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Simulation and Experimental Verification of Alternating Current Electric Arc Furnace with Static Var Compensator

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Non linear and erratic loads like an alternating current electric arc furnace with almost instantaneous fluctuations with its active and reactive power requirements, leads to power quality issues such as poor power factor, harmonic generation etc. We propose to simulate such unique load and prepare its simulation for active and reactive power requirements. Static var compensator is perfect solution for eliminating the above mentioned threats to power quality. SVC behaves like shunt connected variable impedance, which can either generate or absorbs reactive power [2]. Through this review we also present simulation of SVC with AC EAF and prove that all reactive power required by AC EAF during its operation at various power stages is supplied by the SVC only and net reactive power drawn/ supplied from system is almost zero in line with actual field practice.

Keywords: *AC EAF, SVC, TCR, HFB.*

1.0 INTRODUCTION

An integrated steel plant consisting variable and fluctuating loads like alternating current electric arc furnace (AC EAF) and rolling mills represents obscure loads to power suppliers. On one hand the steel plant may be biggest paying power customer while on the other hand it disturbs power quality.

Non linear, erratic and short time varying loads like AC EAF of steel plant with their almost instantaneous fluctuations in both active and reactive power requirements leads to power quality issues like poor power factor, harmonic generation, current and voltage unbalances, voltage flickers, voltage dip and swells.

Static VAr compensator (SVC) is perfect solution for eliminating above mentioned threats to power quality [1]. SVC behaves like shunt connected variable impedance, which can either generates or absorbs reactive power in order to regulate voltage magnitude at the point of common coupling to the power supplier [2]. SVC is extensively used to provide fast reactive power and voltage regulation support.

The AC EAF which heats charged material by means of an electric arc is one of the principle furnace types used for production of steel by electric power. The charged material is directly exposed to the electric arc and the current in the arc furnace electrodes passes through the material to melt it. The AC EAF can demand power up to 240 MVA and temperature inside the AC EAF can reach up to 2000°C [4].

The AC EAF model is developed as combination of variable resistance and inductance unit in

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parallel with current harmonic source. The variable resistance and inductance unit represents the secondary circuit of the AC EAF transformer and the arc resistance. The set points of the electrode regulation system for AC EAF is the impedance of secondary circuit of AC EAF power system, which is easy to measure and control by changing the arc length by moving the arc furnace electrodes up and down [4].

The SVC mainly consists of Thyristor Controlled Reactor (TCR) and Harmonic Filter Banks (HFB). The TCR consumes reactive power while the HFB generates reactive power. Thyristor Controlled Reactor is the only active part of the SVC and works in parallel with AC EAF.

Thyristors used for TCR are Phase Control Thyristors - 5STP 26N6500 with ratings of V_{DSM} Voltage blocking capacity = 6500 V, $IT_{(AV)\ M}$ Average on state current = 2810 A and $IT_{(RMS)}$ RMS on state current = 4410 A [8]. Thyristors are connected in anti parallel to conduct during positive and negative half cycles of supply voltage. De-ionized water is used for cooling of the thyristors with help of water forced air forced cooler and cooling unit.

When SVC is working without any external load i.e. when the AC EAF has gone into tapping, all the reactive power generated by HFB has to be compensated by TCR only otherwise voltage at supply bus will shoot up and when AC EAF is operation reactive power generated by HFB is compensated by AC EAF and TCR together meaning that reactive power drawn by the AC EAF from system is almost zero and ensuring operation at almost unity power factor.

2.0 MODELING AND SIMULATION OF THE AC EAF

2.1 Modeling of AC Electric Arc Furance [4]

An electric arc furnace which heats charged material by means of an electric arc is one of the principle furnace types used for production of steel by electric power. The charged material is directly exposed to the electric arc and the current in the arc furnace electrodes passes through the material to melt it.

AC EAF range in size from small units of approximately one ton capacity up to about 400 tons. Today, arc furnaces are widely used in steelmaking industry for their advantages as allowing steelmaking from a 100 % scrap metal stock and reducing the energy required for steelmaking.

AC EAF have some adverse environmental effects such as high electricity demand followed by power quality problems, high sound levels, dust and off-gas production, slag production and cooling water demand.

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.

As shown in Figure 1, the power circuit of the AC EAF consists of the utility grid, a high voltage/ medium voltage power transformer, cables and bus segments, the EAF transformer, flexible cables, bus tubes and electrodes.

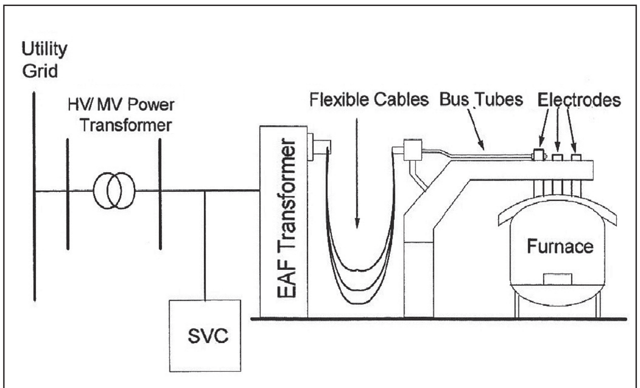

FIG. 1 POWER CIRCUIT OF THE AC ELECTRIC ARC FURNACE

The AC EAF current has a chaotic and random nature, which is the main reason of the power quality disturbing effects of the AC EAF [3]. The three rows of Figure 2 correspond to boring, melting and refining phases of the AC EAF.

The melting process of the EAF consists of three phases: Boring, melting, and refining.

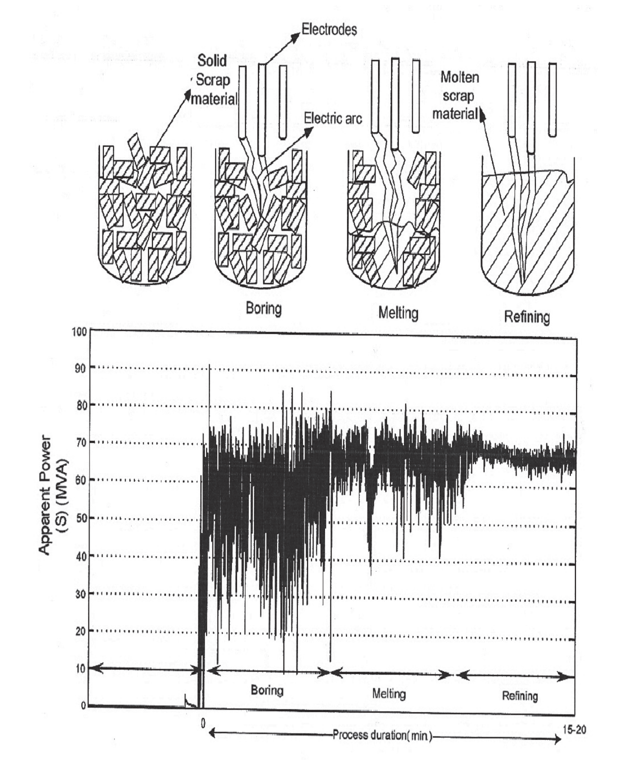

FIG. 2 MELTING PROCESS OF THE AC EAF

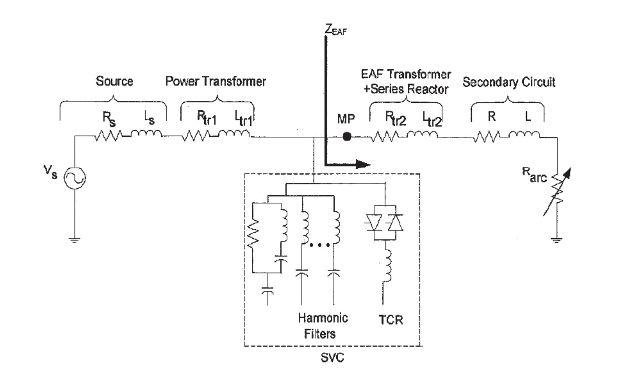

FIG. 3 SINGLE LINE DIAGRAM OF AC ELECTRIC ARC FURNACE

The boring phase is the first part of the smelting process. In this phase the solid scrap metal is loaded into the furnace, and electric arc is initiated in the middle of the scrap to start smelting. The current reaches its most chaotic behavior and the most significant disturbance on the power quality is observed during this phase.

When a hole in the middle of the scrap is achieved the electric arc becomes more stable, but due to the solid scrap that has not molten yet, the current characteristic is still unstable. This phase is called melting.

The final phase, refining, is the most stable of all three, since whole material in the furnace is liquid so that arc length and hence the current demand do not vary as much as in boring or melting.

As can be viewed from Figure 3, secondary circuit of the AC EAF is composed of flexible cables, bus tubes and electrodes. It constitutes nearly 75% of the total impedance as viewed from the low voltage terminals of the AC EAF transformer and varies in time during the operation of the AC EAF. The set-point for the regulation of the power system of an AC EAF is generally the impedance of the system to maintain the drawn current by the AC EAF constant. Not only are the positions of the electrodes but also the AC EAF transformer's taps changed in order to control the active power delivered. Furthermore the non linear arc resistance is changing dynamically depending not only on the state of the scrap and the molten material within the crucible but also on the electrode control system's settings and its capability to maintain the impedance at the set-point.

The proposed model consists of the cascade connected VRL and a current source in parallel with the VRL as seen in Figure 4. By using the VRL, not only the time variations at the fundamental frequency component are represented, but also the voltage dependency of the AC EAF current is taken into account. Equivalent R-L combination as seen from the MV side of the EAF transformer computed from the field-data to constitute a VRL model is only for the fundamental frequency (50 Hz). The parallel

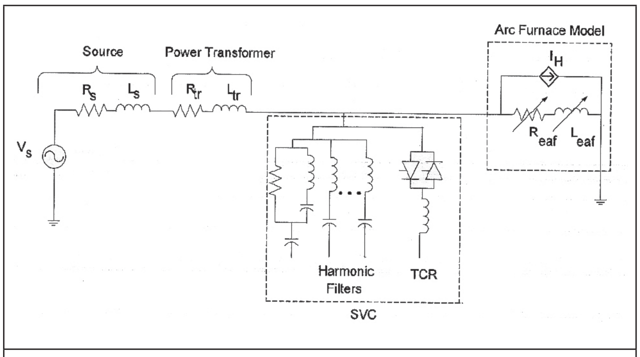

FIG. 4 THE PROPOSED MODEL OF THE AC ELECTRIC ARC FURNACE

connected current sources inject the harmonics and inter harmonics of the AC EAF current to the model.

2.2. Simulation of AC Electric Arc Furance

In line with proposed AC EAF model, our MATLAB Simulation of the AC EAF consists of: 220 kV high voltage supply grid, 220 kV/33 kV, Star-Star connected, 195 MVA High-Voltage/Medium-Voltage Power Transformer, 33 kV XLPE 1 C×630 Sq mm Power Cables, 33 kV/1.45 kV, Delta-Delta connected, 165 MVA Furnace Transformer.

Flexible, water cooled copper cables and bus tubes are represented by resistances and inductances. An AC EAF has three round shaped electrodes corresponding to the three phases. These electrodes are represented by three phase resistance branches connected in star presenting arcing conditions. The value of arc resistance changes with changes with arc length during operation of AC EAF as electrodes moves up and down. Table 1 indicates results of simulation of AC EAF and Table 2 presents comparison of active and reactive power results of actual and simulated AC EAF.

TABLE 1

RESULTS OF MATLAB SIMULATION OF THE AC ELECTRIC ARC FURNACE FOR VARIOUS POWER STAGES

Sl. No. Desc.	Furnace power stages (MW)	Active power (MW)	Reactive power (MVAr)	Primary current (A)	Secondary current (kA)
1	60	62.20	43.35	1384	41.34
2	65	64.04	53.38	1536	45.93
3	85	88.16	62.30	2013	60.23
4	110	109.6	72.70	2486	74.43
5	120	125.8	74.03	2770	82.92
6	130	130.9	102.1	3255	97.49
7	150	148.1	124.4	3913	117.2

TABLE 2

COMPARISON OF RESULTS OF SIMULATED AC ELECTRIC ARC FURNACE WITH ACTUAL AC ELECTRIC ARC FURNACE

	Actual AC EAF		Simulation of AC EAF	
Power of AC EAF	Active power	Reactive power	Active power	Reactive power
60 MW	59.63	42.03	62.20	43.35
65 MW	65.266	47.07	64.04	53.38
85 MW	85.14	68.079	88.16	62.30
110 MW	100.66	74.43	109.6	72.70
125 MW	124.55	106.23	125.8	74.03
130 MW	129.31	98.22	130.9	102.1
150 MW	NA	NA	148.1	124.4

3.0 STATIC VAR COMPENSATOR

Static var compensator (SVC) behaves like shunt connected variable impedance, which either generates or absorbs reactive power in order to regulate voltage magnitude at the point of common coupling to the power supplier [2]. It is extensively used to provide fast reactive power and voltage regulation support.

Static var compensator consists of thyristor controlled reactor (TCR) in parallel with harmonic filter banks (HFB). HFB consists of tuned reactors, capacitors and resistors providing low impedance path to that particular harmonic order and generating reactive power. Capacitors in harmonic filter bank (HFB) are divided in two parts C_1 and C_2.

Filter reactor L is tuned with C_1 for fundamental frequency, so for power frequency supply it is like short circuit and only capacitor C_2 is in circuit and generating capacitive reactive power. Filter reactor L and total C are tuned for particular harmonic order means it will offer least resistance path, virtual short circuit to that particular harmonic eliminating the same from the system. Thus harmonic filter bank (HFB) serves dual purpose of supplying capacitive reactive power at fundamental frequency and eliminates particular order of harmonics.

A 3-phase, 6-pulse Thyristor Controlled Reactor comprises three single-phase TCR connected in delta [5]. The air core reactor in each phase is split into two halves, one on each side of the anti-parallel connected thyristor pair, to prevent the full ac voltage appearing across the thyristor valves and limiting the fault current to protect the thyristors. Three branches are connected in delta so that third harmonic current will have circulating path and same are not propagated to the system.

Variation of the firing angle of thyristor of thyristor controlled reactor changes the susceptance and, consequently, the fundamental current component, which leads to a variation of reactive power absorbed by the reactor because the applied ac voltage is constant.

The firing angle of the thyristors is measured from the zero crossing of supply voltage. The controllable range of the TCR firing angle extends from 90^o to 180^o. A firing angle of 90^o results in full thyristor conduction with a continuous sinusoidal current flow n the TCR. As the firing angle is varied from 90^o to close to 180^o, the current flows in the form of discontinuous pulses symmetrically located in the positive and negative half-cycles [6].

Thyristors used for TCR are Phase Control Thyristors 5STP 26N6500 with ratings of V_{DSM} = 6500 V, $IT_{(AV)\,M}$ Average on state current = 2810 A and $IT_{(RMS)}$ RMS on state current = 4410 A [8]. Thyristors are connected in anti parallel to conduct during positive and negative half cycles. Snubber circuit consisting of water cooled resistor of 45 ohms and capacitor 2 micro farad and 3.8 kV is used for protection of thyristors [8]. De-ionized water is used for cooing of thyristors. De-ionized water is circulated with help of cooling unit pump to thyristors and water forced air forced cooler for cooling.

The SVC measures the load current requirements i.e. AC FAF load current with accurate metering class CT and same input is send to controller, controller based on load current calculates the reactive power requirement of the load, based on this reactive power requirements firing of thyristors of TCR is decided to compensate additional vars generated by HFB. Firing pulses for thyristors are sent by controller through valve based electronics to the thyristors electronic card to thyristors gates.

4.0 SIMULATION OF THE SVC IN FLOATING STATE

The SVC Floating state means SVC is operating without any external load i.e. when AC EAF goes into tapping. At same time all capacitive reactive power generated by harmonic filter banks around 210 MVAr has to be fully compensated by the thyristor controlled reactor only Table 3 indicates current drawn from system incomer is only about 60 A at 33 kV.

TABLE 3			
CURRENT DRAWN BY THE SVC FROM INCOMER IN FLOATING STATE			
Serial No.	**Current drawn from incomer in floating state**		
	Incomer current (A)	**Simulation results (A)**	**Actual output (A)**
1	R	63.45	20
2	Y	65.15	60
3	B	62.52	58

In floating state there will be loss of 1.3 MW of active power in SVC. Figure 7 indicates current drawn from incomer is 60 A with simulation results. Figure 8 shows TCR is compensating all reactive power around 210 MVAr generated by HFB and drawing maximum current around 2100 A. Table 4 compares current drawn by TCR of simulation with actual in floating state.

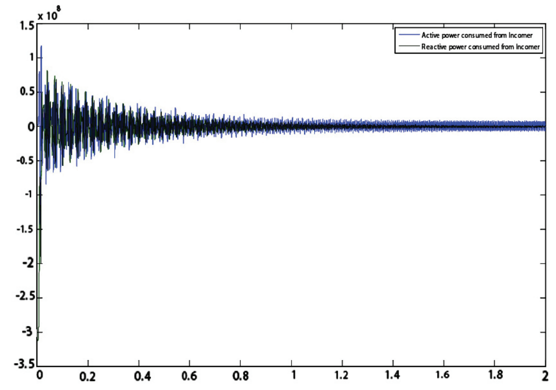

FIG. 7 ACTIVE AND REACTIVE POWER DRAWN FROM INCOMER DURING SVC FLOATING STATE

TABLE 4			
CURRENT DRAWN BY THE TCR FOR EACH PHASE IN SVC FLOATING STATE			
Sl. No.	**Current drawn by TCR for each phase**		
	TCR current (A)	**Simulation results (A)**	**Actual output (A)**
1	R	2172	2070
2	Y	2169	2150
3	B	2164	2123

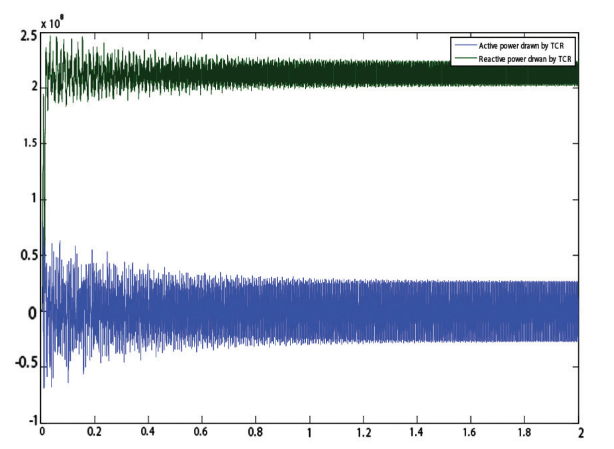

FIG. 8 ACTIVE AND REACTIVE POWER DRAWN BY TCR DURING SVC FLOATING STATE

5.0 SIMULATION OF SVC WITH THE AC EAF LOAD OF 120 MW

When AC EAF is operating at 120 MW it draws 90 MVAr from system, making operational power factor very low. Table 5 indicates current drawn from incomer for simulation and actual field. When connected in parallel with SVC, the SVC delivers the same reactive power and thus reactive power drawn from system becomes almost zero [7]. Figure 9 shows simulation results for EAF load of 120 MW with SVC that active power drawn from system is around 120 MW while reactive power drawn is around zero. Figure 10 indicates reactive power drawn by TCR is now reduced to 120 MVAr as remaining 90 MVAr are consumed by AC EAF operating at 120 MW. As indicated in Table 6 current drawn

TABLE 5			
CURRENT DRAWN FROM INCOMER WITH FURNACE LOAD OF 120 MW			
Sl. No.	**Current drawn from incomer with load of 120 MW**		
	Incomer current (A)	**Simulation results (A)**	**Actual output (A)**
1	R	2066	2090
2	Y	2141	2076
3	B	2034	2106

by TCR is now only 1300 A in comparison of 2100 A drawn in SVC floating state.

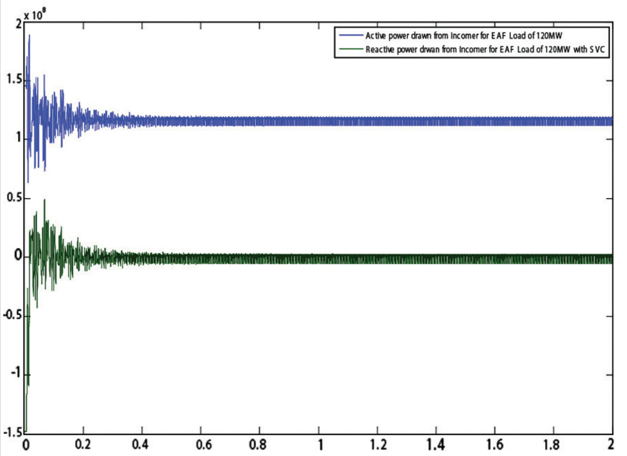

FIG. 9 ACTIVE AND REACTIVE POWER DRAWN FROM INCOMER WITH EAF LOAD OF 120 MW

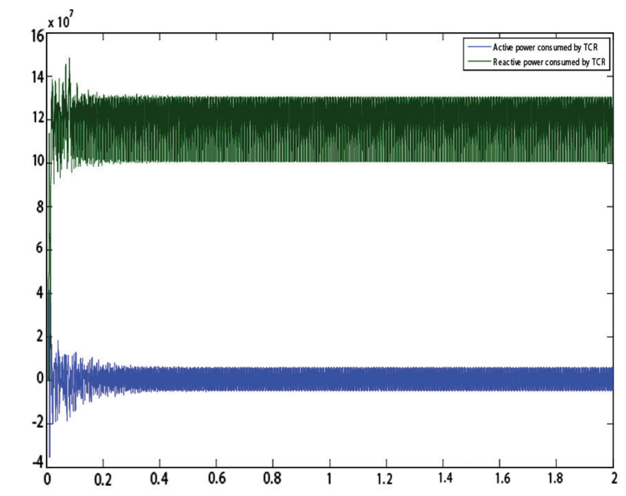

FIG. 10 ACTIVE AND REACTIVE POWER DRAWN BY TCR WITH EAF LOAD OF 120 MW

TABLE 6

CURRENT DRAWN BY TCR WITH FURNACE LOAD OF 120 MW

Sl. No.	Current drawn by TCR with Furnace Load of 120 MW		
	TCR Currents (A)	**Simulation Results (A)**	**Actual Output (A)**
1	R	1297	1240
2	Y	1191	1303
3	B	1363	1385

6.0 REACTIVE POWER GENERATION/ CONSUMPTION CALCULATION FOR SIMULATION OF AC EAF (65 MW) WITH STATIC VAR COMPENSATOR

Reactive power generated by the SVC:

2nd Harmonic Filter Bank	:	61.30 MVAr
3rd Harmonic Filter Bank	:	68.03 MVAr
4th Harmonic Filter Bank	:	81.51 MVAr
Total	:	**210.84 MVAr**

Reactive Power consumed by the SVC and the AC EAF:

Thyristor Controlled Reactor	:	163.3 MVAr
AC Electric Arc Furnace (65 MW)	:	46.73 MVAr
Total	:	**210.03 MVAr**

Power drawn from 33kV Incomer (System) by the AC EAF with SVC:

Reactive Power	:	–791.60 kVAr
Active Power	:	67.45 MW

Thus, Reactive Power required by the AC EAF: 46.73 MVAr is supplied by the SVC and remaining reactive power generated by the SVC is consumed with TCR of the SVC.

Reactive Power drawn/supplied from Incomer (System) 791.60 kVAr is almost nil comparing to furnace power, providing unity power factor operation at system bus.

7.0 REACTIVE POWER GENERATION/ CONSUSMPTION CALCULATION FOR SIMULATION OF AC EAF (100 MW) WITH STATIC VAR COMPENSATOR

Reactive power generated by the SVC:

2nd Harmonic Filter Bank : 60.80 MVAr

3rd Harmonic Filter Bank : 67.46 MVAr

4th Harmonic Filter Bank : 80.83 MVAr

Total : **209.09 MVAr**

Reactive Power consumed by the SVC and the AC EAF:

Thyristor Controlled Reactor : 140.1 MVAr

AC Electric Arc

Furnace (100MW) : 69.51 MVAr

Total : **209.61 MVAr**

Power drawn from 33 kV Incomer (System) by the AC EAF with SVC:

Reactive Power : 468.90 kVAr

Active Power : 98.90 MW

Thus, Reactive Power required by the AC EAF: 98.90 MVAr is supplied by the SVC and remaining reactive power generated by the SVC is consumed with TCR of the SVC.

Reactive Power drawn from Incomer (System) 468.90 kVAr is almost nil comparing to furnace power, providing unity power factor operation at system bus.

8.0 RESULTS OF SIMULATION OF THE AC ELECTRIC ARC FURNACE WITH STATIC VAR COMPENSATOR

Tables 7–9 indicates reactive power required by the AC EAF at three difference power stages.

TABLE 7

RESULTS OF SIMULATION OF THE AC ELECTRIC ARC FURNACE WITH THE STATIC VAR COMPENSATOR

Sl. No.		**Matlab Simulation**		
	AC EAF power stages (MW)	**Active power required by AC EAF (MW)**	**Reactive power required by AC EAF (MVAr)**	**Reactive power drawn from system (MVAr)**
1	65	67.45	46.73	–0.791
2	100	98.50	69.51	0.468
3	125	125.50	82.86	0.149

TABLE 8

RESULTS OF ACTUAL AC ELECTRIC ARC FURNACE WITH THE STATIC VAR COMPENSATOR

		Actual AC Electric Arc Furnace		
Sl. No	**AC EAF power stages (MW)**	**Active power required by AC EAF (MW)**	**Reactive power required by AC EAF (MVAr)**	**Reactive power drawn from system (MVAr)**
1	65	65.266	47.073	0.02
2	100	100.66	74.43	0.00
3	125	124.55	106.23	0.03

TABLE 9			
FIRING ANGLES OF THYRISTORS CONTROL REACTOR FOR VARIOUS POWER STAGES OF THE AC EAF			
Reactive power drawn from incomer with SVC			
Active power (MW)	**Reactive power required by AC EAF (MVAr)**	**Firing angle (degree)**	**MVAr drawn from system (MVAr)**
65	46.73	115	–0.791
100	69.51	120.5	0.468
125	82.86	124.5	0.149

CONCLUSION

Non-linear and short time varying loads like alternating current electric arc furnace leads to power quality issues. Static var compensator is perfect solution for eliminating these threats to power quality.

Through this review we have simulated AC EAF and prepared MATLAB simulation of AC EAF with SVC and Tables 7–9 indicates reactive power required by the AC EAF at three difference power stages and firing angles of thyristor controlled reactor of the SVC to supply the same so that reactive power drawn by the AC EAF from system is almost zero in line with actual field practice.

ACKNOWLEDGMENT

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REFERENCES

Technical Papers:

[1] Noroozian M and Taylor C W. “Benefits of SVC and STATCOM for Electric utility application”.

[2] John D Kueck, Brendan Kirby J, Leon M and Tolbert. “Tapping distributed energy resources”.

[3] Benoit Boulet, Gino Lalli and Mark Ajersch. “Modeling and control of an electric arc furnace”.

[4] Murat Gol. “A New field data based EAF model applied to power quality studies”.

Technical Books and Library:

[5] “A Handbook on Power Electronics” Mohammed Rashid.

[6] “Thyristor based FACTS Controllers for Electrical Transmission System”. R Mohan Mathur

[7] Thristor based Static Var Comepsnator from Library of www.mathworks.com

[8] Static var copensator supplied by M/s ABB Switzerland Limiteds