A New Method of Reference Signals Calculation for Switching Compensator

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Abstract

The switching compensation devices, such as active power filters and static var generator, are growing rapidly for power quality improvement. The current reference signals is one of the important factor affecting the responsible speed and compensation effect. In this paper, a new strategy for reference signals calculation is present based on Current’s Physical Components. Through the orthogonal decomposition of the load current by the CPC power theory, the reference current, for various compensation objectives of switching compensation devices, can be calculated by the combination of the orthogonal current components. It is demonstrated that this strategy can be used for various compensation goals of limited switching compensation devices and changing the compensation objectives on-line according to the power grids. The validity of the developed strategy is verified by the simulation results.

Keywords: Switching Compensator, Compensation Objectives, Current Reference Signals, Current’s Physical Components

1. Introduction

With the increasing popularity of induction motors, adjustable speed drives, controlled rectifiers and other power electronic equipment, issues with power quality are becoming more and more serious. Apart from the inductor motors, the non-linear loads can also be blamed for the reduced power factor which is an effect of the phase-shift between the voltage and current [1, 2]. Meanwhile, the proliferation of the harmonic generating loads (HGLs) contributes to high levels of harmonic distortion in the distribution. The power factor degradation and harmonic distortion and unbalance currents in the power system causes an increase in energy loss and load efficiency.

Recently, switching compensator are superior in filtering performance, smaller in physical size compared to the conventional passive filters, thus becoming popular with the push for power quality of micro-grid. At the same time, different power theory, decomposing the load current into different components, has been defined and developed based on time domain or frequency domain for the operation under non-sinusoidal conditions [3-8]. Depending on the variety of power theory, many compensators has been presented and developed in papers [4], [9-14] in order to improve the power factor. This usually is accompanied with harmonic and unbalance current eliminate. However, those strategies cannot be- lied in some complicate environment, for example, the underground grid of coal mine. In order to avoid unnecessary investment and decrease the rating and size of the switching compensator under complicate environment, specific generation of reference signals for switching compensator is needed. In this paper, a novel strategy of reference signals generation for limited size and rating of switching compensator is proposed. This strategy is based on CPC power theory which decompose the current into mutually orthogonal components associated to the distinctive physical phenomena in the power system. Through the provided orthogonal decomposition of the current, any useless individual component of the current or set of component can be taken into consideration to compensate.

This paper is structured as follows. In section II it is described the conventional schematic of a switching compensator. In sequence, in section III it is described the CPC (Current Physical Components) power theory for power system and the selective generation of reference signals for switching compensator. In section IV simulation results involving the
generation of current reference for switching compensator are presented. In these simulations the reference signals are derived from CPC power theory. Finally, in section V the major conclusions obtained through this work.

2. Description of The Switching Compensator

Switching compensators are devices designed to improve the power quality in distribution networks. Figure 1 demonstrates the conventional schematic diagram of a switching compensator. It should be connected in parallel as close as possible to the harmonic-producing or unbalance load to improve the power quality.

![Figure 1. Schematic Diagram of Switching Compensation Devices](image)

The power circuit of the switching compensator consists mainly of a voltage source PWM inverter using the IGBTs and a DC capacitor. In most of the applications, the control circuit which is based on a modern digital controller, using DSPs, FPGAs, etc, needs sophisticated control. One aim of the switching compensator is to mitigate the harmonic and unbalance current of the load current so that only the fundamental frequency remains in the grid. Due to its capacitive character, the switching compensator is also used to generate reactive power and to increase the power factor. The switching compensator draws the compensating current \( i_c \) from the PWM circuit in such a way as to cancel out the detrimental components exiting in the power system.

3. The Strategy of Selective Generation of Reference Signal Based on CPC Power Theory

3.1. CPC Power Theory

Among the power theories developed by literatures, the CPC power theory formulated by professor Czarnecki for power circuit under sinusoidal or un-sinusoidal voltage conditions is able to give the physical interpretations of power phenomena. In accordance with the CPC theory, the three-phase current vector \( i_L \) of any unbalanced and nonlinear load in a three-wire circuit supplied by a symmetrical sinusoidal voltage system can be decomposed into four orthogonal components, as follows:

\[
\begin{align*}
\vec{i}_L &= [i_d \ i_b \ i_c]^T = i_a + i_c + i_u + i_g
\end{align*}
\]  

Where the active component \( i_a \) is responsible for active power transmission; the reactive component \( i_c \) is associated with the phase shift between the voltage and current and, consequently, the presence of the reactive power; the unbalanced component \( i_u \) is related to the load imbalance; the load generated component \( i_g \) is associated to the load nonlinearity or its parameters’ time-variance.

As the supply voltage is sinusoidal, the three-phase voltage vector is written as a function of the complex RMS voltages.

\[
\begin{align*}
u &= [u_a \ u_b \ u_c]^T = \sqrt{2} \text{Re} \left([u_d \ u_b \ u_c]^T e^{j\omega t}\right) = \sqrt{2} \text{Re} \left(U e^{j\omega t}\right)
\end{align*}
\]  

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**Note:** The image of Figure 1 is not included in the text. It is assumed to be a schematic diagram of a switching compensation device.
And the current components, except the generated current, are included in the current fundamental harmonic, i.e.

\[ i_L = i_{L1} + i_g \]  
\[ i_{L1} = i_u + i_r + i_u \]  
\[ i_g = \sum_{k=2}^{\infty} i_{LK} \]  

By considering the equivalent passive load of delta structure, with respect to active and reactive powers, whose equivalent admittance is:

\[ \{ Y_e \} = \begin{bmatrix} R_e & jw T \end{bmatrix} \]  
\[ \{ F_e \} = \begin{bmatrix} R_e & jw \end{bmatrix} \]  
\[ \{ T_e \} = \begin{bmatrix} R_e & \alpha \end{bmatrix} \]

Starting from the general definitions of the equivalent admittance and the unbalance admittance, convenient fictitious line-to-line admittance of the load can be expressed in the three-wire system in order to reduce the amount of calculation:

\[ Y_e = Y_{AB} + Y_{BC} + Y_{CA} \]

\[ A = -\left( Y_{AB} + a Y_{BC} + \alpha Y_{CA} \right) \]

\[ \alpha = e^{j2\pi/3} \]

\[ \alpha^* = e^{-j2\pi/3} \]

As the measured line-to-line voltages in the experimental setup are \( u_{BA} \) and \( u_{CA} \), the phase-A is chosen as a reference and \( Y_{BC} \) is assumed to be zero. Therefore, the expressions of the equivalent and unbalanced admittances become:

\[ Y_e = Y_{BA} + Y_{CA} = \frac{i_g}{U_{BA}} + \frac{i_c}{U_{CA}} \]

\[ A = -\left( \alpha Y_{CA} + \alpha^* Y_{BA} \right) = \left( \alpha \frac{i_c}{U_{CA}} + \alpha^* \frac{i_g}{U_{BA}} \right) \]

Then, the equivalent conductance \( G_e \) and susceptance \( B_e \) of the load are calculated as:

\[ G_e = \text{Re} \{ Y_e \} \]

\[ B_e = \text{Im} \{ Y_e \} \]

### 3.2. The Strategy of Selective Generation of Reference Signal

The proposed strategy for the generation of reference signal for switching compensator is adapted to the conditions that the size and rating of switching compensator is
limited under the circumstance such as the underground coal mine. Therefore, the primary compensation is to compensated the most severe power conditions which may be the harmonic pollution, unbalance current, reactive current or their combination.

It is advantageous that CPC power theory decompose the load current into mutually orthogonal component, so that the major components of the detrimental current are managed individually and compensated according to a hierarchy of their importance.

1. Compensation to cancellation of reactive current

Reactive current is the effect of phase-shift between the voltage and current which increases the current RMS value. According to the decomposition of CPC power theory, the reactive current can be totally compensated. The reference signals for switching compensator should calculate according to the formula:

\[ j = -i_r \]  

where \( j \) is referred to as the reference signal.

2. Compensation to the symmetric current

Asymmetric of the current occurs due to the load imbalance. The current \( i_u \) is, in general, an asymmetrical current, composed of symmetrical components of the positive and negative sequence in three phase systems. The negative sequence current contributes to the current RMS value decrease and the consequently, the power factor decline in the same way as the reactive current.

The CPC concept provides an exceptionally simple solution to the problem of unbalance system. When the unbalance condition is most severe in the power system, the reference signals should calculate according to the formula:

\[ j = -i_u \]  

3. Compensation to the sinusoidal current

Similarly to the compensation of unbalance system, the load-generated harmonic current, due to the non-linearity or periodic time-variance of load, could also be mitigated in a simple solution when the harmonic compensation is the first goal in the power system. The reference signals should calculate according to the formula:

\[ j = -i_y \]  

4. Compensation to the minimization of current

With respect to the effectiveness of energy delivery in three phase systems, the active current \( i_a \), decomposed by CPC power theory, associated with a permanent flow of energy at the rate of active power of load, is the current of an ideal load. It is the smallest supply current needed for providing, representing the smallest useful active power needed to delivery. The remaining part of the supply current referred to as a ‘detrimental current’ in this paper contains the negative sequence component, as well as the reactive current, load-generated harmonic current. Consequently, the compensator should generate and inject the negative detrimental current \( i_d \) into the load supply lines, meaning that the reference signals should calculated according to the formula:

\[ i_d = i_L - i_u \]  

\[ j = -i_d = i_u - i_L \]

4. Simulation Studies

To verify the accuracy of the proposed strategy, simulation and analysis on the three phase systems is done. The system was modeled using Matlab/Simulink to achieve the variety of compensation goal under different environment. For the simplicity, only the waveform of
voltage and current of phase A is selected to analysis the effectiveness of reactive current compensation. The waveform of voltage and current of phase A, before and after compensation, is shown as Figure 2, Figure 3. The reference signal is shown in Figure 4.

Figure 2. Waveforms Before Reactive Compensation

Figure 3. Current Reference of Reactive Compensation

Figure 4. Waveforms After Reactive Compensation

Figure 3 shows that the waveform of current is identical to waveform of voltage. The reactive current is compensated totally. Figure 5-7 shows the compensation results of unbalance current according the decomposition of CPC power theory, and yields in a better compensation results.

Figure 5. Waveforms Before Unbalance Current Suppressing

Figure 6. Waveforms After Unbalance Current Suppressing
The analysis of the compensation of harmonic current is the same as that of reactive current. The waveform of load current is nearly sinusoidal after compensation. Figure 8-10 shows the compensation results.

The detrimental current, consisting of reactive current and harmonic and unbalance current, will be compensated. Therefore, the desired active current corresponding to the smallest active power utilized by the load draw from the power network. Figure 11-13 shows the compensation results.
5. Conclusion

Switching compensator are used to compensate harmonic, reactive, unbalance current of load current drawn by the nonlinear loads from the power supply. The flexibility of selective compensation, if provide in the generation of reference signal, makes the switching compensator capable of compensation of reactive, harmonic, negative sequence current, and their combinations, depending upon the limited size and rating of the switching compensator. The proposed strategy in this paper is based on CPC power theory which decomposes the load current into orthogonal components. The strategy performs with priority-based strategy, which respects the limited rating of the switching compensator. The simulated results in Matlab/Simulink environment are presented to validate the effectiveness of the strategy.

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