AN EVALUATION OF TIME DOMAIN TECHNIQUES FOR COMPENSATING CURRENTS OF SHUNT ACTIVE POWER FILTERS

Vedat M. Karslı(1) Mehmet Tümay(2) Berrin Süslüoğlu(1)
e-mail: vkarsli@gantep.edu.tr *e-mail: mtumay@mail.cu.edu.tr* *e-mail: susluoglu@gantep.edu.tr*
(1)University of Gaziantep, Faculty of Engineering, Department of Electrical & Electronics Engineering, 27310, Gaziantep, Turkey
(2)University of Cukurova, Faculty of Engineering, Department of Electrical & Electronics Engineering, Balcali/ Adana, Turkey

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ABSTRACT

In this work p-q, i_d-i_q, modified p-q and synchronous detection methods are investigated for determining the reference compensation currents of shunt APF with respect to balanced, unbalanced and distorted source voltage conditions. The simulation is done on a three-phase system with a diode rectifier. Simulation results are used for comparison.

I. INTRODUCTION

The increased severity of harmonic pollution in power networks with the development of power semiconductors and power-electronics application techniques has attracted the attention to develop dynamic and adjustable solutions to the power quality problems. Control of these harmonic perturbations by passive filters can generate additional resonance, which could result in destruction of these filters. This has lead to development of active filters. Shunt active filters have been recognized as a good solution to current harmonic and reactive power compensation of non-linear loads. Figure 1 shows a typical system configuration of a three-phase three-wire, shunt APF with a voltage source inverter. The basic principle of a shunt active power filter is that it generates a current equal and opposite in polarity to the harmonic current drawn by the load and injects it to the point of common coupling, thereby forcing the source current to be pure sinusoidal.

One of the peculiar features of a shunt APF is that it does not require energy storage units in other words; it does not consume any active power absorbed from the source. To accomplish this function, it requires an effective compensation strategy. So far, there are many approaches to determine the APF compensation currents. In this work four of them defined in the time domain are compared; the instantaneous reactive power theory and its modified version, the instantaneous active and reactive current method, the synchronous detection method. Except for the last, all methods are based on reference frame transformation. The APF performance for the investigated methods is evaluated by simulation under balanced, unbalanced and distorted mains voltage conditions.

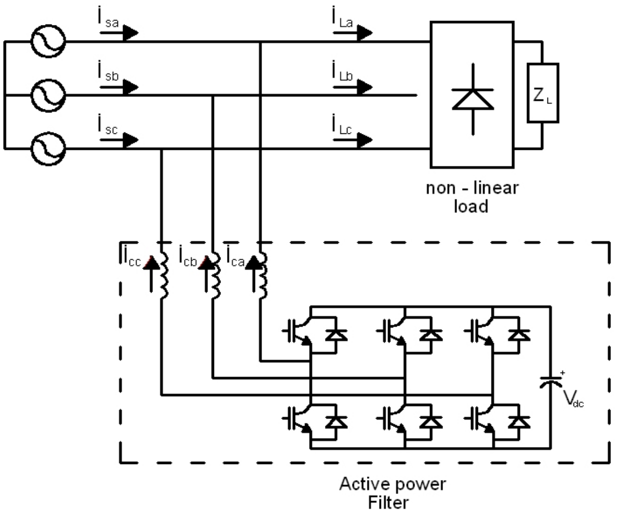


Figure 1. System diagram of a VSI-SAPF

II. P-Q THEORY

The instantaneous p-q method is one of the first compensation schemes develop by Akagi [1]. According to this theory active filter currents are obtained from the instantaneous active and reactive powers of the nonlinear load. This is achieved by previous calculation of the mains voltages and the nonlinear load currents in a stationary reference frame, i.e., in αβ components by (1) and (2) which is named as the Clarke transformation. For simplicity, a null value for zero sequence voltage and zero sequence current are considered. In this case v_α, v_β, i_α, i_β components are given as:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

In a-b-c coordinates; the a, b, c axes are fixed on the same plane parting from each other by 2π/3. In α-β coordinates, the α and β axes are the orthogonal coordinates.

The conventional instantaneous real power in three-phase circuit is defined by [1] as the summation of the products of voltages and current in the same axes.

$$p = v_a i_a + v_b i_b + v_c i_c = v_\alpha i_\alpha + v_\beta i_\beta \tag{3}$$

For the instantaneous reactive power the authors [1] introduced the instantaneous imaginary power space vector defined by as the summation of the products of voltage in one axis and the current not in the same axes but in perpendicular axes.

$$q = v_\alpha \times i_\beta + v_\beta \times i_\alpha \tag{4}$$

In the nonlinear load case both powers are decomposed into oscillatory (denoted by ~) and average (DC) component (denoted by -). The DC component represents the fundamental power, whereas the oscillating component is related with the harmonic power.

The instantaneous real power p and the instantaneous imaginary power q consumed by the nonlinear load are written in matrix form as follows

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} + \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{5}$$

To obtain a sinusoidal current with unity power factor, the oscillating term of p and all terms of q have to be removed. When such compensation is done, the filtering algorithm introduces some harmonics that are not present in the load current [2]. To prevent this phenomenon, the gains of the high-pass filters (HPF) for eliminating the average component of real and reactive power should be the same, so the powers to be compensated chosen as:

$$p_C = -\tilde{p} \quad , \quad q_C = -\tilde{q} \tag{6}$$

The compensation currents in α-β quantities then is

$$\begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} = \frac{1}{{v_\alpha}^2 + {v_\beta}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -\tilde{q} \end{bmatrix} \tag{7}$$

By performing the inverse transformation, the three-phase compensation is obtained by (8).

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}^T \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \tag{8}$$

The Matlab/Simulink simulation diagram of p-q theory is given in Figure 2.

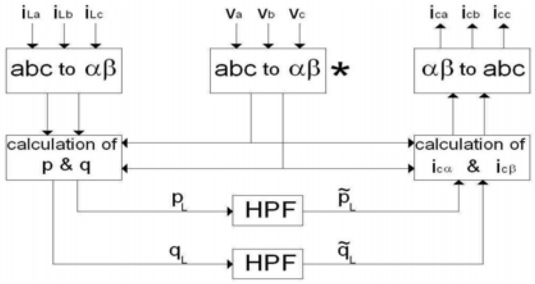


Figure 2. Block diagram of the instantaneous reactive power theory

III. Id-Iq METHOD

The i_d-i_q method is based on a synchronous rotating frame derived from the mains voltages without the use of a phase-locked loop (PLL) [3]. In this theory, active filter currents are obtained from the instantaneous active and reactive current components (i_{Ld} and i_{Lq}) of the nonlinear load in a two-step procedure. In the first step, the load current in the a-b-c reference frame is transformed to the α-β reference frame according to (2). In the second step these stationary reference frame quantities are then transformed into synchronous reference frame quantities based on the Park transformation by (10).

The relationship of the real and imaginary components of the current space vector in the original stationary two-axis reference frame and the new rotating reference frame is shown in Figure 3. In fact the α-β transformation is the subset of d-q transformation.

A rotating coordinate system can be defined to enable the vector representation to become a constant without any time-variation. Thus, a d-q coordinate system has been defined such that the d and q axes rotate at the angular frequency ω in the α-β plane. A balanced three-phase vector representation in this rotating d-q coordinate system will now be constant over all time and the angle θ is a uniformly increasing function of of time. This transformation angle is sensitive to unbalanced and distorted main voltage conditions, so its change with respect to time may not be constant over a mains period.

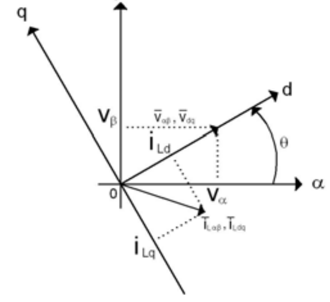


Figure 3. Space vectors representation in the stationary and synchronous frames

From the Figure 3, the direct and quadrature current components can be written as:

$$i_{Ldq} = i_{Ld} + j i_{Lq} \tag{9}$$

which may also be written in matrix form as:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{10}$$

, where $\theta = \tan^{-1} \frac{v_\beta}{v_\alpha}$

The real component of the current space vector in this new reference frame is the direct axis component (id) while the imaginary component is called the quadrature axis component (iq).

With vector rotation (10), the direct voltage component and the quadrature voltage component are:

$$\left|\bar{v}_{dq}\right| = \sqrt{{v_\alpha}^2 + {v_\beta}^2} \quad , \quad v_q = 0 \tag{11}$$

By using the simple geometry, the equation (10) is written in terms of the stationary reference frame load voltage vectors as:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{1}{\sqrt{{v_\alpha}^2 + {v_\beta}^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{12}$$

The Matlab simulation diagram of this theory is given in Figure 4. In the nonlinear load case the instantaneous active and reactive load currents can also be decomposed into oscillatory and average terms. Since the d and q axes rotate at the angular frequency ω (=2*π*$f_{fundamental}$) in the α-β plane; the first harmonic positive sequence current is transformed to dc quantity, and other current components constitute the oscillatory parts. After removal of the DC-component of i_{Ldq} by using high-pass filters, the compensation current is obtained

$$\begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{{v_\alpha}^2 + {v_\beta}^2}} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{i}_{Ld} \\ -\tilde{i}_{Lq} \end{bmatrix} \tag{13}$$

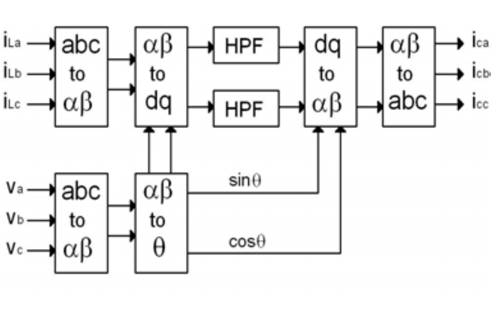


Figure 4. Block diagram of the instantaneous active & reactive current method

Compensation powers derived from the p-q method are the parts other than the average power; from the id-iq method include the load current terms other than the average ones. If the reference frame is chosen as v_q is equal to zero, (look at Figure 3), the nonlinear load powers can be calculated in d-q reference frame as:

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = v_d \begin{bmatrix} i_{Ld} \\ -i_{Lq} \end{bmatrix} = \begin{bmatrix} \bar{p}_L + \tilde{p}_L \\ \bar{q}_L + \tilde{q}_L \end{bmatrix} \tag{14}$$

Under balanced and sinusoidal mains voltages ($v_d = \bar{v}_d$), both methods have the same performance.

$$\begin{bmatrix} p_{Cpq} \\ q_{Cpq} \end{bmatrix} = \begin{bmatrix} p_{Cdq} \\ q_{Cdq} \end{bmatrix} = -\bar{v}_d \cdot \begin{bmatrix} \tilde{i}_{Ld} \\ -\tilde{i}_{Lq} \end{bmatrix} \tag{15}$$

For unbalanced and nonsinusoidal mains voltages, the oscillatory part of the mains voltages is considered. The compensation powers from the p-q theory and the id-iq method can be expressed by (16) and (17) respectively.

$$\begin{bmatrix} p_{Cpq} \\ q_{Cpq} \end{bmatrix} = -\bar{v}_d \begin{bmatrix} \tilde{i}_{Ld} \\ -\tilde{i}_{iq} \end{bmatrix} - \tilde{v}_d \left(\begin{bmatrix} \bar{i}_{Ld} \\ -\bar{i}_{Lq} \end{bmatrix} + \begin{bmatrix} \tilde{i}_{Ld} \\ -\tilde{i}_{Lq} \end{bmatrix} \right) \tag{16}$$

$$\begin{bmatrix} p_{cdq} \\ q_{Cdq} \end{bmatrix} = -\left(\bar{v}_d + \tilde{v}_d\right) \begin{bmatrix} \tilde{i}_{Ld} \\ -\tilde{i}_{Lq} \end{bmatrix} \tag{17}$$

By comparing (16) and (17), it is seen that there exists one more term calculated by the p-q theory resulting in additional power components under unbalanced and nonsinusoidal mains voltages.

IV. MODIFIED P-Q THEORY

As can be understood from the previous part and later from the simulation results, the p-q theory is not effective under the distorted and unbalanced mains voltage conditions. Watanabe, Aredes, and Akagi also have a paper [2] related with this problem. Akagi's original algorithm compensates the load current to guarantee constant instantaneous real power drained from the network. Therefore, under distorted and unbalanced mains voltage conditions positive-sequence voltage detector [4] is needed to achieve the sinusoidal compensated current. The positive-sequence voltage detector, the dual of the p-q theory, is used for the voltage compensation. The important part of it is the phase-locked-loop (PLL) circuit tracking continuously the fundamental frequency of the voltage. The phase angle and frequency must be accurately determined by the detector because the APF must produce fundamental positive sequence currents orthogonal to the fundamental positive sequence voltage to prevent generating active power.

The block diagram of it is the same as the p-q method except the rectangle indicated by the star symbol is changed with the positive sequence detector in Figure 5.

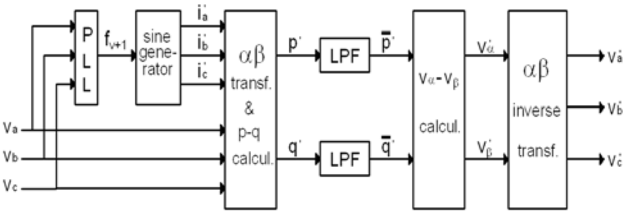


Figure 5. Block diagram of the positive sequence voltage detector

V. SYNCHRONOUS DETECTION METHOD

The idea of synchronous detection was originally applied to radio signals in communication systems [5], but recently it has been extended to three-phase power systems. For the compensation current calculation, the equal current approach of synchronous detection method is investigated [6]. Assume that the source peak phase currents after the compensation are equal and are given by:

$$I_{sma} = I_{smb} = I_{smc} \tag{18}$$

Then the currents can be written in terms of the average power and maximum voltage in each phase:

$$I_{smk} = 2P_k / V_{mk} \qquad \text{k: a, b, c} \tag{19}$$

By using the simple mathematics;

$$i_{sk}(t) = \frac{2(P_a + P_b + P_c)}{(V_{ma} + V_{mb} + V_{mc}).V_{mk}} \cdot v_k(t) \tag{20}$$

Then the reference compensation current of the APF become as:

$$i_{ck} = i_{Lk} - i_{sk} \tag{21}$$

A simulation diagram of the equal current synchronous detection method for phase ‘b’ is shown in Figure 6. The other two phases are exactly the same.

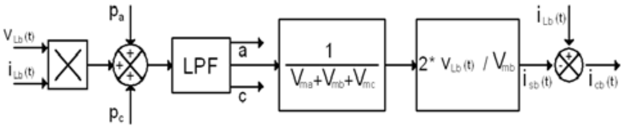


Figure 6. Block diagram of the equal current synchronous detection method

VI. SIMULATION RESULTS

The purpose of the simulation is to show the effectiveness of p-q, i_d - i_q, modified p-q, and synchronous detection methods for maintaining sinusoidal source currents when the source supplying a nonlinear load.

In simulation, a butter-worth type of filter was chosen since its magnitude response is maximally flat in the pass-band and is monotonic in both pass-band and stop-bands. To minimize the influence of the phase responses of the high-pass filter, an alternative high-pass filter is used by means of a low-pass filter [7] as shown in Figure 7.

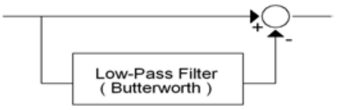


Figure 7. Schematic diagram of high-pass filter

For all of the methods, the choice of the cut-off frequency and the order of the filters have a direct effect on the performance of the detection algorithm.

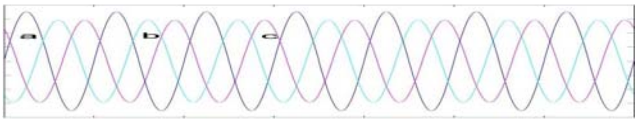
In this work, the performances of the four calculation methods are evaluated and no dynamic voltage source inverter is considered.

Simulation waveforms obtained with Matlab-Simulink/Power System Blockset related to the previously mentioned four methods under unbalanced and distorted mains voltage conditions are presented in Figure 8 and Figure 9. The results obtained from the balanced source case are not shown due to the lack of space but all of the methods work well in this situation.

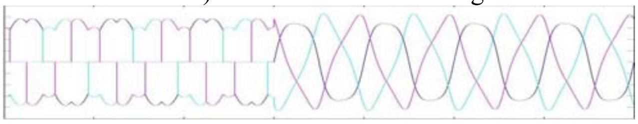
The first case is with unbalanced source voltages, which are:

$$v_a(t) = 311 \sin wt + 41 \sin wt\,,$$
$$v_b(t) = 311 \sin(wt - 2\pi/3) + 41 \sin(wt + 2\pi/3)\,,$$
$$v_c(t) = 311 \sin(wt + 2\pi/3) + 41 \sin(wt - 2\pi/3)\,. \tag{22}$$

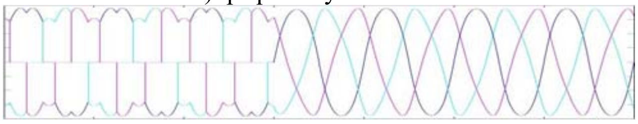
CASE I: UNBALANCED MAINS VOLTAGES



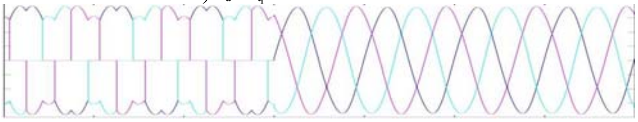
a) unbalanced mains voltages



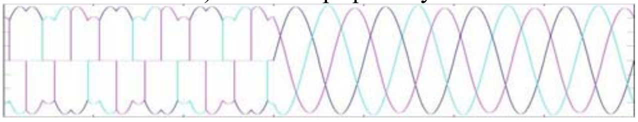
b) p-q theory



c) i_d - i_q method



d) modified p-q theory



e) synchronous detection method

Figure 8. Performance of the methods under unbalanced mains voltages

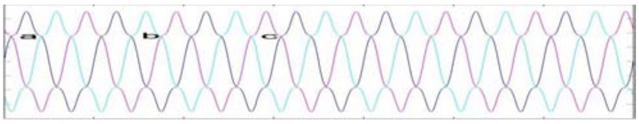
The second case is with distorted source voltages which are:

$$v_a(t) = 311\sin wt + 41\sin 5wt$$

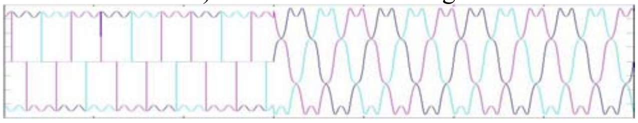
$$v_b(t) = 311\sin(wt - 2\pi/3) + 41\sin(5wt - 2\pi/3),$$

$$v_c(t) = 311\sin(wt + 2\pi/3) + 41\sin(5wt + 2\pi/3). \qquad (23)$$

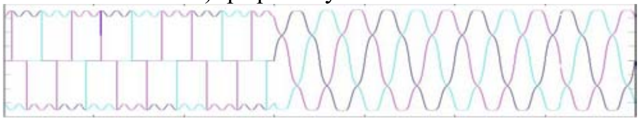
CASE II: DISTORTED MAINS VOLTAGES



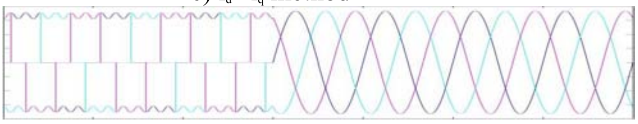
a) distorted mains voltages



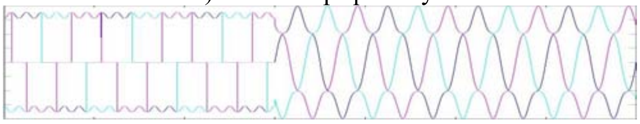
b) p-q theory



c) i_d - i_q method



d) modified p-q theory



e) synchronous detection method

Figure 9. Performance of the methods under distorted mains voltages

Simulations are performed throughout 140ms and at 60ms some kind of switching action was performed for the source currents. Except for the first waveforms in Figure 8 and Figure 9, the first parts of the waveforms of both refer to the source currents before compensation, and the second parts refer to the source currents are after compensation with the indicated methods.

		p-q	id-iq	modified p-q	synchron. detection
	I_{source} in %THD	$I_{compensated}$ in % THD	$I_{compensated}$ in % THD	$I_{compensated}$ in % THD	$I_{compensated}$ in % THD
Ideal condition	30.7	0	0	0	0
Unbalanced Main voltages	24.2	13.4	6.2	2,3	3.9
Distorted Main voltages	23,4	13.3	9.2	0	12.9

Table 1. Comparison of percentage total harmonic distortion (THD)

VII. CONCLUSION

The paper presents a comparative study of four compensation methods for three phase shunt active filters under balanced, unbalanced and distorted mains voltage conditions. In the simulation study, it is shown that the p-q method has poorer performance than the i_d-i_q method under unbalanced and distorted mains voltage conditions. However the solution based on using a PLL circuit for better performance of the p-q theory works well under unbalanced and distorted mains voltage but it has the disadvantage of its fairly complex algorithm and requirement of a PLL circuit. The synchronous detection method's performance is poor in respect to the voltage distortion but good at unbalanced condition and demands less calculations due to the needlessness of reference frame transformation. Another disadvantage of this method is that it assumes equal currents in every phase which meaning balanced load conditions.

Although the historically important p-q theory is limited to balanced voltage conditions, the modified version of it is the most effective method for all voltage conditions.

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