Voltage Flicker Mitigation using a simplified STATCOM model suitable for long time simulations

Jorge L. Agüero, Fernando Issouribehere

IITREE-LAT, FI, UNLP

Calle 48 y 116, B1900AMF, La Plata, Argentina

jla@iitree-unlp.org.ar

Abstract- **Voltage fluctuations caused by fast changes of industrial loads 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 simplified 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. Static and dynamic performance of STATCOM is evaluated and voltage fluctuation mitigation studies are performed and discussed. The voltage fluctuation mitigation is obtained by simulations and according to international standards.

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 behaviour characteristics. However, the main sources of power quality problems affecting large numbers of customers are the high power industrial loads. The fast large swings in active and reactive power required by such loads, cause fast 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 lamps.

EAF loads can cause serious electrical disturbances on a power system. Low level amplitude 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.

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-ton, 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 hereinafter.

The capability of the STATCOM to mitigate voltage fluctuations is demonstrated by digital simulations and experimental results.

II. POWER SYSTEM CONFIGURATION

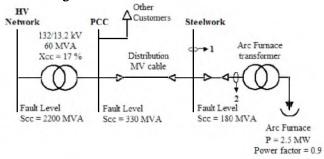The one-line diagram of the steelwork power system is shown in Fig. 1.

Fig. 1. Steelwork one-line diagram

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

III. POWER QUALITY MEASUREMENTS

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

There are several phases in the EAF operation, each presenting a different impact on the power system in terms of flicker, namely: Boring, Melting and Refining periods. Fig. 2 shows the measured EAF active and reactive power during a typical furnace heat.
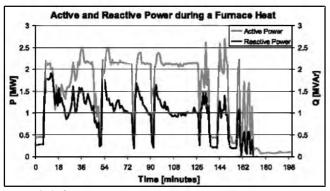
Fig. 2. Active and reactive power measurements during a Furnace Heat.

A. Flicker measurements

Flicker measurements were made by the IITREE-LAT with the IEC 61000-4-15 normalized flickermeter [1]. Fig 3 shows the results obtained from P_{st} measurements in 1-minute interval during a complete furnace cycle. This non normalized measurement was performed to evaluate flicker severity caused by fast voltage fluctuations especially during the first charge of scrap metal.
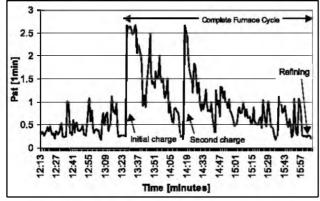

Fig. 3. P_{st} measurements during a normalized period.

The furnace cycle depicted in Fig. 3 was 2 and a half hour long and the furnace was recharged twice after the initial charge. It is interesting to note that the perturbation level decays as the metal becomes liquid and the arc becomes shorter and more stable. Fig 4 shows the normalized one-week, 10-minute-interval P_{st} measurements.
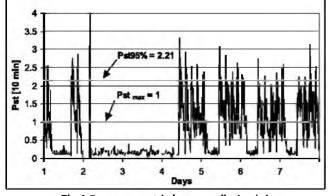

Fig. 4. P_{st} measurement during a normalized period.

The statistical results obtained from the normalized flicker measurement are presented in Table I.

Table I. Statistical result of Flicker measurement

Total observations of 10 minutes	1008
$P_{st95\%}$	2.21
Observations with $P_{st} > 1$	286
Percent of measurement with $P_{st} > 1$	28.6 %

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

B. Flicker compensation ratio and STACOM rating

The arc furnace apparent power could be determined according to the power factor limit described in [2].

$$S_L = \frac{2.5 \times 10^6}{0.85} = 2.95 MVA \qquad (1)$$

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

$$K = \frac{S_L}{S_{sc}} = \frac{2.95 \times 10^6}{180 \times 10^6} = 0.016 \qquad (2)$$

With this K factor, it is possible to obtain the maximum flicker that could be emitted by the steelwork, according to Argentinian regulations [2].

$$P_{stLimit} \leq 0.58 \qquad (3)$$

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

$$FI = \frac{P_{st real}}{P_{st\,limit}} = \frac{2.2}{0.58} = 3.8 \qquad (4)$$

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

From observations of practical installations the approximate equation for estimating the STATCOM rating for the operation with an EAF is given in [3].
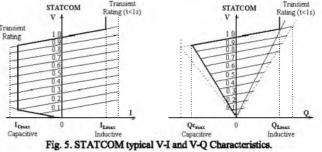
$$Q_{STATCOM} = 0.54 * \sqrt{(FI)} * S_{ratedAF} \qquad (5)$$

With:

FI is the flicker compensation ratio
$S_{ratedAF}$ = (0.55 to 0.65)S_{scf} is the arc furnace rating*
S_{scf} is the arc furnace fault level.

In this case FI = 3.8, S_{scf} = 5.6 MVA and then $S_{ratedAF}$ = 3.65 MVA. By (5), the compensator rating is:

$$Q_{STATCOM} \cong 4MVAr \qquad (6)$$

IV. STATCOM OPERATING PRINCIPLES

The STATCOM is essentially a voltage source behind a coupling reactance with the corresponding V-I and V-Q characteristics [3]-[5] shown in Fig. 5.

Fig. 5. STATCOM typical V-I and V-Q Characteristics.

From Fig. 5, it is possible to conclude that:

- 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.

- The maximum Var generation or absorption changes linearly with the a.c. system voltage.

- 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 full range of system contingencies.

The single line diagram of the STATCOM for reactive power supply to the transmission system is shown in Fig. 6, where U is the voltage of the steelwork busbar and Ec is the controllable output voltage.
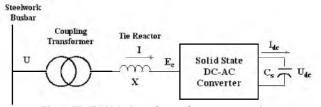

Fig. 6. STATCOM scheme for reactive power generation.

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

$$P_{STATCOM} = \frac{U.Ec}{X}\sin(\delta) \qquad (7)$$

$$Q_{STATCOM} = \frac{U}{X}(U - Ec.\cos(\delta)) \qquad (8)$$

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. 7.
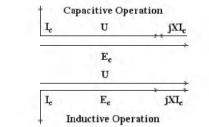

Fig. 7. Capacitive and Inductive behaviour of STATCOM.

V. UTILITY/CUSTOMER POWER SYSTEM MODEL

A digital simulation model of the distribution network is implemented by using the MATLAB/SIMULINK Power System Blockset (PSB). Fig. 8 shows the upper level of the

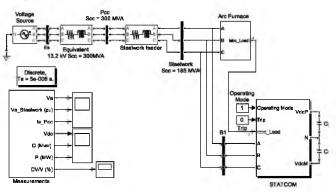distribution system for the voltage fluctuation mitigation study.

Fig. 8. MATLAB model of Utility/Customer system.

The EAF is modeled as three controlled current sources, governed by the measured currents in the EAF during a furnace heat. The arc furnace model is shown in Fig. 9.
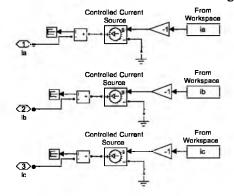

Fig. 9. Arc Furnace model.

VI. STATCOM DETAILED MODEL

The ± 4 MVAr STATCOM SIMULINK detailed model is shown in Fig. 10. It contains a PWM IGBT inverter, two 10000 μF capacitors and a control system. The STATCOM is coupled in parallel with the network through a 0.4/13.2 kV Δ-Y transformer [6]-[8].
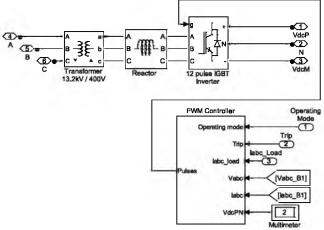

Fig. 10. STATCOM block diagram.

A PWM pulse generator of 1.65 kHz is used to control IGBT bridge. The modulation scheme used is of sinusoidal

type. The controller diagram is shown in Fig. 11. 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 (9)-(10).

The controller outputs are the voltages E_{cd} and E_{cq} that the PWM inverter has to generate according to (11)-(12). Then these voltages are converted into phase voltages E_{ca}, E_{cb} and E_{cc}.
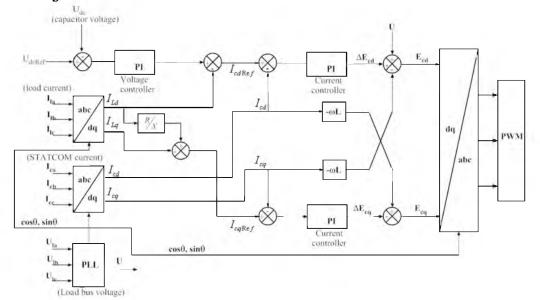

Fig. 11. STATCOM Controller.

The implementation of the control system is based on d-q compensation theory. The compensator input currents track the reference currents by means of the following current controller equations:

$$Ecd = \omega L Icq + U - \Delta Ecd \qquad (9)$$

$$Ecq = -\omega L Icd - \Delta Ecq \qquad (10)$$

$$\Delta Ecd = kp(Icdref - Icd) + ki \int (Icdref - Icd)dt \qquad (11)$$

$$\Delta Ecq = kp(Icqref - Icq) + ki \int (Icqref - Icq)dt \qquad (12)$$

The I_{cqref} and the I_{cdref} are presented in (13) and (14):

$$I_{cqref} = -I_{Lq} + (R_s / X_s)I_{Ld} \qquad (13)$$

$$I_{cdref} = k_p(U_{dcref} - U_{dc}) + k_i \int (U_{dcref} - U_{dc})dt - I_{Ld} \qquad (14)$$

The STATCOM model mentioned above is described in [6] where is presented a detailed model of the inverter that includes the switching of the inverter power switches. This model requires a very small computing time step to represent correctly the PWM waveforms ($T_s = 5$ μs). The simulation time is thus fairly long and it is not possible to perform simulations longer than 5 seconds due to memory requirements.

VII. STATCOM AVERAGED MODEL

If we are not interested to represent the chopping of the

PWM waveforms, we can use instead a voltage source having the same averaged value computed upon a chopping period (Tc = 1/1650) in this case. By using this "Averaged Model", we can simulate the system operation with a larger step time, resulting in a simulation time reduction or, put in another way, the total simulation time can be increased up to 60 seconds.

The Averaged Model can be built based on the energy conservation principle, taking into account that the instantaneous power must be the same on the AC side and the DC side of the inverter (neglecting losses). The DC current in the DC-link capacitor can be then computed from the measured AC instantaneous power and the DC-link voltage U_{dc} as:

$$I_{DC} = \frac{u_a i_a + u_b i_b + u_c i_c}{U_{DC}} \qquad (15)$$

Fig. 12 shows the SIMULINK implementation of the inverter's Averaged Model. On the AC side, the inverter is modeled three controlled voltage sources which are determined by three voltages V_{abc} from the control system. On the DC side, it is modeled by the *DC-link Model*. In this model, a capacitor (represented by an integrator) is charged by a DC current source with a value computed as shown in (15). A Switch block is used to avoid a division by zero at starting when the capacitor has no charge.
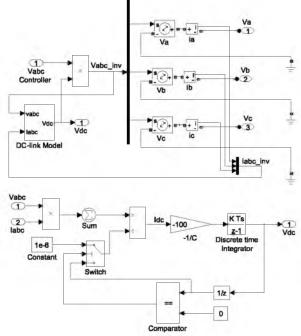
Fig. 12. SIMULINK diagram of the PWM inverter Averaged Model.

VIII. TESTING THE STATCOM AVERAGED MODEL WITH A DYNAMIC LOAD

The ability of a compensator to reduce flicker depends on the compensator size and speed of response. In order to evaluate the speed of response of both STATCOM models, the Three-Phase Dynamic Load from SIMULINK was utilized. The active power was set constant at 2.5 MW, and the reactive power was set at 1.8 MVAr. This load is representative of the active and reactive power levels reached by the arc furnace during a complete heat cycle. As it can be shown in Fig. 13 a positive step change of 1.2 MVAr is applied at time t = 0.4 s then a negative step of -3.4 MVAr is applied at t = 0.7 s, and finally the reactive power recovers its original value at t = 1 s.

Fig. 14 shows the obtained results for the busbar voltage where both models of STATCOM were connected.

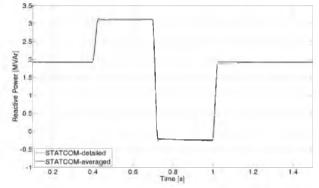As a result, both models (detailed and averaged) showed a similar response.

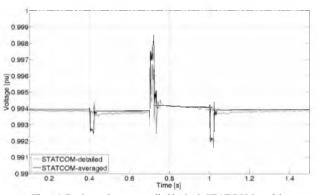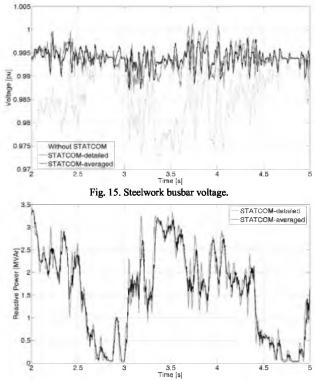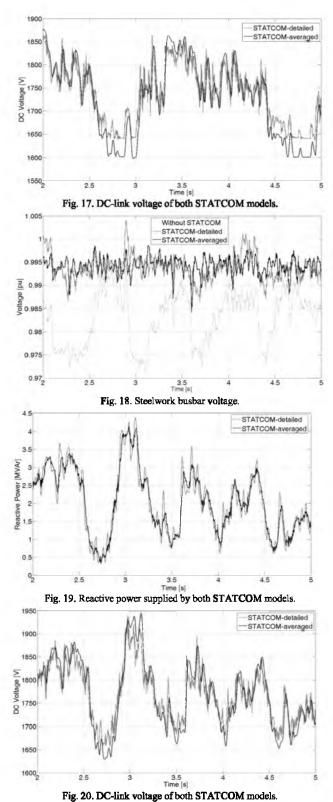Fig. 13. Reactive power supplied by both STATCOM models.

Fig. 14. Busbar voltage controlled by both STATCOM models.

IX. TESTING THE STATCOM AVERAGED MODEL WITH THE EAF MODEL

Digital simulations were performed to evaluate the flicker mitigation in different phases of operation of the EAF when both STATCOM models were connected to the steelwork busbar. The steelwork busbar voltage without STATCOM and with both STATCOM models is shown in Fig. 15 and Fig. 18. The reactive power supplied by both STATCOM models is shown in Fig. 16 and Fig. 19. And finally, the DC-link voltage of both STATCOM models is shown in Fig. 17 and Fig. 20.

Fig. 15. Steelwork busbar voltage.

Fig. 16. Reactive power supplied by both STATCOM models.

Fig. 17. DC-link voltage of both STATCOM models.

Fig. 18. Steelwork busbar voltage.

Fig. 19. Reactive power supplied by both STATCOM models.

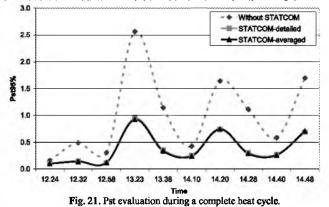Fig. 20. DC-link voltage of both STATCOM models.

As it can be seen in the previous figures, both STATCOM models presented a very similar response.

Finally, Fig. 21 presents the Flicker level (Pst95%) in the steelwork busbar voltage, during a complete furnace cycle. The Flicker level was obtained by digital IEC 61000-4-15 Flickermeter model implemented in MATLAB-SIMULINK

environment. The Pst values obtained in the case without STATCOM in operation were similar to the ones obtained by field measurements performed in the steelwork. It can be seen in this figure that the Pst values obtained with both STATCOM models were practically the same. The averaged STATCOM models has the important additional advantage of being able to perform simulations up to 60 seconds long, and therefore the Flicker values obtained are more representative of those obtained with the connection of a real STATCOM.

Fig. 21. Pst evaluation during a complete heat cycle.

The ability of a compensator to reduce flicker depends mainly in the speed of response of the control system, and in both STATCOM models the control loop parameters were adjusted to be exactly the same. The minor differences in both responses are due to inefficient filtering of high frequencies generated by commutation of high power IGBT switches, in the case of STATCOM detailed model.

Additionally, both STATCOM models reduce Flicker levels under the requirements of International and Argentinian Standards.

X. CONCLUSIONS

In this paper two STATCOM models for voltage Flicker compensation has been compared.

The first model, called "detailed model" was described in detail by the same authors in [6]. This model has the important advantage of been a physical model that includes all the power electronics associated with the PWM converter. However, this model requires a very small computing time step ($T_s = 5$ μs) to adequately represent the PWM waveforms. With this model can not be achieved simulation times of more than 5 seconds.

The second model, called "averaged model" was described in detail in [7], this model is based on the energy conservation principle and the PWM inverter is replaced by three controlled voltage sources and the DC-link is replaced by a control loop where the capacitor is replaced by an integrator. In this model the computing time step can be increased ten times and simulation times of 60 seconds can be achieved.

Both STATCOM models have demonstrated very similar performance in compensating Flicker generated by an EAF, and are valid for Flicker mitigation and propagation studies. However, the 60 second simulations long are suitable for

Flicker studies and for comparison with real Flicker measurements performed every one minute.

XI. REFERENCES

[1] IEC 61000-4-15. Electromagnetic Compatibility (EMC). Part 4: Testing and measurement techniques. Section 15: Flickermeter. Functional and design specifications.

[2] Anexo a la Resolución ENRE 99/97. *Base Metodológica para el Control de la Emisión de Perturbaciones. Etapa 2.*

[3] Static Synchronous Compensator (STATCOM) for Arc Furnace and Flicker Compensation. WG B4. 19. CIGRE Publication. December 2003.

[4] Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. Narain G. Hingorani, Laszlo Gyugyi. Wiley-IEEE Press 1999. ISBN-0780334558

[5] Thyristor-Based FACTS Controllers for Electrical Transmission Systems. R. Mohan Mathur, Rajiv K. Varma. IEEE Press and Wiley & Sons, Inc. 2002. ISBN 0-471-20643-1.

[6] "STATCOM Modeling for Mitigation of Voltage Fluctuations caused by Electric Arc Furnaces". J. Agüero, F. Issouribehere and P. Battaiotto. 2006 PES General Meeting. 1-4244-0493-2.

[7] "Modeling and Simulation of a Distribution STATCOM using Simulink's Power System Blockset". P. Giroux, G. Sybille, H. L. Huy. Pp. 990-994. 0-7803-7108-9/01.

[8] "Voltage Flicker Mitigation Using PWM-Based Distribution STATCOM". J. Sun, D. Czarkowski and Z. Zabar. Pp 616-621. 0-7803-7519-X/02.