# Mitigation of Harmonics using Active Shunt Filter with PEMFC

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**ABSTRACT—** ***This report demonstrates the method of improving the power quality using a shunt active power filter with PEMFC. In this proposed topic comprises shunt active power filter with Proton Exchange Membrane fuel cell, hysteresis current control loop, Synchronous reference frame, DC link capacitor. The trading signal generation for the filter is from hysteresis current controller techniques. With all these elements shunts active power filter reduce the total harmonic distortion. This report introduces the simulation and analysis of the using three phase three wire system active filters to compensate harmonics. The proposed shunt active filter model uses balanced non-linear load. This paper successfully lowers the THD within IEEE and IEC norms and satisfactorily works to compensate current harmonics.***

**Keywords—** Hysteresis current control loop, synchronous reference frame, shunt active filter.

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## 1. INTRODUCTION

The power quality (PQ) problems have been increased reasonably because of increased use of power electronic equipment and motor drives in household, commercial and industrial applications. These troubles, normally referred to as PQ problems, have been of main concern to the international community and spoken by various PQ standards, practices and norms. In sight of these PQ problems, some suitable measures are involved for the recompense of the harmonics [1] & [6]. The most popular method is the use of LC filters. The current dependent non-linear loads and voltage dependent nonlinear loads have dual relations to each other in circuits and properties and need parallel and series filters respectively for controlling the harmonics. The quality of electrical power in the distribution system is an essential factor in developed and developing countries. In industrial and commercial plants insufficient quality of power can lead to the pitiful quality of products, interruption of important industrial processes and hence economic losses.

The PQ improvement has a critical function in day to day power and energy efficiency sector and attempts have been built to improve the PQ as per standard norms using passive and active wave shaping techniques [4] & [5]. The passive wave shaping techniques usually have tuned filters, but these filters cannot be used for all the harmonics. The active filters (AFs) can filter any harmonics through hybrid wave shaping methods with passive topologies provides a safer result of all power quality problems. The topologies for PQ improvement can classified as inactive, active and hybrid wave shaping topologies. Active filters overcome the drawbacks of passive filters using power electronic converters to do away with the current harmonics [2]. Shunt active power filters are established up to stamp down the harmonic currents and compensate reactive power simultaneously. The shunt active power filters are checked as a current source parallel with the nonlinear load [7]. A compensation current equal but opposite to the harmonic and reactive current drawn by the nonlinear loads is generated by appropriately controlling the converters present in the active power filter so as to get to the supply current sinusoidal and in phase with the supply voltage. However, the applications of active power filters used in power system are limited by its high construction cost and power rating of the converters [8] & [14].

However, most of the proposed controllers are open loop based on three-symmetrical components: zero sequence, negative sequence and positive sequence, decomposition to balance and regulate the voltage [11] & [12]. The survey proposes a compensation algorithm using an active power filter associated with the PEM fuel cell, Hysteresis current controller and Synchronous reference frame controller to compensate current harmonics due to non-linear loads [15].

## 2. SYNCHRONOUS REFERENCE FRAME CONTROLLER

The synchronous reference frame theory or d-q theory is based on time-domain reference signal estimation techniques. It performs the operation in steady-state or transient state as well as for generic voltage and current waveforms. It allows controlling the active power filters in real time system. Some other important feature of this theory is the simplicity of the calculations, which involves only algebraic calculation. The basic structure of SRF controller consists of direct (d-q) and inverse (d-q) -1 park transformations as shown in Figure 1. This can be useful for the valuation of a specific harmonic component of the input signals [2].

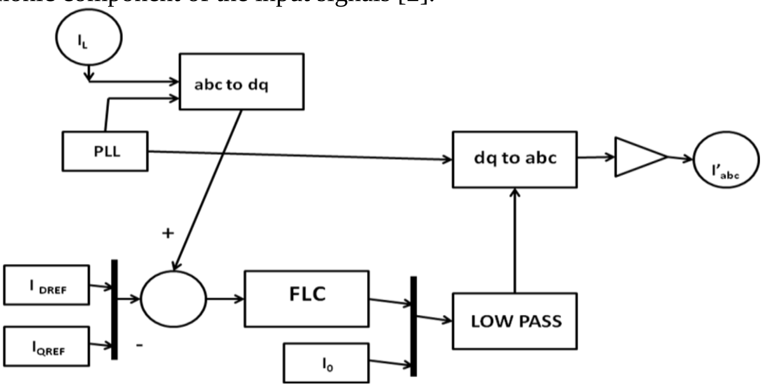


**Figure 1:** Synchronous d-q-0 Reference Frame Based Compensation Algorithm

The reference frame transformation is formulated from a three-phase ABC stationary system to the direct axis (d) and quadratic axis (q) rotating coordinate system. In a-b-c, stationary axes are separated from each other by $120^0$. The instantaneous space vectors, $v_a$ and $i_a$ are set on the a-axis, $v_b$ and $i_b$ are on the b-axis and similarly $v_c$ and $i_c$ are on the c-axis. These three phase space vectors stationary coordinates are easily transformed into two axis d-q rotating reference frame. This algorithm facilitates deriving $i_d$-$i_q$ (rotating current coordinate) from three-phase stationary coordinate load current $i_{La}$, $i_{Lb}$, $i_{Lc}$, as shown in Equation (1)

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} \sqrt{2/3} \begin{bmatrix} \cos(\theta) & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ \sin(\theta) & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3 \\ \sqrt{1/2} & \sqrt{1/2} & \sqrt{1/2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

The d-q transformation output signals depend on the load current (fundamental and harmonic components) and the performance of the Phase Locked Loop (PLL). The a-b-c to d-q-0 transformation is shown in figure 2. The id-iq current is sent through low pass filter (LPF) for filtering the harmonic components of the load current, which allows only the fundamental frequency components. The LPF is a second order Butterworth filter, whose cut off frequency is selected to be 50 Hz for eliminating the higher order harmonics. The FLC controller is used to eliminate the steady state error of the DC component of the d-axis reference signals [10]. Furthermore, it maintains the capacitor voltage nearly constant. The DC-side capacitor voltage of PWM-voltage source inverter is sensed and compared with desired reference voltage for calculating the error voltage. This error voltage is passed through a PI controller whose propagation gain ($K_P$) and integral gains ($K_I$) are 0.1 and 1 respectively [13].

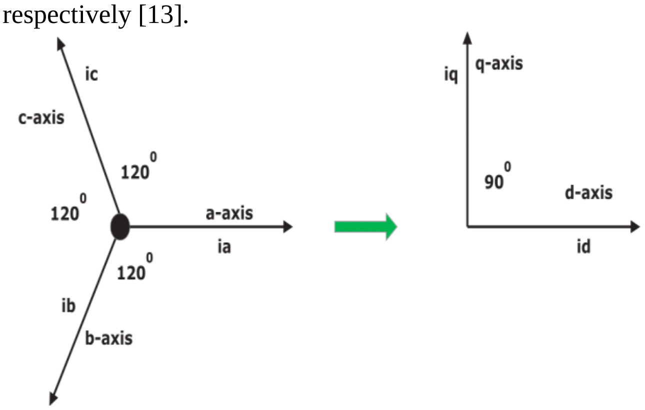


**Figure 2:** a-b-c to d-q-0 Transformation

## 3. HYSTERESIS CURRENT CONTROLLER

In Hysteresis Current Control, two fixed hysteresis bands are defined so that reference current will be right in the middle of the two bands which have a very high dynamic response and are inherently stable. When the measured current hits the upper or lower band, switching will happen accordingly. The current and voltage waveform with hysteresis current controller (HCC) are shown in Figure 3. The PWM frequency varies within a band because peak-to-peak current ripple is required to be controlled at all points of the fundamental frequency wave [3].

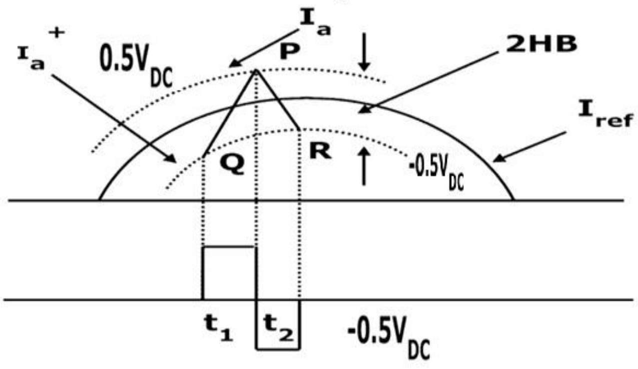


**Figure 3:** Current and Voltage Waveform with HCC

For each phase the two-level PWM-voltage source inverter systems of the hysteresis current controller are utilized independently. The switching signal of the three phases is generated directly by current controller [9]. The error current is the difference between the desired reference current $i_{ref}$ (t)and the actual source current $i_{actual}$(t) .If the error current exceeds the upper hysteresis band limit (+h), the upper switch of the inverter arm becomes OFF and the lower switch becomes ON.

The switching logic of HCC is formulated as follows:

If $\delta$ >HB upper switch is OFF(S1=0)and lower switch is ON (S4=1).
If $\delta$ <-HB upper switch is ON (S1=1) and lower switch is OFF(S4=0).
Where $\delta$ is the difference between load current and reference current.

The switching logic for phase b and phase c is similar to phase a, using corresponding reference and measured currents and hysteresis bandwidth (HB) and is shown in Figure 4.

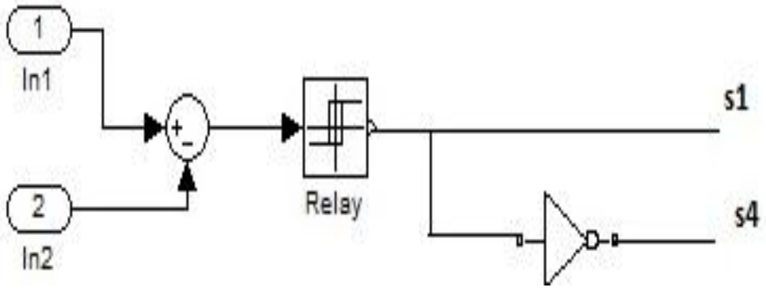


**Figure 4:** Hysteresis Current Controller

## 4. SIMULATION AND RESULTS OF SRF

The SRF controller is designed and implemented for a rectifier load and its simulation results are verified using MATLAB. The Simulink system shown in Figure.5 consists of 'abc to dq' and 'dq to abc' conversion blocks with a discrete PLL for providing synchronization between the two.

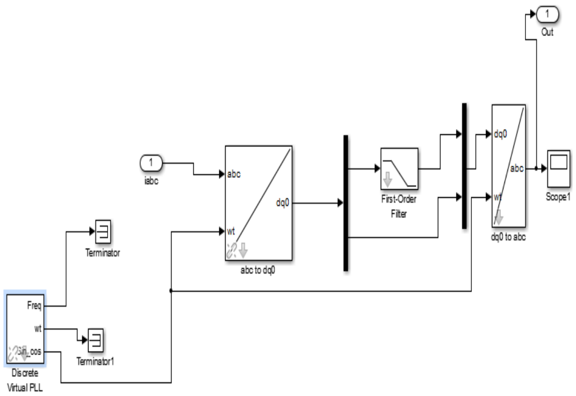


**Figure 5:** Simulation of SRF

The fundamental frequency would be the DC component in dq co-ordinate, while the harmonics present in the current would be detected as AC component. For separating the fundamental component from the harmonics, a low pass filter with a cut-off frequency of 50Hz is used. The output from the LPF is fed to the 'dq to abc' conversion block and the reference current is generated, which is similar to the source current [10] & [13]. It is shown in Figure.6. The fundamental frequency of the reference current is the same as the source current.

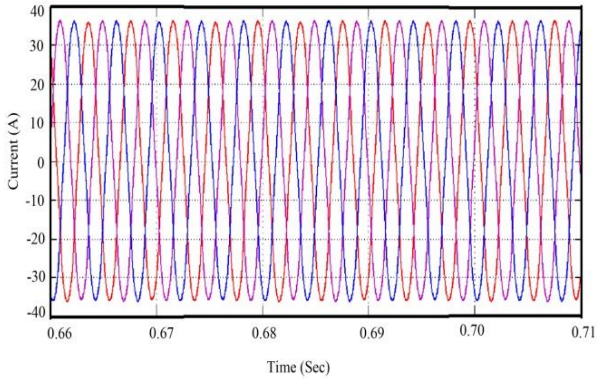


**Figure 6:** Output of SRF Controller

## 5. SIMULATION OF HCC

The hysteresis current controller and SRF controller are simulated and their performances are evaluated. The HCC is simulated using MATLAB Simulink as shown in Figure.7 The reference current and the source current are compared to generate error current and given as input to the HCC [3].

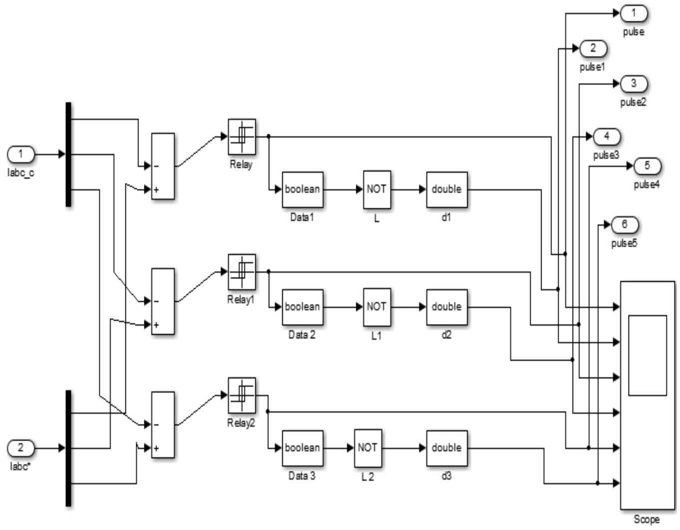


**Figure 7:** Simulation of HCC

The Hysteresis band chosen is 0.5 and is compared with the error signal to provide the output for the three phases of upper arm. The output of 5 Volts from the HCC is used to drive the gates of upper arm switches of the inverter in the APF.

## 6. SIMULATION OF SHUNT ACTIVE POWER FILTER

### *6.1 System Parameters*

The simulation of three phase active power filter is carried out with the system parameters shown in the Table.1

**Table1:** System Parameters

| *Components* | *Values* |
|---|---|
| Line Voltage | 440V |
| Supply Frequency | 50Hz |
| Source Impedance(Resistance, Inductance) | 1Ω, .1mH |
| Non-Linear load (Resistance, Inductance) | 10Ω, 100mH |
| Filter Impedance (Resistance, Inductance) | 1Ω, 2.5mH |
| DC side capacitance | 1400µf |
| Power Converter | 6 MOSFET |

The source to the system comprises of a PEM fuel cell, a DC to DC boost converter and a three phase voltage source inverter. The source current is distorted due to nonlinear rectifier load. The SRF controller uses FLC controller internally to maintain the capacitor voltage constant [2]. The iteration method is chosen to find the membership values of the FLC and the required performance is achieved. A low pass filter is used with the SRF controller for eliminating higher order harmonics. A PLL is an electronic circuit consisting of a variable frequency oscillator and a phase detector, which generates an output signal whose phase is related to the phase of an input reference signal. A phase detector compares the two input signals and generates an error signal proportional to their phase difference. The error signal is filtered and given to drive a Voltage Controlled Oscillator (VCO) to create an output phase. This output is again fed back to the input through a potential divider. If the output phase drifts, it increases the error signal and drives the VCO phase in the opposite direction to reduce the error and to generate the reference signal.

The Inverter with SRF controller and HCC is simulated with a source voltage of 440 volts, source resistance of 1 ohm, impedance of 0.1mH for a rectifier load which is highly non-linear and is shown in Figure.8

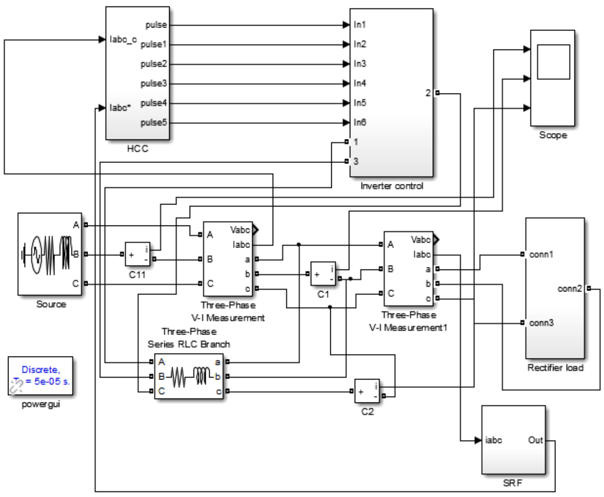


**Figure 8:** Simulation of Shunt APF

### *6.2 Simulation Results Of Shunt Active Power Filter*

The source current waveform is distorted by the harmonics produced due to the rectifier load without filter and is shown in Figure.9

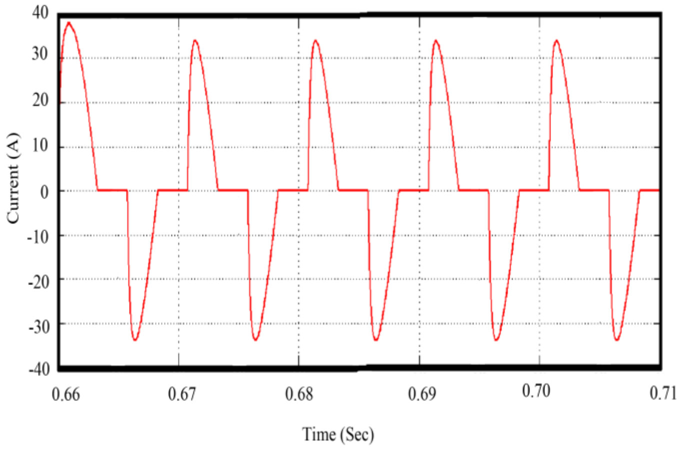


**Figure 9:** Source Current before Compensation

The reference current output from the SRF block with reduced harmonics and frequency of 50 Hz is shown in the Figure.10 This current is used for comparison with load current to provide error input to HCC. The reference current generated mostly depends on the DC capacitor voltage, load current and PLL operation.

The compensating output current of the inverter is shown in Figure.11. The maximum peak value of 30A compensating current is given by the inverter to the PCC and the amount of current fed to the PCC depends directly on the harmonics from the load and PWM pulses from the HCC block.

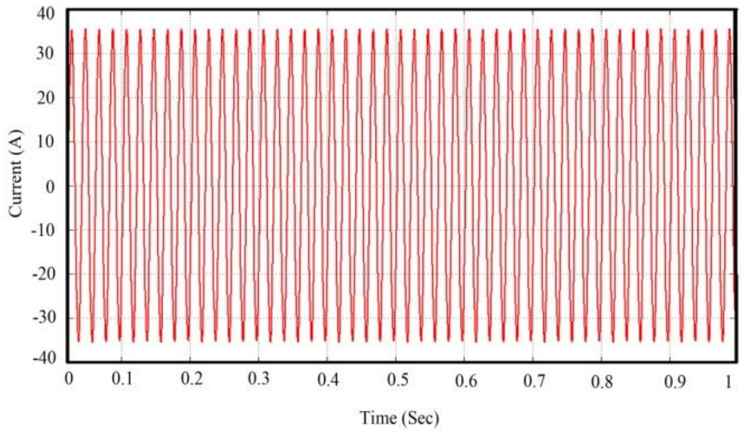


**Figure 10:** Reference Current

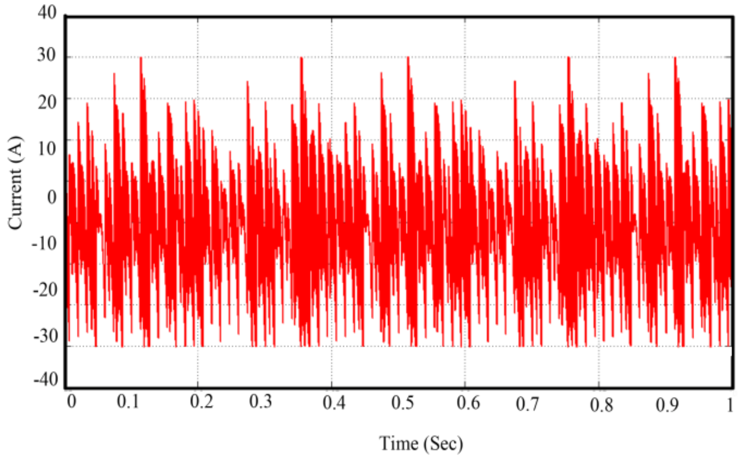


**Figure 11:** Compensating Current

The source current after compensation using APF is shown in the Figure.12 respectively. The source current nearly resembles a sine wave with reduced harmonics.

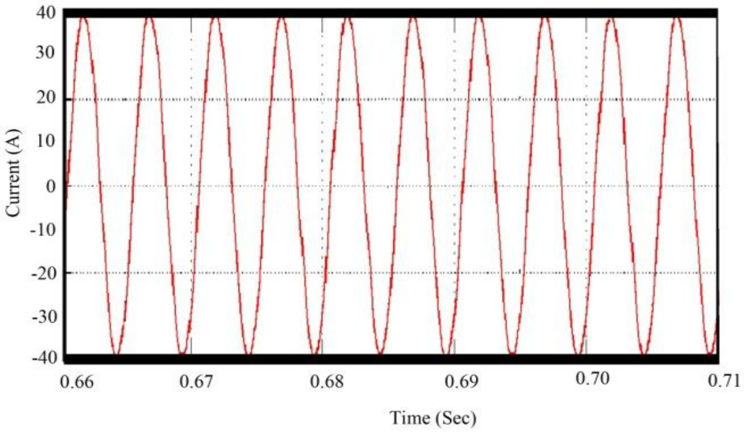


**Figure 12:** Source Current after Compensation

## 7. THD ANALYSIS

Harmonics are AC voltages and currents with frequencies that are integer multiples of the fundamental frequency. The power frequency available is called fundamental frequency. A sinusoidal wave with a frequency K times higher than the fundamental is called harmonic wave and is denoted with amplitude and phase shift to a fundamental frequency signal. The ratio between harmonic frequency and fundamental frequency is called harmonic order. Discrete Fourier Transform (DFT) or its faster version Fast Fourier Transform (FFT) is used to analyze the distorted waveform into sinusoidal component of different Harmonic Order of amplitude & phase shift [13].

The presence of harmonics is evaluated through Total Harmonic Distortion (THD). THD voltage harmonics are asserted with $THD_V$. $THD_V$ is a ratio of the root mean square (RMS) value of the harmonic voltage to the RMS value of the fundamental voltage and is calculated by the following equation. THD is usually stated as a percentage.

$$THD_V = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_1} \qquad (2)$$

Where $V_n$ is RMS value of n order voltage harmonics and $V_1$ is the RMS value of fundamental voltage .Everything presented for Voltage Harmonics is also valid for Current Harmonics and $THD_I$

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots + I_n^2}}{I_1} \qquad (3)$$

Where $I_n$ is the RMS value of n order current harmonics and $I_1$ is the RMS value of fundamental current.

The operation of nonlinear loads in a power distribution system creates harmonic currents that flow throughout the power system [14]. The inductive reactance of the power system increases and the capacitive reactance decreases as the frequency increases. In this three phase system the THD analysis of source current is analyzed by FFT.

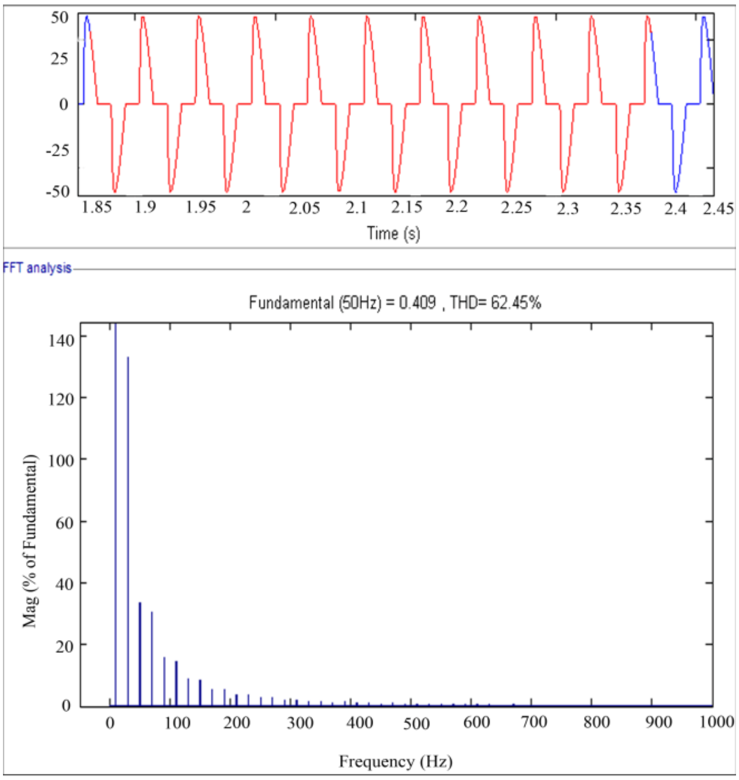


**Figure 13:** THD Analysis of Source Current without APF

The THD analysis of the source current with compensation using APF reduced drastically from 62.45% to 5.21%.

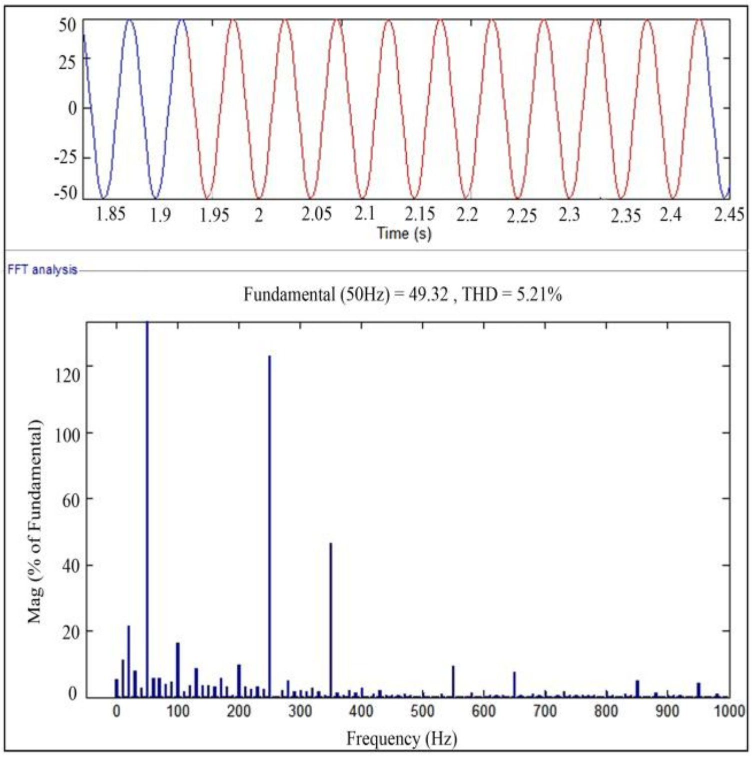


**Figure 14:** THD Analysis of Source Current with APF

The comparison of THDs for both the waveforms (for source current without APF and with APF) is shown in the Table.2. The THD of source current increases a lot due to the odd order harmonics namely the 3$^{rd}$, 5$^{th}$ and 7$^{th}$ order (56.58%, 16.81% and 15.28% respectively). By using the APF for compensating harmonics, the 3rd, 5$^{th}$ and 7$^{th}$ order harmonics are reduced (0.09%, 2.83% and 1.27% respectively). Thus the THD for source current gets reduced drastically.

**Table2:** THD of Source Current with APF

| *Harmonic Order* | *THD (% of Fundamental) without APF* | *THD (% of Fundamental) with APF* |
|---|---|---|
| H3 | 56.58 | 0.09 |
| H5 | 16.81 | 2.83 |
| H7 | 15.28 | 1.27 |
| H9 | 7.84 | 0.02 |
| H11 | 7.22 | 0.25 |

## 8. CONCLUSION

In this paper THD analysis of a three phase system sourced by the Fuel Cell and filtered by a shunt active filter is discussed. The inherent advantage of SRF theory for reference current generation and HCC algorithm for the control of the MOSFETs through the gate pulses are used in this work to improve the performance of the filter. The SAPF with PEMFC was simulated in MATLAB/SIMULINK. It is found that the proposed shunt active power filter improves the power quality of the power system by eliminating harmonics and makes the source current almost sinusoidal. It is seen that the THD of the source current 5%, which is below the harmonics limit imposed by IEEE and IEC standards.

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