Instantaneous Current Vectors in Polyphase Systems: Two Compensation Concepts

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Abstract— **According to the target of minimal line losses and a power factor equal to one, the present work studies two concepts of instantaneous compensation of nonactive current which are generally applied to polyphase systems. The analysis is defined both on the basis of the instantaneous value concept, for arbitrary voltage and current waveforms, and on the basis of the average value concept, for steady-state and periodic conditions. Results of using these concepts for instantaneous compensation are compared by simulation.**

Keywords- Active filters, power control, power quality, reactive power, system analysis and system design.

I. INTRODUCTION

Load compensation in power engineering is the procedure used to obtain the supply currents sinusoidal and balanced or with the same waveforms as the respective source voltages. That is, source currents without harmonic distortion and with balanced components in the first case. At present, active power filters (APF) or active power line conditioners (APLC) make possible to obtain power-electronic solutions to power quality (PQ) problems. In particular, balanced or unbalanced-load compensation in non-sinusoidal situations is possible [1]-[4].

To obtain efficient APLC performance, it is important to choose both a proper current reference and an adequate current control strategy. As far as current reference is concerned, the algorithms of control can be based on waveform compensation [5] or on the power theories. In the former case, the active filter makes the system a sinusoidal current resonant source. The filter or bandpass filter, discrete or fast Fourier transforms, and Kalman filter are some examples in this category [6]-[8].

In the latter case, to obtain the supply currents with the same waveforms as the respective source voltages, the load behaves as a resistive load and, consequently, both its current and voltage are in phase, minimal line losses are obtained and the power factor is equal to one [9]-[12].

There are two forms of instantaneous power theory. Concept 1: the first main branch of power theories was introduced by Fryze [10] and Czarnecki [12], it is based on the *time average-value concept* (AVC). The active current components (which are calculated using time-average measurements) are in phase with the source voltages, and the non-active current components are out of phase with the source voltages. This theory permits to speak of a time-average compensation type to eliminate the non-active current.

Concept 2: the second main branch of power theories was introduced by Akagi and co-authors [9], it is based on the *time instantaneous-value concept* (IVC). Many theories exist which are revisions of the original theory [13]-[14] or completely different in formulation and ideas [15]-[20]. But the main concept is that quantities derived of the analysis of the load current are determined at any single time instant, in particular, the value of the instantaneous non active current and hence the corresponding compensating current. The theory enables instantaneous compensation, using APLC devices so as to minimize the source-current instantaneous norm or rms values, which implies minimization of transmission losses.

In recent papers, Czarnecki demonstrates [21]-[22] that Concept2, contrary to Concept 1, is unable to interpret the Power Theory and, in concrete, the physical interpretation of instantaneous reactive power (imaginary power in the original IVC theory) is erroneous.

However, these deficiencies could be considered as irrelevant when the original IVC theory is used as the fundamental for a switching compensator control algorithm. Although, from the viewpoint of control, a problem arises at nonsinusoidal and/or asymmetrical supply voltage: the original IVC theory-based compensation is unable to obtain zero reactive and constant instantaneous active power [22], i.e., in the presence of the supply voltage harmonics or its asymmetry, any attempt of compensating the oscillating component of the active power causes generation of the

control signal, which may reduce the power factor and distort the supply current.

Nevertheless, we must say in favor of Concept 2 that there is not a true instantaneous compensation of nonactive currents using theories based on the AVC, i.e., under practical conditions, if a variation of the load or the supply occurs, which causes a change of the value of some averaged quantities (power, voltage, etc.,), they have to be newly determined and, in a general case, this needs one full period. Really instantaneous compensation of all nonactive currents is only allowed using the IVC, although it has a negative impact on the distortion of the controlled source-current waveform.

Finally, there are some actions that depend on real-time calculation of instantaneous quantities. Fault detection and classification technique of signal disturbances for transmission lines is a clear example. Flicker compensation is a direct attempt to achieve instantaneous compensation of reactive current using IVC. In general, for applications where time-varying loads exist, an integration interval of one fundamental period T is too long for acceptable reactive current suppression. So, compensators which use the "running average"[1] reactive power must employ a shorter integration interval, $\tau \ll T$, sacrificing accuracy for speed in an attempt to optimize the compensating capability.

The present work uses a generalized instantaneous power theory [23], which can be applied to the above two Concepts of power theories, for arbitrary polyphase systems with the target of 1) minimal line losses and a power factor equal to one; 2) balanced and sinusoidal source currents.

II. CONVENTIONAL NOTATION IN (N-1)-PHASE N-WIRE SYSTEMS

For (n-1)-phase **n**-wire systems, the instantaneous phase voltages and line currents are represented by n-dimension vectors in an orthogonal coordinate system. Phase voltages u_{jN} are elements of the voltage vector:

$$\mathbf{u}_N(t) = \left[u_{1N}(t) \cdots u_{jN}(t) \cdots u_{(n-1)N}(t) \, 0 \right]^T \quad (1)$$

As stated by Kirchhoff's law, the currents $i_j(t)$ supplied to the terminals always sum up to zero. They are zero-sum quantities and can be represented as a current vector

$$\mathbf{i}(t) = \left[i_1(t) \, i_2(t) \cdots i_j(t) \cdots i(t)_N \right]^T,$$
$$\mathbf{1_N}^T \cdot \mathbf{i}(t) = \sum_{j=1}^{n} i_j(t) = 0 \quad (2)$$

where $\mathbf{1_N}$ is the unitary vector of n components and $i_j(t)$ corresponds to the jth wire current, $j \in 1, \dots, n$.

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[1] Reactive power can be defined per phase by $q(t) = \dfrac{1}{T} \displaystyle\int_{t-T}^{t} u(t) i(t-T/4) dt$, that is, as a "running average".

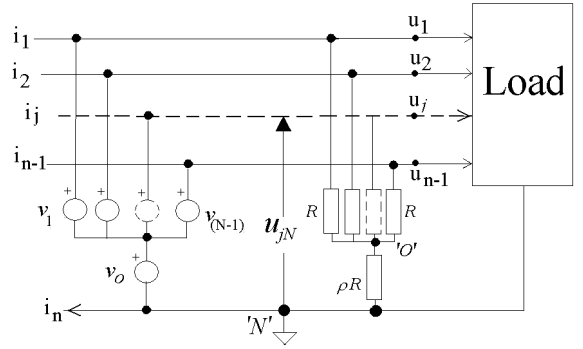

Fig. 1. (n-1)-phase n-wire system. Phase voltages u_j can be referenced to the neutral reference point 'N' or to the virtual star point 'O'.

For the above voltage and current vectors the following instantaneous norms are considered [19]:[2]

$$u_N = \sqrt{\mathbf{u}_N^T \cdot \mathbf{u}_N} = \sqrt{\sum_{j=1}^{n-1} u_{jN}^2}, \quad i = \sqrt{\mathbf{i}^T \cdot \mathbf{i}} = \sqrt{\sum_{j=1}^{n} i_j^2} \quad (3)$$

According to (3), the zero-sequence voltage for (**n**-1)-phase **n**-wire systems can be defined in vector form,

$$\mathbf{v_0} = \frac{v_0}{\sqrt{n-1}} \mathbf{1_{N-1}}, \quad v_0 = \frac{1}{\sqrt{n-1}} \sum_{j=1}^{n-1} u_{jN}$$
$$\mathbf{i_0} = \frac{i_0}{\sqrt{n-1}} \mathbf{1_{N-1}}, \quad i_0 = \frac{1}{\sqrt{n-1}} \sum_{j=1}^{n-1} i_j = -\frac{i_N}{\sqrt{n-1}}, \quad (4)$$

where $\mathbf{1_{N-1}} = [1 \ 1 \dots 1 \ 0]^T$, which differs of the unitary vector in the nth component.[3]

From the above, the source voltage $\mathbf{u}_N$ can be decomposed into a vector without zero-sequence component, $\mathbf{v}$, and the zero-sequence component $\mathbf{v}_0$ [19] (see Fig. 1):

$$\mathbf{u}_N = \mathbf{v} + \mathbf{v_0}, \quad (5)$$

which is subject to the orthogonal condition: $u_N^2 = v^2 + v_O^2$.

Obviously, voltage vector $\mathbf{v}$ includes the rest of symmetrical components, of positive sequence, $\mathbf{v}^+$, and negative sequence, $\mathbf{v}^-$, existing in $\mathbf{u}_N$:

$$\mathbf{v} = \mathbf{v}^+ + \mathbf{v}^-. \quad (6)$$

It permits extracting the positive-sequence component of $\mathbf{v}$ for the generation of the reference compensator-currents under unbalanced and distorted voltages. To this end, the instantaneous norm of $\mathbf{v}^+$ is

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[2] In which follows, the time dependence of quantities will be omitted.
[3] Note that for three-phase four-wire systems the definition of the instantaneous zero-sequence voltage (current) vector obeys to:
$\mathbf{v}_0 = 1/3 \, (u_{1N} + u_{2N} + u_{3N}) [1 \ 1 \ 1]^T$.

$$v^+ = \sqrt{\left(\mathbf{v}^+\right)^T \cdot \mathbf{v}^+} = \sqrt{\sum_{j=1}^n \left(v_j^+\right)^2}, \qquad (7)$$

and v_j^+ is the jth component of the positive-sequence voltage vector.

Analogous relationships are valid also for the negative-sequence voltage vector and for the n-wire current system. In concrete, each line-current vector can be separated in two components

$$\mathbf{i} = \mathbf{i}' + \mathbf{i}_O, \quad \sum_{j=1}^{n-1} i_j = \sqrt{n-1}\, i_O = i_N, \quad \sum_{j=1}^{n-1} i_j' = 0 \qquad (8)$$

where $\mathbf{i}'$ is the current vector without zero-sequence component. Expression (4) has been considered in (8).

The above voltage and current analysis, (5) and (8) respectively, is useful in representation of three-phase four-wire systems using the space phasors notation according to Park's (three-axis representation) and Clarke's (two-axis representation) methods [24].

Some procedures for online estimation of instantaneous symmetrical components of three-phase quantities have been investigated in other works developed with the objective of PQ improvement [2]-[4].

III. INSTANTANEOUS POWER EXPRESSIONS

A. Electrical Quantities Defined in Arbitrary Conditions

The instantaneous power at a cross section of an n-conductor system can be defined as the dot product of the line voltages vector from the neutral reference point, and line currents vector at that section,

$$p_U = \mathbf{u}_N^T \cdot \mathbf{i} = \sum_{j=1}^{n-1} u_{jN} i_j = p_V + p_0 = p_{V^+} + p_{V^-} + p_0, \quad (9)$$

$$p_V = \mathbf{v}^T \cdot \mathbf{i} = \sum_{j=1}^{n-1} v_{jN} i_j, \quad p_{V^+} = \left(\mathbf{v}^+\right)^T \cdot \mathbf{i}, \quad p_{V^-} = \left(\mathbf{v}^-\right)^T \cdot \mathbf{i}, \quad (10)$$

$$p_0 = \mathbf{v_0}^T \cdot \mathbf{i} = \mathbf{v_0}^T \cdot \mathbf{i}_0, \qquad (11)$$

where p_V is the instantaneous power without zero-sequence power components; p_{V^+}, p_{V^-} and p_0 are the instantaneous symmetrical powers, i.e., the instantaneous powers due to the positive-, negative- and zero-sequence voltage-vector components and current vector.

According to the above formulation, one may extend the usual definitions of apparent power, reactive power and power factor terms also to the case of instantaneous quantities corresponding to the IVC [12], [15], [20], (Table I).

B. Quantities Defined in Stationary and Periodic Conditions

Under stationary and periodic conditions, the average value of the instantaneous active power and the rms value of voltage

TABLE I
DEFINITIONS BASED ON TWO INSTANTANEOUS-POWER CONCEPTS

	IVC	AVC
Instantaneous norm or RMS values	$u_N = \sqrt{\mathbf{u}_N{}^T \cdot \mathbf{u}_N}$, $v = \sqrt{\mathbf{v}^T \cdot \mathbf{v}}$, $i = \sqrt{\mathbf{i}^T \cdot \mathbf{i}}$	$U_{jN} = \sqrt{\dfrac{1}{T_0} \int_0^{T_0} u_{jN}^2 dt}$, $V = \sqrt{\dfrac{1}{T_0} \int_0^{T_0} v_j^2 dt}$ $I_j = \sqrt{\dfrac{1}{T_0} \int_0^{T_0} i_j^2 dt} \quad j=1,2,..,n$
Active Power	$p_U = \mathbf{u}_N{}^T \cdot \mathbf{i}$	$P = \dfrac{1}{T_0} \int_0^{T_0} p_U\, dt = \overline{\mathbf{u}_N^T \cdot \mathbf{i}}$
Non-active power	$q = \sqrt{s^2 - p_U^2}$	$Q = \sqrt{S^2 - P^2}$
Apparent power	$s = u_N \cdot i$	$S = U_N \cdot I = \sqrt{\sum_{j=1}^n U_{jN}^2}\sqrt{\sum_{j=1}^n I_j^2}$
Power factor	$pf = \dfrac{p_U}{s}$	$PF = \dfrac{P}{S}$

and current vectors are usually defined within an observation interval T_0 which coincides with the period, or an integer multiple of the fundamental period. The 'active power', P, is the average power over the period T_0, which obeys to the common expression shown in Table I.

So, instantaneous voltage and current vectors, expressed by (1), and (2), can be defined according to respective vectors:

$$\mathbf{U}_N \equiv \left[U_{1N} \cdots U_{jN} \cdots U_{(n-1)N} \quad 0 \right]$$
$$\mathbf{I} \equiv \left[I_1 \cdots I_j \cdots I_N \right] \qquad (10)$$

So, average quantities corresponding to the AVC are expressed in Table I.

IV. THE OPTIMUM SOLUTION FOR NONACTIVE CURRENT COMPENSATION

1) Power theory based on the IVC

Instantaneous power theories are generally based on the decomposition of instantaneous voltages, currents and power into several orthogonal sets. In the procedure stated in [23], which is based on the physical laws of polyphase systems, a set of n-dimensional vectors is defined taking a base coordinate system $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ of Fig. 2:

$$\mathbf{e}_1 = \frac{\mathbf{V}_1}{V_1} = \mathbf{V}_1, \quad \mathbf{e}_2 = \frac{\mathbf{V}_2}{V_2} = \frac{\mathbf{V}_2}{\sqrt{n-1}}, \quad \mathbf{e}_3 = \frac{\mathbf{V}_3}{V_3} \equiv \frac{\mathbf{v}}{V} \quad (11)$$

where

$$\mathbf{V}_1 = \begin{bmatrix} 0 & \cdots & 0 & 1 \end{bmatrix}^T, \quad \mathbf{V}_2 = \begin{bmatrix} 1 & \cdots & 1 & 0 \end{bmatrix}^T = \mathbf{1}_{N-1}, \quad \mathbf{V}_3 = \mathbf{v}$$
$$(12)$$

The required load current vector, **i**, is decomposed into three mutually orthogonal components, $\mathbf{i}_N$, $\mathbf{i}_0$ and $\mathbf{i}_2$, which are obtained by projecting **i** on $\mathbf{V}_1$, $\mathbf{V}_2$ and $\mathbf{V}_3$, respectively [23]. Then, current vector **i** is analyzed according to the 'modified instantaneous power-current', $\mathbf{i}_{pV}$, and the complementary current component, $\mathbf{i}_{qV}$, which have the following properties:

$$\mathbf{i} = \mathbf{i}_{pV} + \mathbf{i}_{qV}, \qquad i^2 = i_{pV}^2 + i_{qV}^2, \qquad (13)$$

where, according to Fig, 2,

$$\mathbf{i}_{pV} = \mathbf{i}_Z + \frac{p_V}{V^2}\mathbf{v}, \qquad \mathbf{i}_Z = \mathbf{i}_0 + \mathbf{i}_N, \qquad \mathbf{i}_{qV} = \mathbf{i} - \mathbf{i}_{pV} \qquad (14)$$

Current vector component $\mathbf{i}_{pV}$ contains the zero-sequence current vector, $\mathbf{i}_0$, the neutral current vector, $\mathbf{i}_N$, and the power-current vector, $k\mathbf{v}$, without neutral current component. Then, the orthogonal components of **i**, can be expressed by

$$\mathbf{i} = \mathbf{i}_{pV} + \mathbf{i}_{qV} = \mathbf{i}_0 + \mathbf{i}_N + k\mathbf{v} + \mathbf{i}_{qV}. \qquad (15)$$

The instantaneous power transmitted by current components of **i** are given by:

$$p_1 = \mathbf{u}_N^T \cdot \mathbf{i}_0 = p_0$$
$$p_2 = \mathbf{u}_N^T \cdot k\mathbf{v} = \left(\frac{p_V}{V^2}\right)\left(\mathbf{u}_N^T \cdot \mathbf{v}\right) = p_V. \qquad (16)$$

Current components $\mathbf{i}_N$ and $\mathbf{i}_{qV}$ transmit zero instantaneous power. Transmission losses will be minimal if the 'useless' current components are eliminated. This would be achieved by injecting the compensating current-vector:

$$\mathbf{i}_{C1} \equiv \mathbf{i}_{qV} + \mathbf{i}_N = \mathbf{i} - k\mathbf{v} - \mathbf{i}_0. \qquad (17)$$

On the contrary, if balanced-and-sinusoidal source current is the final objective of instantaneous compensation, then the injected compensating current-vector must obey expression:

$$\mathbf{i}_{C2} \equiv \mathbf{i}_{qV} + \mathbf{i}_N + k\mathbf{v}^- + \mathbf{i}_0 = \mathbf{i} - k\mathbf{v}^+. \qquad (18)$$

Then, according to (19) and (20), the source current vector after instantaneous compensation is given by

$$\mathbf{i}_{S1} = \frac{p_V}{V^2}\mathbf{v} + \mathbf{i}_0, \qquad (19)$$

or

$$\mathbf{i}_{S2} = \frac{p_V}{V^2}\mathbf{v}^+ \qquad (20)$$

where $\mathbf{i}_{S1}$ is the instantaneous source-current vector after compensation using (19) and $\mathbf{i}_{S2}$ the source-current vector after compensation using (20).
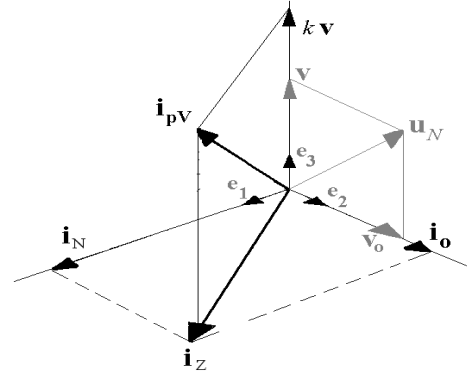
2) Stationary and Periodic Conditions

Fig. 2. Projection of the instantaneous current component $\mathbf{i}_{pV}$ in the *n*-space onto an orthogonal set of vector coordinates.

The above development can be further extended to stationary and periodic conditions. Thus the modified active-current vector of an *n*-terminal circuit is given by

$$\mathbf{i}_{av} = G_{av}\mathbf{v} \qquad (21)$$

with

$$G_{av} = \frac{\overline{\mathbf{v}^T \cdot \mathbf{i}}}{\overline{\mathbf{v}^T \cdot \mathbf{v}}} = \frac{P}{V^2}. \qquad (22)$$

G_{av} is the constant quantity of conductance based on average quantities defined in (12) and (13). Thus, under transient conditions, average values P and V need to be calculated for load compensation during a fundamental voltage period. This period is the minimum delay of a shunt active power filter (SAPF) designed with current reference:

$$\mathbf{i}_{rv} = \mathbf{i} - \mathbf{i}_{av}, \qquad (23)$$

which comprises the total 'nonactive' current. In this situation, $\mathbf{i}_{av}$ transfers to the load the active power P at voltage **v**.

According to the instantaneous value concept, the set of currents i_{qVj}, $j=1,..,n$, defined by (16) does not contribute to the instantaneous active power and can be compensated instantaneously by an APLC under the most general conditions. But in the case of currents i_{rvj}, defined according to the average value concept by (25), some problems can be present in practice. For example, in time varying loads (normally, nonlinear loads are also time varying) if a variation of the load or the supply occurs, which causes a change of G_{av}, the value of this quantity has to be newly determined and, in a general case, this needs of one full fundamental voltage period. Under practical conditions, true instantaneous compensation of all nonactive currents $\mathbf{i}_{qv}$ is, therefore, impossible.

V. SELECTED EXAMPLE FOR SIX-PHASE SEVEN-WIRE SYSTEMS

An illustrative example has been selected in order to show the characteristics of the proposed definitions. A six-phase system with balanced sinusoidal-voltage source of 1V and 5th

harmonic voltage of 4% was simulated using MathCad. The line-to-neutral source voltages are connected to a six-phase seven-wire load consisting of equal inductive RL branches in star connection, $R_L= 0.3\Omega$, $L_L= 1mH$. An ideal neutral is used in this example for assuming the six-phase currents are mutually independent.
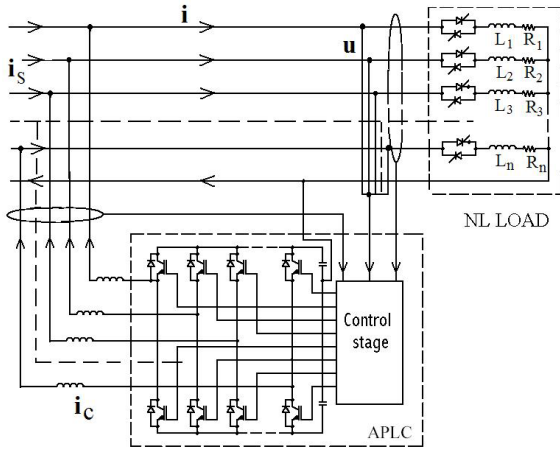

Fig. 4. Simplified functional diagram of an active compensator of nonactive-current components for (N-1)-phase N-wire systems.

Figure 5 shows waveform components of six-phase voltage vector $\mathbf{u}_O$ and load current vector $\mathbf{i}$, under a balanced power-line sag disturbance. The power line sag has two cycle duration and $0.5V_{peak}$ magnitude. Phase-1 of the source voltage is taken as the array origin of quantities in the performed simulation.

Figure 6 shows instantaneous values of collective power, apparent power, non-active power and power factor. Their corresponding average quantities are shown in Fig. 7, where a fundamental period T is assumed for calculation of quantities based on the AVC. So, when disturbance occurs, quantities P, S, Q and PF remain unchanged during one-cycle.

Figures 7 and 8 show results of load compensation obtained by simulation. When compensation starts, the nonactive current component of the source current is eliminated and the resulting current, $\mathbf{i}_{S1}$, presents minimal norm. Thus, instantaneous nonactive power vanishes, apparent power equals collective power, $s1(t)= p_\Sigma(t)$, and unity power factor is reached (Fig. 9).

Figures 9 and 10 show compensation based on the AVC. The source-current component is fully controlled in the first and third periods due to calculations during the respective previous periods. Source currents of Figs. 8 and 10 can be compared in terms of power quality. Equations (21) and (22) apply for $\mathbf{i}_{S1}$ and $\mathbf{i}_{ST}$ calculation.
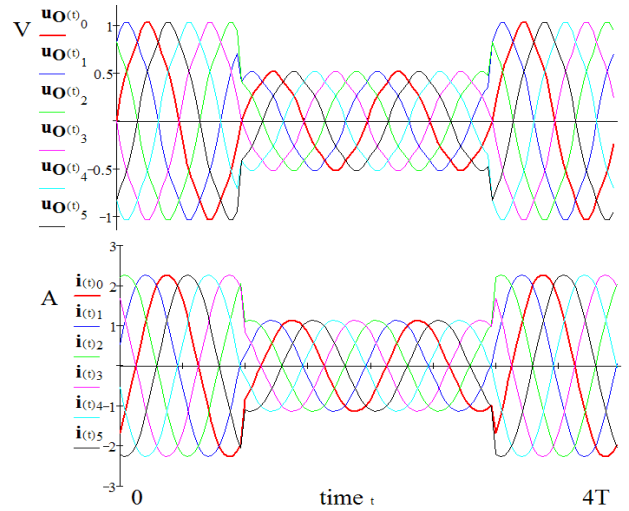
VI. CONCLUSION

It has been shown that:

Fig. 5. Results of sag disturbance obtained by Mathcad simulation: (a) six-phase seven-wire source voltages V(p.u.). (b) Load current components.
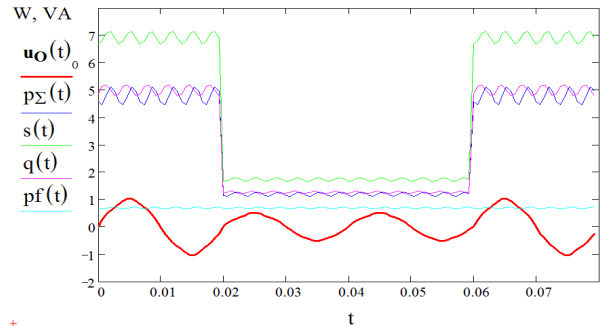

Fig. 6. Results obtained by Mathcad simulation: instantaneous active, apparent, non-active powers and instantaneous power factor.

The use of a general vector space offers the ideal approach to solve polyphase systems under the most arbitrary conditions.

Instantaneous and average compensations permit a drastic elimination of the nonactive power while instantaneous and average powers are respectively maintained unchanged.

The instantaneous value concept provides mathematical fundamentals for the control algorithm design of an APLC, it enables the achievement of the instantaneous control objectives.

The AVC can provide a credible interpretation of power phenomena in polyphase systems dealing with non-sinusoidal voltages and currents. However, for the control algorithm design of an APLC some problems can be present if a variation of the load or the supply occurs.

Under steady-state conditions the controlled source currents through the power line resemble the source phase-voltages if the average value concept is used for control. This is not true for instantaneous compensation, where source currents can degrade the power quality even in the case of sinusoidal phase-voltages.
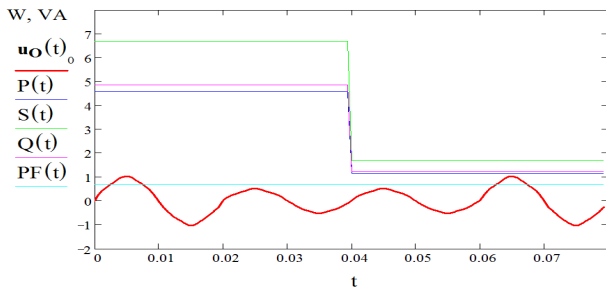
Fig. 7. Corresponding values of quantities of Fig. 5 for definitions based on the average value concept. A delay of one cycle is considered for calculation.
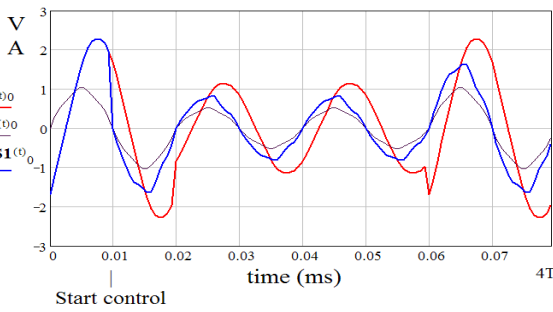

Fig. 8. Instantaneous phase-a source-current component when load compensation starts at 0.5T from the origin.
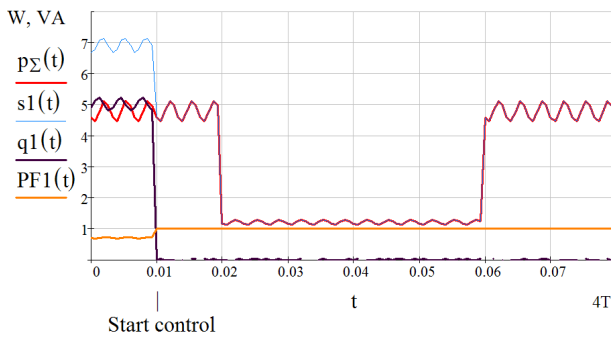

Fig. 9. Results of instantaneous compensation on active, apparent, non-active powers and instantaneous power factor.
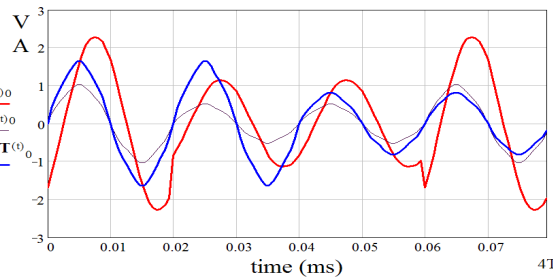

Fig. 10. Instantaneous compensation based on the AVC (phase-1).

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