Harmonic Analysis of Small Scale Industrial Loads and Harmonic Mitigation Techniques in Industrial Distribution System

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ABSTRACT

Distribution system is the part of power system consisting of different combinations of linear and non-linear loads. The widespread application of power electronics is introducing non-linear loads in the distribution system resulting in the distortion of current voltage waveforms. The objective of this project is to study the harmonic distortion in a typical small scale industrial distribution system and suggest suitable harmonic compensation technique. Various domestic loads such as computer, fluorescent lamp, CFL lamp, fan, air conditioner and small scale industry loads such as adjustable speed drive, arc welder and lift are modeled in PSCAD/EMTDC. These models are then used for harmonic analysis of small scale industrial system. Current and voltage harmonic analysis is performed for standard IEEE 13-Bus medium voltage industrial distribution system by performing simulation using PSCAD/EMTDC. Adjustable speed drive is modelled and used as nonlinear loads and RL loads as static loads. The harmonic distribution is found and THD of voltage and current is found at all buses. Harmonic mitigation is performed by using single tuned, double tuned and reactance one-port filters. Also, use of shunt and series active filters is made for mitigating harmonics at PCC. Sensitivity analysis is then performed to analyze the effect on harmonic distribution and filter performance at various load conditions, variation in system or transformer or feeder X/R ratio, change in filter positions and effect of power factor correction capacitor.

Keywords – Modeling of Industrial loads, harmonic Analysis, Active filters and Passive filters.

I. INTRODUCTION

1.1: Power Quality: In an ideal ac power system, energy is supplied at a single constant frequency and specified voltage levels of constant magnitudes. However, this situation is difficult to achieve in practice. The undesirable deviation from a perfect sinusoidal waveform (variations in the magnitude and or the frequency) is generally expressed in terms of power quality. The power quality is an umbrella concept for many individual types of power system disturbances such as harmonic distortion, transients, voltage variations, voltage flicker, etc. Of all power line disturbances, harmonics are probably the most degenerative condition to power quality because of being a steady state condition. The Power quality problems resulting from harmonics have been getting more and more attention by researchers.

1.2: Power Quality Problems

a) The characteristics of the utility power supply can have a detrimental effect on the performance of industrial equipment.
b) Harmonics produced by industrial equipment, such as rectifiers or ASDs, can have a detrimental effect on the reliability of the plant's electrical distribution system, the equipment it feeds, and on the utility system.
c) The characteristics of the current and voltage produced by ASDs can cause motor problems. While power quality is basically voltage quality, it is not strictly a voltage issue. Since the supply system has a finite, rather than an infinite, strength, currents outside the direct control of the utility can adversely affect power quality. These are harmonic load currents, lightning currents, and fault currents. How do we quantify voltage aberrations indicative of power-quality problems? One must employ an accurate voltage-measuring device, such as an oscilloscope.

A power-quality problem is an occurrence manifested in a nonstandard voltage, current, or frequency deviation that results in a failure or a misoperation of end-use equipment. Power quality is a reliability issue driven by end users. All power quality problems are described in below.

1.2.1: Transients-Impulsive

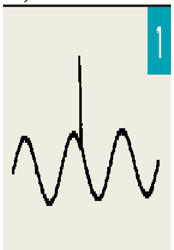
These are commonly known as switching surges or voltage spikes (Fig.1.2.1). They can be caused by circuit breakers out of adjustment, capacitor switching, lightning, or system faults. They are characterized by a sudden, non power frequency change, high amplitude, fast rise and decay times, and high energy content.

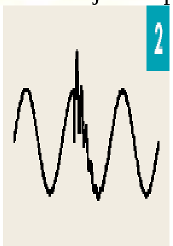
1.2.2: Transients-Oscillatory

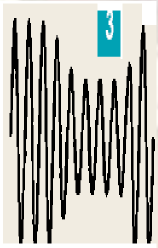
This is a sudden, bidirectional, non power frequency change: a ringing (Fig.1.2.2). For high-frequency ringing over 500 kHz of 1-μs duration and for 5-500 kHz ringing with tens of μs duration, it is likely the result of either the system response or the load response to an impulsive transient. With a frequency of less than 5 kHz and 0.3-50 ms duration, it could have one of a number of causes.

1.2.3: Voltage Sag

This is a short-term, few-cycles duration, drop in voltage (Fig.1.2.3) on the order of more than 10% to less than 90%. Typically, it lasts from 0.5 cycles to a minute. Voltage sags result from the voltage drop, from starting big motors across-the-line, or from a fault on an adjacent power line.





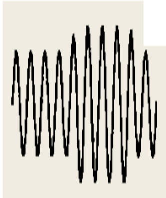


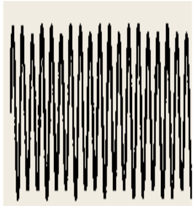
Transients-Impulsive Transients-Oscillatory Voltage Sag

1.2.4: Voltage Swell: This is a short-term increase in voltage of a few cycles duration (Fig.1.2.4). The magnitude of the increase is more than 10% and less than 80%. A swell can result from a single line-to-ground fault that raises the voltage on the other two phases. It can also result from dropping a large load or energizing a capacitor bank.

1.2.5: Interruption: Ninety percent of the faults on overhead distribution lines are of a temporary nature (Fig.1.2.5). Typically, these faults result from lightning, tree limbs, or animals causing grounds or shorts. Distribution lines are protected by a form of circuit breaker called a recloser. Reclosers interrupt faults, and then automatically restore the circuit, or reclose, and, if the fault has cleared, the recloser stays closed. If the fault still persists, the recloser trips and again automatically closes back in. It usually recloses three times before locking out.

1.2.6: Voltage Flicker: Flicker comes from the aggravating, rapid on-off sensation of incandescent and fluorescent lamps as perceived by the human eye. It results from the rapid variation in voltage within the normal allowable voltage range tolerance of 90-110% (Fig.1.2.6). Flicker can result from electric arc furnaces, welders, rapidly cycling loads, or it can result from a large ASD with inadequate dc-link filtering on a weak distribution system. With inadequate dc-link filtering, the inverter harmonics, which are a function of a non-60-Hz fundamental, flow into the power system, causing a pulsating of the 60-Hz fundamental.





1.2.4:Voltage swell 1.2.5:Interruption 1.2.6: Voltage Flicker

1.2.7: Voltage Regulation: Low voltage during peak load periods can result from overloaded lines, improperly set transformer taps, or maladjusted automatic voltage regulators. The volt-age is less than the normal 90% lower limit. Symptoms are dim light bulbs, light bulbs burning out too often, and electric motors failing to start.

1.2.8: Frequency Fluctuations: Normally, the variation in frequency is not significant enough to cause any problems. Frequency tends to lag a little during the day, as central plant generators are well loaded, but at night, with light load, the frequency leads a little, so that, at the end of a 24-hour period, all clocks are correct. Deviations in frequency can occur in weak electric systems, such as, an island system with no main supporting ties to the mainland or at an industrial plant with its own generating system. A weak system could develop during an area-wide system disturbance that separates one part of the system from another.

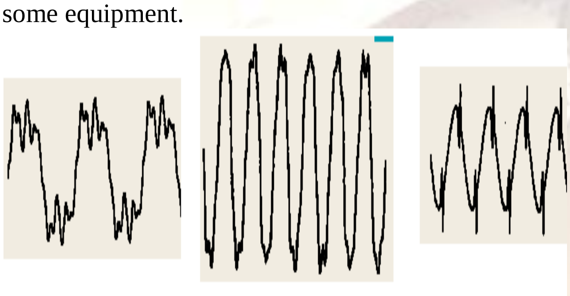
1.2.9: Voltage Distortion: Voltage distortion is the degree to which the voltage wave shape deviates from a sine wave. Distortion can result from the following

- Harmonics
- Inter harmonics
- Voltage notching
- Noise
- DC offset

1.2.9.1: Harmonics: Voltage distortion (Fig.1.2.9.1) is well understood; it is defined and thoroughly discussed in IEEE Standard 519. Nonlinear elements in power systems, such as, power electronic switches, saturated magnetic components, and arc furnaces, create current distortions. Harmonic currents flowing through system impedances create harmonic voltages.

1.2.9.2: Inter harmonics: These are frequency components of distorted voltages that are not integer multiples of the fundamental 60-Hz frequency (Fig.1.2.9.2). They can result from ASDs with insufficient dc-link filtering. With inadequate dc-link filtering, inverter harmonics that are multiples of a non-60-Hz fundamental pass into the power system, where they appear as non multiples of the 60-Hz fundamental. This phenomenon can also occur with cycloconverter-type ASDs that have no dc link and with arc furnaces that develop an infinite spectrum of parasitic frequencies.

1.2.9.3: Voltage Notching: Voltage notching is a periodic voltage disturbance resulting from the normal operation of power electronic devices, such as thyristors. Notching (Fig.1.2.9.3) is not normally a problem since it is controlled by circuit elements associated with the switching devices. It can be a significant problem on weak electric systems, where it can produce noise currents causing control system misoperation. Notching and ringing can cause extra zero crossings, resulting in equipment malfunction in some equipment.



Harmonic distortion Inter harmonics Notching

1.2.9.4: Noise

Fast switching speed and high input impedance give insulated-gate bipolar transistor (IGBT) inverters the potential to produce stray currents resulting in electromagnetic interference (EMI). Stray currents can disrupt communications equipment, ASD control, programmable controllers, sensors, barcode scanners, and position sensing equipment. These common-mode noise currents (Fig.1.2.9.4) are mainly conducted currents. They are superimposed on and can overwhelm low voltage control signals with these adverse effects. The magnitude of the stray currents is determined by the amount of phase-to-ground stray capacitance coupling available during the approximate 0.05-0.1-μs time period when the inverter voltage is transitioning to and from the dc-link voltage level.

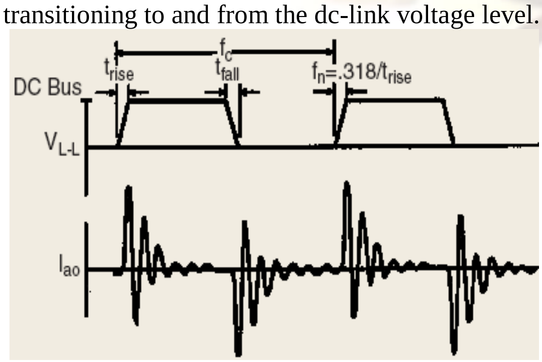


Figure 1.2.9.4: Noise current

The Power quality problem, and the means of keeping it under control, is a growing concern. This is due primarily to the increase in the number and application of nonlinear power electronic equipment used in the control of power apparatus and the presence of sensitive electronic equipment. The non-linear characteristics of these power electronic loads cause harmonic currents, which result in additional losses in distribution system equipment, interference with communication systems, and misoperation of control. Moreover, many new loads contain microprocessor-based controls and power electronic systems that are sensitive to many types of disturbances. Failure of sensitive electronic loads such as data processing, process control and telecommunications equipment connected to the power systems has become a concern as they could result in series economic consequences. In addition, the increasing emphasis on overall distribution system efficiency has resulted in a continued growth in the application of devices such as shunt capacitors for power factor corrections. Harmonic contamination excites resonance in the tank circuit formed by line inductance and power factor correction shunt capacitors, which result in magnification of harmonic distortion levels.

1.3: Mitigation of power quality problem

The control or mitigation of the power quality problems may be realized through the use of harmonic filters. Harmonic filters, in general, are designed to reduce the effects of harmonic penetration in power systems and should be installed when it has been determined that the recommended harmonic content has been exceeded. Shunt passive filters have been widely used by electric utilities to minimize the harmonic distortion level. Filtering harmonics using passive filter is one of the earliest methods used to address harmonic mitigation issues. Many studies have been carried out on harmonic mitigation using different types of filters and the effect of ASD load in contributing harmonics at the point of common coupling (PCC). The problem of harmonics in distribution systems has been studied by using passive filters. They consist of passive energy storage elements (inductors and capacitors) arranged in such a way to provide a low impedance path to the ground just for the harmonic component(s) to be suppressed. The design and performance of single tuned, double tuned filters and reactance one-port compensator has been discussed in below chapters. This type of filter has the advantages in terms of low hardware cost and can be used to improve system power factor because it provides reactive power to the power system depending on the closeness of the position of the filter to a bus. Passive filters are considered as one of the cheapest and most economical way for mitigating harmonics. They have also been used extensively in HVDC systems, arc-furnace installations, and static Var compensators installation. However, harmonic passive filters cannot adjust to changing load conditions; they are unsuitable at distribution level as they can correct only specific load conditions or a particular state of the power system. Due to the power system dynamics and the random-like behavior of harmonics for a short term, consideration has been given to power electronic equipment known as an active power filter. An active power filter is simply a device that injects equal-but opposite distortion into the power line, thereby canceling the original power system harmonics and improving power quality in the connected power system. This waveform has to be injected at a carefully selected point in a power system to correct the distorted voltage or current waveform. The power converter used for this purpose has been known by different names such as: active power filter and active power line conditioner. The rating of the power converter is based on the magnitude of the distortion current and operated at the switching frequency dedicated by the desired filter bandwidth. In addition to its filtering capability, this power converter can be used as a static Var compensator (SVC) to compensate for other disturbances such as voltage flicker and imbalance. From a control system point of view, waveform correction on the system bus can be implemented either in the time-domain or frequency-domain. Both have advantages and disadvantages. The main advantage of a time domain correction technique is its fast response to changes in the power system. Ignoring the periodic characteristics of the distorted waveform and not learning from past experiences are its main drawbacks. The advantage of frequency domain correction lies in its flexibility to select specific harmonic components needed to be suppressed and its main disadvantage lies in the rather burdensome computational requirements needed for a solution, which results in long response times. The concept of active power filtering was first introduced in 1971 by Sasaki and Machida who proposed implementation based on linear amplifiers. In 1976, Gyngyi et.a1 proposed a family of active power filter systems based on PWM current source inverter (CSI) and PWM voltage source inverter (VSI). These designs remained either at the concept level or at the laboratory level due to the lack of suitable power semiconductor devices. Due to recent developments in the semiconductor industry, power switches such as the (IGBTs) with high power rating and the capability of switching at high frequency, are available on the market. This makes the application of active power filters at the industrial level feasible. Several active power filter design topologies have been proposed. They can be classified as:

- Series active power filter (SeAF)
- Shunt active power filter (ShAF)
- Hybrid series and shunt active filter
- Unified power quality conditioner
- Multi level and Multi converter active power filters

Almost al1 of the existing proposed active power filters suffer from one or more of the following shortcomings:

- High Switching Losses: Almost al1 of the recently proposed active power filters utilize PWM switching control strategy due to its simplicity and harmonic suppression efficiency. However, utility companies have been very reluctant in accepting the PWM switching strategy because of the high switching losses incurred in this approach. The power converter used for active filtering is rated based on the magnitude of the distorted current and operated at the switching frequency dictated by the desired filter bandwidth. Fast switching at high power, even if technically possible, causes high switching losses and low efficiency. An important issue in active power filtering is to reduce the power rating and switching frequency. The combinations of active and passive filters as well as employing multi-converter and multi level techniques, have al1 been attempted to meet the above requirements.
- Low Reliability: Most of the active filters connected to distribution systems are mainly a single unit with a high rating taking care of d l the harmonic components in the distorted signal. Any failure in any of the active filter devices will make the entire equipment ineffective. In addition, cascade multi-converter and multi level topology active power filters suffer from low reliability.
- Control Methodology: Active power filtering can be performed in time domain or in frequency domain. The waveform correction in time domain is based on extraction of data from the power line. However, in the frequency domain technique information is extracted rather than data. The main advantage of time domain is fast control response, but, due to lack of information, it cannot control individual harmonics separately or apply various weightings for different harmonic components. Also, ignoring the periodic characteristics of the distorted waveform and not learning from past experiences are additional drawbacks of time domain methods. Correction in frequency domain, which is mainly implemented by FFT, has the advantage of flexible control of individual harmonics (cancel selected harmonics). However, its main disadvantage lies in the rather burdensome computational requirements needed for a solution, which results in longer response times.

In this project all home appliances are simulated by using PSCAD/EMTDC software and then FFT analysis is carried out by considering a home, which is having all above loads. Total harmonic distortion also investigating in a small industry having ASD, lift motor, arc welder and cycloconverter along with some nonlinear loads. Along with that IEEE 13bus industrial distribution system is simulated and investigated the effectiveness of using different types of filters for eliminating harmonics in an industrial distribution system. In this study, focus is made in determining the best location for installing the ASD and filters to get better harmonic reduction, the effect of the power factor correction capacitor (PFCC) on the filter performance, effect of the changing source impedance, effect of the changing transformer and feeder X/R ratio on total harmonic distortions are also investigated and the effect of varying the static load parameters on the generated harmonics are discussed.

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III. HARMONICS

2.1: Definition of Harmonics

The first step toward understanding how to deal with the problems caused by the interaction of harmonics with power systems or power systems equipment was to settle on a definition of harmonics and a useful means of evaluating them. Over the past few decades this has been done. A harmonic is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. Note that, for example, a component of frequency twice that of the fundamental frequency is called the second harmonic. Thus, on a 60 Hz power system, a harmonic component, h, is a sinusoid having a frequency expressed by the following:

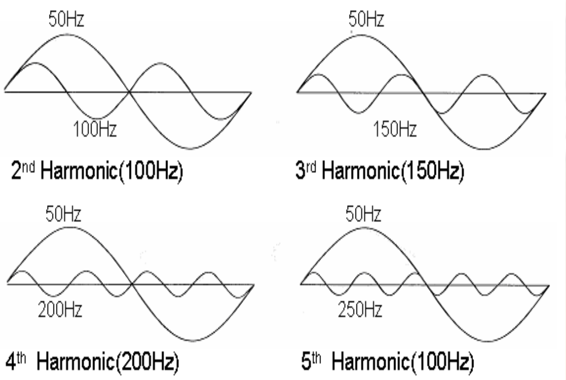


Figure 2.1: Harmonics

Sinusoidal waves that are not an integral multiple of the fundamental are not harmonics but are defined in terms of the fundamental as per-unit frequencies.

2.2: Characteristics of harmonics

Any periodic wave shape can be broken into or analyzed as a fundamental wave and a set of harmonics. This separation or analysis for the purpose of studying the wave shapes effect on the power system is called harmonic analysis.

2.3: Harmonic Analysis

Figure 2.3.1 illustrates one period of a distorted wave that has been resolved into its fundamental and two in-phase harmonic components (the third and fifth). The decomposition of a periodic wave in this manner is referred to as Fourier analysis, after the French mathematician Jean-Baptiste Fourier (1768 -1830).

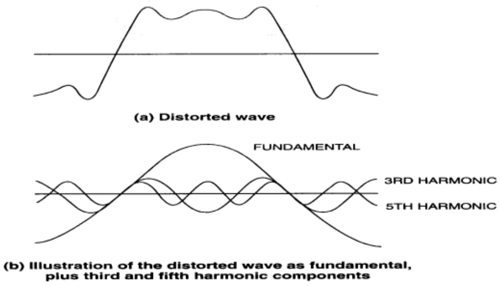


Figure 2.3.1: Decomposition of a distorted wave

2.4: Harmonic Distortion Indices

The presence of harmonics in the system is measured in terms of harmonic content, which is defined as the ratio of the amplitude of each harmonic to the amplitude of the fundamental component of the supply system voltage or current. Harmonic distortion levels are described by the complete harmonic spectrum with magnitude and phase angle of each individual harmonic component. The most commonly used measure of the effective value of harmonic distortion is total harmonic distortion (THD) or distortion factor. This factor is used to quantify the levels of the current flowing in the distribution system or the voltage level at the PCC where the utility cm supplies other customers. THD can be calculated for either voltage or current and can be defined as:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} M_h^2}}{M_1} \times 100\%$$

Where, M_1 is the RMS value of the fundamental component and M_2 to M_n are the RMS values of the harmonic components of the quantity M.

Another important distortion index is the individual harmonic distortion factor (DIF) for a certain harmonic h. HF is defined as the ratio of the RMS harmonic to the fundamental RMS value of the waveform,

$$HF = {M_h}/{M_1} \times 100\%$$

IEEE 519-1992 Standard [3] specifies limits on voltage and current harmonic distortion for Low Voltage, Primary and Secondary Distribution, Sub-transmission, and High Voltage transmission systems'. Table 2.4.1 lists the IEEE 519 recommended harmonic voltage and voltage distortion limits for different system voltage levels.

Table 2.4.1: Harmonic voltage distortion limits (V_h) in % at PCC

Bus Voltage at PCC	Individual Voltage Distortion (%)	THDV (%)
69 kV and below	3.0	5.0
69.001 kV - 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

IEEE 519 Standard also specifies limits on the harmonic currents from an individual customer which are evaluated at the PCC. The limits are dependent on the customer load in relation to the system short circuit capacity at the PCC. Note that all current limits are expressed as a percentage of the customer's average maximum demand load current (fundamental frequency component) at PCC. The term the total demand distortion (TDD) is usually used which is the same as THD except that the distortion is expressed as a percentage of some rated load current rather than as a percentage of the fundamental current magnitude.
TDD is defined as:

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100\%$$

Where, I_h is the RMS magnitude of an individual harmonic current component, I_L is the maximum RMS demand load current and h is the harmonic order.
Table 2.4.2 provides limits on every individual harmonic current component as well as limits on total demand distortion (TDD) for different voltage levels.
Table 2.4.2: Harmonic current distortion limits (I_h) in % of load current (I_L)

V ≤ 69kV						
I_{sc} / I_L	h<11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	h ≥35	TDD
20 <	4	2	1.5	0.6	0.3	5.0
20 – 50	7	3.5	2.5	1.0	0.5	8.0
50 – 100	10	4.5	4.0	1.5	0.7	12.0
100 – 1000	12	5.5	5.0	2.0	1.0	15.0
> 1000	15	7.0	6.0	2.5	1.4	20.0
69kV < V ≤ 161kV						
20 <	2.0	1.00	0.75	0.3	0.15	2.5
20 – 50	3.5	1.75	1.25	0.5	0.25	4.0
50 – 100	5.0	2.25	2.0	1.25	0.35	6.0
100 – 1000	6.0	2.75	2.5	1.0	0.50	7.5
> 1000	7.5	3.5	3.0	1.25	0.70	10.0
V > 161kV						
< 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.5	1.75	1.25	0.5	0.25	4.0

2.5: Relationship between harmonics and symmetrical components

In balanced three-phase circuits where the currents are equal and in 120° relationship, the harmonics can be considered sequence components. The second harmonic has 240° (60 Hz base) between the phasors, the third 360°, etc. Table 2.5.1 lists the lower harmonics and their respective sequence.

Table 2.5.1: Harmonic sequences in a balanced three phase system

Sequence		
Positive	Negative	Zero
1	2	3
4	5	6
7	8	9
10	11	12
13	14	15
16	17	18
Etc		

If the currents are not balanced, as in an arc furnace, each harmonic has its own set of sequence qualities. For example, the third harmonic, 180 Hz, will have its own set of sequence currents and the third-harmonic currents in each phase will not be additive in the neutral circuit.

2.6: Fundamental and harmonic power

Power is the product of in phase current times the voltage, or

$P_{fundamental} = V_{fundamental} \cdot I_{fundamental} \cdot \cos\theta_1$

In the case of harmonics, it is also the in-phase harmonic current times the harmonic voltage, or

$P_{harmonic} = V_{harmonic} \cdot I_{harmonic} \cdot \cos\theta_{harmonic}$

Nonsinusoidal currents can be analyzed by considering the load as a current source for harmonic currents. As these harmonic currents flow through the harmonic impedance of the circuit, they cause a harmonic voltage drop. Since the majority of the impedance is reactive, the amount of harmonic current in phase with the harmonic voltage (harmonic power) is small. The harmonic currents flowing through the resistance of the circuit represent a power loss as

$P_h = I^2_{harmonic} \cdot R_{harmonic}$

R_h can vary with applied harmonics because of skin effect, stray currents, eddy currents, etc. In rotating machinery, the harmonic flux in the air gap produces torques in the rotor. These torques can either add (positive sequence) or subtract (negative sequence) from the fundamental torque, depending upon the phase sequence of the harmonic. In general, the harmonic fluxes are small and their effects tend to cancel.

2.7: Harmonic Distribution in Distribution Systems

In electric distribution systems, the magnitude of the harmonic current component is often inversely proportional to its harmonic order, $I_{h.peak} \alpha \frac{1}{h}$, and $f_h \alpha h$,

Where $i_{h.peak}$ is the peak value of the magnitude of the harmonic current, h is the harmonic order and f, is the harmonic frequency.

IV.SOURCES OF POWER SYSTEM HARMONICS

Power system harmonics are mainly generated by power converters, transformers, rotating machines, arc furnaces, fluorescent lightings, and imperfect system conditions.

3.1: Harmonics Generated by Converters

Harmonic voltages and currents can be generated by different kinds of power converters. In steady state the operation of converter valves changes the shapes of voltage and current waveforms both on the ac-side and the dc side. Consequently, harmonics are produced by the distortion of voltage and current waveforms. The orders of harmonics depend on the pulse numbers of the converters. With n being an integer and p being the pulse number of a converter, the harmonic orders can be Pn + 1 or Pn - 1 on the ac-side and Pn on the dc-side. Harmonics generated by converters can be characteristic or non-characteristic in nature. Non-characteristic harmonics are caused by unbalanced ac voltages, uneven firing time, and interaction between characteristic harmonic currents and fundamental current. Within the converters, non-characteristic harmonics of low orders are normally much smaller than characteristic harmonics of the same orders. However, on the network side low order non-characteristic harmonics have the similar amplitudes of low order characteristic harmonics. High order characteristic and non-characteristic harmonics have similar small amplitudes.

3.2: Harmonics Generated by Transformers

Transformers are also major harmonic producers in a power system. Such harmonics are associated with their design and operation. In addition, during large disturbances transformers can considerably increase their harmonic contribution. For economical reasons a transformer is normally designed to make optimum use of magnetic core materials, resulting in a peak magnetic flux density in its steady state. With this peak operating magnetic flux design, the core materials may be subjected to a large magnetic flux density, which causes considerable saturation. Following load rejection, for instance, transformers connected to a large converter plant can reach their high voltage levels at the converter terminals, driving the converter transformers deep into saturation. The magnetizing current associated with the converter transformer core saturation has all the odd harmonics. Due to the Y-Δ connection of transformer windings, triplen harmonics can be absorbed by delta windings. For balanced operation, if the fundamental component is ignored, harmonics generated by transformers in a power network have orders of 6n+1 and 6n-1, with n being an integer. The distortion of a transformer's magnetizing current is caused by its magnetization non-linearity. Magnetizing current harmonics depend on the time of a day and often reach peak values in the morning in which a system is lightly loaded. Normally, since a transformer is excited by a sinusoidal voltage, it produces a symmetrical exciting current having only odd harmonics. It does not matter if a load connected to the transformer is linear or non-linear. The excitation current contains only odd harmonics as long as the load does not produce a direct current. For unbalanced excitation, the core contains an average flux. The existence of the average flux indicates that a direct component of excitation current exists. Under such unbalanced condition, the transformer excitation current contains both odd and even harmonics.

3.3: Harmonics Generated by Rotating Machines

Electric machines are also main harmonic sources in power systems due to their practical and economical design. If the magnetic flux in a machine has a perfectly sinusoidal distribution around the air gap, the machine is not operated in the saturation region. However, the flux is never exactly distributed in this way, particularly in salient pole machines. Due to the imperfection of the distribution of windings in rotating machines, space harmonics can be generated. The magnetic saturation in the machines can also contribute to the generation of harmonics similar to those generated by transformers.

3.4: Harmonics Generated by Arc Furnaces

Due to arc ignition delays and highly non-linear arc voltage-current characteristics, arc furnaces produce harmonics in power systems. The voltage variation caused by the sudden alteration of arc length produces a spread of frequencies in a range from 0.1 to 30 Hz. Such effects become more pertinent during the melting phase as a result of the continuous motion of a melting scrap and the interaction between electromagnetic forces of arcs. During the refining process arcs do not change too rapidly but some modulation of arc length still remains due to waves on the surface of the molten metal.

3.5: Harmonics Generated by Fluorescent Lighting

Some lighting devices also contribute harmonics to power systems. Luminous discharge lightings and in particular fluorescent tube appliances are highly non-linear, giving rise to considerable odd harmonic currents. In three-phase four wire loads triplens (with third harmonics being the most dominant) are basically added to the neutral. In general, lighting circuits often involve long distances and have very little load diversity. With an individual power factor correction capacitor the complex lighting circuits can approach a condition of resonance at third harmonic frequency.

3.6: Summary of sources of harmonics

Harmonic currents are a result of loads that require currents other than a sinusoidal. The most common of these are static power converters, although several other loads are nonsinusoidal, such as the following:

- Arc furnaces and other arc-discharge devices, such as fluorescent lamps
- Resistance welders (impedance of the joint between dissimilar metals is different for the flow of positive vs. negative current)
- Magnetic cores, such as transformer and rotating machines that require third harmonic current to excite the iron
- Synchronous machines (winding pitch produces fifth and seventh harmonics)
- Adjustable speed drives used in fans, blowers, pumps, and process drives
- Solid-state switches that modulate the current-to-control heating, light intensity, etc.
- Switched-mode power supplies, used in instrumentation, PCs, televisions, etc.
- High-voltage dc transmission stations (rectification of ac to dc, and dc to ac invertors), Photovoltaic invertors converting dc to ac

V.EFFECTS OF HARMONICS ON POWER SYSTEM COMPONENTS

4.1: Generators

- Rotor heating (in cylindrical rotor synchronous generators).
- Production of pulsating or oscillating torques which involve torsional oscillations of the rotor elements and flexing of turbine buckets.

4.2: Motor

- Stator and rotor I^2R losses will increase due to the flow of harmonic currents.
- Core losses increases due to harmonic voltage
- Leakage fields set up by harmonic currents in the stator and rotor end windings produce extra losses.
- In the case of induction motors with skewed rotors, the flux changes in both the stator and rotor and high frequency can produce substantial iron losses.
- Positive sequence harmonics develop shaft torques that aid shaft rotation; negative sequence harmonics have the opposite effect.
- Excessive losses in and heating of induction and synchronous machines.
- Actually, the effects mainly are contributed by low order harmonics with large magnitudes.
- Due to eddy currents and skin effect, the losses in the conductors of stators and rotors with harmonics are much greater than those without harmonics.
- Large harmonic contents in induction machines can reduce their output torques at rated speeds and cause vibration.
- The slips of harmonic frequencies are almost unity. The torques produced by the harmonic currents, therefore, are very small. Since such small torques are generated in pairs, they tend to cancel each other.
- The harmonic currents have little effects on the average torque; however, they produce significant torque pulsation, which causes the shaft vibration of the machine.

4.3: Transformers and reactors

- Winding stray (eddy-current) losses due to nonsinusoidal load currents rise in proportion to the square of the load current and the square of the frequency.
- Hysteresis losses increase.
- Possible resonance may occur between the transformer inductance and the line capacitance.

4.4: Capacitors

- Reactive power increases due to harmonic voltages.
- Dielectric losses increase thus additional heating occurs.
- Capacitor bank failure from dielectric breakdown or reactive power overload.
- Life expectancy decreases.
- Resonance may occur resulting in harmonic magnification.
- Over voltage can occur.

4.5: Cable

- Additional heating occurs due to nonsinusoidal current and because of skin and proximity effects which are a function of frequency;
- Dielectric breakdown of insulated cables resulting from harmonic over voltage on the system;
- R_{ac} increases, therefore ($I^2 * R_{ac}$) losses increase.

4.6: Effects on Series and Parallel Circuits

Resonances at some harmonic frequencies can occur in power systems, such as the resonances between capacitors and other components. Harmonic resonances cause over voltages and excessive currents that dramatically increase the losses of system devices and can even damage them. The large currents caused by harmonic resonances, for instance, can flow in to power factor correction capacitor banks and damage their dielectric materials. Over voltages can reduce the life time of the insulation materials of system components and often lead to their destruction .When a voltage source excites a series circuit, the circuit impedance reaches its minimum value during a resonance and excessive currents flow in the circuit. For a capacitor, the primary concern with series resonance is that a high capacitor current can flow for a relatively small harmonic voltage. The actual current depends on the quality factor of the circuit. A high impedance of a parallel circuit is seen by a harmonic source at a resonant frequency. In general, most of the harmonic sources can be considered as current sources. Thus the harmonic voltage is increased across a parallel circuit at the resonant frequency. Usually, high voltages across capacitors and inductors during resonances are of concern because of the high stress on their insulation. A parallel resonance can occur in different ways and the simplest case may be the one in which a capacitor is connected to the same bus where a harmonic source is connected. The parallel resonance is initiated between the source and the capacitor.

4.7: Effects on Converter Stations

Harmonic currents increase the harmonic voltage drops across circuit impedances. In a "weak" system the harmonic currents, therefore, cause greater voltage fluctuation than in a "stiff' system. When the electric power is transmitted by cables, harmonic voltages increase dielectric stress in proportion to their crest voltages. The high dielectric stress shortens the useful life of the cables. The harmonics also have effects on corona. The corona starting and extinction levels depend on peak-to-peak voltages, which are affected by harmonics. It is sometimes possible for the peak voltages to be above the specified rating values while the effective voltages are well within the specified limits. In addition, harmonic currents increase the copper losses of these devices. The losses can be more serious for converter transformers due to the fact that they do not benefit from filters normally connected on the ac-side of a system. The circulation of triplen currents in the delta windings of power transformers is of great concern to power engineers since the extra circulating harmonic currents can over rate the windings. Another important consideration exists for a transformer supplying an asymmetrical load. If the load current contains a dc component, the resulting saturation of the transformer will greatly increase the harmonic components of the excitation current. The voltage distortion causes additional power losses in the capacitors of a converter station. The effective values of currents through the capacitors are increased by harmonics and can over heat these devices. The total reactive power of a capacitor includes all the reactive power of harmonics.

4.8: Effects on Ripple Control Systems

- A ripple control is used to operate street lighting circuits and to reduce load during the peak hours of a day. The harmonic interference of a ripple control system can cause the mal-function of a relay used to protect the lighting circuit if the interference is significant.
- A ripple relay is essentially a voltage-operated device that has high impedance. Of course, the operation of the relay depends on voltage harmonics, the relay detection circuit, and the difference between reference frequency and frequencies of interfering harmonics.

4.9: Switchgear

- Medium-voltage, single-bar switchgear current carrying parts will behave similar to cables, with regard to skin and proximity effect;
- Changes the rate of rise of the transient recovery voltage;
- Affects the operation of the blow out coil.

4.10: Relaying

- Affects the time delay characteristics.
- Signal interference and relay malfunction, particularly in solid-state and microprocessor-control systems.
- False tripping may occur (in general their sensitivity to currents of higher order discrete frequencies decreases).

4.11: Effects on Power Measurements

- Since measurement instruments are initially calibrated on pure sinusoidal alternating currents, measurement errors will be introduced if they are used on a distorted power supply.
- For instance, when using a wattmeter to measure the power consumed by a device, the magnitude and direction of power flow are the key elements in power consumption calculations.
- The magnitude and direction of harmonic power flow are, therefore, important for revenue consideration. The measurement errors due to harmonics depend on the types of meters.

4.12: Effects on Power Factor

The period of a purely sinusoidal waveform is well defined. The power factor of a device is also well defined with purely sinusoidal waveforms. However, if the waveforms of a voltage and a current are distorted, the power factor defined with the purely sinusoidal waveforms at fundamental frequency cannot clearly describe the phase relationship between the voltage and the current. The power factor of distorted waveforms is different.

4.13: Effects on Communication Circuits

Power system harmonics sometimes cause interference between power systems and telephone networks. The noise on communication circuits degrades the transmission quality of communication signals. Low noise levels lower the communication signal quality and high noise levels can result in the loss of information. The three major aspects related to a noise problem in a communication network include power system harmonic level, coupling between the power system and the communication circuit, and communication circuit operation. Noise voltages may be created in telephone circuits by loop induction, longitudinal electromagnetic induction, longitudinal electrostatic induction, and conduction. When a power line and a telephone circuit are close to each other in crossing, a loop induction happens. If a voltage is induced by the harmonics in the power line into the loop formed by the two wires of the telephone circuit, a loop induction occurs.

The induction manifests the induced voltage directly as it crosses the terminations of the telephone circuit. Due to the operation of the power systems there must be a complete zero sequence path formed by some system components such as ground wires and shunt capacitors. The residual current in the power circuits generates an electromagnetic field. The power systems with ground returns and the telephone circuits with ground returns are coupled by the resultant electromagnetic field generated by the two circuits. A voltage is then induced by longitudinal electromagnetic induction along the conductors of the telephone circuit. Due to the unbalanced telephone circuit, the induced longitudinal voltage gives rise to an unbalanced current which causes a transverse voltage. If the telephone circuit has large across-sectional area, a longitudinal electromagnetic induction will occur in the circuit. A longitudinal electrostatic induction is produced by the difference between the residual voltage on a power line and the voltage on a telephone line. It occurs if a voltage is induced between the telephone conductors and the earth. The induced voltage depends on the residual voltage on the transmission line, the capacitance between the power line and the telephone line, and the loading of the telephone circuit. The longitudinal electrostatic induction is often a problem of long telephone lines in the neighborhood of very high voltage transmission lines. Due to the unbalance of a power system there are always some residual currents flowing in the neutral. The residual currents in a multiple-earthed neutral system flow through the neutral wires and the earth. If a telephone line is grounded in the area where the earth potential is generated, a longitudinal voltage will be produced on the telephone line. Usually, large currents flow in the multiple earthed neutral system if harmonics are significant. Although the telephone circuit has a relatively low impedance earth return circuit, the multiple earthed neutral systems can produce a high noise voltage in the telephone earth exchange system.

4.14: Effects on Consumer Equipment

- Power system harmonics also affect the operation of consumer loads (TV, PC,AC,…).
- The harmonics cause changes in TV picture size and brightness. They also initiate the resonances between the capacitances and inductances in fluorescent and mercury lightings, resulting in their overheating.

In the worse case, the high harmonic distortion in power systems can cause the malfunction of the data processing systems in computers.

V.HARMONIC ANALYSIS OF A TYPICAL SMALL SCALE INDUSTRY

Normally in any small scale industry having ASD, lift motors, drives, arc welders, fans, Cycloconverter, personal computers, air conditioners and fluorescent lamps. All those loads are simulated by using PSCAD/EMTDC are shown in below.

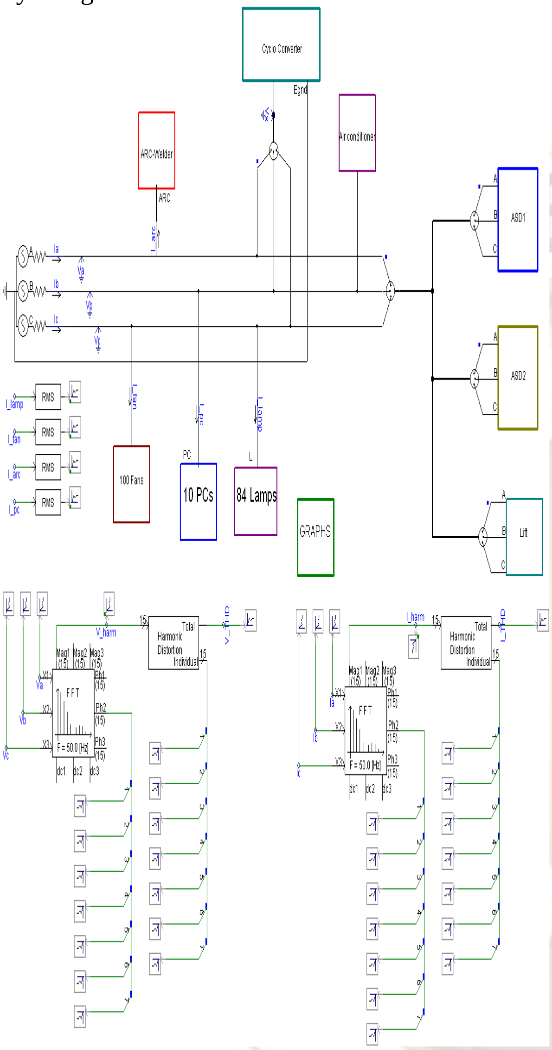


Figure 6.1: Simulation of Typical small scale industry in PSCAD/EMTDC

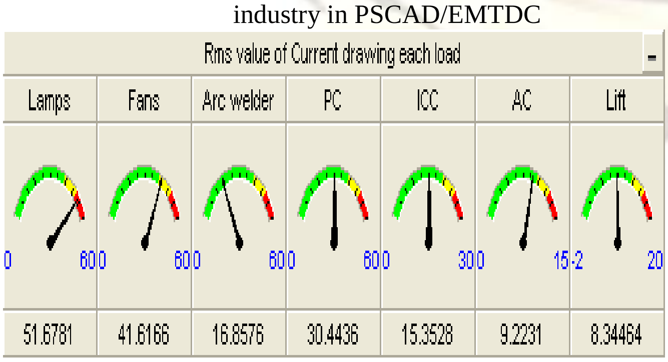


Figure 6.2: Rms value of Current drawn by each load

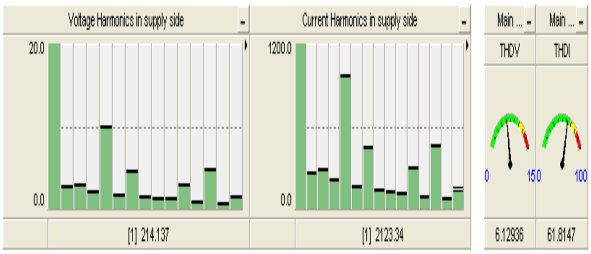


Figure 6.3: FFT Analysis of Small Scale Industry

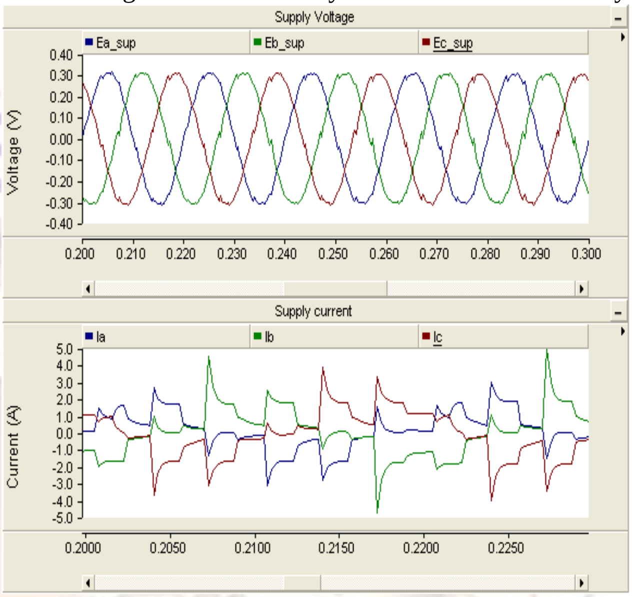


Figure 6.4: Voltage and Current wave forms of a Industry

VI.HARMONIC FILTERS

To eliminate harmonics filter is necessary equipment in power system. These are two types passive and active filters. Passive filters are easy to construct and maintain, again passive filters are two types; single tuned and double tuned filters. These filters operation and construction is shown in below.

7.1: Passive filters

7.1.1: Design of Single Tuned Filter (STF)

Fourier analysis is used to determine the harmonic components from the current and voltage waveforms. The dominant harmonic components at these buses are found to be the 5^{th} and 7^{th}. Therefore, the 5^{th} and 7^{th} harmonic components are the harmonics to be eliminated in the study. The most common type of shunt passive filters used in harmonic mitigation is the single tuned filter (STF) which is either a low pass or band pass filter. This type of filter is the simplest to design and the least expensive to implement. The configuration of a single tuned filter is depicted in Fig.7.1.1.

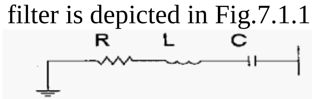


Fig.7.1.1: Single-tuned filter circuit

The major criteria in designing the filter are by selecting a proper size of capacitor that gives a reasonable power factor at fundamental frequency.

The capacitor reactance value, X_c and reactive power relationship is given by, $X_c = \frac{V_{cap}^2}{kVar_{filter}}$

V_{cap} is the line-to line rated voltage of the capacitor; kVar is the reactive power of the capacitor. The filter capacitance is then calculated using $C = \frac{1}{2\pi f X_c}$;

f is the fundamental frequency. The reactor value of the filter can then be obtained from

$$L = \frac{1}{(2\pi f)^2 rhC}$$

7.1.2: Design of Double Tuned Filter (DTF)

The double tuned filter (DTF) can be used to filter two harmonic components simultaneously. Compared to the STF with the same performance, DTF has a few advantages such as only one reactor is subjected to full line voltage and smaller space needed. The basic configuration of DTF is shown in below Fig.7.1.2. It comprises of series resonant circuit with parameters L_1 and C_1 and parallel resonant circuit with parameters L_2 and C_2. All filter parameters are calculated by using below equations.

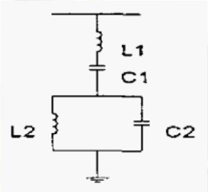


Figure 7.1.2: Double tuned filter circuit

$$C_1 = \left(\omega_f \left(\frac{\omega_p}{\omega_1 \omega_2} \right)^2 - \frac{1}{\omega_f} + \left(\frac{\omega_f \left(\omega_1^2 + \omega_2^2 - \omega_p^2\right)\omega_p - \omega_1^2 \omega_2^2}{\left(\omega_1^2 \omega_2^2 \left(\omega_p^2 \omega_s^2\right)\right)} \right) \right) \frac{V}{Q}$$

;

$$C_2 = C_1 \left(\left(\frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_s^2} \right) - 1 \right)$$

$$L_1 = \left(\frac{\omega_p}{\omega_1 \omega_2} \right)^2 \frac{1}{C_1}$$

$$L_2 = \frac{1}{\omega_p^2 C_2} = \frac{1}{\omega_p^2 C_1} \left(\frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_s^2} \right)$$

7.1.3: Reactance One-Port Filter (ROF)

The third filtering technique that will be examined is the reactance one-port filter (ROF). This filter was successfully applied to linear loads fed from a non-sinusoidal supply. In this study it is employed in order to minimize distortion levels in non-linear systems. This approach depends on calculating the load non-linear susceptance at different harmonic frequencies and then extends the reactance one-port compensator design to utilize it with non-linear systems. The filter susceptance should be equal in magnitude and opposite in sign to the equivalent load susceptance such as:

$$B_{Cn} = - B_{Ln}$$

Where, B_{Cn} = Compensator susceptance at harmonic "n"

B_{Ln} = Load susceptance at harmonic "n".

The calculation of the non-linear load susceptance and the synthesis procedure of a reactance one-port compensator are described in appendix A.1. The main drawback of the ROF is being sensitive to the system configuration and parameters variation; however, it does not create any resonance with the system inductive impedance like the LC filters.

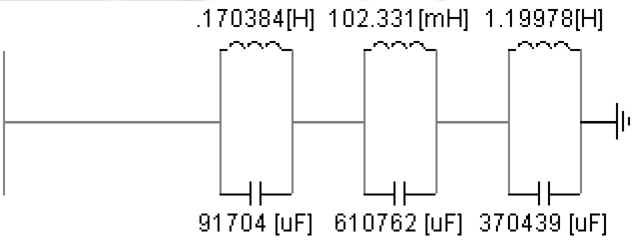


Figure 7.1.3: reactance one-port filter

7.2: Active harmonic filters

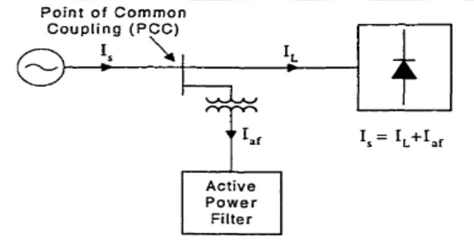
Active power harmonic filtering is a relatively new technology for eliminating harmonics which is based on sophisticated power electronics devices. An active power filter consists of one or more power electronic converters which utilize power semiconductor devices controlled by integrated circuits. The use of active power filters to eliminate the harmonics before they enter a supply system is the optimal method of dealing with the harmonics problem. Active power filters have some interesting features outlined as follows:

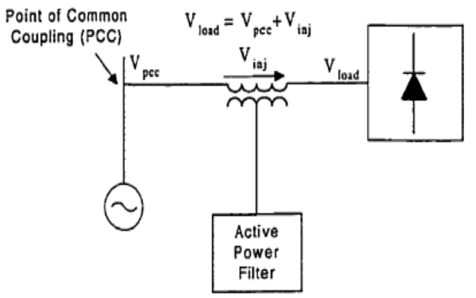
- They can address more than one harmonic at a time and can compensate for other power quality problems such as load imbalance and flicker. They are particularly useful for large, distorting loads fed from relatively weak points on the power system.
- They are capable of reducing the effect of distorted current/voltage waveforms as well as compensating the fundamental displacement component of current drawn by nonlinear loads.
- Because of high controllability and quick response of semiconductor devices, they have faster response than the conventional SVC's.
- They primarily utilize power semiconductor devices rather than conventional reactive components. This results in reduced overall size of a compensator and expected lower capital cost in future due to the continuously downward trend in the price of the solid state switches.

However, the active power filter technology adds to complexity of circuitry (power circuit and control). There will also be some losses associated with the semiconductor switches. The concept of the active power filter is to detect or extract the unwanted harmonic components of a line current, and then to generate and inject a signal into the line in such a way to produce partial or total cancellation of the unwanted components. Active power filters could be connected either in series or in parallel to power systems; therefore, they can operate as either voltage sources or current sources.

7.2.1: Shunt Active Filter

The shunt active filter is controlled to inject a compensating current into the utility system so that it cancels the harmonic currents produced by the nonlinear load. The principle of active filtering for current compensation is shown in Fig. 7.4.1. The load current is nonlinear due to the nonlinear Load. In this figure, the active filter is controlled to draw (or inject) a current I_{af} such that the source current $I_s = I_L + I_{af}$ is sinusoidal.





7.2.2: Series Active Filter

The series active filter is connected in series with the utility system through a matching transformer so that it prevents harmonic currents from reaching the supply system or compensates the distortion in the load voltage. The series active filter is the "dual" of the shunt active filter. Fig. 7.4.2 shows the application of an active power filter in series with a non-linear load. The active power filter in this configuration is referred to in the literature as the series voltage injection type, and it is suitable for compensating the load voltage in a weak AC system. It is controlled to insert a distorted voltage such that the load voltage is sinusoidal and is maintained at a rated magnitude.

There are two fundamental approaches for active power filtering: one that uses a converter with an inductor to store up energy to be used to inject current of appropriate magnitude and frequency contents into the system, called a current source converter (CSC), and one that uses a capacitor as an energy storage element, called a voltage source converter (VSC). When the magnitude and the frequency of the AC output voltage or current is controlled by the pulse-width modulation (PWM) of the inverter switches, such inverters are called PWM inverters.

Active power line filtering can be performed in the time domain or in the frequency domain**.** The correction in die time-domain is based on extracting the fundamental component of the distorted line current using a notch filter, finding the instantaneous error between the distorted waveform and its fundamental component, and compensating for the deviation from the sinusoidal waveform by injecting the computed error into the line. The correction in the frequency-domain, on the other hand, is based on the extraction of the harmonic components of the line current. A distinct advantage of the frequency-domain techniques is the possibility of selected harmonic elimination.

VII.IEEE 13-BUS INDUSTRIAL DISTRIBUTION SYSTEM

8.1: Test system description

1. The IEEE 13-bus industrial distribution system.
2. The system is fed from a utility supply at 69 kV and a Local generator operates at 13.8 kV. Operating at various voltage levels ranging from 69kV to 0.48 kV.
3. A PFCC rated at 6000kVar is connected at the PCC which is at bus 3.
4. There are two harmonic producing loads namely the adjustable speed drives serving customers at bus 7 and bus 10.

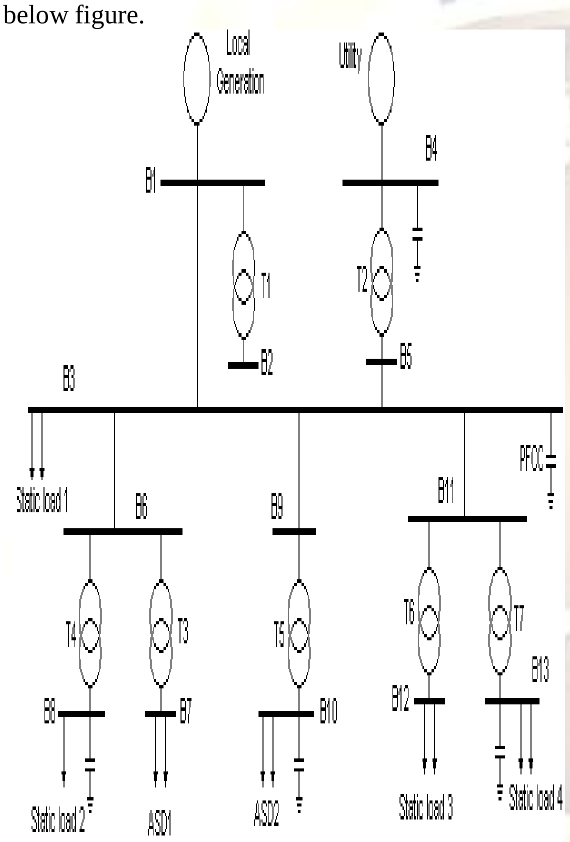
Table 8.1.1: IEEE 13-Bus Industrial Distribution system transformer data

T. f. name	Voltage (kV)	MVA Rating	R (%)	X (%)
T_1	13.8 /0.48	1.50	0.9593	5.6694
T_2	69.0 /13.8	15.0	0.4698	7.9862
T_3	13.8 / 0.48	1.25	0.7398	4.4388
T_4	13.8/ 4.16	1.725	0.7442	5.9370
T_5	13.8 / 0.48	1.50	0.8743	5.6831
T_6	13.8/ 0.48	1.50	0.8363	5.4360
T_7	13.8 /2.40	3.75	0.4568	5.4810

Table 8.1.2: IEEE 13-Bus Industrial Distribution system feeder data

From	To	Resistance (Ω)	Inductance (mH)
1	3	0.023268	0.13800
3	5	0.0265	0.18000
3	6	0.0143	0.03820
3	9	0.0299	0.07924
3	11	0.0208	0.05510

The above IEEE 13-Bus Industrial distribution system is simulated by Using PSCAD/EMTDC software package. Simulated figure is shown in below figure.



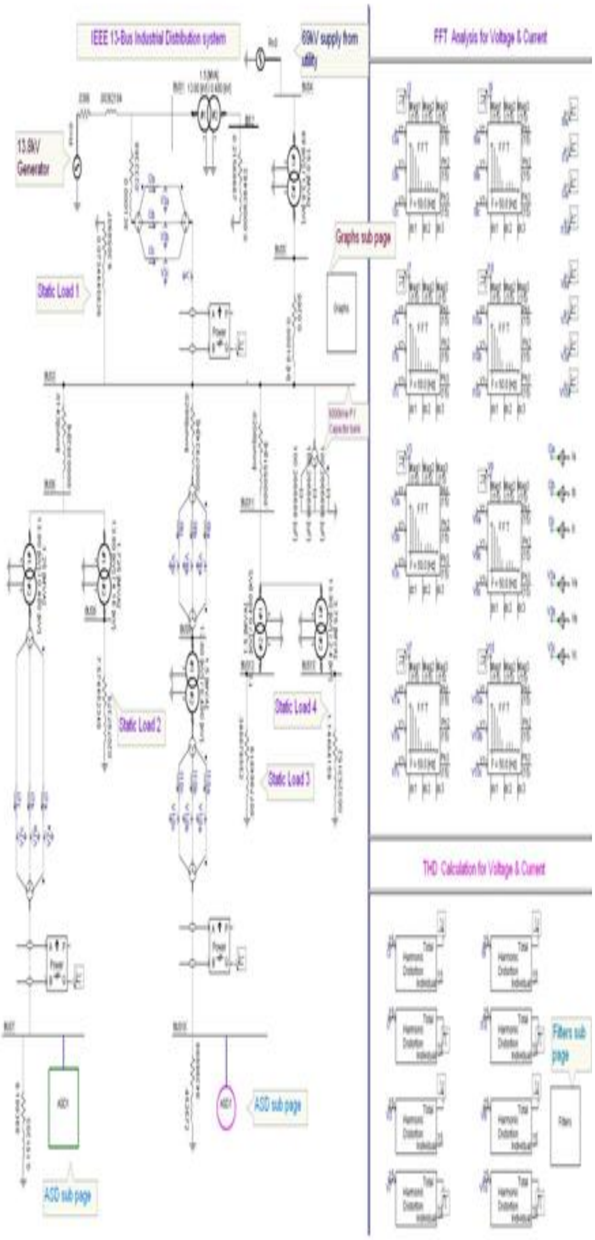


Figure 8.1.1: IEEE 13-Bus Industrial Distribution system simulation in PSCAD/EMTDC

8.2: Harmonic Analysis

In this section, the results of the performed harmonic analysis are reported. Simulations are carried out with and without the filters to investigate the effectiveness of the STF and DTF in mitigating harmonics. The THD for both current and voltage are recorded at various buses as shown in below figures 8.2.3.

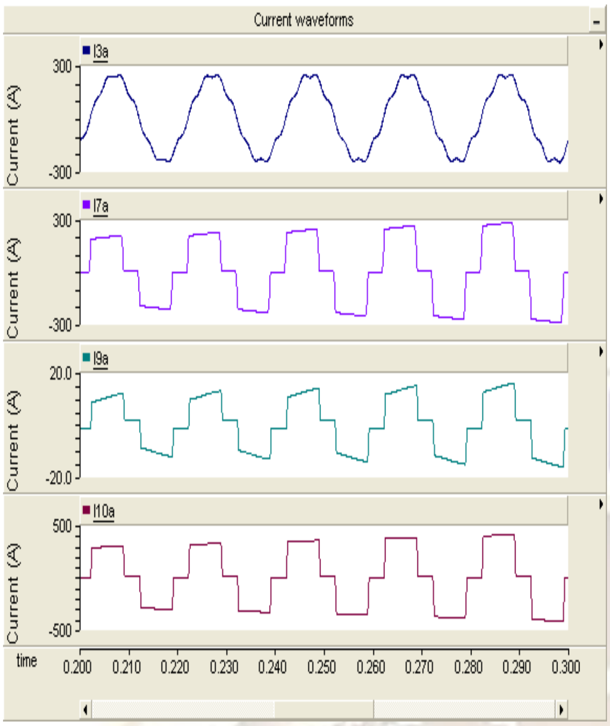


Figure 8.2.1 Current wave forms without any filter

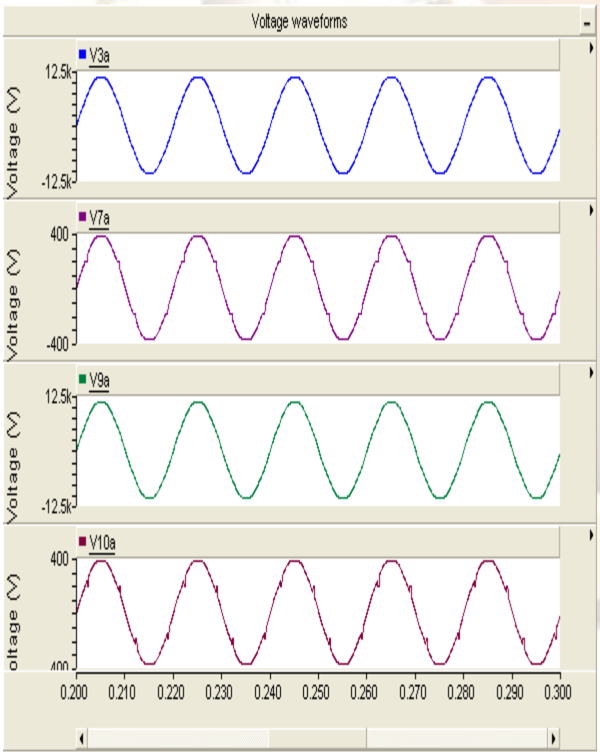


Figure 8.2.2 Voltage wave forms without any filter

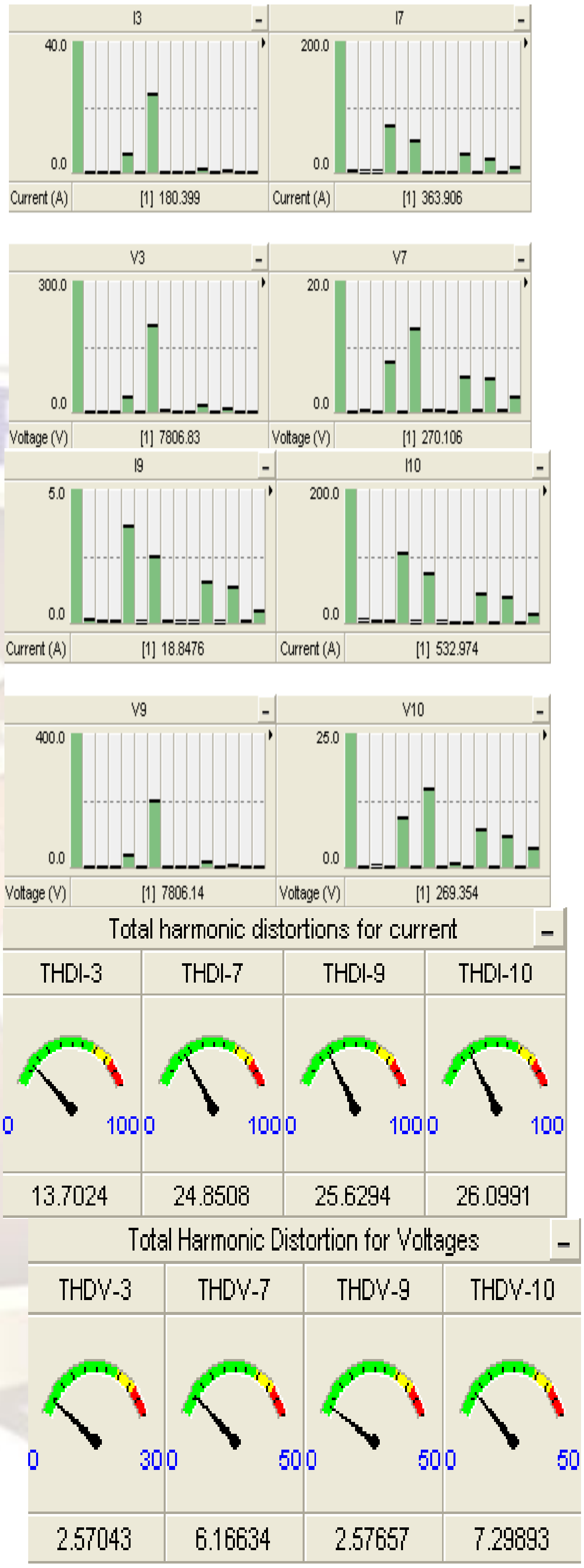


Figure 8.2.3: FFT analysis without any filter

It can be seen that the THDs at both ASD load buses 7 and 10 show that their values exceed the limits of 5% THD for voltage and 20% for THD current. Time domain analysis on the system is carried out and the results record the wave shapes of the voltages and currents at a few buses, namely the

ASD load buses 7, 10 and at the PCC. The current waveforms recorded at bus 3, 7 and 9 are shown in Figure 8.2.1.

8.3: Design and Implementation of Filters to Mitigate Harmonics

From above FFT analysis THD at bus 7, 9 and 10 crossing the limits, so we need to eliminate harmonics to protect the system. As we know filters are the equipments to reduce the harmonics distortion. Below procedure shows the designing and implementation of both passive and active filters.

8.3.1: Passive filters

Passive filters having the components like L, C, these are used to eliminate selected order harmonics consequently it will reduce the THD. Calculation procedure of filter parameters is shown in appendix 1. Different filter parameters are give in below table 8.3.1 and table 8.3.2.

Table 8.3.1: Parameters of single and double tuned filters

Filter type & position → / Parameters ↓	Single tuned		Double tuned	
	3rd bus	7th or 10th bus	3rd bus	7th or 10th bus
L_1 (mH)	9.147	0.10	0.107	0.570
C_1 (uF)	50.1433	6907.77	206.50	2873.4
R (Ω)	0.0000271	0.010	Nil	Nil
C_2 (uF)	Nil	Nil	42.69	358.0255
L_2 (mH)	Nil	Nil	0.140	2.580

Table 8.3.2: Parameters of reactance one port filter

Filter type & position → / Parameters ↓	Reactance one-port compensator		
	3rd bus	7th bus	10th bus
L_1 (H)	37.34120	2.4093870	1.199780
C_1 (F)	0.011902	0.1844640	0.370439
L_2 (H)	3.271550	0.1715512	0.102331
C_2 (F)	0.019104	0.364323	0.610762
L_3 (H)	5.082170	0.317687	0.170384
C_3 (F)	0.0030745	0.0491835	0.0917044

Different passive filter configurations are shown in below figure 8.3.1.

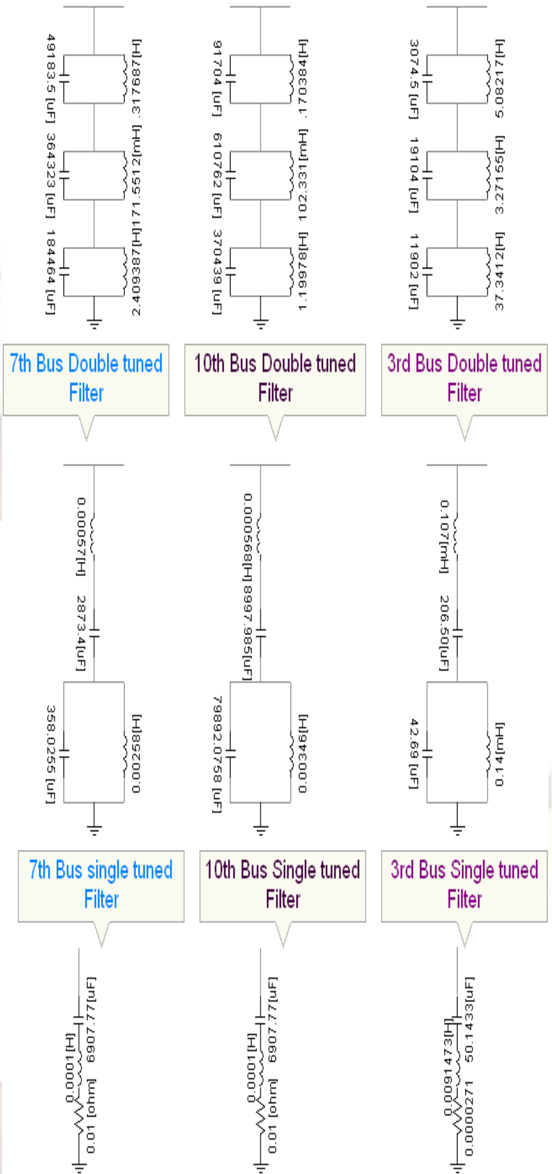


Figure 8.3.1.1: Passive Filter configurations

These filters are placed at buses 7, 10 and 3 to investigate the effect of STF, DTF and ROF on harmonic distortion. The obtained voltage and current wave forms shown in below figure 8.3.1.2 to figure 8.3.1.9. And FFT analysis is shown in figure 8.3.1.10 to figure 8.3.1.15.

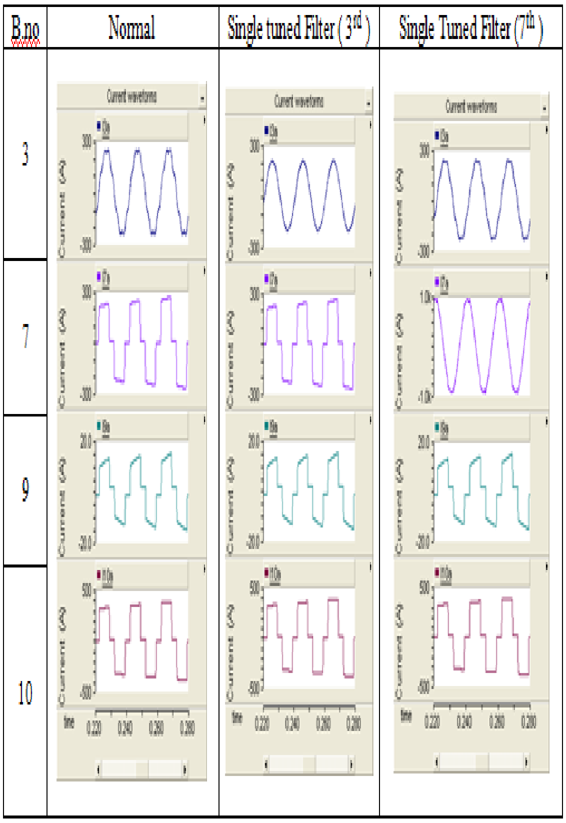
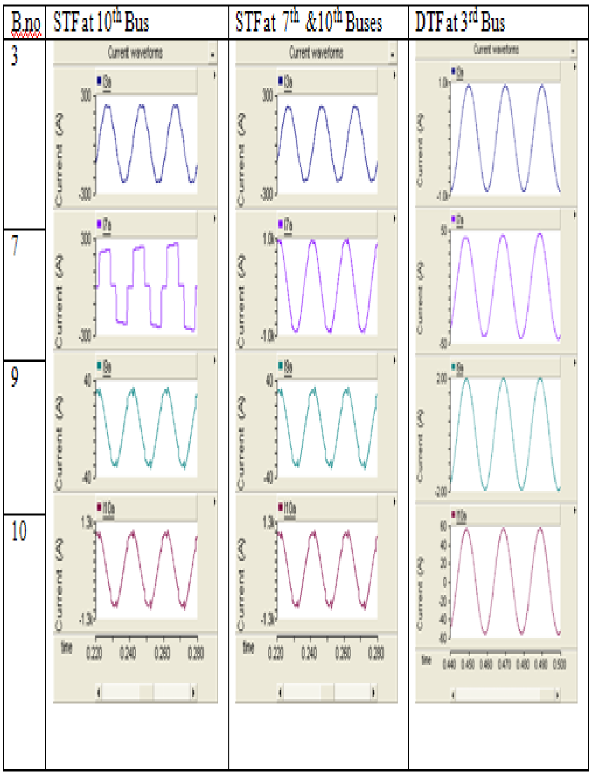


Figure 8.3.1.2: Current wave forms at different buses after placing STF at different buses



Scale: on X axis = Time (sec)

Figure 8.3.1.3: Current wave forms at different buses after placing STF and DTF

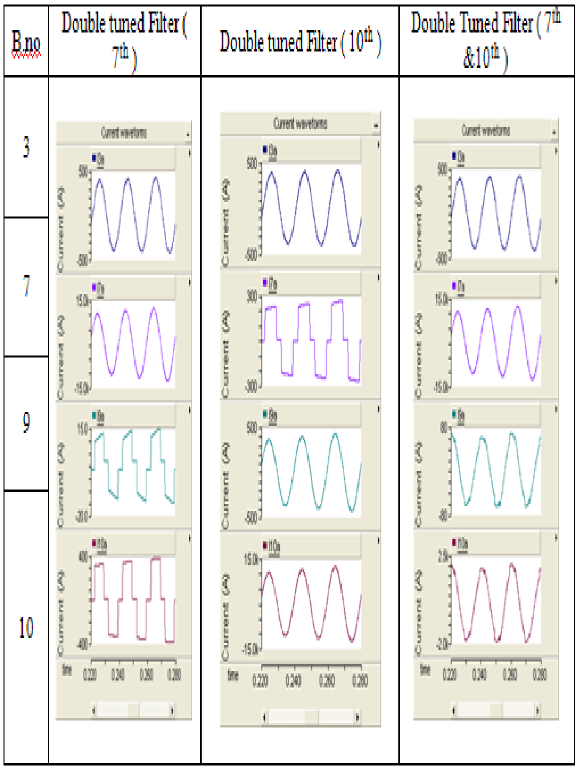
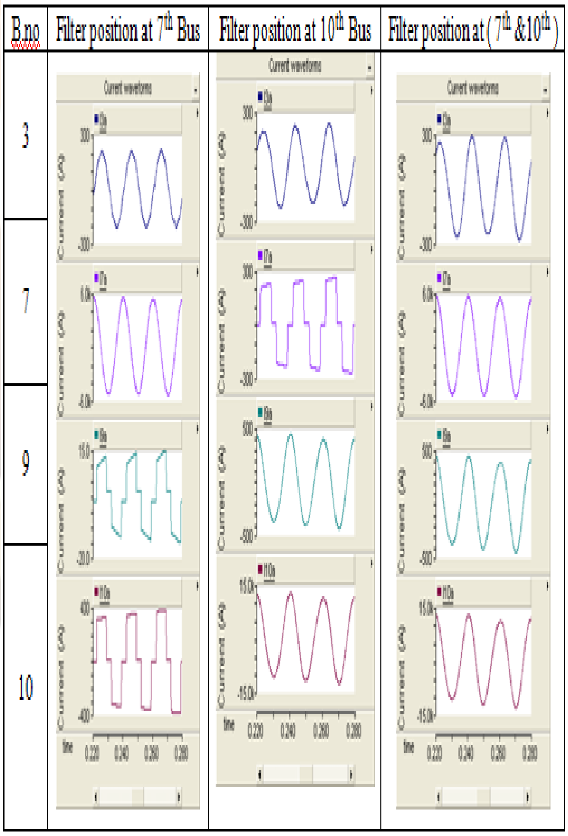


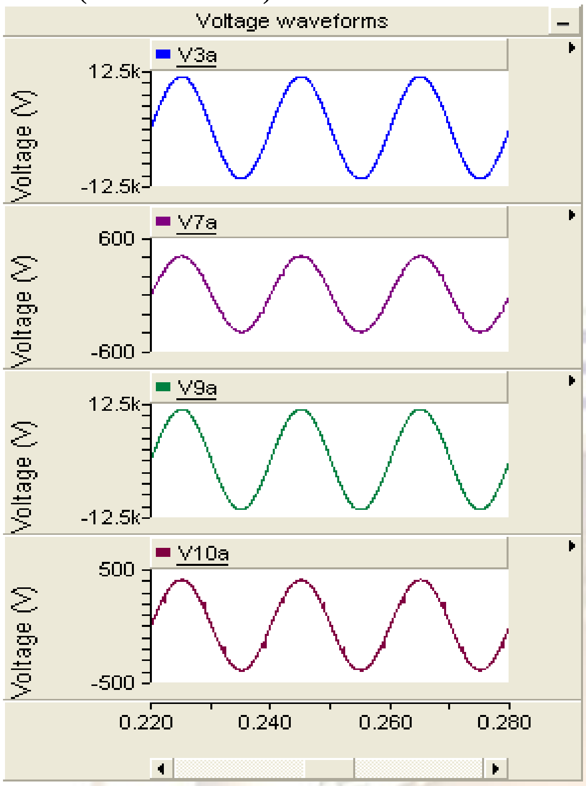
Figure 8.3.1.4: Current wave forms at different buses after placing DTF at different buses



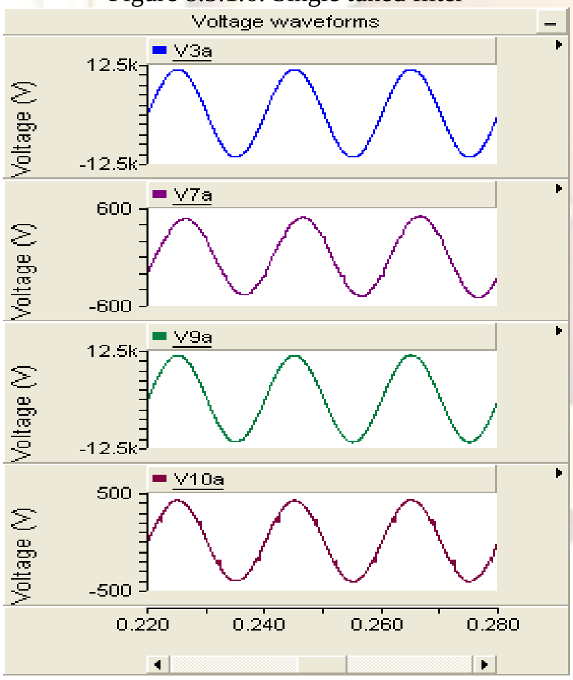
Scale: on X axis = Time (sec)

Figure 8.3.1.5: Current wave forms at different buses after placing ROF at different buses

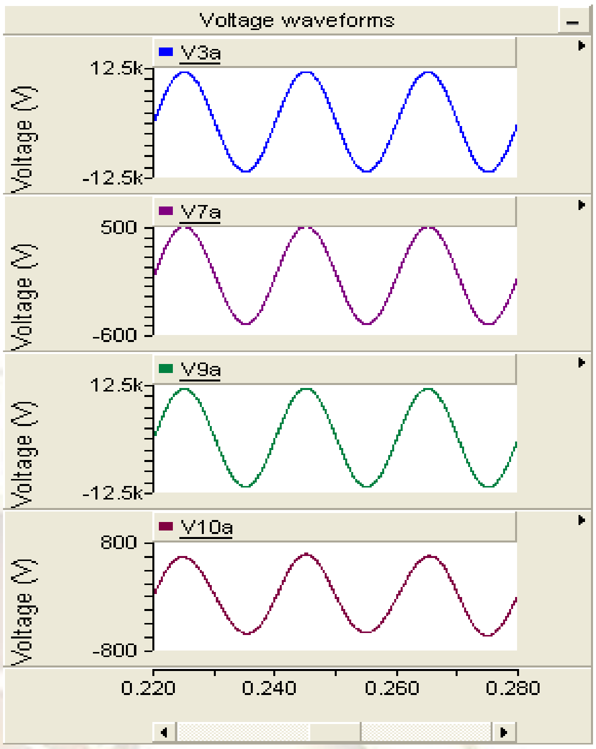
Voltage wave forms at different buses after placing filters (7 and 10th Buses)



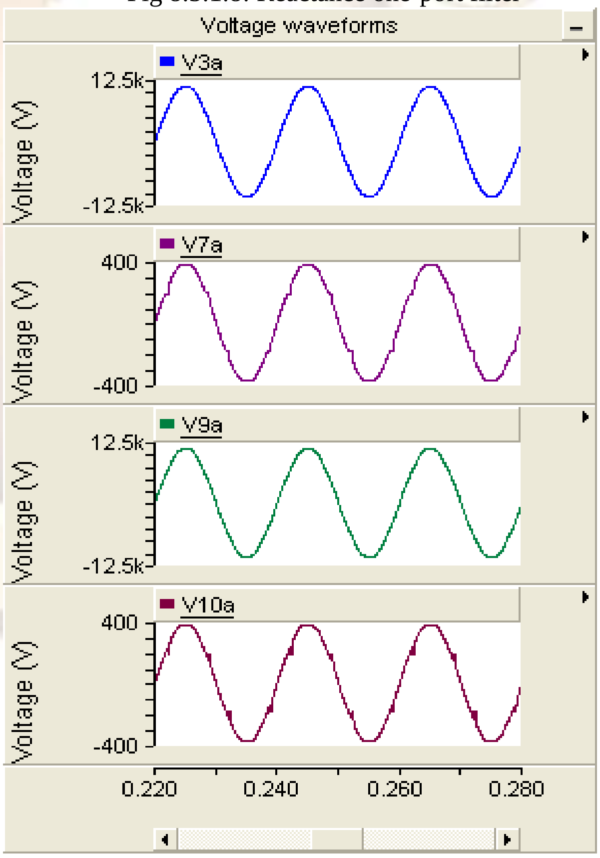
Scale: On X axis = Time (sec)
Figure 8.3.1.6: Single tuned filter



Scale: On X axis = Time (sec)
Figure 8.3.1.7: Double tuned filter



Scale: On X axis = Time (sec)
Fig 8.3.1.8: Reactance one-port filter



Scale: On X axis = Time (sec)
Figure 8.3.1.9: Without any filter

8.3.2. Active Filters

Active filters are having the capability to reduce overall system THD, if we placed it at the PCC bus. Below figures shows how to simulate active filters in PSCAD/EMTDC and its controlling also.

8.3.2.1: Series Active Filter

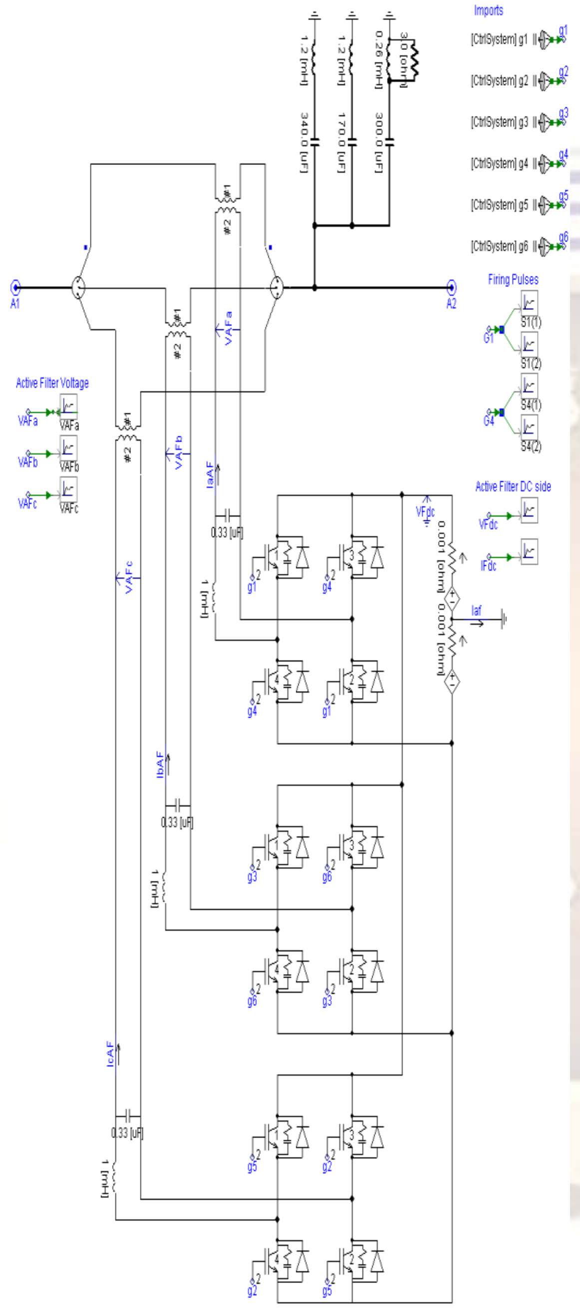


Figure 8.3.2.1.1: Simulation of Series active filter

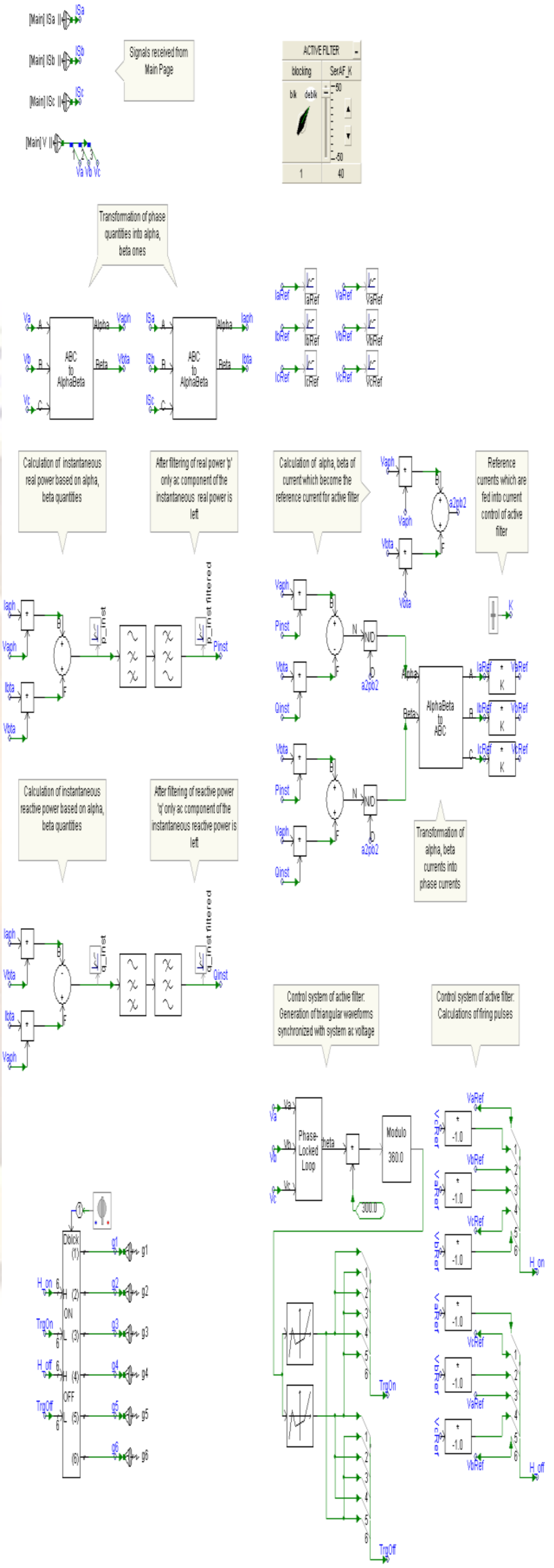
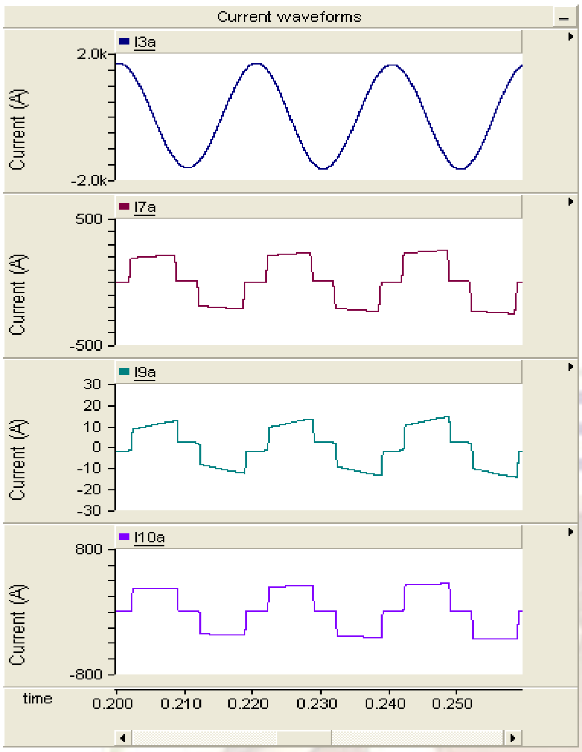
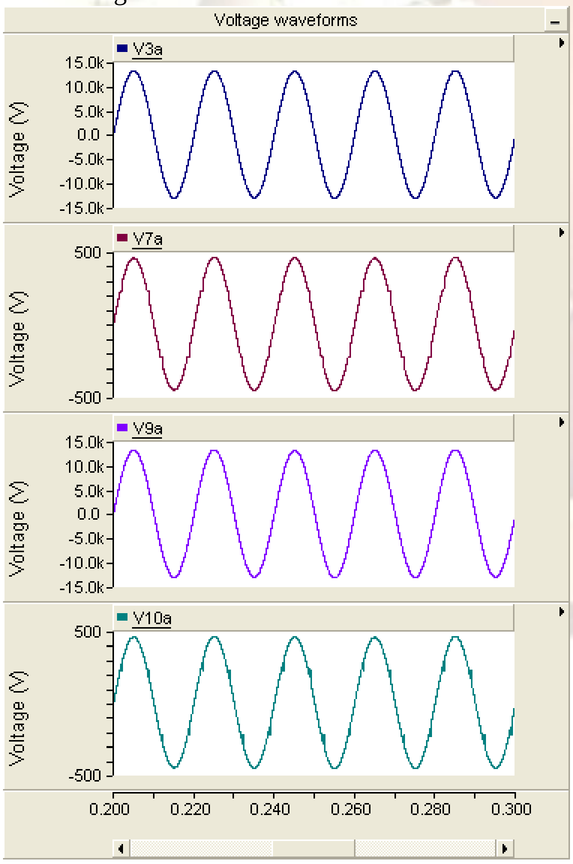


Figure 8.3.2.1.2: Controlling circuit for SeAF



Scale: On X axis = Time (sec)
Figure 8.3.2.1.3: Current wave forms



Scale: On X axis = Time (sec)
Figure 8.3.2.1.4: Voltage wave forms

8.3.2.2: Shunt Active filter (ShAF)

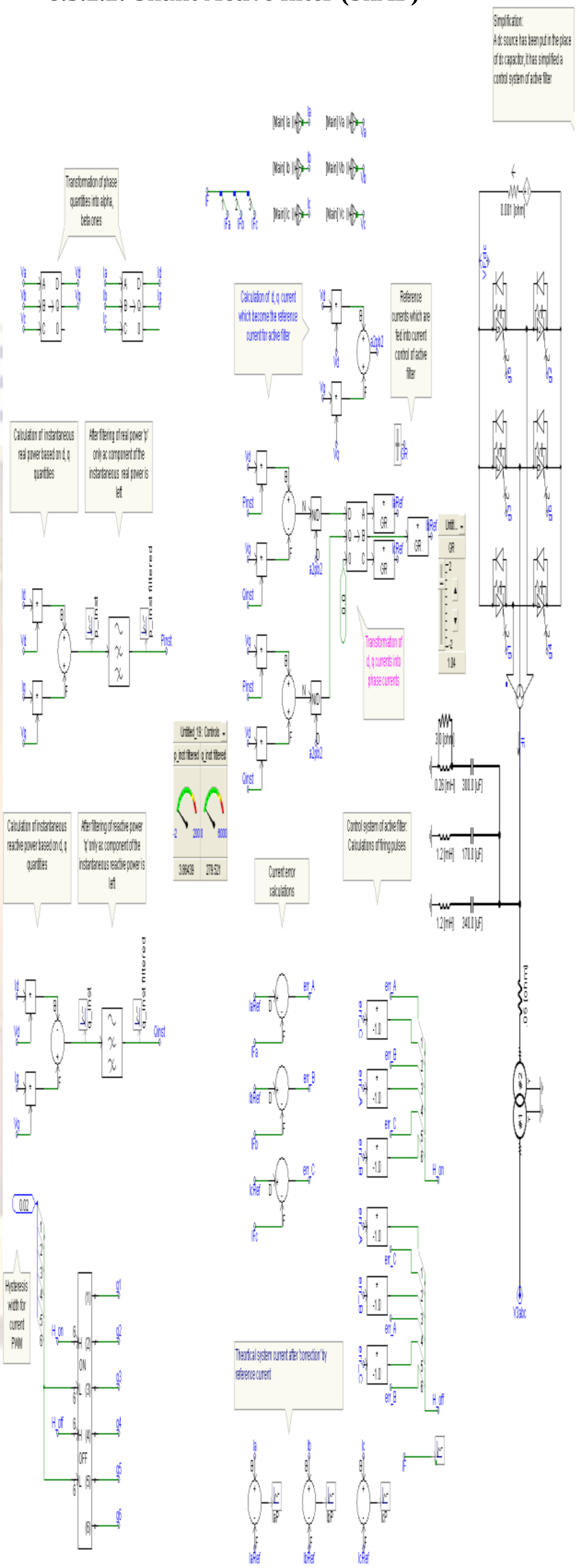
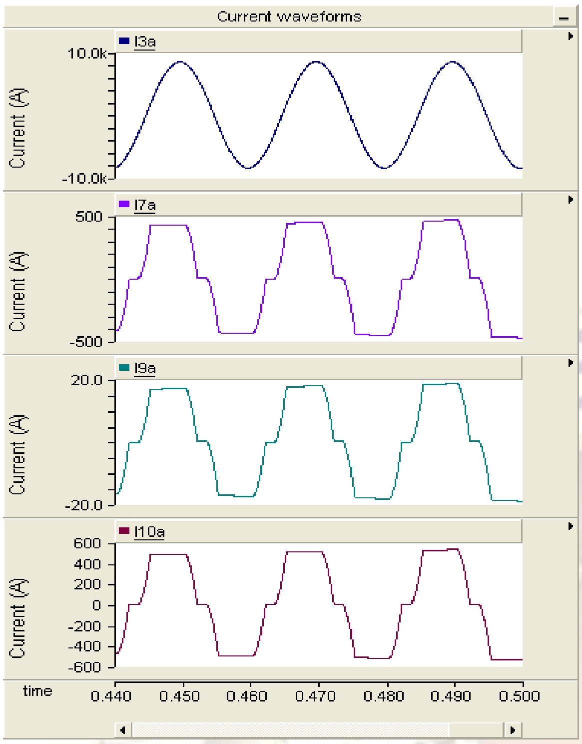
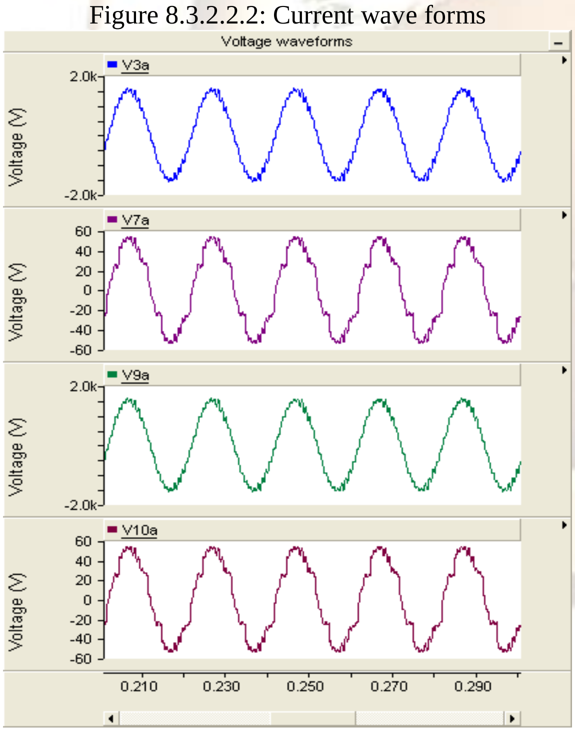


Figure 8.3.2.2.1: Simulation of ShAF in PSCAD/EMTDC

Current and Voltage waveforms after placing Shunt Active filters at PCC



Scale: On X axis = Time (sec)
Figure 8.3.2.2.2: Current wave forms



Scale: On X axis = Time (sec)
Figure 8.3.2.2.3: Voltage wave forms

Filter position	Monitor Bus	Single tuned Filter		Double Tuned filter		Reactance one-port Compensator	
		THDI	THDV	THDI	THDV	THDI	THDV
3	3	3.1902	0.5218	2.2977	0.38599	0.19251	0.11277
	7	25.097	4.7080	25.190	4.22050	25.7845	2.87070
	9	25.856	0.5252	25.957	0.37972	26.0669	0.11314
	10	26.306	5.6862	26.408	5.19652	26.7372	3.35703
7	3	9.6413	1.7411	1.1620	0.36868	6.80886	1.01711
	7	5.1990	3.1426	1.2600	2.68536	0.93137	0.57407
	9	25.723	1.7473	25.616	0.37204	25.7831	1.07712
	10	26.184	6.7128	26.025	5.44070	26.2401	6.13002
10	3	9.0960	1.6478	3.1334	1.12380	6.49529	0.64910
	7	24.991	5.5368	25.199	3.95991	25.1284	4.74791
	9	8.7851	1.6489	1.5361	1.13172	5.60791	0.65116
	10	8.5158	3.8755	1.5343	3.99565	5.58466	4.01910
7 & 10	3	6.1355	1.0769	1.1210	0.253948	5.45765	0.33406
	7	5.4752	2.8413	1.2578	2.72920	1.18869	0.86599
	9	9.2713	1.0793	9.1404	0.254756	6.27693	0.34392
	10	8.9846	3.6516	8.9314	4.59860	6.25104	4.15810

Table 8.3.1.1: THDs at different buses with passive filters placed at different buses

Monitor Bus	Normal		With ShAF		With SeAF	
	THDI	THDV	THDI	THDV	THDI	THDV
3	13.7024	2.5704	0.0923	2.3828	1.5191	0.4324
7	24.8505	6.1663	15.554	17.9257	25.4247	3.8456
9	25.6294	2.5765	15.7201	2.3863	26.0676	0.7809
10	26.9910	7.2989	15.7841	17.1346	26.5899	4.7685

Table 8.3.2.1:THDV & THDI at different buses with Active filter

It can be seen that DTF filter reduces THD better than the STF. This is due to the fact that the DTF eliminate two harmonic components simultaneously as compared to STF which eliminates one harmonic component. Significant reduction of THD is also noticed when the filter is placed at the ASD load buses. Inserting the filters at PCC, 7, 10 and both 7th and 10th succeeded in decreasing the supply current THDI. The supply current along with its harmonic contents before and after inserting the Filters are shown in below figures.

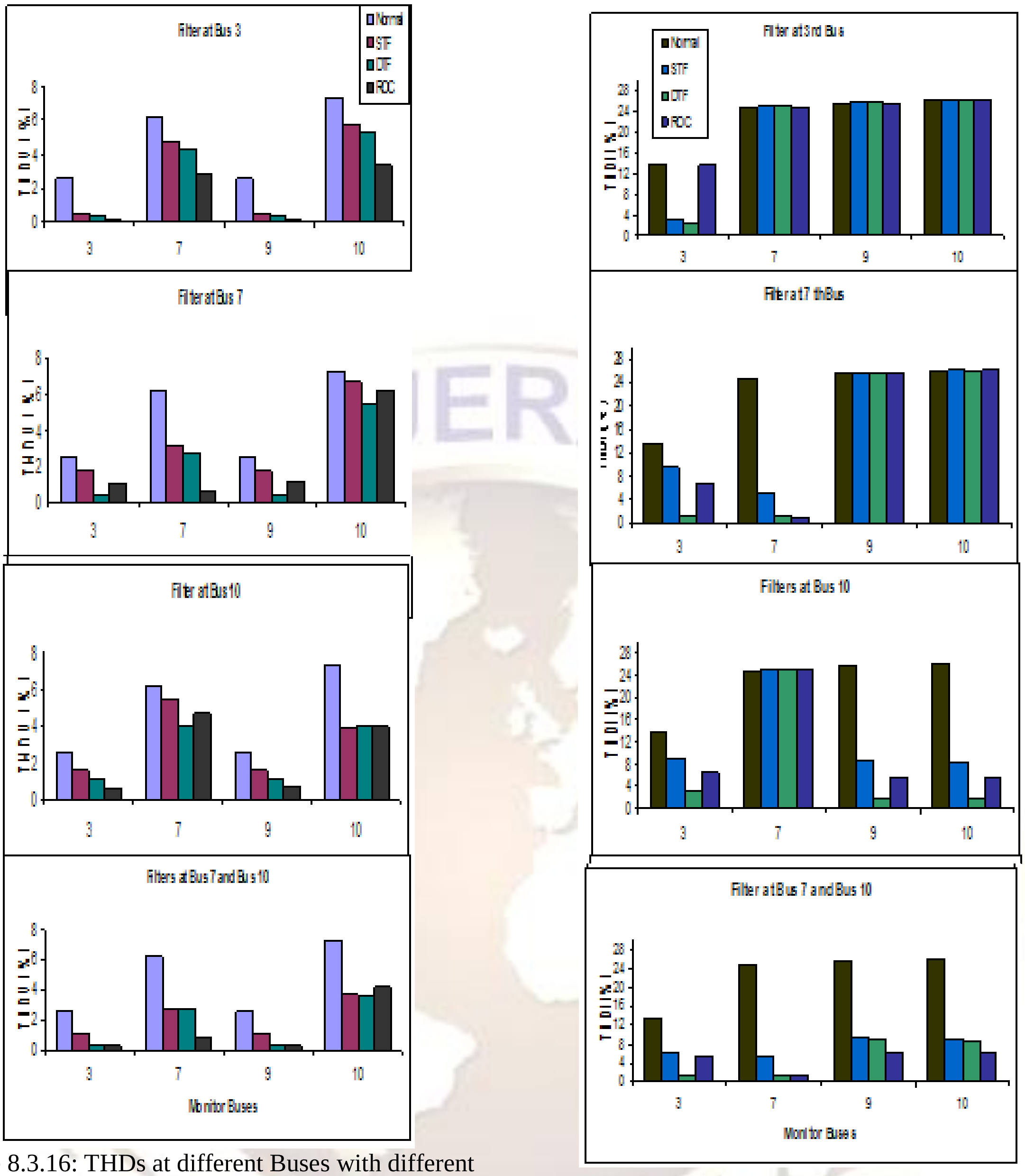


Figure 8.3.16: THDs at different Buses with different Filters in Bar

8.4 Effect on THDs by Parametric Investigation

8.4.1: Different Loading levels

To investigate the load level effect on THD and filter performance, the static loads 1, 2, 3 and 4 at buses are changed to the ratio. ±30% from their rated values. The simulation results showing the effect of changing the static load parameters on harmonic distortion levels are as in Table 8.4.1.1.

From the results shown in Table, it can be observed that by increasing the loads, the harmonic distortion levels or THDs are slightly lower as compared to decreasing the loads. This fact is attributed to attenuation in which by increasing the loads, due to the consideration of both feeders and transformer impedances is increased thereby, decreasing the THD of the system.

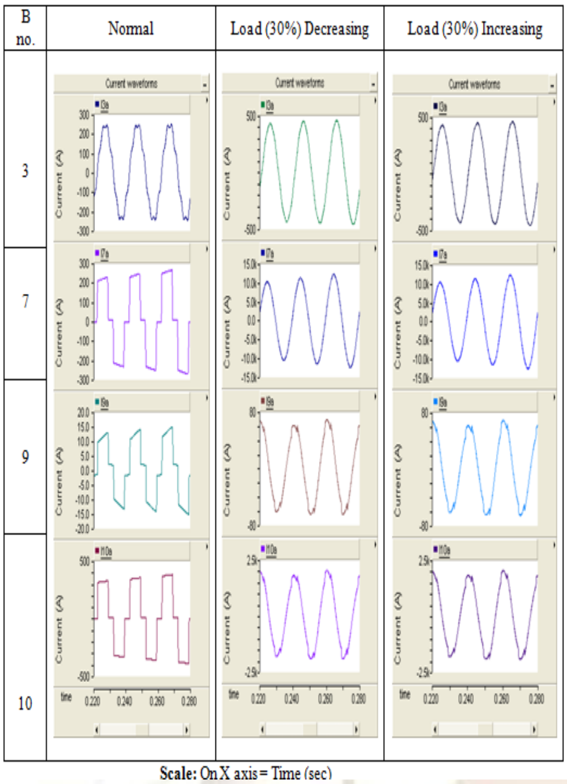


Figure 8.4.1.1: Current waveforms at different loading conditions with DTF placed at 7th & 10th Buses

Table 8.4.1.1: Effect of changing the static load levels on THDs with DTF

F. Pos.	Load (%)	B.no.	R (Ω)	L (H)	THDI (%)			THDV (%)		
					Bus 3	Bus 7	Bus 10	Bus 3	Bus 7	Bus 10
7th	30%↑	3	12.097	0.0954	1.0151	1.256	25.986	0.3383	2.757	5.450
		8	9.8467	0.0270						
		12	0.4509	0.0101						
		13	1.4880	0.0042						
	Rated	3	9.3058	0.0734	1.0418	1.258	25.992	0.3399	2.769	5.460
		8	7.5744	0.0208						
		12	0.3468	0.0078						
		13	1.1446	0.0033						
	30%↓	3	6.8141	0.0514	1.0444	1.262	25.992	0.3373	2.781	5.485
		8	5.3021	0.0145						
		12	0.2428	0.0054						
		13	0.8012	0.0022						
7th & 10th	30%↑	3	12.097	0.0954	1.0195	1.258	8.906	0.2432	2.7911	4.669
		8	9.8467	0.0270						
		12	0.4509	0.0101						
		13	1.4880	0.0042						
	Rated	3	9.3058	0.0734	1.0484	1.258	8.9395	0.2463	2.8017	4.6728
		8	7.5744	0.0208						
		12	0.3468	0.0078						
		13	1.1446	0.0033						
	30%↓	3	6.8141	0.0514	1.0565	1.261	8.997	0.2437	2.8138	4.6943
		8	5.3021	0.0145						
		12	0.2428	0.0054						
		13	0.8012	0.0022						

8.4.2: Changing the source impedance X/R ratio

In order to investigate the effect of changing the X/R ratio of the source internal impedance, the magnitude of the source impedance for different X/R ratios should be kept constant. The distribution system will still be loaded with the same loads that consume the same load percentage. Below figure shows the logic circuit for obtaining the source R, L values for different X/R ratios.

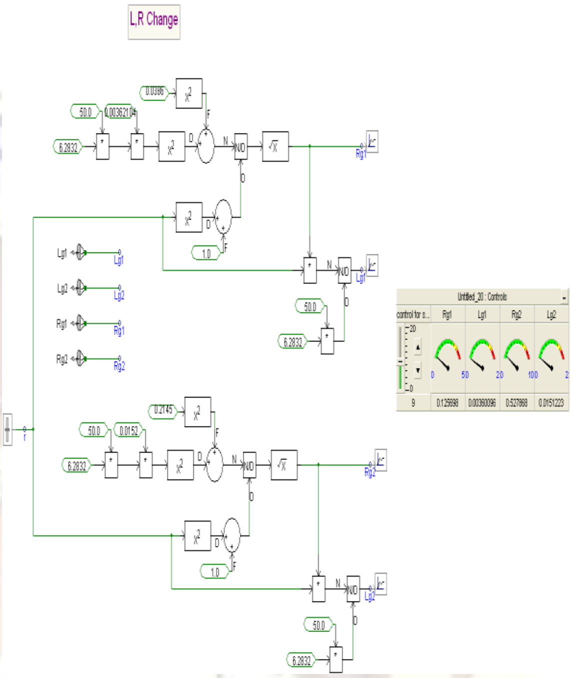


Figure 8.4.2.1: PSCAD logic for changing source impedance X/R ratio

Table 8.4.2.1: Source R, L values for different source X/R ratios

X/R Ratio	13.8kV		69kV	
	R (Ω)	L (mH)	R (Ω)	L (mH)
Normal	0.038600	3.62104	0.21450	15.200
0.5	1.018700	1.62031	4.27540	6.8045
1	0.804858	2.56194	3.38000	10.7589
2	0.504037	3.24062	2.13770	13.6090
4	0.276064	3.51495	1.15933	14.761
6	0.187126	3.57383	0.785835	15.008
8	0.141181	3.59515	0.592892	15.097
10	0.113259	3.60514	0.475632	15.1398

These results show that increasing the source impedance X/R ratio may lead to more harmonic cancellation. Since the phase angle of the source impedance is directly proportional to the

magnitude and phase of the load voltage, changing the X/R ratio will result in different load voltages at different buses. This will take the form of different generated harmonic currents with different phase angles, resulting in more harmonic cancellation among the generated harmonic currents. Also, it must be maintained that for some harmonic orders, increasing the X/R ratio might result in increasing the distortion percentage, since the cancellation depends on the relative phase angle of the perspective harmonic order for different load types.
Below table shows the effect of changing the source impedance X/R ratio on the harmonic levels.

Table 8.4.2.2: Effect of changing the source impedance X/R ratio on THDs

X/R Ratio	3rd Bus		7th Bus		9th Bus		10th Bus	
	THDI	THDV	THDI	THDV	THDI	THDV	THDI	THDV
Normal	13.7	2.5867	24.8464	6.1750	25.6276	2.592	26.0975	7.3093
0.5	4.3619	0.4878	28.0154	4.7392	25.9259	0.4992	26.3846	5.9310
1	6.2704	0.9457	24.9603	5.0483	25.8336	0.9519	26.2931	6.17013
2	11.694	2.1619	24.7929	5.69753	25.7072	2.16839	26.1732	7.04254
4	19.935	3.9544	24.4741	6.79522	25.5012	3.96056	25.9782	8.24867
6	24.282	4.8859	24.2657	7.4568	25.4033	4.8922	25.8873	9.04136
8	26.710	5.4015	24.1496	7.87622	25.3301	5.4784	25.8182	9.50904
10	28.100	5.6960	24.0823	8.14645	25.2821	5.7022	25.7729	9.72447

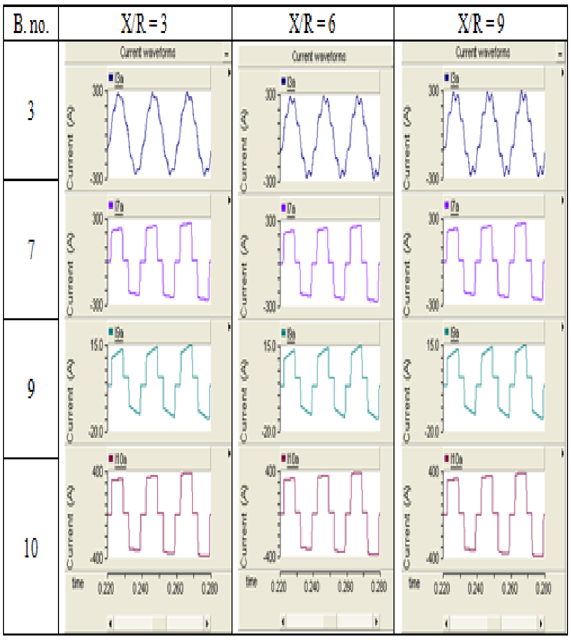
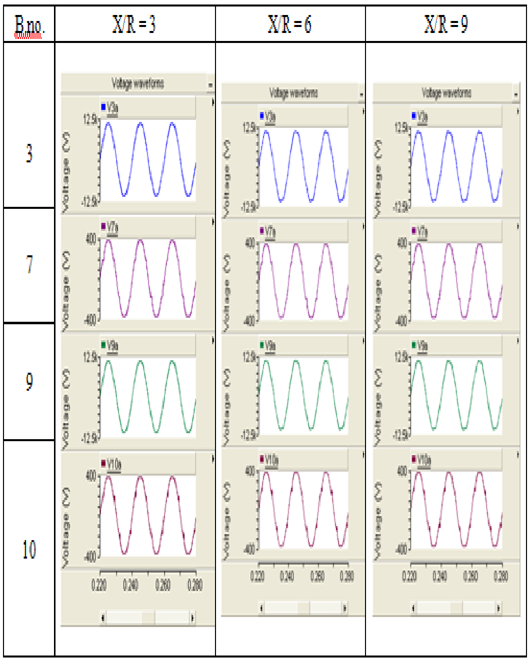


Figure 8.4.2.2: Current wave forms at different buses for different X/R ratios with out Filters



Scale: On X axis = Time (sec)

Figure 8.4.2.3: Voltage wave forms at different buses for different X/R ratios with out Filters

8.4.3: Changing the transformer and feeders X/R ratio

The common X/R ratio of distribution system is always between 1 to 5. The effect of changing this ratio on both voltage and current distortion levels is investigated by changing this ratio by keeping constraint of keeping the percentage impedance of transformer and feeders constant. The results of this scenario are shown in table. This test measurement was done at 3rd, 7th and 10th buses. This results show that as X/R ratio increase the net distortion in the current decreases due to the harmonic phase angle scattering. Varying the X/R ratio will affect the harmonic phase angle of different harmonic orders. X/R ratio In order to investigate the effect of changing the X/R ratio of the source internal impedance, the magnitude of the source impedance for different X/R ratios should be kept constant. The distribution system will still be loaded with the same loads that consume the same load percentage. These results show that increasing the source impedance X/R ratio may lead to more harmonic cancellation. Since the phase angle of the source impedance is directly proportional to the magnitude and phase of the load voltage, changing the X/R ratio will result in different load voltages at different buses. This will take the form of different generated harmonic currents with different phase angles, resulting in more harmonic cancellation among the generated harmonic currents. Also, it must be maintained that for some harmonic orders, increasing the X/R ratio might result in increasing the distortion percentage, since the cancellation depends on the relative phase angle of the perspective harmonic order for different load types.

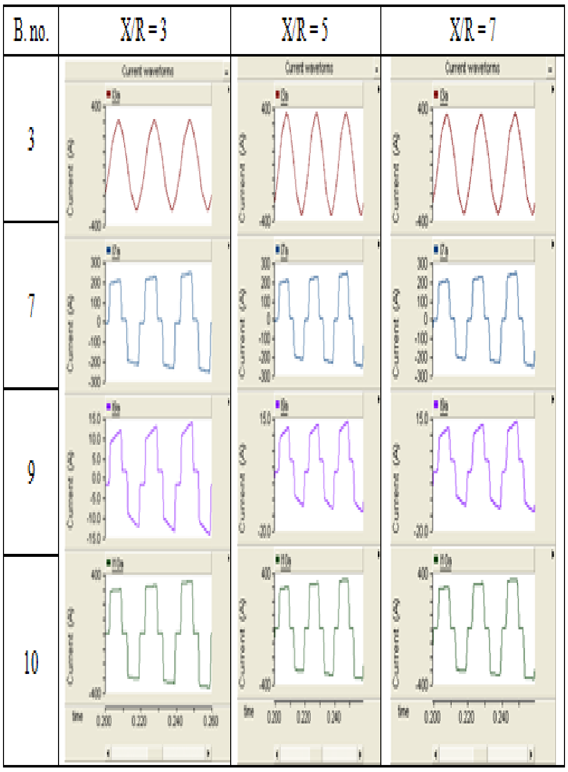
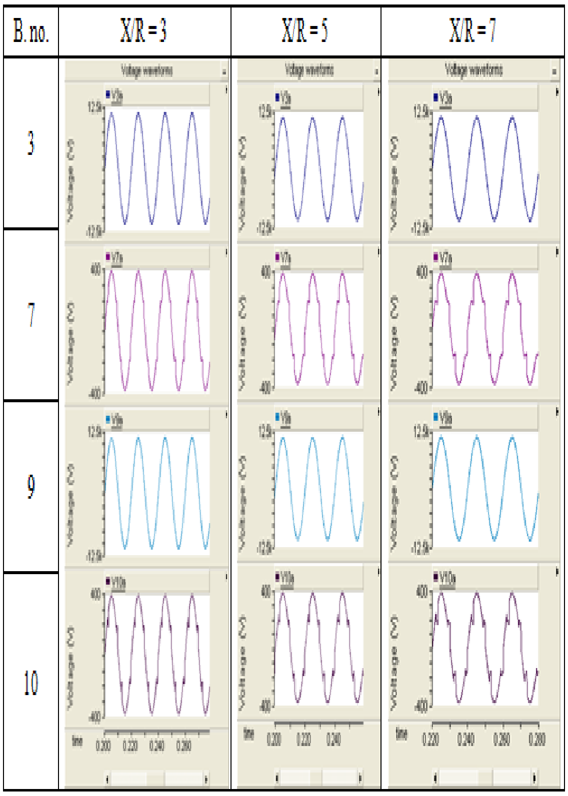


Figure 8.4.3.1: Current wave forms at different buses by changing X/R ratio with out Filters



Scale: On X axis = Time (sec)

Figure 8.4.3.2: Voltage wave forms at different buses by changing X/R ratio with out Filters

Table 8.4.3.1: Effect of changing the Transformer and feeders X/R ratio on THDs with out Filters

X/R Ratio	LP-LQ	R (Ω)	L (mH)	THDI (%)			THDV (%)		
				Bus 3	Bus 7	Bus 10	Bus 3	Bus 7	Bus 10
Normal	1 3	0.2323	0.1474	13.702	24.851	26.099	2.571	6.167	7.298
	3 6	0.0143	0.0382						
	3 9	0.0299	0.0793						
	3 11	0.0208	0.0551						
	5 3	0.0265	0.1795						
3	1 3	0.0164	0.564	7.0405	22.061	22.5844	1.3678	11.102	13.827
	3 6	0.0059	0.0564						
	3 9	0.0123	0.1175						
	3 11	0.0086	0.0817						
	5 3	0.0197	0.1882						
5	1 3	0.0102	0.1616	6.1238	19.596	19.5813	1.2706	15.476	19.03
	3 6	0.0037	0.0583						
	3 9	0.0076	0.1215						
	3 11	0.0053	0.0844						
	5 3	0.0122	0.1945						
7	1 3	0.0073	0.1632	6.0610	17.468	17.1913	1.3111	19.393	23.13
	3 6	0.0026	0.0588						
	3 9	0.0055	0.1226						
	3 11	0.0038	0.0853						
	5 3	0.0088	0.1964						

8.4.4: Changing the Filter positions

Filter location also effect on THDs at different buses. This analysis is done by using shunt active filter, after placing it at different buses FFT analysis is carried out. From that we can observe that after placing shunt active filter at 3rd bus, THDI at different buses are less than to compare with other filter configurations.

8.4.5: Variation in L, C parameters of single tuned filter

Usually, the selection of any passive filter based on economics of the circuit. In practice real component do deviate from their normal values due to initial inaccuracy in fabrication, chemical and mechanical due to ageing. Investigating the filter sensitivity to the deviation of its elements from their normal values will be achieved by allowing the parameter to vary with in certain tolerance. This tolerance is chosen to 5%.

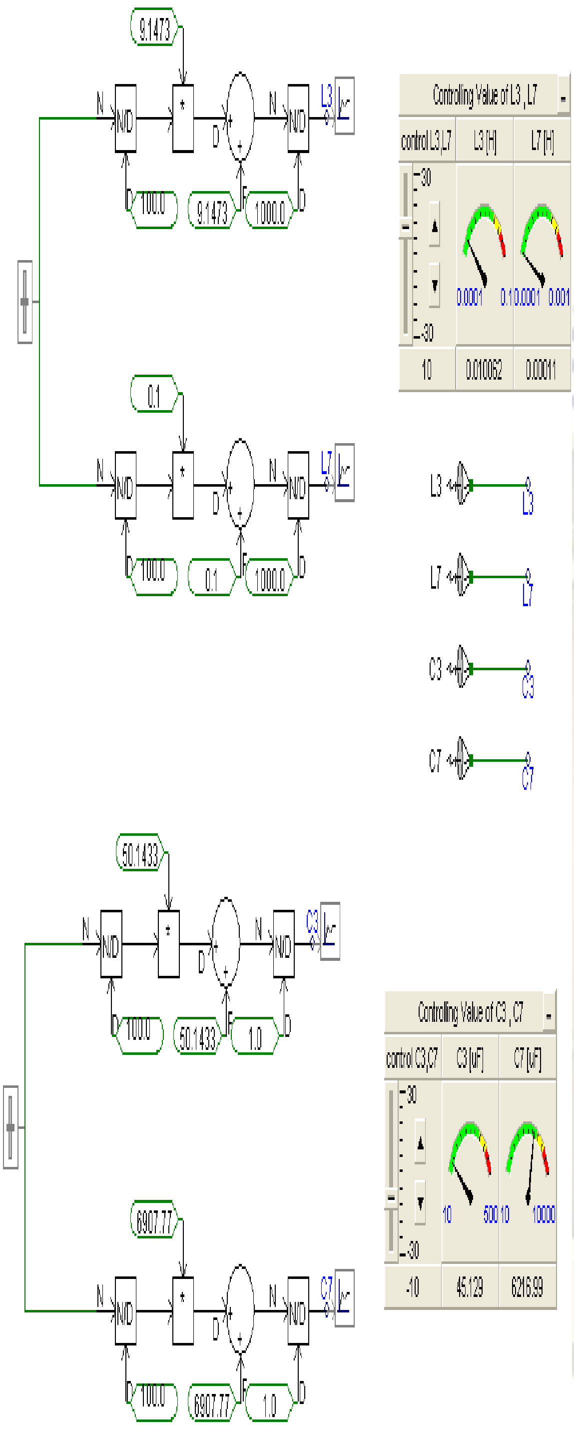


Figure 8.4.5.1: Logic circuit for variations in L and C

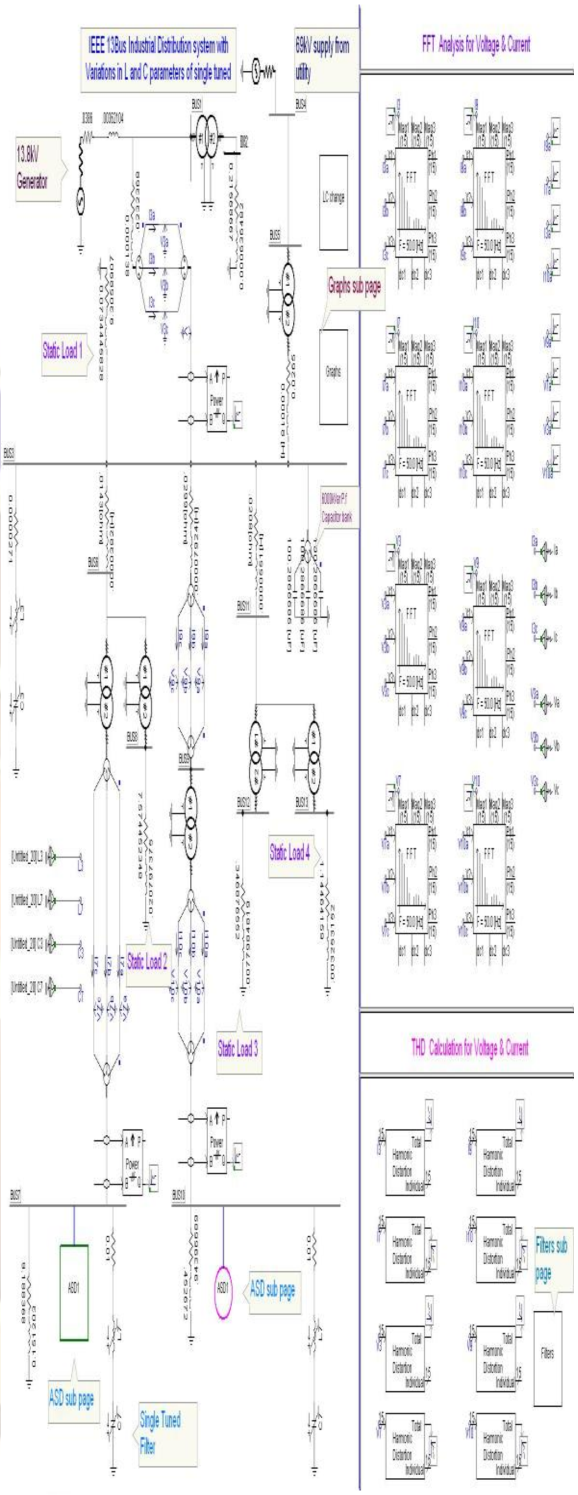


Figure 8.4.5.2: IEEE 13-Bus Industrial Distribution system with variations in L and C (parameters of STF) simulation in PSCAD/EMTDC

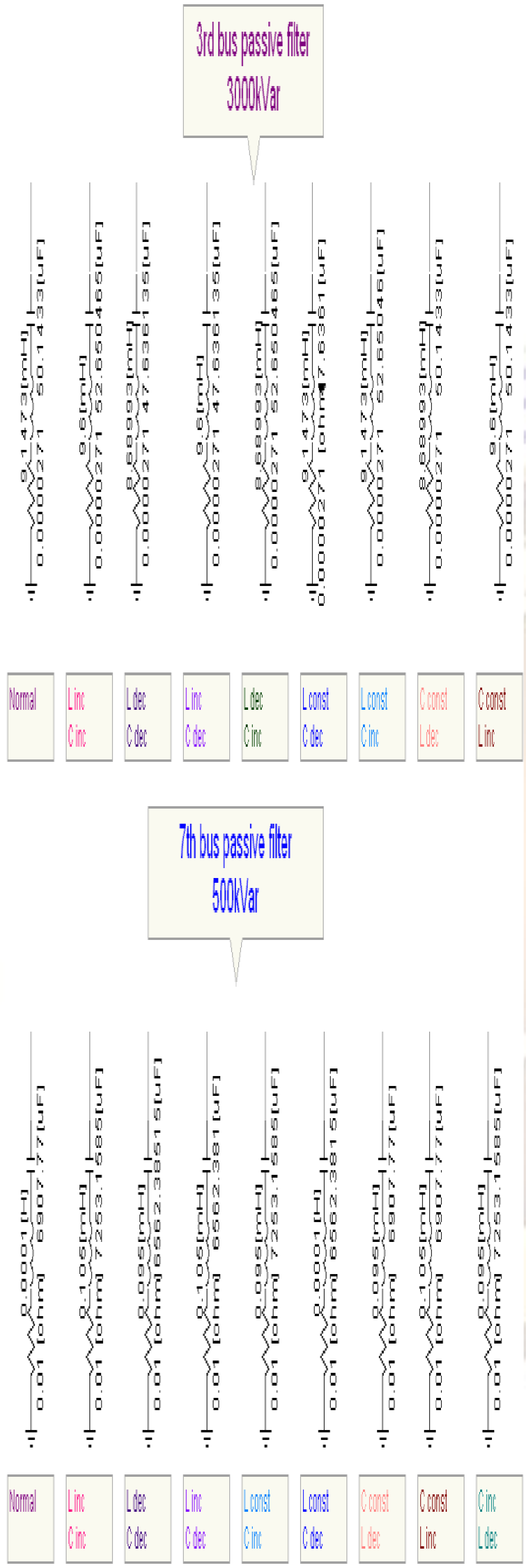
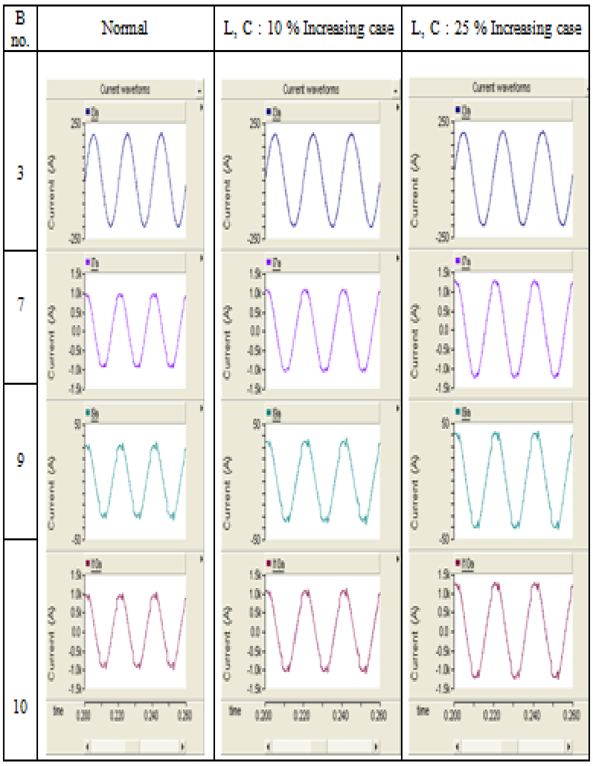


Figure 8.4.5.3: STF configurations for different L, C parameters



Scale: On X axis = Time (sec)

Figure 8.4.5.4: Current wave forms at different buses for different L and C conditions

This study was performed on single tuned passive filter only. The variation in of both THDI and THDV due to the filter elements deviation is given in table7.4.6.1. This table shows the filter is not very sensitive to both elements up to 20% - 25% tolerance value.

8.4.6: Effect of power factor correction capacitor (PFCC)

PFCC is used in industrial power systems to improve system power Factor. A capacitor is normally connected at the PCC to correct the overall plant load power factor. The disadvantage of the capacitor is that it resonates with the system impedance and thus, worsens the harmonic effect. To investigate the resonance effect due to the PFCC, the capacitor at the PCC is de energized and energized accordingly. Table 7.4.7.1 shows the results of THD for both voltage and current when the system is connected with and without PFCC. The results show that THD is lower with the PFCC de energized which is a condition without the PFCC connected.

Table 8.4.5.1: THDs by variation in L, C parameters in single tuned filter

	% Change	THDI			THDV		
		3rd Bus	7th Bus	10th Bus	3rd Bus	7th Bus	10th Bus
	Normal	1.773	6.084	9.662	0.292	2.567	3.303
C↑;L↑	5	2.088	6.109	9.750	0.329	2.667	3.443
	10	2.301	6.095	9.766	0.362	2.771	3.554
	15	2.586	6.051	9.710	0.398	2.878	3.651
	20	2.794	5.981	9.631	0.430	2.96	3.734
	25	3.010	5.843	9.440	0.462	3.018	3.792
C↓;L↓	5	1.518	5.986	9.447	0.254	2.486	3.132
	10	1.289	5.857	9.181	0.226	2.374	2.976
	15	1.413	5.674	8.755	0.223	2.19	2.814
	20	3.719	5.946	8.603	0.445	2.037	2.691
	25	2.156	4.773	7.352	0.275	1.964	2.587
C↑;L↓	5	1.686	5.696	9.128	0.277	2.517	3.201
	10	1.564	5.327	8.612	0.269	2.466	3.108
	15	1.461	4.960	8.094	0.247	2.398	3.017
	20	1.341	4.605	7.576	0.230	2.323	2.924
	25	1.204	4.262	7.072	0.213	2.210	2.859
C↓;L↑	5	1.781	6.483	10.181	0.307	2.619	3.394
	10	1.928	6.900	10.714	0.316	2.678	3.457
	15	1.994	7.323	11.231	0.327	2.734	3.517
	20	2.023	7.779	11.758	0.336	2.783	3.571
	25	2.113	8.233	12.213	0.347	2.832	3.612
C constant L↑	5	1.979	6.384	9.979	0.318	2.645	3.421
	10	2.179	6.501	10.272	0.343	2.733	3.514
	15	2.393	6.677	10.524	0.372	2.827	3.601
	20	2.519	6.861	10.784	0.394	2.912	3.685
	25	2.713	7.002	10.988	0.421	2.983	3.744
C constant L↓	5	1.686	5.696	9.128	0.277	2.517	3.201
	10	1.411	5.619	8.955	0.243	2.425	3.049
	15	1.264	5.352	8.554	0.223	2.336	2.931
	20	1.341	4.605	7.576	0.230	2.323	2.924
	25	1.071	4.731	7.583	0.189	2.078	2.736
C↑; L constant	5	1.887	5.910	9.459	0.309	2.582	3.332
	10	1.977	5.738	9.240	0.314	2.597	3.351
	15	2.051	5.560	9.004	0.323	2.613	3.372
	20	2.075	5.388	8.779	0.329	2.628	3.391
	25	2.157	5.210	8.53	0.338	2.638	3.403
C↓; L constant	5	1.681	6.243	9.838	0.281	2.548	3.269
	10	1.585	6.437	10.01	0.268	2.523	3.228
	15	1.471	6.553	10.114	0.254	2.506	3.179
	20	1.442	6.711	10.186	0.246	2.472	3.118
	25	1.634	6.876	10.242	0.256	2.428	3.050

Table 8.4.6.1: THDs for the case of with and without PFCC

Filter position	Monitor Bus	Double Tuned filter			
		With out PFCC		With PFCC	
		THDI	THDV	THDI	THDV
With out any Filter	3	1.4380	0.40851	13.700	2.56994
	7	24.905	4.96315	24.859	6.16569
	9	25.663	0.41872	25.729	2.57607
	10	26.20	6.06531	26.201	7.2988
7	3	0.774	0.2654	1.1620	0.36868
	7	1.260	2.8759	1.2601	2.68536
	9	25.547	0.2736	25.616	0.37204
	10	25.953	5.4101	26.025	5.4407
10	3	0.966	0.2611	3.13349	1.1238
	7	25.112	4.5106	25.1992	3.95991
	9	1.5223	0.270415	1.53617	1.13172
	10	1.5203	3.62566	1.53434	3.99565
7 & 10	3	0.9628	0.256342	1.12103	0.25395
	7	1.2577	2.88263	1.25786	2.72920
	9	9.1477	0.253714	9.1484	0.25476
	10	9.0372	4.530755	8.93143	4.5986

VIII.CONCLUSION

Linear and non-linear loads are the most sources of harmonic generation. Power electronic devices are introducing non-linear loads in the distribution system resulting in the distortion of current voltage waveforms.

In this project some of domestic loads such as computer, fluorescent lamp, CFL lamp, fan with electronic regulator, and air conditioner are simulated by using PSCAD/EMTDC and Small scale industry loads such as ASD, arc welder, cyclo converter and lift motor are simulated in PSCAD/EMTDC. These models are then used for harmonic analysis of domestic and small scale industrial system to find out THD of voltage and current.

Harmonic analysis is performed for standard IEEE 13-Bus medium voltage industrial distribution system by performing simulation using PSCAD/EMTDC. Harmonics present in that system are found by performing FFT analysis and THDV and THDI values are found at all buses. Harmonic mitigation is performed by using STF, DTF and ROF. Also, use of shunt and series active filters is made for mitigating harmonics at all buses which are placed at PCC. Sensitivity analysis is then performed to analyze the effect on harmonic distribution and filter performance with various load conditions, type of filter we are using, change in filter positions, variation in system or transformer and feeder X/R ratio, small changes in passive filter parameters and effect of power factor correction capacitor.

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