The Journal of CPRI,
Vol. 9, No. 1, March 2013 pp. 117–126

Comparison of Alternate Current Electric Arc Furnace with Direct Current Electric Arc Furnace with their Static Var Compensator configurations

Rajashekar P Mandi*, Janak J Patel**, Hitesh R Jariwala** and Ankur Vashi**

An electric arc is purely resistive load, but the series connected reactor to smoothen the arc makes the combination inductive load creating power quality issues like harmonic generation, poor power factor, voltage flickers etc. An electric arc furnace is heart of integrated steel plant used for smelting of steel with help of electric arc. Temperatures insider the furnace can reach up to 1800° centigrade and capacity wise electric arc furnaces are available from 1–300 tonnes. The charged material is directly exposed to the electric arc and results into hot liquid steel. The charged material can be steel scrap, direct reduced iron and hot metal. The electric arc furnace can be classified as alternate current electric arc furnace (AC EAF) and direct current electric arc furnace (DC EAF) depending upon source of power used at furnace for arcing. The objective of this review is to compare the configuration and harmonics generated by operation of AC EAF and DC EAF. Static Var compensator (SVC) is solution to mitigate the power quality issues generated by the electric arc furnace. This review also compares configurations of the SVCs used for AC EAF and DC EAF.

Keywords: *AC EAF, DC EAF, SVC, Harmonic filter bank (HFB) and Total demand distortion (TDD).*

1.0 INTRODUCTION

World crude steel production was 1518 million tonnes in 2011. Per capita finished steel consumption in 2011 was 215 kg for the world. In 2011–12 (provisional), production for sale of total finished steel (alloy and non alloy) in India was 73.42 million tonnes [4]. Mainly production of steel can be categorized as flat products (i.e. hot rolled coil, cold rolled coil) and long products (rebar, wire rod, angles, and channels). Integrated steel plant mainly consists of iron making unit, steel making unit and rolling units.

The specific energy consumption of an integrated steel plant is around 1000 kWh/tonnes of finished steel. The electric arc furnace as steel making unit is heart of any integrated steel plant used for melting of steel. The specific energy consumption of an alternate current electric arc furnace (AC EAF) is about 250 kWh/tonnes and of a direct current electric arc furnace (DC EAF) is about 400 kWh/tonnes for charged hot metal and direct reduced iron respectively as raw material.

Non linear, chaotic and short time varying loads like electric arc furnace (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.

*Energy Efficiency and Renewable Energy Division, Central Power Research Institute, Bangalore - 560 080, India. E-mail: mandi@cpri.in.
**Department of Electrical Engineering, SVNIT, Surat - 395 007, Gujarat, India. Email: hrj@eed.svnit.ac.in.

This review compares AC EAF and DC EAF and their SVCs with following configurations. Alternating current electric arc furnace of 200 tonne capacity with transformer of the rating 165 MVA, 33/1.45 kV. The power operating range for the AC EAF is up to 120 MW at 33 kV voltage level. Three phase reactor is connected in series with furnace transformer primary to smoothen the electric arc. Shunt connected SVC for harmonic elimination for the AC EAF consists of harmonic filter banks of 100 Hz, 150 Hz and 200 Hz [5].

Direct current electric arc furnace of 150 t capacity with rectifier transformer of rating 2 × 100 MVA, 33 kV/ 800 V DC. The power operating range for DC EAF is 120 MW at 33 kV voltage level. A DC link reactor is connected in series with transformer secondary to reduce the ripples in supply waveform and to smoothen the arc. Shunt connected SVC for harmonic elimination for the DC EAF consists of harmonic filter banks of 100 Hz, 150 Hz, 250 Hz, 350 Hz and 550 Hz [5].

2.0 CONFIGURATION OF AC EAF

An AC EAF has three round shaped electrodes corresponding to the three phases. The electrodes are automatically raised and lowered by either winch hoists or hydraulic cylinders controlled by a regulating system.

The power system of an AC EAF is shown in Figure 1 [1]. It consists of the grid, a high voltage/ medium voltage (HV/MV) power transformer, cables and bus bars, the EAF transformer, flexible cables, bus tubes and electrodes. Current drawn by three phases will be unbalance and chances of generating voltage flicker are always more with the AC EAF.

The AC EAF is rated to operate from 0 MW–120 MW at 33 kV voltage level. The AC EAF furnace transformer is rated 33 kV/1.45 kV, 165 MVA, delta-delta connection. The power rating of the AC EAF can be changed by changing the tap of AC EAF transformer. The utility supply is at 220 kV and HV/MV power transformer is 195 MVA, 220 kV/33 kV, star-star connected. The connection of power transformer secondary side to AC EAF feeding bus is with 33 kV power cables.

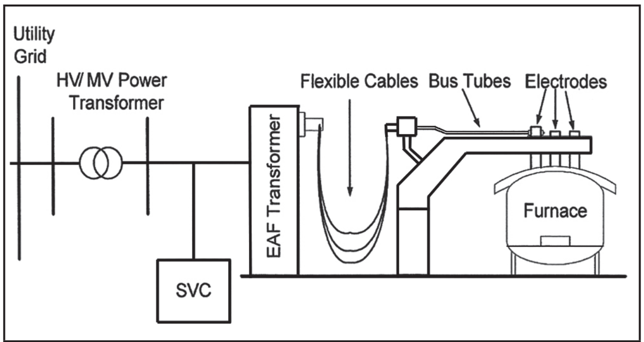

FIG. 1 ALTERNATE CURRENT ELECTRIC ARC FURNACE

Three phase reactor is connected in series with primary of AC EAF transformer to smoothen the electric arc. The secondary circuit of the AC EAF consists of flexible copper cables, bus tubes and electrodes. The resistance and inductance of this combination is in milli ohms and milli henry respectively. The value of arc resistance changes from 6–12 mΩ.

3.0 CONFIGURATION OF DC EAF

A DC EAF has only one round shaped electrode, conducting the DC current to smelt the scrap. DC current is achieved by rectifying the three phase AC current via a rectifier in front of the electrode. The electrode is automatically raised and lowered.

The power system of a DC EAF consists of a 12 pulse rectifier and a DC link reactor different from an AC EAF system as shown in Figure 2 [1].

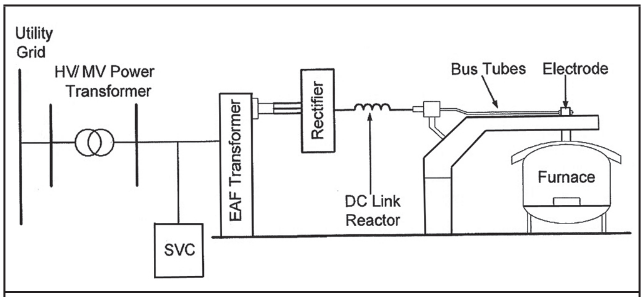

FIG. 2 DIRECT CURRENT ELECTRIC ARC FURNACE

Secondary circuit of the DC EAF also consists of flexible copper cables, bus tubes and electrodes.

The DC EAF consists on single electrodes as positive terminal and furnace shell as negative terminal.

The DC EAF is rated to operate from 0 MW–120 MW at 33 kV voltage level. The DC EAF furnace transformer is rated 33 kV / 800 V DC, 2 × 100 MVA. On secondary side of DC EAF transformer a 12 pulse rectifier is connected to convert AC supply to DC supply. Due to this 12 pulse rectifier, DC EAF generates large amount of 11^{th} and 13^{th} order harmonics. The power rating of the DC EAF can be changed by changing the tap of DC EAF transformer.

The DC link reactor is used to minimize the ripple content available in DC supply and to smoothen the arc. The DC reactor is basically an energy storage device. This is not very much energy but normally enough to keep the arc reasonably stable. There is always enough time to gradually discharge energy of DC reactor through already established arc in case of electrode breakage or scrap charge.

4.0 COMPARISON OF CONFIGURATIONS OF AC AND DC ELECTRIC ARC FURNACES

Table 1 compares configurations of AC EAF and DC EAF.

TABLE 1

COMPARISON OF CONFIGURATIONS OF AC AND DC EAF

Sl. No.	Descrip-tion	AC EAF	DC EAF
1	Electrodes	Three electrodes as per 3-phases	Single electrode as per positive potential. Furnace shell is at negative potential.
2	Rectifier	Not required	12 pulse rectifier in series with secondary side of furnace transformer
3	Reactor	3-phase reactor in series with primary of furnace transformer	DC link reactor in series with secondary of EAF transformer.
4	Secondary current	AC current up to 40 kA	DC current up to 60 kA

5.0 ACTIVE POWER, REACTIVE POWER, THREE PHASE VOLTAGES AND CURRENTS OF AC EAF

Figures 3–5 [2] indicates active and reactive power requirements, voltages and currents of AC EAF respectively.

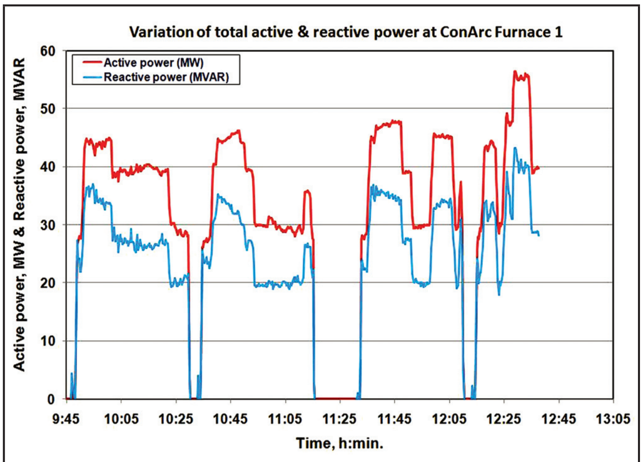

FIG. 3 ACTIVE AND REACTIVE POWER OF AC EAF

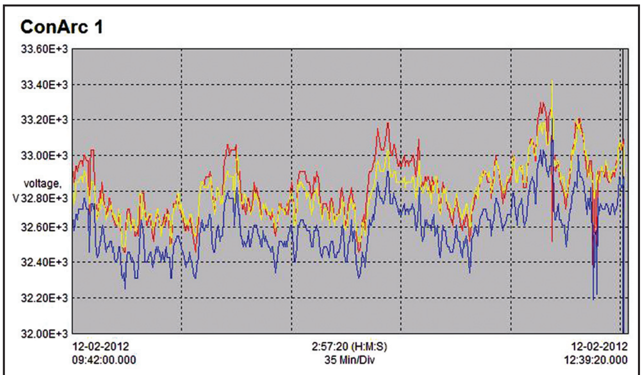

FIG. 4 THREE PHASE VOLTAGES OF AC EAF

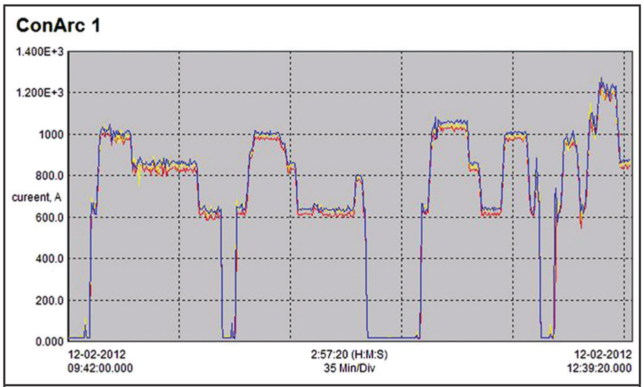

FIG. 5 3-PHASE CURRENTS OF AC EAF

6.0 ACTIVE POWER, REACTIVE POWER, THREE PHASE VOLTAGES AND CURRENTS OF DC EAF

Figures 6–8 [2] indicates active and reactive power requirement, voltages and currents of DC EAF respectively.

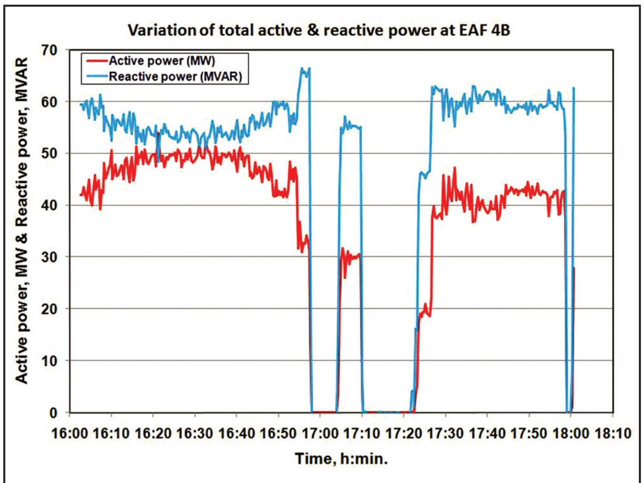

FIG. 6 ACTIVE AND REACTIVE POWER OF DC EAF

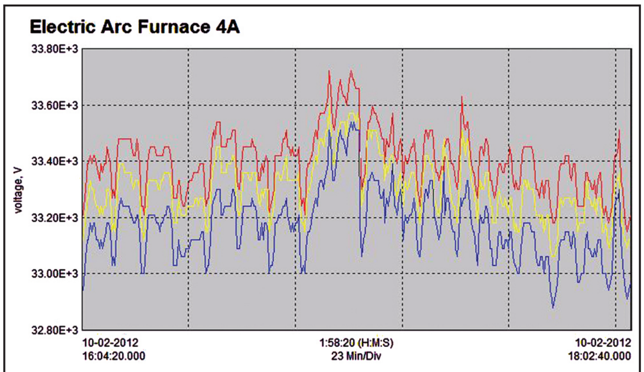

FIG. 7 3-PHASE VOLTAGES (PRIMARY SIDE) OF DC EAF

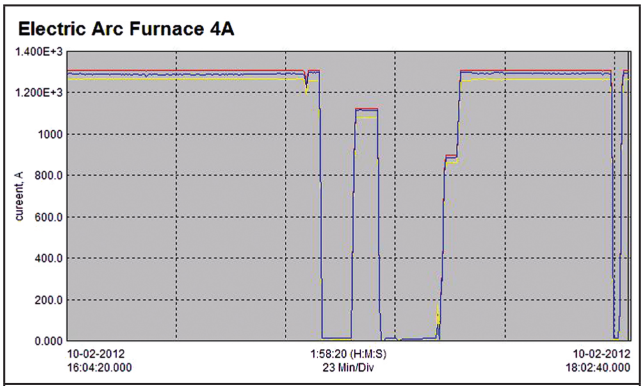

FIG. 8 3-PHASE CURRENTS (PRIMARY SIDE) OF DC EAF

7.0 HARMONICS GENERATED BY AC EAF

Regarding individual current harmonics:

Figures 9–13 [2] indicates harmonics generated by AC EAF [6].

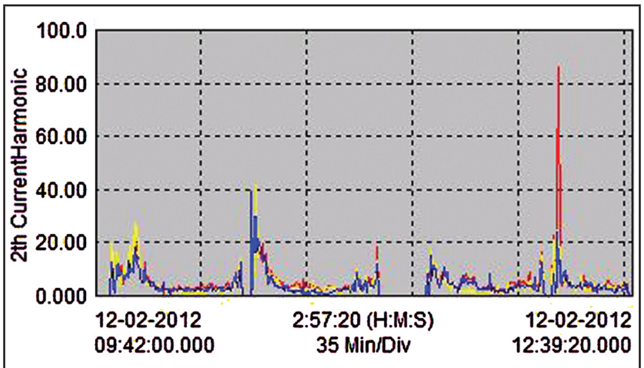

FIG. 9 2ND CURRENT HARMONIC: 3.65 A (0.3%)

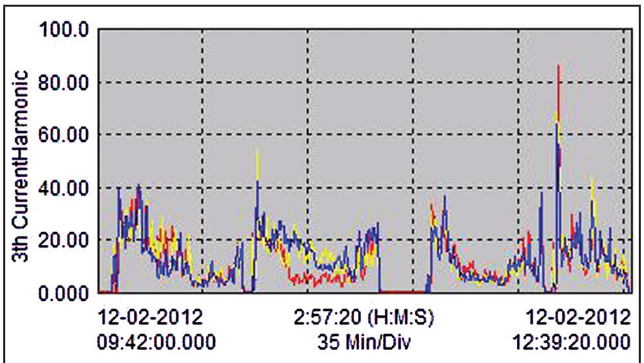

FIG. 10 3RD CURRENT HARMONIC: 19.50 A (1.6%)

For the considered AC EAF:

$$I_{FL} = 2886.75 \text{ A} \quad \text{..... (1)}$$

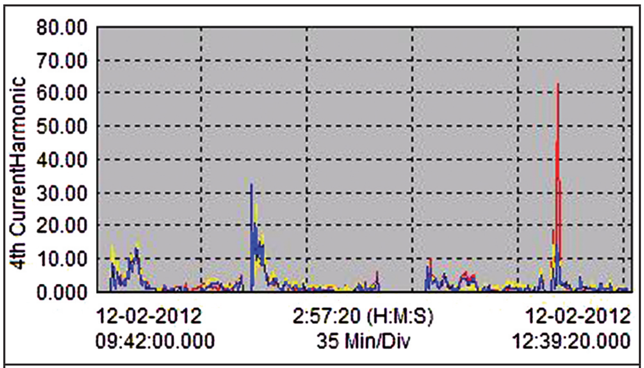

FIG. 11 4TH CURRENT HARMONIC: 2.54 A (0.2 %)

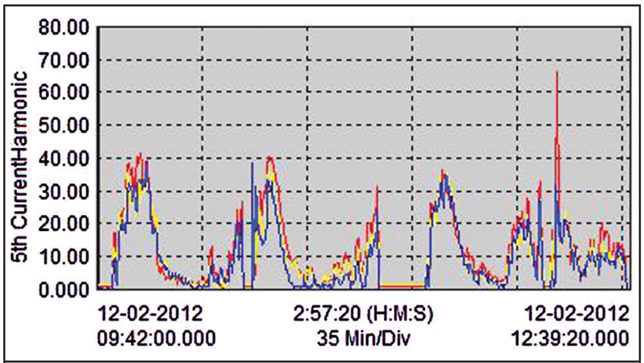

FIG. 12 5TH CURRENT HARMONIC: 14.84 A (1.2 %)

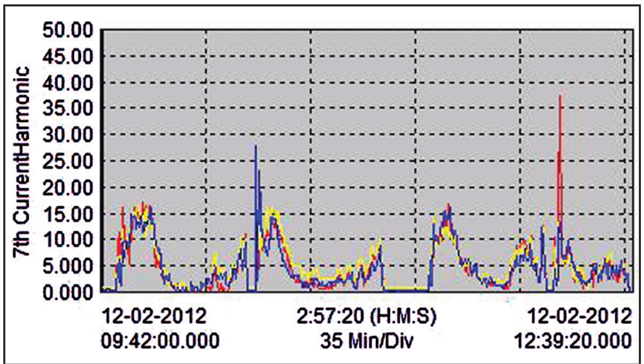

FIG. 13 7TH CURRENT HARMONIC: 6.09 A (0.5%)

I_{SC} =2886.75×100×1.075/14 ≈ 22166 A ..... (2)

I_{SC}/I_L = 22166/1270.3 = 17.45 ..... (3)

The I_{SC}/I_L ratio is 17.45 and is < 20.

The total demand distortion (TDD) must be less than 5.0% as per IEEE 519 [3] standard but the actual measured value is 2.1% which is lower than the limit.

The 5th harmonic is 1.6% and is also lower than the limit of 4.0%.

Mainly the AC EAF generates 2nd, 3rd, 4th, 5th and 7th order harmonic.

8.0 HARMONICS GENERATED BY DC EAF

Regarding individual current harmonics:

Figures 14–17 [2] indicates harmonics generated by DC EAF

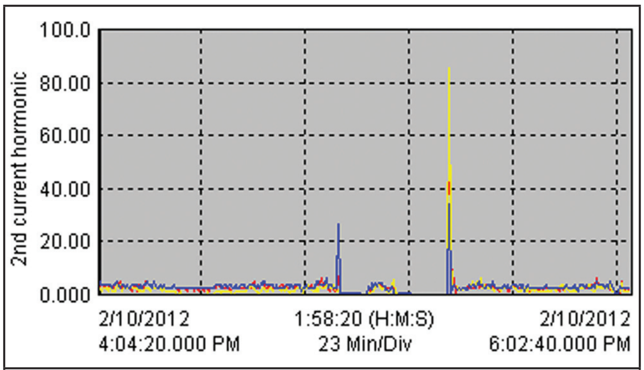

FIG. 14 2ND CURRENT HARMONICS: 2 A (0.3%)

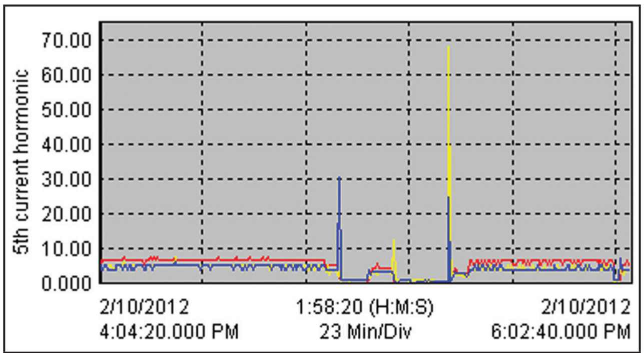

FIG. 15 3RD CURRENT HARMONICS: 5 A (0.5%)

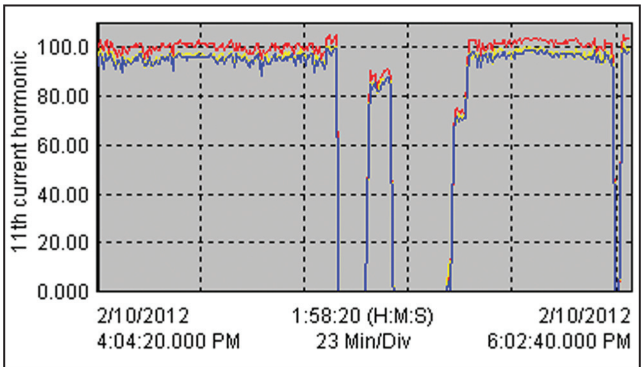

FIG. 16 11TH CURRENT HARMONIC: 100.28 A (7.7%)

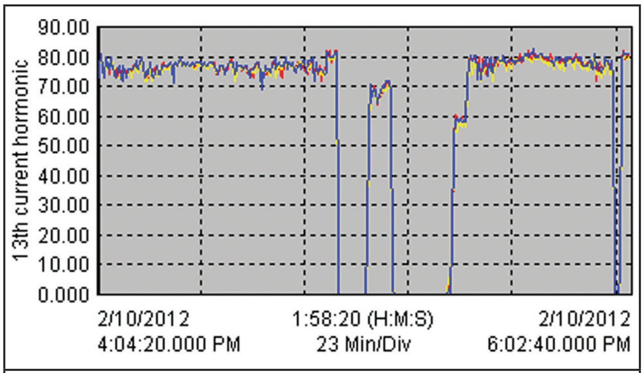

FIG. 17 13TH CURRENT HARMONIC: 76.84 A (5.9%)

For the considered DC EAF:

I_{FL}= 2799 A .... (4)

I_{SC} =2799×100×1.075/14 ≈ 21492 A .... (5)

I_{SC}/I_L = 21492/1309.4 = 16.41 .... (6)

The I_{SC}/I_L ratio is 16.41 and is < 20.

The TDD must be less than 5.0% as per IEEE 519 [3] standard but the actual measured value is 10.1% which is higher than the limit.

The 11th harmonic is 7.7% and is also higher than the limit of 4.0%. The SVC and harmonic filters installed compensate these current harmonics and limit them well under allowable limits of 4.0% as per IEEE 519 standard.

The DC EAF mainly generates odd order harmonics like 3rd, 5th, 7th, 11th and 13th.

The DC EAF consists of twelve pulse rectifier to converts AC supply to DC supply, generates dominant 11th (n–1) and 13th (n+1) order harmonics.

9.0 STATIC VAR COMPENSATOR (SVC) FOR EAF

Static Var compensator (SVC) is the solution to eliminate the power quality issues generated by the electric arc furnaces. SVC mainly consists of thyristor controlled reactor (TCR) and harmonic filter bank (HFB). TCR is made up of delta connected reactors which consumes reactive power. The HFB serves dual purpose of reactive power generation and harmonic elimination. HFB are mechanically switched and feeds continuous reactive power, which is compensated by EAF and TCR in combination. The TCR is active part of the SVC and firing of thyristors of TCR is varied depending upon the operation of EAF.

10.0 STATIC Var COMPENSATOR FOR AC ELECTRIC ARC FURNACE

The SVC for AC EAF is rated 210 MVAr (Capacitive)/230 MVAr (Reactive). This means the SVC is capable to generate 210 MVAr reactive power through harmonic filter banks and is capable to absorb 230 MVAr reactive power through thyristor controlled reactor at power frequency.

The SVC for AC EAF consists of [5]:

Thyristor controlled reactor: 230 MVAr

2nd Harmonic Filter Bank: 63 MVAr

3rd Harmonic Filter Bank: 63 MVAr

4th Harmonic Filter Bank: 84 MVAr

Total reactive power of HFBs: 210 MVAr

Figure 18 [2] indicates that reactive power drawn by AC EAF from incomer is almost nil, proving that reactive power required by AC EAF is compensated by the SVC.

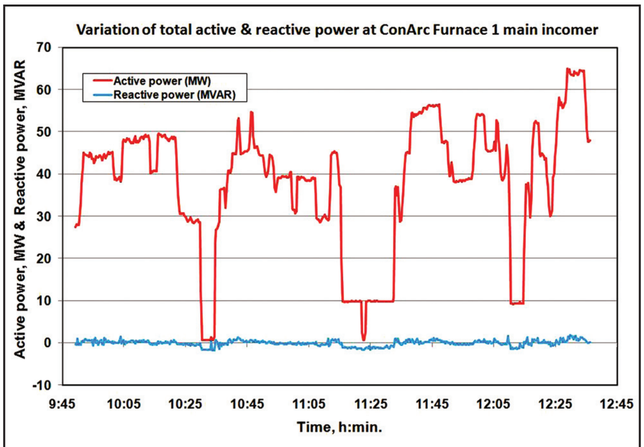

FIG. 18 ACTIVE AND REACTIVE POWER OF INCOMER WITH LOAD OF AC EAF WITH SVC

11.0 STATIC Var COMPENSATOR FOR DC ELECTRIC ARC FURNACE

The SVC for DC EAF is rated 175 MVAr (Capacitive)/180 MVAr (Reactive). This means the SVC is capable to generate 175 MVAr reactive power through harmonic filter banks and is capable to absorb 180 MVAr reactive power through thyristor controlled reactor at power frequency.

The SVC for DC EAF consists of [5]:

Thyristor controlled reactor: 180 MVAr

2nd Harmonic Filter Bank: 36 MVAr

3rd Harmonic Filter Bank: 27 MVAr

5th Harmonic Filter Bank: 35 MVAr

7th Harmonic Filter Bank: 23 MVAr

11th Harmonic Filter Bank: 54 MVAr

Total reactive power of HFBs: 175 MVAr

Figure 19 [2] indicates that reactive power drawn by DC EAF from incomer is almost nil, proving that reactive power required by DC EAF is compensated by the SVC.

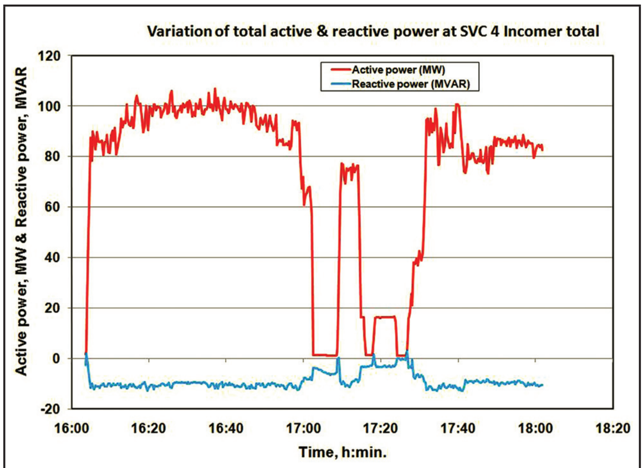

FIG. 19 ACTIVE AND REACTIVE POWER AT INCOMER WITH LOAD OF DC EAF WITH SVC

12.0 COMPARISON OF STATIC Var COMPENSATOR (SVC) FOR AC EAF AND DC EAF

Table 2 compares SVC configurations of AC EAF and DC EAF [5]:

TABLE 2

COMPARISON OF SVC CONFIGURATION FOR AC AND DC EAF

Description	AC EAF	DC EAF
Furnace Capacity	200 tonne	150 tonne
SVC Rating (Capacitive)	210 MVAr	175 MVAr
SVC Rating (Inductive)	230 MVAr	180 MVAr
TCR	230 MVAr	180 MVAr
2nd Harmonic Filter Bank	63 MVAr	36 MVAr
3rd Harmonic Filter Bank	63 MVAr	27 MVAr
4th Harmonic Filter Bank	84 MVAr	Not required
5th Harmonic Filter Bank	Not required	35 MVAr
7th Harmonic Filter Bank	Not required	23 MVAr
11th Harmonic Filter Bank	Not required	54 MVAr

13.0 ADVANTAGES AND DISADVANTAGES OF AC AND DC EAFS

Advantages of AC EAF

- Capital cost is comparatively less to DC EAF as there is no requirement of rectifier and its controls.
- Generates less amount of higher order of harmonics i.e. 11th and 13th harmonics as there is no rectifier.
- Hot iron metal can be directly charged as raw material.
- Keeping the power electrical common, two separate shells can be used continuously for production. i.e. ConArc furnaces.

- Numbers of harmonic filter banks required are less compare to DC EAF.

Disadvantages of AC EAF

- AC EAF's three phase currents cannot be kept symmetrical and balanced.
- AC EAF operates at poor power factor.
- AC EAF power on and off is achieved through switching of the AC EAF transformer.
- The AC EAF always generates more flicker than a DC EAF.

Advantages of DC EAF

- Improvement in power quality on the weak grid is achieved through choosing DC EAF technology instead of AC EAF.
- The DC arc furnace operates at a better power factor.
- Switching transients from energizing the DC EAF transformer can be completely eliminated
- Flicker seen by the DC EAF on the medium voltage bus is approximately half as severe as the AC EAF
- DC EAF technology called shift control, also known as split-α operation mode reduces flicker on the high voltage bus by a factor of 1.5 while, at the same time, also reducing the reactive power generated.
- DC EAFs when used for scrap melting is the reduction in audio noise relative to AC EAF.
- DC electric arc furnaces can work with full tapping, permits partial tapping and can also work as a mixer.
- Due to the electrochemical reactions use for detrimental impurities removal, improvement of the metal stirring and higher process stability the quality of smelted metal improves.

DC EAFs also has following advantages from operation point of view:

- Reduction in electrode consumption almost two times depending on charged raw material.
- Reduction in fire resistant material consumption of 20%.
- Reduction in noise level to 85 dB.
- Reduction in dust and gas emission almost 8 times.

14.0 CONCLUSION

DC EAF technology is more advantageous in weak power systems. i.e. power system's fault feeding capacity in MVA is less comparing to AC EAF technology.

DC EAF is also more advantageous from operation point of view as low electrode consumption, low dust, gas and noise generation.

Table 3 compares AC EAF and DC EAF with reference to power factor, flicker generation and required grid fault level.

From Table 3 it can be concluded that DC EAF operates with better power factor and generate fewer flickers compare to AC EAF.

TABLE 3

COMPARISON OF AC AND DC EAF

	DC EAF		AC EAF	
	with-out	**with SVC**	**without**	**with SVC**
Average power factor	0.7–0.8	up to 1	0.75–0.83	up to 1
Flicker gen	~0.5	~0.25	1	~0.5
Required fault level for furnace input MW	~0.5	~0.25	1	~0.5

Considering capital cost AC EAF is more advantageous as there is no rectifier and its control requirement compare to DC EAF.

For AC EAF numbers of harmonic filter banks required are less compare to DC EAF

Two AC EAF shells can also be used with common electrical for continuous arcing for high levels of production like ConArc furnaces.

ACKNOWLEDGEMENT

We are very thankful to M/s Essar Steel Limited - Main Receiving Sub Station department to provide us the platform for measurement of harmonics for electric arc furnaces.

REFERENCES

[1] Murat Gol. “A new field data based EAF model applied to power quality studies”, September 2009.

[2] “A report on Harmonic Study” at *Essar Steel Complex M/s CPRI*, March 2012.

[3] Application of IEEE Std. 519–1992 Harmonic Limits. Thomas Blooming, Daniel Carnovale, *IEEE IAS Atlanta Section,* September 17, 2007.

[4] Ministry of Steel, India. http://steel.gov.in/overview.htm#over4

[5] SVCs supplied by M/s ABB Switzerland Ltd at M/s Essar Steel Limited, 2010–2011.

[6] Mandi R, Patel J J, Jariwala H R and Vashi A. “Measurement, analysis and elimination of harmonics generated by alternating current electric arc furnace & laddle furnace”, 2012.