ENHANCEMENT OF POWER QUALITY USING ACTIVE FILTERS

ABSTRACT
An Active Filter is controlled current or voltage power electronics converter that facilitates its performance in different modes like current harmonics compensation, reactive power compensation, power factor correction and load balancing in the distribution system. The compensation process uses different control approaches to extract the reference current but they all share a common objective i.e imposing sinusoidal currents in the grid, eventually with unity power factor and load balancing. The prominence of the application of the AI tools has been felt in all the areas of the Power Systems and the need is emphasized. The main aim of the research work is to enhance the power quality using Active Filters. In this thesis three phase three wire voltage source Shunt Active Filter has been implemented. It mainly deals with improvement of major power quality issues like harmonic elimination, reactive power compensation, power factor correction and load balancing due to nonlinear load. The thesis provides a complete framework for the analysis of power quality issues and replaces the conventional PI controller by intelligent computational techniques.

1. INTRODUCTION
In recent years, the advancement in the technology, specifically the evolution of power electronics applications based on semiconductor switches (diode and thyristor rectifiers, electronic starters, UPS and HVDC systems, arc furnaces etc) has fetched many technical eases and economical profits, but it has concurrently introduced new challenges for power system operation studies. To appreciate the maximum asset utilization, secure and reliable operation needs to be maintained regarding various aspects of power system operation.

The electrical transmission system identifies devices such as power electronic circuitry used for power conversion as non-linear load [1]. A nonlinear element in a power system is described by the introduction of a distortion due to their non-ideal characteristics.
Nonlinear loads, including; uninterruptable power supply (UPS), variable frequency drives (VFD), adjustable speed drives (ASD), and switched mode power supplies, present a special challenge to successful delivery of high quality power under all operating conditions. With the increased number of power electronic system connected to the mains, the systems have become more sensitive to supply voltage and current distortions [2,3,4].

Distorted voltages and currents have many harmful effects such as resonance problem arises between the supply inductances and capacitances leading to over-currents and over-voltages. Distorted current increases the $I^2Z$ heat losses in the transformer which promotes thermal and mechanical insulation stresses. Detrimental effects can also be seen in a system powering phase to neutral connected loads. For equipment where proper sequencing of operations depends on a zero crossing for timing, voltage distortion can cause mis-operation. Rapidly changing or varying industrial loads such as electric arc furnaces, welding machines, alternators, rolling mills and motors may also give rise to supply voltage fluctuations which might cause tripping of equipment [5,6,7].

Ideally, AC power systems are a pure sinusoidal wave, both voltage and current, but presence of non-linear loads modify the characteristics of voltage and current from the ideal sinusoidal wave. This deviation is reflected as Harmonics. Harmonics provide current and voltages with different components that are multiples of the fundamental frequency of the system.

The nonlinear load producing harmonics can categories as [8,9]

1. A large number of distributed nonlinear components of small rating consists mainly of single phase diode bridge rectifiers, power supplies of low voltage appliances (SMPS in TV sets, PCs and other IT equipment), and gas discharged lamps.

2. Large static power converters and transmission system level power electronic devices. Static Power Converters (SPC) find their application more extensively for controlling loads. Rectifiers (single-phase, three-phase), inverters (twelve-pulse, six-pulse), cycloconverters are all nonlinear and they inject non-sinusoidal current into the power system.

3. Large and continuously randomly varying nonlinear loads. This refers mainly to electric metal-melting arc furnaces connected directly to the transmission network. It
consists of the carbon electrodes in contact with iron with dissimilar impedances between the positive and negative flows of current. Consequently the furnace arc impedance varies randomly and extremely asymmetrical.

On the basis of nonlinear load injecting harmonic current or voltages in to the distribution network, the nonlinear load can also be categorized as [10]

- Harmonic current source type loads
- Harmonic voltage source type loads

Harmonic current source type load produces harmonic current on the ac supply of the rectifier for their operation. DC drives mainly controlled by thyristors, Current Source Inverters are the examples of harmonic current source type loads. In contrast, harmonic voltage source type loads produce voltages on the ac side of the rectifier for their operation like diode rectifiers with dc side capacitors, variable speed drives (VSDs), etc.

To achieve better performance, to be able to control and to transfer more power over the power system, and to reduce the power consumption of the loads, currently many methods for elimination of harmonic pollution in the power system are developed and investigated. One of the main topics of special concern is the aspect of power quality which deals with, among others, voltage characteristics, current characteristics and most importantly control and prediction of harmonics [11].

2. HARMONIC PROBLEM IN POWER QUALITY

A growing concern of power quality is harmonics distortion that is caused by non-linearity of load. When a sinusoidal voltage is applied to a certain type of load, the current drawn by the load is proportional to the voltage and impedance. Voltage and current follow each other without any distortion. These loads are referred to as linear loads. Examples of linear loads are resistive heaters, incandescent lamps, and constant speed induction & synchronous motors.

However, some loads cause the current to vary inexplicably with the voltage during each half cycle. These loads are classified as nonlinear loads. The current and voltage have waveforms that are non-sinusoidal, containing distortions. Current harmonic distortion is load sensitive devices that draw non-sinusoidal currents According to IEEE Std. 519 [12]
reported in 1981, “A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency is defined as harmonic”.

Most devices only produce odd harmonics but some devices have a fluctuating power consumption, for half cycle or shorter, which then generates odd, even and inter-harmonic currents. The current distortion for each device changes due to the consumption of active power, background voltage distortion and changes in the source impedance [13]. The most common harmonic index is the total harmonic distortion (THD), which is termed as the Root-Mean-Square (RMS) of the harmonics expressed as a percentage of the fundamental component. Thus by definition Total Harmonic Distortion (THD) is the percentage measurement of the distortion resulted in voltage or current waveforms due to harmonics.

Mathematically any periodic signal (waveform) can be described by a series of sine and cosine functions, also called Fourier series

\[ u(t) = U_{dc} + \sum_{n=1}^{\infty} (U_{max} \sin(nwt) + U_{max} \cos(nwt)) \]  

where \( u(t) \) is any periodic waveform

\( U_{dc} \) is the DC component of the periodic waveform \( u(t) \)

Hence, when a signal passes through a non-ideal, non-linear device, additional content is added at the harmonics of the original frequencies, these content are of the multiples of the fundamental frequency \( n_f \), which actually destroy the signal.

\[ \text{THD} = \sqrt{\frac{\sum_{h=2}^{n} I_h^2}{I_1}} \]  

Where \( I_h \) is the single frequency R.M.S. current at harmonic \( h \), \( n \) is the maximum harmonic order to be considered and \( I_1 \) is the fundamental line to neutral R.M.S current.

THD is a measurement of the extent of that distortion and is defined by equation given below [77].

\[ \text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_\infty^2}}{V_1} \]
Hence, THD characterizes the ratio of all signal components of the multiple frequencies except the fundamental frequency, to the first signal component of the fundamental frequency.

3. POWER QUALITY SOLUTIONS

Modern customers uses nonlinear loads induces the appearance of the dangerous phenomenon of power quality problems in the electrical feeder networks, producing distortions in the current/ voltage waveforms. Voltage/current distortions have created problems in the design of AC power system [1]. Many technologies have been developed utilizing power electronics based concepts which are capable of mitigating the issues of power quality.

3.1 Passive Filters

Power line conditioner intended to improve the quality of the power that is delivered to the load equipment. Conventionally, the most common method used for mitigation of harmonics was to install passive filters is a type of line conditioning system. The passive filter installed in a three phase system uses the passive components, are tuned for a particular frequency, thus provide a good solution because of their high efficiency, low-cost and simplicity. Passive filters are used as either to inject a series high impedance to block the harmonic currents or offer a low impedance path for specific high order harmonics thus act as a harmonic isolator. Series connected filters are imperiled to full line current and has lower the reactive power compensation capability whereas shunt coupled passive filters carry merely a fraction of line current. Moreover, the lower installation cost of shunt filters make them more preferable.

However, L-C filters are susceptible to source-sink resonances [14]. L-C filters also attract harmonic current from ambient harmonic-producing loads and background distortion of grid voltages [15]. Filter loading due to background distortion is a key design issue [16]. In the varying utility system where the system configuration changes the filter performance is affected by component tolerances. In contrast for a stiff grid system, strident and precise tuning is required to sink a significant percentage of the load harmonic current thus pretense prodigious efforts for L-C filter design. Thus, after
installation passive filters can neither replace the tuned frequency nor the size of the filter can be changed [17].

### 3.2 Active Filters

The multifaceted design process, constrained capability to eliminate harmonics and immense losses of the passive filters has stimulated the enhancement of harmonic compensation by means of power electronic devices. Thus modern alternative to passive filters is Active Filters (AF) [18, 19, 20].

In the initial phases of AF applications, mostly power MOSFETs and GTOs were operated. However, the existent progress in AF technology has acted on with the commencement of insulated gate bipolar transistors (IGBTs). Furthermore the evolvement of microprocessors, digital signal processors (DSPs), field programmable gate arrays (FPGAs) and inclusion of Hall Effect sensors and isolation amplifiers have spurred researchers and designers. Advancement has made it possible to implement competent control strategies for the AFs to decipher harmonic associated problems in the utility and industrial power systems. The basic principle of Active Filter is to use an inverter to introduce currents or voltages to cancel the load harmonic components.

AF’s can be classified based on converter type, topology, and the number of phases [21].

1. **The converter based Active Filter**
   - Voltage source inverter (VSI)
   - Current source inverter (CSI)
   - The topology based active power filter Series Active Filters
   - Shunt Active Filters
   - Hybrid Active Filters

2. **Phases based Active Filter mainly two types.**
   - Two-wire (single phase) system.
   - Three or four-wire three-phase system
4. CONTROL OF ACTIVE FILTERS

Control algorithm plays a vital role in improving the performance of Shunt Active Filters. The basic steps of the control algorithm can divided in three steps:

- Signal Conditioning
- Derivation of compensating Signal
- Generation of gating signal

Initially, the required voltage and current signals are recognized using power transformers, Hall-effect sensors, and isolation amplifiers.

In the second phase, reference compensating signals are derived by using the assembled current or voltage information based on various control strategies and AF configurations.

In the last phase of control, the gating signals for the switching devices of the AF are generated using PWM, hysteresis, sliding-mode, or fuzzy-logic-based control techniques. The control of the AF's is realized using discrete analog and digital devices or advanced microelectronic devices, such as single-chip microcomputers, DSP's, etc [22].

Fig 1.1 Basic concept of control of Active Filters
Fig 1.1 shows the basic idea of the control of Active Filters. Nonlinear load at the distribution side draws the non-sinusoidal current from the AC mains. It consists of fundamental component and the multiples of the fundamental frequency which adds up to produce harmonics in the source current. In the first stage, current is sensed using Current Transformers (CTs). For the derivation of reference compensating signal, it is passed from low pass filter and subtracted from the load current to get only the harmonic component of current. In the third and final stage these signals can be used to derive the gating signal of the solid state devices. Thus, the filter current adds up to the load current to make the source current with only fundamental component of frequency and making it pure sinusoidal.

The numerous control methods to overcome the grid current harmonics are based on open loop control system and closed loop control system [23]. Open loop control is based on load current measurement only and the reference current is extracted from load current. In contrast closed loop control involves the derivation of injected compensating current by the measurement of grid current and load current. Various control strategies like frequency domain based control are found in the literature grounded on the Fourier analysis of the distorted currents/voltages and in the time domain based on instantaneous derivation of distorted currents/voltages. The frequency domain control methods are based on Fourier and fast Fourier transform (FFT) algorithms [23], sine multiplication technique [24] and modified Fourier series techniques [25] suitable for both single and three-phase systems. The crucial drawback of the Fourier Transform-based methods is that the length of the window is related to the frequency resolution. Moreover, to ensure the accuracy of Discrete Fourier Transform, the sampling interval of analysis should be an exact integer multiple of the waveform fundamental period [26].

Time domain approaches are mainly used for three-phase systems. The instantaneous reactive power algorithm (p-q) [27] and Synchronous Reference Frame (SRF) method [28], are generally preferred to generate the reference signal among the time domain algorithms. Time domain algorithm also includes fictitious power compensation algorithm and synchronous flux detection algorithm [29], constant (unity) power factor algorithm [30], IcosØ algorithm [31], sliding mode control [32] etc. The switching signals for the solid state devices of APF are generated using PWM [33], hysteresis [34], and
space vector modulation (SVM) [35]. Drawback of the analog controllers during real
time implementation and the difficulties can be overcome by adopting digital controller.
Digital controllers are employed in AF for field applications are combination of Digital
Signal Processor (DSP) and Field Programmable Gate Array (FPGA) [36, 37]. Numerous
techniques, methods and tools have been employed for power quality issues in power
distribution network based on Artificial Intelligence (AI). Artificial Intelligence includes
Fuzzy logic and Artificial Neural Network. These computational intelligence techniques
enhance the power quality by using the concepts that cannot be expressed as "true" or
"false" but rather as "partially true" called as Fuzzy logic and intelligent features of the
neuron cell. Neuro-Fuzzy Inference Systems (ANFIS), Genetic Algorithms (GAs) are
other techniques that are in the recent trends.

5. RESEARCH MOTIVATION AND PROBLEM STATEMENT
Wide spread usage of power electronics equipment in modern electrical systems draw
non-sinusoidal current from the AC Mains. These non-linear loads intensify harmonics
disturbance in the grid and degrade power quality in transmission and distribution grid
systems. These harmonics induce malfunctioning of sensitive equipment, overvoltage by
resonance, increased heating in the conductors and harmonic voltage drop across the
network impedance [38]. This affects power factor and create reactive power
disturbances. It is a huge challenge to abolish the adverse effects of these harmonics and
compensate the reactive power from the power system.
Reliability of supply and power quality (PQ) is two most important facets of any power
delivery system today [39]. The proliferation of power converter equipments connected
to the distribution power system which limits harmonic current /voltage injection
maintains good power quality [40]. Some standard regulations and recommendations,
such as IEC 61000-3-2 [41] and IEEE 519 [42], are necessary to limit the harmonic
pollution.
Traditional method of eliminating the harmonics by using passive filters is not
satisfactory due to the drawbacks as discussed earlier. The AF takes the challenge and
offers promising results compare to conventional one based up on suitable control
algorithms. The AF topology can be connected in series or shunt and combinations
(hybrid) configurations [43, 44, 45]. The Shunt Active Filter is most commonly used than the series Active Filter, because most of the industrial, commercial and domestic applications need current harmonic compensation. The Shunt Active Filters are used for providing compensation of harmonics, reactive power and/or neutral current in ac networks, regulation of terminal voltage, suppression of the voltage flicker, and to improve voltage balance in three-phase system [46].

Thus, among the various control strategies, Synchronous Reference Frame (SRF) is based on d-q conversion and requires less computation as compared to other time and frequency domain methods. The reference currents are generated by the dc-link voltage controller based on the active power balance of the system. They are aligned to the phase angle of the power mains voltage vector, by using a d-q phase-locked loop system [47]. Conventionally Active Filters uses proportional plus integral (PI) controllers to calculate the active power losses and reactive power compensation control loops. When using fixed-gains PI controllers, it is necessary to retune gains for different operation conditions. AFs fail to satisfy the conditions of fast transient response, minimum power dissipation, and robustness. Hence the advantages of using the AI techniques like ANN, GA are more flexible, adaptive and robust. These intelligent controllers make use of a knowledge base to generate compensation signals and switching pulses for the Active Filter. The main motivation of this research is to formulate an intelligent framework on Shunt Active Filter using SRF control strategy aiming at minimizing the THD of supply current and reactive power compensation for sustainable and reliable power system operations. The wide range of objectives is achieved either individually or in combination, depending upon the requirements and control strategy and configuration which have been selected appropriately.

6. OUTLINE OF THE RESEARCH

Power distribution system is polluted by harmonic and reactive power disturbances due to the large usages of non-linear loads (Computers, Laser printers, SMPS, Rectifier etc.), which is undesirable. The research works aims to develop a comprehensive methodology of three phase three wire voltage source Shunt Active Filter for harmonic reduction, reactive power compensation, load balancing, their performance and mitigation. The
The main objective of the thesis was to investigate the power conditioning capabilities of the Shunt Active Filter and Hybrid Active Filter. Synchronous Reference Frame control strategy has been executed and investigated for harmonic cancellation, to reduce the THD of source current, reactive power compensation and load balancing power factor improvement. To achieve these objectives DC capacitor voltage of the inverter has been controlled through various Artificial Intelligence Techniques keeping fixed reactive power compensation. The Active Filter is implemented with the hysteresis band current controller because of its simplicity of implementation.

The key intentions of the research work is to propose intelligence based control approach based on AI techniques, which is compared with the other control strategies, in order to improve the performance of Shunt Active Filter. The performance of the Shunt Active Filter is evaluated through MATLAB / SIMULINK environment using Simpower Systems toolbox and the results demonstrate the behavior of Shunt Active Filter using simple and flexible control methods to face the different operating conditions and disturbances inherit in power transmission and distribution system.

7. THESIS ORGANIZATION

The thesis is organized in discussing seven chapters

   Chapter 1 Introduction

This chapter introduces the concept of power quality, issues concerning power quality and motivation of the research work. This has been followed by the description of the problem statement and objectives of this research.

   Chapter 2 Literature Survey

This chapter presents a comprehensive literature review of different topology of Active Filter and its control schemes to review the state of the art techniques that are pertinent to the methods proposed in this research. The theory and control strategies of these methods are summarized to improve the Active Filter current distortion compensation characteristics.
Chapter 3 Shunt Active Filter Using AI techniques
This chapter details the modeling, operating principle and compensation principle (SRF control strategy) of Shunt Active Filter. Since the thesis aims to implement the AI algorithm, design of Fuzzy control scheme, the algorithms used for the Artificial Neural Network training architectures, objective function of PSO and optimization criteria are also discussed. In this chapter the analysis of the performance of Shunt Active Filter with simple PI controller and effective AI algorithm under both steady state and dynamic load conditions has been investigated. Comparison of PI controller and intelligent controllers have been performed for harmonic reduction, reactive power compensation, load balancing, unity power factor control in various operating conditions.
The controller and hence the filter configuration has been working under following system conditions:
(i) Three phase balanced source fed balanced linear/nonlinear load.
(ii) Three phase balanced source fed unbalanced linear/nonlinear load.
(iii) Three phase unbalanced source fed balanced linear/nonlinear load.
(iv) Three phase unbalanced source fed balanced linear/nonlinear load.

Chapter 4 Shunt Hybrid Active Filter Using AI techniques
This chapter focusses on the design and implementation of a three phase shunt connected Hybrid Active Filter. The simulated model is composed of three phase shunt connected VSI with a shunt connected LC passive filter tuned at 250Hz. The amplification phenomenon of the shunt connected passive filter is suppressed by the applied hybrid filter topology. The 5th, 7th and 11th harmonics are greatly reduced and the line currents have become to comply with IEEE Std. 519-1992. Active power loss computed by various controllers like PI controller, Fuzzy controller and ANN controller with fixed reactive compensation leaves the source current perfectly sinusoidal, free from harmonics and in-phase with voltage of the main supply maintaining the unity power factor. The required rating and the losses of the stand-alone Shunt Active Filter has been reduced by the Shunt Hybrid Active Filter.
Chapter 5 Transient Time Study of Active Filter

This chapter introduces the novel concept of reducing the transient time of Active filter. In the SRF control strategy, active power loss computed for maintaining the DC capacitor voltage, plays a major role in the power conditioning activity of Shunt Active Filter. As load condition changes, there is sudden increase/decrease in the capacitor voltage. The time taken by the capacitor to reach a steady state in the transient (changing) load condition is known as Transient Time. Thus a new proposed Energy based method for reducing the transient time of DC capacitor voltage under changing load condition is described in Chapter 5. A comparative analysis has been done to reduce the transient time by conventional PI controller method and proposed method using PI controller, Fuzzy controller and ANN method.

Chapter 6 Distributed Active Filters System

This chapter offers the innovative notion of Distributed Active Filters (DAFs). Distributed Active Filters System (DAFS) are modeled by the parallel operation of power electronics inverters for load sharing conditions in the distribution network. DAFS proves to be an effective solution of harmonic elimination by deploying multiple Shunt Active Filter Units (AFUs) in the system to cooperatively damp the harmonic resonance. Each AFU within the DAFS can share the filtering workload based on its own VA capacity. Emphasis is given on the introduction to various configurations, their performance for harmonic damping in the source current. The current harmonic filtering performance of DAFs was simulated for different operating modes. A comparative study of THD of supply current in different configurations using PI controller has been investigated.

Chapter 7 Conclusion and Future Scope

This chapter summarizes the general conclusions derived from the thesis and presents some future directions for research in the area of “Enhancement of Power Quality Using Active Filters”.
8. RESULTS AND DISCUSSION

Using SRF control strategy aiming at fixed reactive compensation, reference current has been generated by computing the active power loss in DC capacitor voltage. PI controller/Fuzzy controller/ANN controllers/PSO techniques have been used to estimate the peak amplitude of reference current by controlling the dc-voltage of the inverter. The conventional PI controller necessitates specific linear mathematical model of the system. Hence, it is difficult to optimize Active Filter performance under parametric variations viz non-linearity and load disturbances. This shortcoming is resolved by using fuzzy logic controller. It does not involve an accurate numerical calculation; it can work with imprecise inputs. Whereas Fuzzy logic require the operators experience and sometimes intuitive fuzzy design does not clearly outperform well-tuned conventional controller. Since the objective of the thesis is to simulate a harmonic filter configuration which can compensate harmonics and reactive power with reduced active filter rating, Particle Swarm Optimization Techniques has implemented to optimize the PI gain parameter while evaluating the active power loss in Shunt Active Filter. The next approach is the application of Artificial Neural Network controller. ANN controller has been trained with the aim of minimizing the source current harmonics and proves to be the best among the three controllers.

Based on the simulated results obtained in this dissertation we can conclude that that Shunt Active Filter is a potential tool for the growing power quality problems for damping the harmonic resonance, reactive power compensation and load balancing. This work identifies the area of research for power filtering by employing the AI techniques, reduction in the transient time by proposed Energy based method and the concept of DAFs. The easiness in evaluating the ambiguous or non-crisp concepts and the capability of these intelligent controllers to learn due to the technological advancement raised the importance of these soft computing techniques. Among the different AI techniques used ANN which can be substituted for any logical analysis has good performance for minimizing the harmonics. It has much better dynamic response than fuzzy controllers. PSO techniques is motivated by the evolutionary algorithm, provides an optimal solution depending upon the optimal objective function. It has verified its effectiveness in finding the optimal gain parameters for the PI controller and improvement in harmonic
cancellation of source current. Thus these techniques emphasis power utility motivated on providing a better quality of supply power owing to augmented customer prospect in modern day challenging environment.

9. FUTURE SCOPE OF THE THESIS
The thesis presented here concern the development of the various techniques and their validation in different conditions for the enhancement of power quality using Active Filters. This research work can be extended to a multilevel inverter implemented for power conditioning. Three phase three wire system can be extended to three phase four wire system with different conditions like considering the zero sequence voltage present in the system. FPGA based controller for Active Filter can be developed to reduce the hardware requirement. For sustainable growth in power system, recently Renewable and Non-Renewable Energy source are gaining lot of attention. Hence such energy sources feeding the nonlinear load can be investigated for further work in the field of power quality. Further enhancing the coordinated control of the proposed Distributed Active Filters incorporating the design of adaptive gains can also be implemented. Another attractive aspect that can be investigated is the finding the solutions of power quality issues by other emerging Evolutionary algorithm like Ant-Colony Optimization and Bacteria Forging Techniques. Thus, the quality of the power network can be expressively enhanced, and high reliability can be provided.
REFERENCES


