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Performance Improvement of Active Power Filters based on *P-Q* and *D-Q* Control Methods under Non-Ideal Supply Voltage Conditions

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Abstract

In this paper, we investigate the effect of unbalanced and distorted supply voltages on the performance of active power filters that are based on the well-known *p-q* and *d-q* control methods. Our analysis shows that the harmonic suppression performance of the *p-q* and *d-q* control methods deteriorates when non-ideal sources are used. We propose the use of a self-tuning filter (*STF*) with the *p-q* theory or *d-q* method as a way of alleviating the detrimental effects of non-ideal supply voltages. Simulation results show that the proposed method can improve the performance of active power filters under non-ideal voltage conditions.

Introduction

Harmonic distortion has become a major power quality problem in recent years. The main reason is the increasing use of nonlinear loads such as adjustable speed drives, power supplies and soft-starters. These nonlinear loads draw non sinusoidal currents from the utility and cause a type of voltage and current distortion, namely harmonics [1]. These harmonics cause various problems in power systems and in consumer products, such as equipment overheating, blown capacitors, transformer overheating, excessive neutral currents, low power factor, etc. Mechanically switched capacitors (MSCs) and passive filters (PFs) are usually employed to reduce harmonics. However, the use of passive filters has many disadvantages as noted in [2, 3]. On the other hand, the use of an active power filter (APF) to mitigate harmonic problems has drawn much attention since the 1970s [4], because they have excellent compensation characteristics. They are developed to suppress the harmonic currents and compensate for reactive power, simultaneously. APFs are operated as a current source in parallel with non-linear loads. The power converter of an active power filter is controlled to generate a compensation current that is equal to the harmonic and reactive currents. In order to determine the harmonic and reactive components of the load current, several techniques are introduced in the literature. These strategies applied to active power filters play a very important role in the improvement of the performance and stability of an APF.

The control strategy affects the cost, steady state, and dynamic performances of the filter. Techniques for reference current generation may be put into two categories: time-domain and frequency-domain. Number of time-domain methods have been proposed, one of which was proposed by Akagi [4], called instantaneous active and reactive power theory (or *p-q*). However, this method only works correctly in the case when ideal source are used. Another popular method is the *d-q* reference frame method [5, 6, 7, 8 and 9]. The performance of the *d-q* method is dependent on the type of Phase-Locked-Loop (PLL) algorithm used.

In this paper, we first present a performance analysis of *p-q* and *d-q*-based active power filters under ideal and non-ideal supply voltage conditions. We then propose the use of a self-tuning filter (*STF*) with the *p-q* and *d-q* methods in order to increase the harmonic suppression efficiency of active power filters in the case of non-ideal supply voltages.

Instantaneous Active and Reactive Power *(p-q)* Theory

This theory uses a Clarke transformation to voltages and currents from the three-phase 'abc' to a two-phase system 'αβ0', which defines instantaneous powers. The three phase voltage and current are converted into αβ0 using, respectively.

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = [T].\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = [T].\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

Where T is the transformation matrix as

$$\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2)$$

The active and reactive instantaneous power 'p' and 'q' are given by:

$$p = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \quad (3)$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha \quad (4)$$

These relations are given in matrix form in stationary reference by:

$$\begin{bmatrix} p \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \quad (5)$$

In general the case, each of the active and reactive powers are composed of continuous and alternating terms. The continuous term corresponds to the fundamentals of current and voltage. The alternating part represents power related to the sum of the harmonic components of current and voltage. A low-pass filter with feed-forward structure can be used to separate continuous and alternating terms of active and reactive instantaneous power. The current reference signal is obtained by:

$$\begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} = \frac{1}{v^2_{s\alpha}+v^2_{s\beta}} \begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix} \begin{bmatrix} \tilde{p}-p_{dC} \\ \tilde{q} \end{bmatrix} \quad (6)$$

where, the term P_{dc} is the amount of active power that must be delivered to the active filter from the source to keep the dc source voltage (U_{dc})at its preset value. It is obtained from the regulation loop of dc voltage.

The three phase reference current of the active power filter is to obtained by applying the Inverse Clarck Transform to the stationary reference currents, i.e.,

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{f\alpha} \\ i^*_{f\beta} \end{bmatrix} \quad (7)$$

The *D-Q* Method

The *d-q* method is based on the park transformation. The load currents are transformed into the component in the *d-q* coordinate system in order to separate the fundamental and harmonics components of instantaneous currents i_d, i_q, and i_0. The synchronous transform is given by,

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

where, the angle θ is the angular position of the synchronous reference. It is a linear function of the angular pulsation of the source voltages. This angular position can be determined by the aid of a PLL. After the transformation of load currents into the synchronous reference, a low-pass filter with feed-forward effect is used to separate the fundamental and harmonic currents. The reference currents are then transformed to the three phase reference using the inverse synchronous transform as given by,

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta-\frac{2\pi}{3}) & -\sin(\theta-\frac{2\pi}{3}) \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} \tilde{i}_{fd} \\ \tilde{i}_{fq} \end{bmatrix} \quad (9)$$

Proposed Technique

The self tuning filter (*STF*) was proposed by Hong-Song in [10]. The equivalent transfer function is obtained from the integration of the synchronous reference. The transfer function is: of the integration in the synchronous reference frame expressed by the following equation:

$$H(S) = \frac{V_{xy}(S)}{U_{xy}(S)} = \frac{S+j\omega}{S^2+\omega^2} \quad (10)$$

Where

$$V_{xy}(t) = e^{j\omega t}\int e^{-j\omega t}U_{xy}(t)dt \quad (11)$$

It was demonstrated that the input $U_{xy}(S)$ and output $V_{xy}(S)$ have the same phase in addition to the integral effect on the input magnitude. It has also been observed that magnitude and phase responses of this transfer function is similar to those of a general band-pass filter. A constant *k* may be incorporate in to this transfer function such that |H(s)| = 0 dB|, thus

$$H(S) = \frac{V_{xy}(S)}{U_{xy}(S)} = k\,\frac{(S+k)+j\omega}{(S+k)^2+\omega^2} \quad (12)$$

A block diagram depiction of this transfer function is shown in Fig.1.

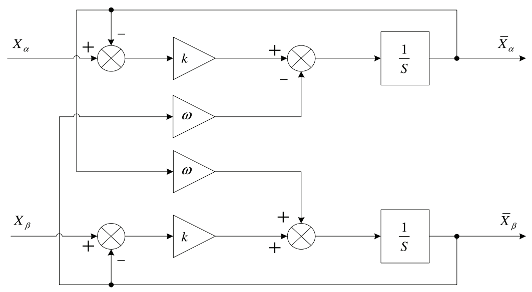

Fig.1. Principle scheme of the *STF*

In the stationary reference, the fundamental components are given by:

$$\overline{X}_\alpha(S) = \frac{k}{S}\left[X_a(S) - \overline{X}_\alpha(S)\right] - \frac{\omega}{S}\overline{X}_\beta(S) \quad (13)$$

$$\overline{X}_\beta(S) = \frac{k}{S}\left[X_\beta(S) - \overline{X}_\beta(S)\right] - \frac{\omega}{S}\overline{X}_\alpha(S) \quad (14)$$

The *STF* can be used as a simple but effective method of suppressing the effects of a non-ideal source on the performance of the APF. In the case of a distorted and/or asymmetric source voltage, the *STF* can be used to extract a three-phase sinusoidal and symmetrical voltage from distorted and asymmetrical source voltage; the output of the *STF* is then used in the calculation of the active and reactive instantaneous power, or provided to the PLL circuit to give an accurate angular position of the three phase source voltage. A block diagram representation of the *p-q* and *d-q*-based active power filter using the *STF* are shown in Figs. 2 and 3.The *STF* is used to extract the fundamental components of load current from the input. The harmonic components are obtained by subtracting the output from the input.

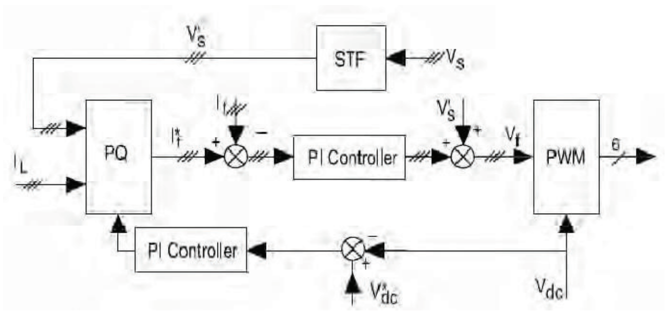

Fig.2. Implementation of *STF* based *p-q* method in APF

We can use this filter to extract the fundamental components of load current, and then subtracts the output from the input to achieve the harmonic components.

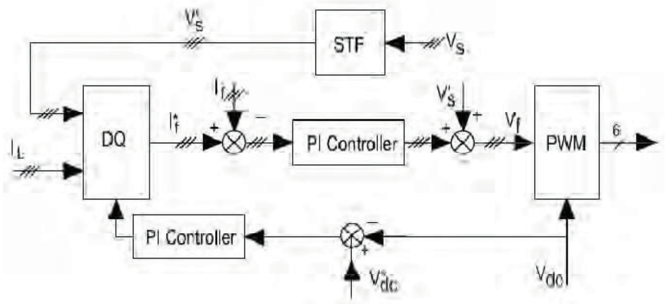

Fig.3. Implementation of *STF* based *d-q* method in APF

Simulation Results

To verify the performance of the proposed technique, the APF was simulated using the MATLAB-SIMULINK software package. A block diagram representation of the simulated APF system, including the non-linear load on a three-phase supply, is shown in Fig. 4. The important parameters of the APF system are given in Table I. The nonlinear load used in our simulations is a three phase uncontrolled rectifier. The rectifiers are feeding R-L type load circuits. The three-phase load current is shown in Fig. 5.

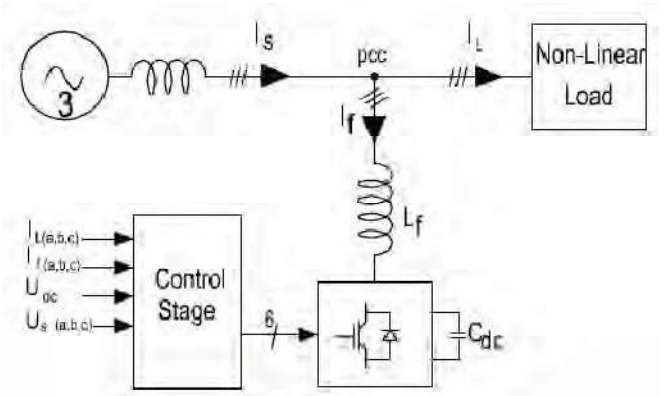

Fig.4.Block diagram of simulated APF

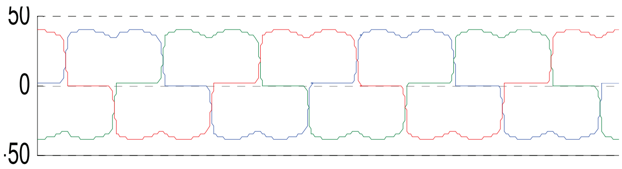

Fig.5 Three phase load current (THD_i= %28.14)

The total current harmonic distortion (THD_i) for the simulated source current was observed in three cases and under two different conditions:

1- Balanced and undistorted supply voltage (ideal) condition
2- Unbalanced and distorted supply voltage (non-ideal) condition

Table 1: Parameters of the Simulated System

Symbol	Quantity	Value
V_S	Source Voltage	240 V
f	Source Frequency	50 Hz
R_s	Source Resistance	3 mΩ
L_s	Source Impedance	2.6 µH
R_{ac}	AC Resistance	10 mΩ
L_{ac}	AC Inductance	0.3 mH
R_{Load}	Non-Linear Load Resistance	15 Ω
L_{Load}	Non-Linear Load Inductance	2 mH
R_f	Filter Resistance	20 mΩ
L_f	Filter Inductor	3 mH
C_{dc}	APF dc Capacitor	5000 µf
V_{dc}	dc- Link Voltage	900 V
f_s	Switching Frequency	14 kHz

Case 1: *Behavior of Classical p-q and d-q method under balanced and undistorted supply voltage conditions.*

The voltages for the three phase *a*, *b* and *c* of the source are given by:

$$\left.\begin{aligned} V_{sa}(t) &= \sqrt{2}V_{sa}\sin(wt) \\ V_{sb}(t) &= \sqrt{2}V_{sb}\sin(wt-\frac{2\Pi}{3}) \\ V_{sc}(t) &= \sqrt{2}V_{sc}\sin(wt+\frac{2\Pi}{3}) \end{aligned}\right\} \quad (15)$$

First, classical *p-q* and *d-q* methods were applied to the APF for the generation of the reference current.

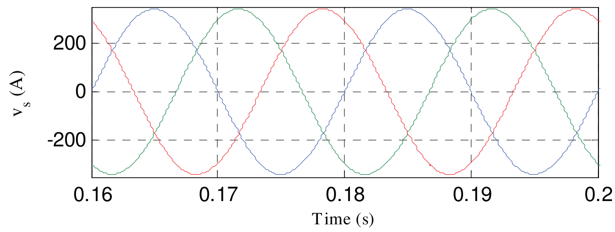

Fig.6 Three phase balanced and undistorted (ideal) source voltage

Where is the a,b,c are the three phase voltages of the source. First, classical *p-q* and *d-q* methods were applied to the Active Power filter for the generation of the reference current.

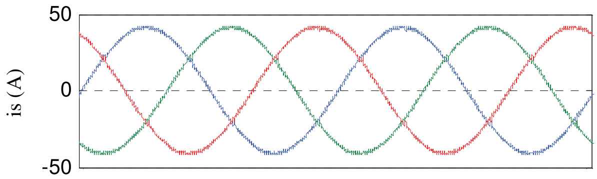

Fig.7. Supply currents with *p-q* method under case 1. (THD_i=2.1%)

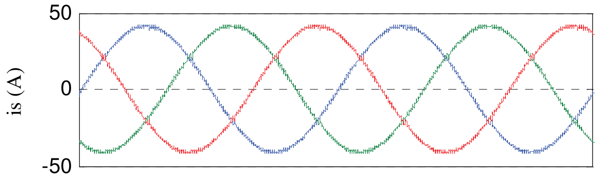

Fig.8. Supply currents with *d-q* method under case 1. (THD_i=2.07)

As seen in Figs.7 and 8, under symmetric and undistorted (ideal) voltage conditions, Active Power Filter compensation works fine with *p-q* and *d-q* methods. The simulation results of the harmonic distortion analysis shows that the THD of the source current (THD_i) are reduced from 28.14% to 2.10% with *p-q* theory as seen Fig. 7. In addition to this, Fig. 8 shows that the THD_i also reduced from 28.14% to 2.07% due to *d-q* method. And it's clear that, all they are meeting with the international standards.

Case 2: *Behavior of Classical p-q and d-q method under unbalanced and distorted supply voltage condition*

In this case, unbalanced and distorted voltage applied to the non-linear load. As a consequence, the reference waveform is not a perfect sine wave, as can be seen in Fig. 9

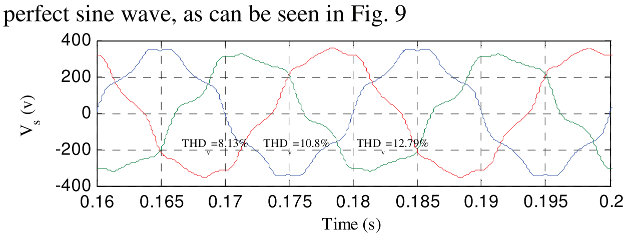

Fig.9. Distorted and unbalanced source voltages for case 2.

Mathematical expressions for the supply voltages are:

$$\left.\begin{aligned} V_{sa}(t) &= \sum_{n=1}^{n} \sqrt{2}V_{sa}\sin(nwt+\phi) \\ V_{sb}(t) &= \sum_{n=1}^{n} \sqrt{2}V_{sb}\sin(nwt+\phi) \\ V_{sc}(t) &= \sum_{n=1}^{n} \sqrt{2}V_{sc}\sin(nwt+\phi) \end{aligned}\right\} \quad (16)$$

The programmed supply voltages are given in (17). For the generation of the reference current the same methods are used as in case 1. Also, as in case 1, results from using *p-q* theory and the *d-q* method were observed. The harmonic analysis showed that the THD of the source currents decreased from 28.14% to around 9%. However, in the case of an ideal source this figure reduced to 2.10%.. It's clear that the unbalanced and distorted supply voltage affects the behavior of the APF while using *p-q* theory. However, the *d-q* method gives better performance. The simulations show that the THD of the source current is around 2.40% when the *d-q* method is applied to the APF under non-ideal source voltages. Conversely, a THD_i of 2.07 % was obtained in case 1.It's clear that both methods are adversely affected by the imperfect supply voltage. So the *d-q* method attains a better performance than *p-q* theory. The improvement in performance is primarily due to the PLL algorithm used.

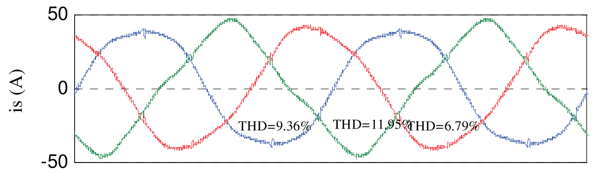

Fig.10. Supply currents with *p-q* method under case 2.

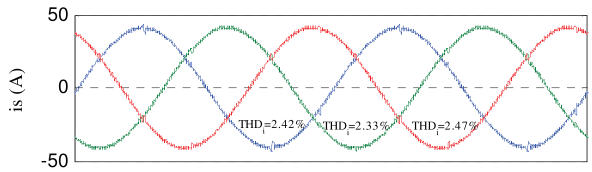

Fig.11. Supply currents with *d-q* method under case 2.

Case 3: *STF based p-q and STF based d-q proposed method under unbalanced and distorted supply voltage condition*

The ability of the APF in suppressing current harmonics was hindered by the non-ideal source in case 2. To solve this problem a self tuning filter (*STF*) is adapted to both *p-q* theory and the *d-q* method. It is important to note that the same APF topology and non-linear load was used in all cases. As with case 2, the source voltage was programmed in accordance to (17).

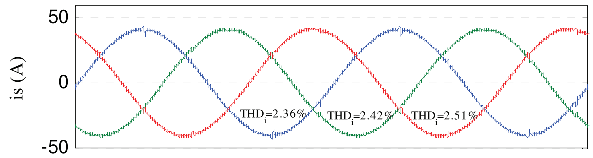

Fig.12. Supply currents with *STF* based *p-q* method under case 3.

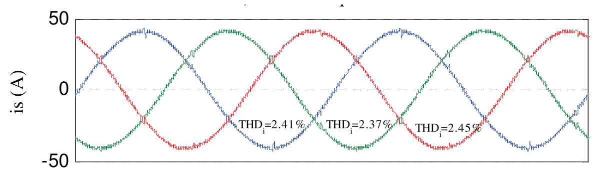

Fig.13. Supply currents with *STF* based *d-q* method under case 3.

$$\left.\begin{aligned} V_a &= 340\sin(wt)+30\sin(5wt)+20\sin(7wt)+7\sin(11wt) \\ V_b &= 320\sin(wt-\frac{2\Pi}{3})+35\sin(5wt-\frac{2\Pi}{3})+9\sin(7wt-\frac{2\Pi}{3})+10\sin(11wt-\frac{2\Pi}{3}) \\ V_c &= 350\sin(wt+\frac{2\Pi}{3})+19\sin(5wt+\frac{2\Pi}{3})+15\sin(7wt+\frac{2\Pi}{3})+13\sin(11wt+\frac{2\Pi}{3}) \end{aligned}\right\} \quad (17)$$

Table II. APF Performance Operation Scenarios Cooperation with Control Methods

Methods	*p-q* Current THD of Phases (%)			*d-q* Current THD of Phases (%)			*p-q + STF* Current THD of Phases (%)			*d-q + STF* Current THD of Phases (%)		
	a	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**	**a**	**b**	**c**
Ideal	2.10	2.10	2.10	2.07	2.07	2.07	2.36	2.42	2.51	2.36	2.42	2.51
Non-Ideal	9.36	11.33	6.79	2.42	2.33	2.47	2.41	2.37	2.45	2.41	2.37	2.45

As seen in Figs.12 and 13, non-ideal voltage conditions, Active Power Filter compensation works fine with *STF*-based *p-q* and *STF*-based *d-q* methods. The simulation results of the harmonic distortion analysis shows that the THD of the source current (THD_i) are reduced from 28.14% to around 2.40 % with both *STF*-based *d-q* method and *STF*-based *p-q* theory. The simulation results show that the use of a self-tuning filter (STF) with the p-q theory or d-q method can improve the performance of active power filters under non-ideal voltage conditions.

Conclusion

In this paper, we consider the effect of an unbalanced and distorted supply on the performance of the well-known *p-q* theory and *d-q* methods for active power filters. The ability of these methods to combat current harmonics deteriorates significantly when a non-ideal supply voltage is used. A modification to the *p-q* and *d-q* methods is then proposed for alleviating the effects of an imperfect supply. This involves the use of a self-tuning filter (*STF*) with *p-q* theory and the *d-q* method. We show that the total harmonic distortion of source current (THD_i) can be reduced by up to around 2.30 % with the use of a *STF* under non-ideal voltage conditions. In addition, our comparative results show that an *STF*-based *d-q* method performs better than an *STF*-based *p-q* theory.

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