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A Hybrid Reference Signal Generator for Active Compensators

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Summary: A new reference generation technique for active compensators based on the use of CPC theory along with the instantaneous reactive power (*p-q*) theory is presented here. Modifications to reference signal generation techniques based on instantaneous reactive power as well as to the synchronous reference frame (*d-q*) method are proposed. The proposed strategy utilizes the CPC theory instead of the filters typically used to extract the desired components of the current. A simulation-based example is provided that shows this new approach retains the "instantaeous" property provided by the *p-q* or *d-q* methods under certain conditions without the negative effects found using the traditional method.

1. INTRODUCTION

The subject of current components not associated with active power, sometimes referred to as useless components, and their compensation has long been a topic of discussion among researchers. In particular the instantaneous reactive power theory, or *p-q* theory, has been used extensively in development of methods for compensating useless components of the current in power systems [1–4]. A variation of the method known as the synchronous reference frame method or *d-q* method is also widely used. These methods are used to generate control reference signals for active compensation systems. Reference signal generation techniques based on *p-q* or *d-q* use filters to extract the desired components of the current. However, this may produce undesired results when trying to select a particular sub-set of current components for compensation. For example, there are some well-known disadvantages to the application of *p-q* theory when used for instantaneous reactive power compensation in unbalanced three-phase systems. It was discussed and shown by Nabae and Tanaka [4] that applying *p-q* theory for reactive power compensation in unbalanced three-phase systems results in third harmonic components on the source side. This was further shown in terms of the CPC theory by Czarnecki [5]. The same effects can be observed with the synchronous reference frame method. The application of an appropriately selected filter, of course, can prevent the occurrence of the third harmonic but at the same time removes the "instantaneous" property of the compensation scheme.

In this paper a new approach is proposed to increase the flexibility of the reference current generation while preserving the property of instantaneous compensation under certain conditions. For example, the method overcomes the problem that occurs when the *p-q* or *d-q* methods are used to instantaneously compensate reactive power under unbalanced conditions. The reference generation technique presented here is an approach that utilizes the CPC theory [6] to determine the components that make up the reference signal. Although compensating all useless components of the current is ideal, it is often desirable to target a sub-set of the possible components of the current due to compensator power and switching speed limitations, etc.

2. SOME TYPICAL REFERENCE SIGNAL GENERATION SCHEMES

The simplified structure of an active compensator is shown below in Figure 1. It is the reference signal generator that determines the components of the current to be compensated at the cross section of the system where the compensator is connected. Many of the reference signal generation schemes suggested in the literature are based on the Instantaneous Reactive Power theory (*p-q*) developed by Akagi et al. [1, 2].

The idea behind the *p-q* theory is derived from the Clarke Transform of three-phase voltages and currents. For three-phase, three-wire systems $x_R+x_S+x_T=0$ where quantitiy x represents either a line current or phase voltage. Thus, the Clarke Transform can be simplified into the form

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \mathbf{C} \begin{bmatrix} x_R \\ x_S \end{bmatrix} \tag{1}$$

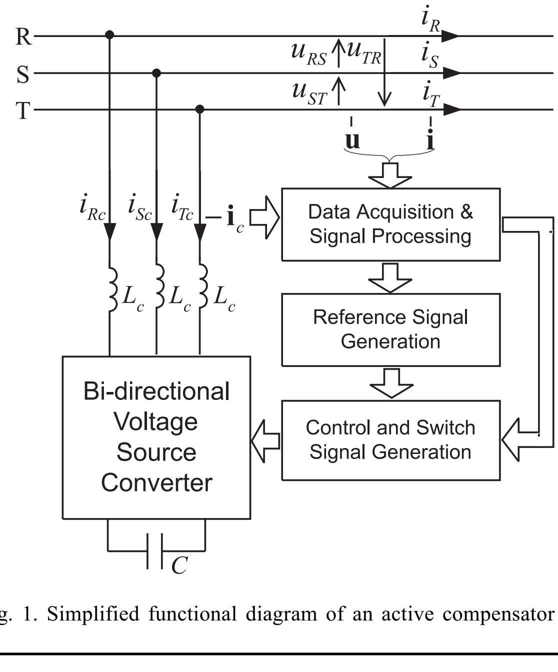

Fig. 1. Simplified functional diagram of an active compensator

where:

$$\mathbf{C} = \begin{bmatrix} \sqrt{\frac{3}{2}} & 0 \\ \frac{1}{\sqrt{2}} & \sqrt{2} \end{bmatrix} \tag{2}$$

The instantaneous active power is defined [1] as:

$$p = u_\alpha i_\alpha + u_\beta i_\beta \tag{3}$$

and the instantaneous reactive power as:

$$q = u_\alpha i_\beta - u_\beta i_\alpha \tag{4}$$

Using these two quantities the instantaneous active current is defined as:

$$i_p = i_{\alpha p} + i_{\beta p} = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} p + \frac{u_\beta}{u_\alpha^2 + u_\beta^2} p \tag{5}$$

and instantaneous reactive current is defined as:

$$i_q = i_{\alpha q} + i_{\beta q} = \frac{-u_\beta}{u_\alpha^2 + u_\beta^2} q + \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} q \tag{6}$$

The Synchronous Reference Frame Method of determining the compensating current reference [7], [8] is essentially the same as the *p-q* method. For this method, the currents are transformed into a reference frame that is synchronized with the ac supply voltage. This transformation, often referred to as *d-q*, is given by:

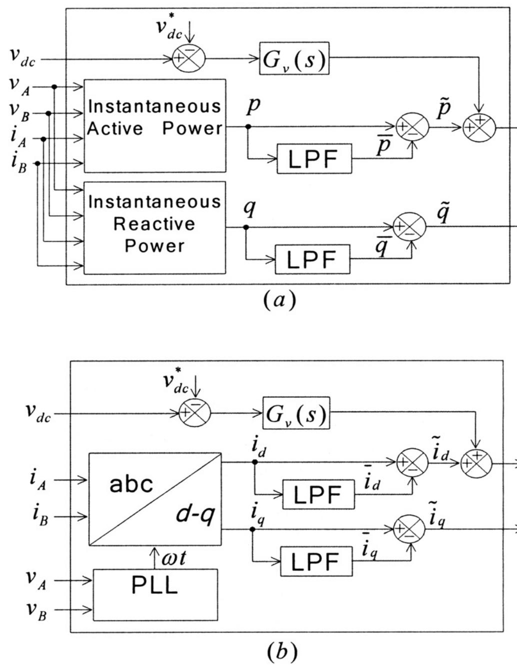

Fig. 2. Reference signal generator structure for (a) instantaneous reactive power method (b) synchronous reference frame method

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\omega_1 t) & \sin(\omega_1 t) \\ -\sin(\omega_1 t) & \cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{7}$$

where i_α and i_β are generated by applying the Clarke transform (2) of the phase currents i_R and i_S. Typical reference signal generator structures for both *p-q* and *d-q* are shown in Figure 2 (a) and (b) respectively. Both utilize filters to extract the desired current components. Of course, if reactive power compensation is required the filters for the *q* component will not be present. Also shown is the dc bus voltage controller which injects an appropriate offset into the term associated with the active power at the fundamental as required by the power losses in the compensator.

3. P-Q AND D-Q IN TERMS OF FREQUENCY DOMAIN CPC POWER THEORY

For a balanced three-phase system, application of the *p-q* method results in a *p* term that is associated with active power and a *q* term that is associated with reactive power. Similarly, for the *d-q* method the *d* current component is associated with active current and the *q* current component with reactive current. However, in an unbalanced system, both *p* and *q* components or *d* and *q* components are affected by the load imbalance, therefore, it is no longer clear what they represent. The effect of asymmetry on *p* and *q* is recognized by Nabae and Tanaka [3] by defining components of each originating from harmonics or asymmetries. They further elaborate in [4] stating that compensating reactive power under unbalanced condition results in third-order harmonics on the source side. Reference [5] shows the relation between the instantaneous reactive power theory and the CPC frequency domain theory so that the effect of unbalanced current on the *p* and *q* terms is revealed.

The CPC theory developed in the frequency domain by Czarnecki [6] is based on orthogonal decomposition of the current.

This theory provides a physical interpretation of power phenomena in three-phase systems under unbalanced and non-sinusoidal conditions. For sinusoidal conditions, a subset of the theory decomposes the current into active, reactive and unbalanced components. In order to perform this decomposition the load is expressed in terms of two admittances, the equivalent admittance and the unbalanced admittance. The equivalent admittance is expressed as:

$$\boldsymbol{Y}_e = G_e + jB_e = \boldsymbol{Y}_{RS} + \boldsymbol{Y}_{ST} + \boldsymbol{Y}_{TR} \tag{8}$$

where G_e and B_e are the equivalent conductance and equivalent susceptance respectively. The unbalanced admittance is:

$$\boldsymbol{A} = |\boldsymbol{A}| e^{j\varphi} = -(\boldsymbol{Y}_{ST} + \alpha \boldsymbol{Y}_{TR} + \alpha^* \boldsymbol{Y}_{RS}) \tag{9}$$

where $\alpha = 1 e^{j120°}$ and $\alpha^* = 1 e^{-j120°}$. Having these admittances the three-phase current vector:

$$\mathbf{i} = \begin{bmatrix} i_R & i_S & i_T \end{bmatrix}^{\mathbf{T}} \tag{10}$$

can be decomposed into mutually orthogonal components as:

$$\mathbf{i} = \mathbf{i}_a + \mathbf{i}_r + \mathbf{i}_u \tag{11}$$

where the active component of the current is:

$$\mathbf{i}_a = \sqrt{2}\, Re\left\{ G_e \left[\boldsymbol{U}_R \quad \boldsymbol{U}_S \quad \boldsymbol{U}_T \right]^{\mathbf{T}} e^{j\omega_1 t} \right\} \tag{12}$$

the reactive component of the current is:

$$\mathbf{i}_r = \sqrt{2}\, Re\left\{ jB_e \left[\boldsymbol{U}_R \quad \boldsymbol{U}_S \quad \boldsymbol{U}_T \right]^{\mathbf{T}} e^{j\omega_1 t} \right\} \tag{13}$$

and the unbalanced component of the current is:

$$\mathbf{i}_u = \sqrt{2}\, Re\left\{ \boldsymbol{A} \left[\boldsymbol{U}_R \quad \boldsymbol{U}_T \quad \boldsymbol{U}_S \right]^{\mathbf{T}} e^{j\omega_1 t} \right\} \tag{14}$$

As demonstrated in [5], applying the Clarke transform to the line currents expressed in terms of the CPC theory and applying the formula for p (3) and q (4) to the resulting current components yields:

$$p = 3U^2 \left[G_e + A\cos(2\omega_1 t + \varphi) \right] \tag{15}$$

$$q = 3U^2 \left[B_e - A\sin(2\omega_1 t + \varphi) \right] \tag{16}$$

This result shows that both instantaneous active and reactive power are associated with load imbalance characterized by the unbalanced admittance (9). Furthermore, the component associated with unbalanced admittance is of the second harmonic.

The same procedure outlined above can be applied to the *d-q* method. The alpha and beta components of the current expressed in terms of (11) are equal to:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{3}U \begin{bmatrix} G_e \cos\omega_1 t - B_e \sin\omega_1 t + A\cos(\omega_1 t + \varphi) \\ G_e \sin\omega_1 t + B_e \cos\omega_1 t - A\sin(\omega_1 t + \varphi) \end{bmatrix} \tag{17}$$

The *d-q* transform (7) can be applied to (17) resulting in an expression of the d and q components of the current as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{3}U \begin{bmatrix} G_e + A\cos(2\omega_1 t + \varphi) \\ B_e - A\sin(2\omega_1 t + \varphi) \end{bmatrix} \tag{18}$$

It can be seen that both the d and q components of the current contain the unbalanced admittance which is present in the case of unbalanced current.

For non-sinusoidal conditions the current can be decomposed as:

$$\mathbf{i} = \mathbf{i}_a + \mathbf{i}_{r1} + \mathbf{i}_{s1} + \mathbf{i}_{u1} + \mathbf{i}_h \tag{19}$$

where $\mathbf{i}_h$ is the lumped harmonic components of the current and $\mathbf{i}_{s1}$ is the fundamental component of the scattered current equal to:

$$\mathbf{i}_{s1} = \sqrt{2}\, Re\left\{ (G_{e1} - G_e) \left[\boldsymbol{U}_{R1} \quad \boldsymbol{U}_{S1} \quad \boldsymbol{U}_{T1} \right]^{\mathbf{T}} e^{j\omega_1 t} \right\} \tag{20}$$

However, if we assume that the active compensator reduces $\mathbf{i}_h$ to zero then active power can only be present at the fundamental. Thus, G_e=G_{e1} and $\mathbf{i}_a$=$\mathbf{i}_{a1}$ so that the scattered current is never present.

4. CURRENT COMPONENT SELECTION STRATEGY

Expression of the reference signal of an active compensator in terms of current orthogonal components, as in (17) and (18), provides a possibility for selecting the components of the current to compensate at the fundamental frequency as well as their percentage. The *alpha* and *beta* components of the current are used to calculate the instantaneous active and reactive power in the *p-q* method and the d and q components of the current in the *d-q* method. Therefore, cancellation of the terms associated with equivalent conductance, equivalent susceptance, and unbalanced admittance can be applied to (17) to yield a current component selection technique that applies to both methods. Adjusted current components, denoted i'_α and i'_β, are defined as:

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha - K_a i_{\alpha a} - K_r i_{\alpha r} - K_u i_{\alpha u} \\ i_\beta - K_a i_{\beta a} - K_r i_{\beta r} + K_u i_{\beta u} \end{bmatrix} \tag{21}$$

where i_α and i_β contain any components of the current that are present including harmonics, $i_{\alpha \mathrm{a}}$ and $i_{\beta \mathrm{a}}$ are the fundamental active components of the *alpha* and *beta* currents respectively, and are equal to:

$$\begin{bmatrix} i_{\alpha a} \\ i_{\beta a} \end{bmatrix} = \sqrt{3}U \begin{bmatrix} G_e \cos\omega_1 t \\ G_e \sin\omega_1 t \end{bmatrix} \tag{22}$$

$i_{\alpha \mathrm{r}}$ and $i_{\beta \mathrm{r}}$ are the fundamental reactive components of the *alpha* and *beta* currents respectively, and are equal to:

$$\begin{bmatrix} i_{\alpha r} \\ i_{\beta r} \end{bmatrix} = \sqrt{3}U \begin{bmatrix} B_e \sin\omega_1 t \\ B_e \cos\omega_1 t \end{bmatrix} \tag{23}$$

and $i_{\alpha \mathrm{u}}$ and $i_{\beta \mathrm{u}}$ are the fundamental unbalanced components of the *alpha* and *beta* currents respectively, and are equal to:

$$\begin{bmatrix} i_{\alpha u} \\ i_{\beta u} \end{bmatrix} = \sqrt{3}U \begin{bmatrix} A\cos(\omega_1 t + \varphi) \\ A\sin(\omega_1 t + \varphi) \end{bmatrix} \tag{24}$$

Finally, K_a, K_r, K_u are scaling coeffiecients for the active, reactive, and unbalanced components respectively. This yields adjusted instantaneous active power equal to:

$$p' = u_\alpha i'_\alpha + u_\beta i'_\beta \tag{25}$$

and instantaneous reactive power equal to:

$$q' = u_\alpha i'_\beta - u_\beta i'_\alpha \tag{26}$$

Table 1. Scaling Coefficients Selection.

Compensation Requirements	K_a	K_r	K_u
Harmonics Only	1	1	1
Harmonics and Reactive Power	1	0	1
Harmonics, and Current Asymmetry	1	1	0
Harmonics, Reactive Power, and Current Asymmetry	1	0	0

Similarly, adjusted d and q components are equal to:

$$\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} cos(\omega_1 t) & sin(\omega_1 t) \\ -sin(\omega_1 t) & cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} \tag{27}$$

Instead of filters the method utilizes frequency-domain quantities to generate the time-domain quantities used to adjust the reference signals. Thus, reference signal generation based on this method will be referred to as *hybrid reference signal generation*. The method provides an alternative to the use of filters in reference signal generation that allows independent manipulation of each current component of the fundamental. It is assumed here that all harmonic components should be compensated. Therefore, harmonic components of the reference current are not manipulated. Table 1 shows values of the scaling coefficients for various compensation requirements.

5. HYBRID REFERENCE SIGNAL GENERATION

In order to calculate the components of the current, the magnitude and phase of the equivalent admittance as well as the unbalanced admittance needs to be determined. As shown in [10] the actual admittances at the point of compensation do not need to be known. Equivalent admittances can be generated based on two phase-to-phase voltages and two current measurements. However, if a periodic signal is disturbed such that the signal is not periodic over some interval, it may not be acceptable to update the adjusted current components after the completion of each cycle. In such a case a moving-window or stationary reference frame Discrete Fourier Transform (DFT) may be used. Assuming that at sample k a window comprises the N values $\{x(k-N+1), x(k-N+2), \ldots, x(k)\}$, the complex rms (CRMS) value of the fundamental harmonic is given by the DFT as:

$$\tilde{\boldsymbol{X}}_1(k) = \frac{\sqrt{2}}{N} \sum_{i=0}^{N-1} x(i+k-N+1) e^{-j(2\pi/N)i} \tag{28}$$

With the moving-window approach a computationally efficient recursive expression for the DFT [7, 10, 11] can be obtained, which is expressed as:

$$\tilde{\boldsymbol{X}}_1(k) = \tilde{\boldsymbol{X}}_1(k-1) + \frac{\sqrt{2}}{N}\left[(x(k) - x(k-N))\right] e^{-j(\frac{2\pi}{N})} \tag{29}$$

Calculating the CRMS values of the measured voltages and currents using (29) their ratio can be interpreted as admittances for the fundamental frequency. The value of these admittances can change as the N sample moving window advances. Therefore, the admittances are considered as time varying quantities denoted by the ~ symbol. The two necessary admittances are referred to as *time varying admittances of an equivalent load* and are calculated by:

$$\tilde{\boldsymbol{Y}}_{TR} = \frac{\tilde{I}_R}{\tilde{U}_{RT}}, \quad \tilde{\boldsymbol{Y}}_{ST} = \frac{\tilde{I}_S}{\tilde{U}_{ST}} \tag{30}$$

Having these two admittances the *time varying equivalent admittance is given by:*

$$\tilde{\boldsymbol{Y}}_{\boldsymbol{e}} = \tilde{G}_e + j\tilde{B}_e = \tilde{\boldsymbol{Y}}_{ST} + \tilde{\boldsymbol{Y}}_{TR} \tag{31}$$

and the time varying unbalanced admittance is given by:

$$\tilde{\boldsymbol{A}} = \left|\tilde{\boldsymbol{A}}\right| e^{j\tilde{\varphi}} = -(\tilde{\boldsymbol{Y}}_{ST} + \alpha \tilde{\boldsymbol{Y}}_{TR}) \tag{32}$$

Therefore, the reference current alpha and beta components are expressed as:

$$\begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} - \sqrt{3}U \begin{bmatrix} K_a \tilde{G}_e \cos\omega_1 t - K_r \tilde{B}_e \sin\omega_1 t + K_u \tilde{A} \cos(\omega_1 t + \tilde{\varphi}) \\ K_a \tilde{G}_e \sin\omega_1 t + K_r \tilde{B}_e \cos\omega_1 t - K_u \tilde{A} \sin(\omega_1 t + \tilde{\varphi}) \end{bmatrix} \tag{33}$$

Thus, the p and q reference signals are given by:

$$\begin{bmatrix} p^* \\ q^* \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} = \begin{bmatrix} p \\ q \end{bmatrix} - 3U^2 \begin{bmatrix} K_a \tilde{G}_e + K_u \tilde{A} \cos(2\omega_1 t + \tilde{\varphi}) \\ K_r \tilde{B}_e - K_u \tilde{A} \sin(2\omega_1 t + \tilde{\varphi}) \end{bmatrix} \tag{34}$$

For the synchronous reference frame the d and q components of the reference current are given by:

$$\begin{bmatrix} i^*_d \\ i^*_q \end{bmatrix} = \begin{bmatrix} cos(\omega_1 t) & sin(\omega_1 t) \\ -sin(\omega_1 t) & cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \sqrt{3}U \begin{bmatrix} K_a \tilde{G}_e + K_u \tilde{A} \cos(2\omega_1 t + \tilde{\varphi}) \\ K_r \tilde{B}_e - K_u \tilde{A} \sin(2\omega_1 t + \tilde{\varphi}) \end{bmatrix} \tag{35}$$

A block diagram of the proposed reference signal generation strategy using *p-q* and using the *d-q* reference frame are shown in Figure 3 (a) and (b) respectively. The scaling coefficients are realized as gain blocks in order to provide scaling for each component of the reference current.

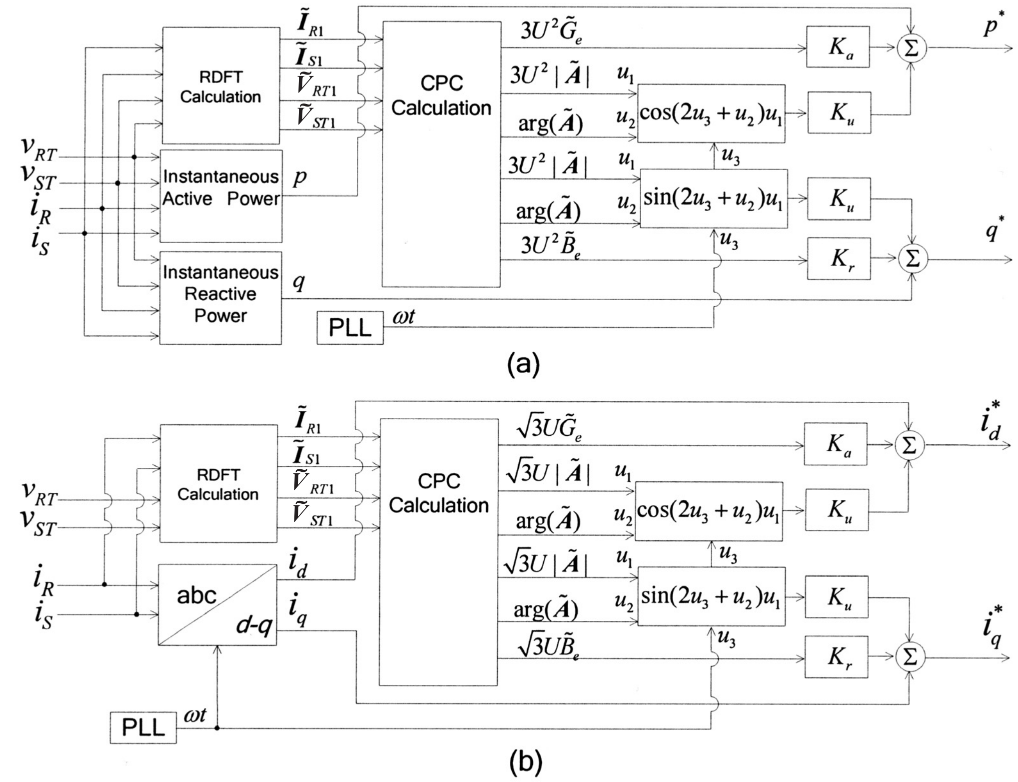

Fig 3. Hybrid Reference Signal Generator using *p-q* (a) and the synchronous reference frame (b)

6. AN INSTANTANEOUS REACTIVE POWER COMPENSATOR TEST CASE

Consider a reactive compensation test case for a simple three-phase circuit with the phase T load disconnected from the supply and with load parameters shown in Figure 4. The supply is a symmetrical positive sequence source with voltage rms value $U = 120$V.

As described in [1] reactive power can be compensated by generating the compensator reference signal $i_C^* = -i_q$. However, as noted by Nabae and Tanaka [3, 4] if the line currents are not balanced then p and q contain a second order harmonic and thus a third order harmonic is introduced into the compensating currents. Of course, the same effects apply to the synchronous referenence frame method.

Simulations were conducted applying the proposed hybrid reference signal generation strategy. In order to compensate for only reactive power while removing the effect of current asymmetry on the reference signal the scaling coefficients are: K_a=1, K_r=0, K_u=1.

The results of three simulations are presented. The first simulation shows the results for the case of phase C open from time zero for two cycles and the unbalanced admittance calculation initialized at a value of zero. The trajectory in the alpha-beta plane of the adjusted reference current is shown in Figure 5. It shows that after one cycle the unbalanced admittance value has converged to the correct value and the second cycle traces a circle as it would for a balanced system. Therefore, the effect of the unbalanced component is removed. This can also be seen in the plot of the p and q components shown in Figure 6.

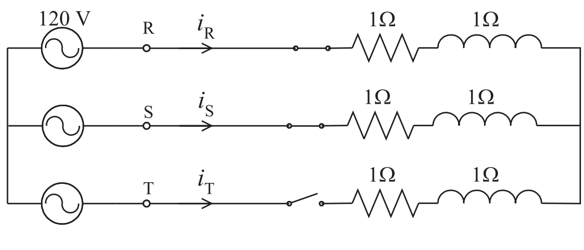

Fig. 4. Example of a circuit with an unbalanced load

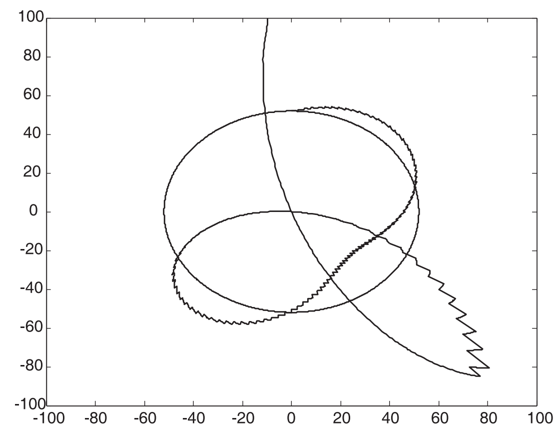

Fig. 5. Simulation result of the path in the alpha-beta plane traced by the adjusted reference current

The second simulation illustrates the behavior of the method for a step change in the unbalanced component of the current. From steady state with the breaker open and phase T disconnected the breaker is closed for several cycles

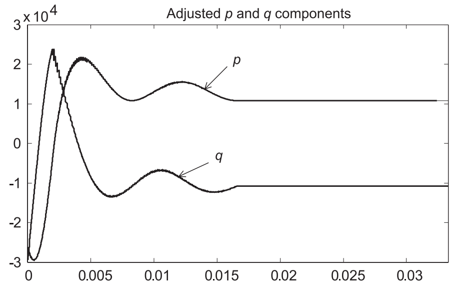

Fig. 6. Simulation result of the adjusted p and q components

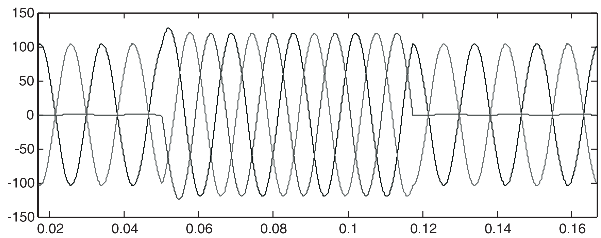

Fig. 7. Simulation result of the phase-currents with breaker closing and re-opening

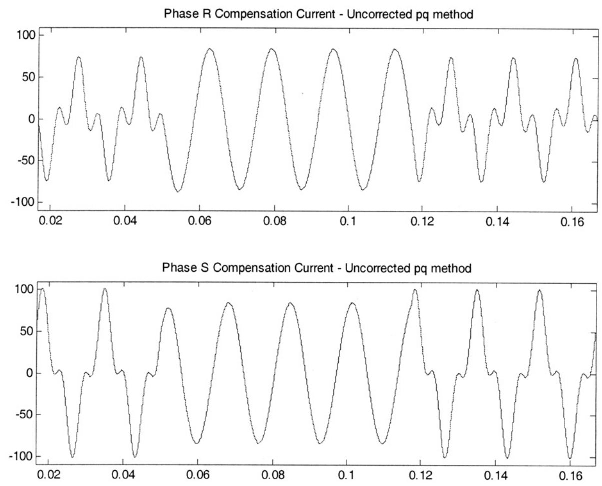

Fig. 8. Compensation currents based on p-q reference signal generation

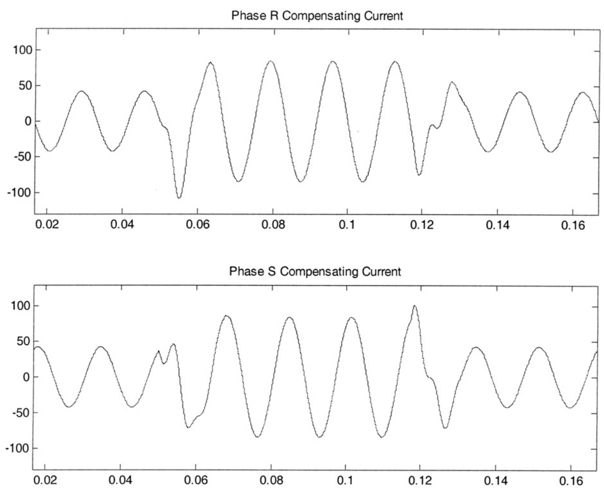

Fig. 9. Corrected compensation currents using the proposed hybrid reference signal generation

and then opened again. The phase-currents for the simulation are shown in Figure 7. The compensating currents for phases R and S generated using the p-q method are shown in Figure 8. Note that the currents are distorted during the intervals that the phase T load branch is disconnected from the supply.

The compensating currents for phase R and S generated using the hybrid reference signal generation strategy are shown in Figure 9. The compensating currents are sinusoidal during the time intervals that the load is unbalanced as well as the interval in which it is balanced.

Distortion only occurs during the load step changes that result when the breaker closes and re-opens. At each step change the value of the unbalanced admittance must converge to the new value and depends on the convergence time of the recursive algorithm (29).

The third simulation demonstrates the case of a balanced system with changing active and reactive power, the compensated current is shown in Figure 10 along with the supply voltage (dotted line) for the p-q method, the proposed hybrid method, and directly using the time varying equivalent susceptance calculated as:

$$i_q^* = -\sqrt{3}U\tilde{B}_e = -\sqrt{3}U\, Im\left\{\tilde{\mathbf{Y}}_{ST} + \tilde{\mathbf{Y}}_{TR}\right\} \tag{36}$$

An additional load is switched on after the first cycle shown in the figure causing a step change in both active and reactive power.

The compensation based on the proposed hybrid approach is nearly the same as for p-q with only a small initial error introduced by the calculation of the unbalanced admittance. However, the compensation based on the direct use of B_e requires one cycle to converge. Thus, the proposed hybrid method retains the fast property of the p-q method while eliminating the problem of the third harmonic in the case of current asymmetry. This cannot be done using a filter based approach to reference signal generation.

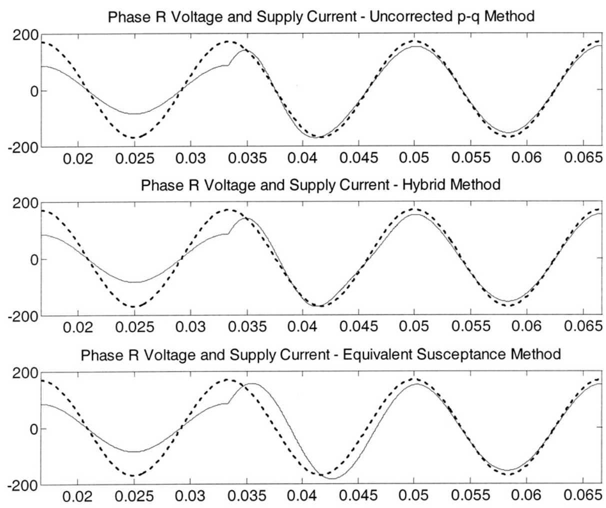

Fig. 10. Simulation results for a balanced load with reactive power step change

7. CONCLUSIONS

A new reference generation technique for active compensators based on the use of CPC theory along with instantaneous reactive power theory is presented here. The CPC orthogonal current decomposition is presented in terms of the Clarke and Park transforms. The resulting expressions are used to extract unwanted components of the current in the *p-q* or *d-q* domain instead of the traditionally used low-pass filters. The method provides better selectivity of the fundamental components in the reference current. To demonstrate this, it was shown that this new approach retains the benefit of fast response provided by the *p-q* or *d-q* methods for reactive power compensation while eliminating the undesirable effects if current asymmetry is present.

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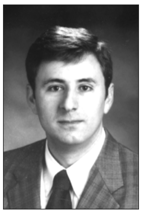

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