Review of Causes and Effect of Harmonics on Power System

Manish Kumar Soni, Nisheet Soni

Abstract— **This paper is intended to give an overview of harmonic distortion in power system. The pure sinusoidal waveform generated by electrical utilities is distorted by the harmonics produced by the increased use of non linear loads. As saving of electrical energy is the main target of industrial consumer and also utility, the use of energy efficient non linear equipment increases rapidly. The modern industrial system increases use of non linear loads as the control becomes simple, more efficient, accurate and widely available. However, it gives rise to more distortions in current and voltage waveforms on the ac power systems and pollutes the system. Here a survey is made to show details of causes and effect of harmonics present in various types of non linear loads.**

Index Terms— **Harmonics, Non linear loads, THD, TDD, Harmonic Distortion.**

I. INTRODUCTION

The main objective of the electric utility is to deliver sinusoidal voltage at constant magnitude throughout their system. This objective is complicated by the fact that there are loads on the system that produce harmonic currents. These currents result in distorted voltages and currents that can adversely affect the performance of power system in different ways. As the number of harmonic producing loads has increased over the years, it has become necessary to address their influence when making any additions or changes to an installation. To fully appreciate the impact of these phenomena, there are two important concepts to bear in mind with regard to power system harmonics. The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

A harmonic component in a power system is defined as the sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple of the fundamental frequency of the system. It is given by, Fh =h* Fundamental frequency, where h is the integer to be multiplied. If the fundamental frequency is f, then the harmonics have frequency f,2f,3f,4f,5f….Even harmonics are 2f,4f,6f,8f…and odd harmonics are f,3f,4f,5f,7f... Generally even harmonics get cancelled because of their symmetrical nature but odd harmonics should be eliminated by some filtering or compensation techniques.

The harmonic distortion is caused by nonlinear devices in which the current is not proportional to the applied voltage. Figure 1 illustrate the sinusoidal applied voltage to a simple nonlinear resistor in which the applied voltage and current vary according to curve shown. While the applied voltage is perfectly sinusoidal but the resulting current is distorted. By increasing the voltage by a small percentage the current is double and take a different waveform.

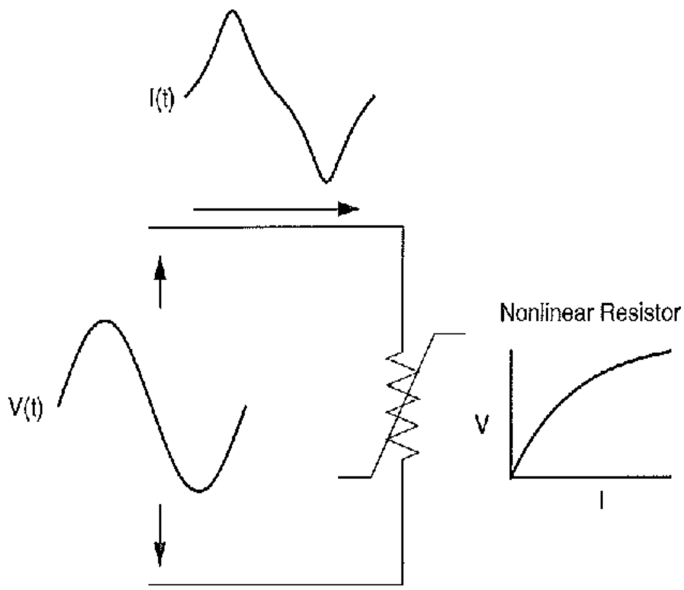

Fig.1. A non linear load drawing current in short pulses

Figure 2 illustrate that any periodic distorted waveform can be expressed by sum of sinusoids of different frequencies in which the frequency of each sinusoids is integer multiple of fundamental frequency. This integer multiple is called harmonic component of fundamental. When both positive and negative half cycle have identical wave shape the fourier series contains only odd harmonics. This offers simplifications for study of power system most harmonic producing devices have both polarities.

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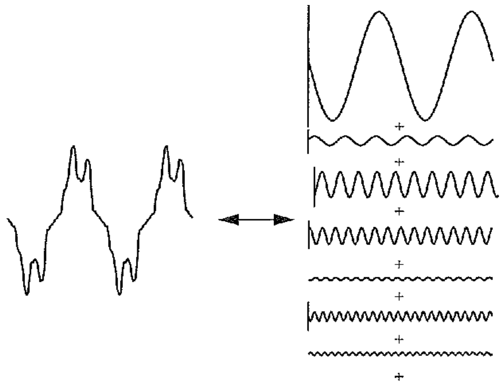

Fig.2 : Fourier series representation of a distorted waveform

Usually, the higher-order harmonics (range from 25th to 50th) are negligible. While it may cause interference with low power electronic devices, but not damaging to the power system. It is also difficult to collect sufficiently accurate data to model power systems at these frequencies because of the occurance of resonance in the system in this frequency range. These resonances can be excited by notching or switching transients in electronic power converters. This causes voltage waveforms with multiple zero crossings which disrupt timing circuits. These resonances generally occur on systems with underground cable but no power factor correction capacitors.

If the power system is depicted as series and shunt elements, as is the conventional practice, the vast majority of the nonlinearities in the system are found in shunt elements (i.e. loads). In transformers, also, the source of harmonics is the shunt branch (magnetizing impedance) of the common "T" model; the leakage impedance is linear. Thus, the main sources of harmonic distortion will ultimately be end-user loads. This is not to say that all end users who experience harmonic distortion will themselves have significant sources of harmonics, but that the harmonic distortion generally originates with some end-user's load or combination of loads.

II. SOURCES OF HARMONICS

Harmonic distortion in power system is generally due to wide spread use of non linear loads. The sources of harmonics can be broadly classified as follows:

A) Harmonic originated at high voltages by supply authorities.

1. HVDC systems
2. Back to back systems
3. Static VAR compensation system.
4. Wind and solar power converters with interconnection.

B) Harmonics originated at medium voltages by large industrial loads like Traction equipment, variable speed drives, Thyristor controlled drives, Induction Heaters, Arc furnaces, Arc welding, Capacitor bank, electronic energy controllers.

C) Harmonic originated at low voltages by consumer end like single phase loadings, uninterrupted power supplier, semiconducting devices, CFL, Solid state devices, domestic appliances and accessories using electric devices, electronic fluorescent chokes, electronic fan regulator , light dimmers.

III. HARMONIC GENERATION MECHANISM

Utility supplies generally pure sinusoidal voltage to the users. The current wave forms of the systems connected to the utility will be sinusoidal only if a linear load like Incandescent bulbs connected to it. However this is not practically possible due to the increased use of nonlinear loads like PC's, UPS, Laser printers, microwave ovens, electronic ballast, process control systems etc. This is due to the non linear characteristic of devices used in equipments drawing current waveform that doesn't follow the voltage waveform.

The total current drawn by the non linear loads is given by.

$$\mathbf{I_T = I_F + I_H}$$

where I_F = Fundamental current
I_H = Total harmonic current.

The circuit draws current only during the peaks of voltage wave form as shown in Figure 2, to charge the capacitor to the peak of the line voltage. This type of power supplies drawing current in short pulses during voltage waveform peak has improved the efficiency of the equipment but at the cost of generating high frequency harmonics. Typical current waveform of a PC measured at the power input is high distortion in current waveform is observed.

A. Harmonic Indices

There are two most commonly used harmonic indices used for measuring the harmonic content of a waveform that are total harmonic distortion and total demand distortion. Both measures the effective value of a waveform and may be applied to either voltage or current.

- Total Harmonic Distortion (THD)

The THD is a measure of the effective value of the harmonic components of a distorted waveform. It is the potential heating value of the harmonics with respect to the fundamental. This index can be used for either voltage or current.

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$$THD = \frac{\left\{\sqrt{\sum_{h>1}^{hmax} M_h^2}\right\}}{M1}$$

where MI, is the RMS value of harmonic component h of the quantity M.

The THD is related to the RMS value of the waveform as follows:

$$RMS = \left\{\sum_{h=1}^{hmax} M_h^2\right\} = M_{1\cdot\sqrt{(1+THD^2)}}$$

The total harmonic distortion is very useful for many application. It provides good idea for how much extra heat generated when a distorted voltage is applied to a resistive load. It also give indication of losses due to current flowing through conductor. But not a good indicator of the voltage stress within a capacitor because it is related to peak value of the voltage waveform. The THD is mostly used to describe harmonic voltage distortion. Harmonic voltage are always referenced to fundamental component of the waveform at the sampling time. Because on varying the fundamental voltage to few percent the voltage THD is nearly a meaningful number.

Variation of the total harmonic distortion over a time follow a distinct pattern representing activity of non linear load in the system. Figure shows harmonic distortion for a period of a week that is taken from 132 KV distribution substation. Figure shows high distortion occurs at night and early morning hours since non linear loads are high as compared to linear load during these hours.

- Total demand distortion (TDD)

The current distortion can be characterized by THD value but this can often misleading. A small current may have high THD value but not significant effect on system. Many adjustable speed drives will exhibit high THD for input current when operating at light loads. This is not significant concern because magnitude of harmonic current is low even though current distortion is high.

Some analyst have attempted to avoid this difficulty by referring total harmonic distortion to total demand distortion that is fundamental of the peak demand load current and serves as the basis for the guidelines in IEEE standard 519 – 1992 recommended practices and requirements for harmonic control in power system.

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L}$$

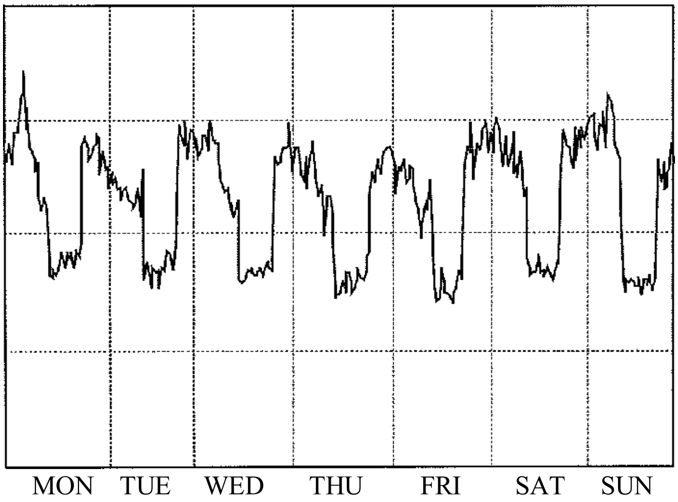

Fig4 : Variation of the voltage THD over a week period

Where, I_L is the peak load current at the fundamental frequency component measured at a point of common coupling (pcc) which is usually at the consumer metering point.

IV. HARMONICS : CAUSES AND EFFECT

In an ideal power system voltage and current waveforms are purely sinusoidal. In practice, non sinusoidal currents result when the current flowing through the load is non linearly related to the applied voltage. In a simple circuit containing only linear circuit elements (resistance, inductance and capacitance), the current which flows is proportional to the applied voltage. So that it results in a sinusoidal current flow. The situation where the load is simple full wave rectifier, current flows only when the supply voltage exceeds that stored on the reservoir capacitor. It says that waveforms tend to distort from the sine wave and this is the cause for harmonics [6]. Non-linear loads create harmonics by drawing current in abrupt short pulses, rather than in a smooth sinusoidal manner [7] as shown in the fig.1.

High levels of harmonic distortion can cause several effects such as increased transformer, capacitor, motor or generator heating, false operation of electronic equipment, incorrect readings on meters, false operation of protective relays, interference with telephone circuits etc. Since harmonic distortion is caused by nonlinear elements connected to the power system, any device that has non-linear characteristics will cause harmonic distortion. Examples of common sources of power system harmonics, some of which never cause serious problems, are: transformer saturation and inrush, transformer neutral connections, MMF distribution in AC rotating machines,

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electric arc furnaces, fluorescent lighting, computer switch mode power supplies, battery chargers, imperfect AC sources, variable frequency motor drives (VFD), inverters, and television power supplies.

V. NON LINEAR LOADS

Due to the changes in the operating conditions and the rapid growth of advanced power conversion devices, electronics equipments, computers, office automation, air-conditioning systems, adjustable speed heating ventilation can cause current distortions. This is due to increase in harmonics drastically. According to the Electric Power Research (EPR) in 1995, 35-40% of all electric power flows through electronic converters. This is expected to increase to 85% by the year 2012. All these devices are named as non linear loads and become sources of harmonics.

VI. SOURCES OF HARMONICS DUE TO DIFFERENT TYPES OF LOADS

A. Harmonic Sources From Commercial load

Commercial facilities such as office complexes, hospitals, internet data centres are dominated with high efficiency fluorescent lightning with electronic ballasts, adjustable speed drives for heating, ventilation and air conditioning loads sensitive electronic equipment and elevator drives supplied by single phase switch mode power supplies. Commercial loads are characterized by large number of small harmonic producing loads. Depending on the diversity of load these small harmonic current may add or cancel each other. The voltage distortion depends on the circuit impedance and harmonic current. The power factor correcting equipments are not used in commercial facility so the circuit impedance is dominated by transformer and conductor impedance. Therefore voltage distortion can be calculated by multiplying the harmonic current by circuit impedance. Different non linear loads with their characteristics are described in following sections.

- Single-phase power supplies

Electronic power converter loads such as adjustable speed drives, electronic power supplies, dc motor drives, battery chargers, electronic ballasts and many other rectifier and inverter are the most important class of non linear loads because of their capacity of producing harmonic currents. A major concern is in the single phase electronic equipments that produces too much harmonic current. The percentage of load contains electronic power supplies increases with the increased use of personal computers. The modern electronic and microprocessor based equipment needs single phase full wave diode rectifier bridge for DC power supply.

There are two common techniques used for single phase supply. One uses ac voltage control methods in which transformer is used to reduce the voltage required for DC bus. The inductance of the transformer provides benefits of smoothing the input current waveform. The second technology uses switched mode power supply for dc to dc conversion to get smooth dc output. The ac line is directly connected to input diode bridge which eliminates transformer. The output dc regulated voltage on the capacitor is converted back to high frequency ac voltage by high speed switches and again rectified. Personal computers, copiers, printers and other single phase electronic devices employ switched mode power supplies. The advantages of switched mode power supplies are compact size, light weight, efficient operation and no need of transformers. The switched mode powers supply can tolerate large variation in input voltage.

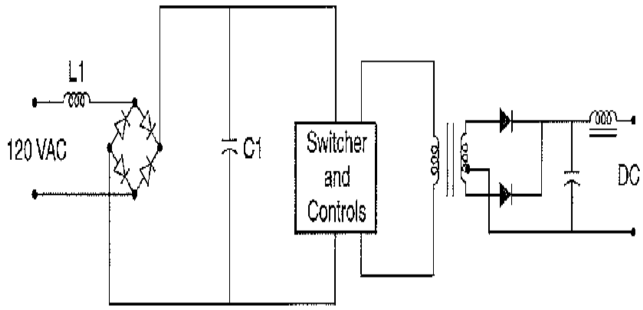

Fig 5 : Switch mode power supply

The switched mode power supply rich in third harmonic current. The third harmonic currents are additive nature in neutral of the three phase system so it causes increasing concern in overloading of the neutral conductors specially in older building where undersized neutral has been installed. There is also transformer overheating problem due to harmonic current, stray flux and high neutral current.

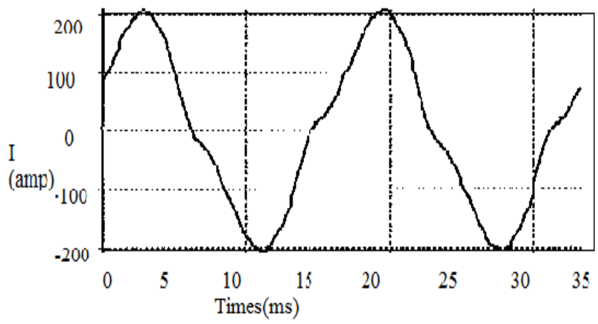

Fig 6 : Switch mode power supply current

- Fluorescent Lightning

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Lighting typically accounts for 40 to 60 percent of a commercial building load. According to the 1995 Commercial Buildings Energy Consumption study conducted by the U.S. Energy Information Administration, fluorescent lighting was used on 77 percent of commercial floor spaces, while only 14 percent of the spaces used incandescent lighting.' Fluorescent lights are a popular choice for energy savings.

Fluorescent lights are discharge lamps; it require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge in the tube is established, the voltage decreases as the arc current increases. It is essentially a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, a ballast is also a current limiting device in lighting applications.

There are two types of ballasts namely magnetic and electronic. The magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. A single magnetic ballast can drive one or two fluorescent lamps and it operates at fundamental frequency, i.e., 50Hz. The iron-core magnetic ballast causes additional heat losses which makes it inefficient as compared to an electronic ballast.

An electronic ballast employs a switch mode type power supply to convert the fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. This high frequency has two advantages. First, a small inductor is sufficient to limit the arc current. Second, the high frequency eliminates or greatly reduces flickering associated with an iron core magnetic ballast.

B. Harmonic Sources From Industrial loads

In Modern industry there are wide spread application of nonlinear loads. These non linear loads inject harmonic currents into the power system that causes harmonic distortion in the voltage. These nonlinear loads have a relatively low power factor. To improve the power factor industrial facilities often utilize capacitor banks to avoid penalty charges. The application of power factor correction capacitors can potentially magnify harmonic currents from the nonlinear loads, giving rise to resonance conditions within the facility. The highest voltage distortion level usually occurs at the facility's low-voltage bus where the capacitors are applied. Resonance conditions cause motor and transformer overheating, and maloperation of sensitive electronic equipment.

- Three phase power electronic converters

Three phase power electronic converters differ from single-phase converters because they do not generate third harmonic currents. This is a great advantage because the third harmonic current is the largest component of harmonics. However, they can still be significant source of harmonics at their characteristic frequencies.

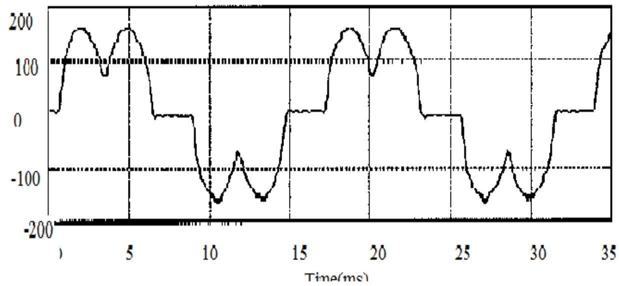

Fig 7 : Current spectrum for CSI type ASD

- Saturable devices

Transformers and other electromagnetic devices with a steel core, including motors come on this category. Harmonics are generated due to the nonlinear magnetizing characteristics of the steel (Fig.8).

Power transformers are designed normally to operate just below the "knee" point of the magnetizing saturation curve. The operating flux density of a transformer is selected based on a complicated optimization of steel cost, no-load losses, noise, and numerous other factors. Many electric utilities will penalize transformer vendors by various amounts for no-load and load losses, and the vendor will try to meet the specification with a transformer that has the lowest evaluated cost. A high-cost penalty on the no-load losses or noise will generally result in more steel in the core and a higher saturation curve that yields lower harmonic currents.

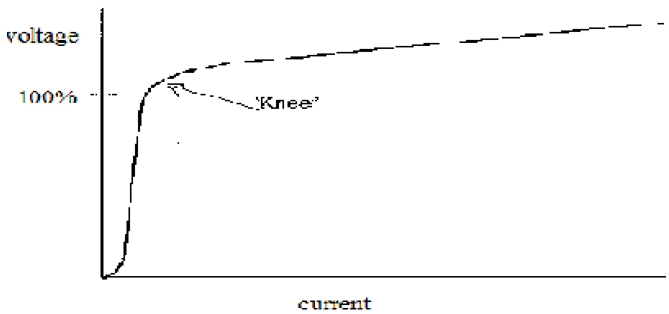

Fig 8: Transformer magnetizing characteristic

Although transformer exciting current is rich in harmonics at normal operating voltage it is typically less than 1 percent of rated full load current. However, their effect will be noticeable on utility distribution systems where there are hundreds of transformer. It is common to notice a significant increase in triplen harmonic currents during the early morning hours when the load is low and the voltage rises. At this condition transformer exciting current is more visible because there is insufficient load to obscure it and the

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increased voltage causes more current to be produced. Harmonic voltage distortion from transformer over excitation is generally apparent only under the light load conditions.

Some transformers are operated in the saturation region. One example is a triplen transformer which is used to generate 180 Hz for induction furnace. Motors also exhibit some distortion in the current when overexcited, although it is generally of little consequence. There are, however, some fractional horsepower, single phase motors that have a nearly triangular waveform with significant third harmonic currents .

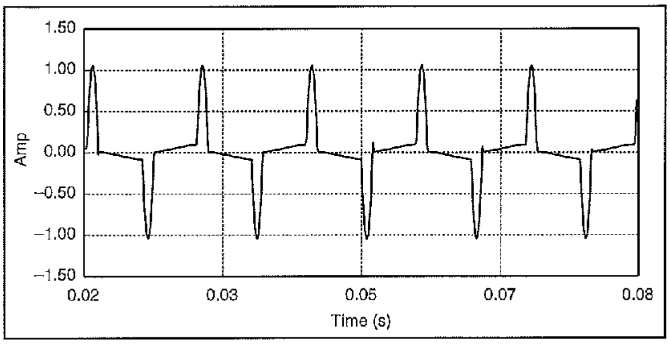

Fig 9: Transformer magnetizing current and harmonics

VII. SOLUTIONS FOR MINIMISING HARMONIC CURRENT EFFECT

A. Over-sizing or derating of die installation

This solution does not eliminate harmonic currents flowing in the low voltage (less than 1KV AC) distribution system but masks the problem and avoid the consequences. The most widely implemented solution is over-sizing of the neutral conductor. In existing installation, the solution is to derate the electrical distribution equipment subjected to the harmonic currents.

B. Specially connected Transformers

This solution eliminates third order harmonic currents. It is a centralized solution for a set of single phase loads.

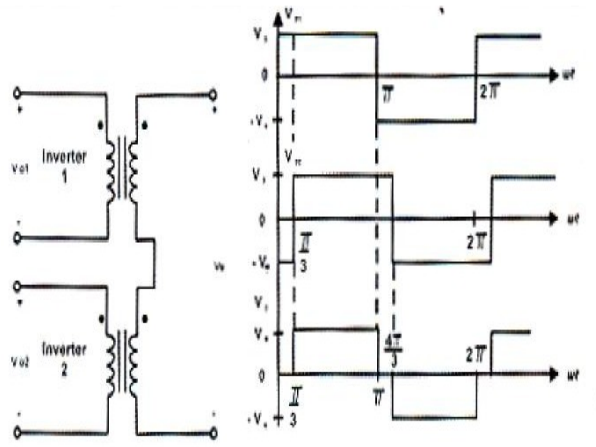

Fig 10: specially connected Transformers

C. Series Reactors

This solution consists of connecting a series reactor with non linear loads.

D. Tuned passive Filter

A filter may be installed for one load or a set of loads. The filter rating must be coordinated with the reactive power requirements of the load.

E. Active harmonic Filter

The active harmonic fillers are used to introduce current component to cancel harmonic components of the non linear loads. There are different types of active harmonic filters such as Series filter, shunt filter and hybrid filter.

The newest technology available for mitigation of harmonics is the active filter. Active filtering techniques can be applied either as a standalone harmonic filter or by incorporating the technology into the rectifier stage of a drive, UPS or other power electronics equipment.

Typically, active filters will monitor the load currents, filter out the fundamental frequency currents, analyze the frequency and magnitude content of the remainder, and then inject the appropriate equal and opposite currents to cancel the individual harmonics. Active filters will normally cancel harmonics up to about 50th harmonic and can achieve harmonic distortion levels as low as 5% THD-I or less. To apply active harmonic filters, determine the magnitude of harmonics (by measurement) that to be remove from the system and select an active filter with suitable harmonic current cancellation capacity.

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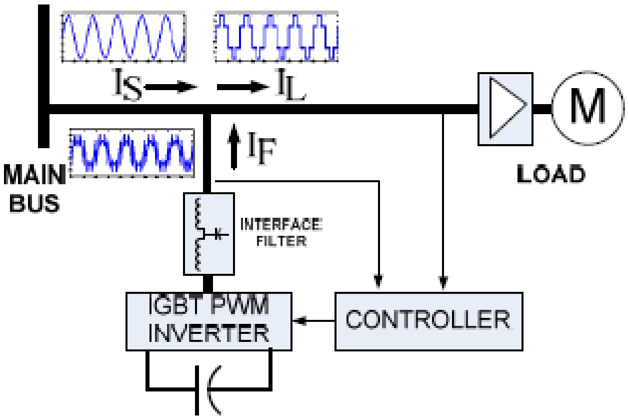

Fig.11. Shunt Active Filter

Active filters utilize power electronics circuitry and therefore maintenance requirement can be higher than for passive solutions and may be similar to that for a variable frequency drive. The losses associated with active filters also tend to be higher than for passive solutions. In terms of harmonic cancellation current, the prices of active filters can range from about $30,000 (50 amps) to $100,000 (300 amps).

VIII. CONCLUSION

This paper present a survey of harmonics distortion in the voltage and current waveforms with an objective to know the existing level of harmonic distortion present in the Power System and future trends. Harmonics injected by some commonly used nonlinear loads are studied. It is observed that significant distortion in the current exists due to the use of computers and other electronic equipments in residential and commercial areas too. Increasing use of these equipments may result in serious problems in near future. The current distortion differs widely from one section to the next. Although, voltage distortion is recorded below the acceptable limit, but it is found above the recommended limit at the places of high current distortion, as it depends on the circuit impedance as well as harmonic generation characteristics. Significant distortion in the current is recorded at customer end with high percentage of 5th and 7th harmonic components.

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