NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

Department of Electronics and Power Engineering

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Power Quality Improvement of LV Systems using Active Power Filter

By

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To start with, this work would not have been possible without the blessings and support of my mother. She constantly kept me motivated and I truly acknowledge her effort in keeping me up for this work. Thank you so much mom for being on my side.

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In the end I would like to dedicate this effort to my father Yusuf Gul Khan (Late) who had dreamt of this day and its his vision that brought me at this stage. Thank you for every bit you did.

Power Quality Improvement of LV Systems using Active Power Filter

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ABSTRACT

The effects of prolonged power outages, high energy rates and demands of constant non-fluctuating power supply has given rise to distributed generation. In the modern world there is a liberty to every person to have his own personal generation sources (Domestic Generators, Solar Plants, Wind Turbines etc). Since these operate on switching devices such as AVRs, Inverters and Buck converters, they are prone to add in harmonics in the power system or national grid. These injected harmonics are severe for the system since they produce various problems like voltage fluctuations, increased THD etc. The power distribution system experiences contamination due to these issues, the system is termed as having poor power quality. The conventional method of passive filtering has existed over decades but the loads are getting more and more precision demanding. This demand has pushed research towards an active solution to harmonic filtering, called Active Filters. Practically, harmonics are not mitigated using passive filtering. Passive filtering being source of reactive power helps in improving power factor. In addition to this, passive filters are known to cause resonance in the system thus affecting stability of the system. On the other hand, Active Filters can be used to mitigate specific or a range of harmonics from the power distribution system.

The problem being addressed here is that due to non-linear loads and distributed generation sources the baseline distribution network gets contaminated with harmonic currents which then result in issues of Power Quality like voltage fluctuation and poor power factor. A solution is required to eliminate or mitigate current harmonics at LV side of distribution transformer making the source current sinusoidal and thus improving the power quality of the distribution network. This work proposes a shunt active power filter for small scale consumers who also rely on alternative source of generation for their facility. The model is mitigating harmonics and reducing the Total Harmonic distortion to the permitted bounds of IEEE. The system is verified by simulation using MATLAB/SIMULINK simulation package.

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Chapter 1

1. Introduction to Power Quality

The advancement in technology and increased use of switching devices and loads like computers and other equipments have cultivated the need to have power systems with more sophisticated power quality. Numerous literatures are available on Power Quality and immense research has been done in the area for last 3 decades. The primary focus of this chapter is on Power Quality definitions, evaluation, analysis, effects and remedies.

1.1 Power Quality - Definition

Power Quality is one of them most discussed topic in power industry nowadays. In its literal sense Power Quality means the quality of power delivered and this is measured and analyzed differently for different equipments. Power Quality points our different things in different scenarios. Like according to one of the understandings, the relative deviation of frequency from required value to supplied value to the customary end is power quality. Now this can be considered valid for Frequency drives and other equipments working primarily on frequency, like speed controllers. However for certain robust equipments, deviation in supplied voltage is considered power quality.

This work considers following definition of power quality and all the work is based on the concept derived from the definition given below:

Power quality is defined as the ability of Electrical Grid to supply steady and stable electrical power such that the source is always available, noise free, sinusoidal and within frequency and voltage tolerances.

1.2 Power Quality Measurement

There are strict basis for measurement of Power Quality as mentioned by IEEE. The measurement varies from equipment to equipment and system to system. Based on tolerance levels, the value regarded as poor power quality can be perfectly fine with other equipment. There are standards which are followed to define the tolerance levels and system deviations beyond the permitted standard are referred to as poor power quality.

The modern era equipments are mostly operated by sophisticated and delicate systems which have less endurance towards deviations and they are sensitive to fluctuations and flicker. Such equipment gets malfunctioned easily in a facility with poor power quality. Degraded power quality affects reliable and consistent operation of computers and systems that are delicate to frequency and voltage changes.

1.3 Power Quality Standards

Table **??** mentions a few standards prescribed and designed by various agencies worldwide.

1.4 Power Quality Evaluation

The evaluation of Power Quality is based on certain parameters. These parameters provide us a base to analyze the quality of power delivered. The three parameters analyzed mostly to evaluate power quality are:

i. Harmonics
ii. Voltage Fluctuation
iii. Power Factor

1.4.1 Harmonics

The non-linear impedances are the major reason of causing voltage and current harmonics in power system. These loads can be represented as harmonic current sources. The non-linear loads see the system voltage to be stiff and hence draws distorted current. These harmonic currents are the multiples of fundamental frequency. It is to be noted that harmonics are a continuous phenomenon and not a onetime transient hence their evaluation and analysis is to be based on continuous time. Harmonics are evaluated according to the procedures mentioned in IEEE 519. It lays down the base for standard of voltage supplied to the customers. The harmonics are evaluated collectively as Total Harmonic Distortion. The acceptable limits for THD and maximum individual harmonic component in comparison to fundamental are mentioned in table **??**.

1.4.2 Effects of Harmonics

There is a certain tolerance level up to which a power system can afford to have harmonics. Problems arise when these harmonic currents exceed the permissible limit as defined by $IEEE519.1992$ standards. If these harmonics or higher frequencies become a significant part of the fundamental, they start creating some serious problems such as:

a) Overheating of Electrical equipment giving rise to safety issues

b) Harmonic resonance can cause transient values of currents and voltages

c) Excessive voltage distortion may cause the system to malfunction

d) Increased internal losses of iron and core, especially in the case of motors and transformers

e) False tripping of breakers

f) Metering errors

g) Fire hazard in power systems

h) Generator failures

i) Lower power factors, causing utility to charge penalties

1.4.3 Voltage Fluctuation

Steady state voltage is a myth in power systems. Loads change continually and the power system is constantly adjusting itself according to the continually hanging load. All these changes result in variations or fluctuations in voltage. These variations can be termed as under-voltage if the voltage level dropped and over-voltage if the voltage exceeded the previous value. The spectrum of voltage in steady state has best explanation profiles with long duration. Most of the end use equipment is not sensitive to these voltage variations provided that they are within permissible limits as described in ANSIC84.1. The standard defines permissible limits of voltage variations to be +6% and -13% of 120/240 Volt system. Primarily voltage unbalance is caused by:

i. Unbalanced single phase loads on a three-phase circuit.

ii. Capacitor banks − Blown fuse on single phase

iii. Severe voltage unbalance (greater than 5%) can result from single-phasing conditions.

1.4.4 Power Factor

Power factor is the parameter which provides ratio of the quantum of active power supplied and total power supplied. This ratio has the power to provide a basis to power quality evaluation. The quantum of power supplied to the end user should be at-least 85%. A reduced power factor mirrors poor power quality because the reactive power required by the load is constantly drawn from the source in addition to the mandatory reactive power. This extra burden of reactive power supply deteriorates system performance and inefficient power transmission may be observed.

Table 1.1: Power Quality Standards List

ORGANIZATION	STANDARD	DESCRIPTION
`ANSI`	141	Industrial Electric Power Systems
	142	Industrial and Commercial Power System Grounding
	241	Commercial Electric Power Systems
	242	Industrial and Commercial Power System Protection
	399	Industrial and Commercial Power System Analysis
	446	Industrial and Commercial Power System Emergency Power
	493	Industrial and Commercial Power System Reliability
	518	Control of Noise in Electronic Controls
	519	Harmonics in Power Systems
	602	Industrial and Commercial Power Systems in Health Facilities
	739	Energy Conservation in Industrial Power Systems
	929	Interconnection Practices for Photovoltaic Systems
	1001	Interfacing Dispersed Storage and Generation
	1035	Test Procedures for Interconnecting Static Power Converters
	1050	Grounding of Power Station Instrumentation and Control
`IEEE`	C62	Guides and Standards on Surge Protection
	C84.1	Voltage Ratings for Power Systems and Equipment
	C37	Guides and Standards for Relaying and Over-current Protection
	C57.110	Transformer Derating for Supplying Nonlinear Loads
	P1159	Monitoring and Definition of Electric Power Quality
	P1250	Guide on Equipment Sensitive to Momentary Voltage Disturbances
`NEMA`		Un-Interruptible Power Supply Specification
`NFPA`	70	National Electric Code
	75	Protection of Electronic Computer Data Processing Equipment
	78	Lightning Protection Code for Buildings
`NIST`	94	Electric Power for ADP Installations
	678	Overview of Power Quality and Sensitive Electrical Equipment
`UL`	1449	Standards for Safety of Transient Voltage Surge Suppressors

Table 1.2: Permissible THDs

Bus Voltage	Individual Harmonic Component (Max %)	THD (Max %)
`69 kV and Below`	3.0	5.0
`69 kV to 161 kV`	1.5	2.5
`161 kV and above`	1.0	1.5

Chapter 2

Active Power Filters

2.1 Basic Principle

The basic principle of the Active Power Filters is to inject the missing part of the sinusoid waveform in the current in a non-linear load. Figure 2.1 illustrates the concept on which APFs operate. There are 2 fundamental approaches for operating the harmonic injection.

– If current harmonics are to be mitigated then an interfacing inductor is placed between APF and PCC so that it stores current and injects at the right time.

– If voltage harmonics are to be mitigated then an interfacing capacitor is placed parallel to APF at PCC so that it stores voltage and compensates at the right time.

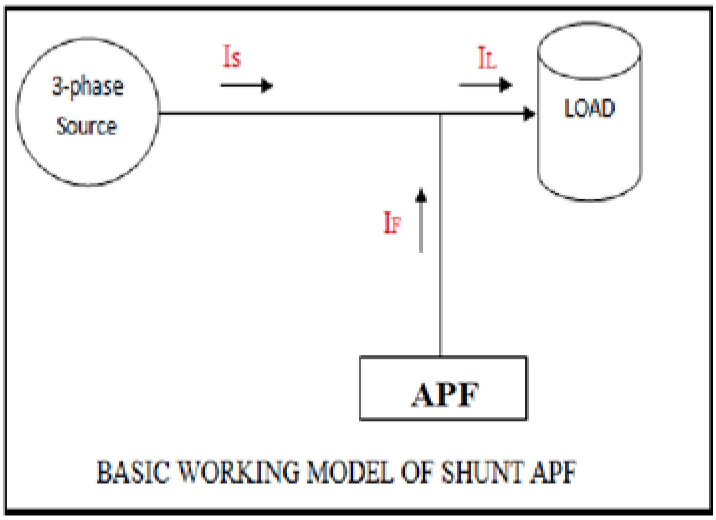

Fig. 2.1: Basic Working of APF

2.2 Basic Blocks of APF

Various methods have been implemented to control APF. There are three basic blocks of every APF:

a. Reference Generator

b. Current Estimator

c. Inverter

The basic block diagram of APF is mentioned below (Fig 2.2).

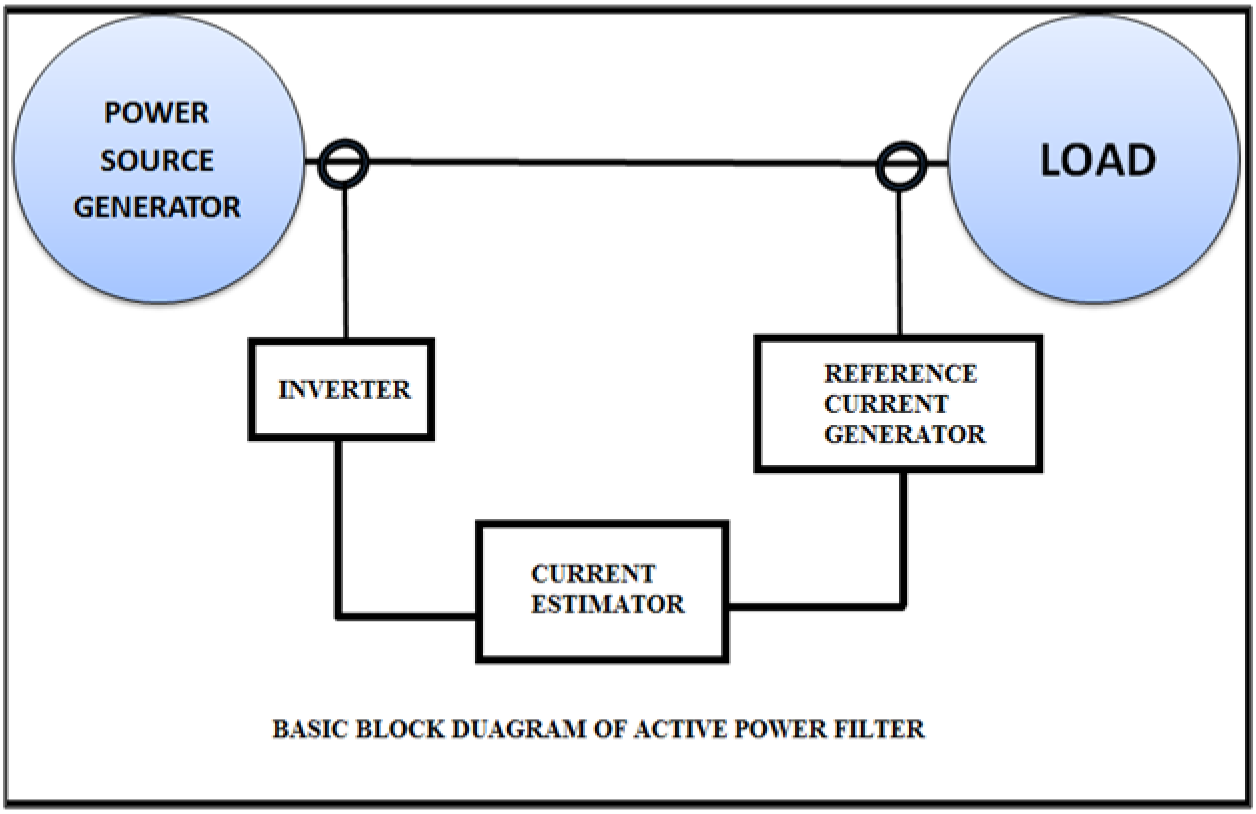

Fig. 2.2: Basic Blocks of APF

2.2.1 Reference Generator

The reference generator block measures the existing voltages and currents in the power system and then it provides a reference or signature signal. The signal obtained is the one that is desired in the system. This signal is generally a unit vector which is in phase with the source voltage having the magnitude equivalent to load current.

2.2.2 Current Estimator

The current estimator is the block which defines the missing part of the waveform that is to be injected into the system. This is the most crucial stage as the estimation needs to be accurate so that the achieved signal when injected into the system, mitigates the harmonics and improves power quality.

2.2.3 Inverter

Inverters are DC to AC converters. The inverter design is one of the most challenging parts of the APF design as the inverters are required to provide the missing content physically. To achieve high caliber accuracy, high precision switching is required which will generate the signal required for harmonics mitigation.

2.3 Types of APF

There are three basic types of Active Filters:

1. Shunt APF
2. Series APF

3. Hybrid APF

2.3.1 Shunt APF

Shunt Active Filters are connected to the system in parallel. These filters can be treated as harmonic current sources since they generate currents that are opposite in phase to the existing harmonic currents. When system is operated with Shunt APF in parallel to the load, the load appears to be linear to the source and only fundamental component is drawn from the source.

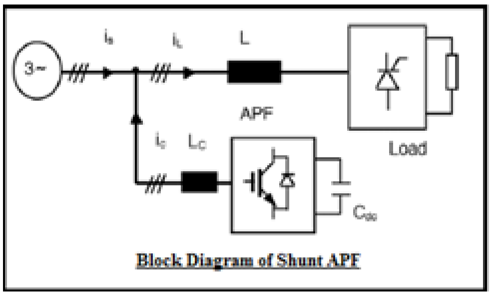

Fig. 2.3: Shunt APF Basic Diagram

2.3.2 Series APF

Series Active Filters are connected in series configuration to the power system through coupling transformers. They isolate the high frequency components of current by creating a high impedance path for them and forcing them to pass through the LC filter placed parallel between the harmonic insulator and load. The voltage that is needed to cancel the high frequency component is utilized as the high impedance path for the component.

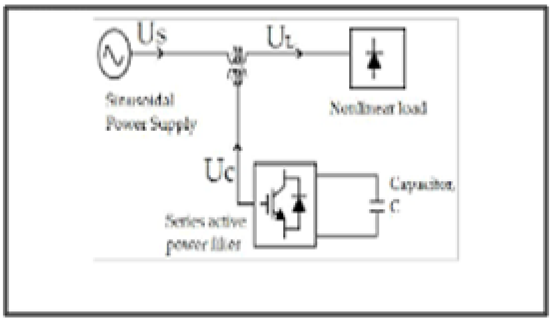

Fig. 2.4: Series APF Basic Diagram

2.3.3 Hybrid APF

A Hybrid Active Power filter is combination of both Shunt and Series Active filters. This system is connected to the power line through a coupling transformer. The currents of high frequency are forced to circulate through the passive filter by imposing a high voltage. These filters were introduced in 80s to improve the characteristics of passive filters.

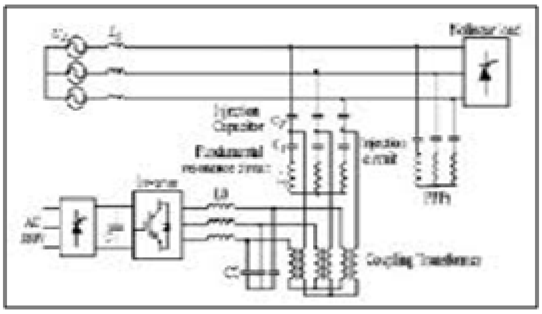

Fig. 2.5: Hybrid APF Basic Diagram

2.3.4 Advantages over Passive Filters

1. Adaptability to changes in network and system loadings is higher.
2. Unlike passive, a single APF can respond and eliminate several orders of harmonics.
3. Resonance between filter inductance and network is eliminated.

4. They are very compact as compared to traditional Passive Filters.

Chapter 3

Control Theories

3.1 Instantaneous Reactive Power Theory

This theory was presented by Hirofumi Akagi in 1983 in his paper "The generalized theory of instantaneous reactive power in three phase circuits". The introduction of this theory made p-q transformation a formal theory of electrical power in three phase systems. The theory works good with balanced and unbalanced three phase three wire or four wire systems for harmonics mitigation but for non-sinusoidal systems the optimum performance is compromised. The theory considers three phases of three phase system (with or without neutral) as a single unit. The theory is powerful enough to work for both steady state and transient systems.

The pq theory is based on transformation of 3-phase values to a-b-0 values using Clarke transformations. These transformations are carried using a real matrix which transforms three phase values to stationary reference frame of a-b-0 using the relation given by:

The inverse transform is given by:

The a-b-0 transformation completely separates zero sequence components on the zero sequence axis and it does not have any contribution from a-b axis and same is the vice versa. If the system is three phase three wire then zero order components can be elimi-

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = T \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = T \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$T = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$$

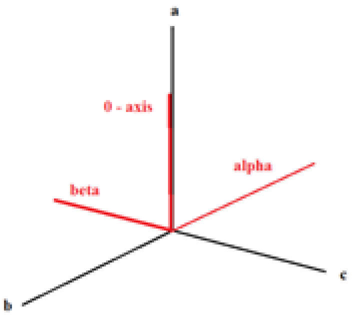

Fig. 3.1: Transformation from abc to synchronous frame

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

Fig. 3.2: Inverse Transformation

nated from above equations, simplifying them further. The Powers components of the system are given by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

Fig. 3.3: Power Equation in Synchronous Frame

Where:

p = The real power (Total power flowing in three phase three wire system per unit time)

q = The imaginary power (The power at an instant in each phase without transmitting energy in that phase at that instant)

3.2 Direct Quadrature Zero Axis Theory

The dq0 transform (often called the Park transform) is a space vector transformation of three-phase time-domain signals from a stationary phase coordinate system (ABC) to a rotating coordinate system (dq0).

As in the Clarke Transform, it is interesting to note that the 0-component above is the same as the zero sequence component in the symmetrical components transform.

The transform and inverse transform applied to time-domain voltages in the natural frame (i.e. ua, ub and uc) is as follows:

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} u_d \\ u_q \\ u_o \end{bmatrix}$$

Fig. 3.4: Transformation in dq0 frame

Where : Î¸ = The angle between the rotating and fixed coordinate system

3.3 Literature Review

3.3.1 Harmonic Mitigation by SRF Theory Based Active Power Filter using Adaptive Hysteresis Control

The authors of this paper have utilized Synchronous Reference Frame theory and adaptive hysteresis current controller to implement a shunt active power filter that is connected to a three phase three wire system. There could be two possible configuration of hysteresis band controller; fixed band and adaptive band. It is shown in the paper that SRF theory can effectively work out for elimination of current harmonics and can prove to be effective in keeping the utility current sinusoidal in power lines. The model is shown to be effective for current harmonics isolation and the results have shown that THD of supply current has dropped to 1.71% from 22.79% after harmonic compensation by the model. This was achieved using the adaptive hysteresis band controller and the obtained results are well below the standards defined in IEEE-519.

3.3.2 Modeling and Power quality analysis of a Grid-connected Solar PV System

This study has developed a model to analyze the power quality issues that arise after integrating a solar PV plant into the distribution network. The problems attributed to harmonic injections and voltage fluctuations are addressed. Three conclusions are drawn:

Case A: Voltage at far end of feeder is less than the bus node near the distribution transformer. The voltage drop is based on feeder length and network distance.

Case B: During minimum load conditions and excessive PV generations there is a significant potential rise at the far end bus of feeder in comparison to other busses. This is due to the reverse power flow.

Case C: At extreme PV generations (minima and maxima) the level of harmonics at far end is higher than harmonic level near distribution transformer. The THD values are reduced in minimum PV generations.

3.3.3 Power Quality Analysis in Off-grid Power System

This paper discusses power quality issues that arise due to off grid distributed generation of wind and solar plants. The paper encompasses problems that are due to decreased short circuit power of local distributed sources. An Analysis on relevant parameters of Power Quality is also carried out on active distribution grids. The authors have reviewed power quality evaluation and both on-grid and off-grid operations are discussed. The increased utilization of wind and solar generation sources for residential use are contradictory to the modern power quality sensitivity requirements. The details of relation between energy radiated in Solar and speed of winds may help in reducing their effects on power quality.

3.3.4 Power Quality Analysis and its Effects on Energy Meter Readings and Life Expectancy

The authors of the paper have presented power quality as a function based on power system faults. The mechanism formulated takes under consideration the events of overvoltage and undervoltage. The test values have helped to provide a working formula that relate faults to thermal issues which are caused by poor power quality. In addition to this the mechanism make use of Arrhenius Equation for expected life of load side equipment. The mechanism developed is capable of updating the values on live monitor. The levels of power quality and losses can be monitored at the hand so that preventive maintenance and immediate measures can be planned and executed.

3.3.5 Smart Grids Power Quality analysis based in classification techniques and higher-order statistics: proposal for photovoltaic systems

The authors of this paper have presented comparison of certain techniques used to determine disturbances caused by power quality. The analysis is carried out in a support frame of smart metering and smart grids infrastructure. The techniques compared are Support Vector Machine (SVM), Learning Vector Quantization (LVQ), Nearest Neighbor Method (kNN) and Linear Discriminant Analysis (LDA). The process of disturbance classification is carried with fourteen features of power quality that have a high rate in statistics. The spectral kurtosis is paid special attention and results have been finalised on the basis of correlation and mistake rates. The paper presents Support Vector Machine (SVM) to be the best classifier and robust classification method as the average correlation rate reached 99%.

3.3.6 Active power filter based on wind turbine for electric power system quality improvement

The authors of the paper have established that wind turbine generators are used for compensation of reactive power. The control scheme is based on a shunt active power filter that is fed by a wind turbine to normalize the voltage harmonics and reactive power at point of common coupling (PCC) so that a smooth voltage supply is obtained. The results are obtained under both steady state and transient conditions. The results have proven that power system need not to facilitate non-linear loads with reactive currents and the main system voltage comes in phase with the load current proving that wind turbine can serve as a perfect power factor corrector.

3.3.7 Power Quality Analyses of a Large Scale Photovoltaic System

The authors in this paper have presented power quality measurement analysis and the realization is carried on a large size photovoltaic system. The 1-MVA PV plant consists of systems based on modern photovoltaic panels and inverters. In addition to the measurements made on physical values of voltage, current, power, power factor and harmonic distortion the inverter response in different time intervals of power generation was also observed. The time periods of sunrise and sunsets are low power generating time brackets for PV systems. The inverter response was extremely contaminated in these periods as compared to periods of extreme sunlight. The study concludes that low power generating periods contribute towards higher harmonic distortion which further leads to poor power factor and degraded power quality.

3.3.8 The Improvement of Power Quality in a Mono-Phase System Through a Single-Phase Active Filter using MATLAB/Simulink

The authors of the paper have worked on harmonic elimination of single phase systems ysing single phase active filters. The idea is to reduce the total harmonic level and interference of electromagnet to get the system in compliance with the international standards of power quality. In single phase systems, active filters are controlled with methods of Pulse Width Modulation. Further in the paper existing trends and standards are discussed and simulation results have shown that the proposed method is in valuable agreement with the standards laid down by IEEE.

3.3.9 Three-Phase Three-Level Inverter Based Shunt Active Power Filter

The authors of this paper have presented a novel approach for harmonic reduction. The determination of losses occurred due to inverter over a period are taken as the base and the unwanted component of the active current is determined. This unwanted component is one of the major reasons that causes fluctuations and the DC voltage level of the inverter falls. The proportional integral controller is used by the team to maintain the reference DC voltage. The results have shown that proposed method can significantly reduce the total harmonic distortion to the IEEE permitted bounds. The results were analysed as half load and full load conditions and under full load conditions the THD came out to be 3.61% from 46.59%.

3.3.10 Power Quality Analysis of Shunt Active Power Filter Based On Renewable Energy Source

The authors of the paper have presented a shunt active filter which is supplied by a renewable source. The Dc input of the active filter needs to be constant so that current harmonics are eliminated effectively. Majority of Active filters which are under service nowadays make use of voltage source inverters. Shunt Active Filters are extensively vital for current harmonic mitigation and reactive power compensation. The model is simulated on Simulink and a conventional PI controller is implied to regulate the results.

3.3.11 A Three Phase Shunt Active Power Filter Based on Instantaneous Reactive Power Theory

The authors of the paper have presented implementation of instantaneous reactive power theory on a three phase shunt active power filter for reducing harmonic content. The power system under consideration is three phase three wire system. Results support the fact that theory is successful in extracting harmonic currents and reactive components. The gating signals are generated using Hysteresis band PWM which is one of the most simple PWM implementation method. The simulation results approve that proposed model is fulfilling reactive power requirement of load and also working in accordance with the standards defined by IEEE.

3.3.12 Power quality improvement with two compensation control strategies for Shunt Active Power Filter based on SMC

The authors of the paper have worked on to develop a robust control strategy so that the performance of the Active Filter is improved. By far the active filter has proved to be an effective and efficient solution to the problems of power quality. SAPF has proven to be one of the best solution for harmonic elimination and reactive power compensation. For a robust control the DC side capacitor is regulated using the Sliding Mode Control (SMC). The results and simulation establish that proposed method is robust and effective in comparison to certain other control methods and it also confirms improvement in performance of the fuzzy logic technique used for current control.

3.3.13 Reactive and Harmonic Compensation Using the Conservative Power Theory

This paper presents the use of the conservative power theory for active shunt compensation, and provides experimental validation of reactive compensation and harmonic filtering. It is aimed to provide a more in-depth review of how the conservative power theory operates as a control algorithm for a shunt compensator. Also there is discussion on some of the challenges associated to practical implementation of active filters. The conservative power theory was introduced as a current reference generator for the APF. The CPT- algorithm is capable of analyzing the load current and splitting it into five current components, each with unique properties. In this experimental study the CPT was incorporated into an APF and harmonic filtering and reactive power compensation were demonstrated.

3.3.14 Active Power Filter with Battery Energy Storage Based on NPC Inverters

The authors of the paper have presented the idea that functionality of the power filter can be extended by adding a energy storing device to the DC power bank. Also, the usage of inverters in parallel with interleaved pulse width modulation will help in designing filters with larger bandwidth. The larger bandwidth shall support in catering frequencies of much higher order. The simulation results presented on Matlab/simulink package clearly show that the proposed method has been successful in conditioning the power of the system. The work also initiates a domain that addition of a real power component in p-q theory allows to compensate both active and inactive components.

3.3.15 A Single Phase p-q Theory Based Active Filter

The authors of the paper have presented the idea that under application of pq theory for the purpose of reference signal extraction the phase shift of complete load current is not required, instead the phase shift of fundamental component will do the job. It is to establish that phase shift of fundamental component is easier as compared to complete load current. The effectiveness is validated by results showing a THD of 4.5% which is well within IEEE Standards.

Chapter 4

Power Quality Improvement in LV Systems Using Active Power Filter

4.1 PROPOSED SYSTEM

The system that has been taken under consideration is a power system that is feeding a certain amount of non-linear load.Harmonics are introduced in the line currents due to non-linearity of loads and as these harmonic currents pass through source impedance they load the source to produce reactive power hence degrading the power factor. Power factor degradation reduces system stability and affects the performance of the system.

The system modeled in Simulink for harmonic mitigation and power quality improvement is shown in Fig 4.1.

4.1.1 LOAD UNDER CONSIDERATION

Since switching mechanisms are the basic reason of non linear impedance hence house hold and general daily life loads like Motors, Fans, Computers, Juicers, Iron press, etc are taken into consideration. For the purpose of larger picture and simplification, rectifiers feeding loads are used. In addition to this, two converter circuits, fed by three phase transformers, are also feeding RL loads. A passive linear load consisting of Resistive and inductive component is also realized.

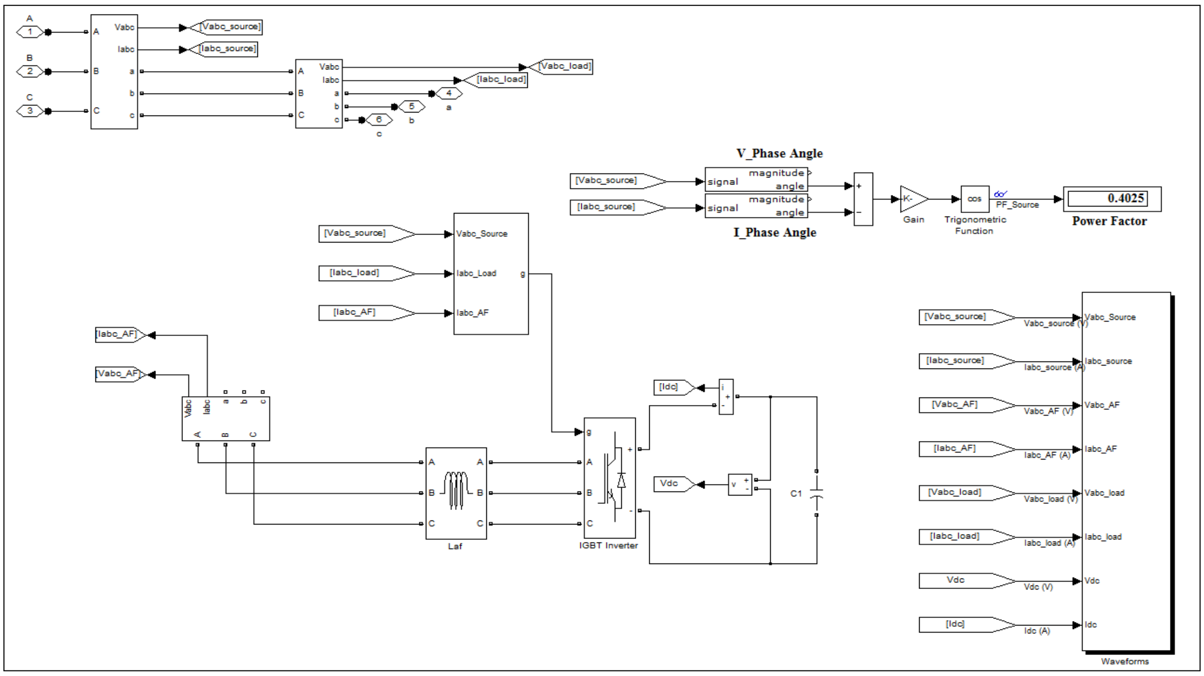

Fig. 4.1: The Proposed Model

PARAMETER	VALUE
Mains Voltage	1 p.u.
Load kVA	1 p.u.
Total Harmonic Distortion (THD)	26.55%
Power Factor	0.4

The APF proposed for the problem discussed in earlier sections is a three phase Active Power Filter that is connected to the power line through an interfacing inductor. The system prototype is given under along with the summary of parameters realized in simulation

4.2 THE DYNAMIC BEHAVIOR AND CONTROL

4.2.1 System Variables Detection

This is the first stage of active power filter working process. The system variables including source voltages and load currents are detected and then passed to the reference current generator stage.

4.2.2 Reference Signal Generation

It is responsible to generate the reference sine wave sin (wt) with unity amplitude and synchronous with the source voltage. The source voltage sensed in the variable detection stage is divided by its magnitude. This results in a unity amplitude sine wave which is in phase with the source voltage. The load current is processed through an RMS BLOCK to have its peak value.

$$\frac{V_m Sin(wt)}{V_m} = Sin(wt)$$

$$I_{L-RMS}(t) * \sqrt{2} = I_{L-MAX} = I_{RCM}$$

The unit amplitude sine wave obtained from source voltage is multiplied with the load current peak to have the reference current.

$$i_{rc}(t) = I_{RCM} Sin(wt)$$

4.2.3 Compensation Current Estimator

The reference current obtained from the reference current stage is then passed to compensation current estimator. Here the reference current is subtracted from the total load current to have the harmonic current which is flowing in the system. This harmonic content is the current that is to be compensated in the system.

$$i_{cc}(t) = i_L(t) - i_{rc}(t)$$

4.2.4 Hysteresis Controller

The current feedback path of active power filter brings the output current of APF in this stage and here it is subtracted from compensation current obtained from the previous block.

$$i_{HYS}(t) = i_{cc}(t) - i_f(t)$$

The hysteresis controller is designed on error signal of Icc(t). The values of If(t) and Icc(t) are measured and compared at each instant and an upper and lower bound, called the hysteresis band, is formed. When the difference or error in the measurement of two signals cross the upper or lower band limit the gating signals are generated. There are no gating signals if the error is within the band. The band limits are determined by estimated reference signal.

Gate Pulse generator

The compared result from the hysteresis controller is passed to this stage. Here the current obtained from previous stage is limited to a unit value band using relays and the relay output is used as gating signals.

$$GateSignal = \begin{Bmatrix} 1 & if error >= H \\ 0 & if error < H \end{Bmatrix}$$

Power Inverter

The inverter block used is a 3phase IGBT based inverter which uses DC Bus of 440V. The Gating signals obtained are used as firing signals for the IGBTs. The inverter output is the current that is to be injected in the system to mitigate harmonics and improve the power factor.

4.3 Simulation

4.3.1 Before Compensation

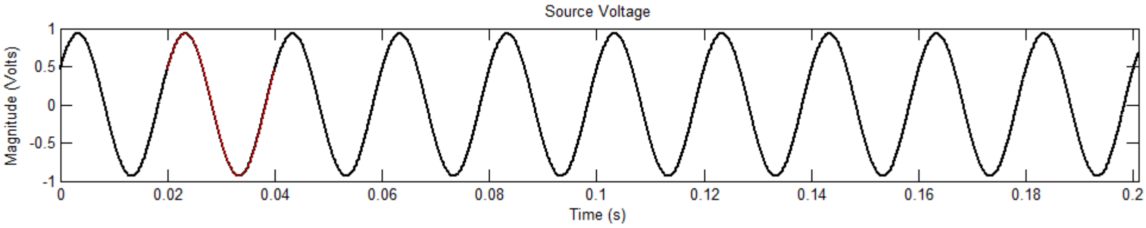

Fig. 4.2: Source Voltage

Fig 4.2 shows the source voltage measured at source end before harmonic mitigation.

Fig 4.3 shows the source current prior to compensation is having harmonics and the waveform is extremely distorted. The waveform is catering the frequencies that are multiples of fundamental generated by the switching of non-linear loads.

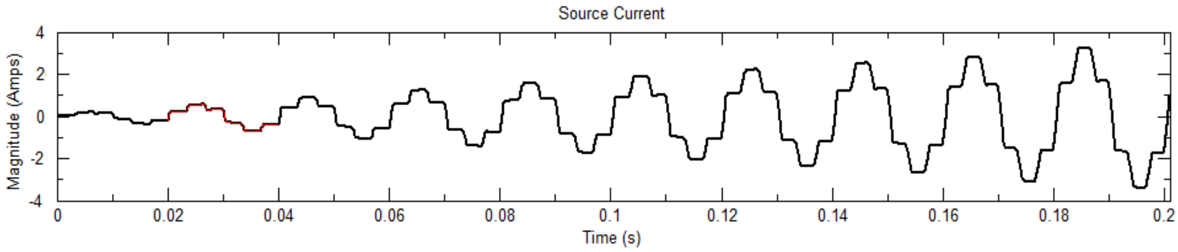

Fig. 4.3: Source Current Before Compensation

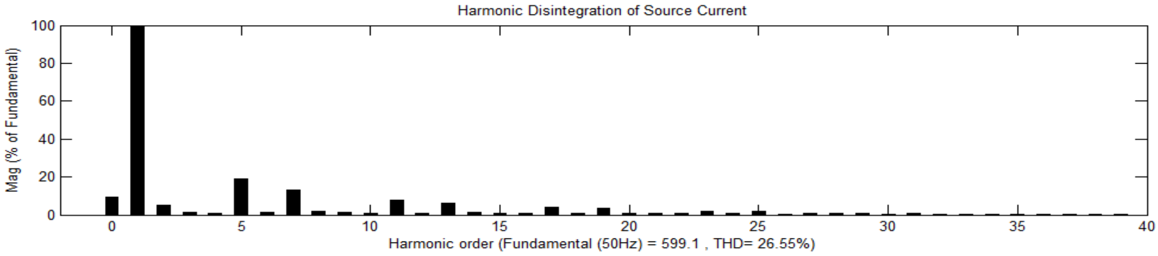

Fig. 4.4: Harmonic Disintegration of Source Current

Fig 4.4 shows FFT of source current gives the harmonic disintegration spectrum of the source current which evidently shows that 5th and 7th harmonic are strong in this case.

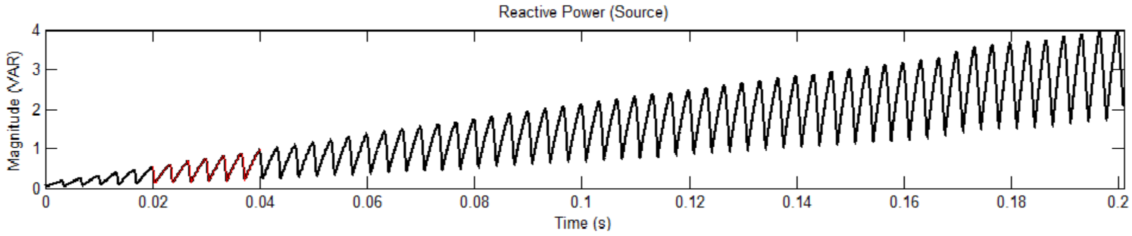

Fig. 4.5: Reactive Power of Source

Fig 4.5 shows reactive power supplied by source due to poor power quality. The degradation of power quality have made it a compulsion on source to provide the extra reactive power to fulfill the system needs. This loading of power source is harmful for its useful life.

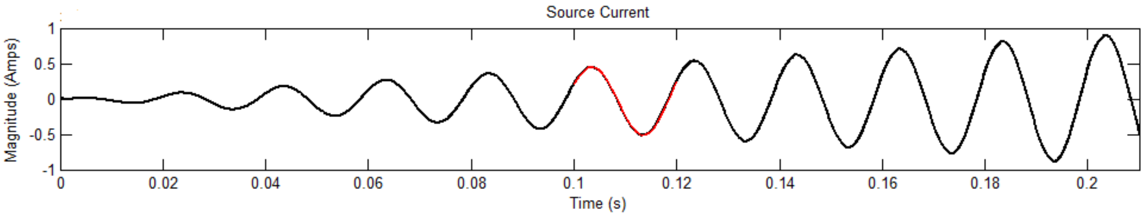

Fig. 4.6: Source Current After Compensation

4.3.2 After Compensation

Fig 4.6 shows source current after compensation has become sinusoidal. The distortions have been removed and harmonics are mitigated. This current waveform is the one most desired and suitable for healthy operation of power system.

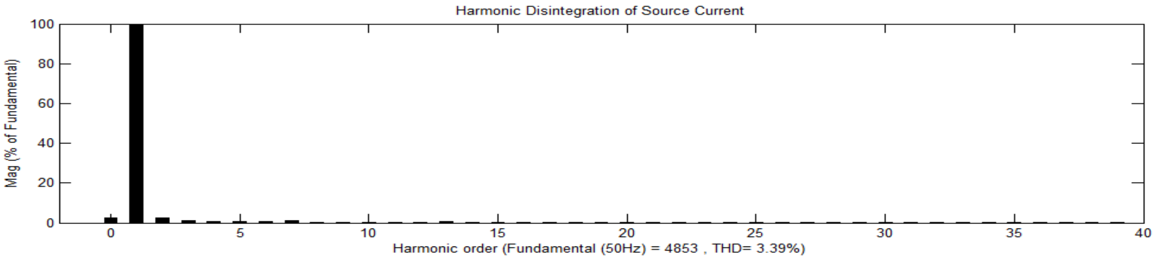

Fig. 4.7: Harmonic Disintegration of source current after APF

Fig 4.7 shows the FFT analysis of Source current after compensation gives the range of harmonics contained by the system. It is clearly shown that all the major and minor harmonics are mitigated and THD is within the permissible limit as standardised by IEEE

Fig 4.8 shows the output voltage of APF is shown in this figure. This is dependant on the DC link or Battery used at the input.

Fig 4.9 shows the output current of APF. This is the most critical part as this is the sum of all the harmonic frequencies that are required to be compensated in the system.

Fig 4.10 shows the reactive power supplied by APF is shown in this figure. This reactive

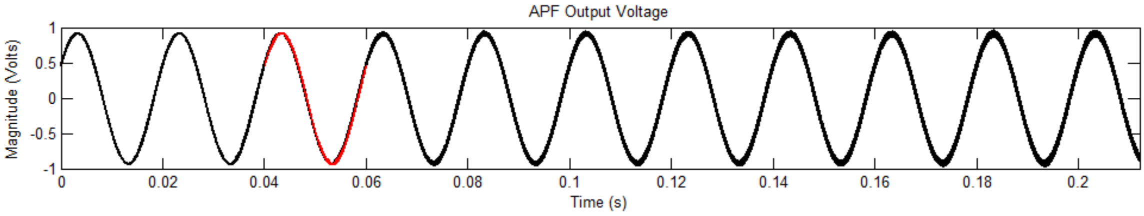

Fig. 4.8: Output Voltage of APF

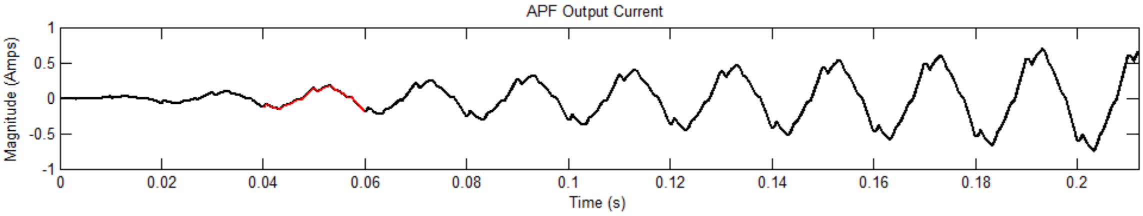

Fig. 4.9: Output Current of APF

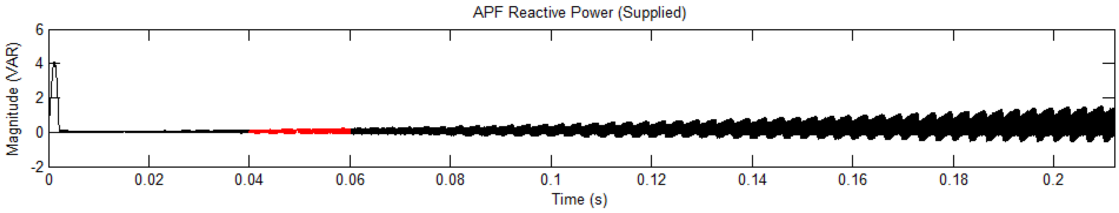

Fig. 4.10: Reactive Reactive of APF

power supports the system and the source is not loaded for reactive power in the presence of reactive power supplied by APF.

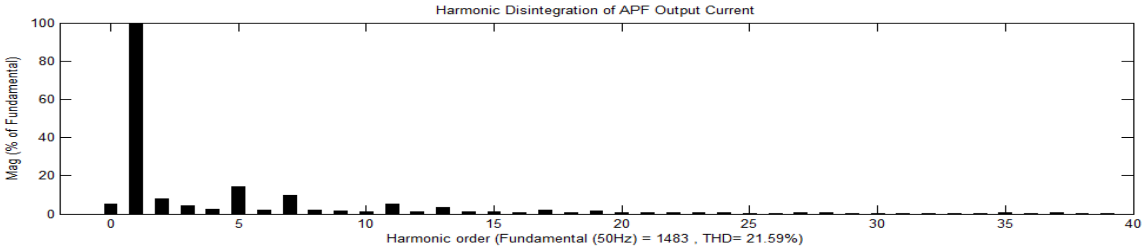

Fig. 4.11: APF Output Current Harmonic disintegration

Fig 4.11 shows the frequencies disintegration of APF output current. It can be seen that major portion of harmonic content is being neutralised by APF and this was achieved by injecting the out of phase harmonics in to the system.

4.4 Results

The objectives of having Sinusoidal source current and reduced Total Harmonic distortion are achieved. As shown in Fig 4.6 the source current has become sinusoidal which was extremely disturbed as shown in Fig 4.3. One more observation is the peak of source current before and after compensation. The source current is having both load and harmonic currents before compensation since the source supplies to both, the actual load and the harmonic load. But it is evident from the results that after compensation the peak of source current has dropped because the harmonic content is being supplied by the shunt APF. Total Harmonic Distortion is reduced to the permitted bound of 5% as shown in Fig 4.7 and harmonics are mitigated. In parallel, reactive power supplied Fig 4.10 by APF has improved the power factor to 0.9 from 0.3. The improved power factor is an inevitable fact that source current is in phase with the source voltage hence improving the power quality.

4.5 Conclusion

The proposed APF system reduces THD of system from 26.6 to 3.39 which is well within the limits defined by IEEE. The APF is adaptive to load changes and has improved system efficiency. The analytical and simulated outcomes have shown that harmonics are being mitigated resulting in improved power factor. The harmonic disintegration obtained through FFT of source current shows that there is drastic reduction in harmonic content of the system. The DC side of inverter could be capacitor or a battery voltage.The APF model is adaptive to load changes and has improved system efficiency.

4.6 References

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