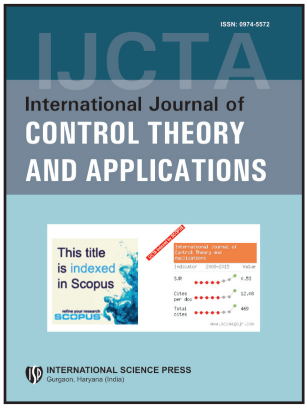

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Performance Analysis of Five Level Cascaded H-Bridge Inverter Based APF to Enhance Power Quality

R. Sheba Rani[a], C. Srinivasa Rao[b] and M. Vijaya Kumar[c]

[a]*Assistant Professor, Department of Electrical and Electronics Engineering, G.P.C.E.T, Kurnool, A.P, India. Email: sheeba1.eee@gmail.com*
[b]*Professor, Department of Electrical and Electronics Engineering, G.P.C.E.T, Kurnool, A.P, India. Email: csr_bit@yahoo.co.in*
[c]*Professor, Department of Electrical and Electronics Engineering, J.N.T.U C.E, Anantapur, A.P, India. Email: mvk_2004@rediffmail.com*

Abstract: Due to rapid increase in the use of non-linear loads, the need for good power quality has gained importance. Non-linear loads draw non-linear currents from the source, thereby leaving the remaining harmonic components at the PCC. This makes the source current distorted, making it unsuitable for other sensitive loads. Over the past few decades, APF has gained attention in the aspects of reducing harmonic content and compensating reactive power. This paper discusses the performance of a Three phase-Three wire Five level Cascaded Inverter based Shunt Active Power Filter. The APF configuration consists of a Cascaded H-Bridge Multilevel Inverter and a DC link capacitor. PQ control theory is implemented for determining the compensating reference currents. Level Shifted PWM technique is chosen for driving the inverter, which generates the compensating currents according to the switching sequence. It is necessary to maintain constant voltage across DC link capacitor which is achieved by PI controller. The performance of APF is observed under varying load conditions and results are compared. The simulation work is carried out on MATLAB/SIMULINK platform.

Keywords: Active Power Filter (APF), Cascaded Multilevel Inverter, DC Link capacitor, Power Factor (PF), Pulse Width Modulation (PWM), PI controller, PQ theory, Point of Common Coupling (PCC), Voltage Source Inverter (VSI).

1. INTRODUCTION

Power quality is defined in the IEEE 100 authoritative dictionary [1]. It is utmost important to sense, control and treat the power being supplied to the consumers and to educate engineers to reduce the adverse effects of power quality related issues [2-8]. Power quality events result in unexpected power failures, equipment overheating, damage to sensitive devices, electronic communication interference, increased system losses, decreased efficiency, need for over sizing of installations and many more [6]. Poor power quality is one factor that affects the economic conditions of both power utilities and end users [3], [5]. Various power quality issues include harmonics, transients, voltage variations, flicker, outages etc [6].

Passive filters are a traditional choice for compensating harmonic pollution. Passive filters mitigate only fixed harmonics for which they are tuned [7]. The parameters of the passive filter produce resonance under certain system conditions that result in adverse effects in power system. Active Power Filter is an alternate solution for passive filters and has been under research for the past few decades. Active Power Filter compensates the current harmonics at PCC, thereby making it feasible for other end users.

2. ACTIVE POWER FILTER

Active Power Filter operates on the principle of injecting compensating currents at PCC that are equal in magnitude but in phase opposition to the harmonic currents injected by non-linear loads [4]. Figure 1 shows the block diagram of APF, injecting compensating current at PCC. Thus the harmonic currents injected by non-linear load at PCC are compensated and make the source current free of harmonics.

The components of APF include:

- System variable detector
- Reference signal Estimator
- Overall system controller
- Gating signal generator
- Power Circuit Interface

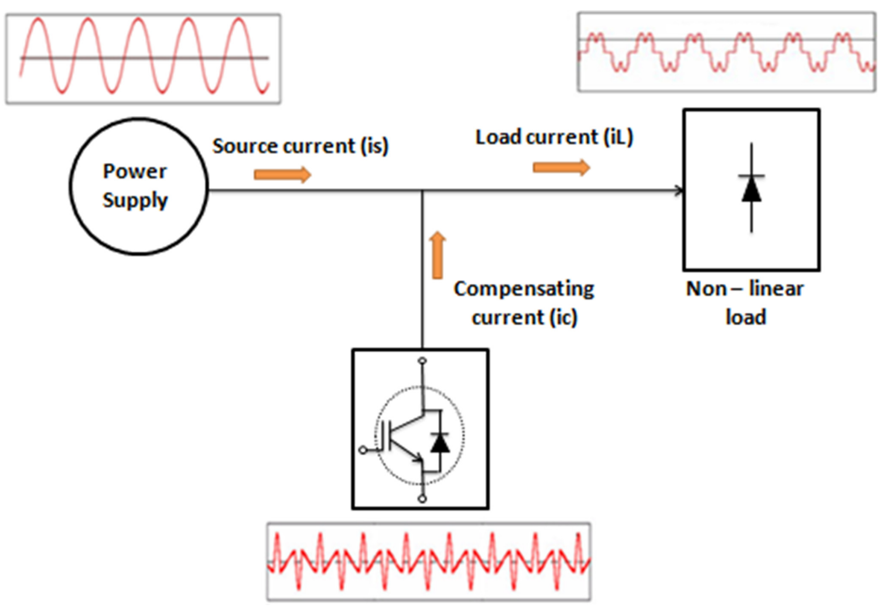

Figure 1: Block Diagram of Active Power Filter

3. FIVE LEVEL CASCADED H-BRIDGE INVERTER BASED APF

Figure 2 shows the configuration of Five Level Cascaded H-Bridge Inverter based APF with control circuitry. As shown the circuit feeds a non-linear load. The load currents and source voltages are sensed by voltage and current sensors. The instantaneous compensating currents are determined by the control strategy chosen. Instantaneous Active and Reactive Control Strategy (PQ control technique) is implemented in this paper. Level shifted PWM control technique is used for determining the switching sequence of power circuit. A simple PI controller controls the DC link voltage of the inverter and maintains it constant.

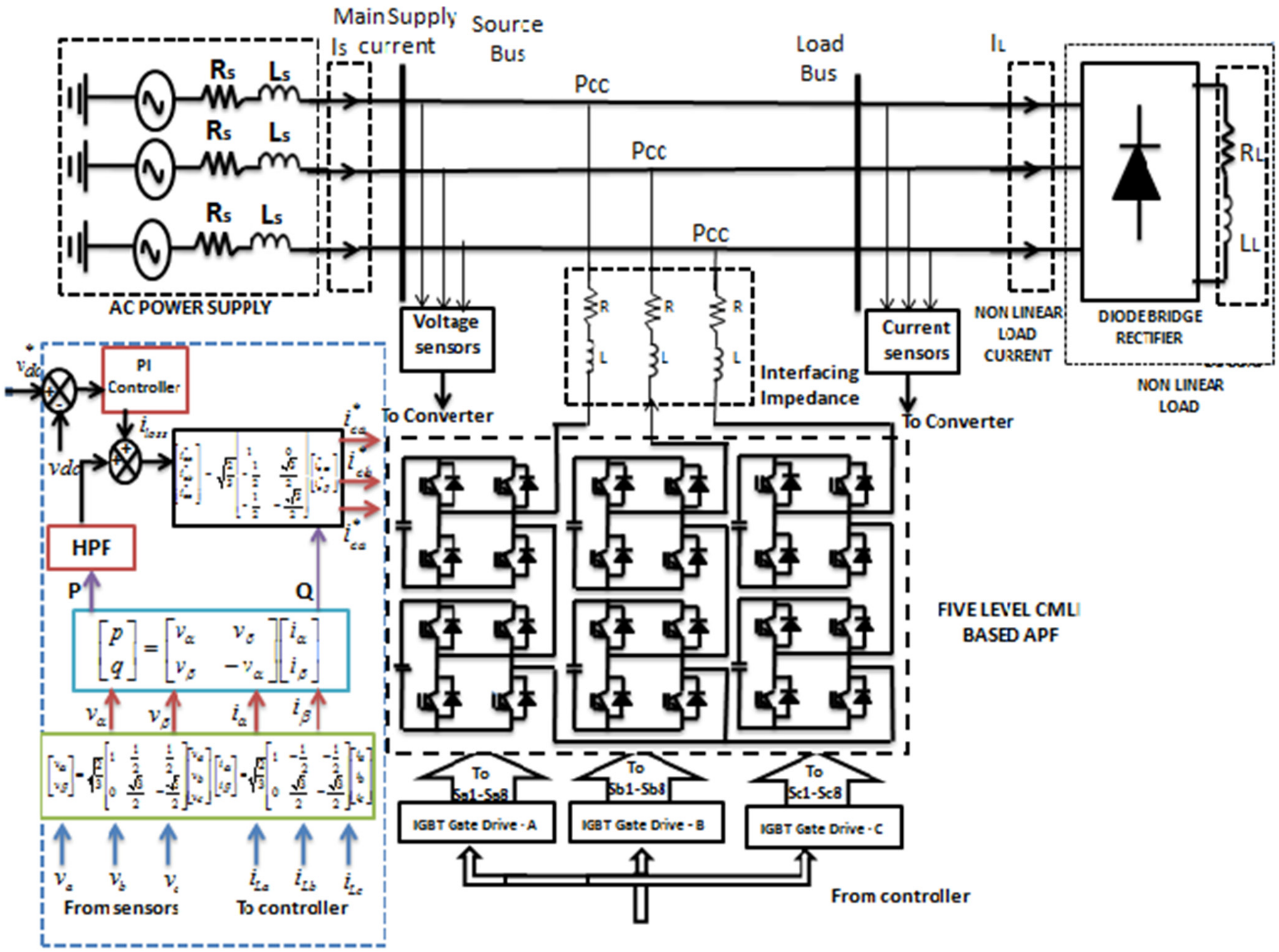

Figure 2: Five Level Cascaded H-Bridge Inverter based APF Configuration

3.1. PQ Control Strategy

PQ theory was proposed by H. Akagi [9]. Figure 3 shows the procedure for derivation of compensating currents. The three phase source voltages and load currents are transformed to $\alpha - \beta$ axis coordinates by using Clarke's transformation. The calculated real and reactive powers can be separated into average $(\bar{p}, \bar{q})$ and oscillating parts $(\tilde{p}, \tilde{q})$.

The undesired portions of real power and reactive power that are to be compensated are used for the calculation of reference currents in $\alpha - \beta$ axis. By using Inverse transformation these currents are transformed into $a - b - c$ axis coordinates. The resultant currents are instantaneous values of three phase compensating reference currents.

3.2. Power Circuit

A Five level Cascaded H-Bridge Inverter is modeled in this paper. Each phase requires 8 switches and 2 DC voltage sources. Among all Multilevel Inverter Configurations, Cascaded Multi Level Inverter has the following advantages.

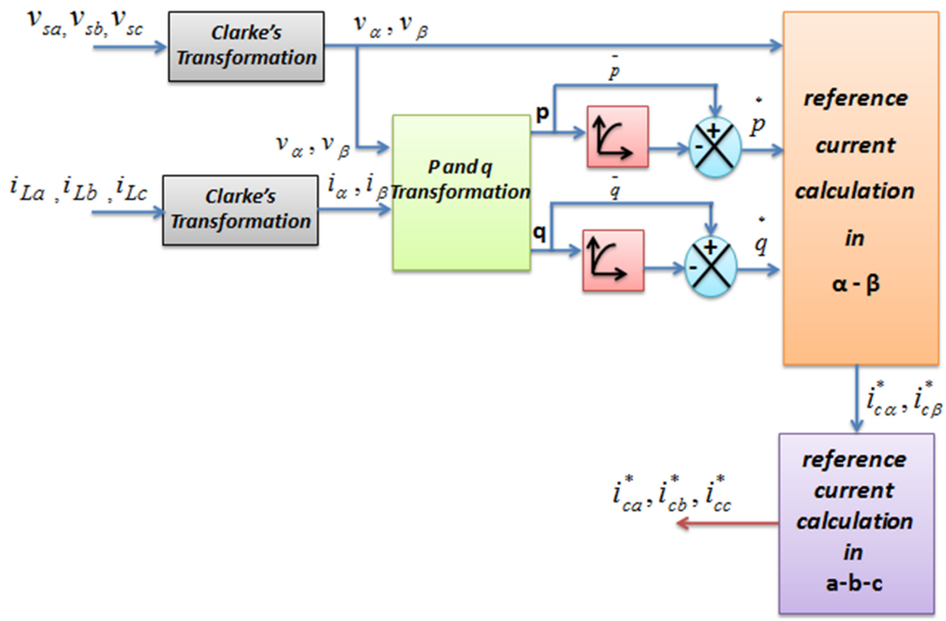

Figure 3: Reference Current Calculation

- Requirement of reduced number of controlled switches, diodes and capacitors.
- Easy to implement.
- Reduced THD in output voltage and current waveforms and
- Improved Power Factor.

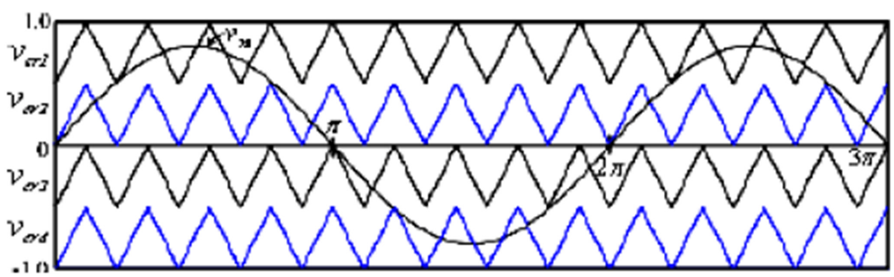

Figure 4: Reference and Carrier waves of Phase Disposition Level Shifted PWM

Level Shifted PWM Strategy is used to generate gate signals for the proposed converter. In Phase Disposition, Phase Disposition Opposition and Opposite Phase Disposition are different methods of Level Shifted PWM Control technique. In Phase Disposition is implemented in this paper. All the carrier signals will have same frequency, with same amplitude and phase in an In-Phase Disposition Level Shifted PWM Technique. When the reference sinusoidal interacts with the carrier level signals, pulses are generated that drive the switches of VSI accordingly. Figure 4 depicts the reference and carrier waves for In Phase Level Shifted PWM. The carrier frequency is mentioned in Table 1.

3.3. PI Controller

Block diagram of PI controller is shown in Figure 5. By trial and error method, values for proportional and integral gains are considered to be 0.8 and 0.5. A comparison of the sensed DC bus voltage to the reference DC bus voltage of VSI results in a voltage error, which, in the n^{th} sampling instant, is expressed as:

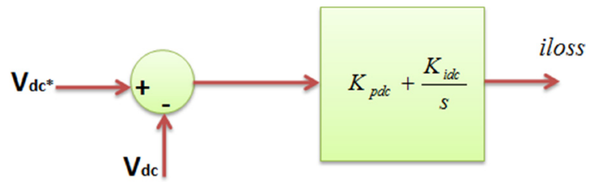

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Figure 5: Block Diagram of PI Controller

$$v_{dcl}(n) = v_{dc}^{*}(n) + v_{dc}(n) \tag{1}$$

This error signal $v_{dcl}(n)$ is processed in a PI controller, and the output $\{I_p(n)\}$ at the n^{th} sampling instant is expressed as

$$I_p(n) = I_p(n-1) + K_{pdc}\{v_{dcl}(n) - v_{dcl}(n-1)\} + K_{idc}v_{dcl}(n) \tag{2}$$

where, K_{pdc} and K_{idc} are the proportional and integral gains of the PI controller. The output of this PI controller accounts for the losses in APF.

4. SIMULATION RESULTS AND DISCUSSION

Table 1
Parameters Chosen

Parameter	*Value*
Source Voltage (Ph-Ph RMS)	11 KV
Source Impedance	0.1+j0.282 Ω
Load Impedance	250+j37.6 Ω
DC Link Capacitance	1500 µF
Proportional Gain	0.8
Integral Gain	0.5
Carrier frequency of level-shifted PWM	3050 Hz
Interfacing Impedance	0.001+j0.01 Ω

Case 1: Without Active Power Filter

The Three phase-Three wire system feeding a non-linear load with prescribed parameters is simulated without APF and the following results are obtained.

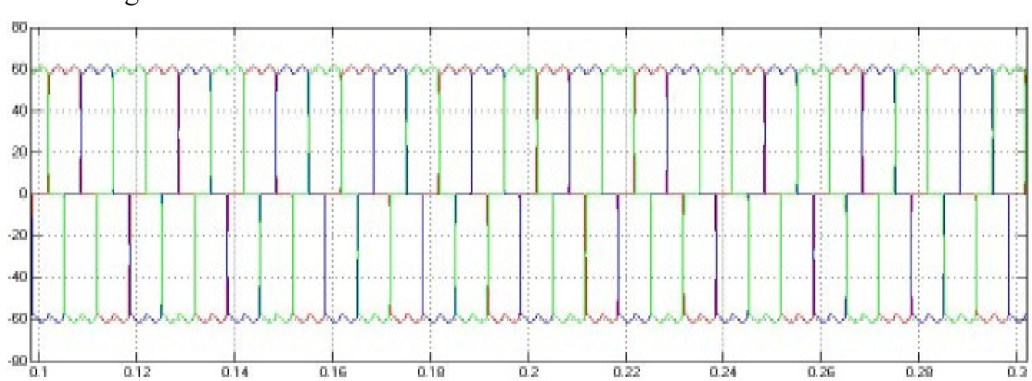

Figure 6: Simulink result of Load Currents

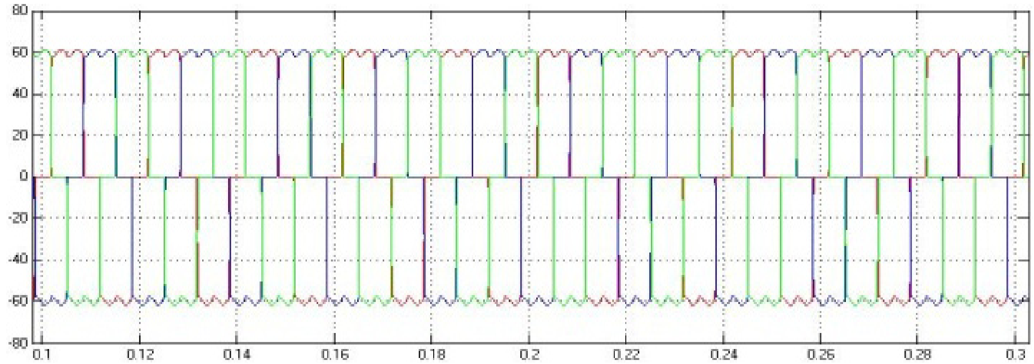

Figure 7: Simulink result of Source Currents

As shown in Figure 6 the waveform of load currents is distorted which in turn disturbs the source currents at PCC. The distorted source currents waveform is shown in Figure 7.

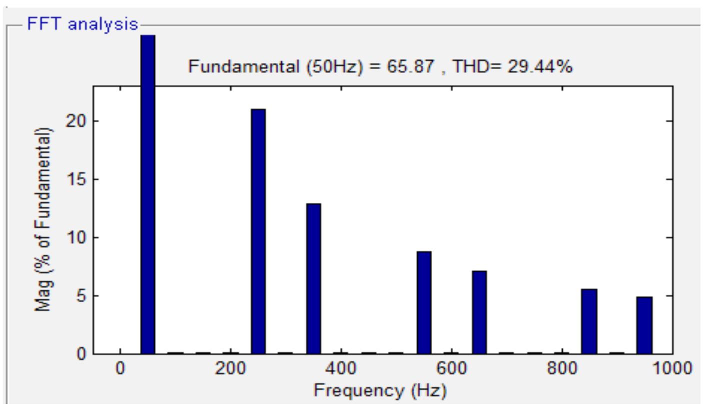

Figure 8: Harmonic Spectrum of Load Current

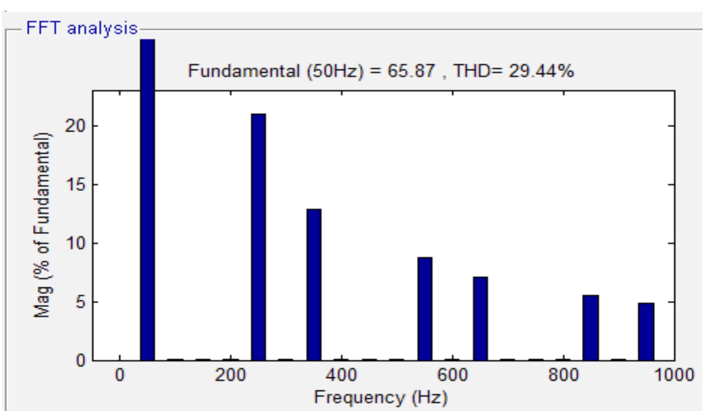

Figure 9: Harmonic Spectrum of Source Current

Figure 8 and Figure 9 display the harmonic spectra of load current and source current without APF. It is observed that %THD in load current is 29.44% and %THD in source current is 29.44%.

Case 2: With Active Power Filter and Fixed Load

The Three phase-Three wire system feeding a fixed non-linear load (parameters given Table 1.) is simulated with APF and fixed load. Following results are obtained.

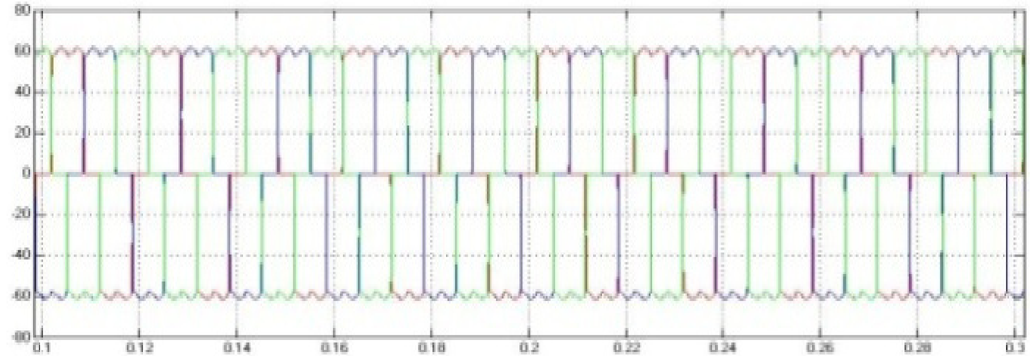

Figure 10: Simulink result of Load currents

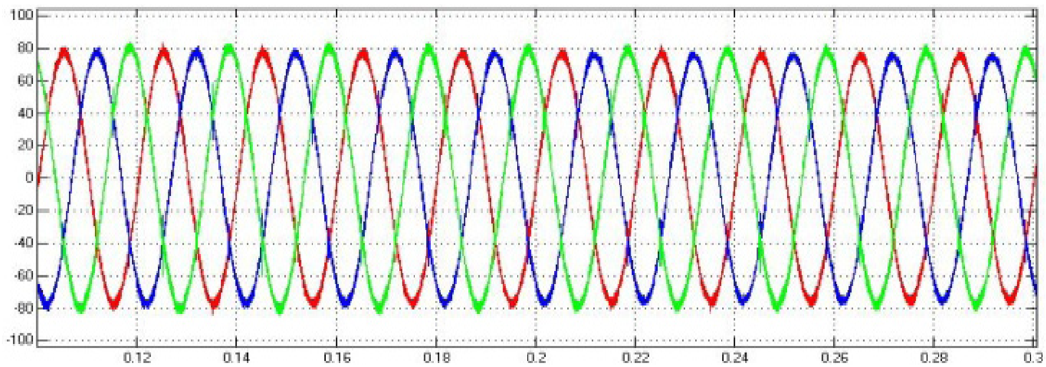

Figure 11: Simulink result of Source Currents

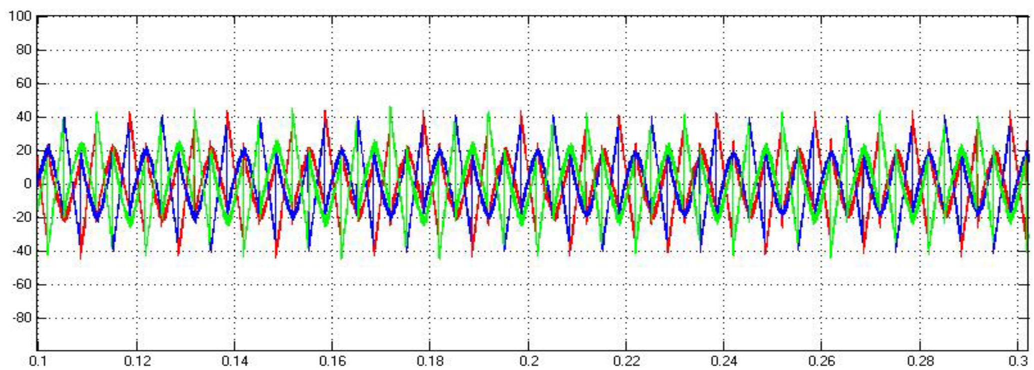

Figure 12: Simulink result of Filter Currents with Five Level APF having Fixed Load

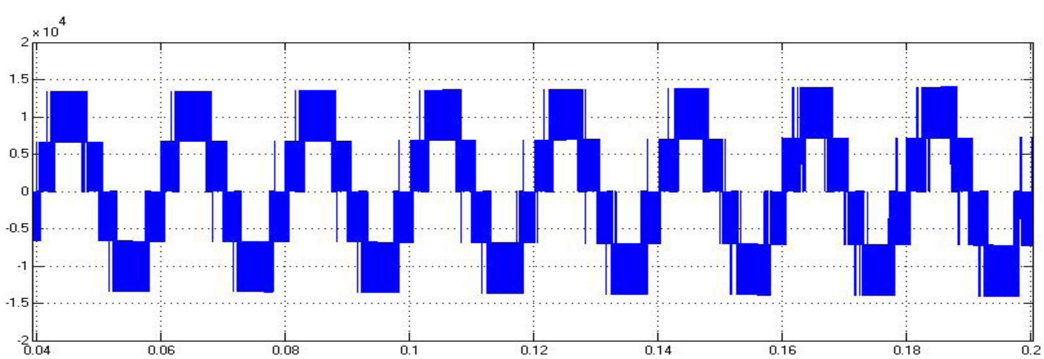

Figure 13: Simulink result of Output Voltage for Five Level APF

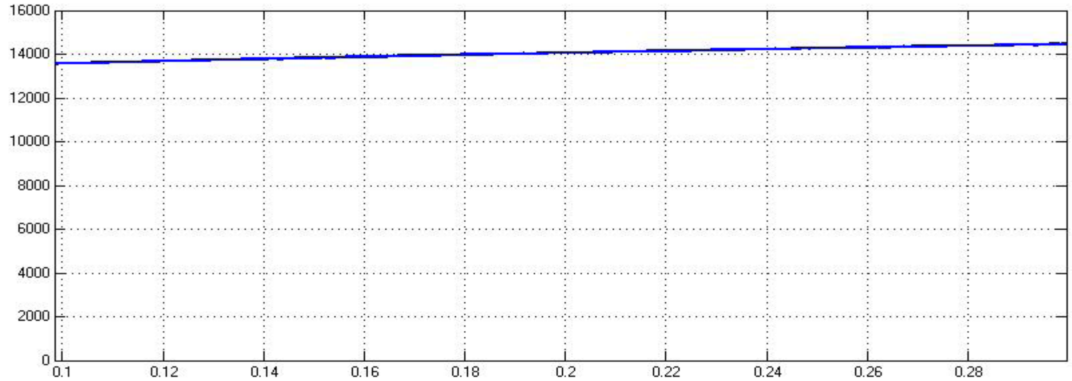

Figure 14: Simulink result of DC Link Voltage

As observed in Figure 10, the waveform of load currents is distorted. Figure 11 shows that the waveform of source currents is almost sinusoidal due to the presence proposed APF. Figure 12 shows the compensating filter currents injected by proposed APF at PCC. Figure 13 shows the five level output voltage of power converter. Also it is observed that the DC link capacitor voltage is maintained almost constant as shown in Figure 14.

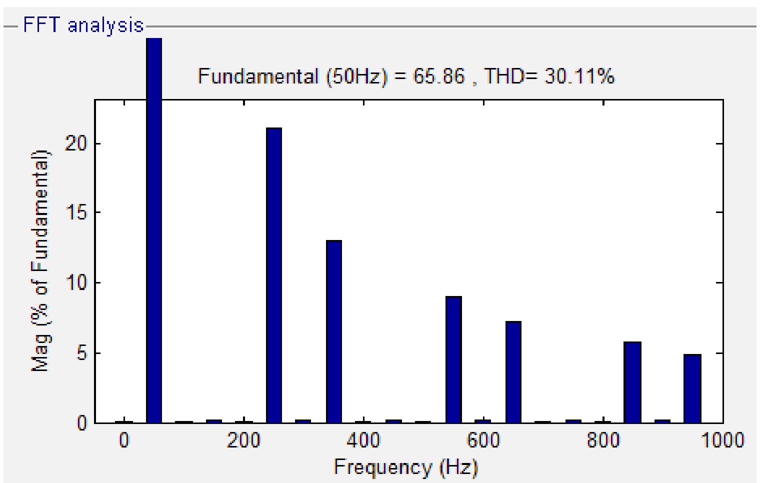

Figure 15: Harmonic Spectrum of Load Current with APF and Fixed Load

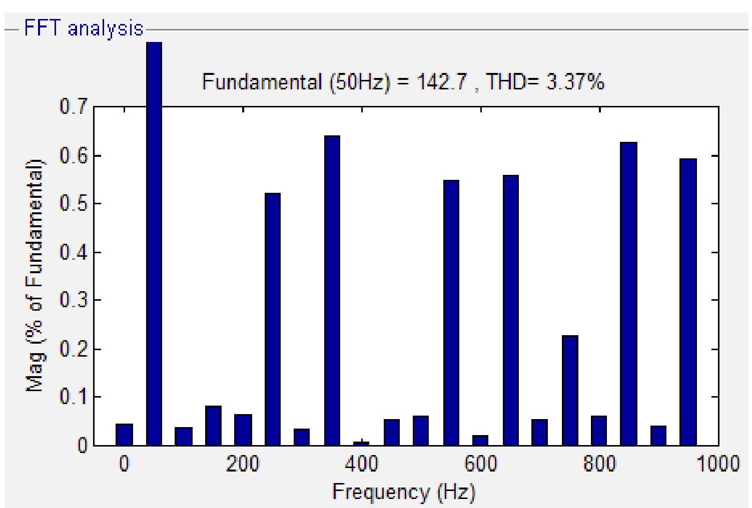

Figure 16: Harmonic Spectrum of Source Current with APF and Fixed Load

Figure 15 and Figure 16 depict the load and source current harmonic spectra respectively. Figure 15 shows that %THD in load current is 30.11 %. Also the source current has 3.37% of %THD when proposed APF is connected at PCC. It is observed that by implementing the Five Level Cascaded H-Bridge Inverter based APF; the Total Harmonic Distortion in the source current is reduced as compared to that of the system without APF (Case 1).

Case 3: With Active Power Filter and Variable Load

The Three phase - Three wire system feeding a variable non-linear load is simulated using proposed APF and the following results are obtained. The changes in the load are mentioned in Table 2.

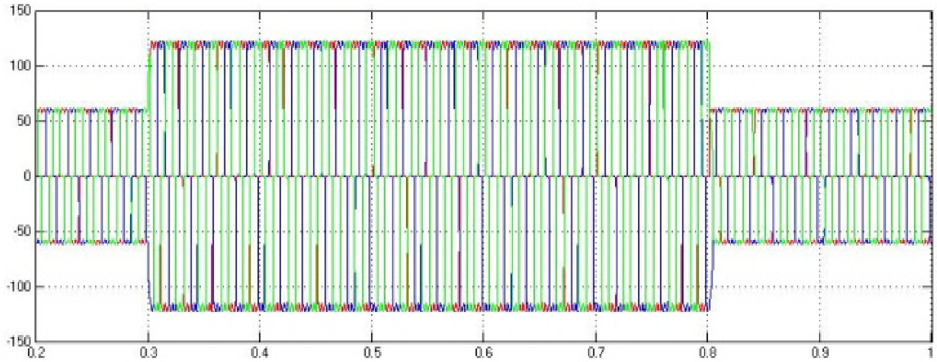

Figure 17: Simulink result of Load Currents

Figure 17 shows the distorted load currents waveform.

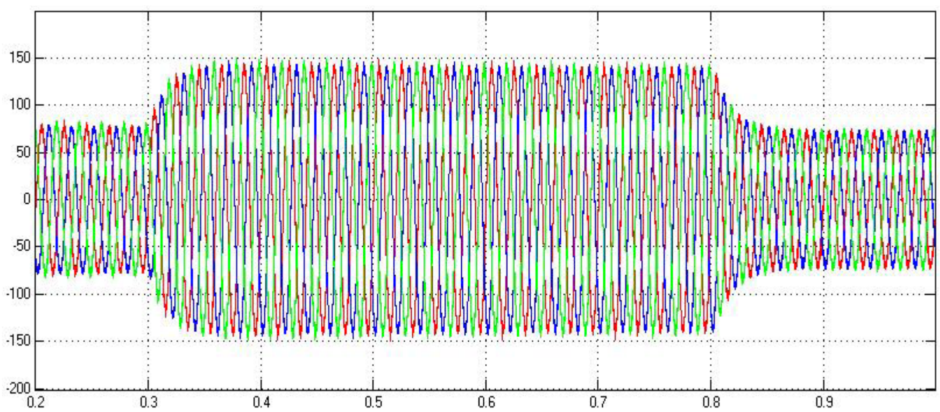

Figure 18: Simulink result of Source Currents

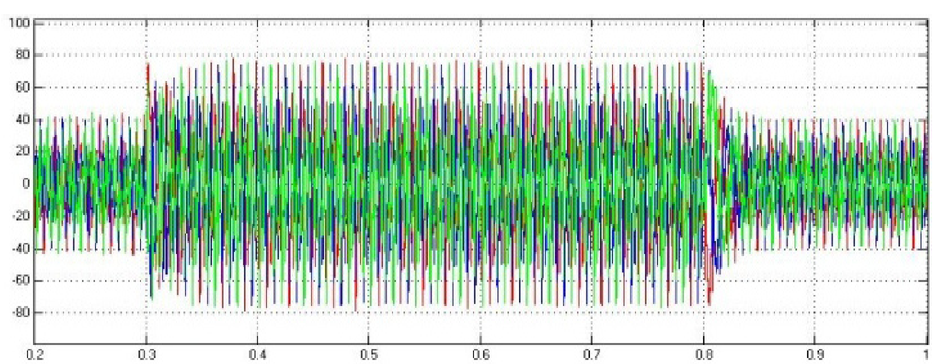

Figure 19: Simulink result of Filter Currents

Figure 18 shows the waveform of source currents when the proposed APF is conneced at PCC and non-linear load being variable. Figure 19 shows the correponding waveform of compensating filter currents injected at PCC.

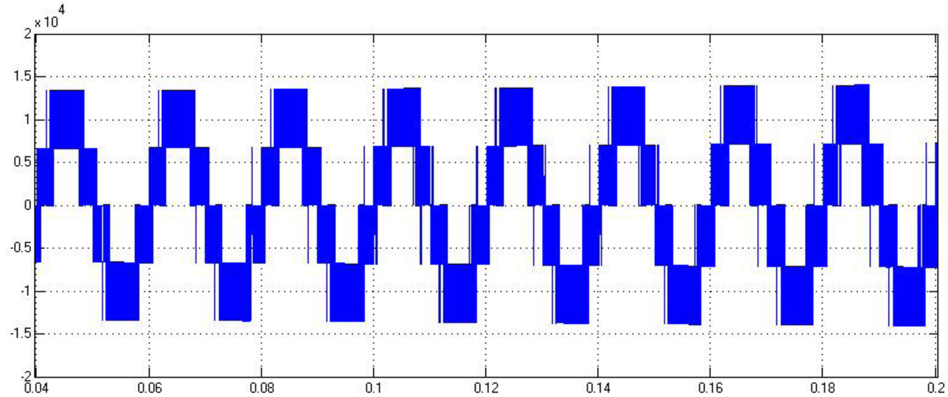

Figure 20: Simulink result of Output Voltage for Five Level APF

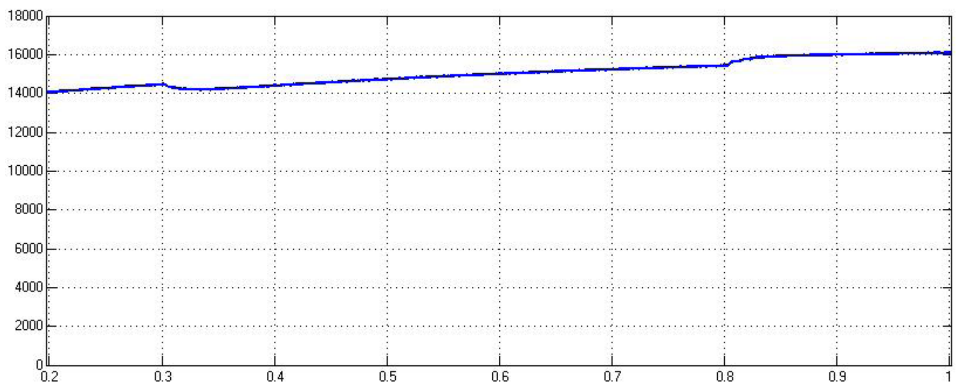

Figure 21: Simulink result of DC Link Voltage

Figure 20 shows the five level output voltage of power converter. It is also observed from Figure 21 the voltage across DC link capacitor.

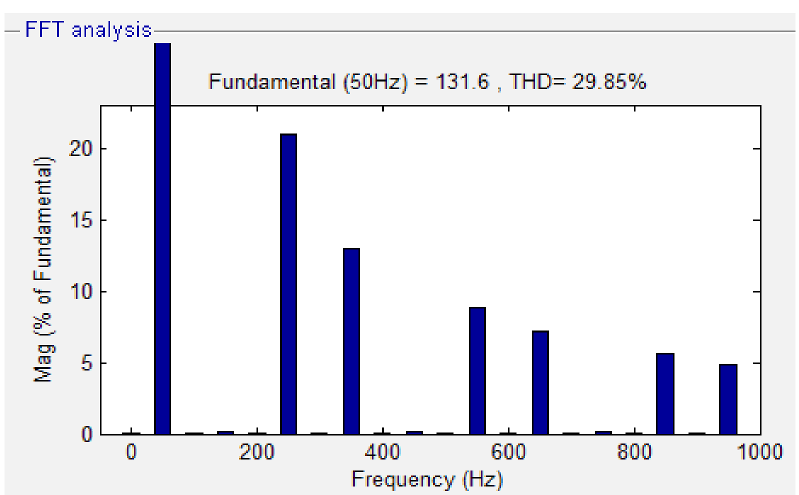

Figure 22: Harmonic Spectrum of Load Current with APF and Varying Load

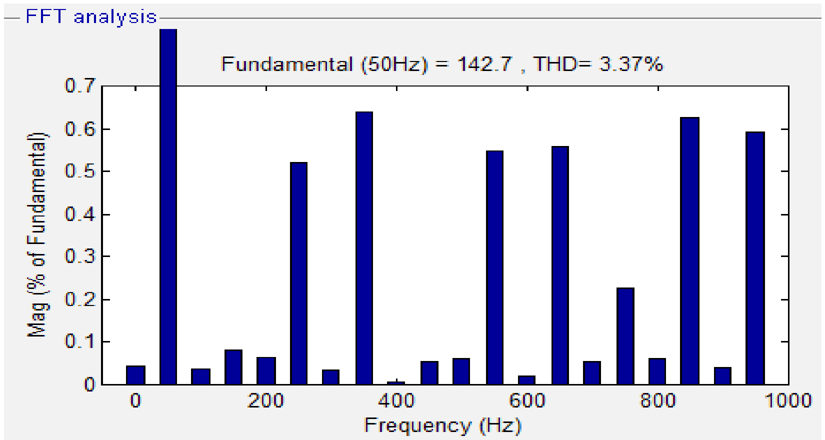

Figure 23: Harmonic Spectrum of Source Current with APF and Varying Load

It is shown in Figure 22 that %THD in load current is 29.85 %. The source current contains %THD of 3.37 % as shown in Figure 23.

Table 2 represents %THD value comparisons for different cases. When there is no APF in the system feeding non-linear loads, %THD is high and when APF is connected, %THD of source current drops to acceptable values. Table 3 represents %THD values of source currents when there is a change in load (for Case 3). For the changes in load, the %THD value is found to be within reasonable limits, thus validating the system. This proves that even when the system undergoes frequent load changes, % THD of source current and Power Factor remain within acceptable limits.

Table 2
THD Comparison

Condition of the system	*%THD of Source current at PCC*	*Power Factor*
System without APF	29.44 %	0.65
System with APF having fixed load	3.37 %	0.998
System with APF with increased non-linearity (Full Load)	3.37 %	0.998

Table 3
THD Comparison with changes in load

Condition of the system	*%THD of Source current at PCC*	*Power Factor*
20 % of Full Load	3.38 %	0.998
40 % of Full Load	3.36 %	0.997
60 % of Full Load	3.35 %	0.997
80 % of Full Load	3.36 %	0.998
Full Load	3.37 %	0.998

5. CONCLUSIONS

The performance of Five Level Cascaded H-Bridge Inverter based APF is validated considering three different cases: system without APF, system with proposed APF having fixed load and system with proposed APF having variable connected load. Simulink models of the system are developed for all the cases and results are discussed in detail. The corresponding results of %THD and Power Factor for all cases are tabulated. With Five Level Cascaded Inverter based APF, even though under varying load conditions, the %THD value of source current is maintained under normal values. DC link Voltage is also maintained constant by using proposed APF. A five level output voltage is obtained which may be suitable for speed drive applications. The advancements in the operation of APF may be extended to eliminate other power quality disturbances like flicker, notches etc. Results validate the application of shunt APF for different loading conditions.

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