure 4 gives the variation of active power and reactive power for electric arc furnace. During arc, the active power is varying between 28.68–56.45 MW and reactive power is varying between 20.75–43.25 MVAr. The reactive power is high because of reactive nature of load. Figure 5 gives the variation of power factor and the power factor is varying between 0.76–0.86 during load. The power factor is poor during load.

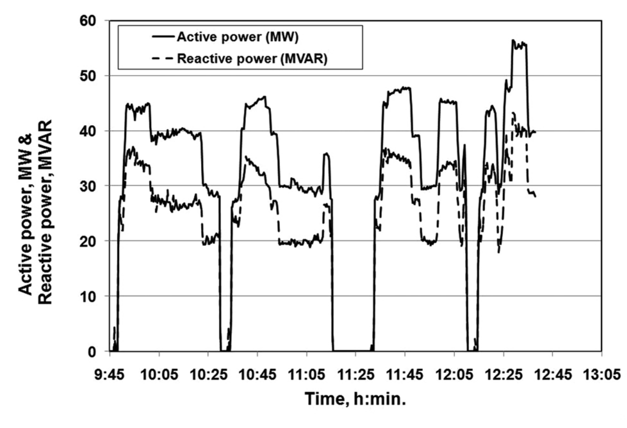

FIG. 4 VARIATION OF ACTIVE AND REACTIVE POWER AT EAF.

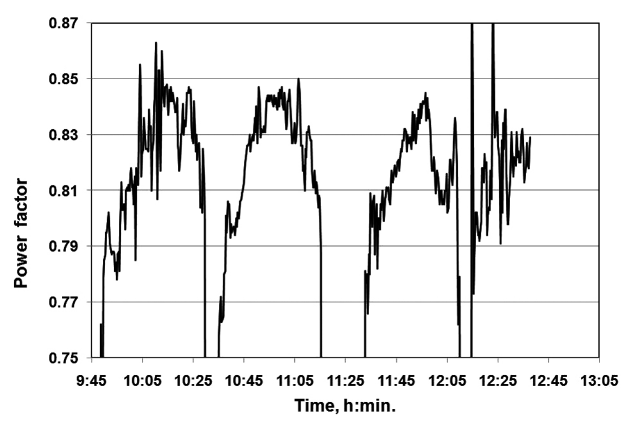

FIG. 5 VARIATION OF POWER FACTOR OF EAF.

Figure 6 shows the variation of current THD during load. Figures 7–9 show the variation of individual current harmonics in magnitude (A) and Figures 10–12 present harmonics in percentage.

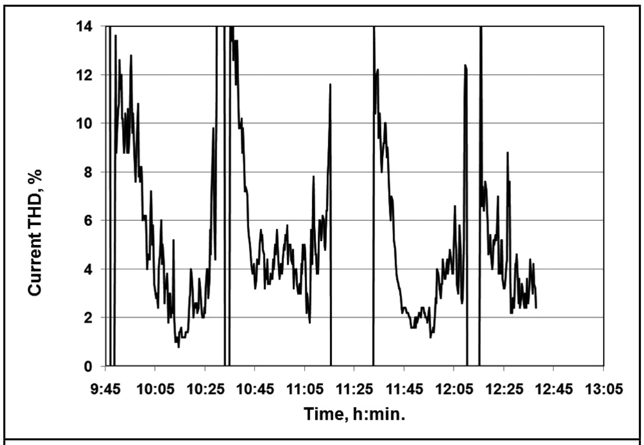

FIG. 6 VARIATION OF CURRENT THD AT EAF.

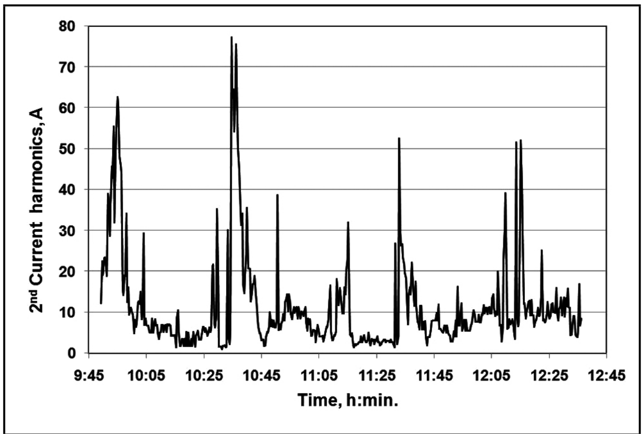

FIG. 7 VARIATION OF 2ND HARMONIC CURRENT OF EAF.

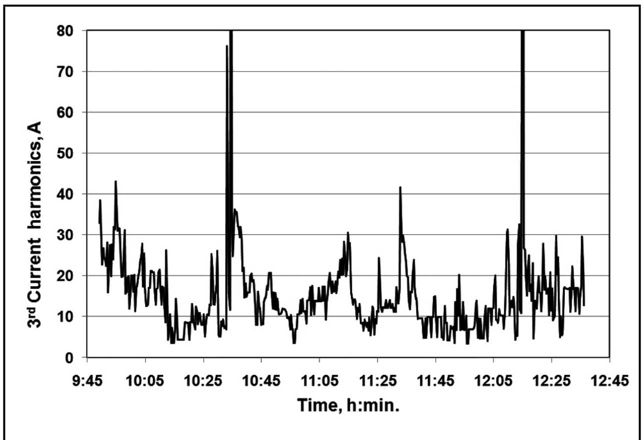

FIG. 8 VARIATION OF 3RD HARMONIC CURRENT OF EAF.

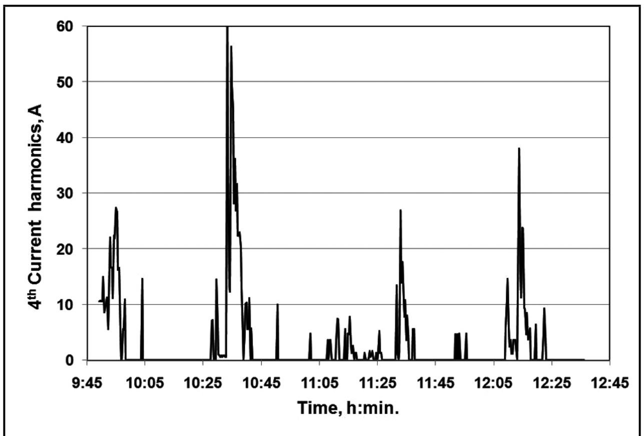

FIG. 9 VARIATION OF 4TH HARMONIC CURRENT OF EAF.

The variation of individual harmonics is during arc are in the range of:

a) **2nd harmonics**: 1.44 A (0.3%) to 77.32 A (15.3%)

b) 3rd harmonics: 3.64 A (0.7%) to 32.75 A (6.5%)

c) 4th harmonics: 7.23 A (1.4%) to 34.38 A (6.8%)

d) Current THD: 2.4–12.8%

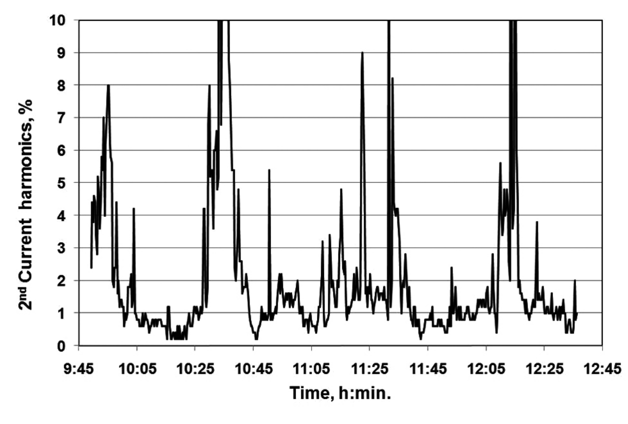

FIG. 10 VARIATION OF 2ND HARMONIC CURRENT OF EAF IN PERCENTAGE.

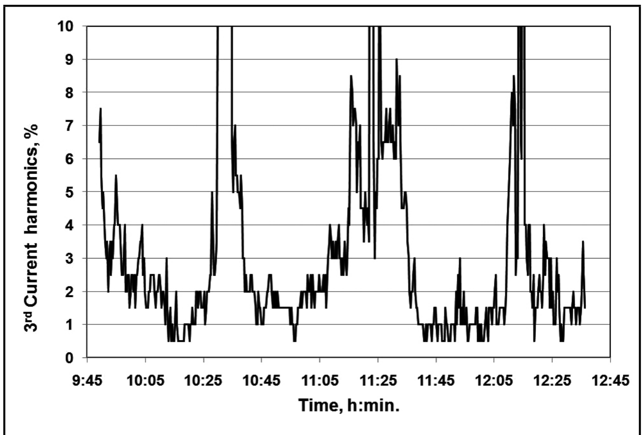

FIG. 11 VARIATION OF 3RD HARMONIC CURRENT OF EAF IN PERCENTAGE.

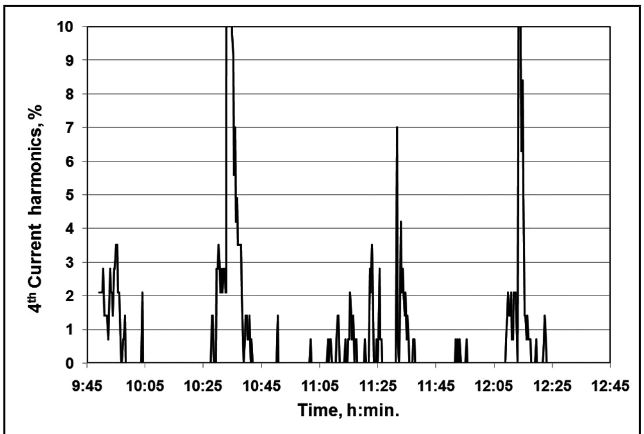

FIG. 12 VARIATION OF 4TH HARMONIC CURRENT OF EAF IN PERCENTAGE.

Whenever arcing is taking place, the reactive load is increased and a harmonic current in magnitude is increasing (harmonic current as percentage of fundamental value is decreasing). At no load or partial load, the current harmonic in magnitude is less but percentage is increased.

4.2 Laddle Furnace (LF)

The Laddle furnace is referred to as secondary metallurgy which is considered, in general, as being all the treatments of the steel melt, after the tapping step up to the beginning of the casting facilities. The aim of the secondary metallurgy in principle is the adjustment of the desired steel quality. The variety of steel types that can be produced via the EAF route requires different treatments of the melt in order to achieve the desired characteristics. The goals of the secondary metallurgy processes are:

- Improvement of the degree of purity,
- Reduction of non-ferrous inclusions,
- Reduction of carbon, sulphur, phosphorus, hydrogen, and nitrogen contents, and

Figure 13 gives the variation of active power and reactive power for electric arc furnace. During arc, the active power is varying between 16.71 MW–18.29 MW and reactive power is varying between 10.18 MVAr–12.08 MVAr. The reactive power is high because of reactive nature

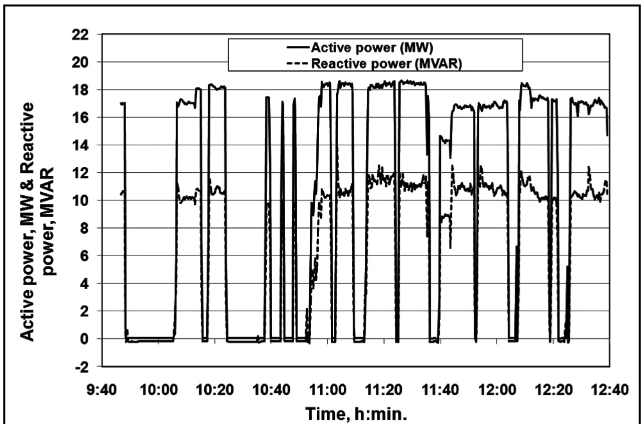

FIG. 13 VARIATION OF ACTIVE & REACTIVE POWER OF LF.

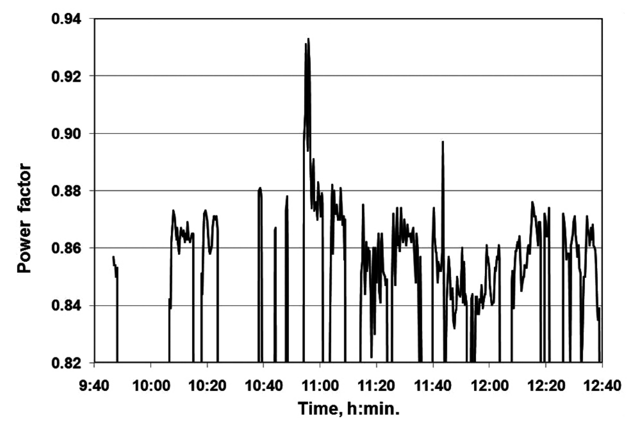

FIG. 14 VARIATION OF POWER FACTOR OF LF.

of load. Figure 14 gives the variation of power factor and the power factor is varying between 0.83–0.93 during load. The power factor is poor during load. Figure 15 shows the variation of current THD during load. Figures 16–18 show the variation of individual current harmonics in magnitude (Amps) and Figures 19–21 present harmonics in percentage. The variation of individual harmonics is during arc are in the range of:

a) **2nd harmonics**: 1.47 A (0.4 %) to 16.40 A (4.4 %)

b) **3rd harmonics**: 6.00 A (1.6 %) to 26.81 A (7.2 %)

c) **4th harmonics**: 0.70 A (0.2 %) to 11.67 A (3.1 %)

d) **Current THD**: 2.5 % to 4.3 %

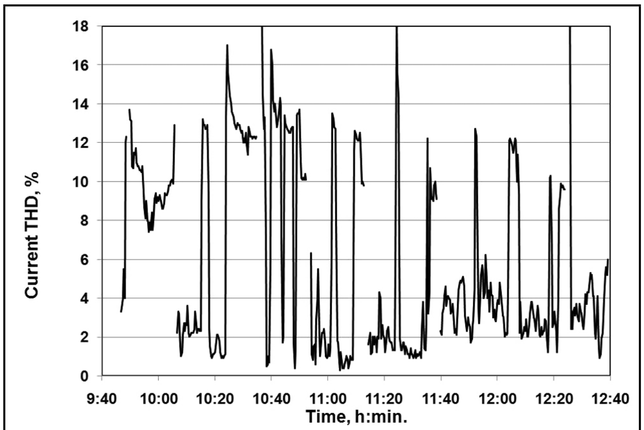

FIG. 15 VARIATION OF CURRENT THD OF LF.

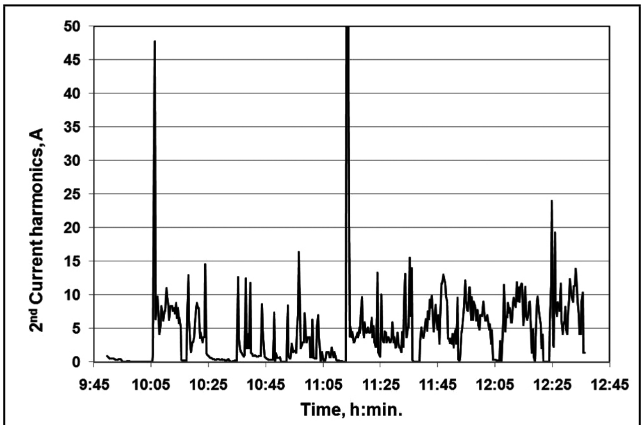

FIG. 16 VARIATION OF 2ND HARMONIC CURRENT OF LF.

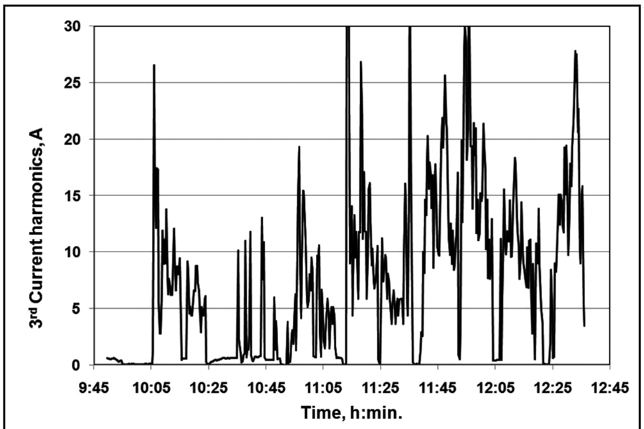

FIG. 17 VARIATION OF 3RD HARMONIC CURRENT OF LF.

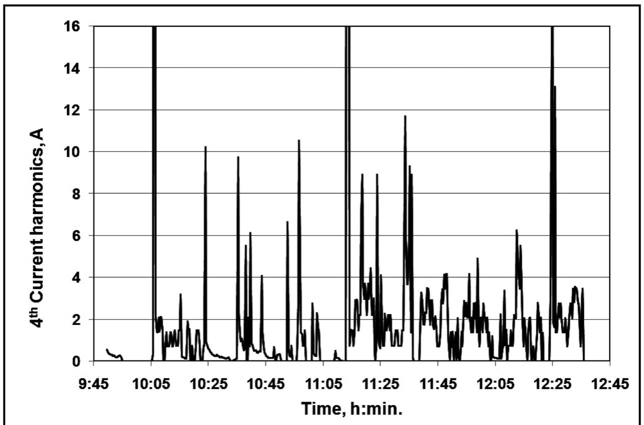

FIG. 18 VARIATION OF 4TH HARMONIC CURRENT OF LF.

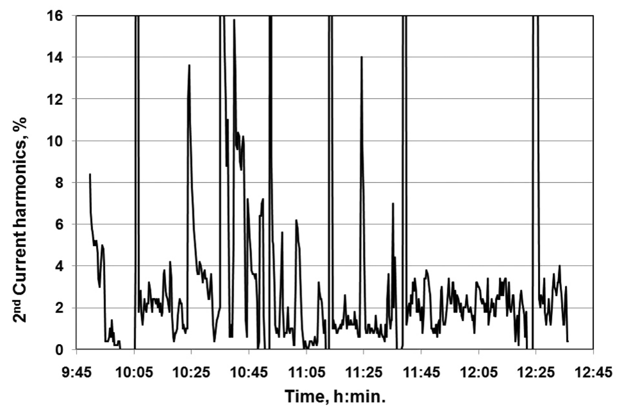

FIG. 19 VARIATION OF 2ND HARMONIC CURRENT OF LF IN PERCENTAGE.

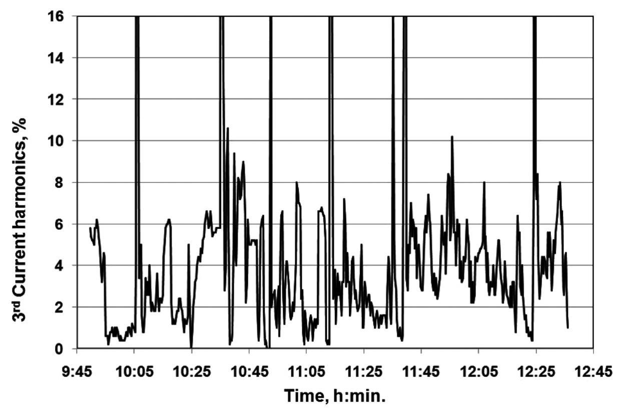

FIG. 20 VARIATION OF 3RD HARMONIC CURRENT OF LF IN PERCENTAGE.

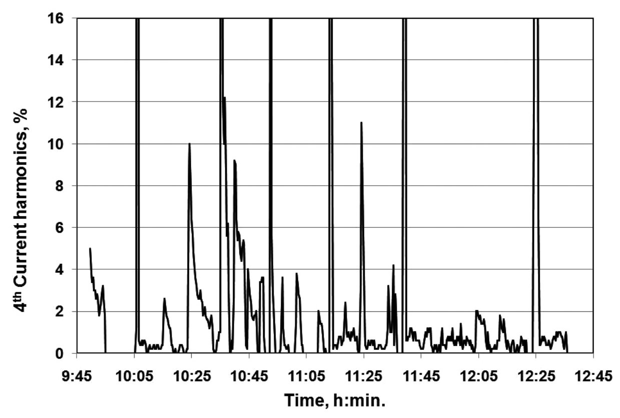

FIG. 21 VARIATION OF 4TH HARMONIC CURRENT OF LF IN PERCENTAGE.

5.0 HARMONIC FILTER BANK (HFB)

To overcome the power quality pollutants, harmonic filters are designed and installed for EAF and LF on a common bus [16]. The harmonic filters are of static Var compensators (SVC). The resonant frequency of HFB is normally expressed by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad ...(13)$$

Where,

f_0= resonant frequency in hertz, L = filter inductance in henrys, C= filter capacitance in farads.

The quality factor, Q_f, of the filter is the ratio between the inductive or capacitive reactance under resonance and the resistance. Typical values of Q_f fluctuate between 15 and 80 for filters that are used in industry [17].

5.1 2nd Harmonic Filter Bank (100 Hz)

The inductance and capacitance of the harmonic filters are given by the equipment supplier and are:

L = 18.9 mH,

C_1 = 540 μF,

C_2 = 180 μF [18]

Inductor L and capacitor C_1 are tuned for power frequency 50 Hz. As shown below:

$$\frac{1}{2\pi\sqrt{LC_1}} = \frac{1}{2*\pi*\sqrt{18.9\times10^{-3}\times540\times10^{-6}}} \approx 50 \text{ Hz} ...(14)$$

But the inductor L and combination of capacitor banks C_1 and C_2 (parallel) are tuned for the 2nd harmonic i.e. 100 Hz which is given by,

$$\frac{1}{2\pi\sqrt{L\frac{C_1\times C_2}{C_1+C_2}}}$$

$$= \frac{1}{2*\pi*\sqrt{18.9\times10^{-3}\times\left(\frac{540\times180}{540+180}\right)\times10^{-6}}} \approx 100 \text{ Hz} ...(15)$$

Impedances are computed as:

$$X_L = 2\pi fL = 5.9376\ \Omega \quad ...(16)$$

$$X_{C1} = \frac{1}{2\pi fC1} = 5.8946\,\Omega \quad ...(17)$$

$$X_{C2} = \frac{1}{2\pi fC2} = 17.683\,\Omega \quad ...(18)$$

$$X_{CTotal} = \frac{1}{2\pi f\left(\frac{C1\times C2}{C1+C2}\right)} = 23.5785\,\Omega \quad ...(19)$$

2nd Harmonic Tuning

$$h = \sqrt{\frac{X_{CTotal}}{X_L}} \approx 2^{nd} \text{ harmonic} \quad ...(20)$$

2nd Harmonic filter bank offers least resistance path to 2nd order harmonics thereby controlling 2nd order harmonics.

Reactive power of C_1 is computed as:

$$P_{VAR} = \frac{V_{L-L}^2}{X_{C1}} = \frac{(33000)^2}{5.89} = 184.88\ \text{MVAr} \quad ...(21)$$

Similarly reactive power of C_2 is computed as 61.56 MVAr.

Reactive power of L_1 is computed as:

$$P_{VAR} = \frac{V_{L-L}^2}{X_L} = \frac{(33000)^2}{5.9356} = 183.5\ \text{MVAr} \quad ...(22)$$

Hence the effective reactive power (capacitive) is:

$$P_{VAR} = (184.88 - 183.5) + 61.56$$
$$= 62.94\ \text{MVAr} \quad ...(23)$$

5.2 3rd Harmonic Filter Bank (150 Hz)

The inductance and capacitance of the harmonic filters are given by the equipment supplier and are:

L = 6.4 mH,

C_1 = 1600 μF,

C_2 = 200 μF [18]

Inductor L and capacitor C_1 are tuned for power frequency 50 Hz. As shown below:

$$\frac{1}{2\pi\sqrt{LC_1}}$$
$$= \frac{1}{2*\pi*\sqrt{6.4\times10^{-3}\times1600\times10^{-6}}} \approx 50\ \text{Hz} \quad ...(24)$$

But the inductor L and capacitor banks C_1 and C_2 (parallel) are tuned for the 3rdharmonic i.e. 150 Hz. it is found by,

$$\frac{1}{2\pi\sqrt{L\frac{C_1\times C_2}{C_1+C_2}}}$$
$$= \frac{1}{2*\pi*\sqrt{6.4\times10^{-3}\times\left(\frac{1600\times200}{1600+200}\right)\times10^{-6}}} \approx 150\ \text{Hz} \quad ...(25)$$

Impedances are computed as:

$$X_L = 2\pi fL = 2.0106\ \Omega \quad ...(26)$$

$$X_{C1} = \frac{1}{2\pi fC1} = 1.9894\,\Omega \quad ...(27)$$

$$X_{C2} = \frac{1}{2\pi fC2} = 15.915\,\Omega \quad ...(28)$$

$$X_{CTotal} = \frac{1}{2\pi f\left(\frac{C_1\times C_2}{C_1+C_2}\right)} = 17.905\,\Omega \quad ...(29)$$

$$h = \sqrt{\frac{X_{CTotal}}{X_L}} \approx 3^{rd} \text{ harmonic} \quad ...(30)$$

3nd Harmonic filter bank offers least resistance path to 3rd order harmonics thereby controlling 3rd order harmonics.

Reactive power of C_1 is computed as:

$$P_{VAR} = \frac{V_{L-L}^2}{X_{C1}} = \frac{(33000)^2}{1.9894} = 547.40\ \text{MVAr} \quad \text{...(31)}$$

Similarly reactive power of C_2 is computed as 68.43 MVAr.

Reactive power of L_1 is computed as:

$$P_{VAR} = \frac{V_{L-L}^2}{X_L} = \frac{(33000)^2}{2.0106} = 541.63\ \text{MVAr} \quad \text{...(32)}$$

Hence the effective reactive power (capacitive) is:

$$P_{VAR} = (547.40 - 541.63) + 68.43$$

$$= 62.94\ \text{MVAr} \quad \text{...(33)}$$

5.3 4th Harmonic Filter Bank (200 Hz)

The inductance and capacitance of the harmonic filters are given by the equipment supplier and are:

L = 2.5 mH, C_1 = 4000 μF, C_2 = 240 μF [18]

Inductor L and capacitor C_1 are tuned for power frequency 50 Hz. As shown below:

$$\frac{1}{2\pi\sqrt{LC_1}}$$

$$= \frac{1}{2 * \pi * \sqrt{2.5\times10^{-3}\times4000\times10^{-6}}} \approx 50\ \text{Hz} \quad \text{...(34)}$$

But the inductor L and capacitor banks C_1 and C_2 (parallel) are tuned for the 4^{th} harmonic i.e. 200 Hz. it is found by,

$$\frac{1}{2\pi\sqrt{L\frac{C_1\times C_2}{C_1+C_2}}}$$

$$= \frac{1}{2 * \pi * \sqrt{2.5\times10^{-3}\times\left(\frac{4000\times240}{4000+240}\right)\times10^{-6}}} \approx 200\ \text{Hz} \quad \text{...(35)}$$

Impedances are computed as:

$$X_L = 2\pi fL = 0.785\ \Omega \quad \text{...(36)}$$

$$X_{C1} = \frac{1}{2\pi fC1} = 0.796\ \Omega \quad \text{...(37)}$$

$$X_{C2} = \frac{1}{2\pi fC2} = 13.263\ \Omega \quad \text{...(38)}$$

$$X_{CTotal} = \frac{1}{2\pi f\left(\frac{C1\times C2}{C1+C2}\right)} = 14.059\ \Omega \quad \text{...(39)}$$

4^{th} Harmonic Tuning

$$h = \sqrt{\frac{X_{CTotal}}{X_L}} \approx 4^{th}\ \text{harmonic} \quad \text{...(40)}$$

4^{th}Harmonic filter bank offers least resistance path to 4^{th}order harmonics thereby controlling 4^{th}order harmonics.

Reactive power of C_1 is computed as:

$$P_{VAR} = \frac{V_{L-L}^2}{X_{C1}} = \frac{(33000)^2}{0.796} = 1368.09\ \text{MVAr} \quad \text{...(41)}$$

Similarly reactive power of C_2 is computed as 82.11 MVAr.

Reactive power of L_1 is computed as:

$$P_{VAR} = \frac{V_{L-L}^2}{X_L} = \frac{(33000)^2}{0.785} = 1387.26\ \text{MVAr} \quad \text{...(42)}$$

Hence the effective reactive power (capacitive) is:

$$P_{VAR} = (1368.09 - 1387.26) + 82.11$$

$$= 62.94\ \text{MVAr} \quad \text{...(43)}$$

6.0 MEASUREMENT OF HARMONICS AT INCOMER OF BUS SUPPLYING AC EAF, LF WITH SVC

The power to EAF, LF and SVC is fed from secondary side of 195 MVA, 220/33 kV power transformer whose short circuit MVA is 1267 MVA.

The harmonic filter banks of 210 MVAr are installed at main incomer to mitigate 2nd, 3rd and 4th harmonics as well as to provide reactive power to improve power factor of system.

Figure 22 gives the variation of active and reactive power at main incoming. The active power is varying 29.4–64.8 MW during arcing at both EAC and Laddle furnace and the reactive power is in the range of 1.05–1.46 MVAr.

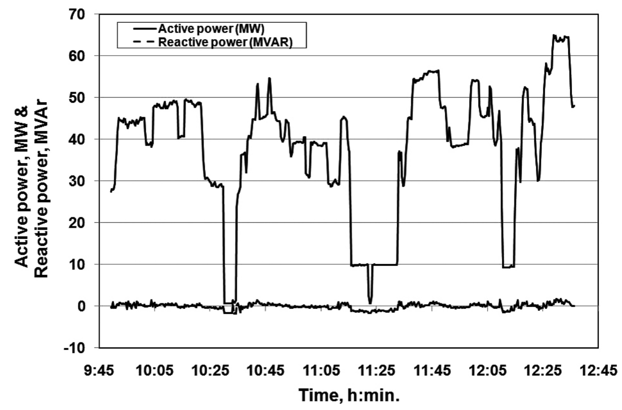

FIG. 22 VARIATION OF ACTIVE AND REACTIVE POWER AT MAIN INCOMER.

The reactive power is on lower side. Figure 23 gives the variation of power factor and the power factor is varying between 0.985–0.999 during load.

Figure 24 gives the variation of voltage THD at main incomer and is varying between 0.7–2.2%. As per IEEE 519 standard, the voltage THD must be < 5.0% and individual harmonics must be < 3%. The voltage harmonics are well within the limits prescribed by IEEE 519 standard.

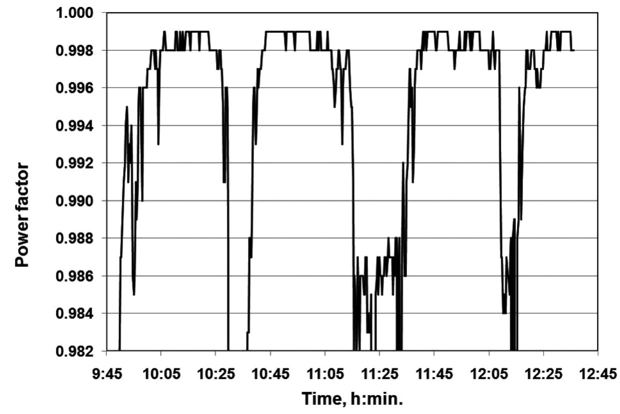

FIG. 23 VARIATION OF POWER FACTOR AT MAIN INCOMER.

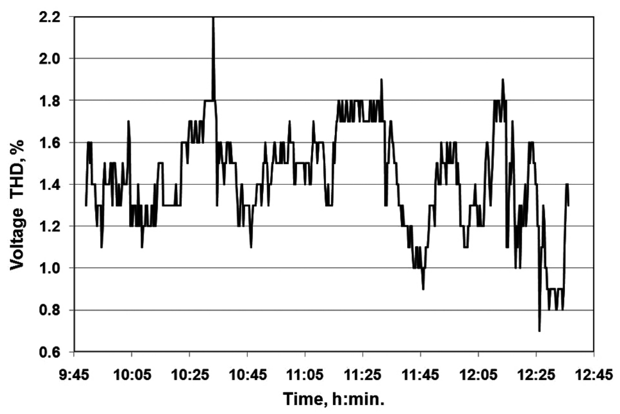

FIG. 24 VARIATION OF VOLTAGE THD AT MAIN INCOMER.

Figure 25 shows the variation of current THD during load. Figures 26–28 show the variation of individual current harmonics in magnitude (A) and Figures 29–31 present harmonics in percentage. The variation of individual harmonics is during arc are in the range of:

a) **2nd harmonics**: 0.70 A (0.1%) to 4.63 A (0.69%)

b) **3rd harmonics**: 0.51 A (0.08%) to 6.99 A (1.04%)

c) **4th harmonics**: 0.29 A (0.05%) to 3.91 A (0.58%)

d) **Current THD**: 1.15% to 3.35%

The short circuit current of the network is 22166 A and the (I_{SC}/I_L) ratio at point of common coupling (PCC) is 18.97 and is < 20.

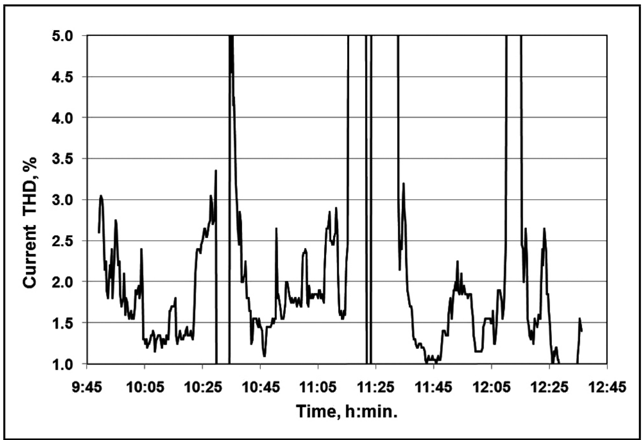

FIG. 25 VARIATION OF CURRENT THD AT MAIN INCOMER.

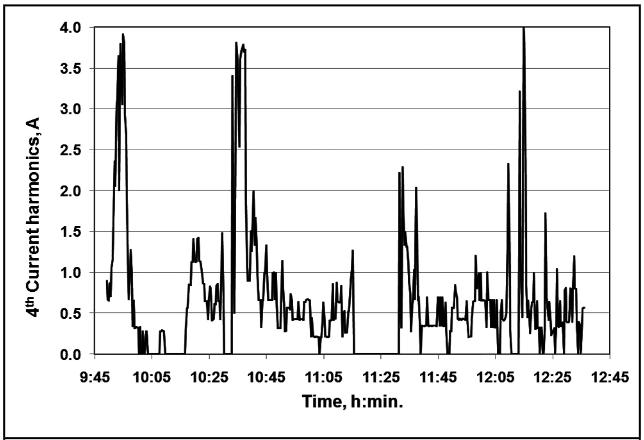

FIG. 28 VARIATION OF 4TH HARMONIC CURRENT AT MAIN INCOMER.

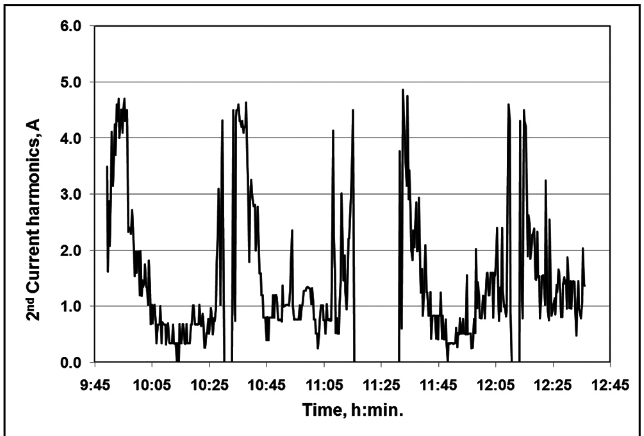

FIG. 26 VARIATION OF 2NDCURRENT HARMONIC AT MAIN INCOMER.

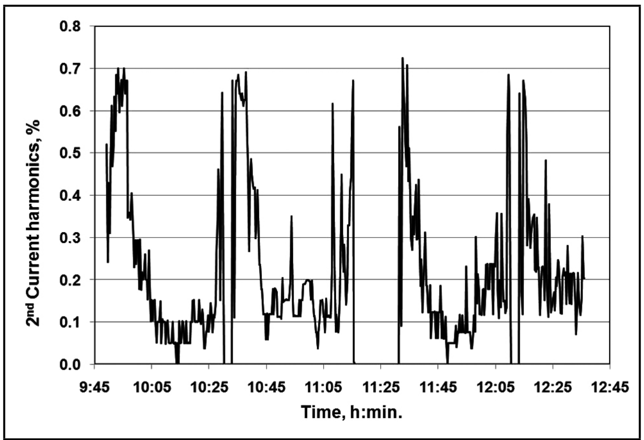

FIG. 29 VARIATION OF 2ND HARMONIC CURRENT IN PERCENTAGE AT MAIN INCOMER.

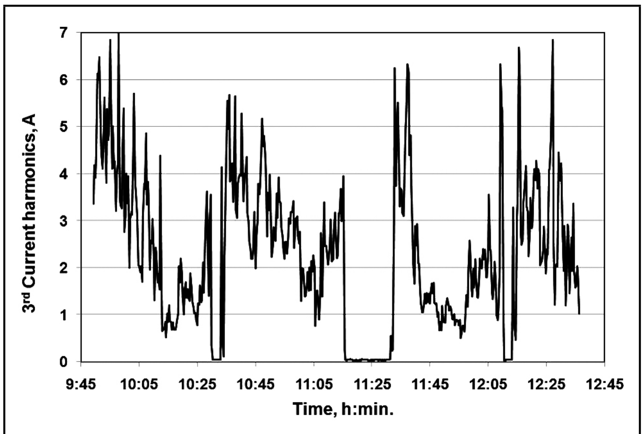

FIG. 27 VARIATION OF 3RD HARMONIC CURRENT AT MAIN INCOMER.

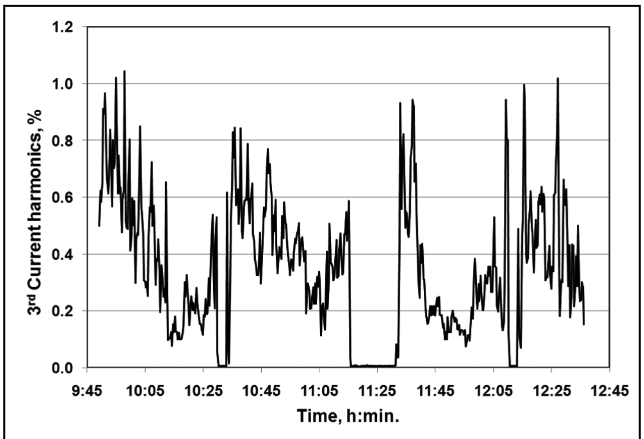

FIG. 30 VARIATION OF 3RD HARMONIC CURRENT IN PERCENTAGE AT MAIN INCOMER.

The individual current harmonics must be < 4.0% and TDD must be less than 5.0%. The measured current harmonics are much lower than the IEEE 519 standard at main incomer.

7.0 CONCLUSION

The specific energy consumption of the CONARC Alternate Current Electric Arc Furnace for one heat of hot metal is 200 kWh/tonne.

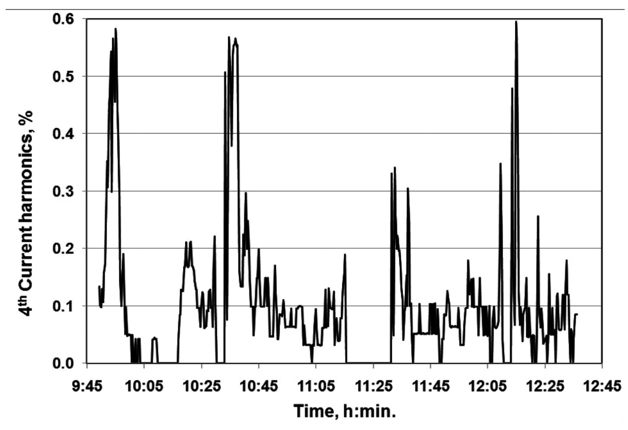

FIG. 31 VARIATION OF 4TH HARMONIC CURRENT IN PERCENTAGE AT MAIN INCOMER.

An electric arc is actually resistive load but reactor used to smoothen the arc makes the AC EAF purely inductive load creating power quality issues like generation of harmonics, poor power factor, etc.

Operation of the AC EAF and LF generates current harmonics, which distorts the supply voltage and current waveform. Harmonic Filter Banks of the SVC serves dual purpose of harmonic control and reactive power compensation.

Harmonic filter banks are tuned to particular harmonic order as per the AC EAF operation to remove the same order harmonic from system. Remaining harmonics amplitude is well under the limits defined by international standards as IEEE Std. 519–1992.

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