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Design and development of harmonic filters for harmonics reduction in polluted distribution network

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ABSTRACT

Recently due to development in the power electronics sector, there is a tremendous increase in nonlinear loads. These nonlinear loads cause distortion in the system current and result in degrading quality of power. The poor power quality causes technical and financial losses in the system which necessitates adoption of techniques to reduce the harmonic distortion to meet IEEE-standards and improve system efficiency. As per literature, passive, active and hybrid filter techniques are implemented to mitigate the harmonics. Each has merits and demerits. Constructive reduction in current harmonics improves the life and efficiency of equipment's also assists to improve power quality and relieves penalties imposed by utilities. In this work, an attempt is made to give a detailed approach used in the designing of harmonic filters. This study will provide a broad outline to the engineer, researcher and consultant working in the field of power quality to design filters for the case under study. The steps to design the filters are well explained with mathematical equations and examples for greater insight. To validate the performance of the filter a MATLAB/Simulink platform is utilized. The outcome of the simulation result proved that current harmonics are minimized with a substantial amount.

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1. INTRODUCTION

Harmonics are integer multiple of the fundamental component of current signal caused by the nonlinear nature of load connected to the system causing poor power quality. The major nonlinear equipment's are variable speed drives used in various industrial processes, power converters in renewable sectors, welding machines, computers, printers and power backup in information technology (IT) industries. These harmonics have a severe impact on the electrical power system. It causes overheating of transformers and motors due to increased losses, malfunction of protective system, heating of cable, failure of capacitor bank, and lightning arrestor. These current harmonics circulate in the system and cause voltage distortion affecting other consumers in the network [1]-[3].

The methods available to filter out these harmonics are classified as passive, active and hybrid. The choice of the methods depends upon the requirements, cost and amount of distortion. Many research papers are available on the passive filters and active filters used for harmonic reduction techniques. It has been noticed that in many research papers, the procedures adopted for the design of harmonic filters are not presented in a clear, systematic manner. While numerous works available on the design of passive filters including mathematical formulations, and various theories adapted for the control of active filters, there is a notable lack of a systematic, straightforward framework that effectively consolidates the design process. Consequently, there remains a gap in the literature for a simplified and effective methodology that provides engineers, researchers, and consultants with a comprehensive understanding of the fundamental assumptions, mathematical equations, and standard procedures required for designing both single-tuned passive filters and power electronics-based active filters.

The objective of this work to provide complete guidelines for designing passive and active filters for engineers, consultants and researcher. Here the procedure involved in designing the passive filter and active is explained with mathematical equations and assumptions to be considered while designing and also illustrated with examples for better comprehending. The MATLAB/Simulink platform is used for implementing the system and the results are observed to validate the performance [4]-[6].

The article is organized as follows: section 2 describes the passive techniques applied for harmonic reduction in industries in detail with mathematical formulas. The most economical technique using tuned passive filter adopted in the industries is described in detail with one case study for practical demonstration. Section 3 describes the detailed procedure followed for the designing of the active power filter (APF) and components selection ratings. The simulation study of the nonlinear system without compensation method and using passive filter and active filter techniques for reduction of harmonics is described in detail section 4. The conclusion and future scope of research work is presented in section 5 followed by the references.

2. PASSIVE TECHNIQUES

2.1. Alternating current line reactor

Reactors are put at the input side of the variable speed drives on the supply side. The main purpose is to reduce harmonics, voltage surges, and spikes and to reduce noise. This is an economical solution being adopted for small reduction in harmonics. The current rating of the reactor is based on the drive full load current and impedance is measured in % impedance (%Z). The percentage impedance represents the nominal voltage drop across impedance and is given by (1):

$$\%Z = \frac{L*I*2\pi f}{V_{LN}} \quad (1)$$

here I is drive current, L is reactance in mH, f is supply frequency in Hz and V_{LN} is phase voltage. Standard reactors available are 1.5%, 3%, and 5%. Generally, 3% impedance is put for many drives in industries [7].

2.2. Direct current choke

Direct current (DC) choke is used along with variable speed drive and is placed between rectifier output and DC bus link. The purpose of this DC choke is to protect DC capacitor by reducing losses, reduce voltage spikes and decrease harmonics on source side [7]. The rating of the DC bus is based on DC bus average current. It is calculated using (2) for given KW machine.

$$I_{rec\ av} = \frac{Motor\ KW}{V_{dc}*\eta_m*\eta_{inv}*\eta_{pf}} \quad (2)$$

Here Vdc is DC bus voltage which is 1.35* RMS AC, $I_{rec\ av}$ is average DC output current of rectifier, η_m and η_{inv} are motor and inverter efficiency, η_{pf} is inverter power factor. Inductance value of DC choke in mH is given by (3).

$$L = \%Z * \frac{V_{DC}}{2*\pi*f*I_{rec\ av}} \quad (3)$$

2.3. Passive filters

Passive filter is the most traditional and economical method adopted by the industries. It is a combination of R, L, and C components. Different topologies are available but the single tuned is most commonly preferred for reducing low order dominant harmonics having large amplitude. Passive filters are either series connected or shunt connected to either block or bypass the harmonics. Mostly shunt passive filter tuned to a particular harmonic frequency is adopted method. Along with harmonic reduction passive filter aid to improve power factor by providing required reactive power [8]-[11].

Passive filter suffers from various flaws such as large size, resonance with system impedance, and resonance with capacitor bank causing failure. Also, it has a slow response under variable load conditions causing overloading of the C component of passive power filter (PPF), and its characteristics are altered due to aging factor which is difficult to change for tuning frequency. Figure 1 shows a few topologies of passive filters.

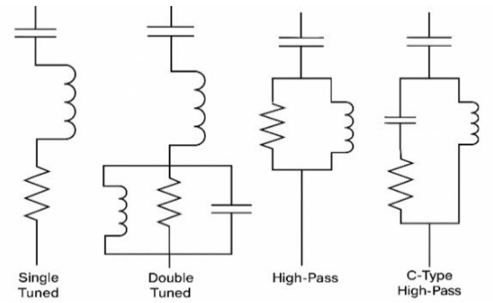


Figure 1. Common passive filter topologies

2.3.1. Design of single tuned filter

The characteristic of single tuned filter for resonant frequency is as shown in Figure 2. While designing the passive filter tuned to particular frequency based on the harmonic distortion level, the following criteria and steps are followed in selecting the filter parameters.

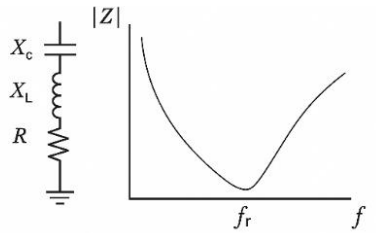


Figure 2. Single tuned filter

The first step is to find the KVAr size of the capacitor needed to compensate for reactive power and to improve power factor expressed by (4):

$$Q_{cKVAr} = P\{tan(cos^{-1}pf_1) - tan(cos^{-1}pf_2)\}\ KVAr \quad (4)$$

here P is power in Watt, pf_2 is desired power factor, pf_1 actual power factor.
Next step is to compute reactance of the capacitor (X_c) using (5):

$$X_c = \frac{Vph^2}{Q_{cKVAR}} \quad (5)$$

here V_{ph} is the phase voltage and Q_c is the KVAr capacity of the filter.
The component C of the passive filter is computed by (6):

$$C = \frac{1}{2\pi f X_c} \quad (6)$$

The component L of the passive filter is determined based on resonance frequency using (7). The resonance frequency (f_r) and harmonic frequency (f_h) to be mitigate are considered as same.

$$f_r = \frac{1}{2\pi\sqrt{L*C}} \quad (7)$$

The component L is computed by (8):

$$L = \frac{1}{(2\pi f_h)^2 C} \quad (8)$$

Harmonic frequency is obtained by multiplying fundamental frequency with harmonic order.

$$f_h = f * h$$

Here h is the order of harmonics and f is the fundamental frequency.
The component R based on quality factor (Q) is given by (9):

$$R = \frac{2\pi f_h L}{Q} \tag{9}$$

where Q is quality factor (20-100) and high Q gives best reduction in harmonics

2.3.2. Kores India Ltd, Dhatav MIDC–a case study for passive filter design and installation

One case study of Kores India Ltd, Dhatav MIDC, the pharmaceutical industry is considered to demonstrate the steps followed while designing the parameters of single tuned filter. KRYKARD ALM 31 power quality analyzer is used for the measurement of various parameter at PCC at kores India Ltd, Dhatav MIDC. Table 1 gives the various parameters noted by the power quality analyzer. From harmonics analysis, it was found that low order 5th harmonics was dominant. By following the steps given by (4)-(9) for designing the R, L, and C components of a single tuned harmonic filter the values listed in Table 2 are gained.

Table 1. Data at PCC using KRYKARD ALM 31 power quality analyzer

Names	Phase values
Voltage (V)	235.55 V
Current (I)	242.7 A
Power factor (Pf)	0.776
Apparent power (S)	177.39 KVA
Reactive power (Q)	107.20 KVAr
Active power (p)	138.53 KW

Table 2. Calculated design parameters for single tuned passive filter

Qc (KVAr)	X_c (Ω)	C (μF)	L(mH)	R (Ω) for Q=100	Method
92.50 KVAr/ph	0.6	5307	0.076	0.003	By using design equations
276 KVAr (3-Ph), 415 V	0.6	5296.06	0.0813	0.002	Online calculator

For designing the parameters initial power factor value is pf1=0.776 which is to be improved to pf2=0.99. Also, design parameters are observed using online harmonic passive filter design calculator. It can be observed that the values calculated by the mentioned design steps and the online calculator appear nearly similar.

3. ACTIVE HARMONIC FILTER TECHNIQUE

To overwhelm the shortcomings of passive filter power-electronics based APFs is enraptured the interest of engineers to trap the harmonics in the power system. The APF operation is based on supplying the equal and phase opposite components of harmonics at the connection point generally termed as point of common coupling. This will cancel the distortion frequency component and keep the supply source sinusoidal. The functioning of APF is not hampered by system parameters. APF generated a wide spectrum of harmonics using fast operating power electronics switches. In addition to harmonic reduction, APF improves reactive power demand, flicker and voltage imbalance [12], [13].

The performance of APF is enormously impacted by the controller which is a crucial part of it. The advancement in the embedded system causes use of microcontrollers and digital signal processor (DSP) processors for controlling the APF. The major part of controlling the APF comprises signal conditioning, reference signal generation, DC capacitor voltage control and lastly controlling power electronics switches. Various time domain and frequency techniques are adopted for reference current generation. With advancements in artificial intelligence reference current can be generated effectively. Commonly proportional integral (PI) controller is used to supervise DC voltage but due to tuning of gain under variable load conditions fuzzy logic, artificial neural network (ANN), fuzzy logic combined with ANN (fuzzy-ANN), and adaptive fuzzy are becoming popular control techniques. For generating a switching signal pulse width modulation (PWM) methods and artificial intelligence methods are employed. To overcome the problem in high power system hybrid filter which take benefit of both passive and active filter is an admirable solution [14]-[18].

3.1. Block diagram of shunt active filter

As shown in Figure 3 it can be seen that the control of APF involves the generation harmonic mitigation current using reference current techniques, DC link control and gate pulse for switching devices. For the effective operation of APF apart from control strategies the selection of various hardware components plays a critical role. The major components of APF are the DC link capacitor, voltage rating of the capacitor, selection of the coupling inductor, switches rating, and power rating of APF. In this study, the design of APF is proposed for 3-ph system. Assumptions followed during the design involve switching frequency greater than highest order of harmonics, linear modulation for PWM switching, and 5% distortion on the AC side line current for the coupling inductor and sinusoidal source [19]-[21].

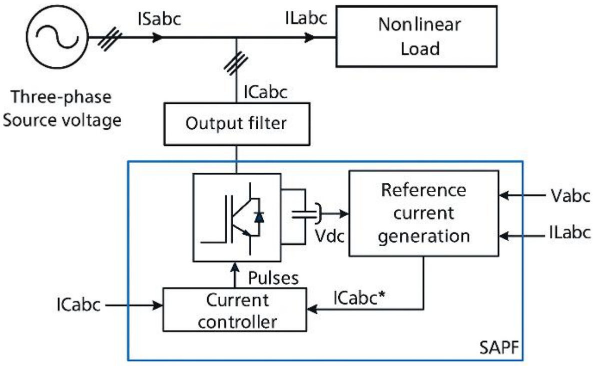


Figure 3. APF working diagram

3.1.1. Direct current capacitor voltage

The peak value of source line voltage decides the capacitor voltage. It is incumbent that capacitor voltage exceeds the line peak value to operate with complete AC cycle. It is computed using (10):

$$V_{DC\ bus} = \frac{2\sqrt{2}\ V_{LL}}{\sqrt{3}\ m} \tag{10}$$

here m denotes modulation index assumed to be 1 and V_{LL} denotes source line voltage.

For realising control of APF as in (11) for injecting current with linear modulation and assuming inductor AC side.

$$V_{DC} = 2\sqrt{2}\ V_C \tag{11}$$

Here the permissible value of converter output voltage Vc is (Vs to 2Vs) and Vs is phase value at PCC. Hence for ensuring the operation of APF, $2\sqrt{2}V_S < V_{DC} \leq 4\sqrt{2}V_S$.

3.1.2. Direct current capacitor of voltage source inverter

DC capacitor value is based on rise and drop of bus voltage with changing load. Using energy balance principle, the value of DC capacitor is computed by (12):

$$0.5C_{DC}\,[(V_{DC}^2) - (V_{DCmin}^2)] = 3V_{ph}(\alpha I)t \tag{12}$$

here V_{DCmin}^2 is lower limit of bus voltage, t is time taken to recoup the voltage, α is overloading factor and I is APF phase current.

By second approach of second harmonic ripple voltage prompted owing to load imbalances at DC bus in (13):

$$C_{dc} = \frac{I_{APF}}{(2\omega V_{DC\,ripple})} \tag{13}$$

here I_{APF} is current rating of APF obtained from KVA rating of filter, $V_{DC\,ripple}$ ripple in DC voltage with limit of 1-3% of V_{DC}.

3.1.3. Alternating current inductor

The inductor at the AC side of APF is found by (14):

$$L_f = \frac{\sqrt{3}\, mV_{DC}}{12\ a\ f_s I_{Crpp}} \quad (14)$$

here I_{Crpp} is current ripple with limit of 5-10% of APF current, a is 1.2, fs is switching frequency, and m is modulation index m.

3.1.4. Voltage rating of switching device

The voltage rating of switches with dynamic conditions is expressed by (15):

$$V_{SW} = V_{DC} + V_{overshoot} \quad (15)$$

here overshoot in the DC bus voltage is taken as 10%.

3.1.5. Current rating of switching device

The current rating of the switches with dynamic conditions is expressed by (16):

$$I_{sw} = 1.25\left(I_{ripple} + I_{peak}\right) \quad (16)$$

where, I_{peak} is the peak value of the filter current and I_{ripple} is the allowable ripple.

3.2. Design of active power filter: a practical example

A 3-ph, 415 V, 50 Hz source is connected to 3-ph, 3 wire rectifier as nonlinear load with rectifier current 224.2 A. A source resistance and inductance are 0.04 Ω, 1 mH respectively. The APF components are calculated by following the steps described previously:

a. Harmonic compensation current

RMS current at the rectifier input:

$$I\ RMS = 0.816 \times 224.2 = 182.9\ A$$

Fundamental current at rectifier input:

$$I_{fund} = 0.779 \times 224.2 = 174.65\ A$$

Harmonic compensation current is:

$$Harmonic\ compensation\ current\ (I_{comp}) = \sqrt{I_{RMS}{}^2 - I_{fund}{}^2} = 54.31\ A$$

b. Active filter rating in KVA

$$S_{APF} = 3 \times V_{ph} \times I_{comp}$$

$$S_{APF} = 3 \times 240 \times 54.31 = 39\ KVA$$

Taking into account dynamic condition consider 25% extra rating

$$S_{APF} = 39 \times 1.25 = 48.75\ KVA \cong 50\ KVA$$

c. DC link voltage

Using (10) and putting line voltage 415 V and with modulation index 1, the value of link voltage V_{DC} is 677.69 V which is selected as 700 V.

d. DC bus capacitor

Using (12) of energy balance with phase voltage 240 V, DC voltage 700 V, V_{DCmin} voltage 678 V, time to recover 0.05 s, and current (I) 25% more than phase current of APF the capacitor (C_{dc}) is 19897 µF which is taken as 20000 µF.

By alternative approach using (13): I_{APF}=KVA/DC link voltage=50×1000/700=71.42 A, $V_{DC\ ripple}$=7 V (1-3% of V_{DC}), C_{DC} is 16238 µF and taken as 20000 µF.

e. AC inductor

The AC inductor with 5-10% current ripple, modulation index 1, DC link voltage 700 V, and switching frequency 10 KHz using (14) is 0.8 mH which is considered as 1 mH.

f. Voltage rating of insulated gate bipolar transistors (IGBT)

By 10% overshoot in DC voltage, rating of switch using (15) is:

$$V_{DC} + V_d = 770\ V$$

IGBT of 1200 V can be selected with safety margin.

g. Current rating of IGBT

By assuming peak value of APF current and ripple, switch current rating is 135 A. Therefore, with suitable safety factor IGBT of 300 A is selected. The final values of active filter components are listed in Table 3.

Table 3. Calculated design components of APF

Parameters	Values
DC link voltage	700 V
DC link capacitor	20000 µF
Interfacing inductor	1 mH
IGBTs rating	1200 V, 300 A

3.3. Sizing of nominal current

The active filter current rating is finalized based on the harmonic content in system obtained by harmonic analysis study. Generally, APF current rating should be 20% more than highest harmonics present in the system as in (17):

$$I_{filter} = 1.2 \times I_{Load} \times THDi \tag{17}$$

where, I_{filter} is nominal filter current, I_{Load} is maximum load current, and $THDi$ is total harmonic distortion.

4. SIMULATION RESULTS AND DISCUSSION

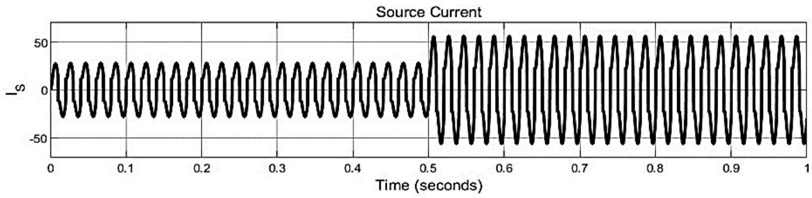
4.1. Simulation with passive filtering system

The performance of passive filter is observed by developing system using MATLAB/Simulink platform. The system parameters used for simulation are listed in Table 4. The single-phase distribution system is connected to the diode bridge rectifier fed RL load, representing as nonlinear load. The passive filter is tuned to dominant and severe 5^{th} order harmonic frequency. By considering reactive power mentioned in the Table 4, the R, L, and C component of passive filter are calculated by (4)-(9). The system is developed for single phase assuming balance system and the response is observed without filtering and after application of filter system. The RL load with diode bride rectifier generates distortion in source current due to nonlinear nature.

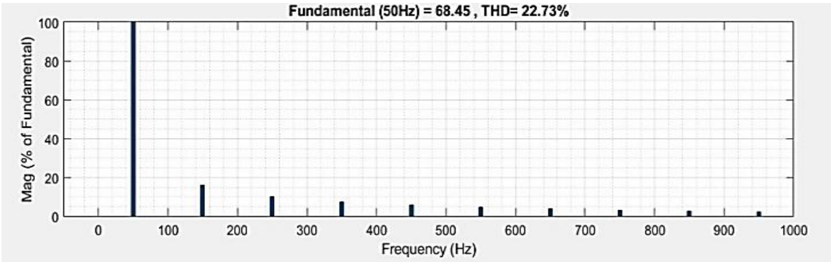
Table 4. Simulation parameters for single tuned passive filter

Source	Load	Single tuned passive filter (5^{th} order) Q=17.65 KVAr
230 Vrms (single phase)	Diode bridge rectifier with R-L load (nonlinear load) R=5 Ω, L=10 mH	C=325.03 µF, L=1.324 mH, R=0.0213 quality factor=100

The simulation model is run for 1 sec, with increase in load at 0.5 s. Figure 4 shows the source current waveform and its harmonic analysis in the absence of passive filter compensation. Figure 4(a) shows that the source current waveform is in the distorted form before the application of passive filter. Figure 4(b) shows that current THDi of source current is 22.73% without filter. The passive filter compensates the 5^{th} order harmonics effectively, reducing THDi to 7.76%. Figure 5 shows the performance of the system under nonlinear load condition after the application of passive filter. Figure 5(a) indicate that the source current waveform is slightly improved to sinusoidal. Corresponding harmonic spectrum of source current is presented in Figure 5(b).

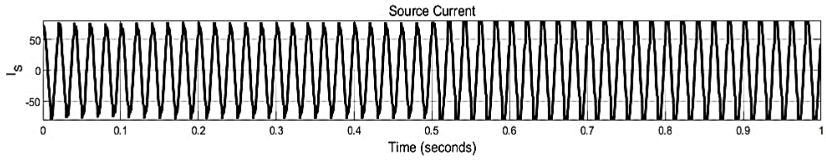


(a)

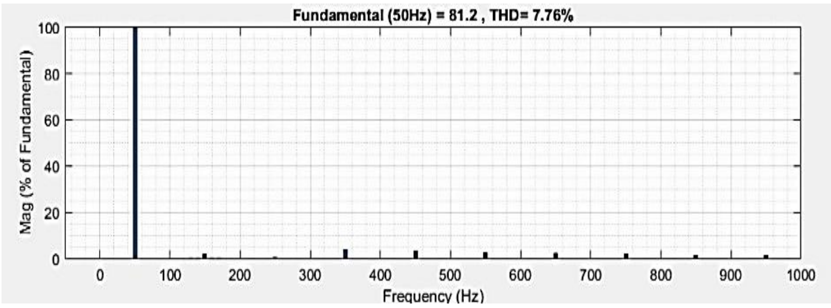


(b)

Figure 4. Performance analysis without passive filter; (a) source current waveform and (b) source current harmonic spectrum (FFT)



(a)



(b)

Figure 5. Performance analysis with passive filter: (a) source current waveshape and (b) source current harmonic spectrum

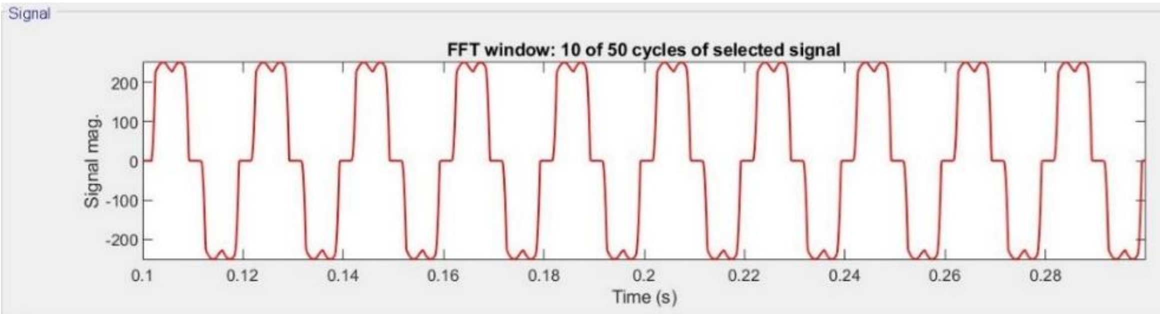
4.2. Simulation with active filter system

The performance of the APF is checked by simulating the system using MATLAB/Simulink. The system parameters used for simulations are listed in Table 5. To control the APF, the instantaneous reactive power theory suggested by Akagi is utilised for generating reference current, PI controller is utilised for supervising DC voltage and hysteresis current controller is applied as current control technique for generating switching signals for converter switches [22]-[25].

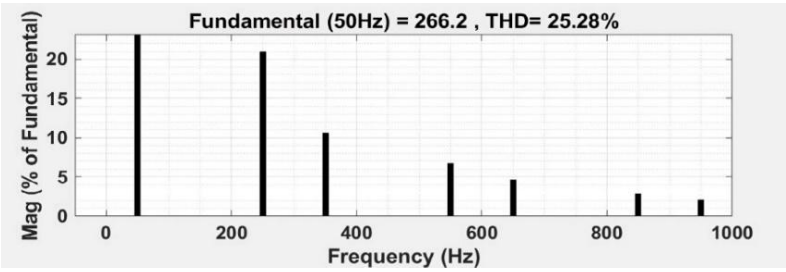
Table 5. System parameters for active filter simulation

System parameters	Values
Voltage source Vrms	3.3 Kv, 50 Hz
Source impedance	Rs=0.2 Ω Ls=0.34 mH
Coupling inductance	R_f=0.5 Ω L_f=0.003 H
DC link voltage	6500 V
DC capacitor (C_{dc})	2000 µF
Bridge rectifier with RL load	$R_{L=}$ 60 Ω, L_L=0.04 H

The performance of the system under nonlinear condition is represented in Figure 6. The simulation result reflects that without any filtering techniques; the source waveform is distorted as shown in Figure 6(a). The FFT analysis of the source current waveform shows that the THDi is 22.28%, as represented in Figure 6(b). Time domain analysis of the source current with the application of APF is shown in Figure 7. It is observed that the source waveform is improved to sinusoidal as shown in Figure 7(a). The FFT analysis for source current waveform shows that the THDi are reduced to 2.64 % as indicated in Figure 7(b). Thus, it is observed that THD are reduced from 22.28% to 2.64%, which indicate the effectiveness of APF to meet IEEE 519 standard. Overall simulation results are listed in Table 6.

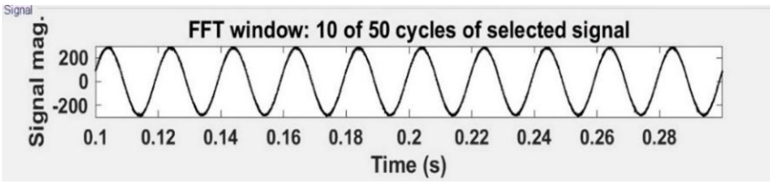


(a)

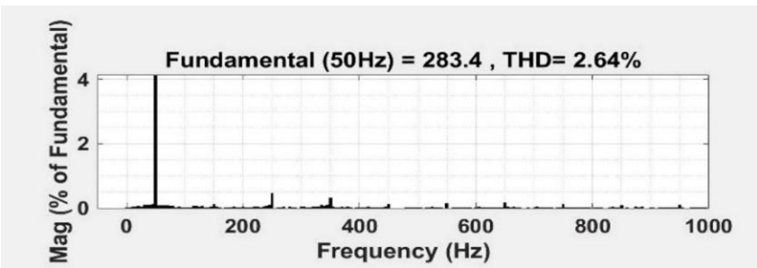


(b)

Figure 6. Performance of the system without active filtering: (a) waveform of source current and (b) FFT analysis of source current



(a)



(b)

Figure 7. Performance of the system with active filtering: (a) source current and (b) source current harmonic spectrum

Table 6. Simulation result with and without compensation

Passive filter		APF	
% THDi Without filtering	% THDi With filtering	% THDi Without filtering	% THDi With filtering
22.73%	7.76%	25.28%	2.64%

5. CONCLUSION

The adverse impact of current harmonics makes it crucial to identify and implement suitable reduction techniques. In this study, an attempt is made to give guidelines for designing passive and active filter techniques to the engineer, researcher and consultant working in the field of power quality. This study will help them to identify and implement a suitable approach for harmonic reduction. Here the design steps mentioned in the literature are followed to obtain various parameters for passive and active filtering techniques.

The performance is validated using a simulation developed in MATLAB/Simulink. The result of the simulation shows that the harmonics are substantially reduced using the passive filter from 22.7% to 7.76% and for the active filter from 25.28% to 2.64%. It is observed that the performance of the APF is superior to that of the passive filter. The choice of mitigation techniques depends upon cost, application and level of distortion. This work includes the basic design of passive and active filters to help researchers and consultants. Further, research can focus on the design of various topologies of passive filters with their merits and demerits. Detailed studies on the design of APF with various inverter configurations and topologies can be explored. Additionally, research can be extended by emphasizing more focus on systematic design of hybrid filter topologies.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Pranita R. Chavan	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			
Babasaheb R. Patil	✓			✓		✓	✓			✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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