Control Strategy for a Versatile Compensation in the Unbalanced and Non-Sinusoidal System Using UPQC

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Abstract: This paper proposes a control strategy for three-phase unified power quality conditioner (UPQC) installed to compensate both voltage flickers and current harmonics for nonlinear unbalanced loads. This approach is based on the control of instantaneous power symmetrical components at the load side. The proposed control strategy of the UPQC, decompose instantaneously the active and reactive current into zero, positive and negative sequences with fundamental and harmonic components. To realize this decomposition in real time a general equations of the instantaneous powers based on symmetrical components are used. To validate the proposed power equations, comparative experimental results are presented in this work. A control strategy based on this approach is applied to the unified power quality conditioner (UPQC). A typical non-linear loads and UPQC model has been implemented in digital simulator to demonstrate the practicality of the proposed approach. And how the UPQC can be controlled to take care of all disturbances.

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1. Introduction

The interruption of an industrial process due to a power outage or voltage dip can result in very substantial additional costs to the operation. Where power quality is lacking, disturbances such as voltage flicker and harmonics may cause problems for both domestic and industrial consumers, far from the source of the problem. Ultimately, the offending equipment will become a concern for many consumers and not just for the owner of the equipment or grid. The quality of a power supply is largely synonymous with the voltage quality. The voltage provided at a given connection point should be as close to the nominal value as possible, and the wave form a pure sine form, free from harmonics and other disturbances.

The unified power quality conditioner (UPQC), shown in Fig1, is the versatile devices that assure these conditions. It composed by a shunt-active filter and a series-active filter. This combination allows a simultaneous compensation of the load currents and the line voltages. The series and shunt-active filters are connected in a back-to-back configuration, were the common DC link voltage are regulated by the shunt converter.

Recent research efforts on power quality have been made for solving almost all PQ problems using the UPQC [1][2]. Therefore to deal with voltage and current related power quality problems, both series and shunt active filters are combined through a common dc link capacitor forming the UPQC. In a UPQC depending upon its application, the arrangement of series and shunt filters are interchangeable. In general when a UPQC is used in a power distribution system [3], the series filter is installed ahead of the shunt filter. Moreover, in a UPQC installed for voltage flicker/unbalance sensitive loads, the series filter is installed at the load side to effectively meet the requirements of the voltage sensitive load [4].

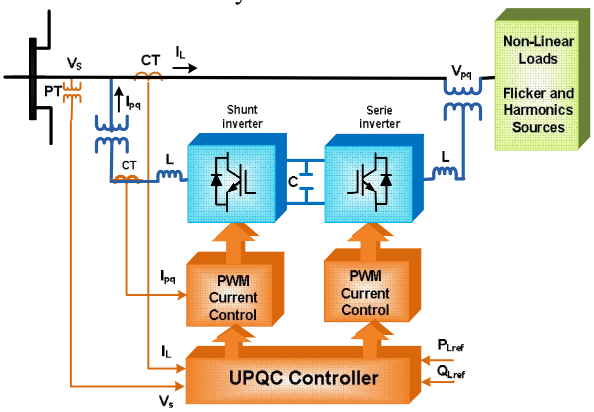
On the other hand, different control strategies are reported in the literature for UPQC. These strategies estimate the derived components based on p-q theory [5], orthogonal decomposition [8], modified p-q theory [6], wavelet transform decomposition [9], control strategy based on neural networks [10], etc. Unfortunately, most of these control strategies are not valid for voltage and current distorted conditions. Further, some schemes based on adaptive techniques [11] are used to compute the different components of current.

Apart from this, a scheme based on current decomposition technique in time domain is also employed for selective compensation by a shunt AF [12].

Also, methods based on frequency domain approach have been reported, which separate out the customer and supply side harmonic contributions [13].

An approach based on frequency domain approach is accurate but involves lot of computation, hence not suitable for on-line applications while, time domain approach is fast but limited to single node applications.

This paper presents a 3-phase UPQC configuration suitable for distributed systems with voltage flicker/unbalance sensitive loads, where the series filter is installed at the load side to effectively meet the requirements of the voltage, and versatile control algorithm for its control. The series AF is controlled to maintain voltage regulation and to eliminate flickers and unbalance from the load terminal voltage. The shunt AF is controlled to mitigate the supply current from harmonics, reactive power and neutral current. The dc bus voltage is maintained constant by the shunt active filter.



Fiig. 1. The scheme of Unified Power Quality Conditioner (UPQC)

To realize this decomposition in real time a general equations of the instantaneous powers based on symmetrical components are used. To validate the proposed power equations, comparative experimental results are presented in this work.

The proposed control strategy of the UPQC, decompose instantaneous load currents into active and reactive components of positive, negative and zero sequences at fundamental frequency and the harmonic frequencies.

2. Instantaneous Power And Load Current Decomposition

The Fortescus transformation of the three phase instantaneous voltages and currents decompose the unbalanced-non-sinusoidal system into three symmetrical component systems. The zero, positive and negative (012) symmetrical component of instantaneous voltage and current can be expressed in terms of their instantaneous values by the equations [17]:

$$[i]_{0,1,2} = [F]^{-1}[i]_{a,b,c} \quad [v]_{0,1,2} = [F]^{-1}[v]_{a,b,c} \qquad \textbf{(1)}$$

where [F] is the Fortescue matrix [7]

Moreover, these instantaneous symmetrical components of voltage and current can be split into two parts: active (p) and reactive (q) [16].

● *The zero sequence system* is considered as a three identical single phase circuits independent of the positive and negative sequences.

The instantaneous power in the zero-sequence system is: $s_o = 3v_o i_o = p_0$ **(2)**

The zero sequence components are always real and they never contribute to the reactive power.

● *The positive-sequence system* is considered as a three phase positive-sequence circuit:

The positive power-sequence in the three phase system is $s_1 = 3v_1 i_1^* = p_1 + jq_1$ **(3)**

● *The negative-sequence system* is considered as a three phase negative-sequence circuit:

The negative power-sequence in the three phase system is $s_2 = 3v_2 i_2^* = p_2 + jq_2$ **(4)**

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)

$$p_{3\phi} = p_o + p_1 + p_2 \qquad \textbf{(5)}$$

Substitution of (1),(2),(3) and (4) into (5) yields the instantaneous active power in the three phase four-wire system.

$$p_{3\phi} = v_a i_a + v_b i_b + v_c i_c \qquad \textbf{(7)}$$

The instantaneous three-phase reactive power q_{3ph} is always equal to the sum of the three reactive power sequences (positive, negative and zero).

$$q_{3\phi} = |q_1| + |q_2| = \tfrac{1}{2\sqrt{3}}[v_a(i_b - i_c) + v_c(i_a - i_b) + v_b(i_c - i_a)) \qquad \textbf{(8)}$$

Unfortunately, the presence of an unbalanced load current produces the oscillating parts of powers $[\tilde{p}]_{0,1,2}\, and [\tilde{q}]_{0,1,2}$.

To identify the relation between the conventional concept of powers and the instantaneous ones, the powers sequences $[p]_{0,1,2}\, and [q]_{0,1,2}$ presented below are divided into the constant components $[\bar{p}]_{0,1,2}\, and [\bar{q}]_{0,1,2}$ and the oscillating parts $[\tilde{p}]_{0,1,2}\, and [\tilde{q}]_{0,1,2}$.

$$[p]_{0,1,2} = [\bar{p}]_{0,1,2} + [\tilde{p}]_{0,1,2} \qquad \textbf{(9)}$$

$$[q]_{0,1,2} = [\bar{q}]_{0,1,2} + [\tilde{q}]_{0,1,2} \qquad \textbf{(10)}$$

If they have the same frequency, the voltage end current harmonics for each sequence component (o,1,2) contribute to the constant components of powers $[\bar{p}]_{0,1,2}\, and [\bar{q}]_{0,1,2}$.

Then, the well known fundamental active and reactive three phase power ($P_{3\Phi}$=3VIcosϕ; $Q_{3\Phi}$ =3VIsinϕ) is one term of the constant power component $\bar{p}_{3\phi}; \bar{q}_{3\phi}$.

$$\bar{p}_{3\phi} = \bar{p}_o + \bar{p}_1 + \bar{p}_2 \qquad \textbf{(11)}$$

$$\bar{q}_{3\phi} = |\bar{q}|_1 + |\bar{q}|_2 \qquad \textbf{(12)}$$

In practical approach, a low-pass filter is used by the control algorithm to separate the oscillating parts of power without influencing the dynamic response of the control system. The The control algorithm does not use any rms value calculation to separate the oscillating parts of powers $[\tilde{p}]_{0,1,2}\, and [\tilde{q}]_{0,1,2}$ which influence the dynamic response of the controlled system. A low-pass filter can isolate the constants parts of powers $[\bar{p}]_{0,1,2}\, and [\bar{q}]_{0,1,2}$.

Instantaneous load current decomposition:

This versatile concept of instantaneous power is used to decompose the load current into five parts: zero positive and negative sequence fundamental frequency active and reactive currents $[i_{Fp}]_{0,1,2}$ and $[i_{Fq}]_{0,1,2}$, active and reactive current at harmonic frequencies $[i_{hp}]$ and $[i_{hq}]$. With these current components, the selective compensation of combinations of them can be made, which respects the limited rating of the shunt converter of three-phase four-wire UPQC and also attributes the responsibility of the customer and the utility at the point of common coupling.

The symmetrical components of the instantaneous fundamental active and reactive line currents can be formulated as,

$$[i_{Fp}]_{0,1,2} = \left[\frac{\bar{p}}{3v}\right]^*_{0,1,2} \qquad [i_{Fq}]_{012} = \left[\frac{j\bar{q}}{3v}\right]^*_{0,1,2} \qquad \textbf{(13)}$$

The fundamental components of active and reactive currents for each phase are given by the inverse transformation of Fortescue [16],

$$[i_{Fp}]_{a,b,c} = [F][i_{Fp}]_{0,1,2} \quad [i_{Fq}]_{a,b,c} = [F][i_{Fq}]_{0,1,2} \qquad \textbf{(14)}$$

The harmonic components of instantaneous active and reactive current can be calculated using the oscillating part of power [15]:

$$[i_{hp}]_{0,1,2} = \left[\frac{\tilde{p}}{3v}\right]^*_{0,1,2} \qquad [i_{hq}]_{0,1,2} = \left[\frac{j\tilde{q}}{3v}\right]^*_{0,1,2} \qquad \textbf{(15)}$$

$$[i_{hp}]_{a,b,c} = [F][i_{hp}]_{0,1,2}\,; \quad [i_{hq}]_{a,b,c} = [F][i_{hq}]_{0,1,2} \qquad \textbf{(16)}$$

Substitution of (1)-(2)-(3) and (4) into (13) and (16) given the instantaneous three phase current decomposed into five components: zero, active and reactive of the fundamental and harmonics [14],

$$[i]_{a,b,c} = [i_o]_{a,b,c} + [i_{FP}]_{a,b,c} + [i_{Fq}]_{a,b,c} + [i_{hP}]_{a,b,c} + [i_{hq}]_{a,b,c} \qquad \textbf{(17)}$$

$$[i]_{a,b,c} = [i_o] + [M_p]\bar{p} + [M_q]\bar{q} + [M_p]\tilde{p} + [M_q]\tilde{q} \qquad \textbf{(18)}$$

Where

$$p = p_1 = \bar{p} + \tilde{p}\ ; \qquad q = q_1 = \bar{q} + \tilde{q}$$

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

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

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

3. Exprimental Results

In order to validate the proposed instantaneous power theory, a three phase unbalanced system as illustrated in figure2 has been implemented in the laboratory. Digital instruments are used for the conventional measurements and a data acquisition interface with 10 kHz sampling frequency is used to measure the three phase instantaneous voltages and currents. For each sample these three-phase instantaneous active and reactive power components are computed based on the proposed theory.

One can see in figure 4 the waveforms obtained of the three phase voltages and currents with an unbalanced and nonlinear load. The spectrum analysis of three phase voltages and currents are depicted in figure 5. The latter shows the distortion factors and the fundamental components values (cursers C1, C2).

Using the data acquisition interface, a computer based system determines the instantaneous active and reactive power given by equations (5) and (8) in the proposed theory. Also, a low-pass filter have been used to isolate the DC quantities namely constant parts of powers $\bar{p}_{3ph}\ \&\ \bar{q}_{3ph}$ as given by equations (11) and (12).

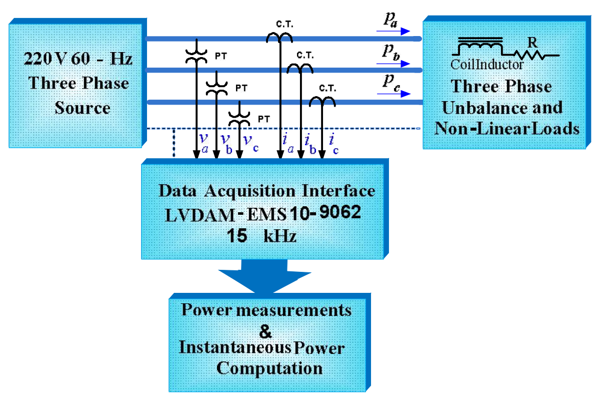


Fig. 2. The experimental circuit of the three phase system with unbalance and nonlinear load.

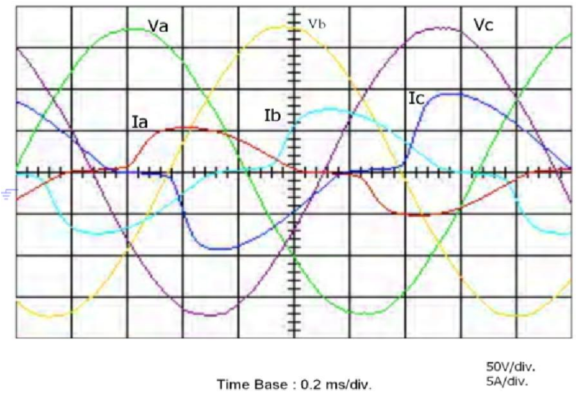


Fig. 4. Experimental waveforms of three phase voltages and currents

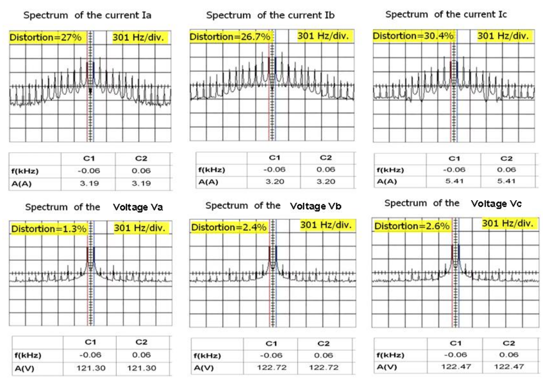


Fig. 5. The spectrum analysis of three phase voltages and currents with the fundamentals values and distortion factors.

These results are compared with the conventional power measurements given by the digital instruments in table 1. The errors between the measured and the computed powers are less then 0.6%. These results confirm that the physical meaning of the real and imaginary powers in time domain agrees with the conventional definition of the instantaneous active and reactive powers.

Table 1. A comparative table of the experimental results given by the conventional power measurements and the proposed power equations in unbalance and nonlinear system.

Source Voltages (V)	Load Currents (A)	Active power (W)	Reactive power (VAR)
V_a= 121.92	I_a= 3.317	P_a= 230.91	Q_a= 316.87
V_b= 123.21	I_b= 4.648	P_b= 378.73	Q_b= 406.88
V_c = 122.77	I_c= 5.668	P_c= 601.78	Q_c= 289.15
Three-phase power (measured)		P_{3ph}=1211.4	Q_{3ph}= 1012.9
Instantaneous power (calculated)		$\bar{p}_{3ph}$=1209.6	$\bar{q}_{3ph}$= 1007.1
Three-phase power error (%)		P_{3ph}=0.15%	Q_{3ph}= 0.57%

4.The Control Strategy Of Upqc

Control strategy of the series inverter

The proposed control strategy of the series inverter aims mainly to determine the references of injected three-phase voltages $[v_{pq}^*]_{abc}$ at the load terminal, which compensate the distortions and flickers present in the line voltages ($[v_s]_{abc}$) to make it perfectly sinusoidal with a desired amplitude.

The amplitude of the reference injected voltage (V_p,V_q) is computed as follows: A comparison of the computed instantaneous power given by equations (11) and (12) and the references values delegated by the master controller results in a power error (ΔP_L;ΔQ_L), which is fed to a proportional integral (PI) controller and the output of the PI controller is taken as the reference amplitude of the injected voltages. To generate the instantaneous values of the injected voltage$[v_{pq}]$,we multiply the voltage amplitude V_p and V_q with the instantaneous active and reactive line current ($[i_{Fp}]_{abc}$;$[i_{Fq}]_{abc}$) given by equation(14).

Therefore, the three phases instantaneous series injected voltages are given by,

$$[v_{pq}]_{a,b,c} = K_p.\frac{\Delta P_L}{P_L}[i_{Fp}]_{a,b,c} + K_q.\frac{\Delta Q_L}{Q_L}[i_{Fq}]_{a,b,c} \quad \textbf{(19)}$$

K_p and K_q have to be properly chosen to obtain stable performance.

Control strategy of shunt inverter

The control strategy for the shunt inverter is based on the decomposition method of the line current given by equations (14),(16). In the following section the control strategy adopted for the versatile compensations is explained in detail.

To sustain the dc voltage V_{dc} across the dc link to provide the required series injected voltage, 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 real power P_{sh} supplied by the shunt side:

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

The instantaneous series power components are given by,

$$p_{sh} = \bar{p}_{sh} + \tilde{p}_{sh} \quad \textbf{(21)}$$

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

$$\tilde{p}_{sh} = 0 \quad \textbf{(22)}$$

To assuring a balance of energy and retain the dc capacitor voltage around its reference $V_{dc\ ref}$ the shunt converter should draw the required current given by,

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

In the other hand, from the shunt side the UPQC achieve a selective compensation of all undesirables load currents $[i_o]_{abc}$;$[i_{Fq}]_{abc}$;$[i_{hp}]_{abc}$;$[i_{hq}]_{abc}$).

To achieve the active filtering of current harmonics the shunt converter should draw the compensating currents $[i_C]_{abc}$ given by

$$[i_C]_{a,b,c} = [i_{hp}]_{a,b,c} + [i_{hq}]_{a,b,c} = [M_p]\tilde{p}_L + [M_q]\tilde{q}_L \quad \textbf{(24)}$$

where $[M_p]$ and $[M_q]$ are given by equation (18).

The instantaneous load power p_L and q_L are calculated using equation (7) and (8). However, the oscillate parts $\tilde{p}_L$ and $\tilde{q}_L$ are isolated using a low-pass filter.

Further, the shunt side of UPQC can balanced the load currents, and improves the power factor by drawing the reactive power of the fundamental load current. In this case the compensating currents are given by

$$[i_C]_{a,b,c} = [i_o] + [i_{hp}]_{a,b,c} + [i_{hq}]_{a,b,c} + [i_{Fq}]_{a,b,c} = [i_o] + [M_p]\tilde{p}_L + [M_q]\tilde{q}_L \quad \textbf{(25)}$$

However, shunt converter should draw the active power which is required by the series inverter and sustain the source voltage. On this basis the total shunt currents of the UPQC are the sum of the selected compensating currents:

$$[i_{pq}]_{a,b,c} = [i_o] + [i_{hp}]_{a,b,c} + [i_{hq}]_{a,b,c} + [i_{Fq}]_{a,b,c} + [i_{sh}]_{a,b,c} \quad \textbf{(26)}$$

Simulation Results

The use of loads with non-linear voltage-current characteristics, such as the arc furnaces, result in the generation of voltage and current harmonic distortion. In fact, arc furnaces may be the most prominent harmonic producers because of their great capacity lumped together at one place. Hence to improve power quality of the system, mitigation devices have to be applied.

In order to validate the proposed control strategy for flicker mitigation and harmonic compensation, the simulation of the system illustrated in figure 7 is carried out. The system 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 UPQC as shunt and series active filter is an effective way of minimizing harmonics and voltage distortion caused by arc furnace operations.

In the first case, figure 8 shows waveforms of voltage and currents with and without compensation of harmonics at the point of common coupling of the arc furnace and the shunt active filter.

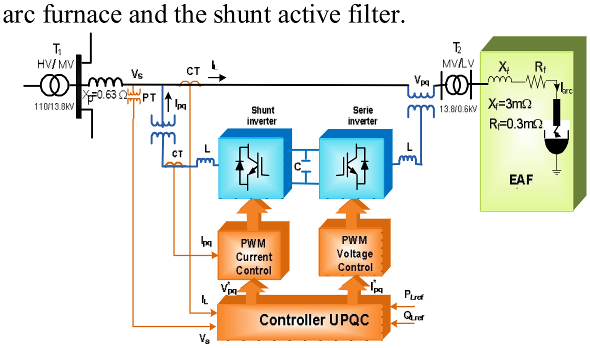
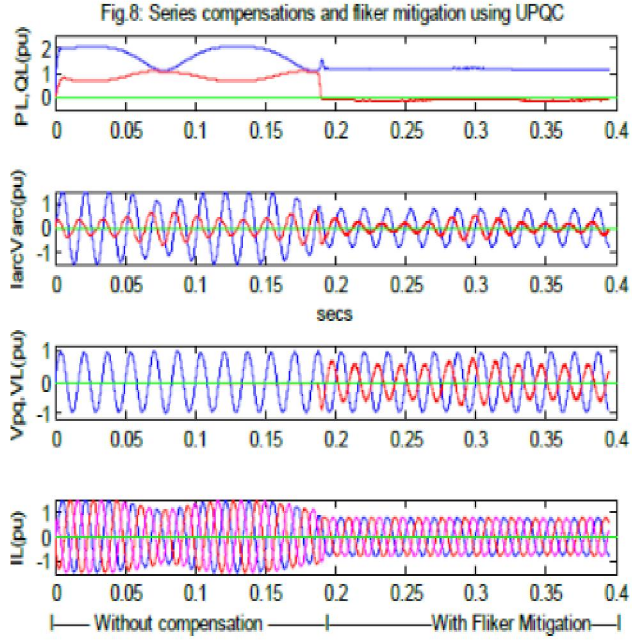


Figure 7: Illustrative diagram for UPFC with arc furnace

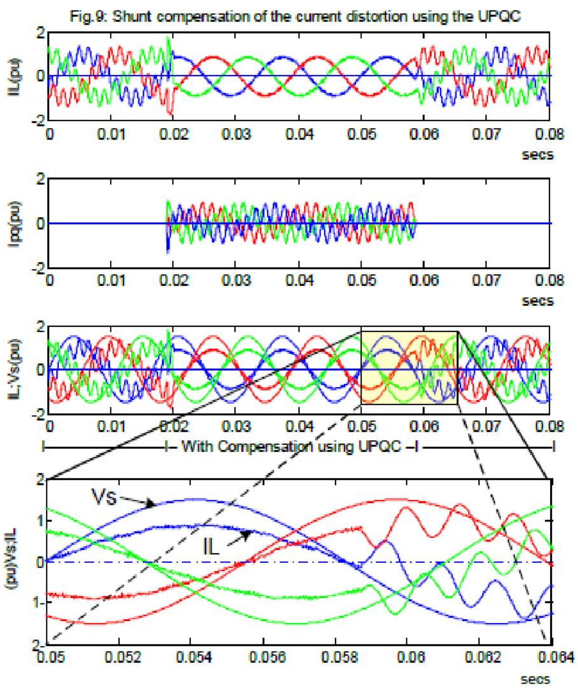
Fig.8: Series compensations and fliker mitigation using UPQC



In the second case study, figure 9 shows the voltage wave at the Point of Common Coupling (PCC) where the arc resistance fluctuates and cause the flicker phenomenon. The PCC voltage is varying at a frequency of 10Hz and causing voltage flicker of about 20% which is not in the threshold limit of flicker as per IEEE standard. The series injected voltage of the UPQC is controlled as variable negative or positive resistance in order to compensate arc resistance fluctuation. As shown in figure 9, the UPQC 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.

5.Conclusions

This Work is a contribution to clarifying the physical meaning of the instantaneous powers and their relation with the three-phase "measured" powers representing the energy quantity per time unit, when unbalanced and non-sinusoidal three-phase systems are concerned. A practical approach to the theory of instantaneous power in non-sinusoidal and unbalanced-three-phase systems is presented and supported by experimental results. This approach is based on the instantaneous symmetrical components. The physical meaning of the real and imaginary powers sequences in time domain agrees with the conventional definition of the instantaneous active and reactive powers. The results of some experimental essays and industrial application proved this theory.



Moreover, a new control strategy for flicker mitigation and harmonic compensations based on the proposed instantaneous power theory is presented as an application. In order to test these control strategy, detailed control unit of the UPQC is given and their implementation using simulink demonstrate the good characteristics in mitigating flicker and filtering.

The implementation of the method is completely digital, thus, the number of acquired signals and the external analog circuitry are therefore reduced to a minimum.

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