A COMPARISON OF DIFFERENT COMPENSATION CURRENT GENERATION SCHEMES FOR SUPPRESSING CURRENT HARMONICS GENERATED BY COMPACT FLUORESCENT LAMPS

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ABSTRACT - *Active Power filters (APF) are an effective method of compensating for harmonic distortion. APF see wide application in industry where Adjustable Speed Drives (ASD) and Thyristior bridge rectifiers are used. Different current estimation techniques are employed in separating harmonics from the fundamental current. Most of such techniques have been developed for large rectifier fed industrial loads. However, when these schemes are used with a smaller load having greater harmonic distortion such as compact fluorescent lamps (CFL), the results are unsatisfactory. This work focuses on analyzing the performance of current estimation techniques when used with a load composed of compact fluorescent lamps (CFL). Percentage current harmonic distortion (%THDi) of resulting waveform after harmonic compensation has been taken as a figure of merit.*

Key Words: Power Quality; Active Power Filter; Self Tuning Filter, Compact fluorescent Lamp.

1. INTRODUCTION

Harmonics are sinusoidal waveforms having frequencies that are integral multiples of power line frequency. [1]. Non-linear devices draw current in the form of pulses. Such waveforms are rich in higher order harmonics that create problems in the power system. Some of these problems are over heating of neutral conductors, overloading and early failure of transformers, mal-operation of protective devices.

Harmonics in voltage result from current harmonics. These may get amplified due to interaction with capacitors installed for power factor correction. [2]

Harmonic mitigation techniques are therefore, a much studied area of interest. There are largely two approaches to solving the harmonic suppression problem: active and passive. The passive approach involves harmonic cancellation, damping, or shifting them to other frequencies [2, 3, 4,5]

The active method uses active power filters to compensate for harmonic and reactive currents. This method tends to be more effective when working with loads such as AC drives that generate random harmonics [2]. The shunt active power filter (SAPF), introduced by Gyugyi and Strycula [6], is a popular configuration for implementing an active power filter. It has good harmonic suppression characteristics. In addition, it can compensate for reactive power.

Harmonic current estimation methods are essential to Active power filter schemes. These methods calculate the amount of harmonics present in a current waveform. Most of these techniques are used when compensating for large industrial loads as adjustable speed drives (ASD) and Silicon Controlled Rectifier (SCR) bridges. However, when used with smaller loads having individually more Current Harmonic Distortion (THDi) performance of these current estimation techniques varies. This paper analyses the performance of instantaneous reactive power theory (IRPT, p-q theory) [7] and d-q theory when working with Compact Fluorescent Lamps (CFL) installed in large numbers.

To this end, Simulink models have been developed for the p-q and the d-q theories. CFL equivalent model has been used to simulate a per phase balanced non-linear load. The results of how effectively these two schemes work in this manner have been summarized

2. HARMONIC CURRENT ESTIMATION METHODS

This section discusses two major harmonic current estimation techniques

2.1 Instantaneous Reactive Power Theory (IRPT, p-q Theory)

IRPT theory was proposed by Akagi *et al* [7]. In this method three phase currents and voltages a-b-c are transformed into two-phase co-ordinates α-β-0 using Clarke transformation as in equation (1). Where 0 represents the equivalent zero sequence components. Instantaneous active and reactive powers are then calculated as in equations (3-5). Each of the Active Power (P) and reactive power (Q) are composed of continuous and alternating terms. The continuous terms reflect fundamental components of current and voltage. Whereas, alternating terms reflect harmonic part of the waveforms. A low pass filter (LPF) or a high pass filter (HPF) is used to separate fundamental and harmonic parts. Compensation currents in α-β axis are computed according to equation (6). Inverse-Clarke transformation is then applied to obtain reference compensation currents Ia*- Ib*-Ic*as in equation (2). [8]

Clarke transform

$$\begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (1)$$

Inverse Clarke transform

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \sqrt{\frac{2}{3}} . \begin{bmatrix} 1 & 1 & 1 \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} & 1 \\ -\frac{\sqrt{3}}{2} & -\frac{1}{2} & 1 \end{bmatrix} . \begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} \quad (2)$$

Where X_0 represents the zero sequence components

Instantaneous active and reactive power

$$\begin{bmatrix} p \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \qquad (3)$$

$$p \quad = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \qquad (4)$$

$$q \quad = v_\alpha i_\beta - v_\beta i_\alpha \qquad (5)$$

$$\begin{bmatrix} i_\alpha * \\ i_\beta * \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p' \\ q' \end{bmatrix} \qquad (6)$$

[9]

Where *p'* and *q'* are the harmonic part of real and reactive power respectively

Under distorted grid voltage conditions, IRP-theory doesn't produce accurate current references for APF. Additional LPF have to be used to filter out voltage harmonics [8,9]

2.2 Stationary Reference Frame Method (d-q method)

The d-q method is based on Park transformation. Load current a-b-c are transformed into two co-ordinate system d-q-0, where 0 represents the zero sequence component as in equations (7). Inverse park transform is given in equation (8). Park transform requires angular position of the rotating reference frame. To this end, a phase locked loop (PLL) is required. Once the currents (Ia,Ib,Ic) are transformed into (Id, Iq, I0) a high pass filter (HPF) or low pass filter (LPF) in feed forward arrangement is used to separate harmonic components from fundamental ones. Inverse Park transform is used to obtain compensation current reference. [8]

Park transform

$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (7)$$

Inverse park transform

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} cos\theta & -sin\theta & \frac{\sqrt{2}}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix}$$

(8) [8]

Where X_0 represents the zero sequence components.

Performance of d-q method depends on the angular reference generated by a phase locked loop (PLL). Grid voltage reference is filtered by LPF to obtain pure sinusoidal waveforms for PLL input [8, 9]

3. METHODOLOGY

Six different scenarios have been implemented to assess the performance of different harmonic current estimation techniques under varied circumstances. The IRP-theory has been used with Low Pass filters (LPF); with Self Tuning Filters (STF); and both. Current Harmonic Distortion (THDi) w.r.t fundamental is taken as a measure of effectiveness of the method being used. In similar way d-q theory has been used with LPF, STF and both.

Finally the effect of zero sequence currents has been highlighted by adding and removing them from equations (7) and (8) of the Park transform

4. SIMULINK MODEL

A Simulink model has been developed for testing the effectiveness of various current estimation techniques when handling highly distorted current waveforms: such as those produced by CFLs. This includes a three phase programmable source module, Voltage- Current measurement blocks, CFL model and a harmonic current estimation block. Sim power systems block set has been utilised

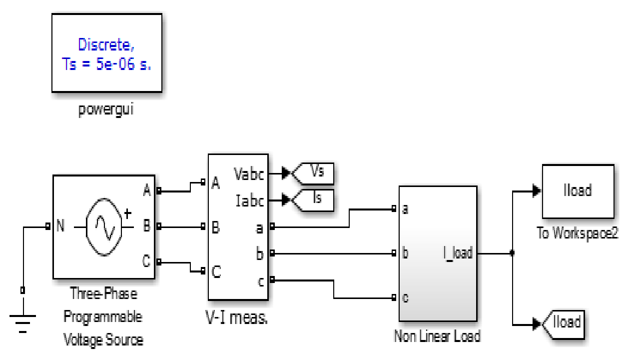

Figure 1: Simulink model of experimental set up

4.1 Compensation Current Calculation

Compensation current is calculated from the non-linear load current (Ia Ib Ic) and source voltages (Va, Vb,Vc). This section calculates two parameters: firstly the compensation current that needs to be injected into the system and secondly the current waveform resulting from mathematical addition of the compensation and load current. Figure-2 shows the inputs and output of current estimation block

Figure-3 shows the usage of an STF block in α-β reference frame to filter out voltage harmonics. The pure sinusoidal reference of the grid voltage thus obtained is input to a phase locked loop (PLL) and angular position of the rotating angular d-q frame can be obtained.

Figure-4 shows the park transformation of load current using angular reference obtained as in Figure-3. LPF are used in feed forward configuration to obtain harmonic compensation currents.

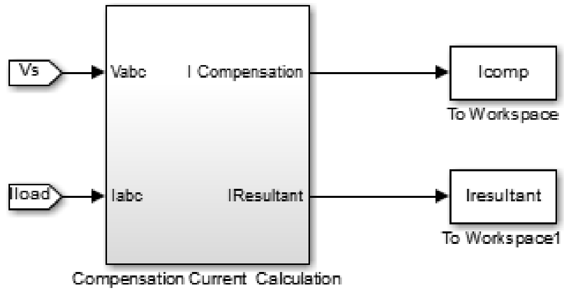

Figure 2: Current Estimation

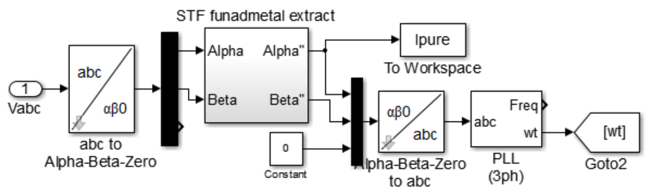

Figure 3: Obtaining accurate angular position of the rotating frame for Park transformation

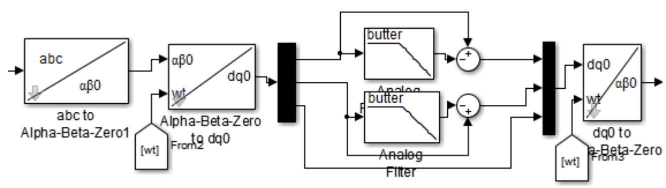

Figure 4: Park transformation of load currents and current estimation using LPF

Table 1: LPF parameters

Filter Order	Cutt-off frequecy (f_c) Hz	Angular Cutt-off frequency (W_c)
8	60	$2\pi f_c$

Table 1 details Low Pass filter (LPF) parameters

4.2 Compact Fluorescent Lamp (CFL) Modelling

Compact florescent lamps employ a small inverter circuit to create high frequency arcs that cause fluorescence in inert gas filled tubes. The authors in [10] have proposed a method to model Compact fluorescent lamps wherein the said inverter circuit and tube can be modelled as an equivalent resistance. This simplifies the overall modelling where many CFLs are to be simulated at one time. An equivalent model for 23 watt CFL lamp has been used as shown in Figure 5 whereas details of parameters are given in Table 2.

Table 2: parameters for CFL used in simulation

Parameter	Value
Input resistance	3.59 ohms
Capacitance	6.53 μ Farad
Inverter and tube equivalent Resistance	3997 ohms

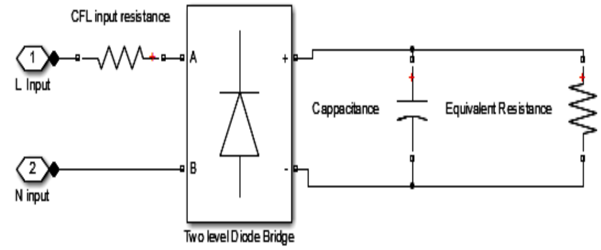

Figure 5: CFL Simulink model

4.3 Self-Tuning Filter (STF) Model

Self-tuning filter refers to the arrangement shown in figure 6

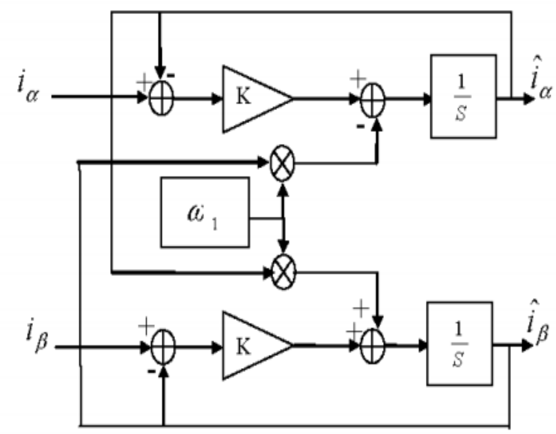

Figure 6: Self Tuning Filter (STF)

[9]

It has characteristics similar to a Band-Pass filter. There is no phase delay between input terms and corresponding output terms

Equations (8) and (9) govern an STF

$$X'_{\alpha} = \left(\frac{K}{s}\left[X_{\alpha}(s) - X'_{\alpha}(s)\right] - \frac{\omega}{s} \cdot X_{\beta}(s)\right) \quad (9)$$

$$X'_{\beta} = \left(\frac{K}{s}\left[X_{\beta}(s) - X'_{\beta}(s)\right] - \frac{\omega}{s} \cdot X_{\alpha}(s)\right) \quad (10)$$

Where K is a constant such that total gain of STF is zero. [9]

Self-Tuning Filter (STF) can simplify the control scheme used in active power filters [11]. An STF is added after Clarke transformation block. It takes distorted α-β Voltages as input and gives undistorted α-β voltages as output as in equations (10). The STF method can be used to separate harmonic components from fundamental ones by using the STF in feed forward configuration as in equations (11). Harmonic current can be calculated when applied after the Clarke transformation of distorted load currents. The STF has been used with the p-q and d-q theories [11]

Simulink model for STF has been shown in figure-7 whereas table 3 gives details of its parameters.

$$\begin{cases} V_{\alpha\ Fundamental} = V_{\alpha\ Source} - V_{\alpha\ Harmonic} \\ V_{\beta\ Fundamental} = V_{\beta\ Source} - V_{\beta\ Harmonic} \end{cases} \quad (10)$$

And

$$\begin{cases} i_{d\ Harmonic} = i_{d\ Load} - i_{d\ Fundamental} \\ i_{q\ Harmonic} = i_{q\ Source} - i_{q\ Fundamental} \end{cases} \quad (11)$$

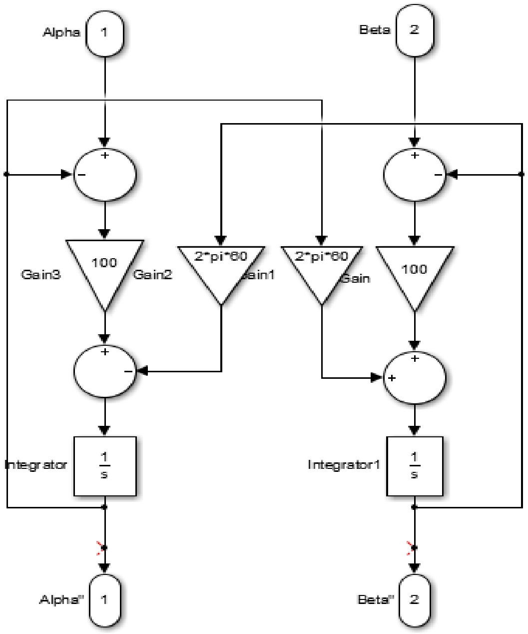

Figure 7: Self Tuning Filter Simulink implementation

Table 3: Self Tuning Filter parameters

Variables	**Value**
Fundamental frequency (f)	60
Fundamental frequency angular (W)	2πf
K	100

5. RESULTS: HARMONICS LEVELS AFTER FILTERING

This section presents the results of filtering distorted current waveforms through active power filter using different current harmonic detection methods

5.1 Frequency Domain Analysis

FFT tool (Sim Power systems) in Simulink ® has been used to analyze three current waveforms. i.e: a Thyristor bridge rectifier fed DC motor drive; a bank of twenty CFLs per phase, 23 watt each; CFLs under distorted mains voltage. The current harmonic distortion (THDi) with respect to the fundamental is compared

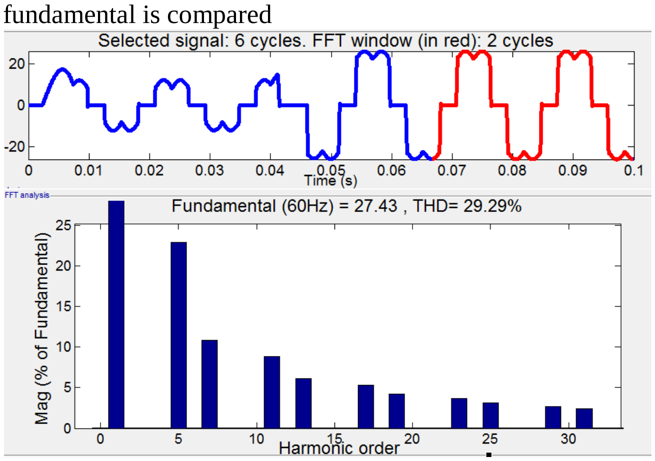

Figure 8: Six pulse rectifier fed DC motor current waveform and FFT analysis

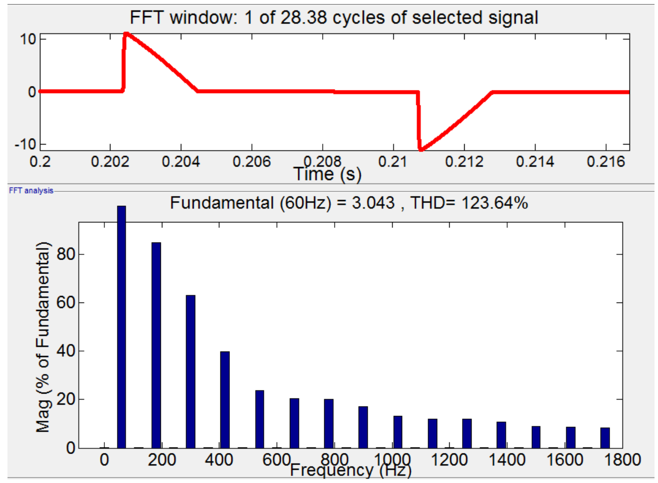

Figure 9: Simulated CFL bank current waveform and FFT analysis

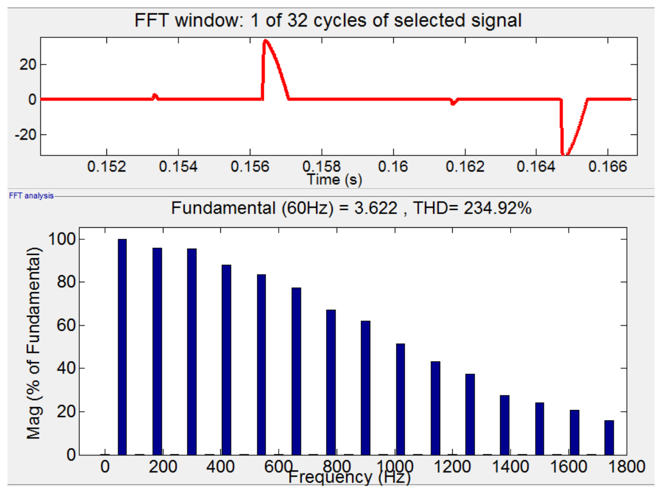

Figure 10: Current waveform of CFL load under distorted grid voltage and FFT analysis

Table 4: Comparison of current harmonic distortion

Load	**% THDi**	**Current peak (Amperes)**
Thyristor bridge fed DC motor	29	20 A
23 watt CFL bank	124	10A
23 watt CFL bank with distorted mains voltage	235	20 A

Referring to table 4 and figures 8-10 it is evident that the current harmonic distortion of CFL waveform is far greater than Thyristor fed DC motor. Under distorted mains voltage IHD increases further

5.2 Instantaneous Reactive Power Theory. (P-Q theory) Results.

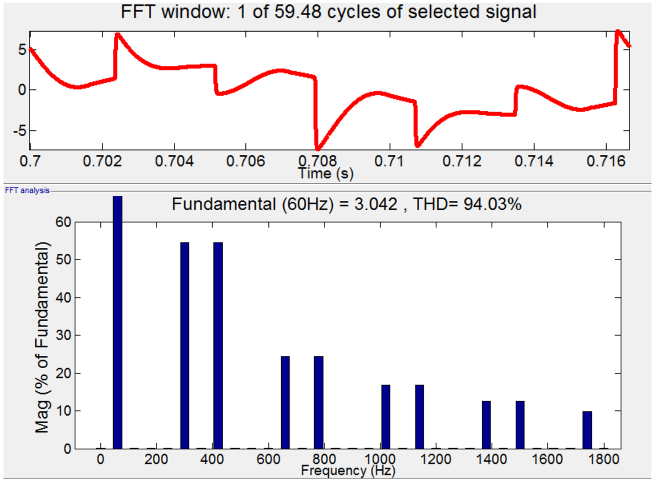

Figure 11: Resulting waveform after p-q theory based compensation and FFT analysis

Figure 11 shows resultant waveform achieved through p-q theory based harmonic compensation. The THDi is still at 94% of fundamental.

5.3 Instantaneous Reactive Power Theory. (P-Q theory) –Under Distorted Voltage Conditions

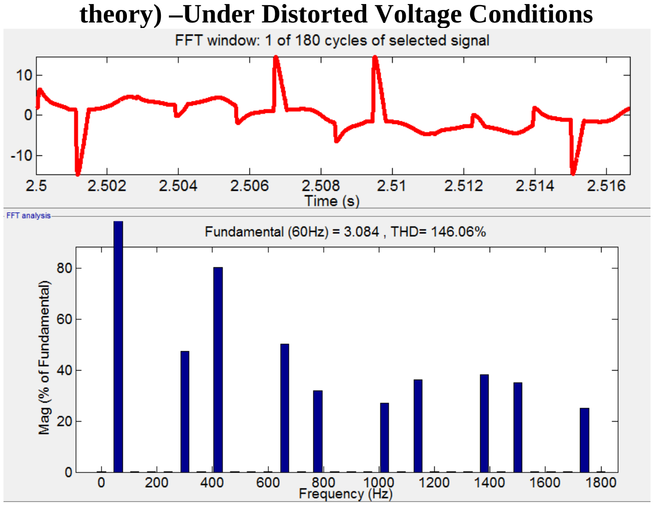

Figure 12: Resulting waveform after d-q based current compensation under distorted grid voltage and FFT analysis

Figure 12 shows resultant waveform achieved through p-q theory based harmonic compensation under distorted grid voltage. The THDiincreases to 146% of fundamental. Compensation current calculation involves grid voltage in two dimensional co-ordinates V_α and V_β as in equation (6). Distorted grid voltage implies that these quantities are distorted as well. So in- accurate harmonic current references are produced.

5.4 Stationary Frame Method (d-q method)- Using Low Pass Filters in Feed Forward Configuration

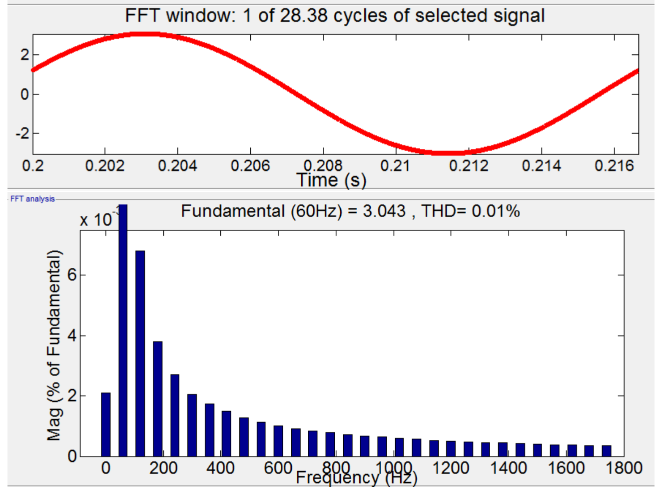

Figure 13: Resulting waveform after d-q based current compensation with LPF used in current estimation and FFT analysis

Figure 13 shows results of using d-q theory where LPF have been used in feed-forward configuration to filter out harmonic current. The current waveform after harmonic compensation is a nearly perfect sinusoid with THDi at 0.01%

5.5 Instantaneous reactive power theory (P-Q theory) using STF

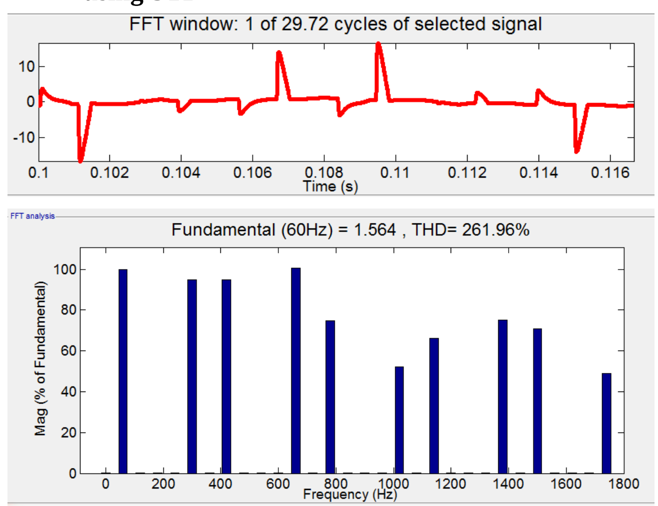

Figure 14: Resulting waveform after p-q theory based current compensation with STF used in current estimation and FFT analysis

Figure 14 shows results of p-q theory based compensation where Self tuning filters tuned to the fundamental frequency are used to filter out harmonic part of active and reactive power. The results are anomalous with THDifurther increasing to 261.9%

5.6 Stationary Frame Method (d-q Method)- Using STF in Feed Forward Configuration

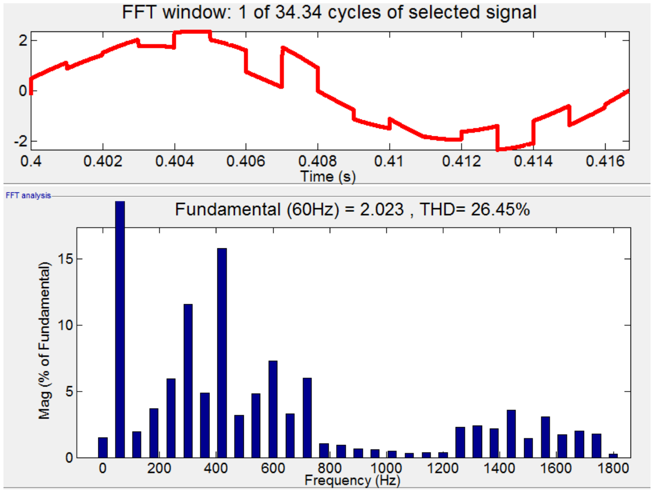

Figure 15: Resulting waveform after d-q based current compensation when STF has been used in current estimation and FFT analysis

Figure 15 shows results of using d-q theory with STF to filter out current harmonics from I_d and I_q. The THDi in this case is 26.5%. A zero order hold has been introduced in both *d* and *q* legs of the STF.

5.7 Stationary Frame Method (d-q Method)- Using STF And Low Pass Filter in Feed Forward Configuration

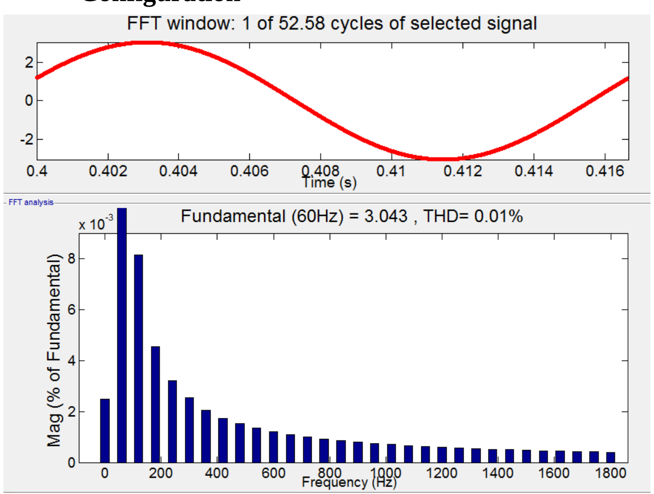

Figure 16: Resultant waveform and FFT anlysis after d-q based current compensation when both STF and LPF are used in current estimation

Figure 16 shows the result of using STF to filter out grid voltages before phase locked loop (PLL) block. This produces a more accurate reference of angular position for the d-q frame. LPF has been used in feed forward configuration to separate harmonic currents in d-q.
This method gives 0.0% THDi in the resultant waveform

5.8 Effect of Zero Sequence Current

Most current estimation techniques have been developed to work with three phase three wire systems where zero sequence current is non-existent. Leaving out zero sequence current in the scenarios being analysed result in poor performance.

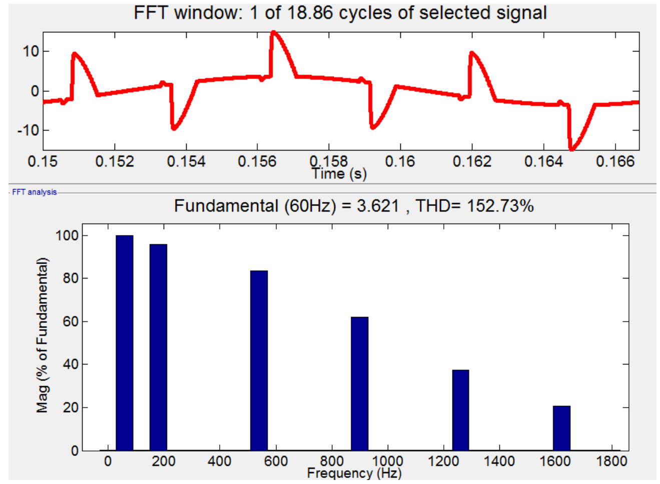

Figure 17: Resultant waveform and FFT analysis after d-q compensation when zero sequence current has been assumed zero in current estimation

6. DISCUSSION

Table 5: Comparison of results: different current estimation techniques used

Current Estimation Method	Filtering Method used in Improving Grid Voltage Reference	Filtering Method used in Current Estimation	% THDi of resulting Current Waveform
p-q theory	none	Low Pass filter in feed forward	94
p-q theory (distorted mains voltage)	none	Low Pass filter in feed forward	146
p-q theory (distorted mains voltage)	none	STF	261.9
d-q theory	Low pass filter	Low Pass Filter	0.01
d-q theory	STF	Low pass filter	0.00
d-q theory	STF	STF	26.5

Table-5 summarizes the results presented for harmonic compensation. Waveforms being analyzed are a mathematical sum of harmonic compensation current and the initial distorted waveforms. This is an ideal experiment where the inverter switching and carrier frequency effects are not accounted for. Thus %THDi here represents the degree of effectiveness of each current estimation method employed.
The STF block filters out voltage harmonic distortion effectively. However, in case of current waveform where IHD is much greater it doesn't produce appreciable results.

Incorporating a Zero order hold in both d-q legs of STF improves overall performance of the current estimation scheme

7. CONCLUSION

The IHD of current waveform is greater for current drawn by CFLs compared to that of Thyristor bridge rectifiers. THDi further increases for a distorted mains voltage.

For a given THDi of distorted current, different current estimation schemes produce different results depending on what method is used to separate harmonic component from the fundamental. In all circumstances, pre-processing of mains voltage to extract fundamental voltage reference improves harmonic current estimation. Excluding zero sequence currents from the current estimation process causes the scheme to perform poorly and THDi in resulting waveform is appreciably large

Comparing all six scenarios discussed STF based filtering for distorted voltages and LPF filtering for distorted currents give the best results in combination.

8. ACKNOWLEDGMENTS

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