

Comparison of applicability of power theories to switching compensator control

Abstract. Various methods are used to generate the control reference signals for power electronics based compensators. With increased flexibility requirements and non-ideal grid conditions, the applicability of reference signal generation methods for compensation applications should be evaluated. Targeted compensation requires an understanding of power components that are present to enable priority based decisions with respect to the compensation. This paper compares the applicability of several reference signal generation methods for power electronics based compensators from a power theory perspective.

Streszczenie. Wiele różnych metod stosuje się dla generowania sygnałów porównawczych, potrzebnych do sterowania kompensatorów energo-elektronicznych. Wraz ze wzrostem wymagań odnośnie uniwersalności kompensatorów pracujących w warunkach zaburzeń sieciowych, przydatność różnych metod generowania sygnałów porównawczych do sterowania kompensatorów winna być przedmiotem oceny. Kompensacja dedykowana, oparta na ocenie hierarchii ważności całów kompensacji, wymaga zrozumienia zjawisk energetycznych i składowych mocy. Niniejszy artykuł porównuje przydatność szeregu metod generowania sygnałów porównawczych z perspektywy teorii mocy. (Porównanie przydatności różnych teorii mocy do sterowania kompensatorów kluczujących)

Keywords: voltage-source converters, active compensator, active filters, power theory.

Słowa kluczowe: falowniki ze źródłem napięciowym, kompensatory aktywne, filtry aktywne, teoria mocy.

Introduction

The subject of components not associated with active power, sometimes referred to as useless components, and their compensation has long been a topic of discussion among researchers. Various methods are used to generate the control reference signals for power electronics based compensation systems. Such systems, when harmonic compensation is included, are usually referred to as active filters, active power filters or active harmonic filters. In some cases compensation objectives may not include harmonics and the more general term active compensator is used to indicate that any component or group of components of the current may be compensated. Such power electronics based compensators are referred to in this paper as switching compensators as in [1] since they rely on semiconductor switching in order to compensate for some undesirable components of current or voltage in a system.

In particular time-domain methods such as the instantaneous reactive power theory, or $p-q$ theory and its variants, have been used extensively in development of methods for compensating useless components of the current in power systems [2]-[8]. A variation of the method known as the synchronous reference frame method or $d-q$ method is also widely used. Frequency domain methods based on computationally efficient Fourier analysis have been far less prevalent although they have seen a recent increase in interest [9]-[14]. The maturity of development in the area of switching compensators is evidenced by the large body of literature, and in recent years comparisons of the various proposed methods of reference signal generation [15]-[21].

There have been recent trends toward multi-functionality of power electronic converters combining compensation

with other functions or requiring flexible compensation. For example, it may be desirable to perform compensation with converters used for interfacing of renewable sources during time intervals that they are not fully utilized for active power transfer. Also, non-ideal supply conditions are warranting more attention as weak grids such as microgrid systems are gaining interest. With increased flexibility requirements and non-ideal grid conditions, the applicability of reference signal generation for compensation applications should be evaluated. Many switching compensator control algorithms are not based on a specific power theory, however, targeted compensation requires an understanding of power components that are present to enable priority based decisions with respect to the compensation. Thus, power theory should be used to evaluate a compensation strategy's suitability if not to determine the strategy initially.

This paper compares the applicability of several power theories to the generation of reference signals for the control of switching compensators.

Power electronic converter based compensators

Power electronic converters used in compensation applications can be grouped into one of three broad categories: shunt connected current compensators, series connected voltage compensators, and combinations thereof. The shunt connected current compensator is the most prevalent and will be the focus of compensation examples in this paper. Figure 1 depicts a generalized voltage source converter (VSC) based current compensator with the control partitioned into several hierarchical layers.

The control layers can be grouped into two main parts. The first is the current controller [22] and lower level controls that cause the power electronics hardware to behave as a controlled current source, as depicted by the

$$(9) \quad i_d = \bar{i}_d + \tilde{i}_d$$

$$(10) \quad i_q = \bar{i}_q + \tilde{i}_q$$

where the fundamental positive sequence becomes a constant and all harmonics along with the negative sequence fundamental become oscillating quantities.

c. Currents' Physical Components (CPC) theory

The CPC theory developed in the frequency domain by Czarnecki [25], [26] is based on orthogonal decomposition of the current. The theory provides a physical interpretation of power phenomena in three-phase systems under unbalanced and non-sinusoidal conditions. For sinusoidal conditions, 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

$$(11) \quad Y_e = G_e + jB_e = Y_{RS} + Y_{ST} + Y_{TR}$$

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

$$(12) \quad A = |A|e^{j\varphi} = -(Y_{ST} + \alpha Y_{TR} + \alpha^* Y_{RS})$$

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

$$(13) \quad \mathbf{i} = [i_R \quad i_S \quad i_T]^T$$

can be decomposed into mutually orthogonal components as

$$(14) \quad \mathbf{i} = \mathbf{i}_a + \mathbf{i}_r + \mathbf{i}_u$$

where the active component of the current is

$$(15) \quad \mathbf{i}_a = \sqrt{2} \operatorname{Re} \left\{ G_e [U_R \quad U_S \quad U_T]^T e^{j\omega t} \right\},$$

the reactive component of the current is

$$(16) \quad \mathbf{i}_r = \sqrt{2} \operatorname{Re} \left\{ jB_e [U_R \quad U_S \quad U_T]^T e^{j\omega t} \right\},$$

and the unbalanced component of the current is

$$(17) \quad \mathbf{i}_u = \sqrt{2} \operatorname{Re} \left\{ A [U_R \quad U_T \quad U_S]^T e^{j\omega t} \right\}.$$

For non-sinusoidal conditions of voltage and current, the current can be decomposed as

$$(18) \quad \mathbf{i} = \mathbf{i}_a + \mathbf{i}_{r1} + \mathbf{i}_{s1} + \mathbf{i}_{u1} + \mathbf{i}_h$$

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

$$(19) \quad \mathbf{i}_{s1} = \sqrt{2} \operatorname{Re} \left\{ (G_{e1} - G_e) [U_{R1} \quad U_{S1} \quad U_{T1}]^T e^{j\omega t} \right\}.$$

d. Hybrid p-q and CPC

This method is based on the relation between the p-q and CPC theories. As demonstrated in [20], applying the Clarke transform to the fundamental 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

$$(20) \quad p = 3U^2 [G_e + |A| \cos(2\omega t + \varphi)]$$

$$(21) \quad q = 3U^2 [B_e - |A| \sin(2\omega t + \varphi)].$$

This result shows that both instantaneous active and reactive power are associated with load imbalance characterized by the unbalanced admittance (12). Furthermore, the component associated with unbalanced admittance is of the second order 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) and (12) are equal to

$$(22) \quad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{3}U \begin{bmatrix} G_e \cos \omega t - B_e \sin \omega t + |A| \cos(\omega t + \varphi) \\ G_e \sin \omega t + B_e \cos \omega t - |A| \sin(\omega t + \varphi) \end{bmatrix}.$$

The d - q transform (8) can be applied to (22) resulting in an expression of the d and q components of the current as

$$(23) \quad \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{3}U \begin{bmatrix} G_e + |A| \cos(2\omega t + \varphi) \\ B_e - |A| \sin(2\omega t + \varphi) \end{bmatrix}.$$

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. This result also highlights the relationship between the p - q and d - q frameworks.

e. Conservative Power Theory

The conservative power theory [24] is a hybrid time and frequency domain theory aimed at distributed compensation. The theory decomposes powers differently than the CPC theory resulting in scattered active and scattered reactive current in addition to active, reactive and generated currents. It is a relatively recent theory and as such has not been applied extensively to switching compensator reference generation except in the case of [27]. Thus, it is not considered in the reference signal generation discussion below but should be mentioned since it promises to offer a very high degree of flexibility in compensation applications.

Compensation objectives

The desired form of compensation depends upon the objectives. Three common objectives are:

1. The source current should have a minimum RMS value
2. Source current should be sinusoidal and may also be required to have a particular phase and degree of symmetry
3. Instantaneous active power at the supply should be constant

Under the condition that the supply is non-sinusoidal and/or asymmetrical these goals cannot be simultaneously met. The tradeoff between sinusoidal current and minimum RMS value are best described in the frequency domain. If the supply is non-sinusoidal and sinusoidal supply current is desired then only fundamental currents are present so that the compensator current is

$$(24) \quad j = i_{r1} + i_{u1} + i_h = i_{r1} + i_{u1} + i - (i_{a1} + i_{r1} + i_{u1})$$

and the supply current after compensation becomes

$$(25) \quad i' = i - j = i_{a1} = i_a + \sum_{n \in N} i_{sn} - \sum_{n \in N} i_{an}$$

If voltage distortion is not reduced to zero by the compensation of the harmonic components then the supply current RMS value will always be higher than its minimum. However, the supply current will be sinusoidal. If the scattered currents are computed then the supply current

RMS value can be minimized, however, some distortion will remain since the active current i_a is not sinusoidal.

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 power electronic converter power and switching speed limitations, etc. Furthermore, the compensation objectives may vary over time.

An example of a switching compensator reference signal for variable compensation objectives and sinusoidal supply current is the linear form

$$(26) \quad j^* = K_r i_{r1} + K_u i_{u1} + K_h i_h + i_c$$

where K_r , K_u and K_h are scaling coefficients of the reactive, unbalanced and harmonic components respectively. The final term in the expression is the switching compensator active power which is needed to active maintain power balance as well as to supply power to the compensator due to losses. Depending on the compensation goals and power components present in the system the compensator active current may also consist of active power at harmonic frequencies or negative sequence.

The reference signal will take on different forms depending on the goals of compensation and whether it is expressed in the time domain, frequency domain or both.

Generation of reference signals

Whether a reference signal generation method is based on a time-domain or frequency domain approach, the basic elements are the same. Power or current components present at a measurement point are determined followed by extraction of selected subsets of those components. Finally, a compensation command signal is constructed from the selected subset. Some reference signal generators for both time domain, frequency domain, and hybrid methods are presented along with their major advantages and disadvantages.

a. Time domain methods

Typical reference signal generator structures for shunt compensation in three-wire systems for both $p-q$ and $d-q$ are shown in Fig. 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 as required by the power losses in the switching compensator. In the case of the $p-q$ reference generator, the references are converted back into currents by the inverse Clarke transform prior to sending to the current control layer.

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 [4] 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 [20] 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. This effect is shown in *Illustration 1* below.

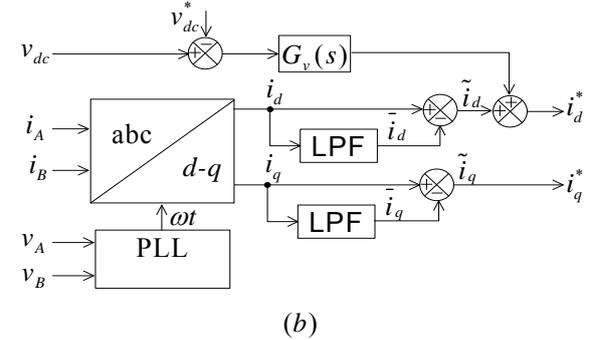
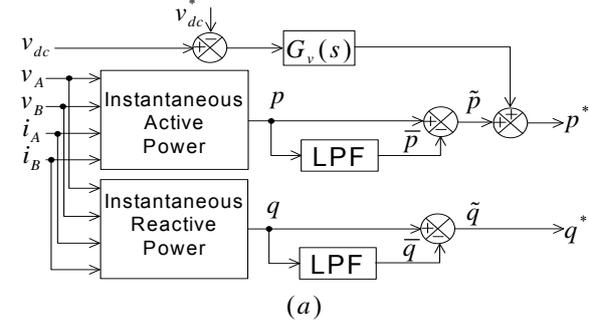


Figure 2. (a) general reference generator structure for $p-q$ methods (b) general reference generator structure for $d-q$ methods

Illustration 1: Consider a simple three-phase circuit with the phase T load disconnected from the supply as shown in Figure 3.

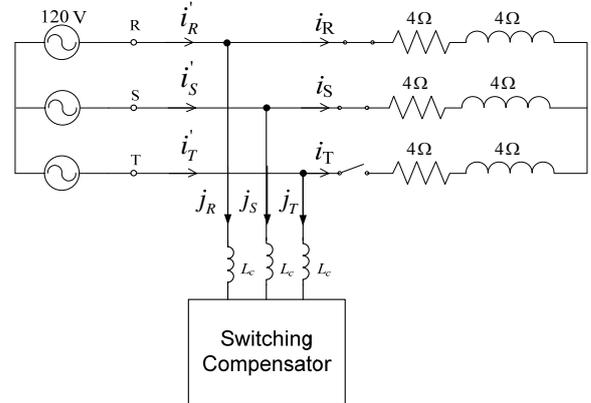


Figure 3. Example of a circuit with an unbalanced load.

The supply is a symmetrical positive sequence source with voltage RMS value $U = 120V$. In this case applying the Clark transform yields

$$(27) \quad \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \mathbf{C} \begin{bmatrix} \sqrt{2}U \cos \omega_1 t \\ \sqrt{2}U \cos(\omega_1 t - 120^\circ) \end{bmatrix} = \begin{bmatrix} \sqrt{3}U \cos \omega_1 t \\ \sqrt{3}U \sin \omega_1 t \end{bmatrix}$$

The currents in each line are equal to

$$(28) \quad i_R = \sqrt{2}I \cos(\omega_1 t - 15^\circ), \quad i_S = -i_R, \quad i_T = 0$$

where $I = 18.38$ A. Thus, the currents mapped into the $\alpha-\beta$ coordinates are

$$(29) \quad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \mathbf{C} \begin{bmatrix} i_R \\ i_S \end{bmatrix} = \begin{bmatrix} \sqrt{3}I \cos(\omega_1 t - 15^\circ) \\ -I \cos(\omega_1 t - 15^\circ) \end{bmatrix}$$

Instantaneous reactive power can be calculated from (4) as

$$(30) \quad q = -\sqrt{3}UI \left[\frac{1}{\sqrt{2}} + \sin(2\omega_1 t + 15^\circ) \right].$$

From (7) the reference signal alpha and beta components are

$$(31) \quad i_\alpha^* = -i_{q\alpha} = \frac{u_\beta}{u_\alpha^2 + u_\beta^2} q = -I \left[\frac{1}{\sqrt{2}} + \sin(2\omega_1 t + 15^\circ) \right] \sin \omega_1 t$$

$$(32) \quad i_\beta^* = -i_{q\beta} = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} q = I \left[\frac{1}{\sqrt{2}} + \sin(2\omega_1 t + 15^\circ) \right] \cos \omega_1 t.$$

Taking the inverse Clarke Transform

$$(33) \quad \begin{bmatrix} i_{Rq} \\ i_{Sq} \end{bmatrix} = I \left[\frac{1}{\sqrt{2}} + \sin(2\omega_1 t + 15^\circ) \right] \mathbf{C}^{-1} \begin{bmatrix} -\sin \omega_1 t \\ \cos \omega_1 t \end{bmatrix}$$

yields the compensating currents injected into the system

$$(34) \quad i_{Rq} = \frac{-I}{\sqrt{6}} \left[\sqrt{2} \sin \omega_1 t - \cos(\omega_1 t + 15^\circ) + \cos(3\omega_1 t + 15^\circ) \right]$$

$$(35) \quad i_{Sq} = \frac{I}{\sqrt{6}} \left[\sqrt{2} \cos(\omega_1 t - 30^\circ) + \sin(\omega_1 t + 45^\circ) + \sin(3\omega_1 t - 15^\circ) \right]$$

Thus, the compensating currents are distorted due to third harmonic as shown in Fig. 4. Furthermore, as can be seen by (34) and (35), the third harmonic generated is of positive sequence. This means that, unlike most cases where the third harmonic is zero sequence, third harmonic current will flow regardless of the lack of zero sequence current paths.

The Synchronous Reference Frame Method of determining the compensating current reference is quite similar to the p - q method. In fact, it is subject to the same effects when unbalanced phase currents exist in the lines. Applying the d - q transform yields

$$(36) \quad \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\omega_1 t) & \sin(\omega_1 t) \\ -\sin(\omega_1 t) & \cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} \sqrt{3}I \cos(\omega_1 t - 15^\circ) \\ -I \cos(\omega_1 t - 15^\circ) \end{bmatrix}.$$

Thus the q component of current is

$$(37) \quad i_q = -I \left[\frac{1}{\sqrt{2}} + \sin(2\omega_1 t + 15^\circ) \right].$$

In order to compensate for reactive power the reference current is generated from the negative of the q component of the current and transformed back into the stationary or α - β reference frame as

$$(38) \quad \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \begin{bmatrix} \cos \omega_1 t & -\sin \omega_1 t \\ \sin \omega_1 t & \cos \omega_1 t \end{bmatrix} \begin{bmatrix} 0 \\ i_q^* \end{bmatrix} = I \left[\frac{1}{\sqrt{2}} + \sin(2\omega_1 t + 15^\circ) \right] \begin{bmatrix} -\sin \omega_1 t \\ \cos \omega_1 t \end{bmatrix}.$$

Note that the reference current α - β components given in (38) are the same as in (31) and (32).

Harmonic distortion in the current similarly creates an oscillating component in both p and q or i_d and i_q terms. Thus, distortion will be present in the compensated currents in any case that those pairs are not equal after extraction of the reference signal. These are called "hidden currents" in [7]. Care must be taken when designing filters used in the

reference signals generators so that mismatch of the hidden current pairs does not occur.

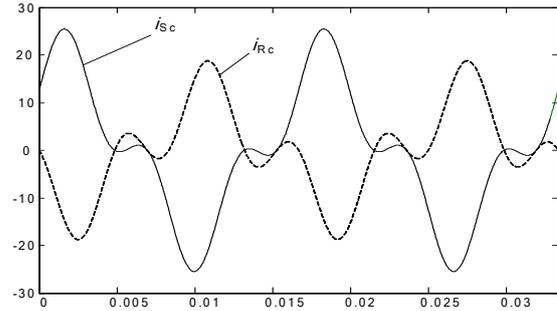


Figure 4. Compensating currents computed by instantaneous reactive power theory for the circuit in Fig. 3.

If the goal of the compensation is constant instantaneous active power then the reference signal alpha components are

$$(39) \quad i_\alpha^* = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} \tilde{p} + \frac{u_\beta}{u_\alpha^2 + u_\beta^2} q$$

and the reference signal beta components are

$$(40) \quad i_\beta^* = \frac{u_\beta}{u_\alpha^2 + u_\beta^2} \tilde{p} - \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} q.$$

So that only the low pass filter in the p branch of the reference generator of Fig. 2 (a) is present and the constant component of q is not removed. In this case distorted supply voltage and/or supply voltage asymmetry results in distortion of the compensating currents generated by the p - q method and its variants, the modified p - q and p - q - r methods, as demonstrated in [6]. It is obvious that distorted voltages will result in distorted compensating currents. Distortion of the compensating current due to negative sequence component of the voltage occurs since in that case both positive and negative sequence components of the current are present. The positive sequence component of the current and negative sequence component of the voltage results in second harmonic oscillating component contribution into both p and q terms for the same reasons illustrated above. However they combine with the second harmonic oscillating components due to the positive sequence voltage and negative sequence currents in such a way that the oscillating components in the p and q terms are different which is the condition for compensating current distortion.

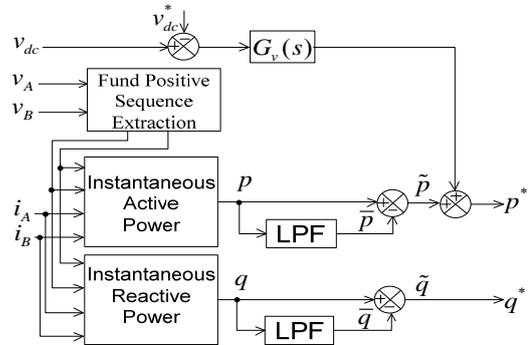


Figure 5. General reference generation structure for p - q method for non-sinusoidal and asymmetrical supply.

To avoid effects of non-ideal supply voltage the d - q method can be used. However, the impact of non-ideal

voltage on the phase-locked-loop (PLL) required to synchronize the frame with the fundamental or with a particular harmonic must then be considered.

In the case that the goal of the compensation is sinusoidal and balanced supply currents then the positive sequence fundamental of the voltage must be separated out prior to application of the Clarke transform [7]. A reference signal generator for this case is shown in Fig. 5.

b.) Frequency domain method using CPC

Calculating the CRMS values of the measured voltages and currents using a RDFT [11] their ratio can be interpreted as admittances for the fundamental frequency. The value of these admittances can change as the RDFT N sample moving window advances. Therefore, the admittances are considered as time varying quantities and the two necessary admittances are referred to as *time varying admittances of an equivalent load*. They are calculated by

$$(41) \quad \tilde{Y}_{TR} = \frac{\tilde{I}_R}{\tilde{U}_{RT}}, \quad \tilde{Y}_{ST} = \frac{\tilde{I}_S}{\tilde{U}_{ST}}.$$

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

$$(42) \quad \tilde{Y}_e = \tilde{G}_e + j\tilde{B}_e = \tilde{Y}_{ST} + \tilde{Y}_{TR}$$

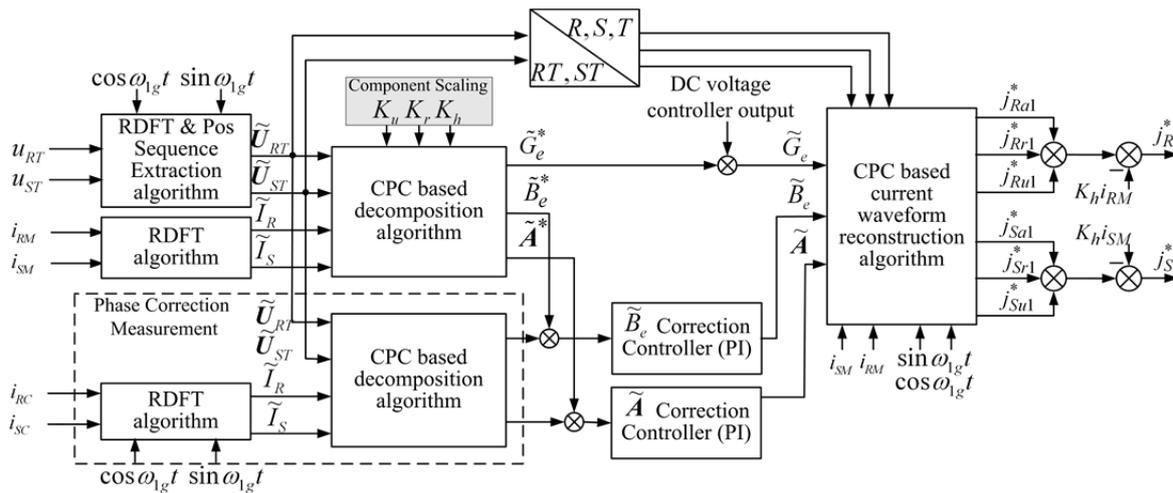


Figure 6. CPC reference signal generator.

A simplified block diagram of a CPC reference signal generation strategy to realize (26) is shown in Fig. 6. The main feature of this architecture is the RDFT and orthogonal current decomposition that provides the current reference signals. The reference signal generator is shown divided into two parts: the RDFT measurement and decomposition algorithm used for measuring the necessary voltages and currents and decomposing them into equivalent and unbalanced admittances, and the current waveform reconstruction algorithm that transforms the frequency-domain references back to time-domain current waveforms. In addition to these there are two feedback control loops associated with the reference signal generation. The first is an active current controller which determines the value of equivalent conductance associated with the active current at the fundamental as required by the power losses in the power electronic converter system. Of course, it is the typical DC bus voltage controller found in most VSC control systems. The second is a reactive current controller that ensures the reactive current is equal to the set-point in the

and the time varying unbalanced admittance is given by

$$(43) \quad \tilde{A} = |\tilde{A}| e^{j\tilde{\phi}} = -(\tilde{Y}_{ST} + \alpha\tilde{Y}_{TR}).$$

With the time varying equivalent and unbalanced admittances, current components can be generated. As in [11] in order to provide flexibility of the compensation objectives the current control reference signal is expressed as a linear form given in (26).

One condition of the non-ideal supply considered here is asymmetry. In the case that the supply is asymmetrical, voltage sequence must be separated in order for unbalanced current to have meaning. In order for the converter to inject or draw balanced currents, only positive-sequence voltage is used by the reference signal generator. Thus, active component of the converter, i_{Ca} , is equal to

$$(44) \quad i_{Ca} = \frac{\Delta P_{sc} + \left\| i_{a1}^N \right\| \left\| u_1^N \right\| + \sum_{n \in N_h} \left\| i_{an} \right\| \left\| u_n \right\|}{\left\| u_1^P \right\|^2} u_1^P$$

where ΔP_{sc} are losses of the converter. Superscripts 'P' and 'N' denote positive and negative sequences respectively. Active component of the converter is adjusted by the DC bus voltage control as needed to satisfy the power balance.

presence of any RDFT induced phase error. The RDFT calculation of the measured voltage can contain a phase error due to lack of synchronization of the RDFT with the fundamental [14]. In that case, the reference currents generated by the current reconstruction algorithm will contain a constant phase error, δ . This introduces a phase shift in the converter current output relative to the desired phase setting. However, the CPC equivalent admittance computed at the active rectifier input terminals is computed correctly due to cancellation of the phase error in the admittances calculation. This provides a correct value of the equivalent susceptance, B_e , that can be used to correct the phase error in the current. The addition of the rective control loop to force B_e equal to the desired set-point removes the phase error introduced into the current reconstruction algorithm by the RDFT of the measured supply voltage.

c.) Hybrid methods

Instead of filters hybrid time-frequency reference signal generators utilize frequency-domain quantities to generate

the time-domain quantities used to adjust the reference signals.

It was shown in [23] that applying the Clarke transform to the line currents expressed in terms of the CPC based decomposition and applying the formula for p and q to the resulting current components provides insight into the relation between components of the current and the instantaneous active and reactive power terms. The same approach can be taken in order to develop a CPC based reference signal generator in the synchronous reference frame.

The alpha and beta components of the current expressed in terms of (22) are equal to

$$(45) \quad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{3}\tilde{U} \begin{bmatrix} \tilde{G}_e \cos(\omega_1 t + \delta) \\ \tilde{G}_e \sin(\omega_1 t + \delta) \\ -\tilde{B}_e \sin(\omega_1 t + \delta) + |\tilde{A}| \cos(\omega_1 t + \delta + \tilde{\varphi}) \\ +\tilde{B}_e \cos(\omega_1 t + \delta) - |\tilde{A}| \sin(\omega_1 t + \delta + \tilde{\varphi}) \end{bmatrix}$$

where

$$(46) \quad \omega_1 t = \omega_{1g} + \Delta\omega$$

under the assumption that the RDFT window may not be synchronized and $\Delta\omega$ is the frequency difference from the control nominal frequency ω_{1g} . The additional phase angle $\tilde{\delta}$, defined in (45), is introduced by any frequency deviation from the nominal control frequency.

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. Therefore, cancellation of the terms associated with equivalent conductance, equivalent susceptance, and unbalanced admittance can be applied to yield a current component selection technique that applies to synchronous reference frame methods. Adjusted current components, denoted i_α^* and i_β^* , are defined as

$$(47) \quad \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \begin{bmatrix} K_m i_{\alpha m} - K_a i_{\alpha a} - K_r i_{\alpha r} - K_u i_{\alpha u} \\ K_m i_{\beta m} - K_a i_{\beta a} - K_r i_{\beta r} + K_u i_{\beta u} \end{bmatrix},$$

where i_α and i_β contain any components of the current that are present including harmonics, $i_{\alpha a}$ and $i_{\beta a}$ are the fundamental active components of the *alpha* and *beta* currents respectively, $i_{\alpha r}$ and $i_{\beta r}$ are the fundamental reactive components of the *alpha* and *beta* currents respectively, and $i_{\alpha u}$ and $i_{\beta u}$ are the fundamental unbalanced components of the *alpha* and *beta* currents respectively. Finally, K_a , K_r , K_u are the scaling coefficients for the active, reactive, and unbalanced components respectively. Then d and q components of the reference current are given by

$$(48) \quad \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} \cos(\omega_1 t) & \sin(\omega_1 t) \\ -\sin(\omega_1 t) & \cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} i_\alpha - i_\alpha^* \\ i_\beta - i_\beta^* \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \sqrt{3}U \begin{bmatrix} K_a \tilde{G}_e \cos \delta + K_u |\tilde{A}| \cos(2\omega_1 t + \delta + \tilde{\varphi}) \\ K_r \tilde{B}_e \cos \delta - K_u |\tilde{A}| \sin(2\omega_1 t + \delta + \tilde{\varphi}) \end{bmatrix}$$

In addition to providing the needed quantities for the current decomposition calculations, the properties of the fixed-window RDFT can be used to provide phase correction information summed with the nominal ω_{1g} for the generation of a synchronous reference frame at the supply frequency. The phase angle due to frequency variation, $\tilde{\delta}$, must be accounted for in the reference signal generation as well. It can be considered as an offset in the angle of the d -axis of the reference relative to the actual d -axis. The CPC equivalent admittance computed at the measurement terminals is computed correctly due to cancellation of the phase error in the calculation of admittances. Thus, the offset will cause a difference in the reference value of the equivalent susceptance and the equivalent susceptance as seen from the phase terminals of the VSC. The equivalent conductance must be the same due to the DC voltage controller. This provides a method to estimate the phase offset and correct for it.

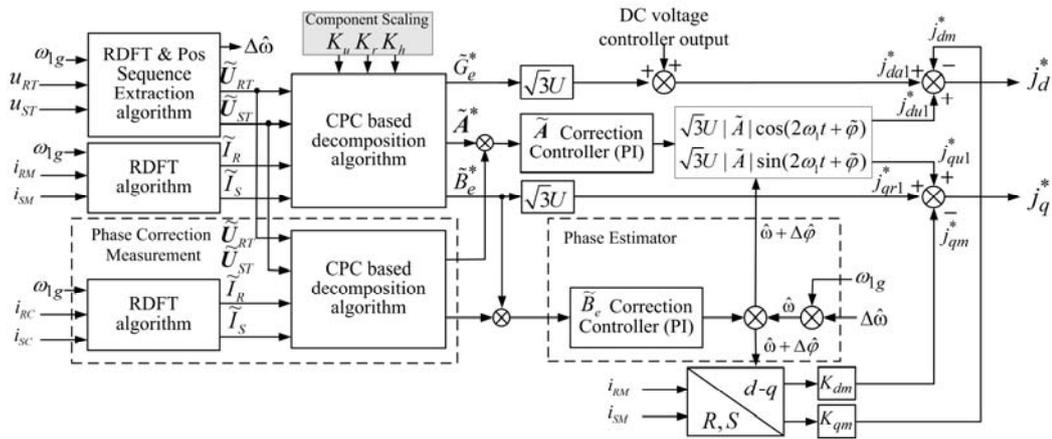


Figure 7. Hybrid d-q and CPC reference signal generator.

A simplified block diagram of the hybrid reference signal generation strategy is shown in Fig. 7. A main feature of this RSG is the use of voltage positive sequence as well as the additional RDFT and CPC based current decomposition that allows removal of the phase error present in expression (48). This second set, shown in the dashed box, provides a correct value of the equivalent admittances that can be used to correct the phase error. The addition of a simple PI control loop to force B_e to the desired set-points in addition

to information on phase variation from the RDFT of the supply voltage form a phase estimator. Alternatively, a PLL could be used to provide the phase information and to adjust the RDFT window width to match the fundamental as in [23].

The results of two simulations for reactive power compensation are presented using the same test circuit from Illustration 1 shown in Fig. 3. The first 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 and then opened again. The compensating currents for phases R and S generated using the p-q method are shown in Fig. 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 Fig. 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 RDFT.

The third simulation demonstrates the case of a balanced system with changing active and reactive power, the compensated current is shown in Fig. 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

$$(49) \quad i_q^* = -\sqrt{3}U\tilde{B}_e = -\sqrt{3}U \operatorname{Im}\{\tilde{Y}_{ST} + \tilde{Y}_{TR}\}.$$

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 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 hybrid method retains the fast property of the p-q or d-q methods while eliminating the problem of the third harmonic in the case of current asymmetry.

Simulation comparison of reference signal generation methods

In order to compare the performance of the reference signal generators a simulation the three-phase three-wire test system shown in Fig 11 is used. The test system is composed of an AC load bank in parallel with load generated current harmonics and a switching compensator. The AC load bank consists of a linear RL load that can be unbalanced. The switching compensator uses controlled current sources to represent the portion inside the dashed line of Fig. 1. This idealized model removes the effects of the current control and modulation systems of a switching compensator from the comparison.

The supply voltage may contain both asymmetry as well as harmonic distortion in addition to frequency variation and is expressed as

$$(50) \quad \mathbf{u} = \mathbf{u}^P + \mathbf{u}^N + \mathbf{u}_h,$$

where \mathbf{u}^P is a positive sequence sinusoidal voltage vector and \mathbf{u}^N is a negative sequence sinusoidal voltage vector with line-to-neutral voltage at terminal R equal to

$$(51) \quad u_R^P = \sqrt{2}U^P \cos \omega_1 t \quad u_R^N = \sqrt{2}U^N \cos \omega_1 t.$$

Distorted component of the voltage is given by \mathbf{u}_h with line-to-neutral voltage at terminal R equal to

$$(52) \quad u_{Rn} = \sqrt{2}XU^P \cos n\omega_1 t$$

with RMS value of X percent of the positive sequence fundamental.

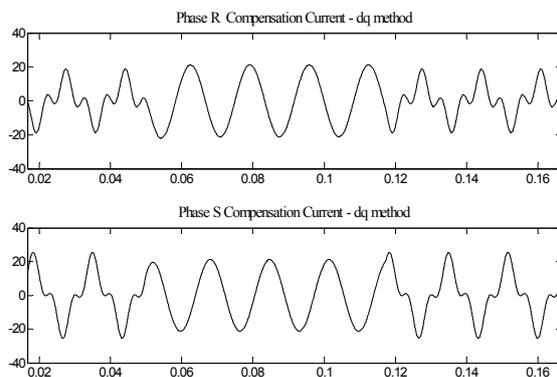


Figure 8. Compensation currents based on p-q reference signal generation.

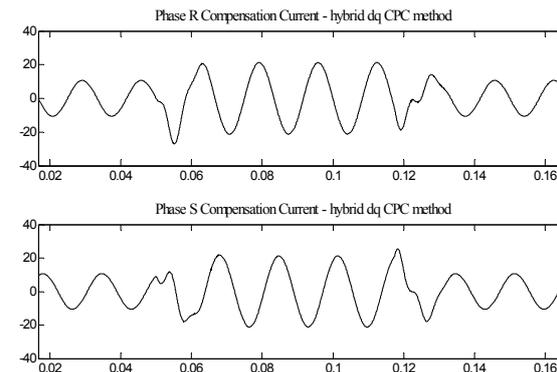


Figure 9. Corrected compensation currents using the proposed hybrid reference signal generation.

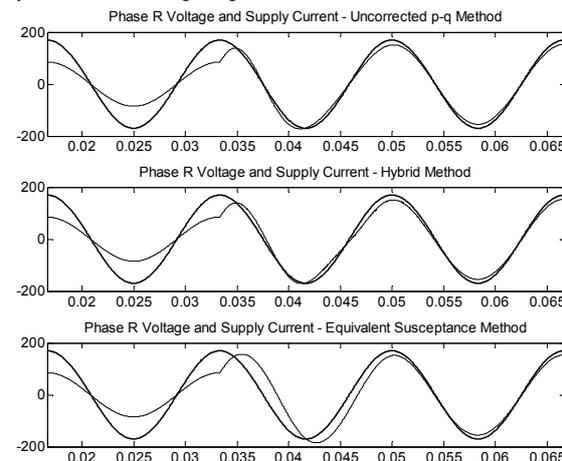


Figure 10. Simulation results for a balanced load with reactive power step change.

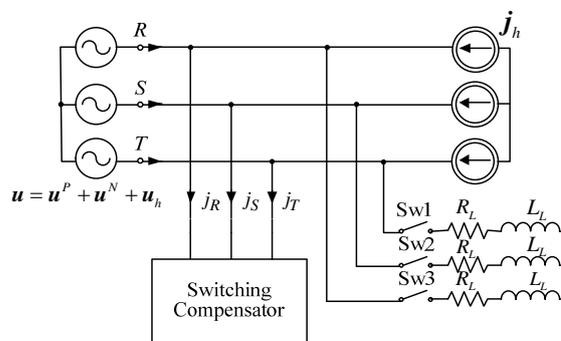


Figure 11. Simulation test system for reference signal generator comparison.

The supply voltage is initially sinusoidal and symmetrical with $U^P=120$ volts. Then negative sequence and harmonic components are added to the supply voltage at time $t =$

8.5/60 having $U^N=U^P/2$ and a 5th order harmonic with X equal to 10% of the fundamental. During the entire simulation the load is unbalanced with switch Sw3 open and load generated harmonics of the 11th order are injected by harmonic current sources.

The supply voltage and load current for the test case are shown in Fig. 12. Compensation results for the $p-q$ method, the CPC method and the hybrid method based on reference generators shown in Fig. 5, Fig. 6 and Fig. 7 respectively are shown in Fig. 13, Fig. 14 and Fig. 15.

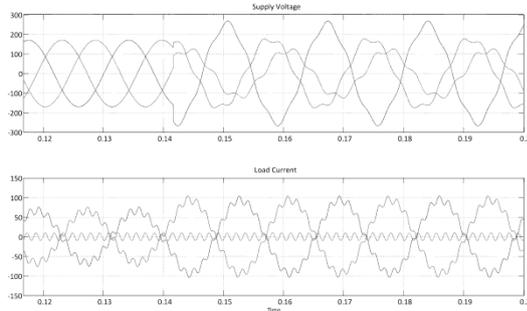


Figure 12. Distorted and asymmetrical supply voltage, and load current.

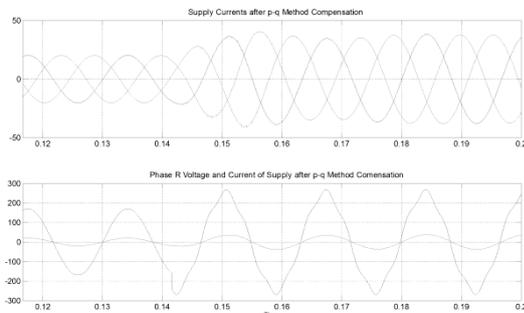


Figure 13. Supply currents and Phase R voltage and current after compensation with the $p-q$ method.

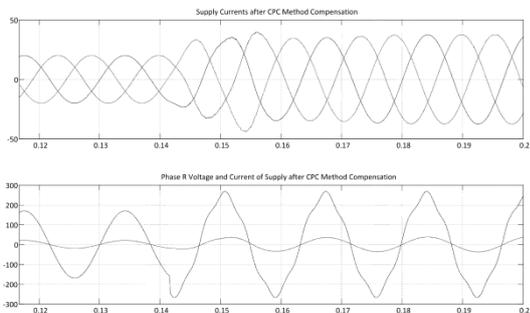


Figure 14. Supply currents and Phase R voltage and current after compensation with the CPC method.

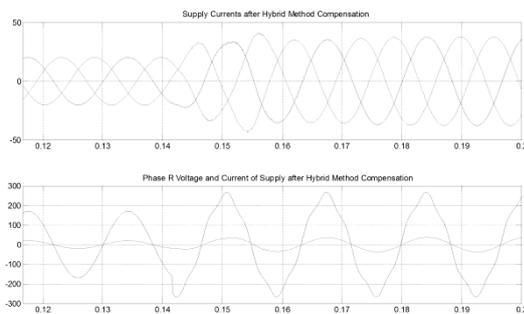


Figure 15. Supply currents and Phase R voltage and current after compensation with the hybrid method.

The $p-q$ method utilizes a sixth order low-pass Butterworth filter tuned to 60Hz for the removal of the instantaneous active power constant component as suggested in [7]. Each of the methods uses the same controller to maintain power balance. Despite some very minor differences all of the methods are comparable under non-ideal supply conditions where extraction of the positive sequence fundamental voltage is required.

Conclusions

The applicability of a particular power theory to switching compensator control depends on the goals of compensation as well as expected system conditions. If the supply voltage is close to ideal and all components of reactive power must be compensated then time domain $p-q$ and variants provide an instantaneous response from the reference generator. However, under non-ideal supply conditions or if selection of particular components of the fundamental or harmonics is required then the required filtering removes the instantaneous property from the time domain methods and they are no longer instantaneous.

Frequency domain methods such as the CPC based methods derive many benefits from the properties of the RDFT but require one cycle of the fundamental to converge. An additional advantage is that compensation components are easily selectable since they are not mixed among two quantities as in $p-q$ and its variants. Thus, it is more suited to selective compensation. Time domain methods can also be used for selective compensation if various appropriate filters are inserted. A major disadvantage of CPC methods is that they have not been adapted to four-wire system compensation.

Hybrid time-frequency domain based reference signal generators attempt to maintain the instantaneous property of time domain methods under some conditions while providing the flexibility of the frequency domain methods.

For the case where sinusoidal current is a requirement under non-sinusoidal and asymmetrical supply conditions all methods require extraction of positive sequence voltage fundamental.

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