Development of VSI Based STATCOM for Voltage Improvement & Reactive Power Compensation

Babita Gupta, S. V. Phanidhar, B. Venkatesh

Abstract—Voltage fluctuations caused by rapid industrial load changes have been a major concern for both power companies and customers in the area of power quality. The fast response of the Static Compensator (STATCOM) makes it an efficient solution for improving power quality in distribution systems.This paper describes a model for a PWM-based STATCOM used in a distribution system for mitigation of voltage fluctuations produced by an Electric Arc Furnace (EAF).The analyzed system is modeled using MATLAB/Simulink Power system Blockset (PSB), including a complete STATCOM model with its power circuits and its control system. The complete model is validated by field test.Static and dynamic performance of STATCOM is evaluated and voltage fluctuation mitigation studies are performed and discussed. The voltage fluctuation mitigation is obtained by measurements and according to international standards.

Index Terms- Arc Furnaces. Flicker. Harmonics. Power Quality. STATCOM.

I. INTRODUCTION

Many loads connected to electric power systems may cause power quality problems at all voltage levels and for very different power ratings due to their unbalanced and non-linear behavior characteristics. However, the main sources of power quality problems affecting large numbers of customers are the high power industrial loads. The rapid large swings in active and reactive power required by such loads cause rapid repetitive voltage variations with appreciable voltage distortion caused by harmonics and unbalance. The residential and commercial customers supplied by the same network are subjected to the impact of these voltage variations that produce disturbances to their equipment and flicker in the light output of their electric lamp

EAF loads can result in serious electrical disturbances on a power system. Low level frequency modulation of the supply voltage of less than 0.5% can cause annoying flicker in lamps and invoke public complaints when the frequencies lie in the range of 3-10 Hz.

Some form of reactive compensation is usually required to limit the disturbances injected by EAF into the electric power system, in particular the flicker. This is usually achieved by connecting a compensator to the busbar in which the disturbing load is situated.

The most effective way to control voltage fluctuations and therefore to limit flicker is to compensate the reactive power variations of the fluctuating loads at medium/high voltage levels.

This paper presents the voltage flicker measured at a steelwork busbar, where an 8-tons, 2.5 MW EAF is connected. To mitigate the voltage fluctuation phenomenon, a 4 MVAr STATCOM was included in the steelwork busbar. The mathematical model and the control strategy to compensate voltage fluctuations are explained and described in detail. The capability of the STATCOM to mitigate voltage fluctuations is demonstrated by digital simulations and experimental results.

II. POWER SYSTEM CONFIGURATION

The lay-out of power system is shown in Fig. 1.

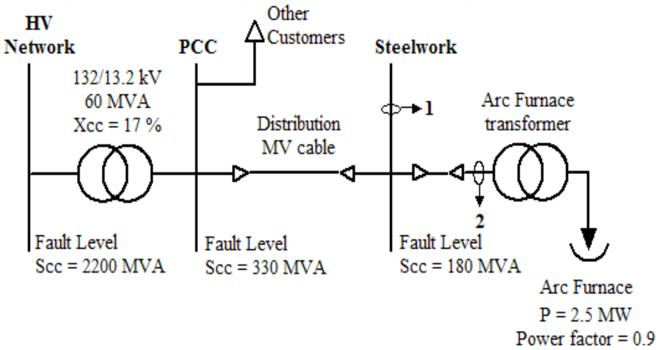

Fig. 1: Electrical system configuration.

The steelwork is supplied directly from public distribution network at 13.2 kV. Measurements of three-phase voltages and currents were taken at point 1 (steelwork supplying point) and point 2 (primary of EAF feeding transformer).

III. CHARACTERISTICS OF ELECTRIC ARC FURNACES

An EAF consists of a refractory lined shell which holds the charge, usually scrap metal. Three large electrodes, usually of graphite, are held in special clamps on a swing support structure which can be swung aside for charging, and which allows each electrode to be raised or lowered according to the output of the control system.

After the furnace is charged with scrap, operation begins by lowering the electrodes to strike electric arcs between the electrodes and the scrap. The heat generated by the three electric arcs provides the heat for melting and refining the scrap.

There are several phases in the EAF operation, each presenting a different impact on the power system in terms of flicker, namely the:

- Boring period.
- Melting period.
- Refining period.

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Fig. 2 shows the measured EAF active and reactive power during a typical furnace heat.

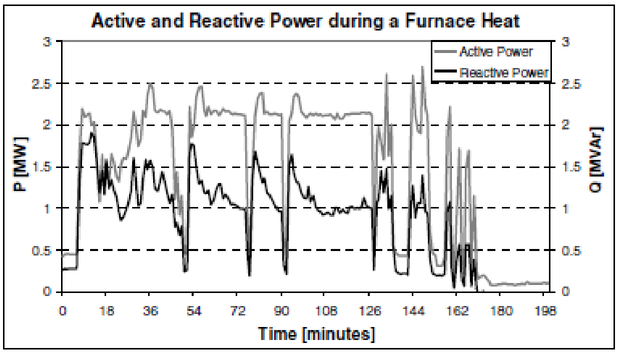

Fig. 2: Active and reactive power during a Furnace Heat.

Depending on the operating states, the furnace load may change from a complete open circuit to a 3-phase short circuit.

The reactive power drawn by the furnace will have a major impact on the feeding voltage generating a voltage drop on the primary side of the furnace transformer.

Given the continuously changing nature of the arc, dynamically fast reactive compensation, such as that provided by STATCOM, is needed to stabilize the voltage of the feeding network during the whole scrap charge.

The arc can be represented as a variable resistance in a simple single phase equivalent of the furnace and its supply system [1], as it is shown in Fig. 3. Although this model is a simplification of the real furnace and implies balanced EAF operation, it gives accurate account of furnace operation in terms of averaged quantities, as it was demonstrated in [7].

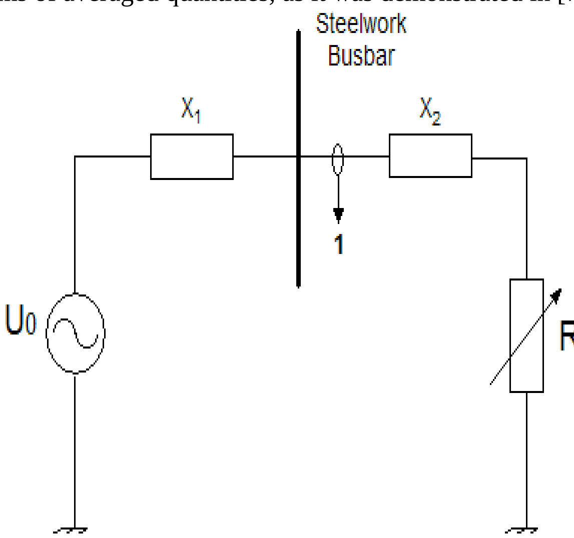

Fig. 3: Single-phase circuit for estimating furnace characteristics.

If the electrodes are immersed in the liquid scrap, the load will be a 3-phase short circuit, which is equivalent to make Rf = 0 in Fig. 3. In these operating conditions, the IITREE measured 3-phase voltages and currents in point 1 of Fig. 3.

The short circuit test is of fundamental importance to estimate the operating characteristics of the EAF.

The parameters obtained from this test were:

The short circuit reactance of the supply network:

$$X_1 = \frac{|U_0 - U_{cc}|}{I_{cc}} = \frac{|10.853x10^3 - 10.523x10^3|}{345.3} = 0.95\,\Omega$$

The reactance of the flexible leads, the electrodes and the furnace transformer:

$$X_2 = \frac{U_{cc}}{I_{cc}} = \frac{10.523x10^3}{345.3} = 30.5\,\Omega$$

The short circuit power at the steelwork substations

$$S_{sc} = \frac{U_L^2}{X1} = \frac{(13.28x10^3)^2}{0.95} = 185\,MVA$$

The furnace short circuit power:

$$S_{scf} = S_{sc}\frac{|U_0 - U_{cc}|}{U_0} = 5.6\,MVA$$

It is possible now to estimate the general load variations of the electric arc furnace by using the equivalent circuit shown in Fig. 3. The results are shown in Fig. 4.

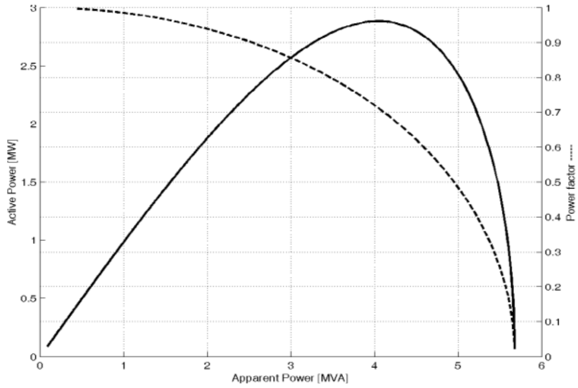

Fig. 4: Furnace operating characteristics.

A. Flicker Measurements

Flicker measurements were made by the IITREE with the IEC 61000-4-15 normalized flicker meter [8]. Fig 5 shows the normalized one-week, 10-minute-interval P_{st} measurements.

The obtained value of $P_{st95\%}$ = 2.21 is above the limits of European and Argentinian Standards.

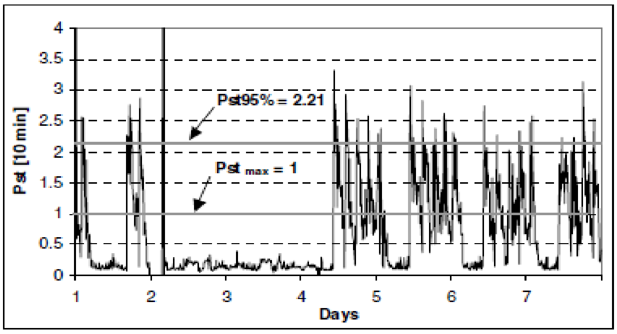

Fig. 5: P_{st}measurements during a week.

B. Flicker compensation ratio

The arc furnace apparent power could be determined according to the power factor limit.

$$S_L = \frac{2.5x10^6}{0.85} = 2.95MVA$$

It is possible now to estimate the ratio between the EAF apparent power and the short circuit level at the steelwork substation.

$$K_2 = \frac{S_L}{S_{sc}} = \frac{2.95x10^6}{180x10^6} = 0.016$$

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With this K factor, it is possible to obtain the maximum flicker that could be emitted by the steelwork, according to Argentinian regulations [10].

$$P_{stLimit} = \leq 0.58$$

According to this value, it is possible to estimate the flicker compensation ratio:

$$FI = \frac{P_{streal}}{P_{st\,lim\,it}} = \frac{2.2}{0.58} = 3.8$$

This parameter is of fundamental importance for the determination of the STATCOM compensator size.

IV. UTILITY/CUSTOMER DISTRIBUTION SYSTEM MODELING

A digital simulation model of the distribution network is implemented by using the MATLAB/Simulink Power System Blockset (PSB). Fig. 6 shows the upper level of the distribution system for the voltage fluctuation mitigation study.

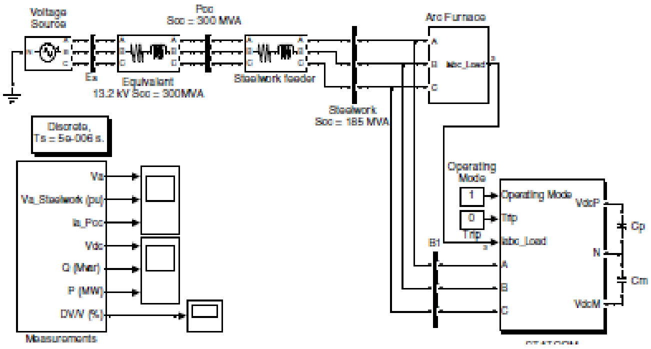

Fig. 6: MATLAB model of Utility/Customer system.

The EAF is modeled as three controlled current sources, controlled by the measured currents in the EAF during a furnace heat. The arc furnace model is shown in Fig. 7.

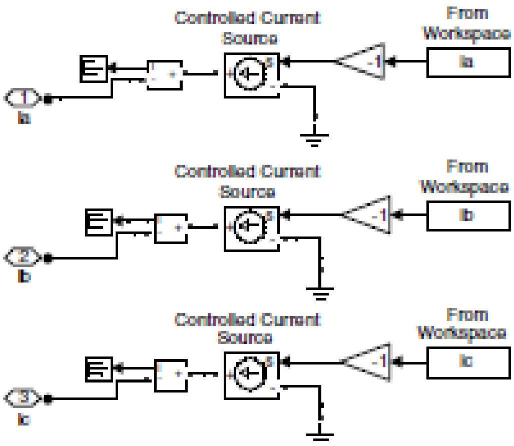

Fig. 7: Arc Furnace model

These currents were injected into the model and the three phase to ground voltages at the steelwork busbar were measured. These voltages were compared with the voltages measured at the same point. The purpose of this simulation was to validate the power system model. The results are shown in Fig. 8.

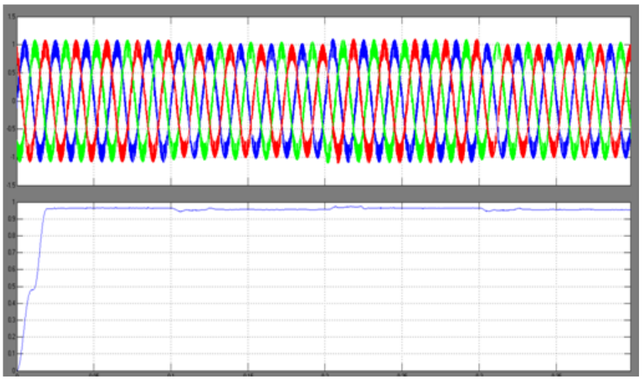

Fig. 8: Simulated and measured phase-to-ground voltages.

The obtained results validate the EAF proposed model.

V.STATCOM OPERATING PRINCIPLES

The STATCOM is essentially a voltage source behind a coupling reactance with the corresponding V-I and V-Q characteristics [2]-[4] shown in Fig. 9.

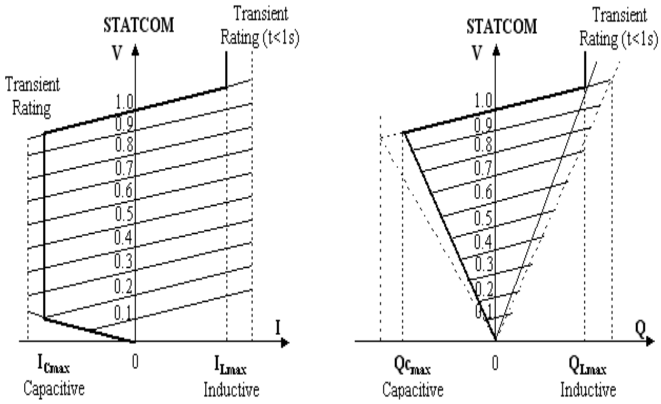

Fig. 9: STATCOM typical V-I and V-Q Characteristics.

From Fig. 9, it is possible to conclude that:

1) The STATCOM can be operated all over its full output current range even at very low system voltage levels. In other words, the output current can be maintained independently from the a.c. system voltage.
2) The maximum VAr generation or absorption changes linearly with the a.c. system voltage.
3) The independence of STATCOM output from equivalent system impedance means that the voltage regulator controlling the STATCOM output can be designed for a faster response rate and can provide stable regulation over the range of system contingencies.

The single line diagram of the STATCOM for reactive power supply to the transmission system is shown in Fig. 10, where U is the voltage of the steelwork busbar and $E_c$is the controllable output voltage.

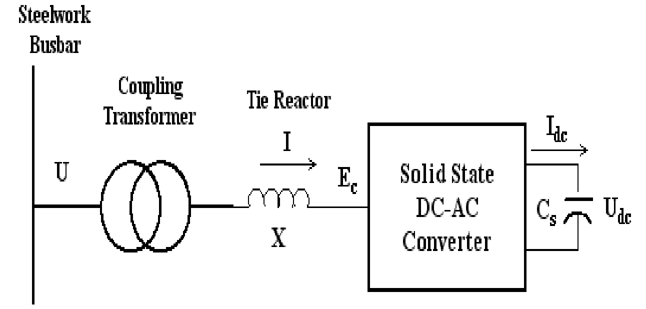

Fig. 10: STATCOM scheme for reactive power generation.

The active and reactive power exchanged between the network is given by:

$$P_{STATCOM} = \frac{U.E_c}{X}\sin(\delta) \qquad (9)$$

$$Q_{STATCOM} = \frac{U}{X}(U - E_c.\cos(\delta)) \qquad (10)$$

If the amplitude E_c of the output voltage phasor (E_c) is increased above the amplitude U of the a.c. voltage (U), then the current phasor leads the voltage phasor and current flows from the converter to the a.c. system and the converter generates reactive (capacitive) power to the system.

If the amplitude of the output voltage phasor is decreased below that of the a.c. system voltage phasor, then the reactive current flows from the a.c. system to the converter, and the converter absorbs reactive (inductive) power from the a.c. system. This operation is illustrated in Fig. 11.

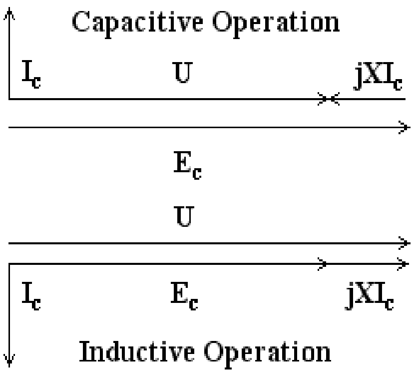

Fig. 11: Capacitive and Inductive behavior of STATCOM.

A. Obtaining the Compensator Rating

From observations of practical installations the approximate equation for estimating the rating for an EAF STATCOM is given in [2].

$$Q_{STATCOM} = 0.54 * \sqrt{(FI)} * S_{ratedAF} \qquad (11)$$

Where:

FI is the flicker improvement ratio

$S_{ratedAF}$= (0.55 to 0.65)*S_{scf} is the rating of the arc furnace

S_{scf} is the fault level of the arc furnace.

In this case FI ≅ 4, S_{scf}= 5.6 MVA and then $S_{ratedAF}$= 3.65 MVA. By using (11), the compensator rating is obtained:

$Q_{STATCOM} \cong 4MVAr$

VI. DESIGNING STATCOM CONTROL SYSTEM FOR MITIGATING THE VOLTAGE FLUCTUATION

The power system at the point of connection to the disturbing load busbar is characterized by its non-load voltage **E_s** and its impedance **Z_s**. At this point, the voltage is **V** and the load consumes active power **P** and reactive power **Q**. The representation of the power system with the EAF and the STATCOM is shown in Fig. 12.

The voltage at the point of connection is given by the following equation, assuming per unit quantities on nominal rating base of EAF transformer and on nominal rated voltage.

$$\dot{U} = \dot{E}_s - R_s\dot{I}_s - L_s\frac{d\dot{I}_s}{dt} \qquad (13)$$

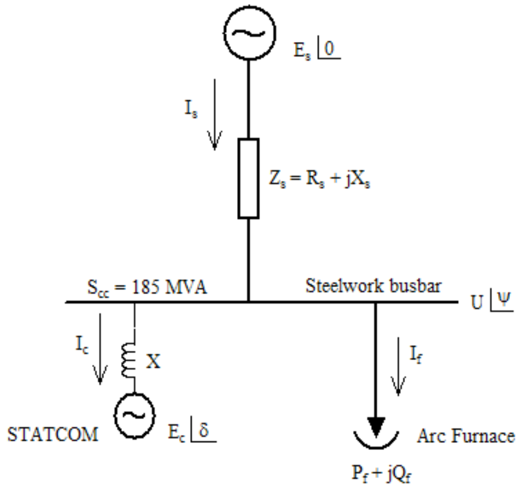

Fig. 12: Power system single line diagram.

The current circulating in the network impedance is the sum of the current drawn by the arc furnace and the current injected by the STATCOM.

$$\dot{I}_s = \dot{I}_f + \dot{I}_c \qquad (14)$$

The voltage drop in the network impedance is defined by:

$$\Delta\dot{U} = \dot{E}_s - \dot{U} = R_s\dot{I}_s + L_s\frac{d\dot{I}_s}{dt} \qquad (15)$$

In polar form, the vectors can be expressed as:

$$\dot{E}_s = E_s e^{j\omega t} \qquad (16)$$

$$\dot{U} = Ue^{j(\omega t + \psi)} \qquad (17)$$

$$\dot{I}_s = I_s e^{j(\omega t + \phi)} \qquad (18)$$

Giving:

$$\frac{d\dot{I}_s}{dt} = j\omega I_s e^{j\omega t}e^{j\phi} + e^{j\omega t}\frac{d}{dt}\left[I_s e^{j\phi}\right] \qquad (19)$$

If we substitute wt = 0 and replace (19) in (13) then:

$$Ue^{j\psi} = E_s - R_s I_s e^{j\phi} - L_s\left[j\omega I_s e^{j\phi} + \frac{d}{dt}\left[I_s e^{j\phi}\right]\right] \qquad (20)$$

With wt = 0, it is possible to obtain the active and reactive part of each vector:

$$\dot{I}_s = I_s e^{j\phi} = I_{sd} + jI_{sq} \qquad (21)$$

$$\dot{E}_s = E_{sd} \qquad (22)$$

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$$\dot{U} = Ue^{j\psi} = Ud + jUq \qquad (23)$$

If we replace the active and reactive part of each vector in (20) we obtain:

$$Ud + jUq = Esd - (Rs + j\omega Ls)(Isd + jIsq) - Ls\frac{d}{dt}[Isd + jIsq] \qquad (24)$$

If we take the real and imaginary part of (24), we obtain:

$$Ud = Esd - RsIsd + XsIsq - Ls\frac{dIsd}{dt} \qquad (25)$$

$$Uq = -RsIsq - XsIsd - Ls\frac{dIsq}{dt} \qquad (26)$$

The real and imaginary part of the voltage drop in the network impedance can be written as:

$$\Delta Ud = RsIsd - XsIsq + Ls\frac{dIsd}{dt} \qquad (27)$$

$$\Delta Uq = RsIsq + XsIsd + Ls\frac{dIsq}{dt} \qquad (28)$$

The vector diagram corresponding to (24) is shown in Fig. 13.

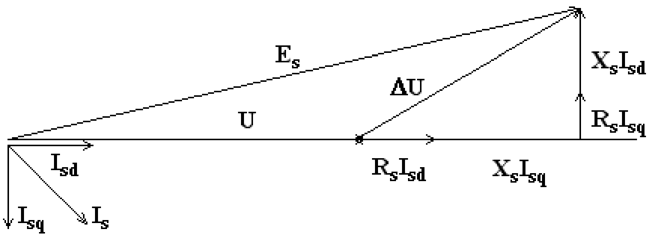

Fig. 13: Vector diagram corresponding to (24).

The voltage drop in the network impedance caused by the arc furnace can be compensated by the step by step procedure described below:

Step 1: The first step in achieving full compensation is to compensate the reactive current drawn by the arc furnace so that I_{sq}= 0 by injecting a current reference equal to ($-I_{fq}$) into the compensator control system.

$$Icqref = -Ifq \qquad (29)$$

With I_{sq}= 0, (27)-(28) become:

$$\Delta Ud = RsIsd + Ls\frac{dIsd}{dt} \qquad (30)$$

$$\Delta Uq = XsIsd \qquad (31)$$

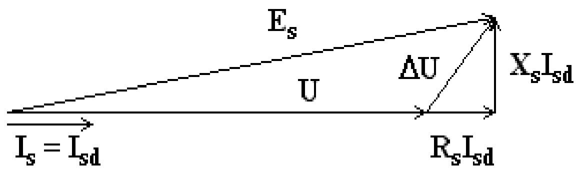

Fig. 14: Vector diagram of (24) with I_{sq}= 0.

Step 2: Since the voltage fluctuation due to the active power drawn by the EAF remains, in the second step, compensation of the active power fluctuation is attempted by injecting an additional current I_{sq}= $(R_s/X_s)I_{sd}$ to the reference of the compensator control system, i.e., injecting capacitive power proportional to I_{sd} to compensate the remaining voltage drop.

The reactive current reference for the STATCOM compensator becomes:

$$Icqref = -Ifq + (Rs/Xs)Ifd \qquad (32)$$

Substituting with I_{sq}= $(R_s/X_s)I_{sd}$ in (27)-(28) results:

$$\Delta Ud = Ls\frac{dIsd}{dt} \qquad (33)$$

$$\Delta Uq = Xs\left(1 + \frac{Rs^2}{Xs^2}\right)Isd + \frac{Rs}{\omega}\frac{dIsd}{dt} \qquad (34)$$

The vector diagram after the compensation of the real power fluctuations is illustrated in Fig. 15.

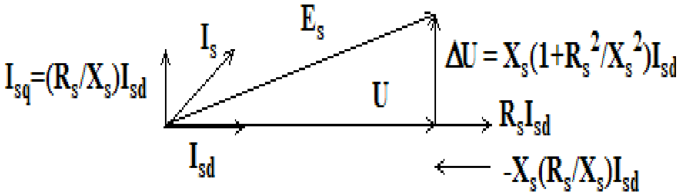

Fig. 15: Vector diagram of (24) with I_{sq}= $(R_s/X_s)I_{sd}$

STATCOM compensates the full reactive power absorbed by the arc furnace, and delivers some capacitive power Q to the network to reduce the remaining voltage fluctuation.

VII. STATCOM CONTROL IMPLEMENTATION

The DC-AC converter shown in Fig. 10 is a PWM synchronous inverter connected to a capacitor. The implementation of the control system is based on D-Q compensation theory. The voltage equations at the point of connection of the compensator, in the stationary a-b-c frame, are:

$$\dot{U}_a = L\frac{d\dot{I}_{ca}}{dt} + \dot{E}_{ca} \qquad (35)$$

$$\dot{U}_b = L\frac{d\dot{I}_{cb}}{dt} + \dot{E}_{cb} \qquad (36)$$

$$\dot{U}_c = L\frac{d\dot{I}_{cc}}{dt} + \dot{E}_{cc} \qquad (37)$$

The voltage equations in the stationary x-y frame are given by:

$$\begin{bmatrix}\dot{U}_x\\ \dot{U}_y\end{bmatrix} = \frac{2}{3}\begin{bmatrix}1 & \frac{-1}{2} & \frac{-1}{2}\\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}L\frac{d\dot{I}_{ca}}{dt} + \dot{E}_{ca}\\ L\frac{d\dot{I}_{cb}}{dt} + \dot{E}_{cb}\\ L\frac{d\dot{I}_{cc}}{dt} + \dot{E}_{cc}\end{bmatrix} = \begin{bmatrix}L\frac{d\dot{I}_{cx}}{dt} + \dot{E}_{cx}\\ L\frac{d\dot{I}_{cy}}{dt} + \dot{E}_{cy}\end{bmatrix} \qquad (38)$$

And by transforming the voltage equations from stationary x-y frame to the synchronous d-q frame, which is rotating with the angular frequency ω, we obtain:

$$\begin{bmatrix}Ud\\ Uq\end{bmatrix} = \begin{bmatrix}\cos(\omega t) & \sin(\omega t)\\ -\sin(\omega t) & \cos(\omega t)\end{bmatrix}\begin{bmatrix}\dot{U}_x\\ \dot{U}_y\end{bmatrix} = L\frac{d}{dt}\begin{bmatrix}Icd\\ Icq\end{bmatrix} + \omega L\begin{bmatrix}-Icq\\ Icd\end{bmatrix} + \begin{bmatrix}Ecd\\ Ecq\end{bmatrix} \qquad (39)$$

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$$p=\frac{3}{2}\left(Ud.Icd+Uq.Icq\right)=\frac{3}{2}Ud.Icd \qquad (40)$$

$$q=\frac{3}{2}\left(Uq.Icd-Ud.Icq\right)=-\frac{3}{2}Ud.Icq \qquad (41)$$

It can be seen that I_{cd} and I_{cq} can completely describe the instantaneous values of real and reactive powers produced by the STATCOM, therefore the control of the power injected into the system can be implemented by controlling I_{cd} and I_{cq}.

The voltage equations transformed from the stationary a-b-c frame to the synchronous d-q frame are:

$$U=L\frac{dIcd}{dt}-\omega.LIcq+Ecd \qquad (42)$$

$$0=L\frac{dIcq}{dt}+\omega.LIcd+Ecq \qquad (43)$$

To make the compensator input currents track the filter reference currents, the PI type current controllers can be utilized. However, the PI controllers do not work well for the coupled system described in (42)-(43). To avoid this problem, the following current controllers are more effective:

$$Ecd=\omega.LIcq+U-\Delta Ecd \qquad (44)$$

$$Ecq=-\omega.LIcd-\Delta Ecq \qquad (45)$$

$$\Delta Ecd=kp\left(Icdref-Icd\right)+ki\int\left(Icdref-Icd\right)dt \qquad (46)$$

$$\Delta Ecq=kp\left(Icqref-Icq\right)+ki\int\left(Icqref-Icq\right)dt \qquad (47)$$

The I_{cqref} is obtained as described in section VI. The I_{cdref} is obtained comparing the desired reference voltage for the capacitor V_{DCRef} with the present capacitor voltage with a PItype voltage controller.

VIII. STATCOM PSB SIMULATION MODEL

The □4 MVAr STATCOM Simulink model is shown in Fig. 16. It contains a PWM IGBT inverter, two 10000 □F capacitors and a control system. The STATCOM is coupled in parallel with the network through a step-up 0.4/13.2 kV □-□ transformer [5]-[6].

A PWM pulse generator of 1.35 kHz is used to control IGBT bridge. The modulation scheme used is of sinusoidal type. The controller diagram is shown in Fig. 17. It consists of several subsystems: a phase-locked loop (PLL), a measurement system, an a.c. voltage regulator, a d.c. voltage regulator and a current regulator.

The PLL is synchronized to the fundamental of the transformer primary voltage to provide the synchronous reference required by the abc-dq0 transformation. The measurement block computes the d-axis and q-axis components of the voltages and currents.

The current regulation consists of two PI controllers that control the d-axis and q-axis currents according to (46)-(47). The controller outputs are the voltages E_{cd} and E_{cq} that the PWM inverter has to generate according to (44)-(45) . Then these voltages are converted into phase voltages E_{ca}, E_{cb} and E_{cc}.

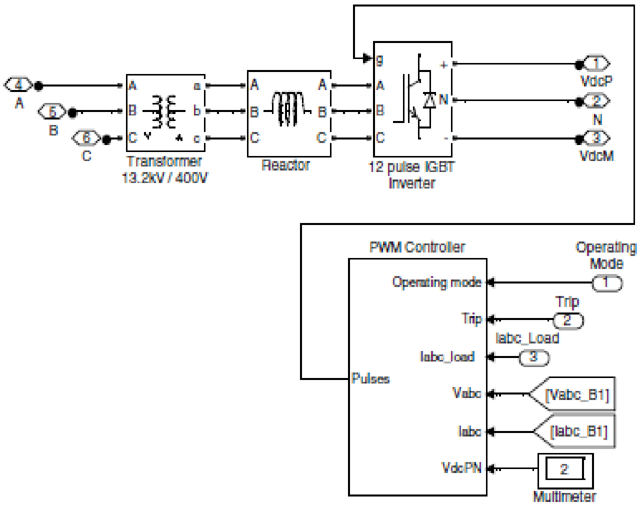

Fig. 16: STATCOM circuit.

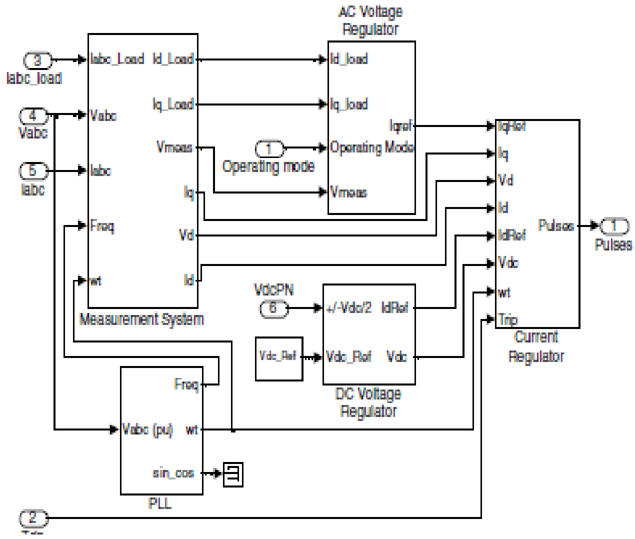

Fig. 17: STATCOM Control System.

IX. STATCOM PERFORMANCE

The ability of a compensator to reduce flicker depends on the compensator size and the speed of response. In order to evaluate the speed of response and the frequencyresponse of the compensator, the Three-Phase Dynamic Loadfrom Simulink was utilized. The active power was set constantat 2.5 MW, and the reactive power was set at 1.6 MVArconstant plus a sinusoidal part of 1.2 MVAr. This load isrepresentative of the active and reactive power levels reachedby the arc furnace during a complete heat cycle.Each simulation was performed at a single modulatingfrequency between 0.5 and 10 Hz and the voltage spectralcomponents at the steelwork busbar were obtained with and without the STATCOM. The ratio between the spectral component is proportional to the flicker improvement ratio. The simulation was repeated with different values of proportional gain Kp in the current regulator. The results are shown in Fig. 18.

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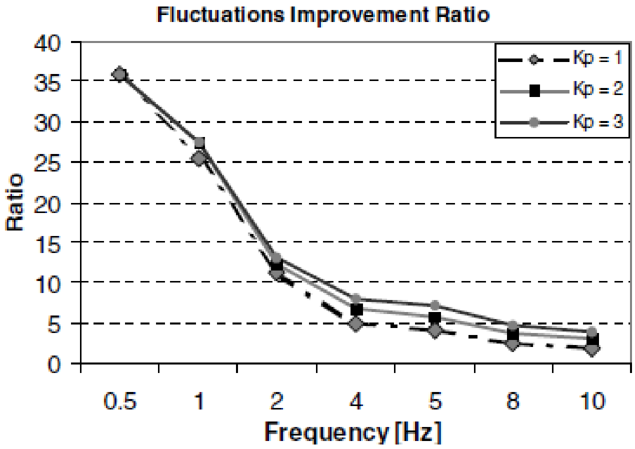


Fig. 18: STATCOM frequency response.

X.STATCOM OPERATION WITH THE ARC FURNACE

Digital simulations were performed to evaluate the flicker mitigation in different phases of operation of the EAF when the STATCOM was connected to the steelwork busbar.

A. Boring period

The voltage at the steelwork busbar and waveforms illustrating STATCOM performance are shown in Figs. 19-21.

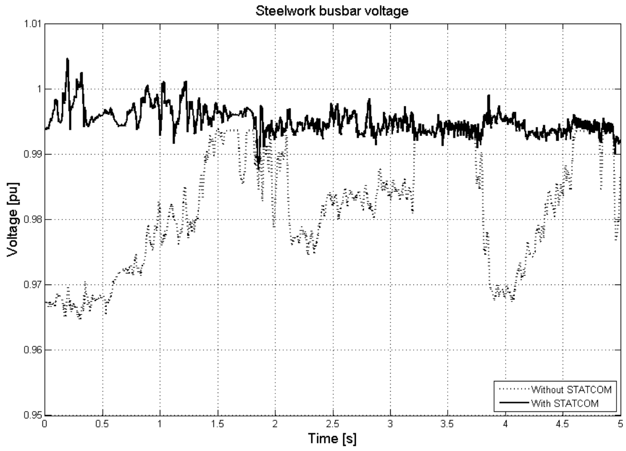


Fig. 19: Steelwork busbar voltage.

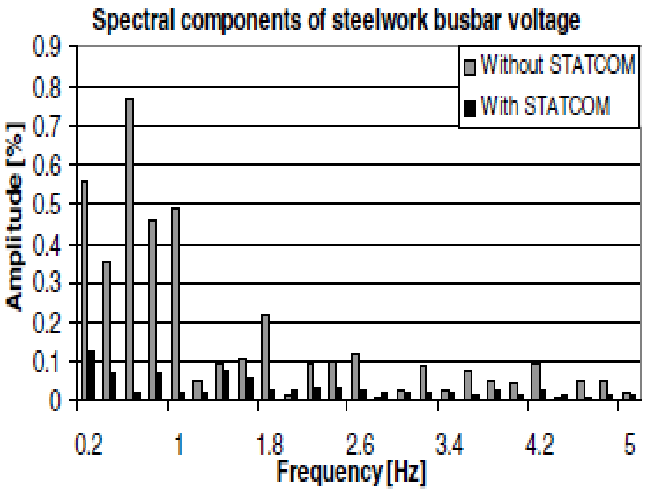


Fig. 20: Voltage spectral components.

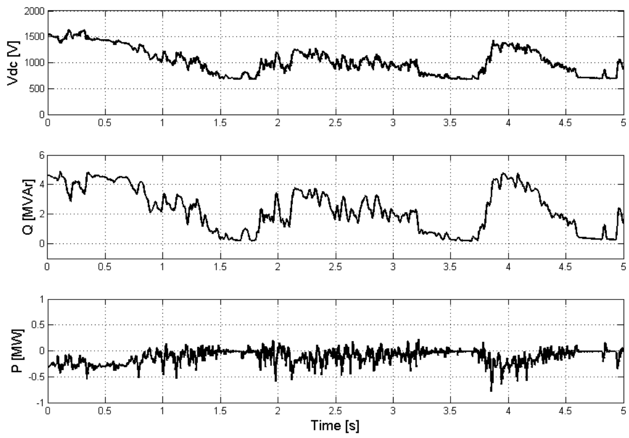


Fig. 21: Waveforms illustrating STATCOM performance.

According to International Standards [9] and Argentinian Rules [10], the method to evaluate the flicker improvement ratio ($P_{stwithout}/P_{stwith}$) is by performing normalized 10-minutes $P_{st95\%}$ measurements with and without the compensator.

The Simulink simulated voltage at the steelwork busbar was sent to the Hewlett Packard 33120A Arbitrary Waveform Generator for generating a voltage proportional to the voltage fluctuation.

The output of the waveform generator was used to modulate the amplitude of a 220 Volt, 50 Hz sinusoidal voltage generated by a phantom load.

This amplitude modulated signal was measured with the IEC 61000-4-15 normalized flicker meter Boconsult B9-DSP. The $P_{st95\%}$ values obtained are:

$P_{st95\%without} = 1.96$ (48)

$P_{st95\%with} = 0.97$ (49)

FI = 2.02 (50)

It must be taken into account that the flicker improvement ratio should not be constant because the speed of fluctuations varies and the performance of STATCOM varies as well.

B. Melting period

The results obtained are shown in Figs. 22-24.

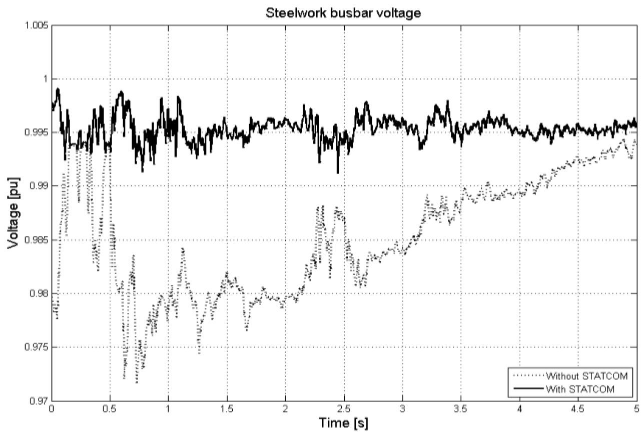


Fig. 22: Steelwork busbar voltage.

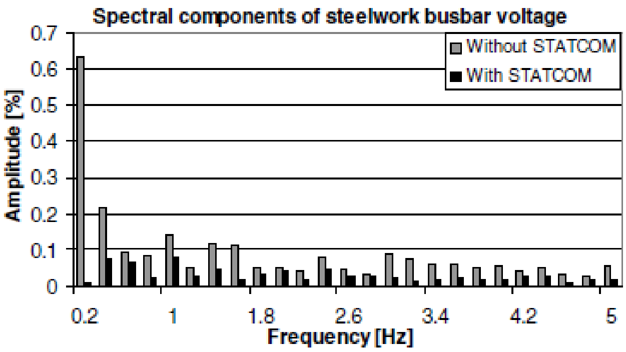
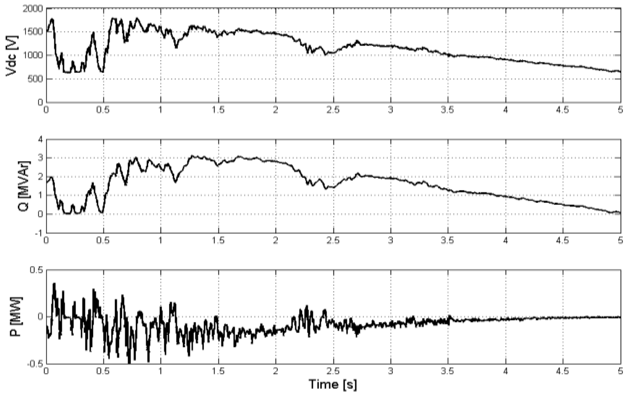


Fig. 23: Voltage spectral components



.Fig. 24: Waveforms illustrating STATCOM performance.

The simulated voltage during the melting period was measured with the flicker meter applying the same procedure. The values obtained are:

$P_{st95\%without} = 1.70$ (51)

$P_{st95\%with} = 0.58$ (52)

FI = 2.93 (53)

XI. CONCLUSIONS

In this paper a detailed model of a STATCOM for arc furnaces voltage flicker compensation has been developed. Models of both power circuit and control system are described in detail and have been implemented in MATLAB/Simulink environment with Power System Blockset.

The arc furnace was modeled as three controlled current sources controlled by the measured currents during the several phases of operation of a real arc furnace. The model was validated against the real measurements.

The simulation results and the experimental flicker measurements performed show that the fast response and the flexible control system of the STATCOM allow an efficient mitigation of voltage flicker caused by electric arc furnaces.

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10. Anexo a la Resolución ENRE 99/97. Base Metodológicapara el Controlde la Emisión de Perturbaciones. Etapa 2.