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Performance Improvement of Active Power Filter under Distorted and Unbalanced Grid Voltage Conditions

S. Biricik[1, 2], O. C. Ozerdem[1], S. Redif[2], M. I. O. Kmail[1]
[1]*Department of Electrical & Electronic Engineering, Near East University*
[2]*Department of Electrical & Electronic Engineering, European University of Lefke*
N. Cyprus
sbiricik@eul.edu.tr

***Abstract*—In the case of balanced and undistorted supply voltages, shunt APFs can achieve current harmonic cancellation and give unity power factors. However, this is not possible when grid voltage is non-sinusoidal and unbalanced. In this paper, we first show that the harmonic suppression performance of the well-known p-q theory deteriorates in non-ideal grid voltage conditions. A technique for alleviating the detrimental effects of a distorted and unbalanced grid voltage is proposed that uses a self-tuning filter with p-q theory. The proposed control technique gives an adequate compensating current reference even for non ideal voltage condition. The results of simulation study are presented to verify the effectiveness of the proposed control technique in this study.**

***Index Terms*—Active power filter, self-tuning filter, p-q theory, non-ideal grid voltages.**

I. 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, because they have excellent compensation characteristics. They are developed to suppress the harmonic currents and compensate for reactive power, simultaneously. 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], [5], called instantaneous active and reactive power theory (or p-q). Most APFs have been designed on the basis of p-q theory to calculate the desired compensation current. However, this method only works correctly in the case when three phase grid voltages are balanced and undistorted [6], [7]. Non-ideal grid voltage conditions are frequently encountered in industry. The distorted currents cause non-sinusoidal voltage drops and as a result the network voltages become distorted. The unbalanced voltages usually occur because of variations in the load – arising from differing phases of the load current due to, e.g., different network impedances [8].

In this paper, we propose the use of a self-tuning filter (STF) with the instantaneous reactive power theory in order to increase the harmonic suppression efficiency of active power filter in the case of non-ideal grid voltage condition.

II. ACTIVE POWER FILTER

In this study, we consider three-phase systems with variable nonlinear loads. The block diagram of a basic three-phase active power filter (APF) connected to a general non-linear load is shown in Fig. 1.

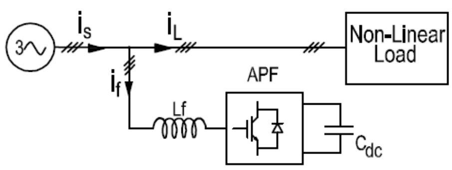

Fig. 1. Block diagram of the APF.

The main aim of the APF is to compensate for the harmonics and reactive power dynamically. The APF overcomes the drawbacks of passive filters by using the switching mode power converter to perform the harmonic current elimination. It is important to note that in a number

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of applications, the APF has been connected to the main distribution board of the system. In such a system, the harmonics would have detrimental effects on the internal system equipment, which cannot be prevented. A way of minimising the damage to equipment is to place the APF as close to the load as possible.

It is well known that the three-phase load current has a non-unity power factor. Therefore, the current drawn by the possibly reactive load with harmonics and is given by

$$I_L(t) = I_1(t) + I_h(t) + I_q(t), \tag{1}$$

where $I_L(t)$ is the load current, $I_1(t)$ is the fundamental current, $I_h(t)$ is the harmonic currents and $I_q(t)$ is the reactive current.

As is convention, APFs are operated as a current source that is parallel with the loads. The power converter of an APF is controlled to generate a compensation current, $I_f(t)$, which is equal to the harmonics and opposite phase, i.e.

$$I_f(t) = -\left(I_h(t) + I_q(t)\right). \tag{2}$$

This yields a sinusoidal source current given by

$$I_S = I_1 \sin(wt). \tag{3}$$

III. Instantaneous Active and Reactive Power (p-q) Theory

The basic idea is that the harmonic currents caused by nonlinear loads in the power system can be compensated with other nonlinear controlled loads. The p-q theory is based on a set of instantaneous powers defined in the time domain. The three-phase supply voltages (ua, ub, uc) and currents (i_a, i_b, i_c) are transformed using the Clarke (or α-β) transformation into a different coordinate system yielding instantaneous active and reactive power components. This transformation may be viewed as a projection of the three-phase quantities onto a stationary two-axis reference frame. The Clarke transformation for the voltage variables is given by:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}. \tag{4}$$

Similarly the transformation can also be applied for the current variables as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \tag{5}$$

The inverse voltage and current transformations are respectively:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 & 1 \\ \frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ \frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 & 1 \\ \frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ \frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}. \tag{7}$$

Then, the active and reactive instantaneous powers ‘p’ and ‘q’ are given by, respectively,

$$p = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{8}$$

and

$$q = v_\alpha i_\beta - v_\beta i_\alpha. \tag{9}$$

These relations may be expressed in matrix form by:

$$\begin{bmatrix} p \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}. \tag{10}$$

In the general case, each of the active and reactive powers are composed of continuous and alternating terms. The continuous term corresponds to the fundamentals of the 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:

$$\begin{bmatrix} i_{f\alpha}^* \\ i_{f\beta}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} - p_{dc} \\ \tilde{q} \end{bmatrix}, \tag{11}$$

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 link source voltage (U_{dc}) at its pre-set value. This U_{dc} value is obtained from the PI regulation loop of dc voltage. The three phase reference current of the active power filter can be obtained by applying the Inverse Clarke transform to the stationary reference currents, i.e.

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{f\alpha}^* \\ i_{f\beta}^* \end{bmatrix}. \tag{12}$$

However, this theory only works correctly in the case when three-phase grid voltages are balanced and undistorted. As may be gleaned from (11) distorted or un-balanced three-phase grid voltage will have an adverse effect on the final parameters, which will reduce the harmonic detection performance.

In the following subsection, we propose an elegant method of suppressing the effects of a non-ideal grid voltage.

IV. Self-Tuning Filter

The self-tuning filter (STF) was first used in order to estimate the phase angle of PWM converter outputs [9]. In [10], the transfer function is obtained from the integration of the synchronous reference. The transfer function is defined as

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = K\frac{s + j\omega}{s^2 + \omega^2}, \tag{13}$$

where

$$V_{xy}(t) = e^{j\omega t}\int e^{-j\omega t} U_{xy}(t)dt. \tag{14}$$

The STF has a magnitude and phase response that is similar to those of a general band-pass filter. Apart from the integral effect on the input magnitude, the STF does not alter the phase of the input, i.e. the input $U_{xy}(s)$ and output Vxy(s) have the same phase. Note that in order to have unit magnitude, i.e. |H(s)| = 0 dB, a constant k is incorporated in to (15), that is,

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = K\frac{(s+K) + j\omega}{(s+K)^2 + \omega^2}. \tag{15}$$

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

$$\bar{v}_\alpha(s) = \frac{k}{s}\left[v_a(s) - \bar{v}_\alpha(s)\right] - \frac{\omega}{s}\bar{v}_\beta(s), \tag{16}$$

$$\bar{v}_\beta(s) = \frac{k}{s}\left[v_\beta(s) - \bar{v}_\beta(s)\right] + \frac{\omega}{s}\bar{v}_\alpha(s). \tag{17}$$

The STF can be used as a simple but effective method of suppressing the effects of a non-ideal source, which allows for improved harmonic compensation by the APF.

Finally, the output of the STF is used as in (16) and (17). A block diagram representation of the p-q based APF using the STF is shown in Fig. 2.

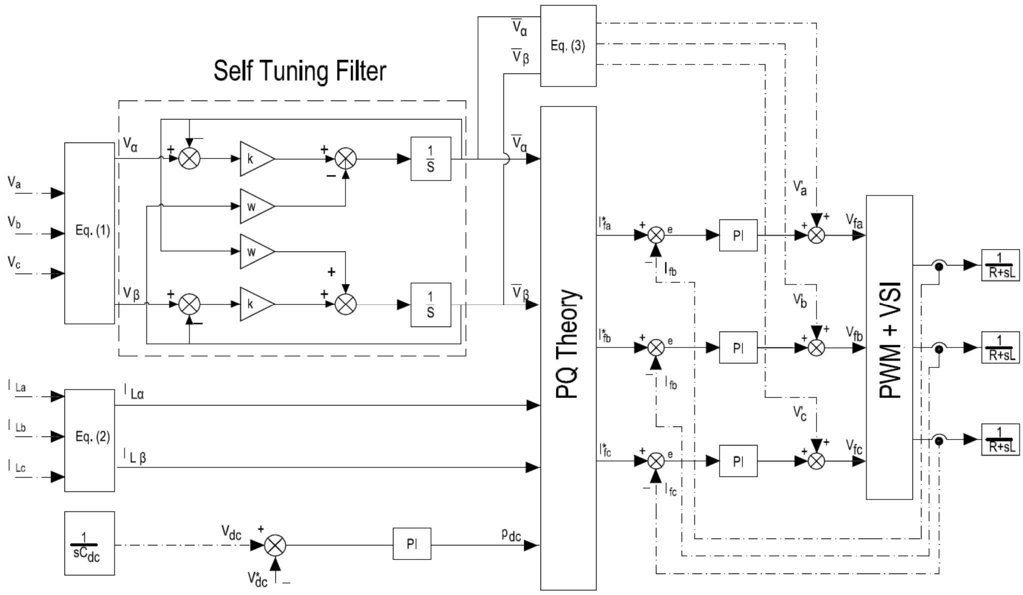

Fig. 2. The block scheme of the proposed control system.

V. Simulation Results

The control system and compensation by APF is simulated using MATLAB/Simulink and power system blockset environment to verify the performance of the proposed technique. Two variable RL type non-linear load groups (Load 1 & Load 2) are used to see dynamic performances of the APF. The system parameters used in these simulations are given inTable I.

TABLE I. PARAMETERS OF THE ANALYZED SYSTEM.

Symbol	Quantity	Value
v_S	Ideal Grid L-N RMS Voltage	240 V
f	Grid Frequency	50 Hz
R_s	Grid Resistance	3 mΩ
L_s & L_f	Grid & Filter Impedance	2.6 µH & 1.5 mH
$Load_1$	Non-Linear Load Res. and Ind.	10 Ω,30 mH
$Load_2$	Non-Linear Load Res. and Ind.	7 Ω,18 mH
C_{dc}	APF dc Capacitor	2200 µf
V_{dc}	dc- Link Voltage	900 V
K_p & K_i	Proportional & Integral Gain	0.0932 & 1.244
f_s	Switching Frequency	14 kHz

A. Case 1: Performance Analysis of p-q theory based APF under ideal voltage condition

In this section first, conventional p-q theory was applied to the APF under ideal grid voltage condition in order to generation of the reference filter current. The ideal grid voltages for the three phases (a, b and c of the phases) are purely sinusoidal as seen in Fig. 3.

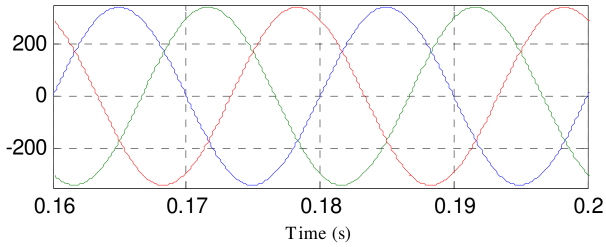

Fig. 3. Three phase balanced and undistorted (ideal) grid voltages.

The performance results pertaining to the system under case 1 is shown in Fig. 4.

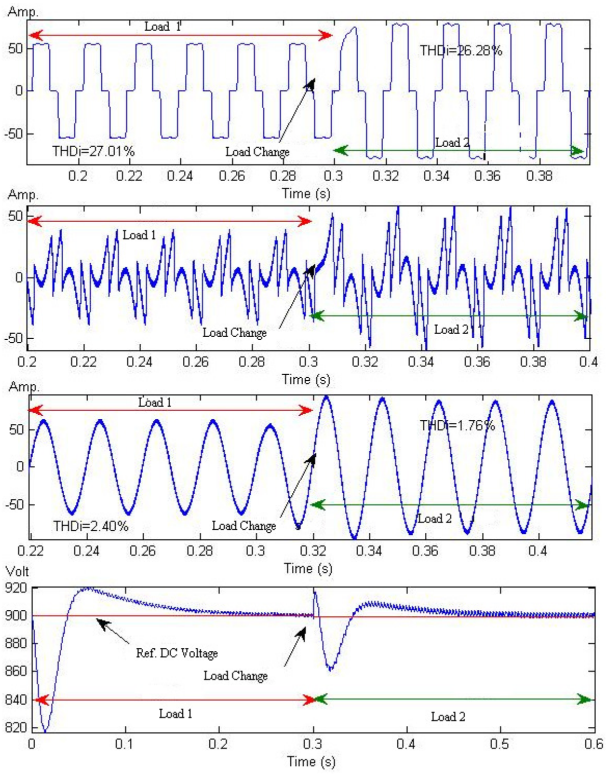

Fig. 4. Performance of the APF under ideal grid voltage and step-up load change. Top waveform: Load current of phase a. Compensating current of phase a. Grid current of phase a. Bottom waveform: DC link capacitor voltage.

Under this condition, the line current becomes sinusoidal and the capacitor-voltage behaviour is as expected. The simulation results of the harmonic distortion analysis show that the THD_i of the load 1 is reduced from 27.01 % to 2.40 % and load 2 is reduced from 26.28% to 1.76%.

B. Case 2: Performance Analysis of p-q theory based APF under non-ideal grid voltage condition

In this section, we evaluate the p-q theory based APF performance for the case where unbalanced and distorted voltages are applied to the loads. Here, the simulation that was performed for Case 1 is repeated for the non-ideal grid voltage scenario.

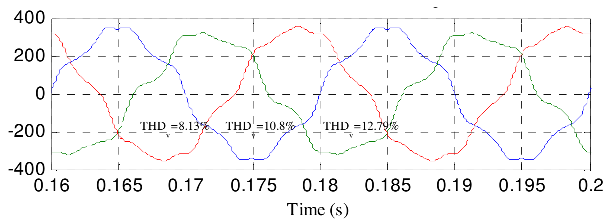

Fig. 5. Three phase unbalanced and distorted (non-ideal) grid voltages.

As seen in Fig. 5, the grid voltage waveforms are not pure sinusoidal. This grid voltage condition was programmed as given in (18).

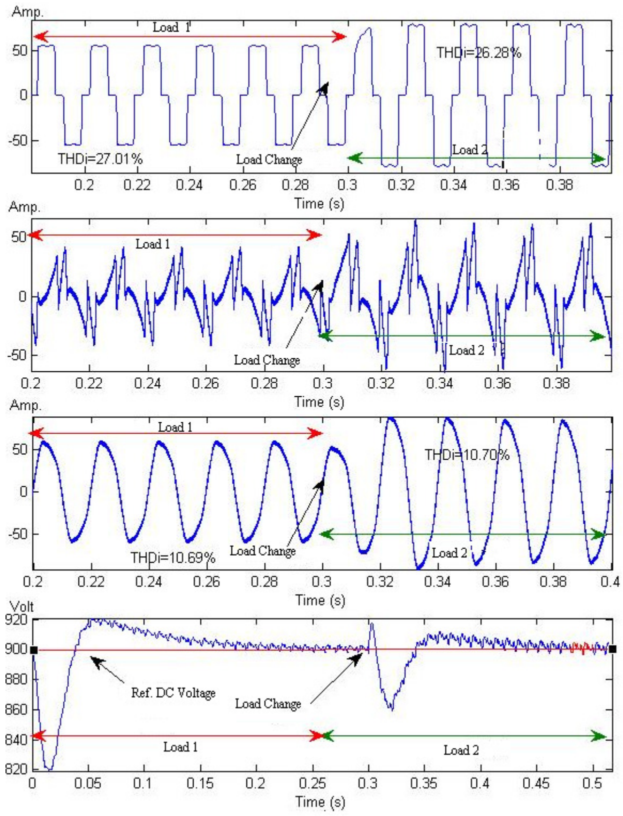

Fig. 6. Performance of the APF under non-ideal grid voltage and step-up load change. Top waveform: Load current of phase a. Compensating current of phase a. Grid current of phase a. Bottom waveform: DC link capacitor voltage.

As seen in Fig. 6, the presence of distortion in the grid voltage has a notably adverse effect on the performance of the system. The THD of the grid current is over 10%, compared to only 2.30 % obtained in Case 1. It is clear that, the performance and working characteristic of the APF under non-ideal grid voltage condition is reduced.

C. Case 3: Proposed method under unbalanced and distorted supply voltage condition

The harmonics suppression performance of the APF is limited because of the non-ideal grid voltage, as observed from the experiments in Case 2. In this subsection, we demonstrate the harmonic cancellation effectiveness of the proposed control system. The performance and working characteristic of the APF under non-ideal grid voltage condition is given in Fig. 7.

From the results given in Table 2, it is evident that the effects of the non-ideal source are lessened with the application of the proposed control system.

$$\begin{cases} v_{sa} = 340\sin(wt) + 30\sin(5wt) + 20\sin(7wt) + 7\sin(11wt), \\ v_{sb} = 320\sin(wt - \frac{2\Pi}{3}) + 35\sin(5wt - \frac{2\Pi}{3}) + 9\sin(7wt - \frac{2\Pi}{3}) + 10\sin(11wt - \frac{2\Pi}{3}), \\ v_{sc} = 350\sin(wt + \frac{2\Pi}{3}) + 19\sin(5wt + \frac{2\Pi}{3}) + 15\sin(7wt + \frac{2\Pi}{3}) + 13\sin(11wt + \frac{2\Pi}{3}), \end{cases} \quad (18)$$

TABLE II. SYSTEM ANALYSES UNDER IDEAL AND NON-IDEAL GRID VOLTAGE CONDITIONS.

Control technique	Under ideal grid voltage (PQ theory)		Under non-ideal grid voltage (PQ theory)		Under non-ideal grid voltage (STF+PQ theory)	
$THD_{v\ (abc)}$	% 0 % 0 % 0		% 8.13 % 10.8 % 12.79		% 8.13 % 10.8 % 12.79	
THD_i (Load)	% 27.01	%26.28	%24.41	%23.44	%24.41	%23.44
THD_i (Grid)	%2.40	%1.76	%10.69	%10.70	%2.44	%1.78
Load	Load 1	Load 2	Load 1	Load 2	Load 1	Load 2

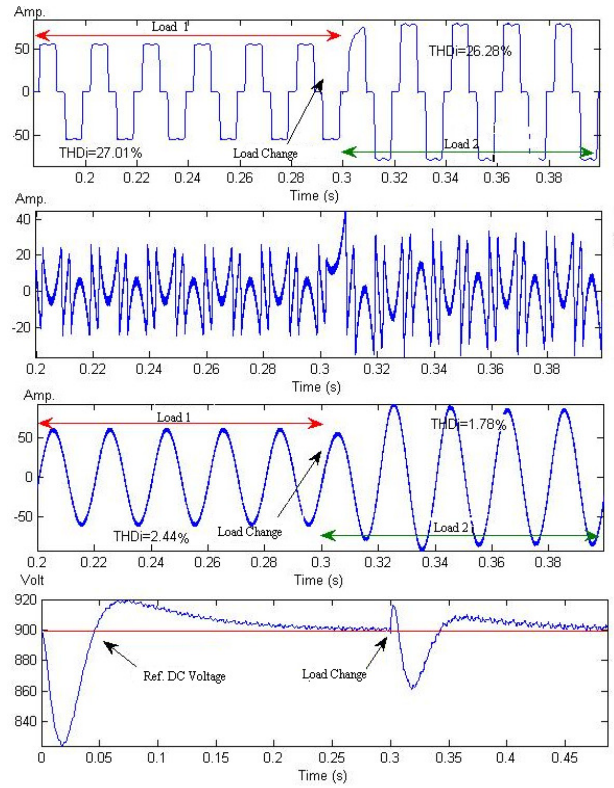

Fig. 7. Performance of the STF based APF under non-ideal grid voltage and step-up load change. Top waveform: Load current of phase a. Compensating current of phase a. Grid current of phase a. Bottom waveform: DC link capacitor voltage.

Given comparison in Table II is based on the conditions that have the same switching frequency, and the same load conditions. The presence of distortion in the grid voltage has a notably adverse effect on the performance of the APF, as is clearly ascertainable from comparing Table II. Simulation results show that the proposed method can be used to filter the distorted α-β components in order to extract the sinusoidal and symmetrical voltage from the distorted and asymmetrical grid voltage.

VI. CONCLUSIONS

The case of distorted and unbalanced grid voltage condition has been considered in this paper. This study shows the performance of the p-q theory based active power filter (APF) degrades in the case of an unbalanced and distorted supply voltage condition. The use of a self-tuning filter (STF) is proposed in order to increase the harmonic suppression efficiency of APF. Simulation results show that the proposed method can improve the performance of active power filters under non-ideal grid voltage conditions.

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