Flicker Compensation in Arc Furnace Power systems Using the UPFC

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Abstract: *This paper presents a new approach for the dynamic compensation of flicker and harmonics in arc furnace power systems based on the UPFC. An arc furnace induces different kinds of disturbances caused by the harmonics and transient over voltage during the melting of scraps. Dynamic compensation is needed to improve the efficiency of process and to mitigate the disturbances caused to the network.*
The arc furnace load actually looks like a voltage source of harmonics behind a series of impedance consisting of the secondary cables to the electrodes. The UPFC with series active compensation capability opposed to variations of the arc resistance and suppress voltage flicker at the source. The design and control strategy of the UPFC based on the instantaneaous power calculation are detailed by this paper.
A typical arc furnace and UPFC model has been implemented in digital simulator to demonstrate how the UPFC can be controlled to take care of all disturbances.

Keywords: Arc Furnace, Flicker, harmonics, UPFC and active filtering

I-INTRODUCTION

Many loads on the system today are very sensitive to harmonic distortions. Constant distortion can also result in increases in losses and cause heating of motors, transformers, switchgear, and capacitors. Also, fuses, protective relays, metering devices, and power electronic equipment could have operation- problems due to harmonics.

Very small variations are enough to induce lightning disturbances for the human eye. For a standard lamp, the disturbance becomes perceptible for a voltage variation frequency of 10 Hz and relative magnitude of 0.26%.

The use of loads with nonlinear characteristics, such as arc furnaces, result in harmonic voltage and current generation. On the power system today, arc furnaces may be the most notorious harmonic-producers because they have great capacity lumped together in one place. It has been found that the arc at the electrode tips is basically a voltage clamp with trapezoidal shape waveform [1].

The fast variations of the current absorbed by an arc furnace during melting time are connected with arc-length variations which are mainly caused by metal-scrap adjustments, electrodynamic forces and arc-electrode variable displacement.

How much harmonic distortion is acceptable to the system with arc furnace applications is addressed in IEEE Standard 519. This standard is widely used as a guideline for the generated harmonics in arc furnace power systems.

The UPFC with active compensation capability behaves as a negative or positive resistance opposing to variations of the arc resistance and suppress voltage flicker at the source. After compensation , the system side or the load side, are maintained at their initial values.

In this paper, the compensation of the arc furnace by the UPFC are explained. Three-phase investigations are performed, since the main purpose is to propose a new approach for dynamic compensation of flicker and harmonics.

II- ARC FURNACE OPERATION AND MODEL

The complex nature of these phenomena does not favor a physical approach to the study of arc-length variation. Therefore, flicker investigations have been performed on the basis of the harmonic analysis. The arc furnace load looks like a voltage source of harmonics behind a series of impedance consisting of the secondary cables to the electrodes. A typical arc furnace model for simulation will include the furnace lead impedance and a constant voltage source behind it at each harmonic of concern. A typical arc furnace system is shown in fig.1.
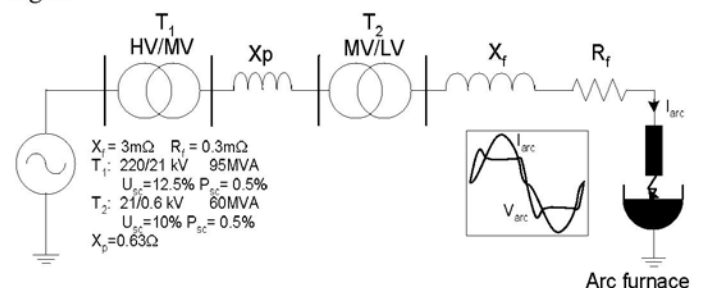

Fig. 1. Typical arc furnace system diagram.

Under unbalanced conditions of electrode arcing, there could be significant amounts of third harmonic and its multiples. Also, fifth and seventh harmonics that occur under balanced conditions could increase under unbalanced arcing conditions. Measurements of arc furnace voltage have indicated a varying harmonic output. The recorded fifth harmonic voltage has varied from 8%, 6%, and 2.5% of the fundamental voltage during beginning of meltdown, end of meltdown, and refining, respectively [1]. The process is optimized to operate around the

rated regime, where the active power is maximum . But one heating is in fact composed of at least three steps[2]:

(i) The bore down, lasts one or two minutes. The electrodes have to dive deeply into the scrap to heat it, thus inducing a high instability of the arc (succession of arc extinction and short-circuit between electrodes and scrap).

(ii) When the scrap is hot enough, the electrodes arc set higher to begin the melting phase (about 10 minutes). Due to collapses in the scrap, the arc is still quite unstable.

(iii) As the scrap becomes liquid, the laden phase takes place for another 10 minutes. During this phase, the operating point is quite stable.

Flicker is usually linked to the variation of arc length which is proportional to the arc voltage value V. Hence. We represent the flicker phenomenon by imposing a 10 Hz sinusoidal variation on V which provides the worst case of arc furnace operation. It is useful to investigate the effects of flicker compensation by UPFC.

In order to approach periodic flicker behavior, simulations can be made attributing to arc length a sinusoidal law with frequency close to the most sensitive for flicker perceptivity. For example, the frequency of 10 Hz can be chosen, which lies in the center of the sensitivity range, close to the minimum of the flicker perceptivity threshold curve for sinusoidal voltage fluctuations.

III- HARMONIC AND FLICKER COMPENSATION

A different Kinds of arc furnace-harmonic-compensation are used. Unwanted harmonic currents could be prevented from flowing through the power system by diverting them through a low-impedance shunt path. A detailed description of harmonic filter design is contained in ref. [3].

Experience has shown that a capacitors bank selected for an industrial system on the basis of economics will frequently resonated with the source impedance around the fifth harmonic. Also the main cause of harmonic problems in arc furnace operations is the interaction of power factor correction capacitors with the inductive reactance of the system.

The power fluctuation which causes the voltage drop can be separated in two parts:

Mean reactive power absorbed by the furnace, which could be compensated by fixed shunt-capacitor, and the instantaneous variation of the reactive power around its mean value whith can only be compensated with a dynamic device. The instantaneous

Variation of the reactive power can be canceled by means of several solutions. Two compensations can be distinguished:

- Shunt compensation: the reactive power consumed by the arc furnace must be kept constant. This type of compensation does not protect the arc furnace, consequently, in case of short-circuit the installation of the furnace undergoes high currents. A shunt compensation of active power does note seem very interesting because of the inductive nature of the feeding system.

- Series compensation: two types of compensation can be achieved by this structure: active and reactive compensation.

To control the real and reactive power consumed by the arc furnace we need to inject series voltages of the appropriate magnitudes and angles. The instantaneous injected voltage (v_{pq}) can be split into two components which are in phase (v_p) and in quadrature (v_q) with the source voltage.

It is to be noted that the UPFC is located near the LV transformer (Fig.3). The voltage of the network at the connection point of the UPFC is used as reference to define the pq coordinate system for the instantaneous parameters. As a result the UPFC has four controllable parameters: the V_p and V_q components of the series injected voltage and the I_p and I_q components of the shunt current.

IV- INSTANTANEOUS POWERS DEFINED IN TERMS OF SYMMETRICAL COMPONENTS

The total instantaneous energy flow per time unit, that is, the instantaneous active three-phase power, is always equal to the sum of the three active power sequences (positive, negative and zero) [4].

$$p_{3ph} = p_o + p_1 + p_2 \qquad (1)$$

where ,

$$p_o = \tfrac{1}{3}(v_a + v_b + v_c)(i_a + i_b + i_c) \quad , \quad q_o = 0 \qquad (2)$$

$$p_2 = p_1 = \tfrac{1}{2}[v_d i_a + v_b i_b + v_c i_c - \tfrac{1}{3}(v_a + v_b + v_c)(i_a + i_b + i_c)] \qquad (3)$$

$$q_2 = -q_1 = -\tfrac{1}{2\sqrt{3}}[v_a(i_c - i_b) + v_c(i_b - i_a) + v_b(i_a - i_c)] \qquad (4)$$

The instantaneous active power in the three phase four-wire system is given by :

$$p_{3ph} = v_a i_a + v_b i_b + v_c i_c \qquad (5)$$

The instantaneous reactive power in the three phase four-wire system is given by [4]:

$$q_{3ph} = \tfrac{-1}{\sqrt{3}}[v_a(i_c - i_b) + v_c(i_b - i_a) + v_b(i_a - i_c)] \qquad (6)$$

Unfortunately, the presence of more than one harmonic component or an unbalanced load current produces the oscillating parts of powers.

To better visualize the relation between the conventional concept of power and the instantaneous ones, the powers sequences $[p]_{012}$ and $[q]_{012}$ presented below are divided into the constant components $[\bar{p}]_{012}$ and $[\bar{q}]_{012}$ and the oscillating parts $[\tilde{p}]_{012}$ and $[\tilde{q}]_{012}$.

$$[p]_{012} = [\bar{p}]_{012} + [\tilde{p}]_{012} \qquad (7)$$

$$[q]_{012} = [\bar{q}]_{012} + [\tilde{q}]_{012} \qquad (8)$$

All harmonics in voltage and current can contribute to the constant components of powers $[\bar{p}]_{012}$ and $[\bar{q}]_{012}$ if they have the same frequency and are from the same kind of sequence component (positive, negative or zero).The well known

fundamental active and reactive three phase power (P_{3ph}=3VIcos(phi),Q_{3ph}=3VIsin(phi)) is one term of the constant power component $\overline{P}_{3ph};\overline{q}_{3ph}$.

$$\overline{P}_{3ph} = \overline{P}_o + \overline{P}_1 + \overline{P}_2 \qquad (9)$$

$$\overline{q}_{3ph} = \overline{q}_o + \overline{q}_1 + \overline{q}_2 \qquad (10)$$

The control algorithm does not use any rms value calculation to separate the oscillating parts of powers $[\widetilde{p}]_{012} \, and [\widetilde{q}]_{012}$ which influence the dynamic response of the controlled system. A low-pass filter can isolate the constants parts of powers $[\overline{p}]_{012} \, and [\overline{q}]_{012}$.

The instantaneous three phase current decomposed into three components: zero, active and reactive [4],

$$[i]_{abc} = [i_o] + [M_p]p + [M_q]q \qquad (11)$$

where

$$[M_p] = \begin{bmatrix} \dfrac{2v_p}{3(v_p^2 + v_q^2)} \\[2mm] \dfrac{\sqrt{3}v_q - v_p}{3(v_p^2 + v_q^2)} \\[2mm] \dfrac{-\sqrt{3}v_q - v_p}{3(v_p^2 + v_q^2)} \end{bmatrix} \quad [M_q] = \begin{bmatrix} \dfrac{2v_q}{3(v_p^2 + v_q^2)} \\[2mm] \dfrac{-\sqrt{3}v_p - v_q}{3(v_p^2 + v_q^2)} \\[2mm] \dfrac{\sqrt{3}v_p - v_q}{3(v_p^2 + v_q^2)} \end{bmatrix}$$

$$v_p = \tfrac{1}{3}(v_a - \tfrac{1}{2}v_b - \tfrac{1}{2}v_c); \qquad v_q = \tfrac{1}{3}(\tfrac{\sqrt{3}}{2}v_b - \tfrac{\sqrt{3}}{2}v_c)$$

$$i_o = \tfrac{1}{3}(i_a + i_b + i_c) = \tfrac{i_n}{3}$$

$$p = p_1 = \overline{p} + \widetilde{p} \; ; \qquad q = q_1 = \overline{q} + \widetilde{q}$$

$$\begin{cases} i_a = i_o + i_{ap} + i_{aq} \\ i_b = i_o + i_{bp} + i_{bq} \\ i_c = i_o + i_{cp} + i_{cq} \end{cases} \qquad (12)$$

The instantaneous active and reactive currents are given by

$$[i_p]_{abc} = [M_p]p \qquad (13)$$

$$[i_q]_{abc} = [M_p]q \qquad (14)$$

where

$$p = \overline{p} + \widetilde{p} \; ; \qquad q = \overline{q} + \widetilde{q}$$

The fundamental component of instantaneous active and reactive currents can be calculated using the constant component of power:

$$[i_{Fp}]_{abc} = [M_p]\overline{p} \qquad (15)$$

$$[i_{Fq}]_{abc} = [M_p]\overline{q} \qquad (16)$$

The harmonic components of instantaneous active and reactive current can be calculated using the oscillating part of power:

$$[i_{hp}]_{abc} = [M_p]\widetilde{p} \qquad (17)$$

$$[i_{hq}]_{abc} = [M_p]\widetilde{q} \qquad (18)$$

V - UPFC CONCEPT AND DESCRIPTION OF THE CONTROL STRATEGY

The UPFC is the most versatile FACTS-equipment and is able to insert a voltage in series with the line. This voltage can have any phase and magnitude referred to the line voltage. The UPFC consists of a parallel and a series branch, each consisting of a three-phase transformer and a PWM converter. Both converters are operated from a common dc link with a dc storage capacitor. The real power can freely flow in either direction between the two ac branches. Each converter can independently generate or absorb reactive power at the ac output terminals [5]. The controller provides the gating signals to the converter valves to provide the desired series voltages and simultaneously drawing the necessary shunt currents.

In order to provide the required series injected voltage, the inverter requires a dc source with regenerative capabilities. One possible solution is to use the shunt inverter to support the dc bus voltage. The PWM technique is used to provide a high-quality output voltage, to reduce the size of the required filter, and to achieve a fast dynamic response. The harmonics generated by the inverter are attenuated by a second order filter, providing a low THD voltage to the transformer.

Fig.3 shows a UPFC application in arc furnace compensation connected through a transformer. Active and reactive power flow in the line and the voltage source are controlled. The arc furnace is represented by harmonic voltage sources. The UPFC is modeled as a series voltage source V_{inj} representing the series branch and a current source I_{pq} representing the parallel branch. Note that the series insertions transformer has an associated leakage inductance, X_T.

Control strategy of the series side

In practice, it is desirable that the series voltage injection is made to achieve the desired steady state active and reactive power as well as to ensure satisfactory dynamic response. Fast system response can be ensured only if the injected voltages are deduced in real time on instantaneous value basis. The real time controller should monitor the system conditions and generate the appropriate injected voltages for each time step. From the local measured voltage and current, the controller generates the instantaneous values of the injected series voltages (v_p, v_q) and shunt currents (i_p, i_q) for each phase. These values can be derived based on the active and reactive powers references which can be locally fixed or delegated by the master controller.
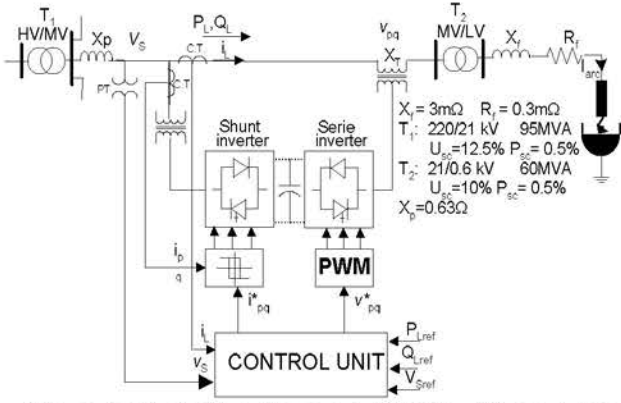
Figure 3: Illustrative diagram for UPFC with arc furnace

If v_{pq} is the instantaneous voltage injected by the UPFC, the components V_p and V_q are related to the active and reactive power errors dP_L and dQ_L.

The active and reactive power references (P_{Lref}; Q_{Lref}) which can be locally fixed or delegated by the master controller, is compared with the instantaneous measured values given by equations (5) and (6). The error signal (dP_L;dQ_L) is passed through a proportional controller to determine the necessary V_p and V_q components of the series injected voltage amplitude (V_{pq}). To generate the instantaneous values v_{pq}, we combined the voltage amplitude V_p and V_q with the instantaneous active and reactive line current (i_p, i_q) given by equation (13-14).

The instantaneous series injected voltages for the three phases are given by,

$$[v_{pq}]_{abc} = K_p \cdot \frac{dP_L}{P_L}[i_p]_{abc} + K_q \cdot \frac{dQ_L}{Q_L}[i_q]_{abc} \qquad (19)$$

In a practical approach, the proportional gains K_p and K_q linking the power changes [dP_L, dQ_L] and the injected voltage components [V_p, V_q] have to be properly chosen to obtain stable performance. A different controller can replace the proportional gain in this strategy to performed the results such as adaptive controller or the fussy logic.

Control strategy of shunt side

In order to provide the required series injected voltage, the inverter requires a dc source with regenerative capabilities. One possible solution is to use the shunt inverter to support the dc bus voltage. The three instantaneous shunt currents [i_{pq}]$_{abc}$ of the UPFC represent the active components [i_{shp}]$_{abc}$ in phase with v_s corresponding to the real power P_{sh}, and the reactive components [i_{shq}]$_{abc}$ corresponding to the reactive power q_{sh}.

To sustain the dc voltage V_{dc} across the dc link of the UPFC, the shunt converter should draw the active power which is required by the series inverter. Neglecting the power losses in the inverter, the real power P_{se} becomes the link power $V_{dc}I_{dc}$ supplied by the shunt side:

$$p_{sh} = p_{se} = v_{pqa}i_a + v_{pqb}i_b + v_{pqc}i_c \qquad (20)$$

The instantaneous series power components are given by,

$$[p_{sh}]_{012} = [\bar{p}_{sh}]_{012} + [\tilde{p}_{sh}]_{012} \qquad (21)$$

If [v_{pq}]$_{abc}$ and [i]$_{abc}$ are balanced systems,

$$[\tilde{p}_{sh}]_{012} = 0 \qquad (22)$$

The active component of the shunt current is *given* by,

$$[i_{sh}]_{abc} = M_p \bar{p}_{sh} \qquad (23)$$

the inverter, the real power P_{se} becomes the link power $V_{dc}I_{dc}$ supplied by the shunt side:

From the shunt side the UPFC is compensating all undesirable powers of the load ($[\tilde{p}]_{Load}$, $[\tilde{q}]_{Load}$, $[\bar{q}]_{Load}$) and is assuring a balance of energy to retain the dc capacitor voltage around its reference $V_{dc\,ref}$.
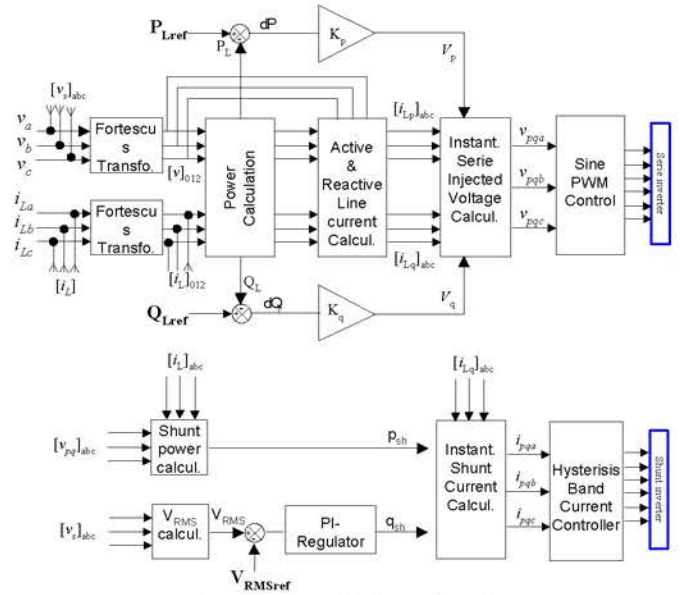

Figure 4. UPFC Control Unit

To achieve the instantaneous compensation of harmonics the compensating currents [i_C]$_{abc}$ are given by

$$[i_C]_{abc} = [i_{hp}]_{abc} + [i_{hq}]_{abc} = [M_p]\tilde{p}_{Load} + [M_q]\tilde{q}_{Load} \qquad (24)$$

where

[M_p] and [M_q] are given by equation (11).

$\tilde{p}_{Load}$ and $\tilde{q}_{Load}$ are isolated by the low-pass filter from the instantaneous power p_{Load} and q_{Load} respectively. The latter are calculated using equation (5) and (6).

This harmonic current is compensated by the shunt converter [i_{pq}]$_{abc}$ of the UPFC to provide constant instantaneous power to the source. Further, the shunt converter can compensate also the reactive power of this load and balanced the currents. In this case the compensating currents are given by

$$[i_C]_{abc} = [i_o] + [i_{hp}]_{abc} + [i_q]_{abc} = [i_o] + [M_p]\tilde{p}_{Load} + [M_q]q_{Load} \qquad (25)$$

On the other hand, shunt converter should draw the active power which is required by the series inverter and sustain the source voltage.
On this basis the shunt current of the UPFC is given by

$$[i_{pq}]_{abc} = [i_C]_{abc} + [i_{sh}]_{abc} \qquad (26)$$

VI-SIMULATION RESULTS

In order to validate the proposed control strategy for flicker mitigation and harmonic compensation, the system illustrated in fig3 has been implemented using Simulink software. The control strategy is applied to a complete system model with arc furnace impedance and series transformers inductance.
Using The UPFC as a shunt active filter is an effective way of minimizing voltage distortion caused by arc furnace operations. Figure 5 shows the compensation of the harmonic currents using the shunt converter of the UPFC without any time delay.
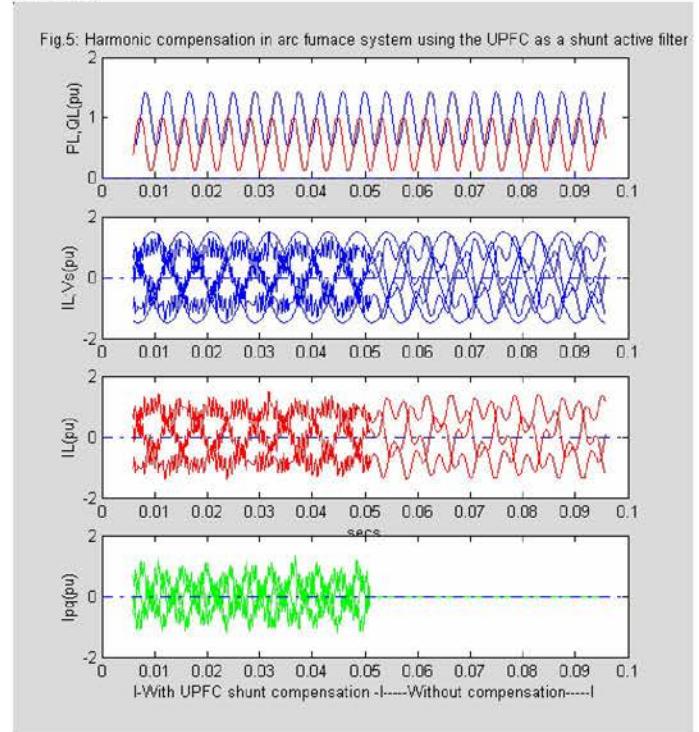In the second case study, figure 6 shows simulation results of a case where the arc resistance fluctuates and cause the flicker phenomenon. The UPFC is controlled as variable negative or positive resistance in order to compensate arc resistance fluctuation. To achieve this function, at t=200ms the UPFC injected the appropriate voltage (v_{pq}) to annulated arc resistance fluctuations. This compensation is achieved by keeping constant both active and reactive current of the arc furnace based on the power references (P_{Lref}, Q_{Lref}). The active shunt current Ipq is drawn to maintain voltage capacitor (V_{dc}) constant.

Fig.6: Fliker mitigation using UPFC series compensations
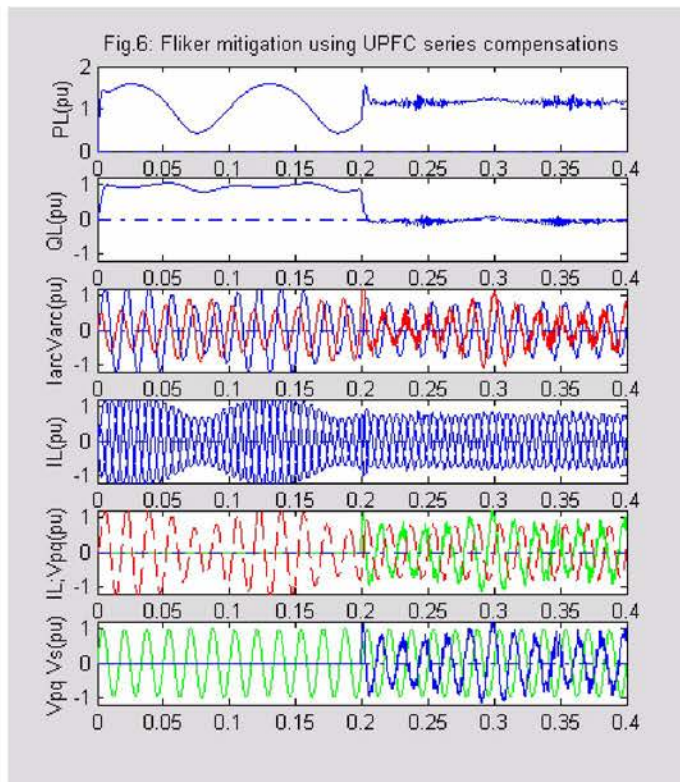
VII – CONCLUSIONS

A new control strategy for flicker mitigation and harmonic compensations is detailed in this paper. In order to test these control strategy, detailed control unit of the UPFC is presented and their implementation using simulink demonstrate their excellent characteristics in mitigating flicker.
The UPFC compensation allows arc furnace to operete at high power and current constraints are reduce. It allows steel manufacturers to improve furnace efficiency at lower costs compared to classic compensator and to expand arc furnace lifetime.

Fig.5: Harmonic compensation in arc fumace system using the UPFC as a shunt active filter
I-With UPFC shunt compensation -I-----Without compensation-----I

VIII – REFERENCES

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