APPLICATION OF ACTIVE FILTERS FOR POWER QUALITY IMPROVEMENTS IN AC DISTRIBUTION NETWORKS

BY

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Dedicated to my beloved father, mother(late) and wife

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LIST OF ABBREVIATIONS

THD	**:**	Total Harmonic Distortion
LED	**:**	Light Emitting Diode
UPS	**:**	Un-Interruptible Power Supply
PWM	**:**	Pulse Width Modulation
IGBT	**:**	Insulated Bipolar Gate Transistor
CSI	**:**	Current Source Inverter
MOSFET	**:**	Metal-Oxide Semiconductor Field Effect Transistor
VSI	**:**	Voltage Source Inverter
PI	**:**	Proportional Integral
HAPF	**:**	Hybrid Active Power Filter
APF	**:**	Active Power Filter
UPEC	**:**	Unified Power Control Flow
PCC	**:**	Point of Common Coupling
SLD	**:**	Single Line Diagram

ABSTRACT

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Due to the large integration of semiconductor loads, power quality has become the most persistent issue in electrical system studies. Both utility and the end user have their own criteria to evaluate the power quality standards. Power quality is becoming incessant concern equally for end users and the utility also. As for as the concerned utility, power quality is not more than reliability of the supply whereas, the end user is more concerned about the continuous operation of even sensitive loads. Traditional power quality compensation methodologies have their own disadvantages like resonance, bulkiness and fixed compensation. Therefore, the researchers need to focus this issue and to develop static power compensators.

Shunt active power filter with synchronous frame of reference (d-q) control theory is proposed in this work to eliminate the harmonic and to address the reactive power issues. Shunt active power filter connected to AC distribution network in the presence of different shares of power electronic loads is investigated. Using Matlab/Simulink tool, many simulations are carried out to examine and verify that shunt active filter can eliminate the harmonics even in the presence of unbalanced and distorted distribution system network voltages to acceptable limits specified by IEEE 519. Model is tested for actual residential, commercial and industrial linear & non-linear loads and harmonics data.

The results indicate the effectiveness of active filters for balanced as well as unbalanced system. Harmonics in source currents are reduced from 16.65, 5.32, 11.15 to 4.23, 3.44, 3.12 for residential, commercial and industrial loads respectively. Reactive power demanded by the non-linear loads is also compensated by the active filters which otherwise must be supplied from the source system. Proposed active filter is also tested for large industrial loads and results are found satisfactory.

ملخص الرسالة

الاسم الكامل: بابر مرتضى

عنوان الرسالة: استعمال الفلاتر النشطة لتحسينات جودة الطاقة في شبكات التوزيع الكهربائية

التخصص: الهندسة الكهربائية

تاريخ الدرجة العلمية: أكتوبر ٢٠١٧

بسبب الدمج الكبير لأحمال أشباه الموصلات، أصبحت جودة الطاقة القضية الأكثر إلحاحاً في دراسات النظام الكهربائي. لدى كلٍ من من الشركة و المستخدم النهائي معاييرهم الخاصة لتقييم مقاييس جودة الطاقة. جودة الطاقة أصبحت ذات اهتمامٍ متواصل لكل من المستخدمين النهائيين و الشركة الموزعة أيضاً. فيما يتعلق بالشركة الموزعة، فجودة الطاقة ليست أكثر من موثوقية التزويد، في حين أن المستخدم النهائي مهتمٌ أكثر بالتشغيل المستمر للأحمال الحساسة. الطرق التقليدية لتعويض جودة الطاقة لديها عيوبها مثل الرنين، و الضخامة، و التعويض الثابت. لذلك، يحتاج الباحثون إلى التركيز على هذه المسألة و تطوير معوضات الطاقة الساكنة.

يعرض هذا العمل فلتر الطاقة النشط المتوازي مع إطار متزامن لمرجع (d-q) نظرية التحكم من أجل القضاء على التوافقيات، و لمعالجة مشاكل الطاقة غير الفعالة. سيتم بحث فلتر الطاقة النشط المتوازي و المتصل بشبكة توزيع كهربائية في وجود نسبٍ مختلفةٍ من أحمال إلكترونيات الطاقة. باستخدام أداة المحاكي Simulink في برنامج ماتلاب (Matlab)، سيتم إجراء العديد من المحاكاة للاختبار و التحقق من أن الفلتر النشط المتوازي قادرٌ على إزالة التوافقيات بالرغم من وجود جهود أنظمة التوزيع غير المتوازنةِ و المشوهةِ للشبكة في حدودٍ مقبولةٍ يحددها نظام IEEE 519. سيتم اختبار النموذج باستخدام أحمالٍ حقيقيةٍ سكنيةٍ، و تجاريةٍ، و صناعيةٍ، خطيةٍ و غير خطيةٍ، و بياناتٍ توافقيةٍ.

تشير النتائج إلى فعالية الفلاتر النشطة للأنظمة المتوازنة و غر المتوازنة. تم تقليل التوافقيات في تيارات المصدر من 16.65 و 5.32 و 11.15 إلى 4.23 و 3.44 و 3.12 للأحمال السكنية و التجارية و الصناعية على التوالي. كما تم تعويض الطاقة غير الفعالة، التي تتطلبها الأحمال غير الخطية، عن طريق الفلاتر النشطة، و لولا ذلك لوجب تزويدها من مصدر النظام. كما تم اختبار الفلتر النشط على أحمالٍ صناعيةٍ كبيرةٍ، و أعطى نتائج مرضيةً.

CHAPTER 1

INTRODUCTION

1.1 Introduction

With the passage of time, the demand for electricity is increasing extensively day by day which leads to complex power systems that are more multidimensional than ever before. To deal with the high demand of electricity, renewable and non-conventional distributed energy sources are becoming more important which made the system controls more complex and intricate [1][2]. With the advancement of power electronics, power system control is more efficient, reliable and user friendly. But at the same time, the widespread use of semiconductor diode and electronic devises creating serious power quality issues and is a major concern that need to be addressed for utility, customer and for the manufacturers. Harmonic pollution in the power system can be identified and measured by total harmonic distortion or THD. High harmonic contents in the power supply can cause increased operating temperature and excessive heat in electrical equipment resulting the early failures [3]. THD can be measured with reference to the fundamental voltages.

Utilities are incessantly pressurized to improve the quality and reliability of power supply with the integration of large number of electronic devices. The semi electronic based loads include printers, electronic ballasts, LED lighting, UPS, faxes, adjustable speed drive system and computers. These loads cause distortion in distribution network through inducing harmonics. All these loads are collectively categorized as non-linear loads comprising the converters and bridge rectifiers [4].

Major reason of harmonics generation by non-linear loads is drawing the current from source in an abrupt manner. The harmonics generated by nonlinear loads cause overheating and exceeding operating temperature of static and rotating machines leading to winding insulation failure and finally flash over may occur resulting in permanent damage of electrical equipment and loss of generation that causes huge blackouts which are highly undesirable.

In the competitive electricity market customers have great flexibility in selection of the serving utility, putting more pressure to deal with the disturbances to reduce financial and economical negative impacts. Power quality issues and objectives are much significant in the new electricity market which draw great attention to the application of shunt active filters as an essential part of the distribution network.

Performance and effectiveness of the active filter for power quality applications is largely dependent upon the current control technique that is the nucleus of filter. The reference current of the varying load is extracted to compensate harmonics distortion in load current. Therefor active filter controller plays a key role in the achievement of desired results by calculating the reference current demanded by the non-linear loads.

1.2 Thesis Motivation

Filters are the major technologies to mitigate the harmonic problems in distribution networks. Any reduction in the harmonic output of the converter in addition to reactive power compensation are normally achieved and accomplished by harmonic filters. There are two types of filters used in the market for harmonic elimination which are passive filters and active filters. Both have their own advantages and disadvantages. Passive filters offer low impedance path acting as harmonic isolator for the specific order of the harmonics and are used because of low cost and simplicity in implementation and operation.

In modern world, active filters are used as an alternative to the passive filters because of high operational speed and absence of resonance problem. Earlier, active filters were using GTOs which have low response time in high switching applications. But with the advancement in technology, IGBTs, due to lower voltage drop and better power handling capability, are proposed and implemented in this work.

The basic principle of the active filters is to introduce compensation currents with the help of converters to cancel the harmonic component of the load currents. Active filters are classified with respect to the converter type used like voltage source Inverter (VSI) and current source Inverter (CSI) or with respect to number of phases as single phase and three phases inverters. The performance of the active filters is mainly dependent upon the control topology used. Based on the method of extraction of reference harmonic current from load current, many techniques have been evolved like open loop, closed loop, time domain and frequency domain for the active filters. In contrast to the closed loop system, which required injected compensation currents are derived, an open loop system involves only the load currents measurements used for the extraction of reference currents. Time domain methodology is normally implemented for three phase systems.

The application of the active filters utilizes many theories for the extraction of the harmonic current for the non-linear load that are instantaneous reactive power theory (p-q) and synchronous frame of reference theory (d-q). The majority of the research uses two theories because of simplicity and accurate results. But there is major drawback of these existing techniques as they are applicable only for the ideal system conditions. The ideal conditions are balanced supply voltage and balanced loads. However, in practical distribution networks, one must always face with varying and distorted loads with un-balanced and non-sinusoidal source voltages. This needs to address properly and pay more attention for prolific application of the active filters.

The main motivation behind this work is to develop a new model of shunt active filters with modified control strategy of synchronous frame of reference (d-q) based theory, The filter should be capable of mitigating the harmonics to acceptable level of international standards of power quality like IEEE-519. The filter must be tested under adverse distribution networks conditions of non-sinusoidal, distorted, un-balanced voltages supply and non-linear, un-balanced, distorted continuously varying load conditions.

1.3 Thesis Objective

The main aim of this thesis work is to investigate the harmonics at point of common coupling (PCC) and design a filter which can mitigate the harmonics and improve reactive power compensation. Following are the main objectives of the thesis work,

1. To have a dynamic and versatile solution in the form of Active Power Filters that solves the power quality problems.
2. To implement the synchronous frame of reference theory (d-q) to extract reference currents for shunt active power filters.
3. To develop a new model of Active Power Filters with modified control theory that enables the filter to mitigate the harmonics even in presence of non-sinusoidal and distorted supply with varying non-linear loads.
4. To test the proposed active filter model in a network with different operating modes.
5. To analyze the impact of active filter parameters on the system performance.
6. Use the real-time residential, industrial and commercial loading and harmonic data to test and verify the proposed active filter model.
7. Compare the results of proposed active filter with published research work.

1.4 Thesis Outlines

The thesis is organized as follows: Chapter 2 covers details about different control theories used for extraction of harmonic currents injected by shunt active filters. Chapter 3 explains the problem formulation, mathematical modeling and algorithms. In chapter 4, the d-q theory and system network modeling along with the proposed model of shunt active filter is presented. In chapter 5, the simulation procedure for different operating modes of shunt active filters and its results are discussed. The conclusions and future works are presented in chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Control Theory for Filters

Electrical power quality has important factor in electrical power system. Generally for the power conversion from AC to AC or from AC to DC or otherwise and for voltage regulations or for controlling of induction motors, electronic based devices are always preferred on transformer based devices because of smaller sizes, fast operation and low cost [5], regardless of the fact that these electronic based devices are the main source of unwanted harmonics which causes equipment severe heating problems, insulations deterioration, shortening life of the electrical equipment, capacitor failure, communication interference, transformer failure, harmonic resonance, malfunctioning of protection devices, distortion of supply voltages and unwanted shutdowns. Wide Applications of different filters like passive and shunt active filters are commonly observed on industrial and commercial scale. But shunt active filters are always preferred because of their small size and absence of resonance problem and fixed compensations [6].

Paper [7] describes active power filters with two different control techniques, harmonic extraction and current modulator to mitigate the harmonics. Many theories have been evolved such as instantaneous power theory (p-q), d-q theory, frieze controller, fuzzy logic controller technique, neural networks to generate the reference currents for successful harmonics extractions. However, researches show that p-q and d-q theories comprises about 70% of the research work because of its simplicity and good results. Gate pulse is provided to the active filters with PWM technique.

With the advancement in modern electronics, harmonics comes as the by-product of them. Mostly, the harmonics are observed in the network with large number of computers, UPS variable AC to DC speed drives or any other electronics solid state power switching devices to convert AC supplies to DC quantities [8]. Harmonics are produced by non-linear loads because these draw current in abrupt and short pulse manner instead of smooth manner.

Paper [9] & [10] classified the filters in three different types depending upon their distinctive capabilities of eliminating harmonics. These are passive, shunt active and hybrid filters. Application of each filter mainly depends upon nature of the problem and economic factor associated with their implementation. Harmonic part of the distorted load current is efficiently replaced by the injection of negative harmonics provided by shunt active filters using IGBT transistors. Effectiveness of shunt active filters for non- linear loads is shown and simulated for the two-bus network in paper [11].

Another paper [12] discuss and describes two different aspects of the shunt active filters with respect to their performance analysis which are quantitative and qualitative. In qualitative analysis, the device is evaluated for technical merits like semiconductor characteristics, power conversion methodology, type of diode devices, GTOs and MOSFET. Quantitative analysis is carried out with different linear and non-linear loads for distribution systems. Filter effectiveness and capacity are the two indexes to measure THD of currents with & without application of the active filters as per international standards like IEEE 519 & EN 61000-3.

Distribution static compensator (D-Statcom) is a voltage controller device comprises on filter, a suitable voltage source converter, storage device for the DC energy and coupling transformer connected in parallel to the distribution network. Paper [13] discuss in detail the role of D-Statcom for elimination of source side voltage sags and interruptions.

Voltage sag in electrical power system is defined as the reduction of the voltage magnitude from 10% to 90% last from 0.5 to couple of seconds [14]. The main reasons of voltage sags are faults, fault clearing process itself, temporary disconnection of power supply and appearance of large currents associated with switching processes. Two main power quality disturbances which are voltage sag and harmonic distortions are discussed in detail in this paper. Power quality issues in the power system leading to the interruption of power supply, causes huge business losses which are un-desirable.

Synchronous frame of reference or d-q theory is presented in paper [15] [16] to calculate the desired reference currents for VSC of the active filter. The controlled performance of shunt active filters greatly depends upon the proportional Integral (PI) controller to get the desired reference signal for PWM using synchronous frame transformation from three coordinates a-b-c systems to two coordinate d-q system.

There are many publications which exclusively describes different types of filters and discuss in details different control strategies for extraction of reference currents for eliminating harmonics. Also, there are numerous papers which explains different indices for the performance evaluation of filters like THD, inverter efficiency, cost of the filter and discuss about their advantages and disadvantages either in time domain or in frequency domain [17]. It can be easily noticed that if there exist a small error in estimating any performance attributes, overall performance of the filter could be seriously degraded and even a refined control algorithm could not be able to get the desired results. Therefor there is a great debate among the scientist that which area like detection accuracy, speed, filter stability or cost should be focused.

Similarly, papers [18] [19] [20] [21] evaluate different control strategies for active filters. These are p-q, d-q and I-C (indirect control) strategy. The results show that The p-q strategy can achieve reduction in THD up to 2.85%, the d-q strategy can achieve THD reduction for each phase respectively 1.91% on phase a, 2.19% on phase b and 2.60% on phase c. Similarly, indirect current control strategy also can achieve THD reduction for each phase respectively 2.67% for phase a, 2.97% for phase b and 3.22% for phase c, which are within international standard limits.

Paper [22] discuss and propose three different control techniques for shunt active power filters which are hysteresis, fuzzy logic and PI controller. The comparative analysis of three techniques clearly depicts that uncertain system conditions are dealt with fuzzy logic technique while in hysteresis control technique, reference currents are generated using Fourier transform to compensate harmonic contents of the load currents and third one PI controller compensate the harmonics in the source current and regulates the capacitor voltages based on reference voltages. Analysis shows that fuzzy logic technique [23] [24] [25] is the best one among three because it does not require mathematical modeling and reduces THD in an efficient way.

Paper [26] describes the advantages and disadvantages of using different types of filters for harmonic compensations. Passive Filters and Active Power Filters have some advantage and disadvantages, but hybrid active power filters contain their advantages but not the disadvantages. Passive filter has been traditionally used in industrial power systems to reduce the distortion and harmonic content but has the limited applications because of their generic drawbacks like resonance, larger size, system impedance dependency and harmonic propagation in power system due to absorption of non- linear load harmonic currents. Active power filters (APF) generate either harmonic currents or voltages in a manner such that the grid current or voltage waves conserve the sinusoidal form. The APFs can be connected to the grid in series (Series APF) or shunt (SAPF) to compensate voltage harmonics or current harmonics respectively. Or can be associated with passive filters to construct the hybrid active power filters (HAPF).

Three different control techniques for shunt active filters were discussed and analyzed in detail in paper [27] with respect to their applications for power quality problem in addition to the conservative power theory presented by Tenti which discuss different form of the power, energy and loads. According to the comparative studies, p-q theory with persistent power approach is not a good solution for asymmetrical and sinusoidal voltage circumstances and similar is the case for CPT and d-q theories. Similarly, in case of symmetrical and non-sinusoidal conditions p-q and CPT control techniques may result in voltage distortions.

Another paper [28] shows the application of shunt active filters for harmonics reduction from 38.90% to 9.65%. In shunt active filters, harmonic current is compensated by injecting current equal in magnitude but in opposite direction and phase shift of 180-degree with the help of pulse width modulated VSI which act as current source in shunt active filters.

Reactive power and load current harmonics are compensated by active filters by injecting current waveform with the help of PI controller [29]. Successful operation of the shunt active filters depends upon the DC capacitor as energy storage device to maintain constant DC link voltages whereas PI controller is used to reduce the error. Performance of shunt active power filter mainly depends upon the reference current extraction technique and the way it is injected to the line for harmonic compensation. From the analysis of the shunt active filter circuit it is seen that the THD before compensation 23.27% is reduced to 4.72% after compensation which is within IEEE standards limits thereby enhance power quality improvement.

Due to multi-voltage level application of cascaded VSI [30] for low switching losses and high harmonic compensation, multi-level VSI based active filter is implemented in MATLAB/Simulink for extraction of three phase reference currents with the help of real power loss calculations.

Harmonic current compensation and power factor improvement at point of common coupling (PCC) [31] [32] is achieved by the application of active power line conditioners using pulse width current controlled VSI.

Proposed current control technique can compensate harmonics current with non-linear varying loads. Several symptoms of power quality issues like flickers, communication interference, blackouts, overheating and malfunctioning of sensitive equipment are discussed and highlighted in paper [33].

Another paper [34] propose the matrix converter technique in shunt active filters for harmonic current compensation instead of using conventional reference current extraction technique for power quality improvements. MATLAB/Simulink analysis is carried out before and after the application of shunt active filters and results shows that proposed technique reduces the harmonics effectively up to 30%.

2.2 Pulse Width Modulation and PI Controller

Three different types of voltage source inverters PWM, single phase and square wave are discussed and described in paper [35] which have wide power applications in conversion of fixed DC voltage to controlled AC output. PWM technique is most commonly used because of less harmonic distortion generation in the output voltages within AC phase load [36].

DC link voltage balancing is one of the main problem in using multilevel inverters drives which badly effects its performance due to the uncharacteristic harmonic generation in the output voltages and presence of over voltages across the semiconductor switches. Paper [37] propose the solution of this problem by using neutral point clamped structure. Power flow control in electrical power transmission system is achieved in complex and most advance manner by using unified power flow controller (UPFC) [38] which is based on d-q axis theory in which three phase currents are transformed into two coordinate system currents and the local bus voltage is regulated by controlling real and reactive power individually.

At the point of common coupling PCC [39], system owners or operators should limit current harmonics and International regulations now require that all electronic equipment meets these strict limits for harmonic currents for individual and total harmonics.

Paper [40] discuss different types of flickers in power system which causes noticeable illumination changes in lighting equipment and the it provides specifications for acceptable levels for two different powers system parameters 120 V ,60Hz and 230 V, 50Hz system.

Application of the shunt active filters is shown in another paper [41] by simulation in MATLAB/Simulink and the results are shown before and after the compensation. It was clearly shown that before active filter compensation the THD was 10.87%,21.31%,13.87% in three phases a, b and c respectively whereas after the compensation these THD of the line currents reduces to 2.14%,1.85% and 1.85% respectively.

Paper [42] discuss about the optimization of filter sizing and placement as per needed applications because these factors have direct economic impact and must be considered with other performance evaluation factors. Economical costs are of the great importance because still passive filters, having worse characteristics in eliminating higher harmonics and higher costs are being used instead of active filters. 17-Bus system consisting linear and non-linear motor loads were considered for harmonic evaluation. Main strategy used for optimal sizing and placement is minimization of THDI coefficient in busses to which active filters are connected.

Driving problems, influencing factors and solution of harmonics in MV and LV distribution network is presented in paper [43]. Capacitor banks, which are installed in distribution networks for power factor improvements are the main source of resonance near 5th harmonics and two case studies are presented to solve resonance issues. 5th harmonics are monitored on MV and LV buses for the period of three months and concluded that capacitor banks are the major source of resonance in distribution system. Rescheduling of capacitor bank switching and reducing capacitor bank power are the proposed solution for harmonics resonance in distribution system.

Paper [44] discuss about the history of battel between AC and DC sources which ends in taking over the AC sources but evolution of converters used for the application of DC drives and these converts act as noon linear loads and are the main source of harmonics in distribution system.

Harmonics distortion effects in commercial buildings are investigated in paper [45]. Current drawn by nonlinear loads in in abrupt and non-linear manner are the source of harmonics in power supply which can affect the other customers connected to the same feeder.

Efficiency, reliability and flexibility improvement of rotating machines with reduced cost is being achieved with advanced power electronic excitation control and conversion devises. All these steps can easily be eroded if resulting harmonics are not considered in the design of these machines. Finite element formulation method is used in [46] to analyze the performance parameters of rotating machines.

Application and performance analysis of the combination of two filters, shunt active and passive filters was analyzed in paper [47]. Simulation results shows that this hybrid technique work efficiently to reduce the THD in source current in less than two cycles.

In paper [48], linear and non-linear industrial loads were analyzed for harmonic distortion level and time varying character of the loads. Petrochemical, pharmaceutical, telecommunication, educational and financial industrial loads were studied and simulations carried out to show the effectiveness of switching compensation devices like active and passive filters to reduce the distortion level in source supply and eliminating harmonics.

Sliding mode controller for DC bus voltage converter is proposed for power quality improvement and harmonics compensation in AC networks. Experimental results prove that self-tuning filter is successfully compensate the harmonic currents in source supply [49].

New strategy of active power filters for compensation of reactive power and eliminating harmonics without considering DC bus voltage regulation of voltage source converter is presented in paper [50]. Simulation results shows that filter is still capable to generate reference currents even in the absence of DC voltage in control algorithm but these kinds of filters are used in low power application only due to reduced reliability and accuracy.

Effect of harmonics and voltage distortion in hydro power plant of Cotopaxi electric utility company Ecuador, caused by industrial customers are discussed and analyzed in paper [51] [58] [62]. All calculations related to state variable and nonlinear load currents are carried out using MATLAB simulated load flow analysis.

Locating and sensing the source of harmonics is also of major concern in well-developed and large power systems. State estimating technique is used in Paper [52] to sense and locate the source of harmonics. Simulation Results shows that 6 number of sensor can locate two sources of harmonics in 50 bus network power system.

In paper [53], impact of distributed generation, typically photovoltaic and car charging stations, on power quality is analyzed. These distributed loads, in addition to other non-linear load that are already present in the network, causes immense distortion in source supply voltages. A case study was carried out in isolated, actual MV/LV distributed grid, supplying energy to the residents of an Italian island. The author explains the reason of using network connected system that in network connected to infinite bus, harmonics effects are damped.

Active power filters are first option to cater the harmonic distortion problem in distribution network and compensation of reactive power but high cost makes can make this application non-productive if not properly de-rated for the bus voltage distortion. Number of active filters were reduced from 6 to one after derating gradually and still the voltage and currents harmonic distortion levels are within IEEE-519 standard which result in huge cost saving [54].

In recent years, harmonic distortion is being observed more in residential sector as compared to industrial and commercial areas and therefore of the great importance to address this issue in residential sector. Extensive field measurements were taken in 7 residential homes, 8 station service transformers, feeding from 10 feeders of different substations and found that residential feeders are dominate with 3rd and 5th harmonics more than the others [55].

Curve fitting technique is used in paper [56] to develop the mathematical relationship with harmonics. Group of commercial personal computers were monitored for harmonics generation that can circulate to the supply feeder and hence causing overall system power factor low and reduced efficiency.

Switching frequency and power handling capability of the converter are inversely related to each other as limiting switching frequency of the device, enhance power handling capability of the converter. Induction motors operating at high power and currents have large switching losses and therefor for reliable operation of the induction motor, switching frequency should be limited. Detailed investigation is carried out in [57] on optimal pulse width modulation to minimize THD in line currents.

Active filters show excellent results in harmonics elimination for power quality and power factor improvements for low voltage applications. It does not apply stress to input converter switches as it does in passive filters. Power factor also remains constant with time varying loading conditions in active filters. Comparative study of active and passive filters for medium voltage PWM current source rectifier [59] [66] [67] shows that passive filters have high performance at increased loading conditions.

Performance of shunt active filters greatly depend upon the precision and accuracy of voltage source converter. Multi-level voltage source converters [60] [63] [65] are best in performance for application of shunt active filters.

Detection and precise measurement of harmonic pollution in distribution network is also an important aspect of the power quality in power system networks. Inclusion of Large number of sensors for power quality monitoring may increase overall cost of the project which is highly undesirable. Therefore, optimal allocation of monitoring equipment is required which is achieved through vertex-coloring approach [61] [64]. Number of monitors are concluded based on percentage of non-linear loads on the bus.

Paper [68] describe the application of the shunt passive filters for harmonics elimination and power factor improving in distribution systems. Performance analysis for single tuned and second order high pass filters is carried out for industrial systems. Single tuned filter is connected in shunt to the main distribution system and is tuned for the specific frequency to offer the low impedance path.

Selection of the proper capacitor size is the most important in filter sizing because of the relationship between reactive power and capacitor reactance.

Resonance will be observed in passive filters when the capacitive reactance is equal to inductive reactance. Quality factor Q of the passive filter is selected in range of 20 to 100 to set the resistance value for filter.

Single tuned and second ordered high pass filters are tuned individually for specific frequencies to mitigate the harmonics within prescribed limits as per IEEE-519 standard. It is evident from the results that THD in source currents is reduced from 20.77% to 4.32% and the source currents became sinusoidal and in phase with the supply voltages after the application of passive filters.

There comes some conclusion when the passive filters are compared with the proposed active filters in term of cost, reliability, power losses and selectivity.

A slight upward shift in the frequency can detuned the filter from the target frequency for which the filter is tuned which is highly undesirable making the selection of passive filter questionable. Capacitor blowing is very common in passive filters which result in raising the frequency by reducing the total capacitance.

Lower and higher order frequencies up to 20th order is of the most concern in power quality analysis because higher order harmonics are either very low or negligible.

Installation of many single tuned and high pass tuned filters for individual frequencies increase passive filters cost more than double as compared to active filters.

Large number of passive filters are required to install to reduce the specific harmonic order current which is achieved with single shunt active filters in which current magnitude of the induvial harmonic are reduced in addition to lowering the THD within prescribed limits.

Current magnitude is reduced from 2A, 18A, 8A, 2A, 4A, 3A, 1A, 3A, 2A to 0.3A, 5A,1A, 0.5A, 0.7A ,1A, 0.5A, 1A, 1A for 3rd, 5th, 7th 9th, 11th, 13th, 15th, 17th and 19th harmonics respectively in passive filters.

Whereas in case of shunt active filters where we are using only one filters instead of many passive filters tuned for the induvial frequencies, the reduction in current magnitude for the specific harmonic is as from 2A, 22A, 10A, 2A, 9A, 7A, 3A, 5A, 4A to 0.2A, 0.5A, 0.1A, 0.1A, 0.3A, 0.2A, 0.1A, 0.4A, 0.1A for 3rd, 5th, 7th 9th, 11th, 13th, 15th, 17th and 19th harmonics respectively. Overall THD for the source current are reduced from 27.35% to 4.59%.

Active Power filters don’t have all mentioned issues making it reliable, cost effective and selective.

CHAPTER 3

SYNCHRONOUS FRAME OF REFERNCE THEORY:

PRINCIPLE AND IMPLEMENTATION

3.1 Problem Formulation

The control strategy for reference current extraction in active filters is the heart of the operation. Many theories for the control of active power filters have been developed and implemented for the power quality improvements. These include instantaneous power theory (p-q theory), synchronous frame of reference theory (d-q theory), hysteresis current control theory and fuzzy logic.

In this thesis work, synchronous frame of reference theory(d-q) is used for the power quality improvements in AC distribution networks. The theory is valid only for the sinusoidal voltage supply. Therefore, for non-sinusoidal supply voltages, standard d-q theory needs to be implemented with modified control strategy.

3.2 Mathematical Model

3.2.1 Synchronous Frame of Reference Theory

The synchronous frame of transformation refers to transformation from three phase stationary co-ordinates a-b-c to two d-q rotating axes.

3.2.2 Park Transformation

Direct–quadrature or d-q transformation is a simpler form of mathematical transformation that rotates the three-phase reference frame systems to make simpler the analysis of 3-Phase circuits. This is very like the Park’s transformation that was first presented by Robert H. Park in 1929 [70]. d-q transform reduces three AC quantities to 2 DC quantities to make calculation and simulation simpler and easy and at the end again 3-phase quantities are retrieved in a balance three phase system. Harmonic contents are separated from the fundamental currents using park transformation in which load currents from three phase frame of reference *a-b-c* are transformed to two d-q synchronous frame of reference.

Three phase currents *ia, ib & ic* are transformed to two axis *Id, Iq* as follow:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\theta\left(\theta-\frac{2\pi}{3}\right) & -\sin\theta\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.1}$$

Whereas:

Id, Iq and *ia, ib & ic* are the currents in the synchronous d-q frame of reference with respect to *a-b-c*-frame of reference and θ is the reference angle.

Park transformation of three phase voltages is given by:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\theta\left(\theta-\frac{2\pi}{3}\right) & -\sin\theta\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.2}$$

Whereas:

> V_d, V_q and v_a, v_b & v_c are the voltages in synchronous d-q frame of reference with respect to *a*-*b*-*c*-frame of reference and θ is the reference angle.

3.2.3 Inverse Park Transformation

To recover the three-phase currents, Inverse park transformation [70] is used to find the active power filter currents as follow:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta-\frac{2\pi}{3}\right) & -\sin\theta\left(\theta-\frac{2\pi}{3}\right) \\ \cos\left(\theta+\frac{2\pi}{3}\right) & -\sin\theta\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{3.3}$$

Similarly, the voltage equations for inverse park transformation can be written by replacing the currents with voltage notations as given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\theta\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\theta\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{3.4}$$

3.2.4 Calculation of Reference Harmonic Current

A simple high pass filter is used to extract the harmonic reference currents from the load currents as follow:

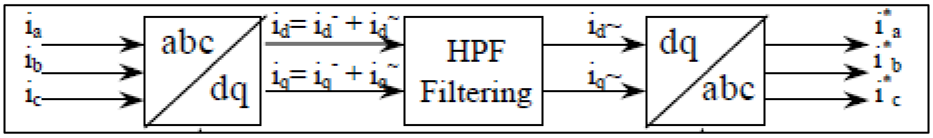

Figure 3.1 Extraction of Load Currents [12]

Three phase source currents are transformed from three coordinates a-b-c to two coordinates d-q as shown in the fig 3.1. Currents in the synchronous frame of reference are decomposed into two quantities using following equations [35]:

$$\begin{aligned} I_{id} &= \bar{I}_{id} + \tilde{I}_{id} \\ I_{iq} &= \bar{I}_{iq} + \tilde{I}_{iq} \end{aligned} \tag{3.5}$$

High pass RC filter is used to segregate the average and oscillating part of the currents. A high-pass filter allows the signals to pass away with a frequency higher than a certain cutoff frequency and block the signals with frequencies lower than the cutoff frequency. Typical high pass filter is shown in Figure 3.2.

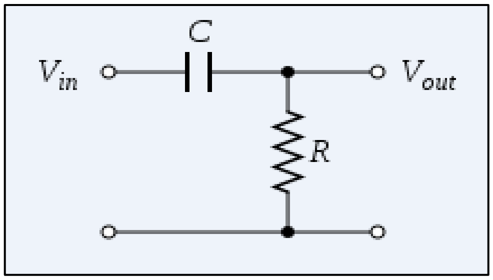

Figure 3.2 High Pass RC Filter Circuit [71]

If the frequency is higher than cut-off frequency, ω >>1/RC, capacitor will act as a short circuit and output gain will be 1 and signal will be passed.

$$\frac{V_\circ}{V_i} = \frac{R}{\frac{1}{sC} + R} = \frac{sCR}{1 + sCR} \tag{3.6}$$

$$\left|\frac{V_\circ}{V_i}\right| = \left|\frac{sCR}{1 + sCR}\right| = \left|\frac{j\omega CR}{1 + j\omega CR}\right| = \frac{\omega CR}{\sqrt{1^2 + (\omega CR)^2}} \tag{3.7}$$

If the frequency is lower than cut-off frequency, ω <<1/RC, capacitor will act as an open circuit and output gain will be zero and signal will be blocked.

At the end, we will get only the alternating terms in the output that are associated with the harmonic contents. Required reference active power filters currents that need to inject in the system can be found using following equation.

$$\begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix} = \begin{bmatrix} \tilde{I}_{id} \\ I_{iq} \end{bmatrix} \tag{3.8}$$

These currents calculated with synchronous frame of reference theory are the harmonic part of the currents and injected to the system with the help of pulse width modulation.

3.2.5 Power Calculations

Three phase instantaneous active power of the system can be written as:

$$p = v_a i_a + v_b i_b + v_c i_c \tag{3.9}$$

If a-b-c variables are replaced by the equivalent d-q variables

$$p = v_d i_d + v_q i_q \tag{3.10}$$

Real and reactive powers are defined with the voltages and line currents in synchronous frame of reference theory as in the following equation 3.11

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_d & vq \\ -vq & vd \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{3.11}$$

From equation 3.11, the instantaneous imaginary power can be written as follow:

$$q = v_d i_d - v_q i_q \tag{3.12}$$

In three phase system v_a, v_b, and v_c are the phase voltages and i_a, i_b, & i_c are instantaneous values of line currents. Real and reactive powers as per d-q theory can be written as follow:

$$\begin{aligned} p &= \tilde{p} + \overline{p} \\ q &= \tilde{q} + \overline{q} \end{aligned} \tag{3.13}$$

Real and reactive powers p, q is decomposed into average and oscillating part (3.13) with the help of high pass filters. All powers are explained as follow,

> "p" is the total active power and is the energy which is exchanged per second between load and source.
>
> "q" is the total imaginary power and is exchanged within the phase of power system and does not add energy transfer between load and the source.
>
> "$\tilde{p}$" this is the harmonic component of the power and must be compensated as it does not add the transfer of energy between load and the source.
>
> "$\tilde{q}$" this part of energy is also due to the harmonic current and is unwanted and therefore must be compensated as it does not involve in the energy transfer between the load and the source.

These powers are explained in Fig.3.3

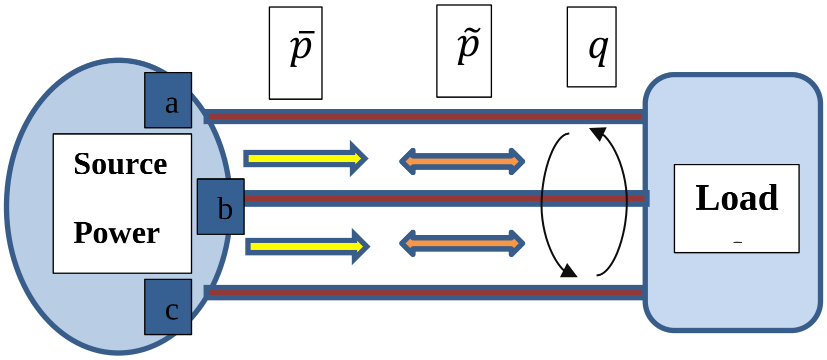

Figure 3.3 Exchange of Powers in Distribution Network System [13]

Shunt active filters should be installed near to non-linear loads and oscillating part of the real power of load should be compensated. Reactive power supplied by compensator

$$q_c = -q \tag{3.14}$$

And active power supplied by compensator will be

$$p_c = -\tilde{p} \tag{3.15}$$

3.2.6 Phase Lock Loop and Positive Sequence Voltage Detector

Phase locked loop is a complete control system which produce a signal related to the input phase signal. Phase locked loop is widely used in telecommunication networks, power system control and electronic applications. Their application involves recovering a stable frequency from multiple unstable frequencies. Phase detector is used to compare the output signal to input phase signal to match the different phases. Feedback loop is used to bring the output signal back to input signal for comparison, forming a complete loop. Positive sequence voltage detector is an essential part of the phase locked loop and is used to compare the difference between the two phases.

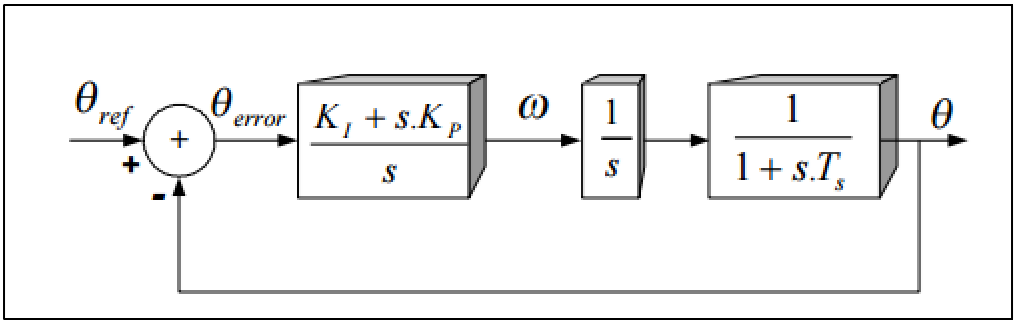

Figure 3.4 PLL Model [72]

Inputs to the active filter controller are the load currents and source voltages and the power is calculated based on these voltage and currents. Controller determine the reference currents for the active filter, demanded by non-linear loads with the application of synchronous frame of reference theory. If the filter is designed to mitigate the currents harmonic, then it is assumed that source voltages are perfectly balanced and harmonics are present only due to non-linear loads. But if the source voltages are unbalanced and distorted with harmonics then the algorithm shown below cannot be able to generate accurate reference currents for the active filter and its performance will be not ideal. This situation gives arise the need of fundamental positive sequence voltage detector. Algorithm for reference current calculation is shown in fig 3.5

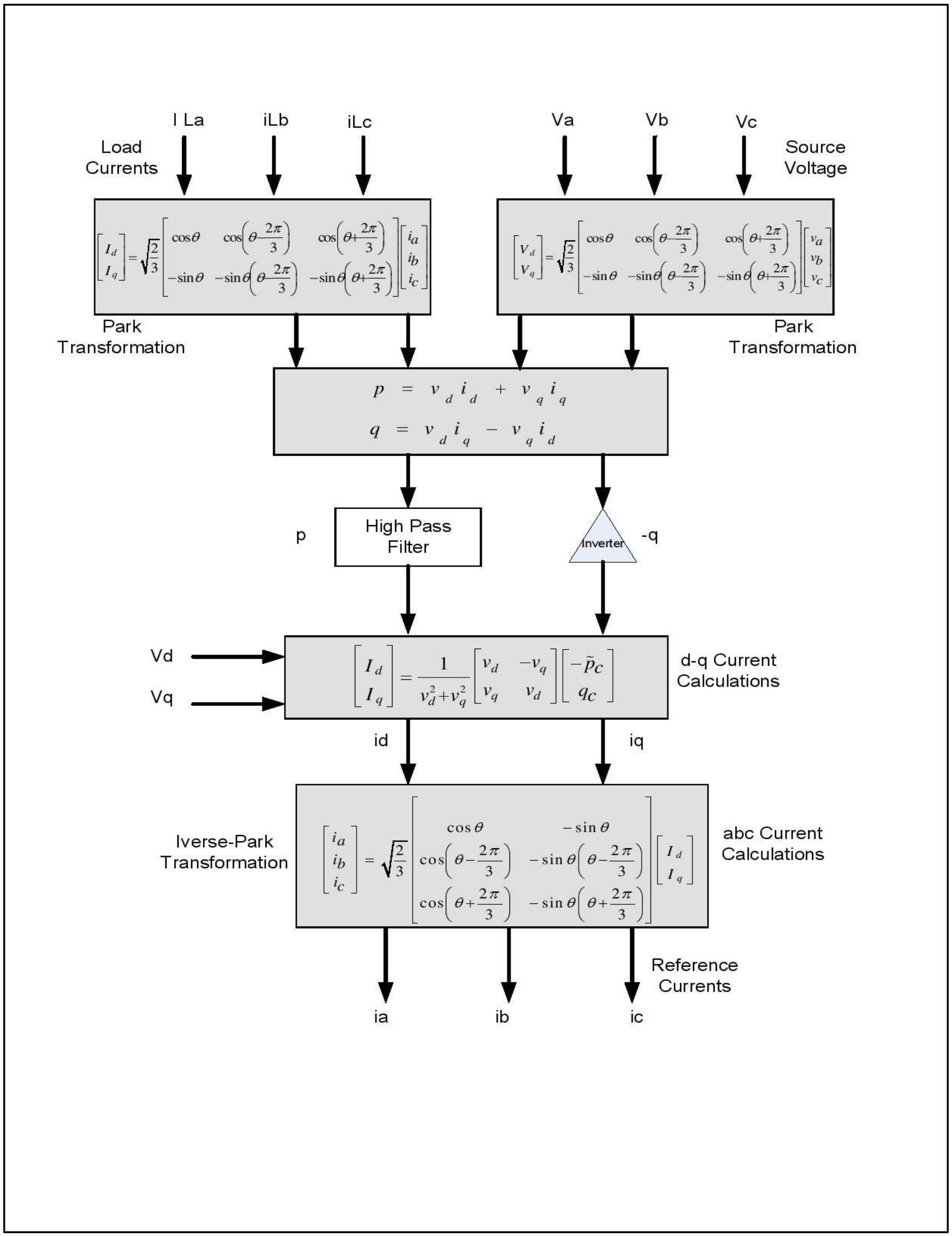

Figure 3.5 Algorithm for Reference Current Calculation

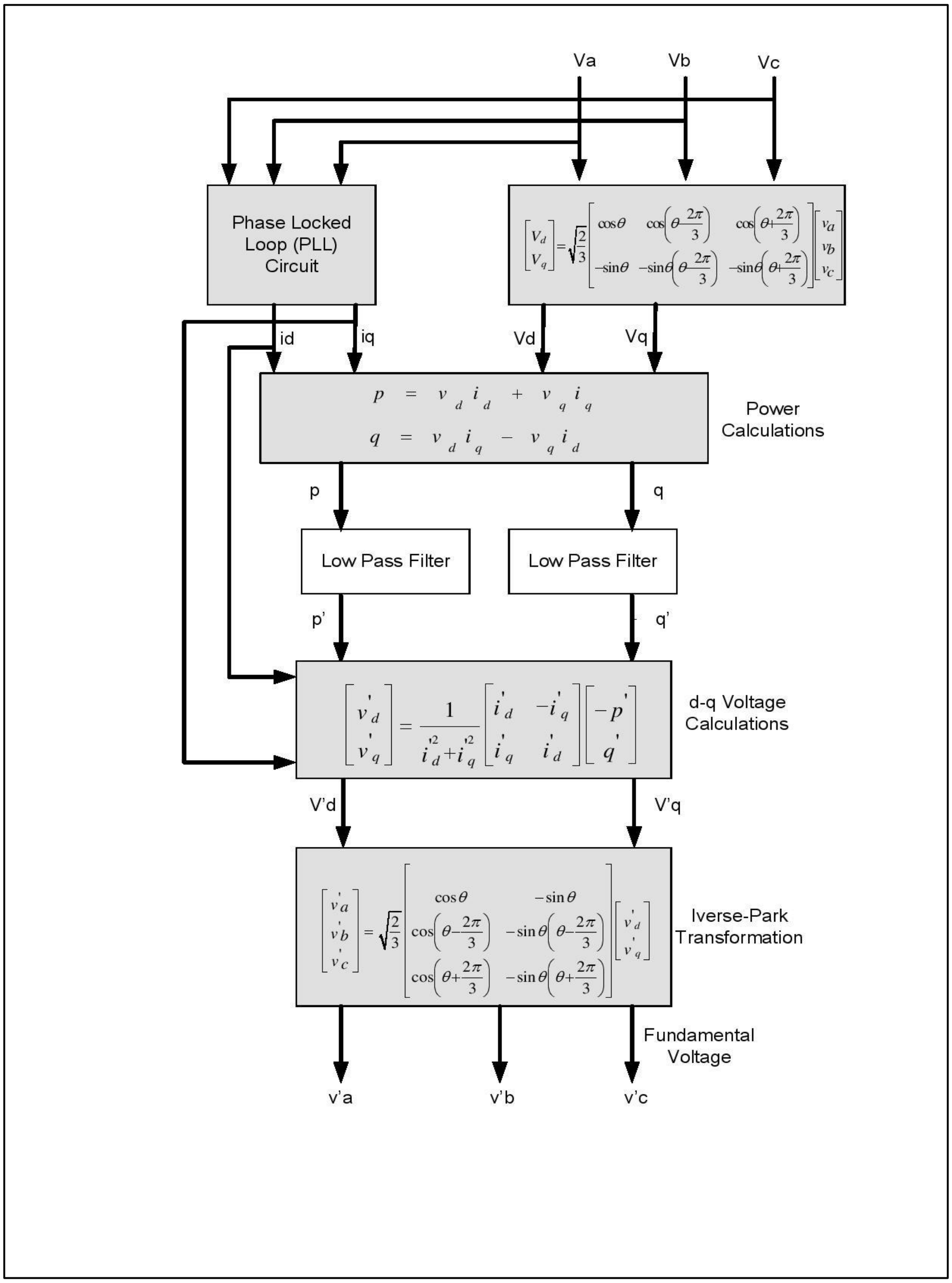

Figure 3.6 Fundamental Positive Sequence Voltage Detector

Positive sequence voltage detector shown in fig3.6 derive the fundamental positive signal from the unbalanced phase voltages. Positive sequence voltage at the fundamental frequency of highly distorted and unbalanced voltage are tracked by phase locked loop which is the important part of positive sequence voltage detector.

3.2.7 Voltage Source Converter

Power conversion from DC to AC is achieved through electronic converters. DC source is normally a battery or the output of the rectifier. Output voltage of the converter are controlled by pulse width modulations techniques and such converters are called PWM converters.

Inverters are mainly classified into two types as current source inverters and voltage source inverters. Both controller have their own different design but having the same technique to force the converter to behave like current controller device.

VSC are preferred over CSC due to many reasons like smaller physical size, high efficiency and low initial cost.

In the recent years, due to the improved voltage and current ratings of semiconductor devices, 2 level converters are used to feed the required current calculated by any control theory. Their applications range from motor drive units to reactive power compensations.

For perfect function of the inverter, it should be able to generate perfectly sinusoidal output voltages which is possible only if it does not contain low harmonic frequencies.

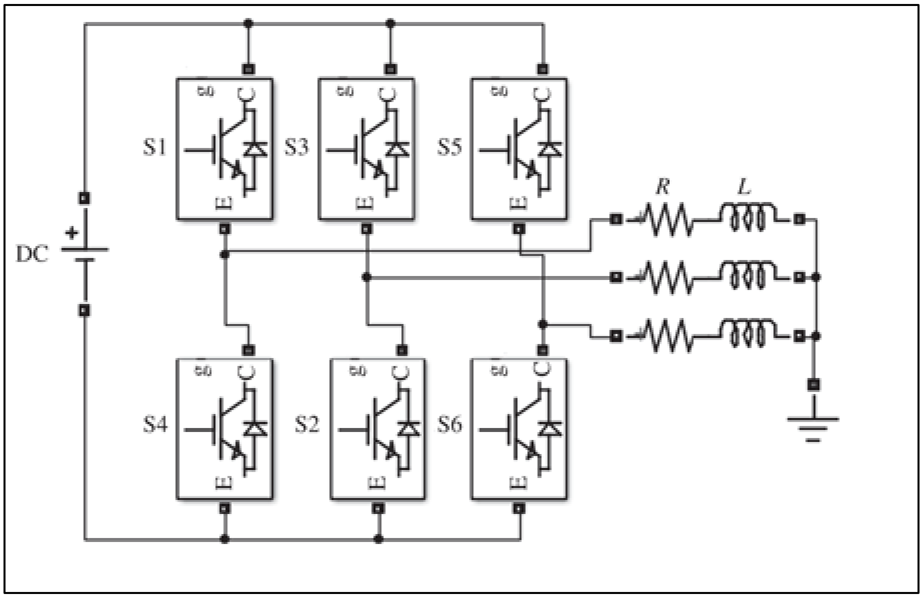

Figure 3.7 Two level Voltage Source Converter [73]

2-Level converter is used in this work which can produce the required harmonic current calculated by synchronous frame of refence theory demanded by load from the source to eliminate the harmonics and compensate reactive power.

3.2.8 Pulse Width Modulation and Current Controller

Pulse width modulation technique is used to encode message into pulsing signal but its main area of application is to control the power supplies to electrical equipment, especially motors and filters. Feeding of voltage and current to load is controlled by continuous switching between load and source at a very fast rate. As the switching on time is more than off time, more total power will be supplied to the load. Switching frequency vary greatly from few Hz's to tens of KHz, depending upon the load applications.

Biggest advantage of PWM is the minimum power loss in switching devices. There is no current flowing when the device is off and no voltage drop when the device is ON. So practically there is no power loss.

Active filter performance is greatly depended on current controller and the method employed to generate the gating signal for Voltage source converters. There are many strategies implemented for current modulation but triangular carrier control PWM technique is being used for this work as shown in the Figure 3.8.

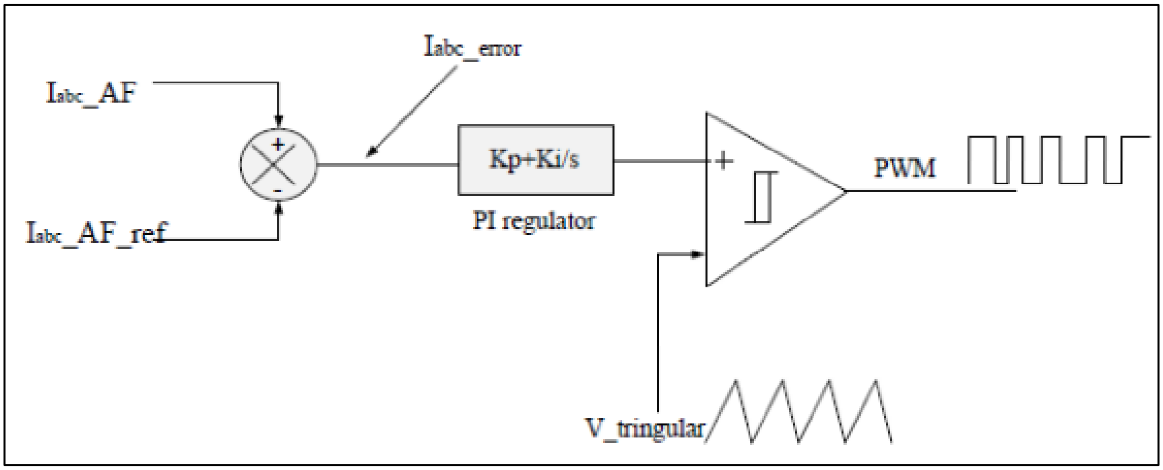

Figure 3.8 Triangular Carrier PWM Current Controller [74]

Active filter reference currents calculated by synchronous frame of reference theory and actual filter currents are compared at the input to produce error. PI controller is used here to make the error steady and then this error is compared with the triangular wave with fixed carrier frequency.

CHAPTER 4

NETWORK SIMMULATION MODELING

4.1 Preliminary Simulation

Work on the thesis objectives started with some preliminary simulations. The results of the simulation are shown in the proceeding sections.

In order to develop the complete Simulink modeling of the network, it requires to model each part of the network separately. Modeling of individual sections of the network are shown below and the results are briefly explained here.

4.2 System Network Modeling

The simulation parameters for system network used for the shunt active power filters are shown in Table 4.1. These are the general parameters used for the standard model and will be modified with respect to each simulation accordingly.

Table 4.1 Typical Distribution System Network Parameters

Parameters	Symbols	Values
Distribution supply voltages	V_{abc}	390 V
System frequency	f	60 Hz
Supply side commutation inductance	Ls	2 μH

Supply side resistance	Rs	0.0091 Ω
Filter side inductance	LF	2 mH
Filter side resistance	RF	0.0001 Ω
DC Link voltage of the shunt inverter	Vdc	800 V
Switching frequency	fs	10 kHz
Load side commutation inductance	Ld	2 mH
Load side resistance	Rd	0.0091 Ω
Load: Diode bridge loads at PCC	R-L Load	65Ω + 65 mH

Non-Linear load of different ratings is added and connected to the system in steps at different time intervals to check the validity and effectiveness of the shunt active filters with varying loading conditions because in the actual distribution systems the loads are not constant all the time. SLD of active filters is shown in fig.4.1

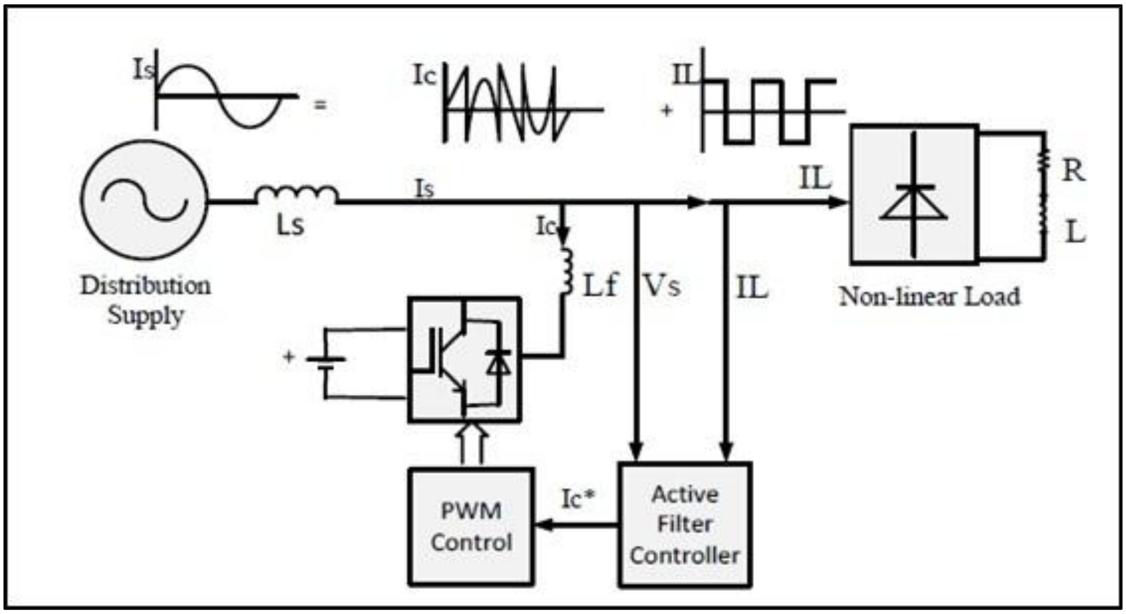

Figure 4.1 Single Line Diagram of Shunt Active Filters [15]

Simulation model of the system network is shown in Figure 4.2

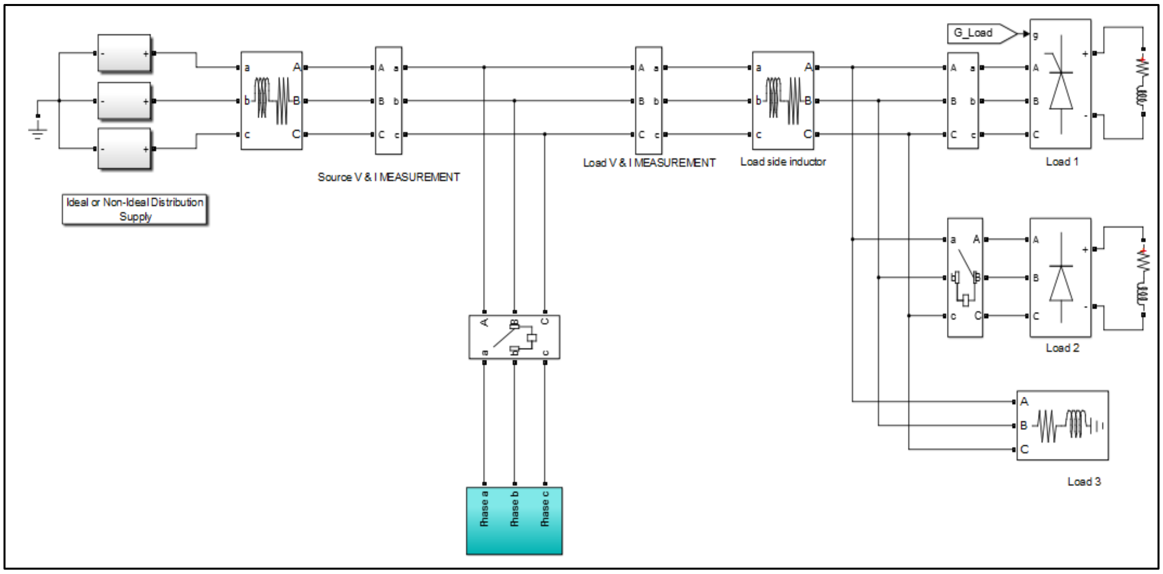

Figure 4.2 Network Modeling of the System Network

Source supply is connected to the left side of the model and it can be ideal, non-ideal and distorted under different conditions of the simulations. Next to the source supply is the inductance of the system that may be a line or transformer. To the right side of the model is the non-linear load that can also be balanced, un-balanced and distorted under different conditions of the simulations and will be connected to the system at different time instants. In the middle of the system is Active Filters with complete control algorithm and it will be connected in parallel to the system to provide the compensating current to mitigate the harmonics.

4.3 Simulation Modeling of d-q Theory

The d-q theory is modeled and simulated as shown in Figure 4.3 Inputs to the controller are three phase non-linear load currents and source voltages which are fundamental and are extracted from the fundamental positive sequence extractor. This enables the operation of standard d-q theory for the non-sinusoidal and distorted source supply voltages also. In d-q block voltages and currents are transformed from three coordinates a-b-c to d-q coordinates using park transformation to make the calculations simpler and straightforward. In next step d-q currents are compared with compensator currents to reduce the error. The steady state output is fed to inverse d-q block to retrieve the original currents in a-b-c coordinates. These reference currents are the required currents that needs to compensate and are injected to the system by voltage source converters with the help of pulse width modulation.

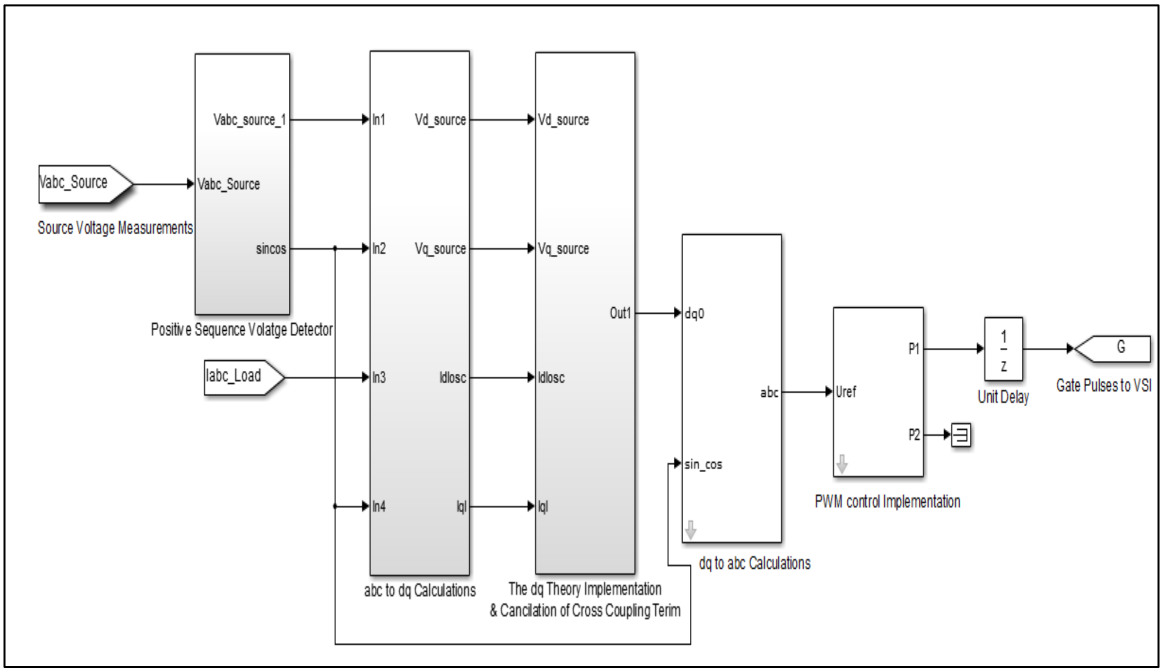

Figure 4.3 Modeling of d-q Theory

4.4 Simulation Modeling of Source Supply

Distribution supply can be considered and simulated as an ideal source or as an unbalanced, highly distorted according to the condition of simulations as shown in Figure 4.4 and 4.5 respectively.

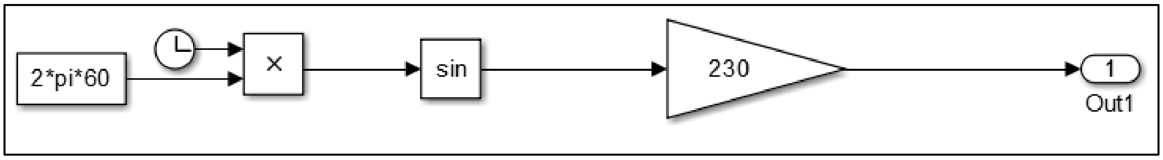

Figure 4.4 Simulation Model of Balanced Source Supply Voltages, phase-a

Three phase voltages Va, Vb and Vc are balanced and sinusoidal. Phase-b voltages are 120 Degree displaced from phase-a voltage, whereas phase c voltages are 120 degrees displaced from phase-b voltages.

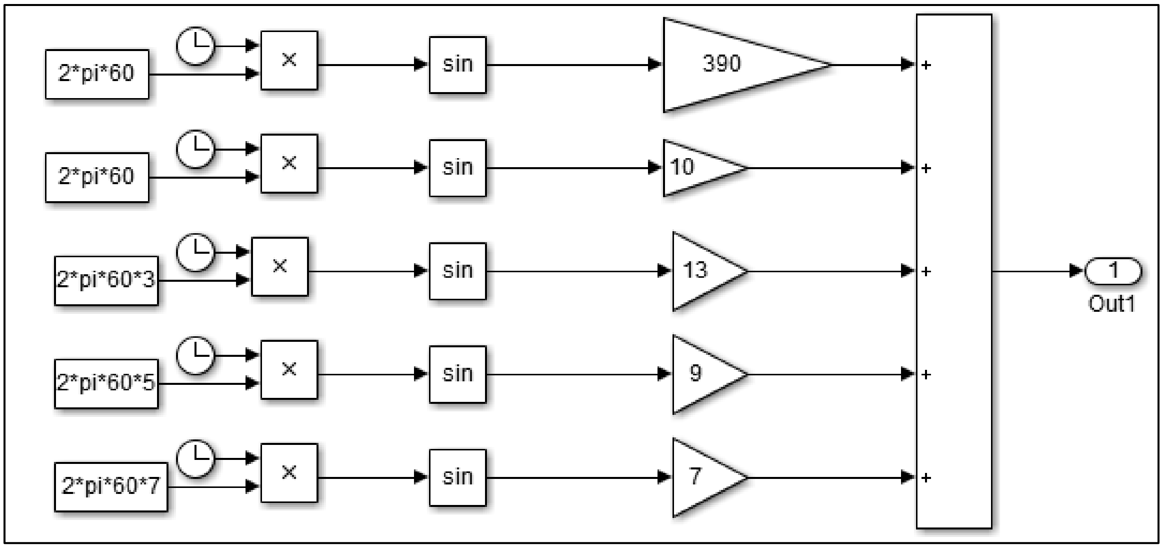

Figure 4.5 Un-Balanced & Distorted Source Supply Voltages, phase-a

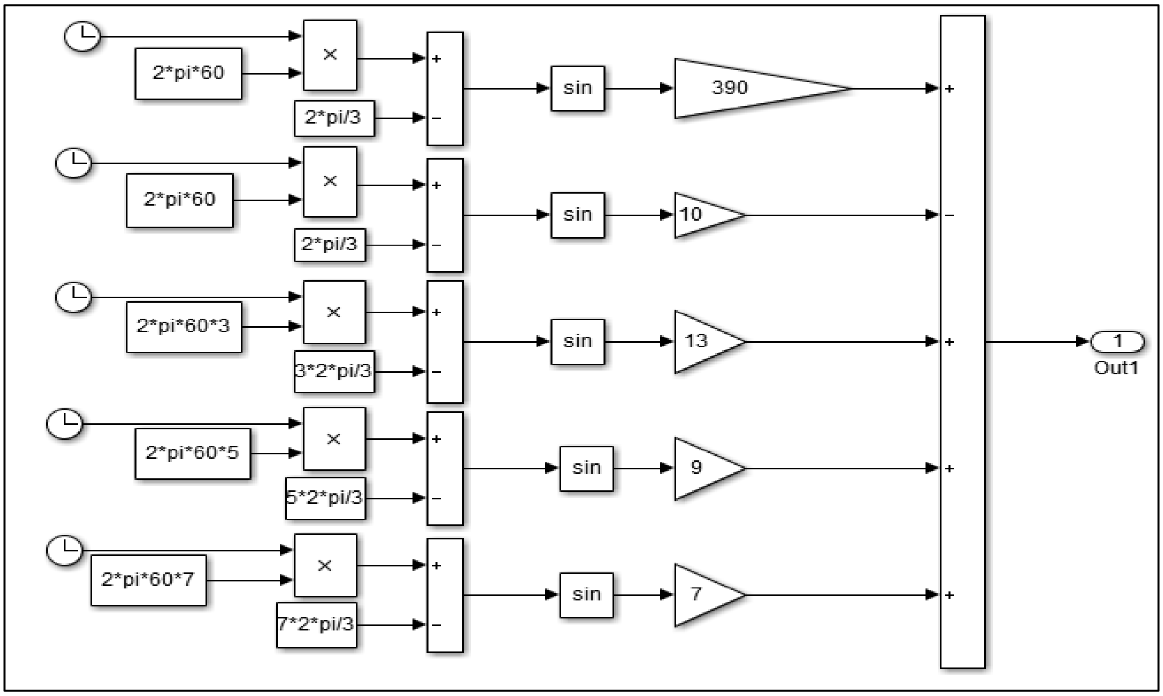

Figure 4.6 Simulation Model of Non-Ideal Source Supply Voltages, phase-b

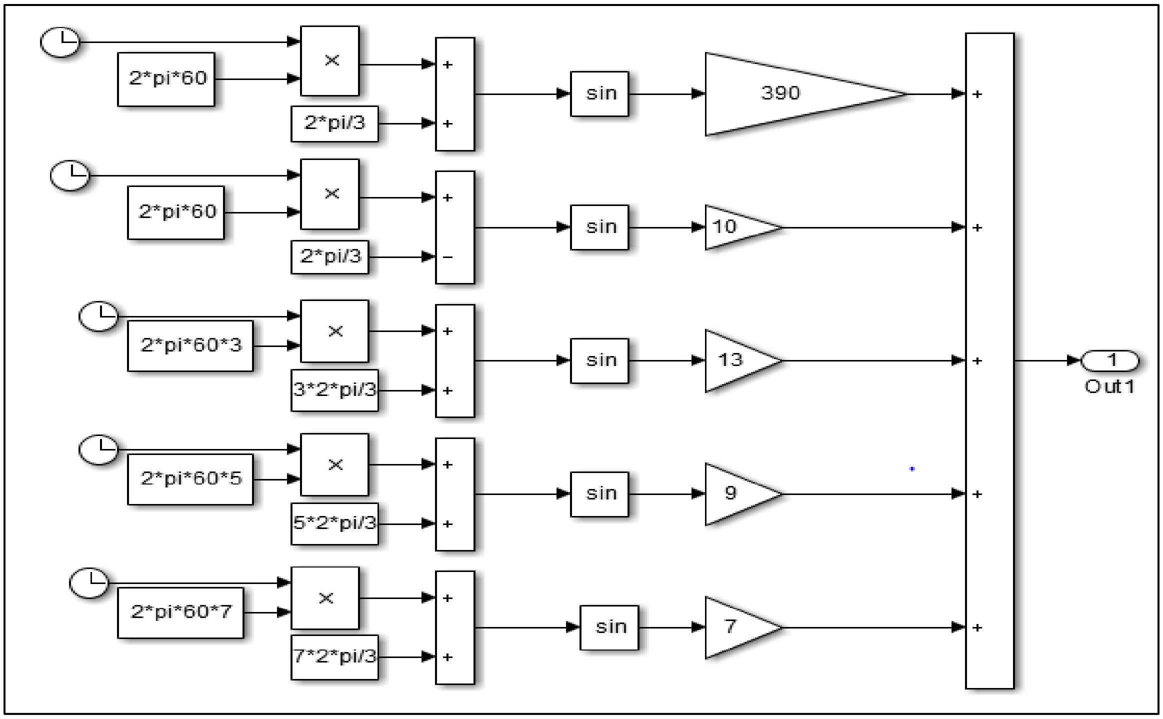

Figure 4.7 Simulation Model of Non-Ideal source Supply Voltages, phase-c

Fig.4.5 shows the simulation of unbalanced and highly distorted source supply. Unbalanced is created by adding 10 volts' magnitude and displacing the phase -b 120° with phase-a and displacing phase-c -120° form phase-a. This makes the source supply highly unbalanced. Distortion is created by adding 3rd, 5th and 7th harmonics of 13, 9 and 7 magnitudes respectively.

Similarly, phase-b and c of the non-ideal source supply are simulated as shown in Figure 4.6 and 4.7.

Fig 4.8 shows the output of the modeled 3-phase non-ideal source supply.

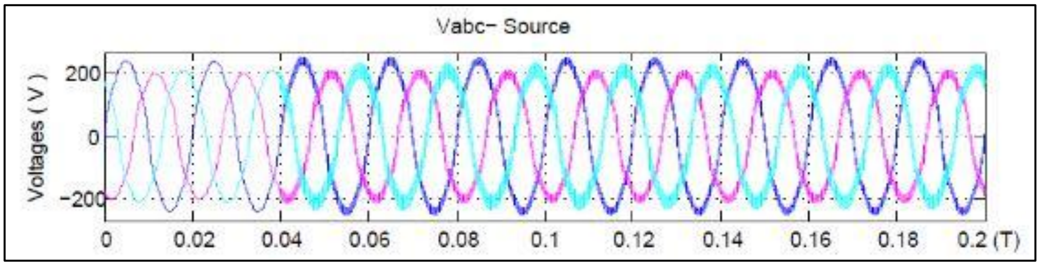

Figure 4.8 Waveform of Non-Ideal 3-phase Source Supply

4.5 Non-Linear Load Modeling

Effectiveness of the electricity consumption for useful work is measured by power factor. For non-linear loads, power factor remains the ratio of KW to KVA but additional harmonic component $kVAR_H$ is added to the basic KVA. Therefore, the True power factor becomes the combination of displacement power factor and distortion power factor. The displacement power factor is near unity for non-linear loads but true power factor is very low because of the distortion factor. The mathematical relationship is shown in equations 4.1 to 4.4.

$$pf = \frac{P}{S} = \mathrm{Cos}\,\phi \tag{4.1}$$

$$S = \sqrt{P^2 + Q^2 + H^2} \tag{4.2}$$

$$kVA = \sqrt{kW^2 + kVAR^2 + kVAR_H{}^2} \tag{4.3}$$

$$\text{True Power Factor} = \text{Displacement pf x Distortion pf} \tag{4.4}$$

In presence of harmonic component in nonlinear loads, the apparent power is the combination of P, Q and H, as shown in equation number 4.2

Thyristor bridge Non-Linear load with R & L is modeled as shown in Figure 4.9 and connected to the network to check the filter dynamics in presence of non-linear loads.

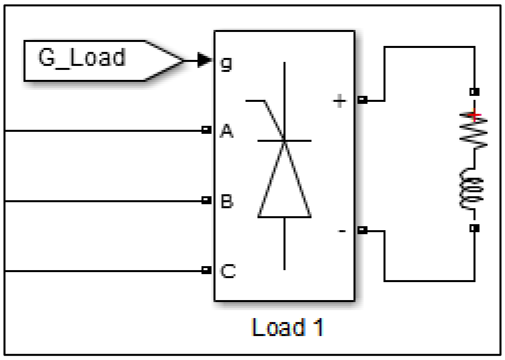

Figure 4.9 Thyristor Bridge Non-Linear Load

Three inputs of the load are connected to supply phases a, b and c whereas the fourth input G is for control signal of the load which specify the system frequency and firing angle. The current waveforms of non-linear load for three phases is shown in Figure 4.10

Three phase RLC load-3 is connected to the network. Load1 and load 3 are constant loads whereas load 2 is connected to the system at time 4 second to create varying load condition for the system network. Also, any phase of the load can be switched off to create the unbalanced loading condition for the simulation.

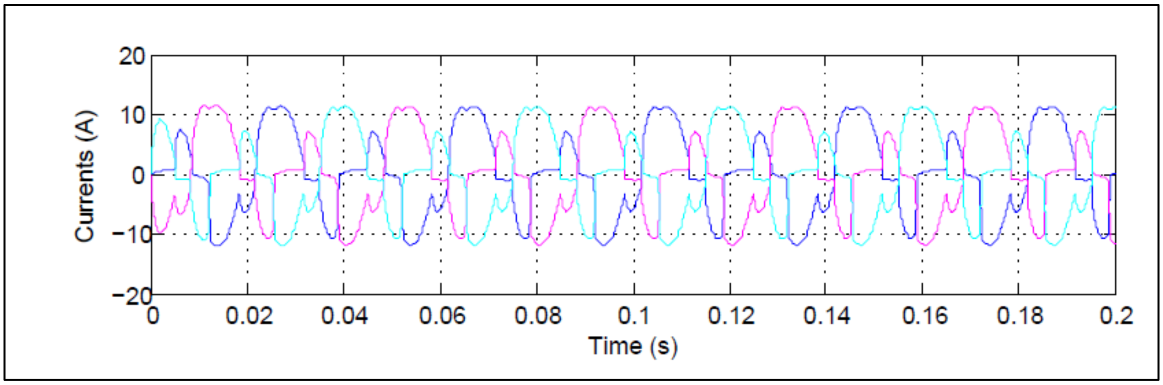

Figure 4.10 Current of Non-Linear Load, 3-phase

Figure 4.10 shows the variations of the load currents in different phases. Non-linear load draws current from the source supply in abrupt and discrete manner causing the system voltages non-sinusoidal and distorted.

4.6 Active Filter Design

Control theory is the heart of active filters. The existing d-q theory and active filter model deal with ideal system conditions of sinusoidal and balanced source supply voltage and balanced loads. In practical distribution networks, one must always face with varying and distorted loads with un-balanced and non-sinusoidal source voltages which needs to address properly and pay more attention for prolific application of the active filters.

The performance and effectiveness of the active filter for power quality applications is largely dependent upon the current control technique which is the nucleus of filter in which reference current of the varying load is extracted to compensate harmonics distortion in load current. Therefor active filter controller plays a key role in the achievement of desired results from active filters. Fig.4.11 shows the typical schematic for active filters.

In this work, new control strategy is developed which enables active filter to perform in unbalanced, distorted source supply and varying loads.

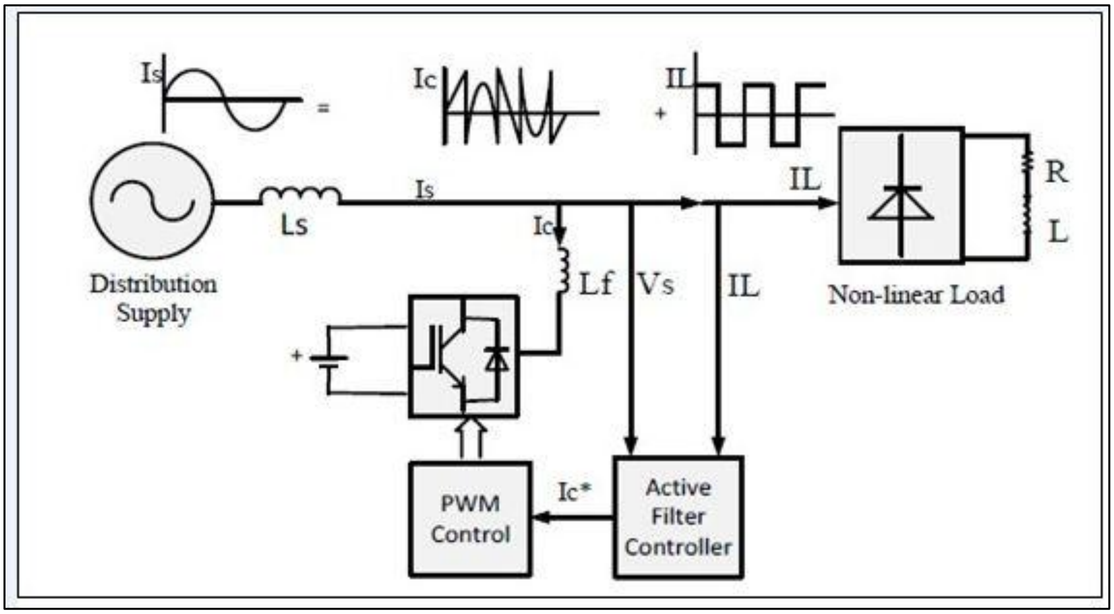

Figure 4.11 Shunt Active Power Filter Configuration [15]

The controller of the shunt active filter is designed to cater with adverse system conditions. Unbalanced supply voltages are neutralized with positive sequence voltage detector and fed to d-q theory for reference current calculations. The reference currents are supplied to the system with help of PWM. Positive sequence voltage detector is modeled as shown in fig. 4.12.

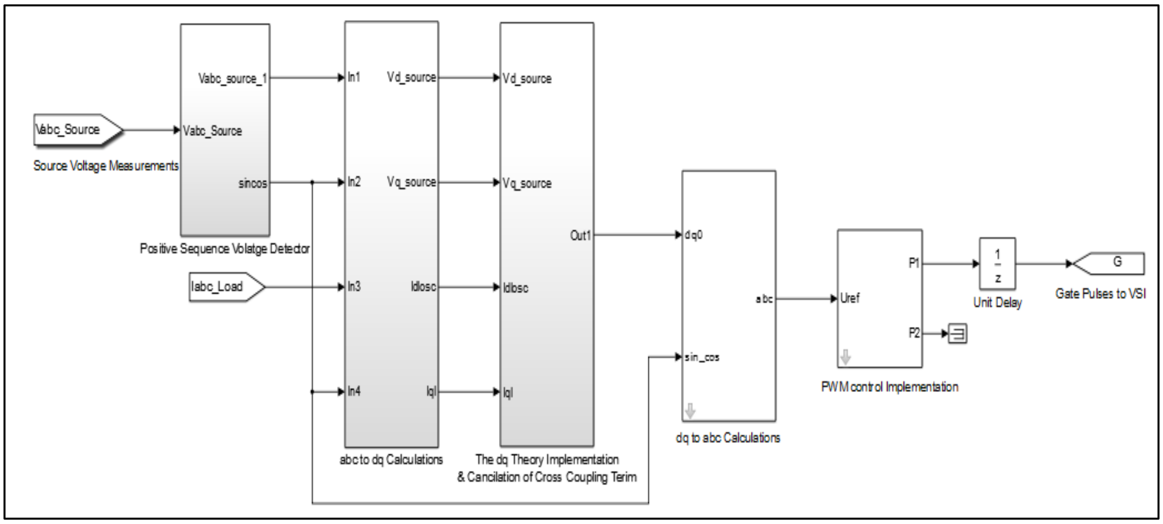

Figure 4.12 Positive Sequence Voltage Detector

The selected parameters of phase locked loop and pulse width modulations are given below,

Kp=180

Ki=3200

Kd=1

Damping factor(zeta)=1

Cut-off frequency= 60Hz

Converter Level= 2

Carrier Frequency(Hz)= 10000

By adjusting these parameters to suitable values given above, the phase locked loop (PLL) can extract the fundamental voltages from the unbalanced supply and fed to d-q theory to calculate the reference currents for system demanded by the nonlinear loads.

4.7 Sensitivity Analysis for Filter Parameters

Unbalanced supply voltages are fed to Phase locked loop PLL where the fundamental voltages are extracted with the help of fundamental positive sequence detector making it possible for shunt active filters to mitigate the harmonics in adverse power system conditions. Optimal operation of active filters mainly depends upon the proper selection of the parameters for phase locked loop. Sensitivity analysis is carried out to observe the effect of input variables to the output.

Kp is the proportional gain and have significant impact to proportionally increase the control signal for the same value of error. Another effect of increasing the Kp gain is to reduce but not eliminate the error.

Similarly, Ki integral gain tend to eliminate the error but at the same time it makes the system unstable and causes oscillation.

Kd, the derivative gain has no effect on error but it makes the system stable.

Summary of all these parameters are shown in table 4.2

Table 4.2 Summary of Filter Parameters

Parameters	Rise Time	Overshoot	Settling Time	Error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Decrease
Kd	Small Change	Decrease	Decrease	No Change

Individual effect of these parameter to THD is graphically shown below,

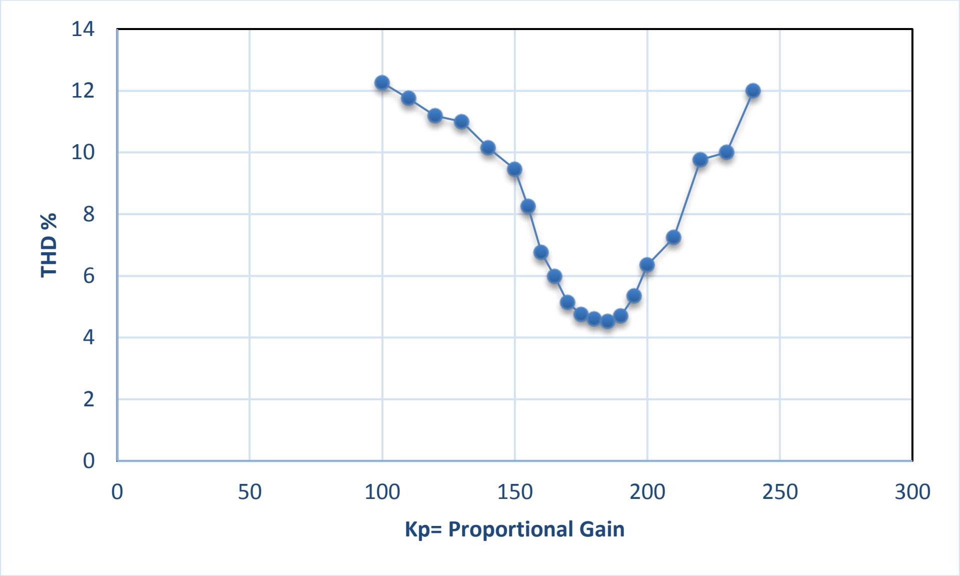

Figure 4.13 Proportional Gain Constant

It is clear from the fig 4.13 that proportional gain constant is more sensitive to the total harmonic distortion THD in range betwee160 to 200. Optimal value of Kp is 185.

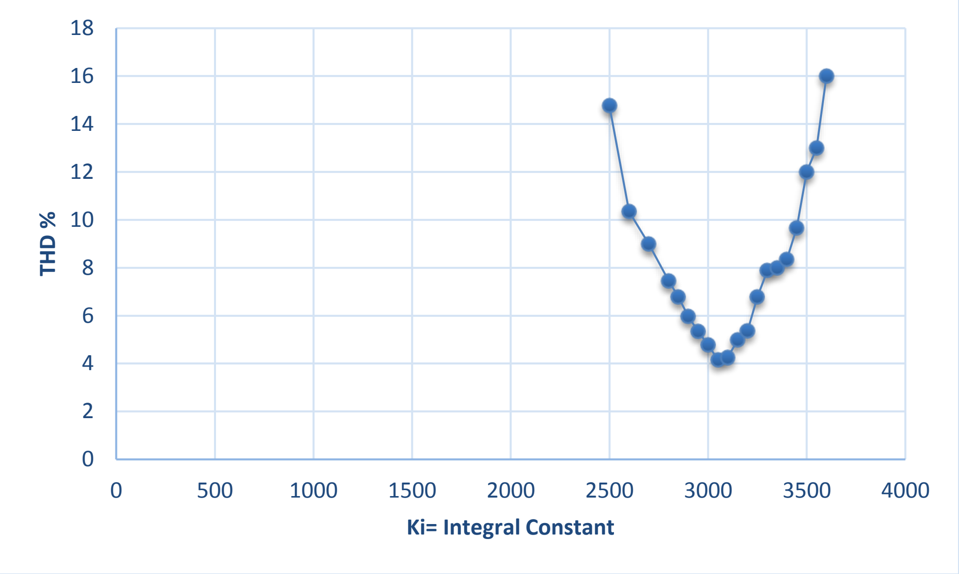

Figure 4.14 Integral Gain Constant

Integral gain constant in fig.4.14 is more sensitive to the THD in the range of 2600 to 3400. Optimal value of the integral constant is 3050.

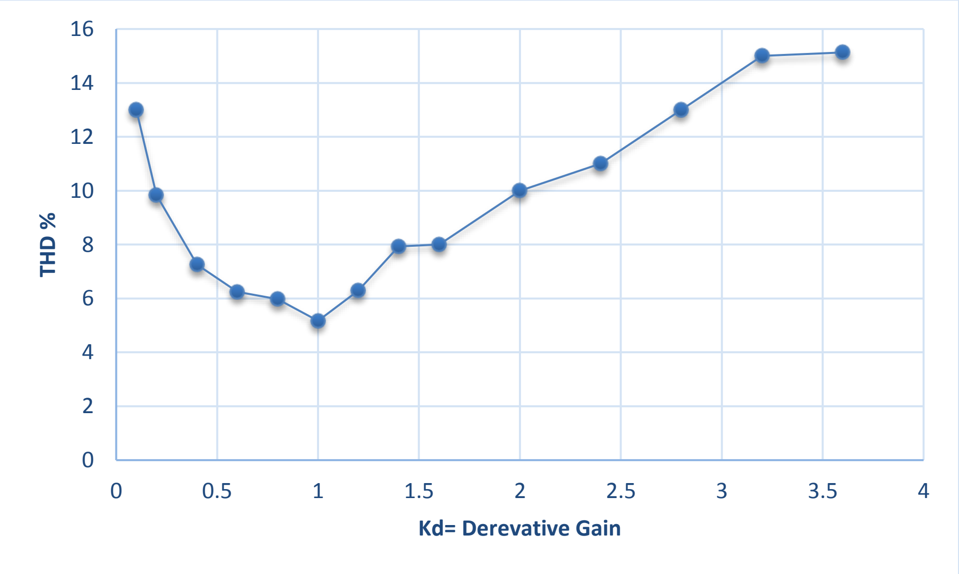

Figure 4.15 Derivative Gain Constant

Derivative constant is more sensitive to the range of 0.25 to 1.4. Optimal value of Kd is 1. However, when we see the accumulative effect of these constants to the variation of THD output of the active filter, we observe that minimal THD 4.6 is obtained at different values other than the optimal values of these parameters as shown in table 4.4

In view of the sensitive analysis of active filter parameters, an optimal range of these parameter can be set as shown in the table 4.3

Table 4.3 Range of Filter Parameters

Parameters	Minimal Range	Maximum Range
Kp	160	200
Ki	2600	3400
Kd	0.25	1.4

Summary of the effect of active filter parameters to the performance of the filter in term of THD is shown in detail in table 4.4

Table 4.4 Optimal Selection of Filter Parameters

Kp	THD %	Ki	THD %	Kd	THD %	Overall THD %
100	12.26	2500	14.76	0	0	12
110	11.75	2600	10.34	0	0	11
120	11.19	2700	8.98	0	0	10.34
130	11	2800	7.45	0	0	9
140	10.15	2850	6.78	0	0	8.34
150	9.45	2900	5.97	0	0	7.47
155	8.25	2950	5.34	0.1	13	6.87
160	6.75	3000	4.78	0.2	9.84	6.45
165	5.98	3050	4.15	0.4	7.25	5.99
170	5.13	3100	4.24	0.6	6.25	5.34
175	4.75	3150	4.98	0.8	5.98	4.75
180	4.6	3200	5.36	1	5.17	4.67
185	4.52	3250	6.78	1.2	6.29	4.85
190	4.7	3300	7.87	1.4	7.93	5
195	5.34	3350	8	1.6	8	6.45
200	6.35	3400	8.35	2	10	7.45

210	7.24	3450	9.67	2.4	11	8.24
220	9.76	3500	12	2.8	13	10.23
230	10	3550	13	3.2	15	11.23
240	12	3600	16	3.6	15.13	13

Performance of the active filter is greatly depending upon the control strategy of the active filters and is called the heart of the filter. Initially the optimal parameter were determined by hit and trial method and then sensitivity analysis is used to determine the effect of these parameter to the performance of the filters and optimal range is concluded for these parameters.

CHAPTER 5

SIMULATIONS AND RESULT DISCUSSIONS

5.1 Different System Conditions of AC Distribution Networks

A number of simulations are carried out to test the performance and validity of shunt active filters with number of non-linear, distorted & varying loads and un-balanced, distorted source supply voltages. Proposed shunt active filter will be able to compensate harmonic currents and address reactive power issues even under worst system network conditions. Application of the shunt active filter will be analyzed possibly for the following system conditions.

5.2 Balance Supply Voltages with Balance Load

In this case, the system will be considered perfectly ideal with balance supply voltages and balance loads. IEEE-519 also recommends considering ideal conditions for sake of computer analysis of the system. All the system parameters are listed in table 4.1.

The system equations will be like as follow:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = 230 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t + 120^\circ) \end{bmatrix} \tag{5.1}$$

5.2.1 Simulation Results & Discussion

All the system parameters are listed in Table 4.1. Source supply voltages and currents are shown in Figure 5.1.

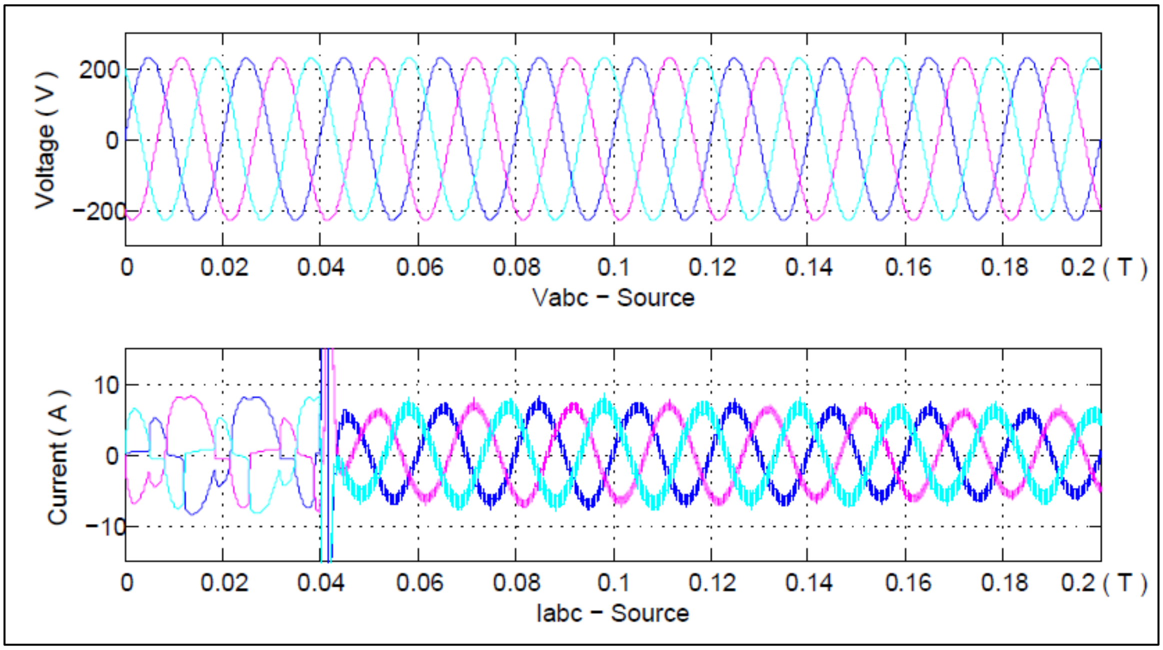

Figure 5.1 Source Supply Voltages and Currents

Three phase Voltage waveforms are perfectly sinusoidal and equally spaced from each other as for the case under discussion the source supply is considered balanced and free from distortion. Source currents are initially distorted and non-sinusoidal because of the non-linear load but it became sinusoidal at the instant when the active filters are connected to the system by injecting compensating currents calculated by synchronous frame of reference theory.

Figure 5.2 clearly shows active filter voltages and currents. Voltages are present across the active filter even before connecting to the system because active filters are connected to the constant voltage supply. Currents are zero across the filter as AF is not supplying any

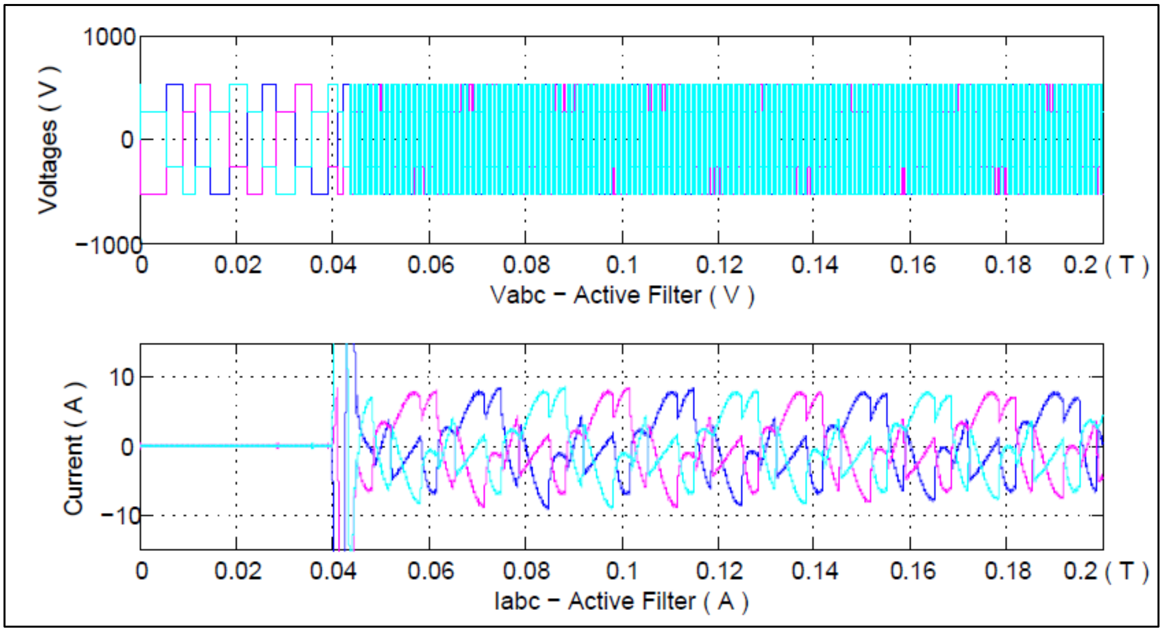

Figure 5.2 Active Filter Voltages and Actual Currents

compensating current to the system but it starts supplying compensating currents to the system after connecting to the system making source supply perfectly sinusoidal.

Figure 5.3 shows the input reference currents of the active filter and actual reference currents compensated by the shunt active filters for phase-a.

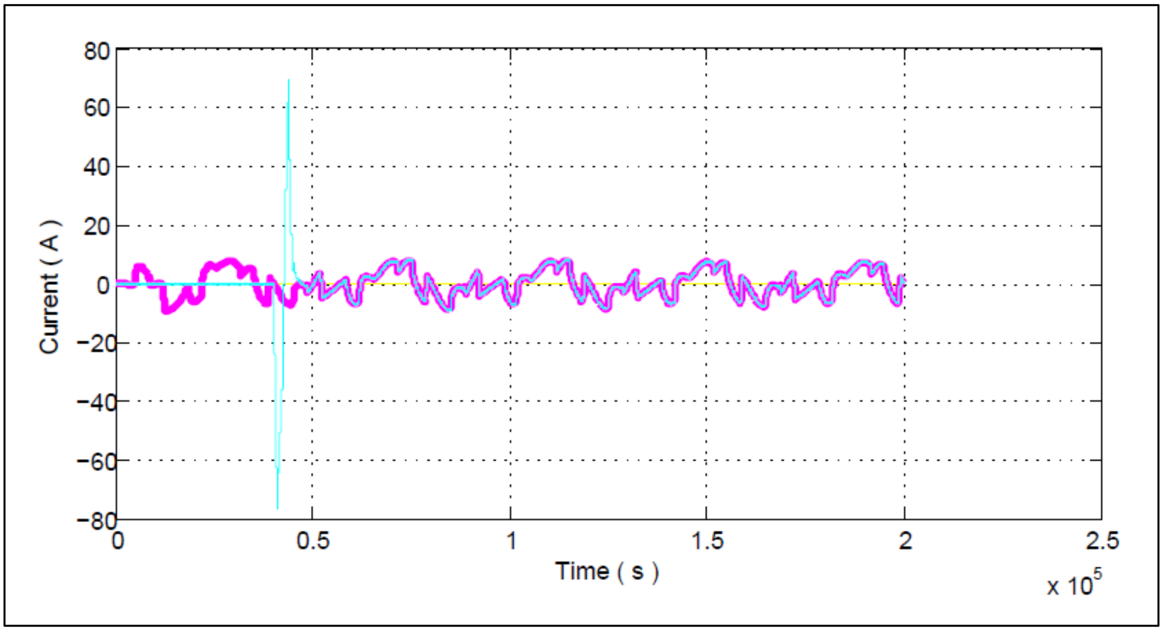

Figure 5.3 Active Filter Reference Currents-Phase a

The instant when the active filter is connected to the system, it starts following reference currents in less than a cycle making sure successful compensation of the harmonic currents demanded by the non-linear loads from the distribution system.

Figure 5.4 shows the input reference currents of the active filter and actual reference currents compensated by the shunt active filters for phase-b.

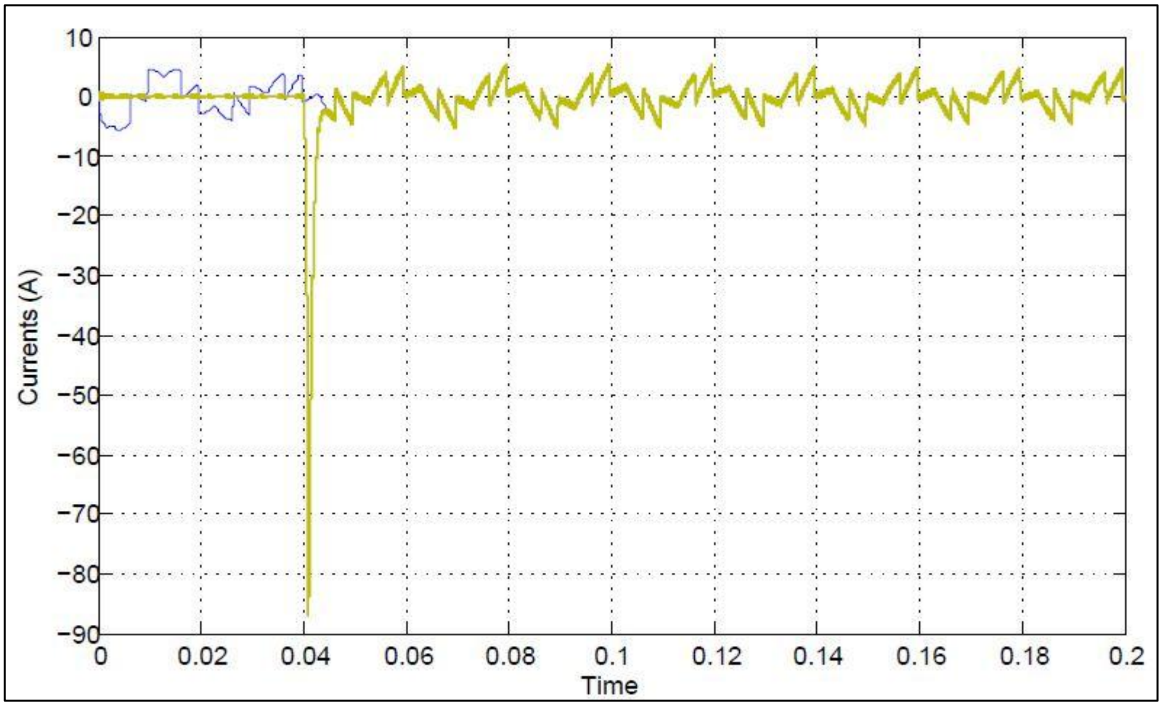

Figure 5.4 Active Filter Reference Currents- Phase b

Figure 5.5 shows the input reference currents of the active filter and actual reference currents compensated by the shunt active filters for phase-c.

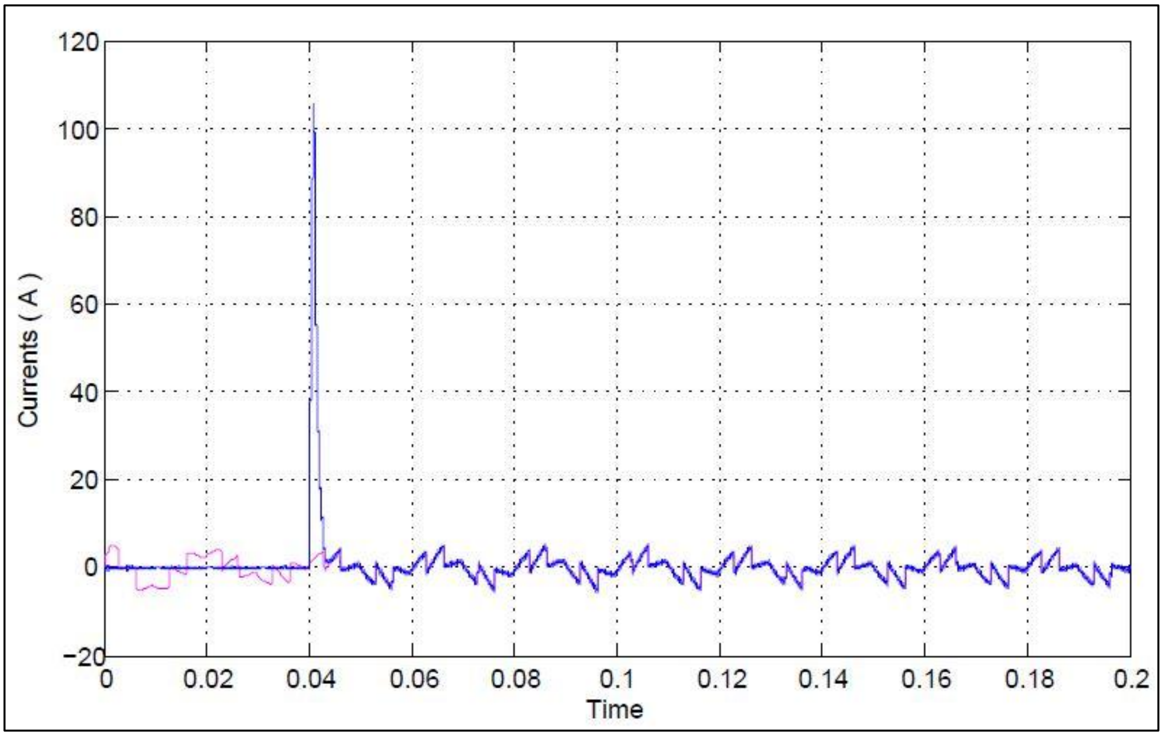

Figure 5.5 Active Filter Reference Currents- Phase c

Figure 5.6 shows the voltages and currents of the non-linear load. It draws non-sinusoidal currents from the source in an abrupt manner causing harmonics in the system network.

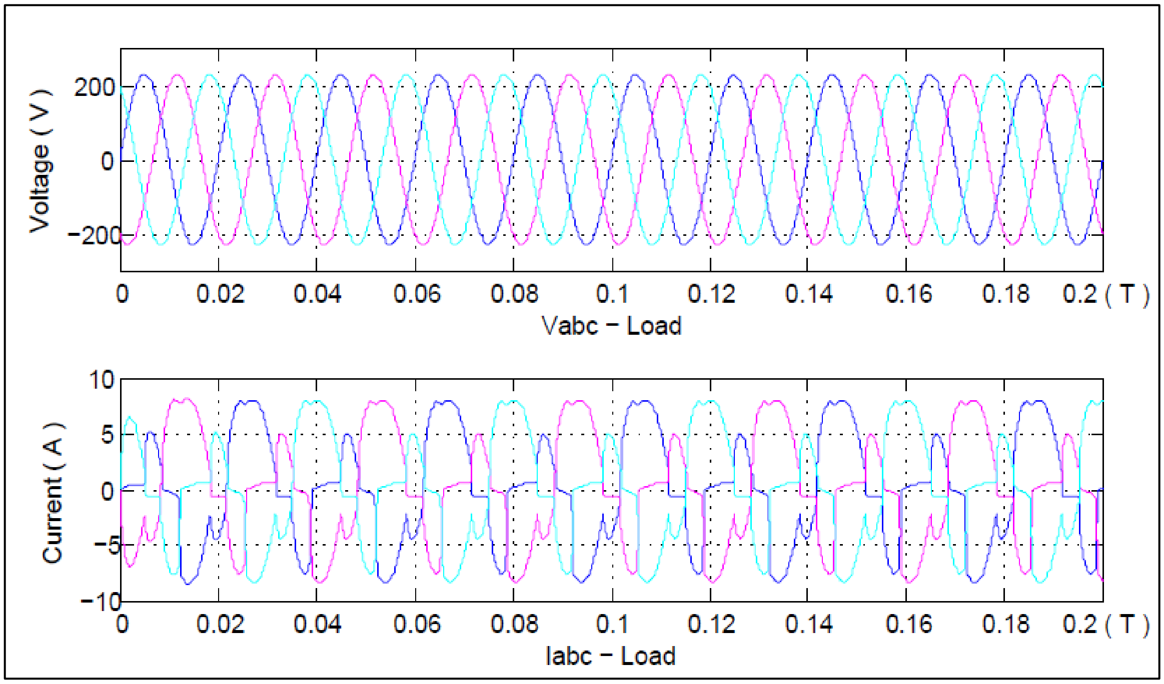

Figure 5.6 Non-Linear Load Voltages and Currents

Shunt active filters successfully manages the power factor of the system and bring it close to unity as the source voltages are exactly in phase with the source currents shown in Figure 5.7, 5.8, 5.9 for phase a, b and phase c respectively.

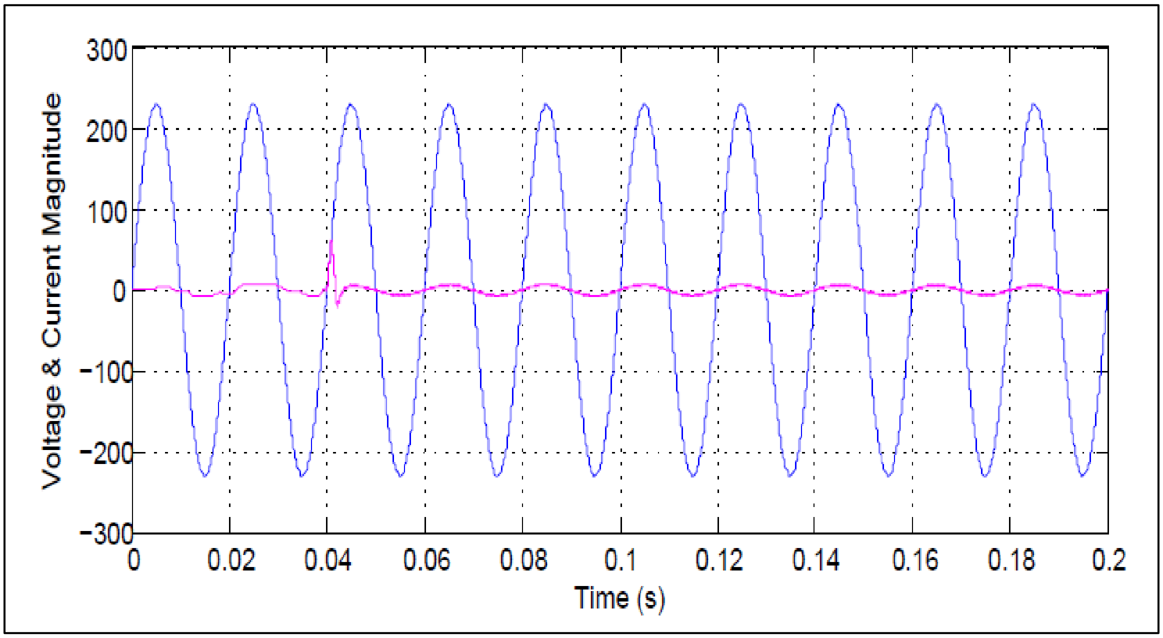

Figure 5.7 Source Voltages and Currents of phase-a

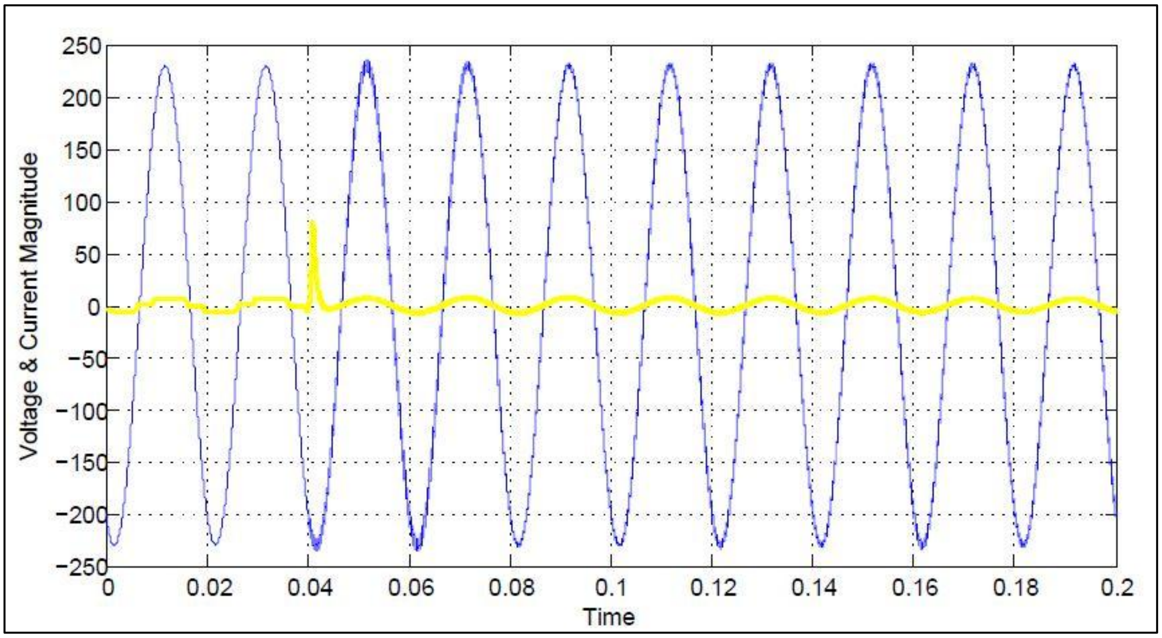

Figure 5.8 Source Voltages and Currents of phase-b

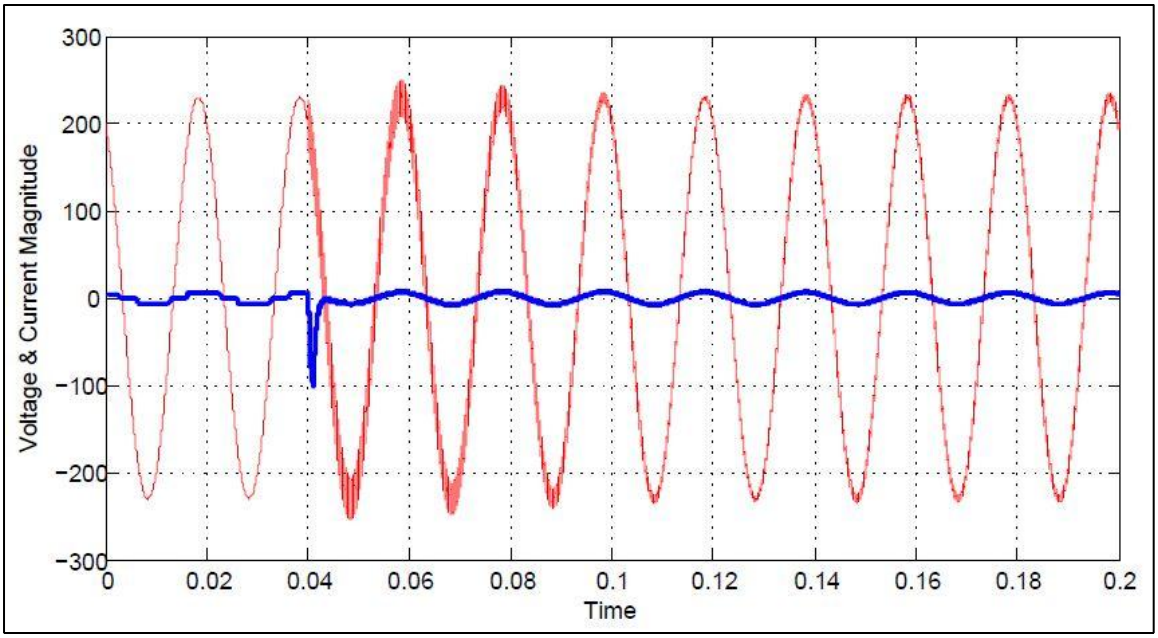

Figure 5.9 Source Voltages and Currents of phase-c

Figure 5.10 show the THD in the three-phase source current before the operation of shunt active filters and the harmonics level is 27.35% which is very high and violating acceptable limits defined by international standards.

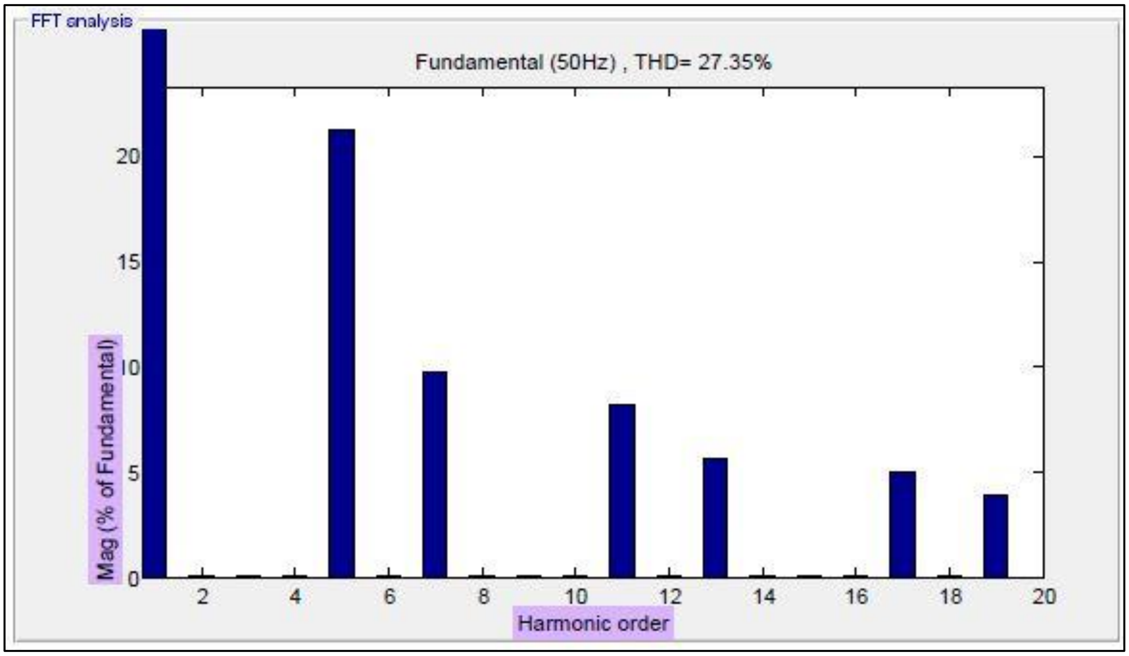

Figure 5.10 Iabc Source current THD Before Active Filtering

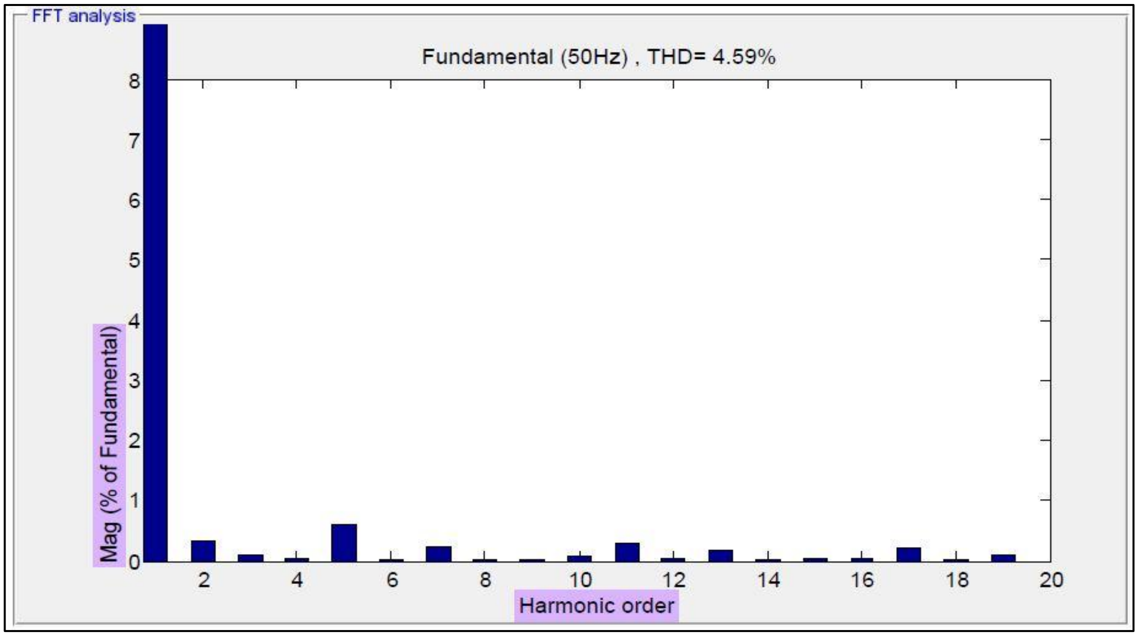

Figure 5.11 Iabc Source Current THD After Active Filtering

Whereas Figure 5.11 shows THD level after the working of active filters which is 4.59 % and is within acceptable range of limits defined by the international standards.

5.3 Un-Balanced and Distorted Supply Voltages with Un-Balanced and Distorted Load

In this case, simple d-q theory is not valid one because it deals only with balanced system conditions. Therefor it required some modifications to deal with abnormal conditions when the supply voltages are un-balanced and non-sinusoidal.

This is the worst case in the power system as the source supply is heavily unbalanced and distorted which have severe effect on the controllability of the load connected to the supply. Shunt active filter must work efficiently in presence of unbalanced and polluted supply voltages and must compensate the reactive power of the system.

Fundamental voltages are extracted from positive sequence voltage extractor and fed to the controller which makes the d-q theory applicable for non-ideal source supply.

Load is also considered as unbalanced nonlinear load. Load 1 and 3 are constant three phase loads and are connected to the system from the start of the simulation whereas load 2 is step nonlinear load which is connected at 4 seconds after the start of the simulation. Step load 3 is connected between the phase a and c thus making the source supply heavily unbalanced.

Supply voltage equations are as follow:

$$\begin{bmatrix} v_{uda} \\ v_{udb} \\ v_{udc} \end{bmatrix} = \begin{bmatrix} v_{ua+} \\ v_{ub+} \\ v_{uc+} \end{bmatrix} + \begin{bmatrix} v_{ua-} \\ v_{ub-} \\ v_{uc-} \end{bmatrix} + \begin{bmatrix} v_{uah} \\ v_{ubh} \\ v_{uch} \end{bmatrix} = \begin{bmatrix} v_{daf} \\ v_{dbf} \\ v_{dcf} \end{bmatrix} + \begin{bmatrix} v_{ua-} \\ v_{ub-} \\ v_{uc-} \end{bmatrix} + \begin{bmatrix} v_{uah} \\ v_{ubh} \\ v_{uch} \end{bmatrix} \qquad (5.2)$$

Whereas Vuda are the unbalanced and distorted supply voltage. Vua+ is positive sequence voltage, Vua- is the negative sequence voltage, Vdaf is the fundamental voltage and Vuah is the harmonic distorted voltage. Unbalanced and distorted supply voltages will be written as,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = 220\begin{bmatrix} \sin(wt) \\ \sin\left(wt-120^{\circ}\right) \\ \sin\left(wt+120^{\circ}\right) \end{bmatrix} + 10\begin{bmatrix} \sin(wt) \\ \sin\left(wt-120^{\circ}\right) \\ \sin\left(wt+120^{\circ}\right) \end{bmatrix} + 13\begin{bmatrix} \sin(3wt) \\ \sin\left(3wt-120^{\circ}\right) \\ \sin\left(3wt+120^{\circ}\right) \end{bmatrix}$$

$$+9\begin{bmatrix} \sin(5wt) \\ \sin\left(5wt-120^{\circ}\right) \\ \sin\left(5wt+120^{\circ}\right) \end{bmatrix} + 7\begin{bmatrix} \sin(7wt) \\ \sin\left(7wt-120^{\circ}\right) \\ \sin\left(7wt+120^{\circ}\right) \end{bmatrix} \tag{5.3}$$

5.3.1 Simulation Results & Discussion

All the system parameters are listed in Table 4.1. Unbalanced and distorted distribution supply voltages are simulated to test and validate the performance of the shunt active filters for harmonics elimination and reactive power compensation. As we aware about the fact that synchronous frame of reference theory is valid only for balanced source supply. Therefor to deal with unbalanced and distorted supply voltage, there is a need of extraction of fundamental positive sequence voltages.

Figure 5.12 shows the unbalanced and distorted supply voltages.

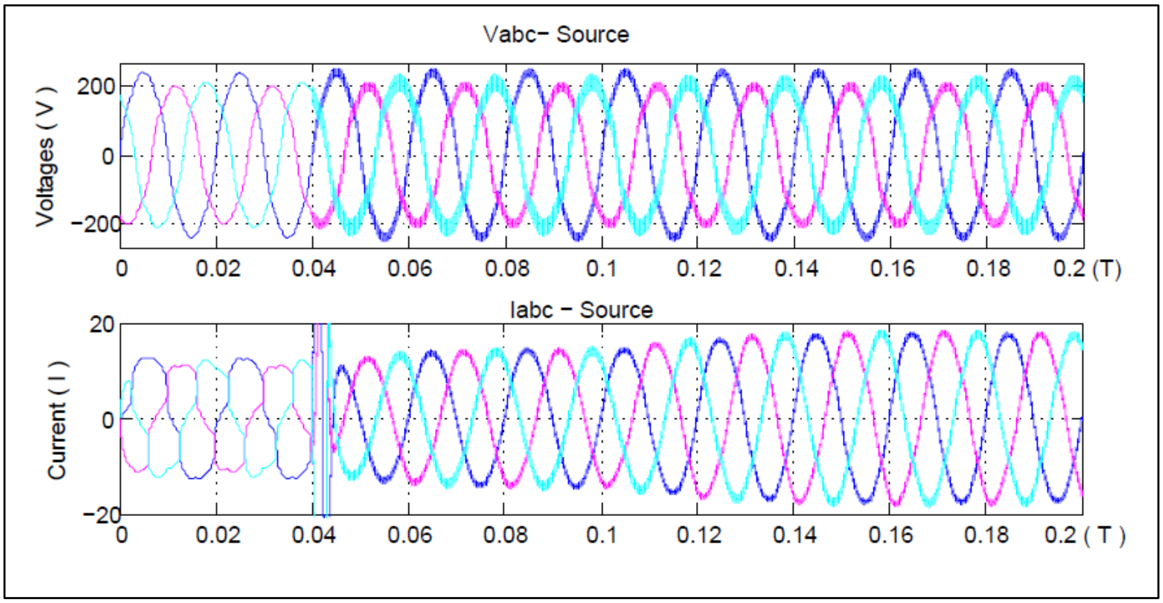

Figure 5.12 Source Supply Voltages and Currents

Source currents are becoming perfectly sinusoidal and harmonics free at the instant when active filters are connected to the system.

Active filter voltage and currents are shown in fig.5.13

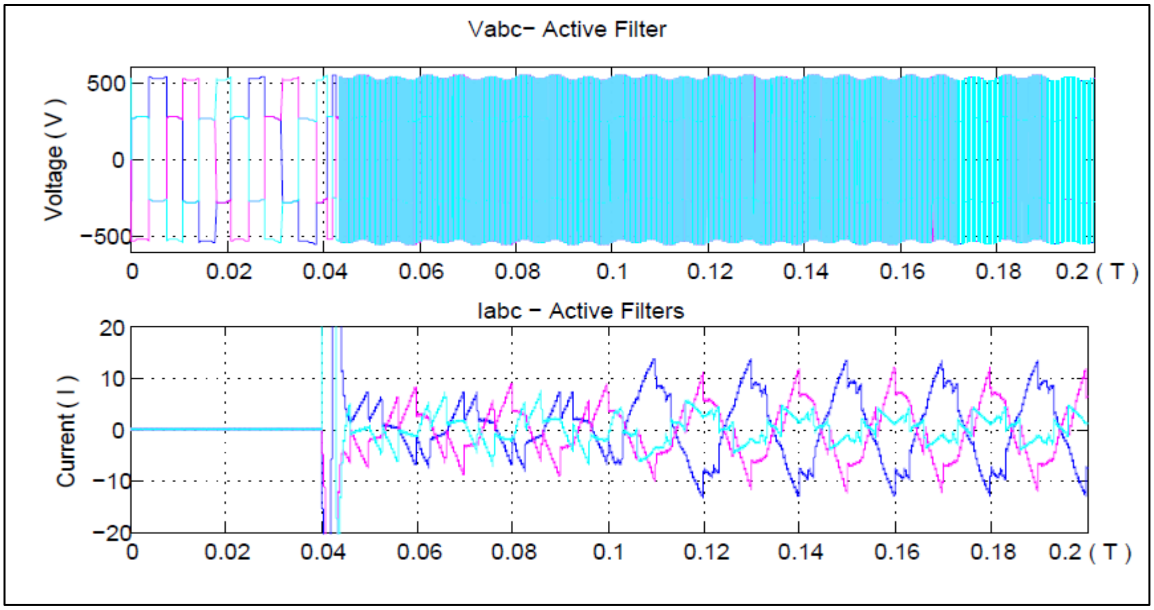

Figure 5.13 Active Filter Voltages and Actual Currents

Active filter reference currents are shown in fig.5.14.

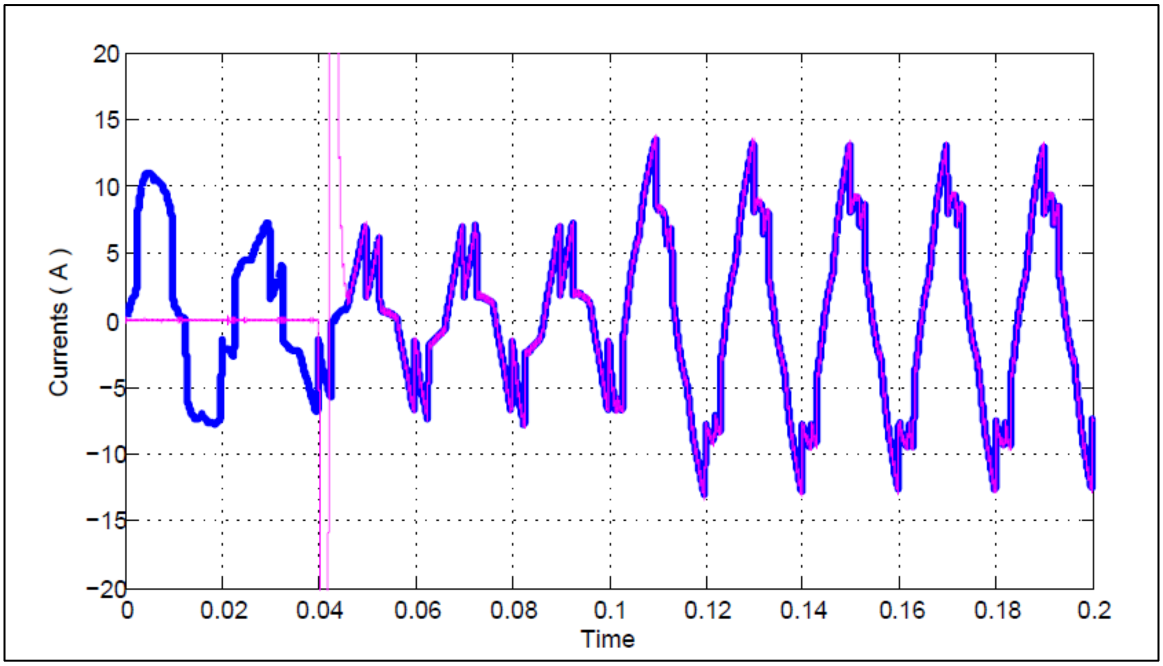

Figure 5.14 Active Filter Reference Currents

Whereas non-linear load voltages and currents are shown in fig.5.15

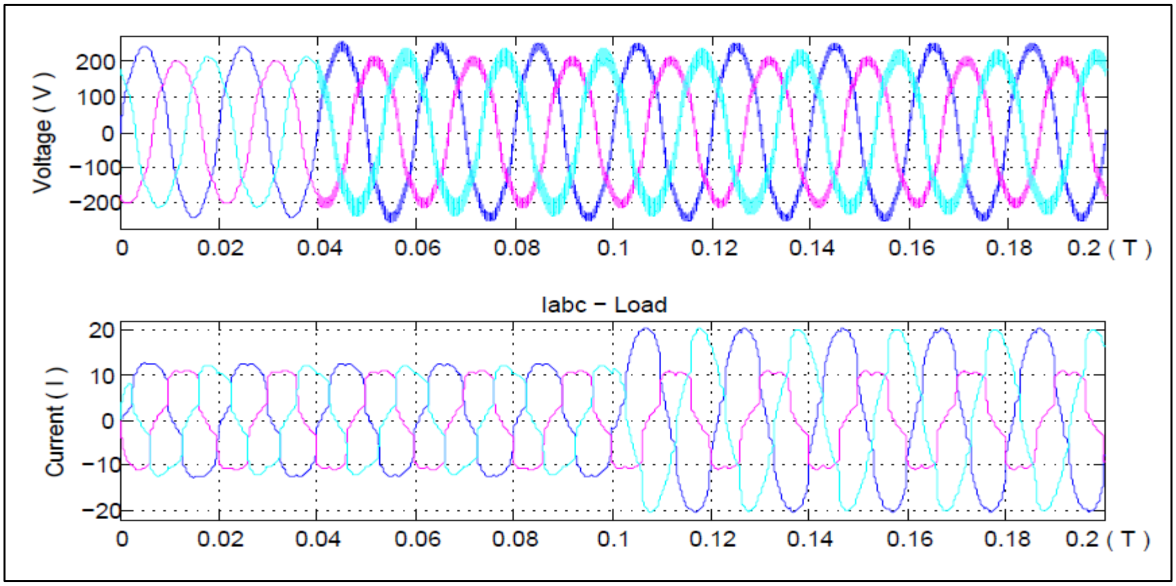

Figure 5.15 Non-Linear Load Voltages and Currents

Figure 5.16 & 5.17 shows the active and reactive power of the system before and after active filtering.

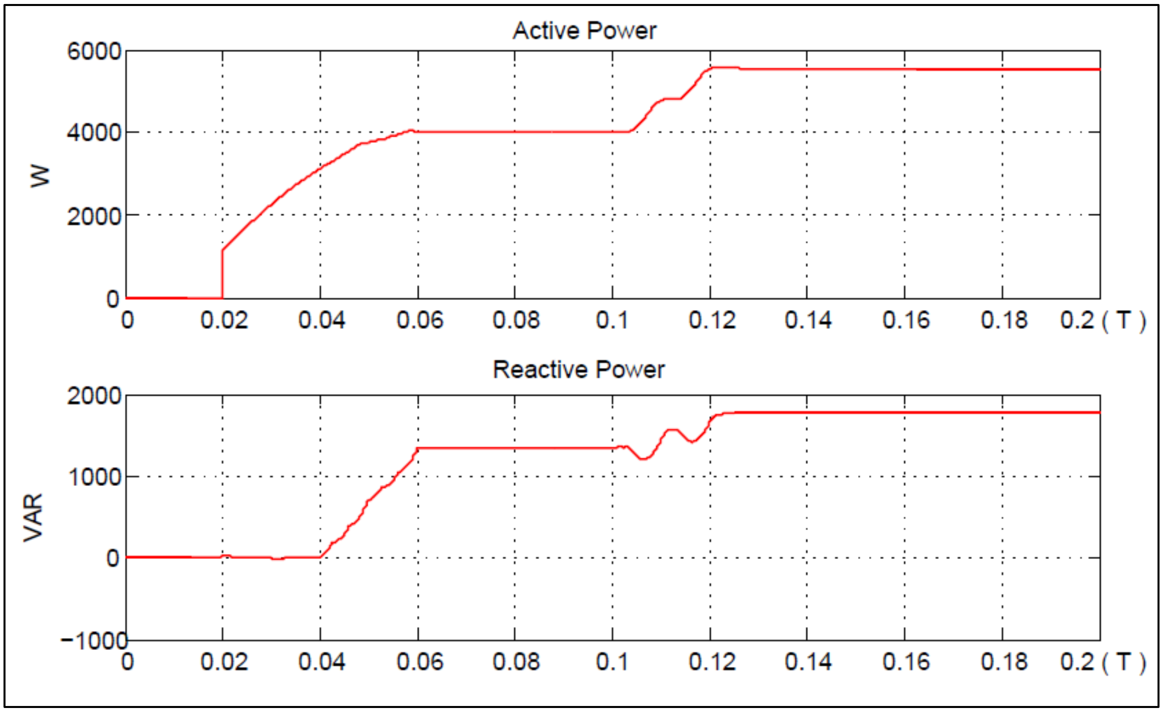

Figure 5.16 Active and Reactive Power-Before Active Filter

It can be observed from the graph that very large amount of reactive power is demanded by the nonlinear electronic load from the supply system which result in very low power factor and excessive power loss and is highly undesirable in the modern power system.

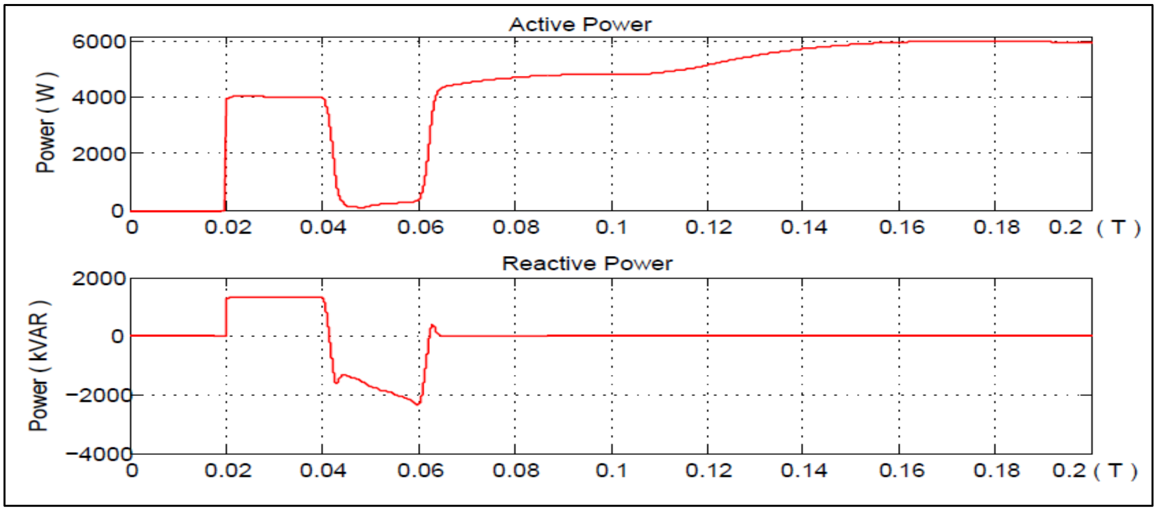

Figure 5.17 Active and Reactive Power-After Active Filter

Figure 5.18 shows that voltage and current of the source supply are exactly in phase making the power factor approaching to unity and compensation reactive power successfully demanded by the nonlinear load from the source.

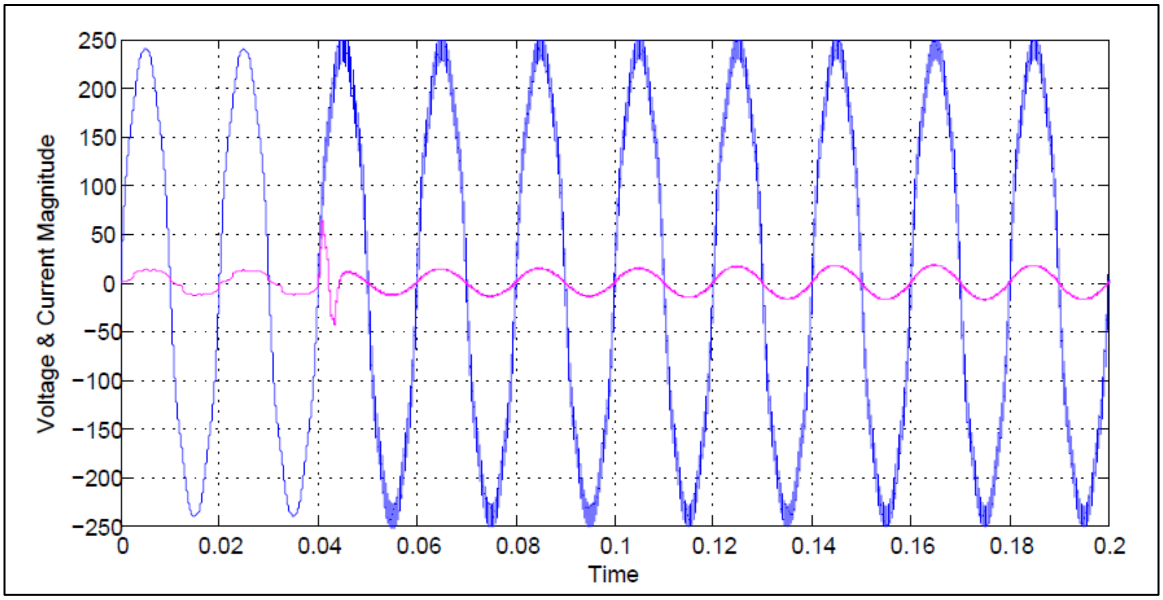

Figure 5.18 Source Voltages and Currents of phase-a

THD level of the source supply before active filtering is 12.02% exceeding the limits as shown in Figure 5.19

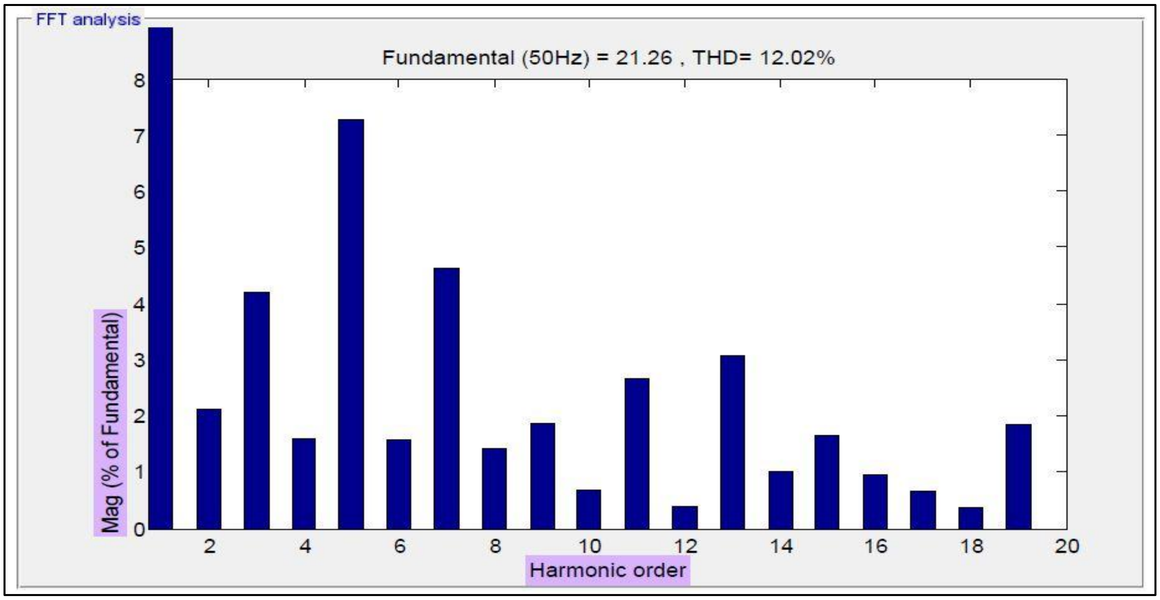

Figure 5.19 Iabc Source current THD Before Active Filtering

Whereas Figure 5.20 shows the THD level after active filtering is 4.67 % which is well within the acceptable harmonics limits.

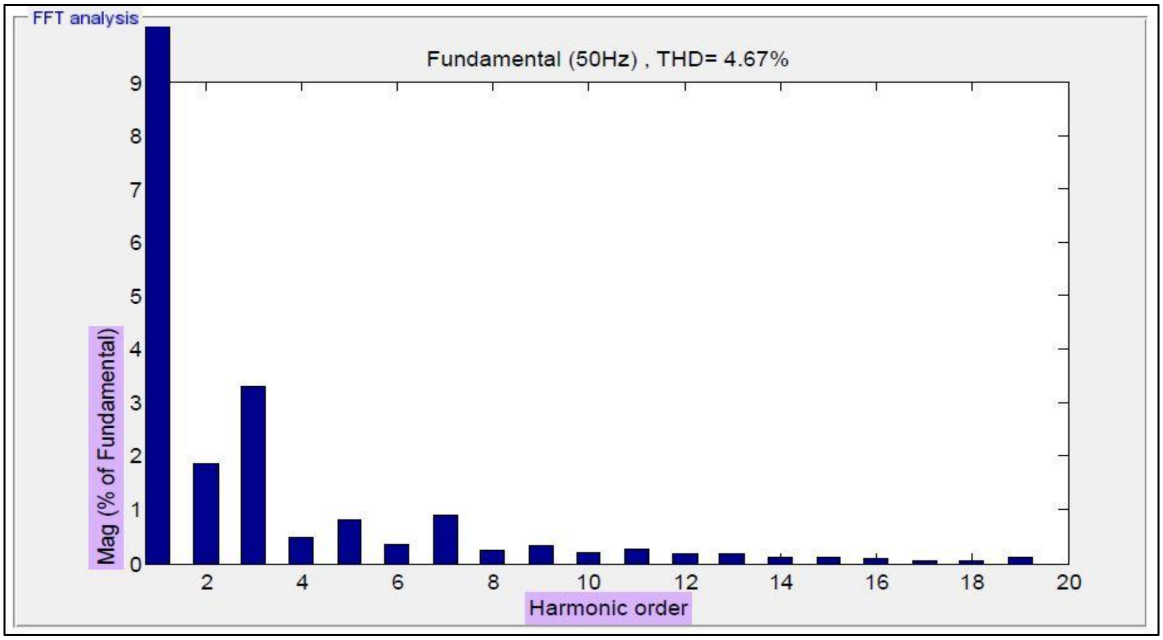

Figure 5.20 Iabc Source Current THD After Active Filtering

It is evident from the above discussion that synchronous frame of reference d-q theory is not only applicable in balanced conditions but also works efficiently to eliminate harmonics and compensate reactive power in case of unbalanced and distorted conditions.

5.4 Case Study: Small vs Large Distribution System

A practical problem of harmonics in industrial, commercial and residential distribution feeders is considered here. Nonlinear loads in distribution network are the main source of harmonics and justify the need of power conditioners to improve the power quality. Current harmonics are the major concern for utilities causing voltage distortion at distribution level. Utilities frequently face problems caused by harmonics such as higher transformer and transmission line losses, neutral overcurrent, derating of distribution equipment, reactive power issue, resonance, system stability and reduced safe operating margins.

Harmonic propagation is the main issue in using tradition capacitor bank compensation and passive filters. Many topologies have been proposed for power quality improvements in ac distribution networks. Purpose of the study case is to test the new shunt active filter model in real power system conditions. Shunt active filters for industrial, Commercial and residential feeders are investigated in this work for harmonic elimination and reactive power compensation.

The Dranetz Power Guide 4400, a three-phase power quality analyzer is used for measurement of harmonics and other loading parameter required for harmonic studies [75].

5.4.1 Residential Distribution System Loading

Continuous monitoring of typical residential apartment for 24 hours was made. The schematic diagram of the residential distribution system under study is shown in fig 5.21

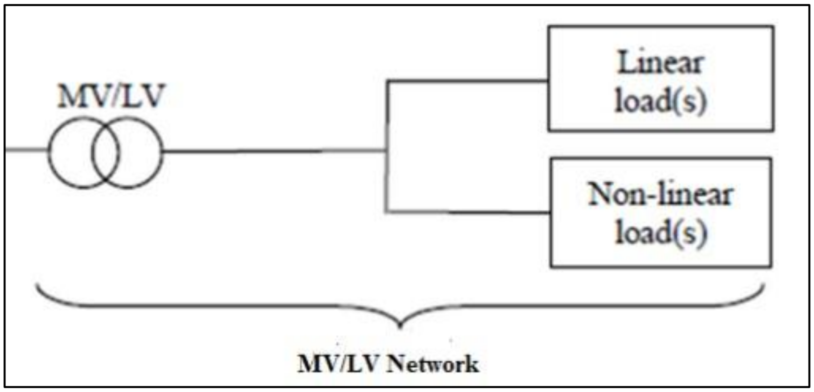

Figure 5.21 Schematic Diagram of Residential Distribution System

linear and non-linear load including, lighting, air conditioning, microwave oven, vacuum cleaner, hair dryer, television and washing machine, are connected to the main supply. System was observed for 24 hours with actual and routine loadings. System Parameters observed with power quality analyzer are as follow Table 5.1

Table 5.1 Residential System Network Parameters

Parameters	Symbols	Values
Nominal voltages	V_{abc}	390 V
System frequency	f	60 Hz
Voltage-rms	V_{ab} ,V_{bc}, V_{ca}	404.23, 404.77,406.55
Current-rms	Irms, Ia,Ib,Ic	19.6A, 18.6A,20A
Power Demand-Active (Peak)	kW	12.71
Power Demand-Reactive	kVAR	5.04
Harmonics-Current	THD-I	18.32 %
Power Factor	pf	0.96

All these actual system parameters that are observed in a typical residential apartment are simulated in MATLAB Simulink. Shunt active filters are connected in parallel to this system to eliminate the harmonics and compensate the reactive power in addition to improve the power factor of the system network. Simulation results are shown and discussed below:

5.4.1.1 Simulation Results & Discussion

In this case, active filters are connected in parallel to the source and load in distribution network. Harmonics currents demanded by nonlinear load from the system are calculated by synchronous frame of reference theory and injected to the system by voltage source converter with the help of pulse width modulation.

When we compare the measured and simulated data for the residential loads, we observed there is a slight difference between actual and measured values. However, proposed active filter is successfully eliminating the harmonics in all system conditions. Summary of the measured and simulated parameters is shown in table- 5.2

Table 5.2 Comparison of Measured and Simulated Parameters

Parameters	**Symbols**	**Measured Values**	**Simulated Values**
Voltage-rms	V_{ab} ,V_{bc}, V_{ca}	404.23, 404.77,406.55	401, 400, 402
Current-rms	Irms, Ia,Ib,Ic	19.6A, 18.6A,20A	22.0A, 21.2A, 22.1A
Power Demand-Active	kW	12.71	12.59
Power Demand-Reactive	kVAR	5.04	5.81
Harmonics-Current	THD-I	18.32 %	16.13%
Power Factor	pf	0.96	0.96

Figure 5.21 shows the unbalanced and distorted supply voltages.

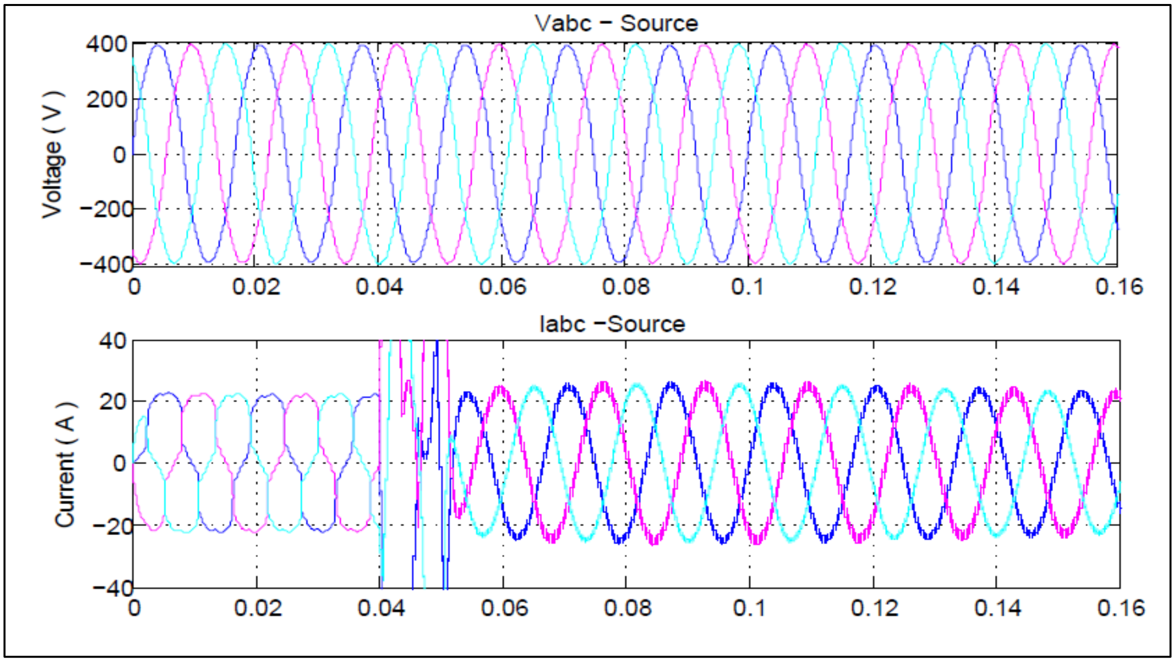

Figure 5.21 Source Supply Voltages and Currents

whereas Figure 5.22 shows the active filter currents which are exactly following the reference currents calculated with d-q theory.

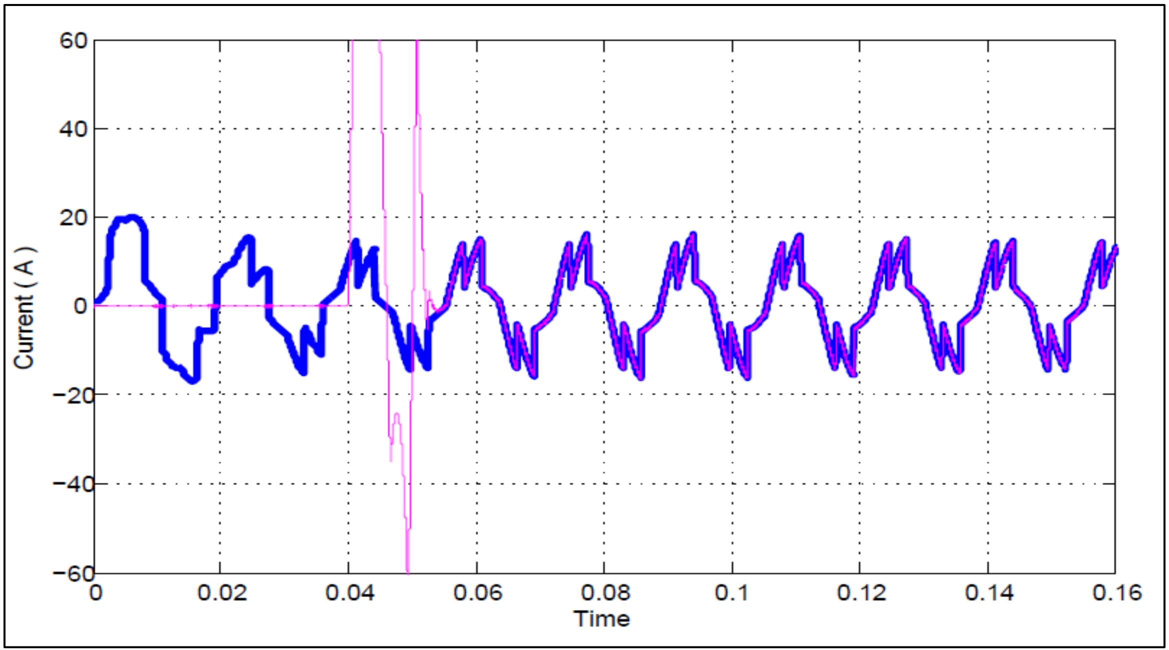

Figure 5.22 Active Filter Reference Currents

Source currents are becoming perfectly sinusoidal with voltage and are harmonics free as shown in the graph of Figure 5.23.

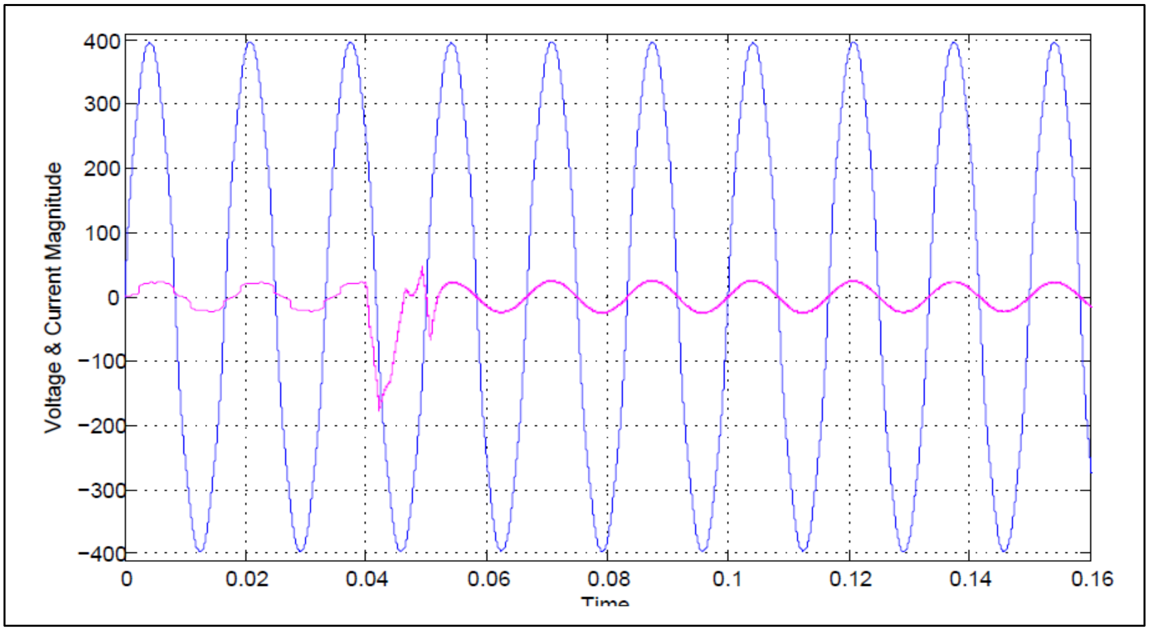

Figure 5.23 Source Voltages and Currents of phase-a

The voltages and currents of the source supply are exactly in phase making the power factor approaching to unity and compensation reactive power successfully demanded by the nonlinear load from the source.

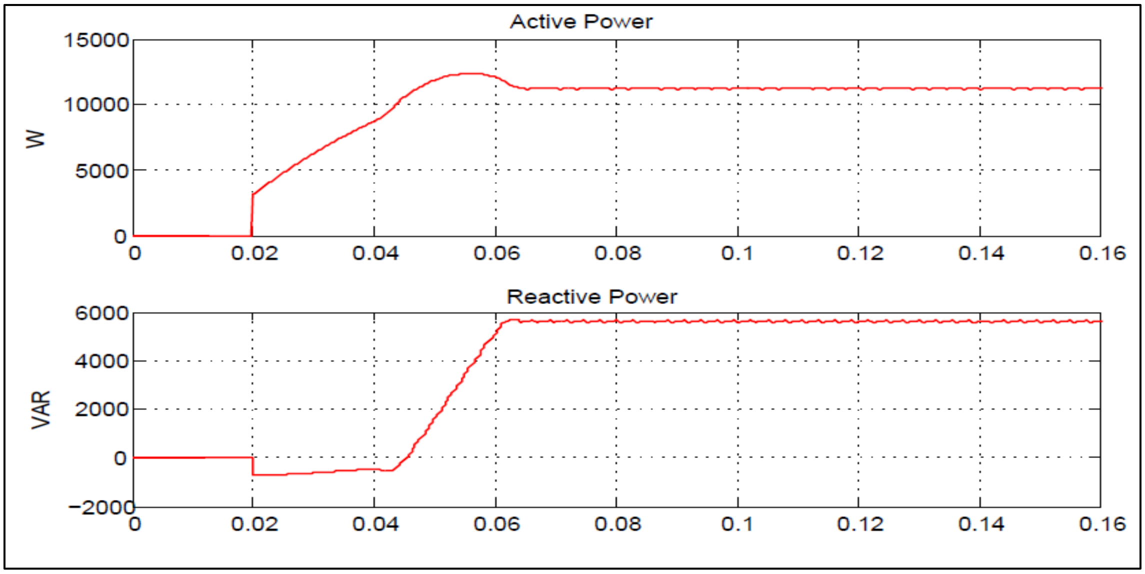

Figure 5.24 Active and Reactive Power-Before Active Filter

Figure.5.24 shows the active and reactive power of the system before active filtering. It is observed that very large amount of reactive power is demanded by the nonlinear load from the supply system which is highly undesirable in the modern power system. Figure 5.25 shows the reactive power compensation by active filters.

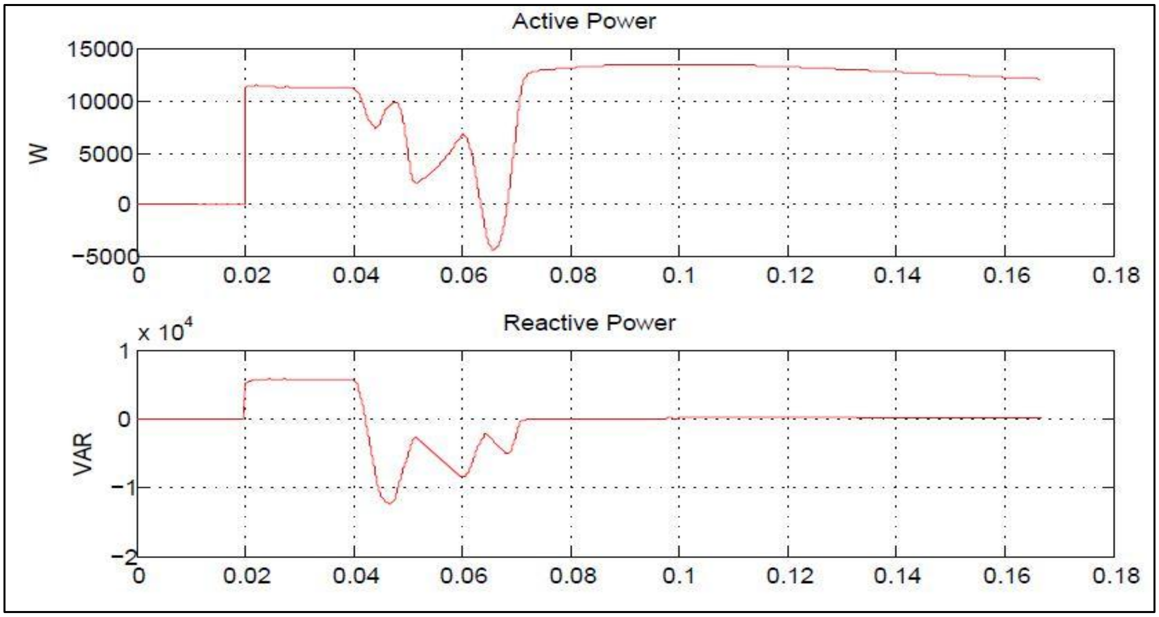

Figure 5.25 Active and Reactive Power-After Active Filter

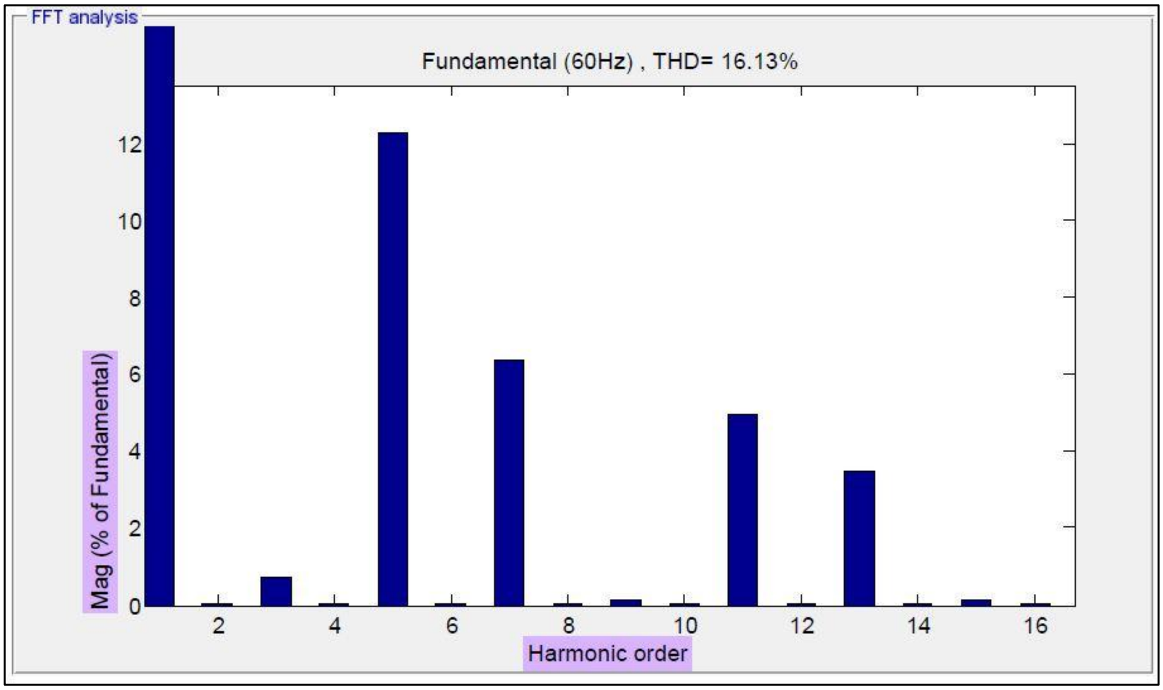

Figure 5.26 Iabc Source Current THD Before Active Filtering

THD level of the source supply before active filtering is 16.13% exceeding the limits as shown in Figure. 5.26

Figure 5.27 shows the THD level after active filtering is 4.23 % which is well within the acceptable international harmonic standards.

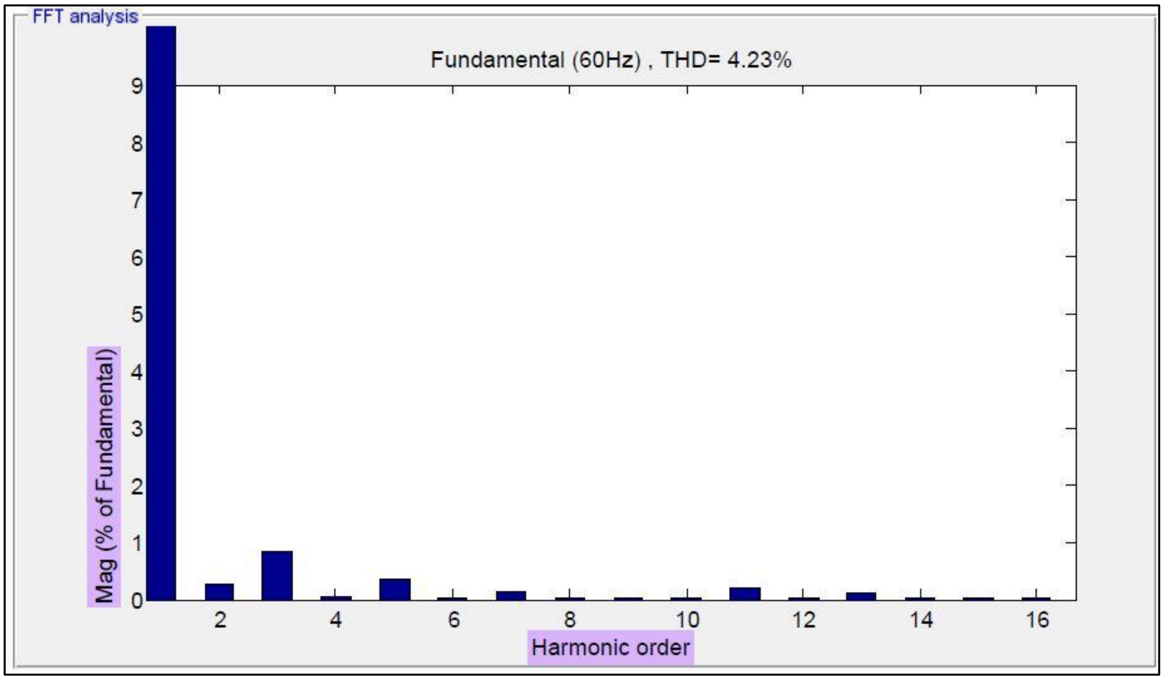

Figure 5.27 *Iabc* Source Current THD After Active Filtering

It is evident from the above discussion that synchronous frame of reference d-q theory is not only applicable in balanced conditions but also works efficiently to eliminate harmonics and compensate reactive power in unbalanced and distorted conditions.

5.4.2 Commercial Distribution Network System Loading

Continuous monitoring of typical commercial facility for 6 hours was made.

linear and non-linear load including, lighting, air conditioning, CCTV, computers and LCD are connected to the main supply. System was observed for 6 hours with actual and routine loadings. System Parameters observed with power quality analyzer are as follow Table 5.3.

Table 5.3 Commercial Network System Parameters

Parameters	Symbols	Values
Distribution supply voltages	V_{abc}	220 V
System frequency	f	60 Hz
Voltage-rms	V_{ab} ,V_{bc}, V_{ca}	224.13, 222.64, 221.51
Current-rms	Irms, Ia,Ib,Ic	31A, 33A, 34A
Power Demand-Active (Peak)	kW	11.3
Power Demand-Reactive	kVAR	5.54
Harmonics-Current	THD-I	5.32 %
Power Factor	pf	0.74

All these actual system parameters that are observed in a typical commercial office facility, are simulated in MATLAB Simulink. Shunt active filters are connected in parallel to this system to eliminate the harmonics and compensate the reactive power in addition to improve the power factor of the system network. Simulation results are shown and discussed below

5.4.2.1 Simulation Results & Discussions

Figure 5.28 shows the unbalanced and distorted supply voltages.

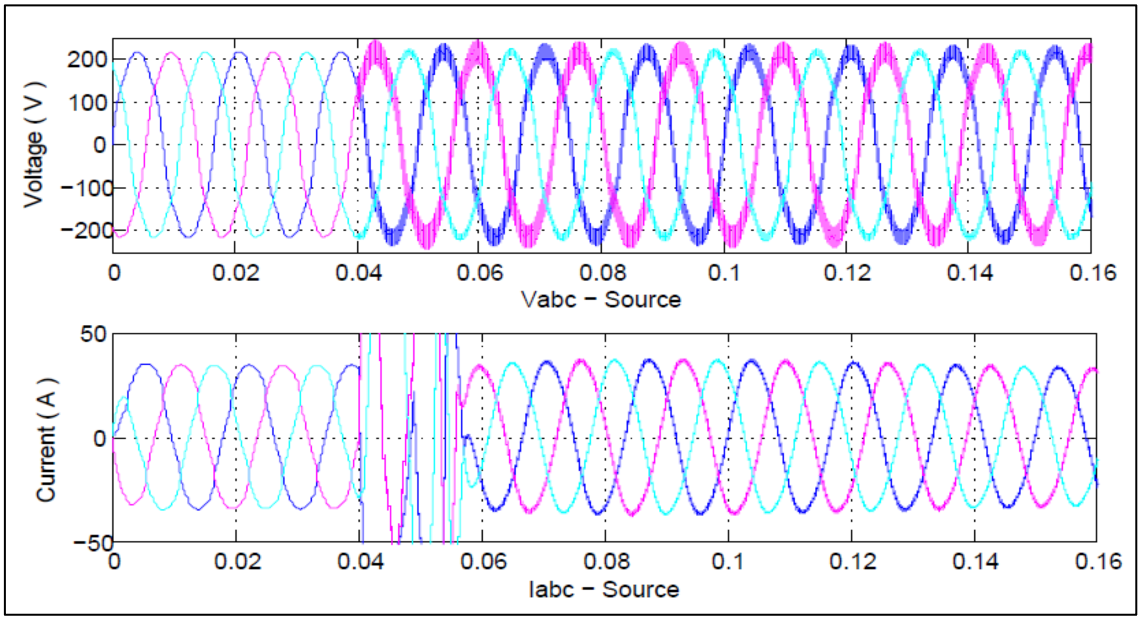

Figure 5.28 Source Supply Voltages and Currents

Whereas Figure 5.29 shows the active filter currents which are exactly following the reference currents calculated with d-q theory.

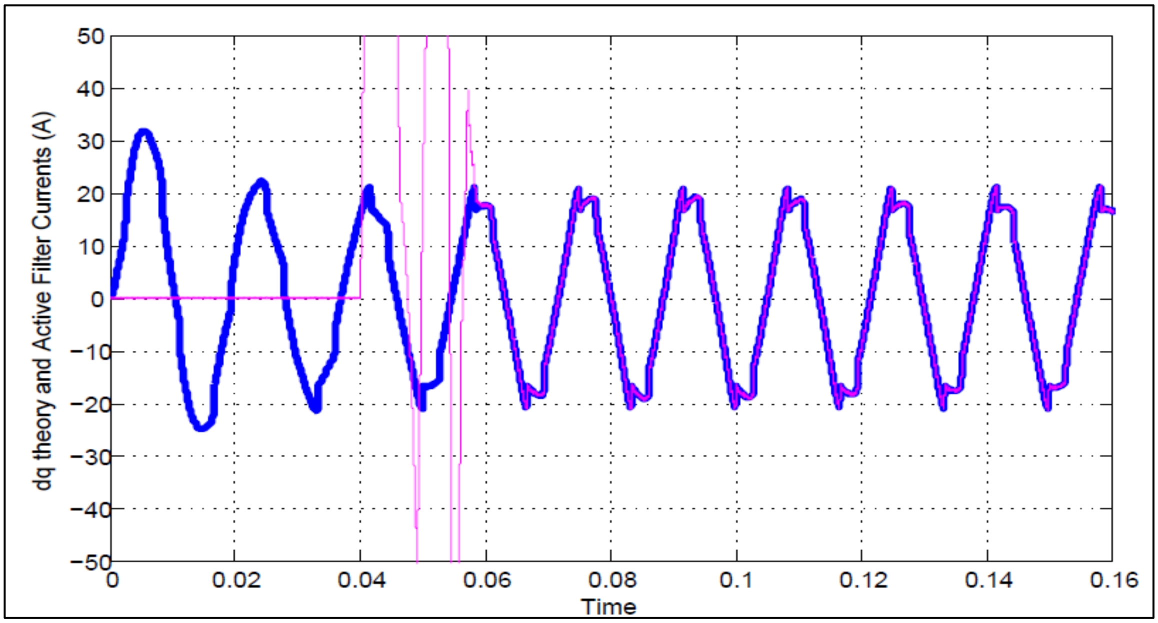

Figure 5.29 Active Filter Reference Currents

Source currents are becoming perfectly sinusoidal with voltage and are harmonics free as shown in the graph of Figure 5.30

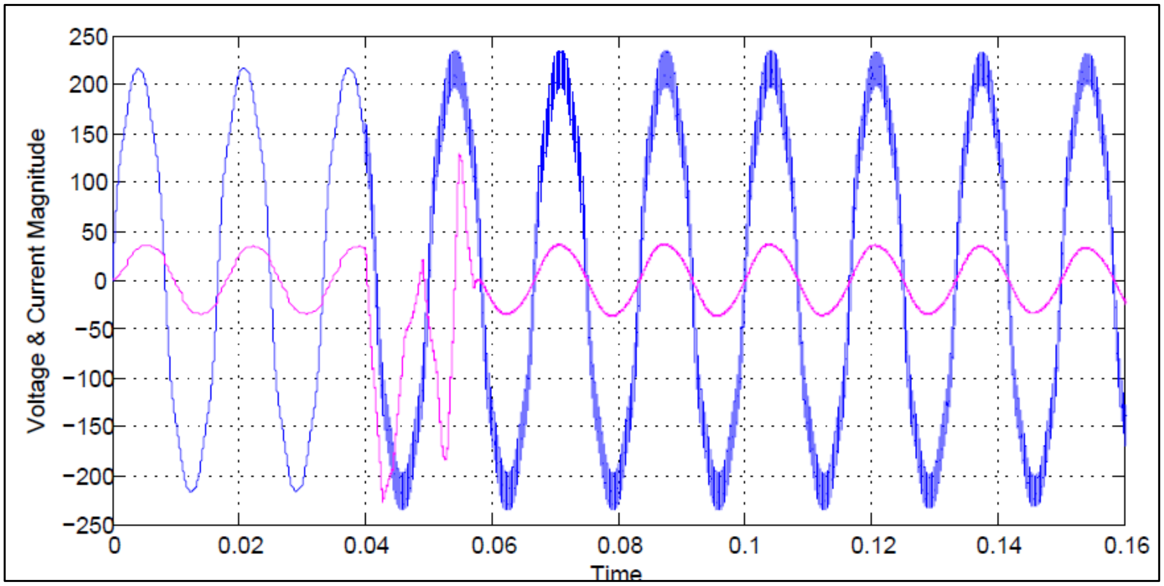

Figure 5.30 Source Voltages and Currents of phase-a

Figure 5.31 shows the reactive power compensation by active filters.

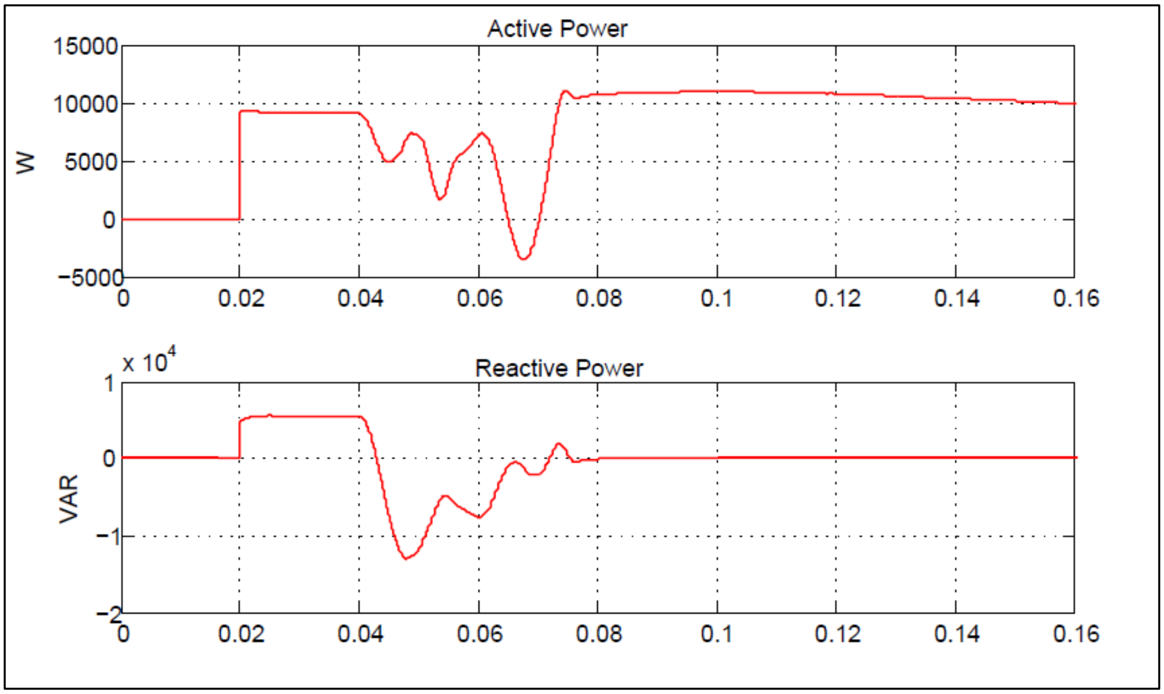

Figure 5.31 Active and Reactive Power-After Active Filter

Figure 5.32 shows the THD level before active filtering is 5.76 %

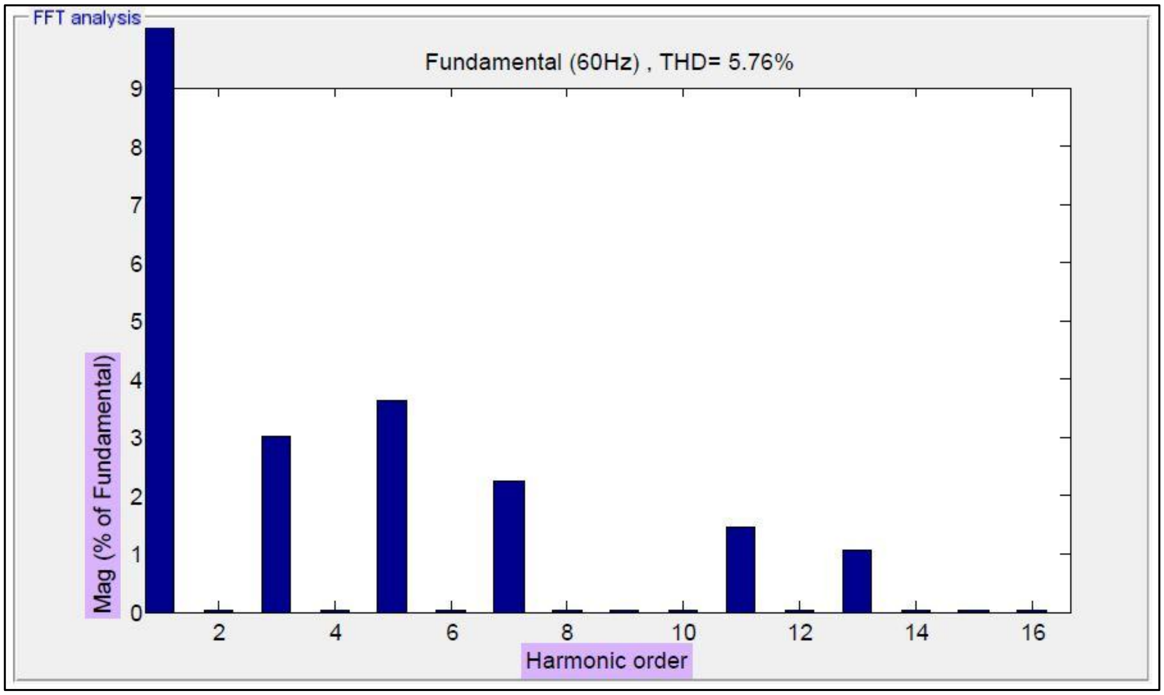

Figure 5.32 I*abc* Source Current THD Before Active Filtering

Figure 5.33 shows the THD level after active filtering is 3.44 %

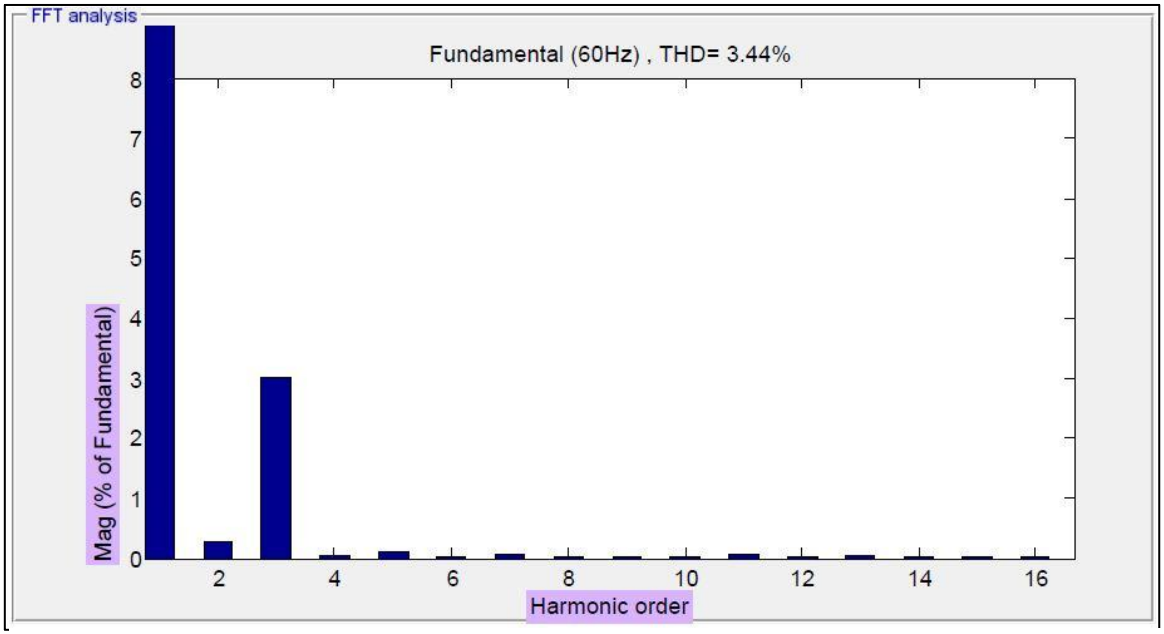

Figure 5.33 I*abc* Source Current THD After Active Filtering

Results shows that shunt active filter is working well for commercial loads also. Its eliminating the harmonics from source supply and compensating the reactive power demand of the system. THD of the source current is improved from 5.76%, an unacceptable limit to 3.44% an acceptable limit as per international standard. Load current and voltages are also in phase with improved power factor. Active filter current is also following the d-q current requirements.

5.4.3 Industrial Distribution Network System Loading

Continuous monitoring of typical industrial facility for 6 hours was made.

Linear and non-linear load including, lighting, air conditioning, motors and welding plant, are connected to the main supply. System was observed for 6 hours with actual and routine loadings. System Parameters observed with power quality analyzer are as follow Table 5.4.

Table 5.4 Industrial System Network Parameters

Parameters	Symbols	Values
Distribution supply voltages	V_{abc}	380 V
System frequency	f	60 Hz
Voltage-rms	V_{ab} ,V_{bc}, V_{ca}	401.2, 403.2, 402.6
Current-rms	Irms, Ia,Ib,Ic	22A, 27A,25A
Power Demand-Active (Peak)	kW	5.72
Power Demand-Reactive	kVAR	4.87
Harmonics-Current	THD-I	10.15 %
Power Factor	Pf	0.68

All these actual system parameters that are observed in a typical industrial facility, are simulated in MATLAB Simulink. Shunt active filters are connected in parallel to this system to eliminate the harmonics and compensate the reactive power in addition to improve the power factor of the system network. Simulation results are shown and discussed in proceeding section.

5.4.3.1 Simulation Results & Discussions

Figure 5.34 shows the unbalanced and distorted supply voltages.

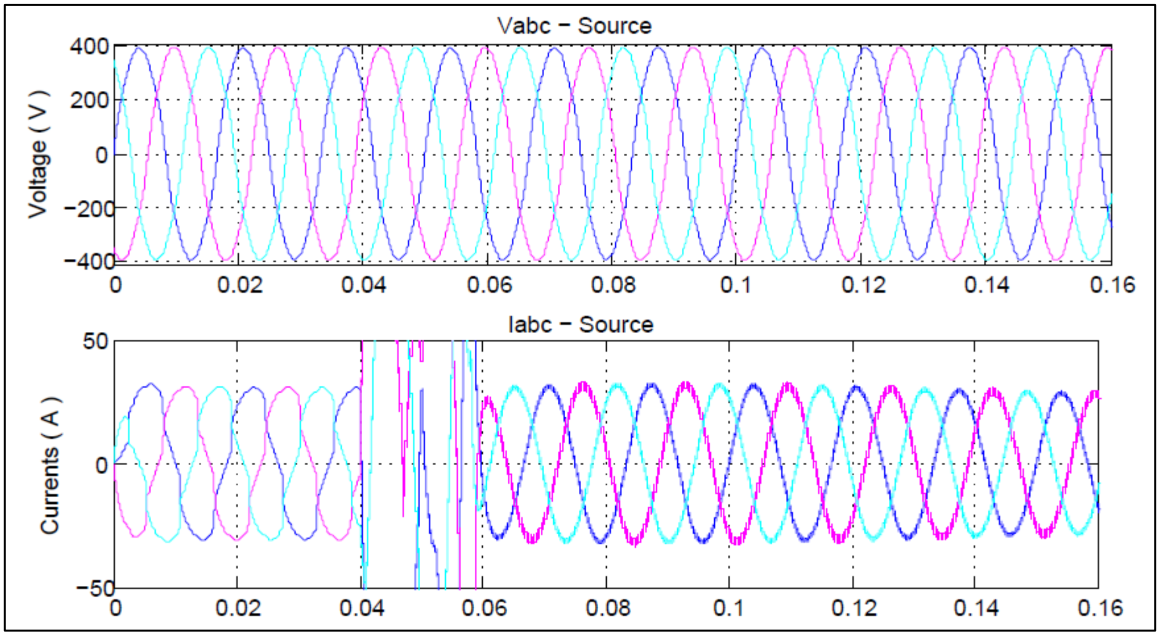

Figure 5.34 Source Supply Voltages and Currents

Figure 5.34 shows the source supply voltages and currents. Initially the currents were non-sinusoidal and distorted. But when the active filters are connected to the system at 0.04 second, these currents became sinusoidal.

Figure 5.35 shows the active filter currents are exactly following the required reference currents.

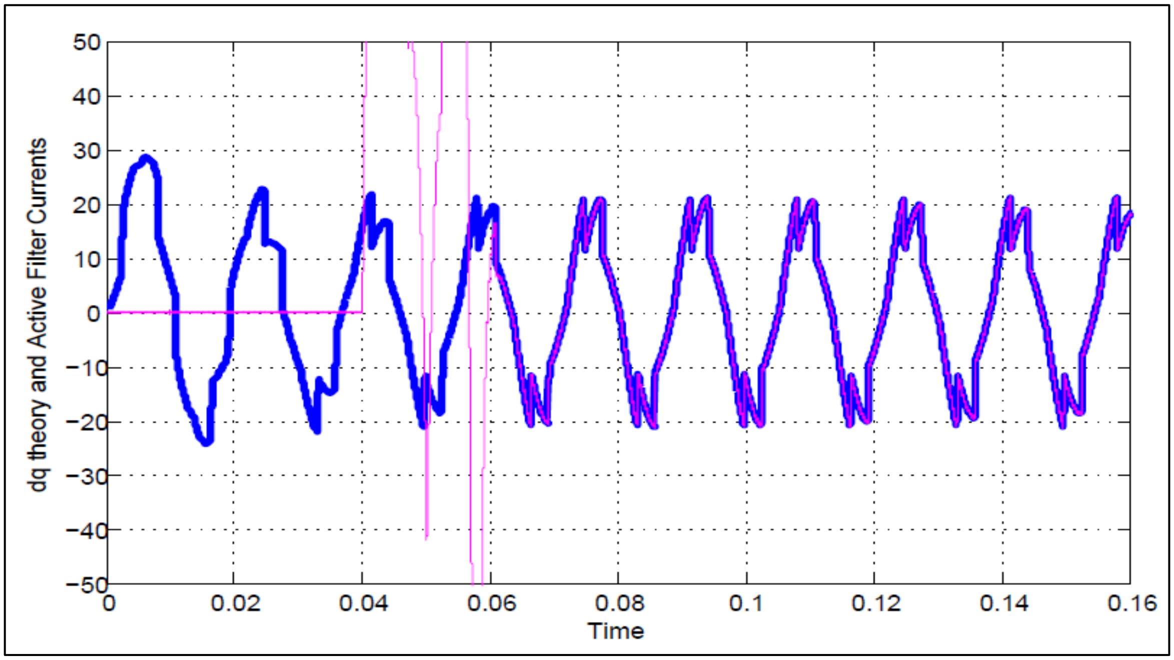

Figure 5.35 Active Filter Reference Currents

Figure 5.36 shows the reactive power after compensation.

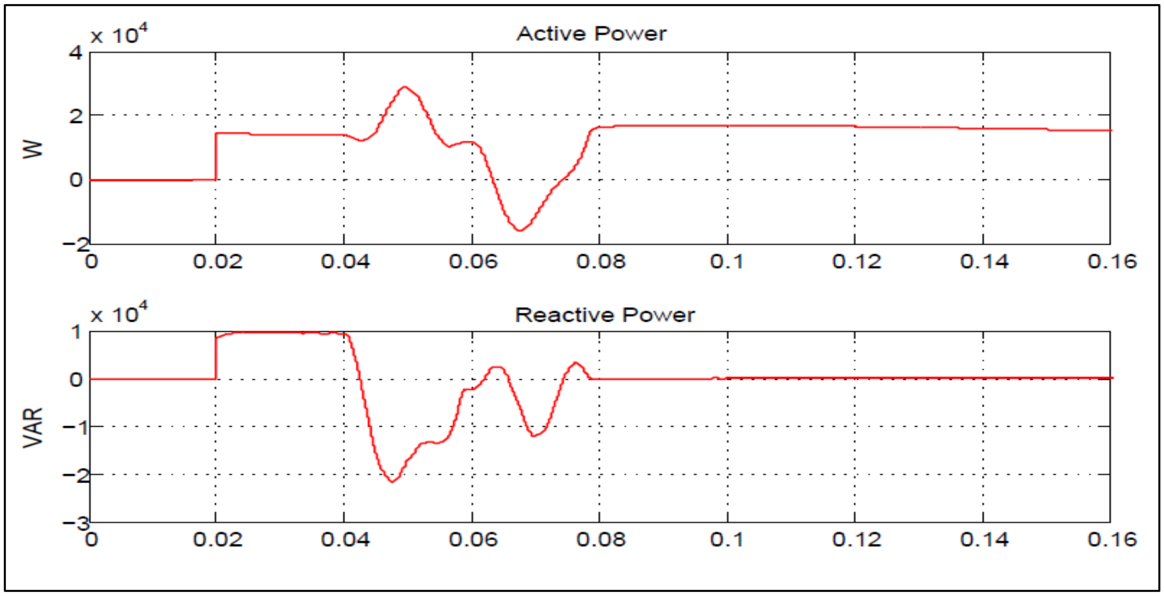

Figure 5.36 Active and Reactive Power-After Active Filter

Perfectly in phase source voltage and currents are shown in figure 5.37

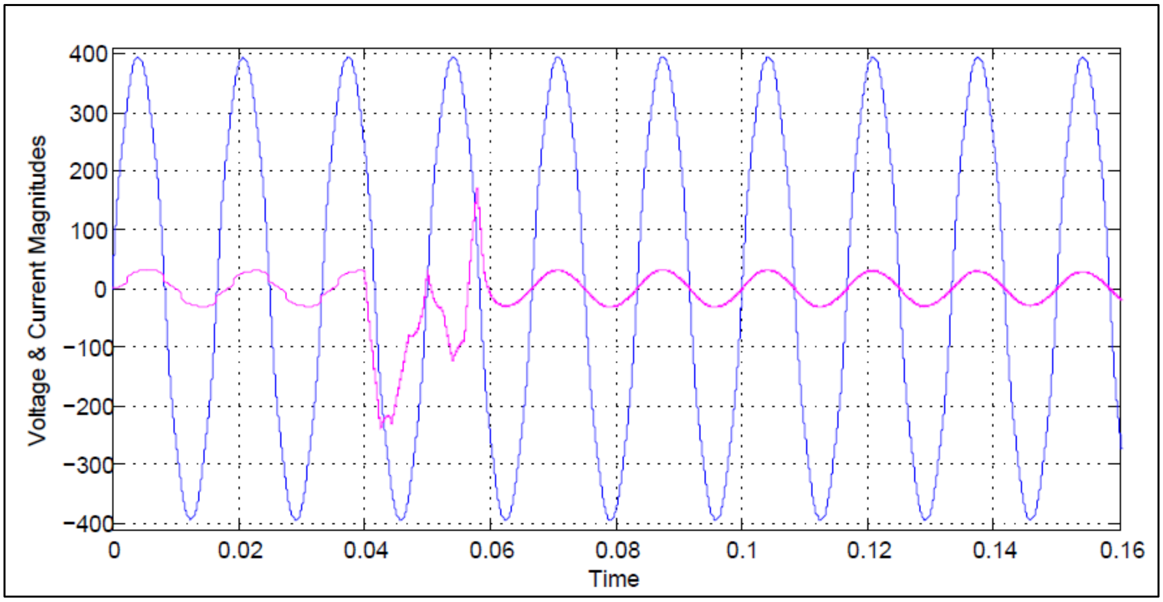

Figure 5.37 Source Voltages and Currents of phase-a

Figure 5.38 shows THD before active filtering.

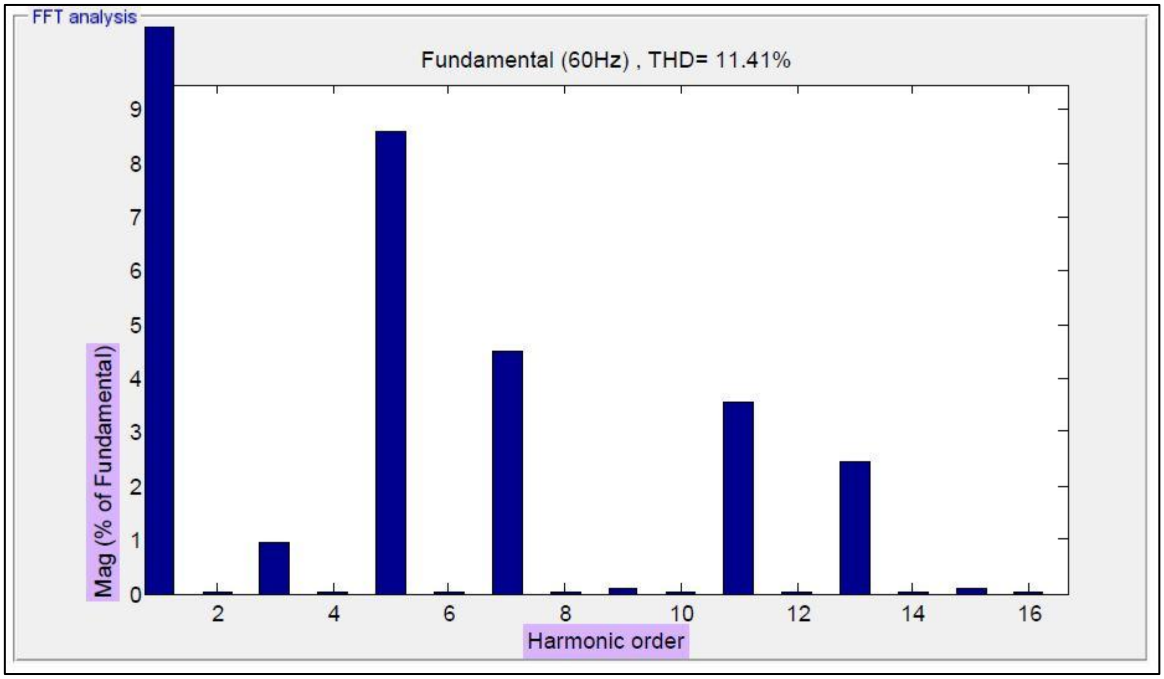

Figure 5.38 Source Current THD Before Active Filtering

Successful compensating of THD after active filtering is shown in figure 5.39

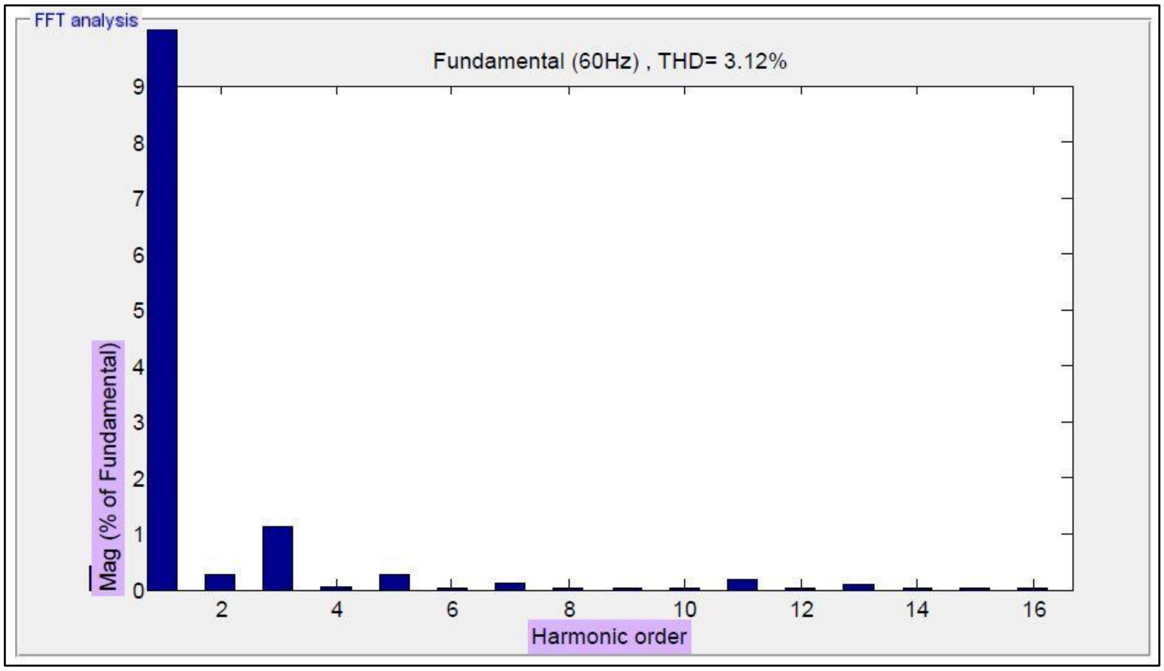

Figure 5.39 Source Current THD After Active Filtering

Results shows that shunt active filter is working well for Industrial loads also. Its eliminating the harmonics from source supply and compensating the reactive power demand of the system. THD of the source current is improved from 11.41 an unacceptable limit to 3.12% an acceptable limit as per international standard. Load current and voltages are also in phase with improved power factor. Active filter current is also following the d-q current requirements

5.5 Industrial Distribution System with Larger Loads

The proposed system is tested on a large industrial network [69].

Normally the shunt active filters are installed near the loads at the PCC point of common coupling to eliminate the harmonics and to supply the required harmonic current to the system which is normally demanded by the nonlinear loads from the source supply. Active filters are not installed in the substations to the entire distribution feeders but to the specific loads which are highly sensitive to the harmonic distortion and malfunctioning to these loads have serious security and economic impact. These are called special loads like data centers, microprocessor based loads and harmonic presence above allowable limits are highly undesirable for these kinds of loads.

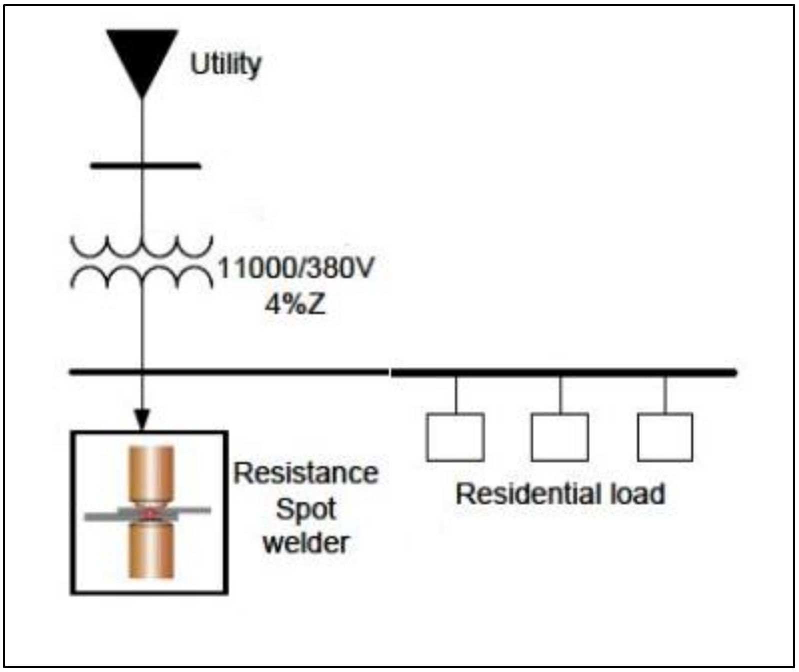

Figure 5.40 Distribution System Under Study [69]

Single line diagram of the system under study is shown in fig.5.40

A distribution transformer 11/0.380kV, Z-4% is connected to the utility, and is supplying power to industrial and domestic loads. Major industrial load considered for the system is the resistance spot welder. Accumulative load considered is 110kW.The Resistance spot welding machine comprises the front-end diode rectifier for power conversion, IGBTs and medium frequency transformer which makes the input supply highly polluted with low order harmonics which have undesirable impacts on the power system.

System network parameters are shown in table 5.5

Table 5.5 Large Industrial System Network Parameters

Parameters	Symbols	Values
Distribution supply voltages	V_{abc}	380 V
System frequency	f	60 Hz
Current	Ia,Ib,Ic	250A, 272A,256A
Power Demand-Active	kW	110
Power Demand-Reactive	kVAR	45
Harmonics-Current	THD-I	89.02%
Power Factor	Pf	0.85

5.6 Simulation Results & Discussion

Source supply voltages and currents are shown in figure 5.41.

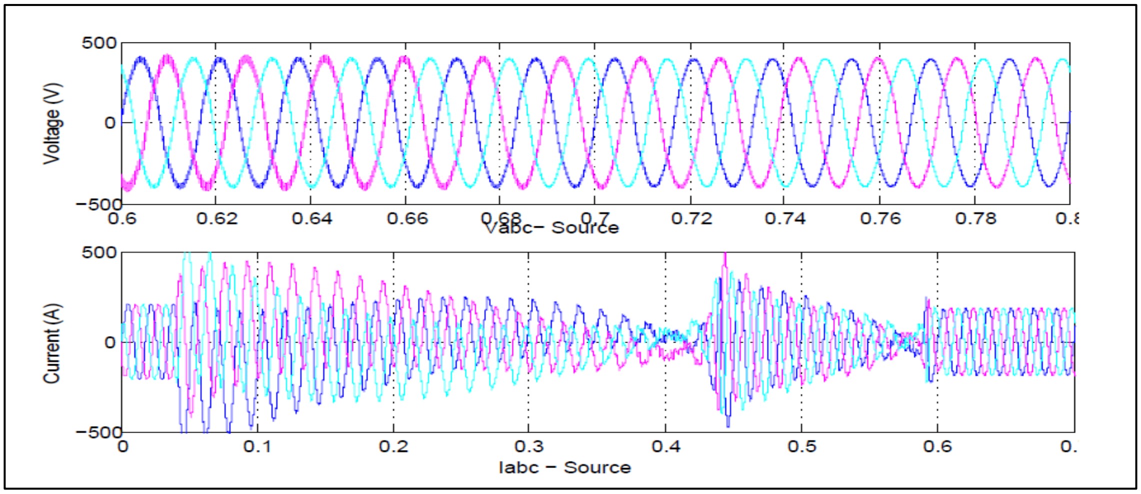

Figure 5.41 Source Supply Voltages and Currents

Figure 5.42 shows the active filter actual voltage and currents

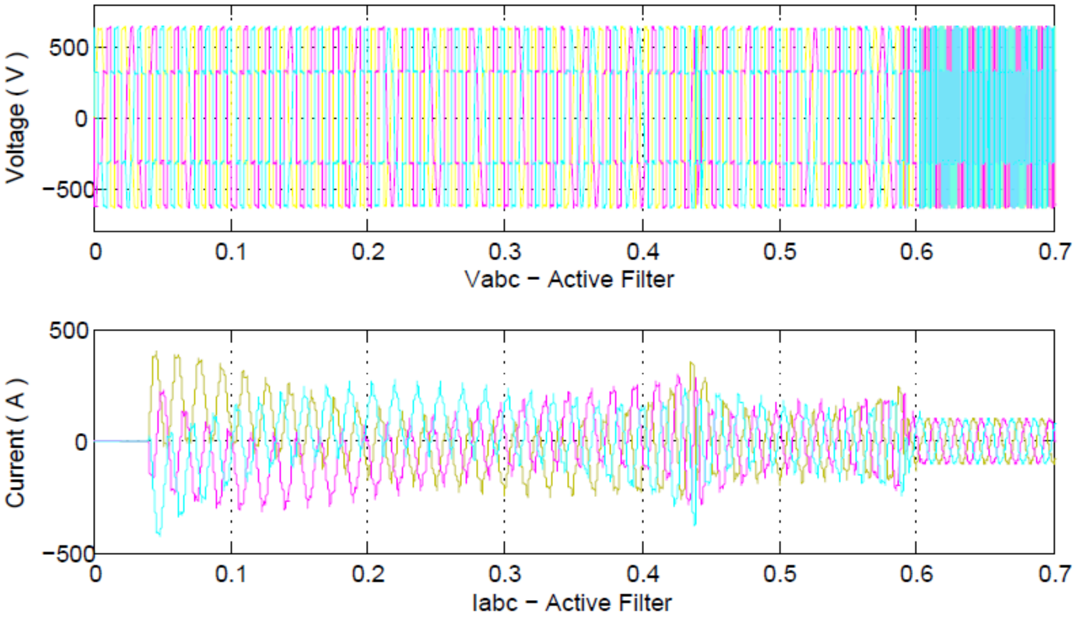

Figure 5.42 Active Filter Voltages and Actual Currents

Active filter reference currents are shown in the figure 5.43.

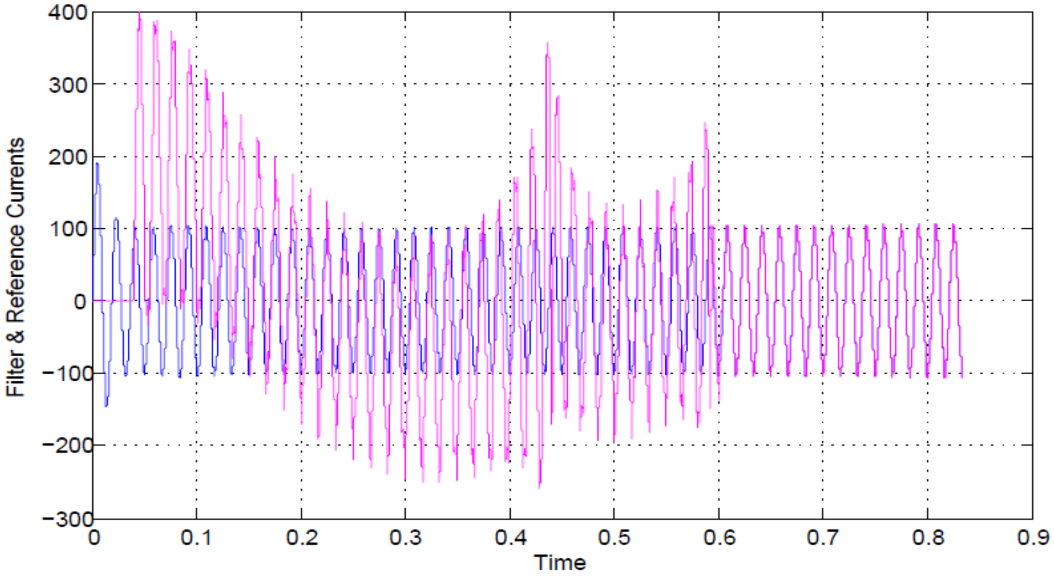

Figure 5.43 Active Filter and Reference Currents

Source voltage and current are shown in figure 5.44

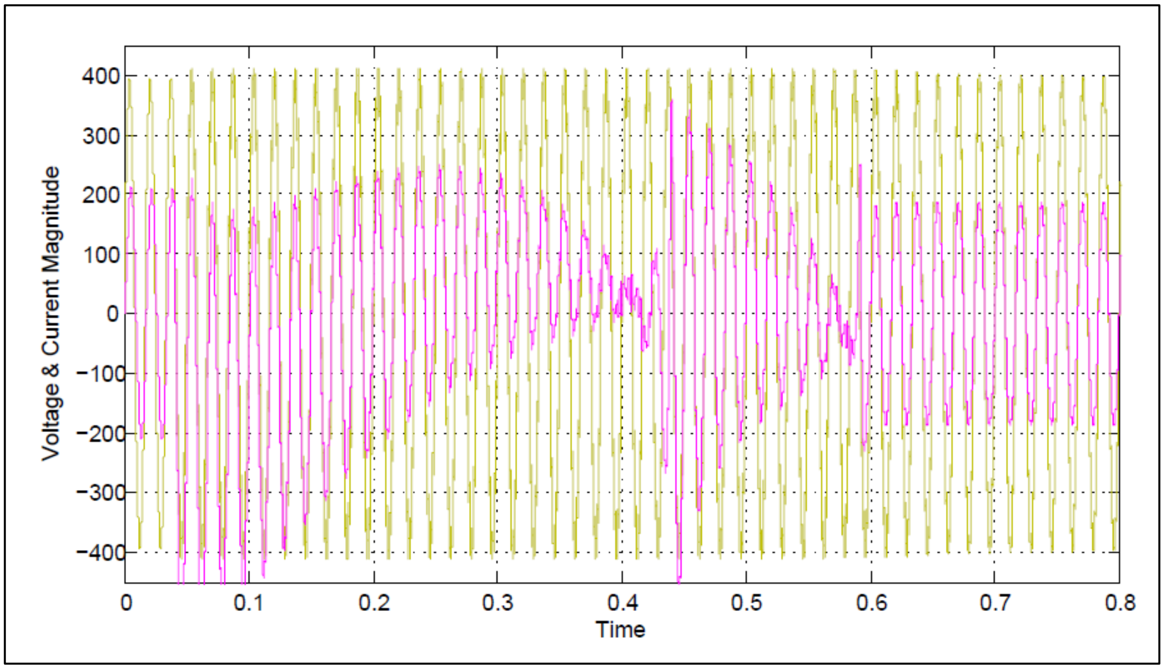

Figure 5.44 Source Voltages and Currents of phase-a

Active and Reactive powers before active filtering are shown in figure 5.45

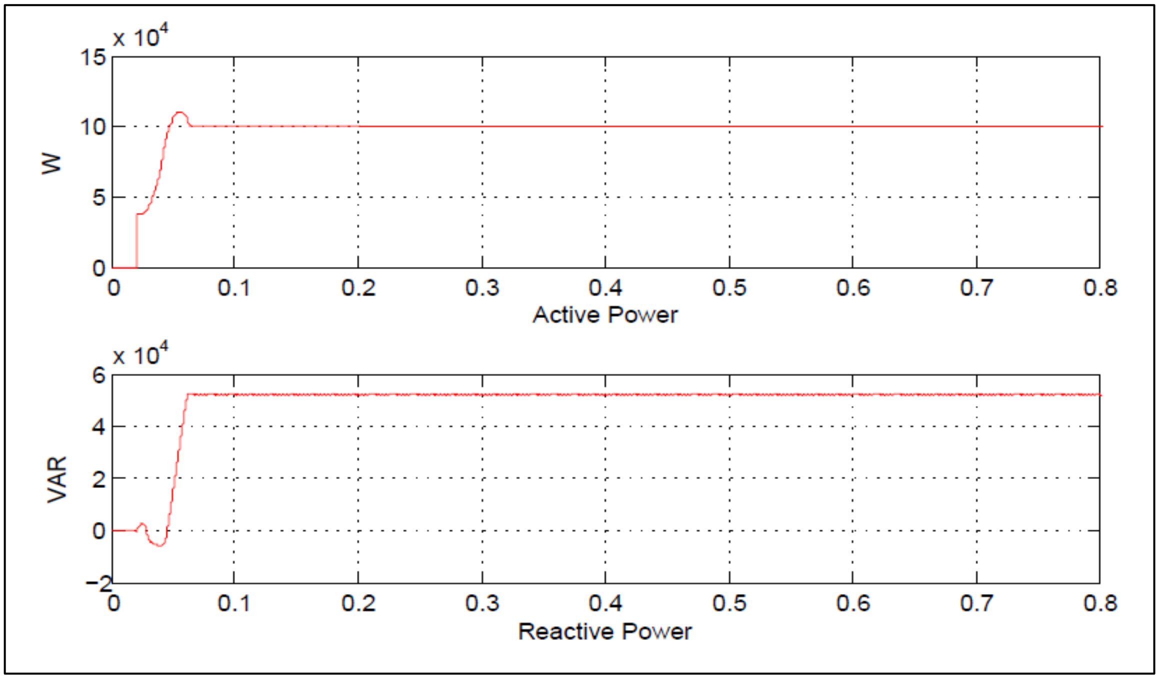

Figure 5.45 Active and Reactive Power-Before Active Filter

Figure 5.46 shows the reactive power compensation after active filtering.

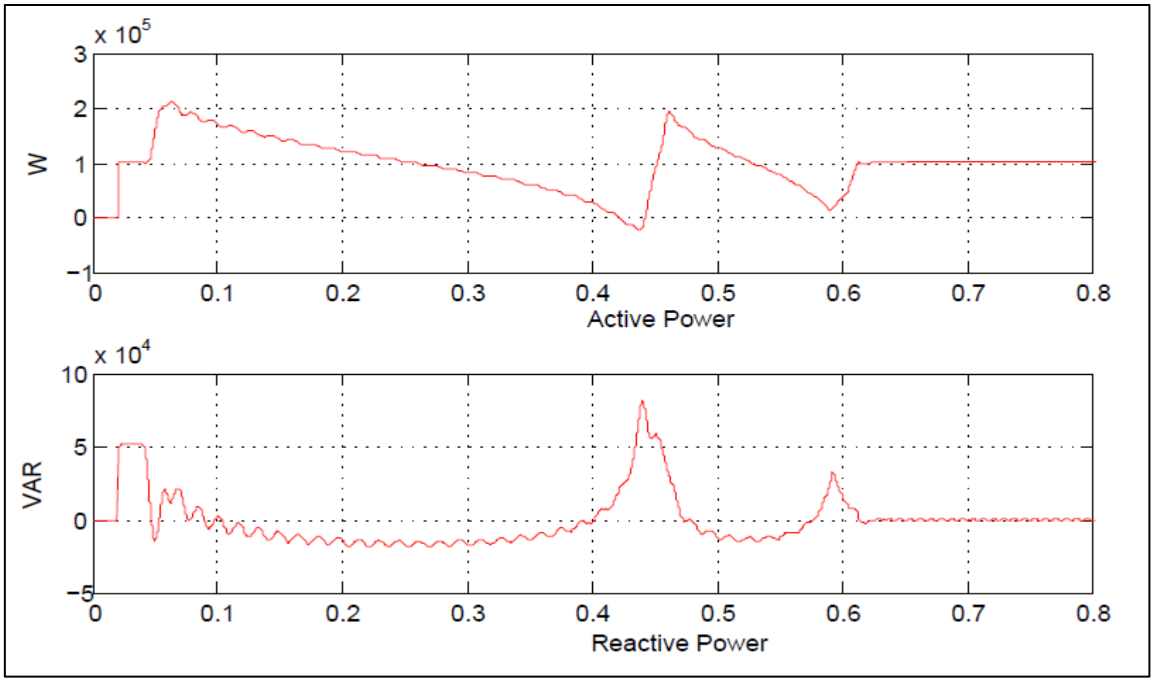

Figure 5.46 Active and Reactive Power-After Active Filter

THD of source current before filtering is shown in figure 5.47

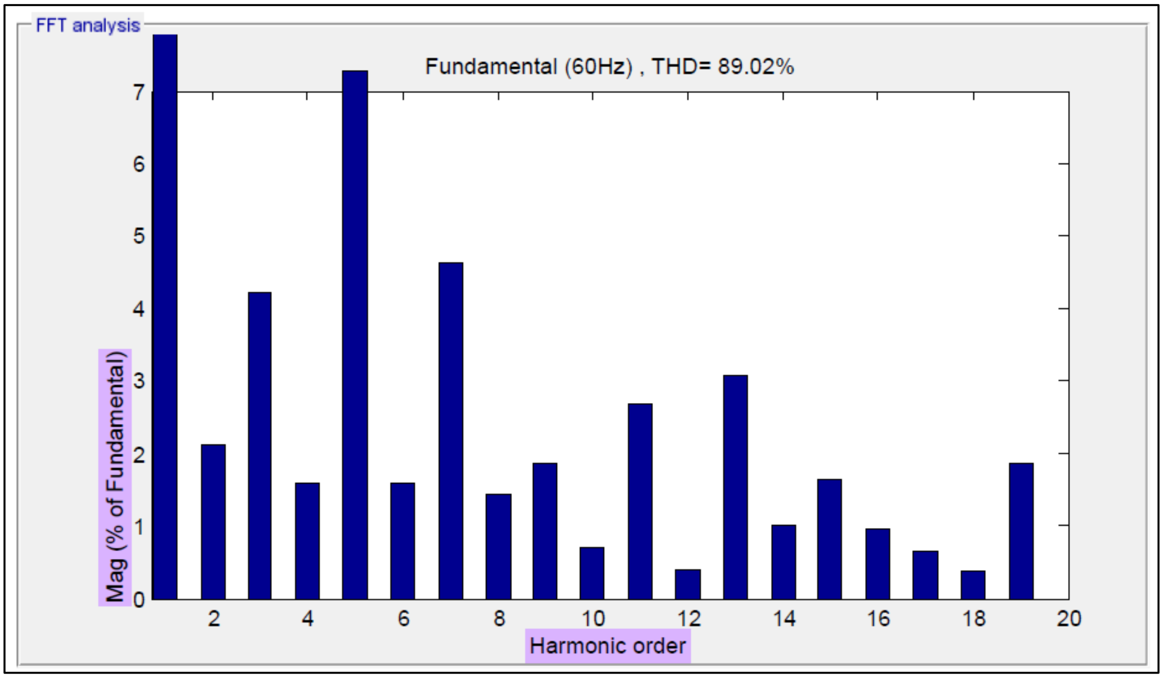

Figure 5.47 Source Current THD Before Active Filtering

Source current THD after active filtering are shown in figure 5.48

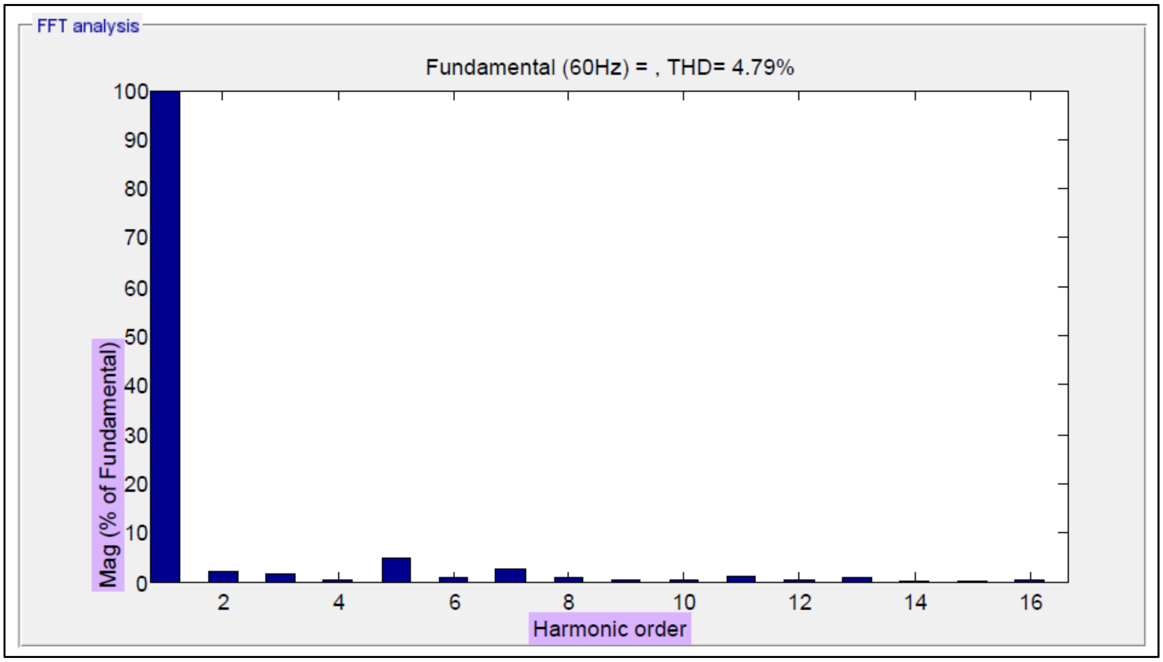

Figure 5.48 Source Current THD After Active Filtering

Results shows that shunt active filter is working well even for large Industrial loads also. Its eliminating the harmonics from source supply and compensating the reactive power demand of the system. THD of the source current is improved from 89.02% an unacceptable limit to 4.79% an acceptable limit as per international standard. Load current and voltages are also in phase with improved power factor. Active filter current is also following the d-q current requirements. Only thing we notice when we compare the results of active filtering for larger loads with those of smaller loads is that the settlement time is increasing with respect to the load. As the load is increasing, time required to make the current waveform sinusoidal, reference current following he d-q currents and power factor improvement time is increasing which is not alarming. It will not affect the system performance as still the filter is capable to eliminate the harmonics from the source supply well with in the international acceptable limits.

5.7 Conclusion

Results and discussion in 5.4 & 5.7 shows that proposed shunt active filters working efficiently in actual network conditions for not only commercial, residential and industrial loadings but also for larger industrial loads and are able to eliminate harmonics and successfully compensate the reactive power demand of the load from source. Shunt active filters not only reduce the THD level to acceptable limits but also reduce the individual harmonic magnitude. Also, reactive power of the system demanded by the load from the source is compensated.

5.8 Summary of Results

Results for application of shunt active filters for Residential, commercial and industrial sectors are shown and discussed in detail. Here is the summary of results shown in table.5.6. The proposed active filter is capable to reduce the THD from high percentage 89.02 % to an acceptable limit of 4.79%. Power factor is also improved approaching to unity.

Table 5.6 Result Summary

Parameters	Residential Feeder		Commercial Feeder		Industrial Feeder	
	Before	After	Before	After	Before	After
THD-I	16.65%	4.23%	5.32%	3.44%	89.02%	4.79%
Power Factor	0.96	0.97	0.74	0.96	0.85	0.97
Load-kW	12.7		11.3		110	

CHAPTER 6

CONCLUSION

6.1 Conclusions

Due to the extensive use of power electronics, harmonics are commonly observed which increased deterioration of general power systems voltage and current waveform and voltages at the point of common coupling PCC are no more sinusoidal. Ideally no system has balance and normal supply voltages with balance and clean load. Shunt active filters are implemented with synchronous frame of reference control theory to improve the power quality and mitigate harmonics from source supply. Improved active filter design with modified control theory is capable to mitigate harmonics even in the presence of distorted, unbalanced source supply and varying loads. Proposed active filters are tested with different system conditions and found working efficiently.

Practical field study in domestic, commercial and industrial sectors was conducted to estimate the harmonics in actual working environment. Then shunt active filter model was tested with actual data and the results show that new active filter design is capable to perform in adverse system conditions.

6.2 Future Work

Proposed active filter model shall be implemented in lab and tested with the actual power quality parameters.

Also, KWH reduction should be monitored with the application of shunt active filters. If it does so, active filter can play a vital role in energy reservation.

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