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Research paper

A Survey on Harmonic Mitigation Techniques in Power System

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Abstract

In recent years, one of the most frightening criteria in power system is the generation of harmonics, due to the advancement in power semiconductor devices. Today most of the commercial, residential and industrial loads include advanced semiconductor technology and the utility of these non-linear loads results in harmonics generation on consumer's premises. These harmonics plays a vital role in polluting the power quality of a distribution network by introducing losses which results in the failure of distribution side electrical equipment like transformer, protection, measuring devices, distribution feeders and so on. Hence to enhance the power quality, harmonic mitigation technique should be implemented in a distribution network. This paper surveys about the availability of various harmonic mitigation techniques with the analysis of its merits and demerits.

Keywords: *Harmonic mitigation Techniques, Distribution network, Power quality.*

1. Introduction

Electricity plays a major role in the day to day life of each and every citizen of the world. None of us can sustain without electricity. In order to fulfil the needs of every consumer, it is necessary that a power utility company should supply a quality power with fundamental voltage and current waveform of specified frequency range [1]. Generally, the electrical loads are classified under two categories as linear loads and Non-linear Loads [2]. A load is said to be linear if it obey ohms law as well as the applied voltage and current are directly proportional to each other whereas a load is said to be Non-linear if it doesn't obey ohms law and also the voltage and current are not in direct proportion with each other. Most of the power electronic devices and converters are non-linear in nature. When these non-linear devices are utilised as loads in a system, they generates non-sinusoidal voltage and current waveforms. This non-sinusoidal waveform injects harmonics in the system that tries to interact with the impedance of the distribution system which in turn distort the voltage and current waveforms at customer end. Let us see the definition for harmonics as per IEEE 519 -1992 regulation, "Harmonic is defined as a voltage or current waveform that superimposed with the sinusoidal current or voltage waveform with an integral multiple of frequency which is higher than that of the fundamental frequency"

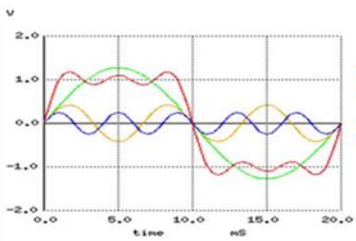

Fig.1 Voltage Harmonic Waveform

Fig.1 interprets the voltage harmonic waveform with different distorted and harmonic voltages. Green colour waveform represents the sinusoidal voltage waveform with fundamental frequency of 50 Hz. Yellow and Blue colour waveforms are also sinusoidal waveform but they are with higher order harmonics of 150 Hz and 250 Hz respectively. They indicate the 3^{rd} and 5^{th} order harmonic propagated in the system because of non-linear loads. Red colour waveform represents the distorted waveform.

This paper reviews about the harmonics, tolerances for standard current and voltage quantities to be operated in a distribution network and various mitigation techniques used to enhance power quality by reducing harmonic content in the system. In Part 2 harmonic study, Sources of harmonics, and operating tolerances for voltage and current quantities are discussed and the values are tabulated as per IEEE 519-2014 standard. In part 3 effects of harmonics in power system and its remedies are explained. Part 4 deals with various harmonic mitigation techniques followed by comparison of techniques in part 5 and conclusion in part 6.

2. Harmonic Study

The already known factor about harmonics is that it is not any drop or rise in voltage or current quantities. Also it is not injected by any oscillations, transients or sudden occurrence of spikes in the system. It is just a simple deviation from the existing sinusoidal signal with the frequency as multiples of primary frequency. The presence of harmonics in a periodic waveform is measured by the percentage of fundamental frequency. The generated harmonics are named as 3^{rd} order, 5^{th} order, 7^{th}order and so on [3]. Thus a periodic sinusoidal waveform with harmonic orders can be expressed by the following equation.

$$f(t) = \frac{a_0}{2} + \sum_{n=0}^{\infty} \left(a_n \cos\frac{n\pi t}{T} + b_n \sin\frac{n\pi t}{T} \right) \quad (1)$$

$$a_n = \frac{1}{T}\int_{-T}^{T} f(t)\cos(n\pi \frac{t}{T})\, dt \quad (2)$$

$$b_n = \frac{1}{T}\int_{-T}^{T} f(t)\sin(n\pi \frac{t}{T})\, dt \quad (3)$$

In the above equations,
f(t) represents the time domain function.
n represents the harmonic index.
T represents the time period in Sec.

Hence, harmonics are nothing but the distortion in the voltage, current and power waveforms. This distortion can be measured on the percentage basis which can be termed as THD (Total Harmonic Distortion) [4-5]. THD is defined as the ratio of square root of squares of harmonic voltages to the fundamental voltage as in Eqn.no.4.

$$\%THD = \frac{\sqrt{\Sigma({V_{hn}}^2)}}{V_f} \times 100 \quad (4)$$

Where,

V_{hn} - Harmonic voltages
n - varies from 2 to N^{th} order harmonic
V_f - Fundamental Voltage

2.1 Sources of Harmonics

Fig.2 shows the major sources for the generation of harmonics in power system. I_S represents the source current and I_H represents the harmonic current that is the non-linear current circulating in the system generated because of the non-linear loads. Here the AC supply voltage is fed to the system and harmonic injecting sources are explained below [6].Electronic Switching devices: All electronic switching devices involve the utility of semiconductor devices.It is not necessary that all the switching devices should synchronize with the supply voltage. Due to lack of synchronization harmonics are generated in the system. Examples: Rectifiers, thyristor controlled devices, all power converters, Variable Frequency Drives and so on. Non-linear Loads: These are the loads where the current and voltage are not in proportion with each other. Though these loads are energized by fundamental sinusoidal supply voltage, the non-linearity property leads to the generation of harmonics in the system. Examples: Arcing devices, fluorescent lamps, rotating machines, Transformers, household appliances etc.,

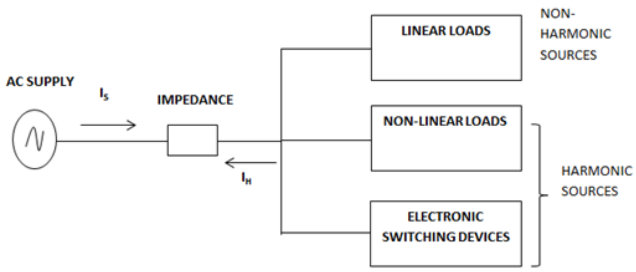

Fig.2 Sources of harmonics

2.2 Operating limits for voltage and current quantities in power system

Because of the propagation of harmonics in the power system, the voltage and current parameters got distorted. As per IEEE 519 – 2014 regulations there is a limit for these distortions that is given in the following table no.1 and 2.

Table.1 Distortion limits for voltage

Voltage Values	Individual harmonic in %	THD in %
V≤1kV	5	8
1kV<V≤ 69kV	3	5
69kV<V≤161kV	1.5	2.5
V>161kV	1	1.5^2

Table.2 Distortion limits for current from 120V through 69kV

Maximum harmonic current distortion of I_L in %						
Individual Harmonic order (Odd Harmonics)						
I_{SC}/I_L	**3≤h <11**	**11≤h <17**	**17≤h <23**	**23≤h <35**	**35≤h ≤50**	**TDD**
<20	4	2	1.5	0.6	0.3	5
20 <50	7	3.5	2.5	1	0.5	8
50 <100	10	4.5	4	1.5	0.7	12
100 <1000	12	5.5	5	2	1	15
<1000	15	7	6	2.5	1.4	20

Where I_{SC} - Maximum Short-Circuit Current
I_L – Maximum demand Load Current

3. Effects of Harmonics in Power System

The effect of harmonics in power system has been perceived from the 19th century onwards [7]. Now a day, the effect of harmonics got increased due to technology improvement in the field of power electronics, industrial and residential automation. Thus wide power distortions are happening in the present scenario which leads the way for poor power quality. Due to these power distortions the electrical equipment connected in power transmission and distribution networks are subjected to impoverished working condition such as distortion in real power [8], reduces the efficiency of motors, generators and transformers connected in the network, increases the losses in the system, interrupts the activation of protection relay [9], results in excess heating of transformers, neutral conductors, tripping of circuit breakers [10], capacitor bank failure, telephone circuitry interferences and also results in resonance when the harmonic frequency is merely equivalent to the system's natural frequency. Thus the different problems encountered in due reason of harmonics is listed in below Table no.3 [11-15].

Table.3 Effects of harmonics in power system

S.NO	Equipment Name	Complications due to harmonic propagation in power system
1	Transmission line	Increase in percentage level of THD in receiving end when compared with the sending end.
2	Electrical Equipment	Poor power quality
3	Transformers	1. Excess heat generation due to high load current 2. Occurrence of resonance due to interaction between transformer inductance and system capacitance. 3. Insulation failures because of vibration and overheating
4	Rotating Machines	Results in vibrations, Excess heating and abrasive sounds by distorted voltage and current.
5	Consumer Loads	Experiences potential damage because of distorted parameters.
6	Capacitor banks	Dielectric breakdown and overloading of reactive power.
7	Insulated Cables	Over voltage causes dielectric breakdown.
8	Conductors	Increases skin effect and proximity effect
9	Fuses and Protecting Devices	1. Reduces the interruption capability which in turn affects the lifetime of the equipment. 2. Malfunction of Relays and Circuit Breakers.

10	Inductance / Capacitance	Resonance problems results in interaction with communication networks.
11	Measuring Devices	1. Inaccurate measurement. 2. Unreliable. 3. Failure of meters.
12	Controllers and Excitation Systems	Non-Uniform Output.
13	Firing Circuits for Switching Devices	Unstable Operation
14	Electronic Equipment	1. Repeated Zero Crossing Detections that increases the switching time of the devices connected in the circuit. 2. Increases switching losses. 3. Faulty operation of the switches.
15	Lighting	Lamps are sensitive to voltage variations. So, distorted voltage and current reduces the lifetime of the lamps and results in overheating.

a. Countermeasures for reducing Harmonics

From the above discussions it is clear that the presence of harmonics spread in the power system results in failures, losses and malfunctioning of many electrical and electronic equipment connected in the system. Minimizing these harmonics is necessary to safeguard the equipment as well as to reduce the electricity bill of particular concern [16]. So, a specially designed system should be introduced in the power system to reduce the effect of harmonics. But as per our old phrases like prevention is better than cure, some specific methodologies should be made in the manufacturing stage itself. By practicing this we can reduce the harmonics of power system to some extent [17]. The steps to be considered during the manufacturing process are given below.

1. The electrical equipment used in the system should be designed in such a way to prevent equipment damage due to harmonics.
2. Harmonic analysis is required to determine the causes of them on equipment so that we can conceive solutions for that.
3. We know that for transferring any cause some medium is required so diagnosis and eradication of that harmonic propagating medium is required.
4. Introduction of power conditioning technique is used to reduce harmonics.

There is occurrence of low level and high level harmonics in the system. To reduce the harmonic effects completely some methodology should be followed. There are two major methods to eliminate the harmonics. They are

1. Harmonic cancellation techniques.
2. Filtering techniques.

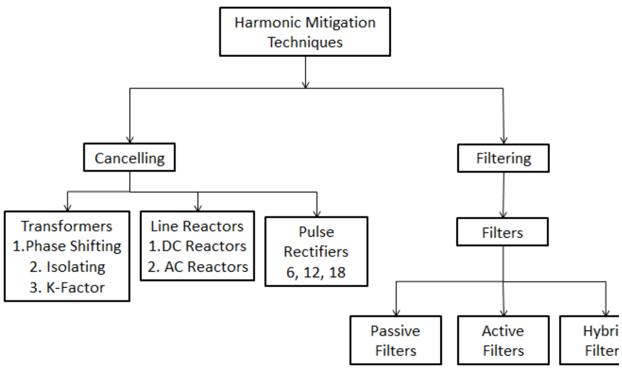

Fig.3 Harmonic Mitigation Techniques

Fig.3 shows various harmonic mitigation techniques used in the power system for power quality improvement. This survey paper explains about these different mitigation techniques in detail. All these techniques have its own merits and demerits [18]. One has to select this for their respective application. The factors considered are as follows

1. Application Consideration
2. Factors of Compactness
3. Simple in Construction
4. Effectiveness in harmonic Mitigation
5. Energy Efficiency
6. Cost Effectiveness of the Technique

Variable Frequency Drive plays an important role in most of the industrial applications [19-20]. VFDs are used to control the speed of the motor, limiting the inrush current in the system, and also it helps in saving the energy. But it acts as a medium for harmonics propagation in the system. So, the system should be a harmonic free system. These harmonics are reduced by using these mitigation techniques. All these techniques can also be applied for reducing harmonics in power transmission as well as distribution systems due to loads [21].

4. Mitigation Techniques for Harmonics

In this part various harmonic mitigation techniques are explained. For designing a harmonic filter the following parameters are required.

1. Local power system information.
2. Environmental studies.
3. Nominal line to line voltage.
4. Fundamental Frequency.
5. Impedance of the system component.
6. Equipment location.

4.1 Line Reactors

The basic working principle is that a voltage is induced across the reactor in the opposite direction of the applied voltage which in turn reduces the harmonics generated in the system [22 – 24].
The induced voltage is given by the equation below in reactors.

$$e = L\frac{di}{dt} \quad (5)$$

There are two types.

1. AC Line Reactor
2. DC Line Reactor

4.1.1 AC Line Reactor

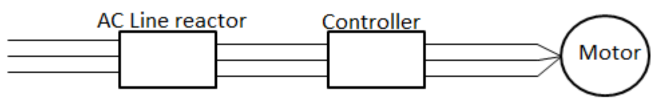

Fig.4 AC line reactor or choke for harmonic reduction

Fig.4 represents the AC line reactor for harmonic mitigation due to the variable drives and controllers. These reactors are simple inductance of a coil connected in series with the non-linear device to reduce harmonics. These are the simplest form of mitigation technique and it operates at low cost.

Merits:

1. Minimum operating cost.
2. It reduces the voltage and current distortions reasonably.
3. Various values for per unit impedance is available for the reactor.

Demerits:

1. Line reactors with fixed inductance value are used.

2. Line reactors more than 5% are not advisable for use in the system.
3. It won't reduce the harmonics as per guidelines of IEEE standard
4. Causes excess voltage drop due to line inductance.

4.1.2 DC Line Reactors

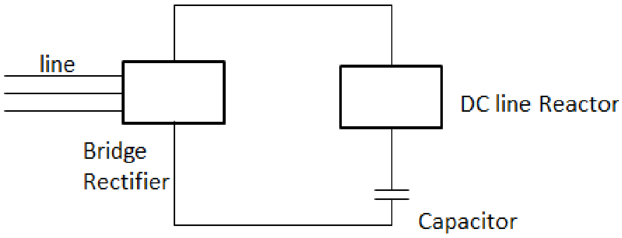

Fig.5 DC line reactor or choke for harmonic reduction

Fig.5 represents the DC line reactors which are simple inductance connected in series with the dc link of VFD drive to reduce mostly the odd harmonics probably 5^{th} and 7^{th} Harmonics of the system.

Merits:
1. Cheapest method for harmonic reduction.
2. It is integrated in the VFD control circuit.
3. The voltage drop due to reactor is minimum than the AC reactor.

Demerits:
1. The reactor has fixed reactance value.
2. The harmonic levels are not reduced as per the IEEE std.
3.

4.2 Transformer connection

Some transformers are connected in the system to reduce the harmonic content. Few types of transformers are explained below

4.1.3 Phase Shifting transformer

The basic principle of working of phase shifting transformer is that it shifts the harmonic 180º out of phase with the harmonic generated by the individual sources connected in the system. If both the magnitude of harmonics are equal then they get cancelled with each other. For achieving these both the harmonic generating sources should be at same ratings [25 – 26]. Here, Phase shifting transformers are connected in such a way that one transformer is connected in Y-Y configuration and the other transformer is connected in Δ-Y configuration.
Connection of phase shifting transformer in the system is given below in fig.6

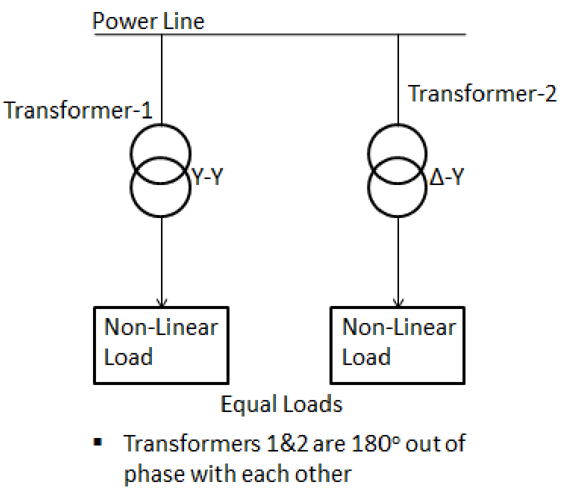

Fig.6 Phase Shifting Transformers for harmonic mitigation

Merits:
1. Transmission line efficiency is increased.
2. Effectively control the power flow of the line.

Demerits:
1. A special Protection scheme is required.
2. Occurrence of transient voltages at the transformer terminals.
3. Possibility of short circuit between the two transformers.

4.1.4 Isolating transformers

An isolating transformer is a dry type transformer where the primary and secondary side of the transformer is separated by a conductor which does not possess the magnetic properties. This material is connected to the ground to prevent the disturbances which gets transferred through the transformer. so, it act as a shelter to prevent the system from the propagation of harmonics and especially noise generated by a non-linear load [27 – 29]. A typical isolating transformer is given below in fig.7.

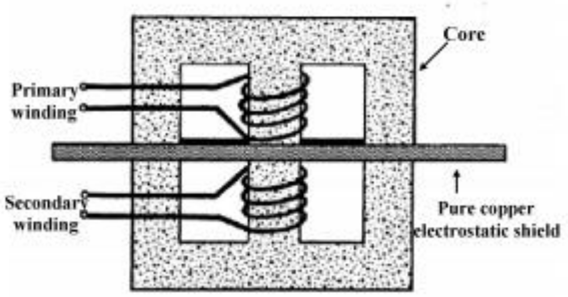

Fig.7 Isolating transformer for harmonic reduction

Merits:
1. It enhances the power quality.
2. It provides safety for the equipment connected in the system.

Demerits:
1. The voltage stability is not obtained.
2. It does not have the ability to store energy so can't be used during power outages.

4.1.5 K-Factor Transformer

K-factor is a constant introduced by UL laboratories and transformer manufacturers for dry type transformers to reduce the amount of heat generated in the transformer due to harmonic currents. The heat generation is mainly due to harmonics and because of eddy currents. This k-factor enhances the effectiveness of the transformer to handle the harmonic current losses supplied by a non-sinusoidal current [30-32].
The formula used to calculate k-factor is given by eqn.no.6

$$k = \sum_{h=1}^{\infty}(h^2) \times \frac{{I_h}^2}{{I_l}^2} \quad (6)$$

Where I_l stands for line current
I_h stands for harmonic current
h represents the harmonic order
The standard K -factor ratings used are 4,9,13,20,30,40 and 50.Based on this K-factor rate the effective impedance of the non-linear load can be calculated. The requirement of K-factor is minimum when the transformer is energizing both linear and non-linear loads than used for only non-linear loads.

Merits:
1. Performance of the transformer is increased by reducing the damages caused due to heat generation.
2. Current and voltage distortions are reduced moderately.
3. It can also be used along with phase shifting transformers for harmonic cancellation.

Demerits:
1. It is not economical as that of the standard transformers.
2. It is not an effective method for harmonic reduction.

4.3 Pulse rectifiers

Pulse rectifiers are another technique used to reduce the harmonics introduced in the system. It is a known fact that the semiconductor switches introduces harmonics in the system. By introducing the pulse rectifiers we can also reduce the amount of harmonics generated. It is similar to that of phase shifting transformers. The standard pulse rectifiers used are 6, 12, 18 and 24. Here one rectifier is operated with 180°out of phase with the other [33 – 36]. Due to this the harmonics generated by one system is cancelled by the other rectifiers. These rectifiers are supplied by isolating transformers. The transformers should be operated with 30° phase shift with each other. The 6 pulse rectifier is a cheapest method for harmonic reduction when compared with the higher versions of pulse rectifiers.

The number of harmonics and the pulses present in a system is given by the relation below by eqn.no.7

$$h_p = P \times n \pm 1 \tag{7}$$

Where h represents order of harmonics
P represents the number of pulses
n represents the integer.
Merits:

1. Power factor is increased.
2. Excessive energy losses in the system are reduced.
3. Satisfies the harmonic reduction as per IEEE standard.

Demerits:

1. As the number of pulses increases the technique become more complex and uneconomical.
2. It requires special cooling systems for some system.

4.4 Passive Filters

Passive filters are combination of resistors, capacitors and inductors that are tuned to resonate at a frequency. These passive filters are employed in power systems to suppress harmonic current and voltage results from non-linear part of the system and also it provides reactive power compensation [37 – 42]. The passive filters are also known as line harmonic filters or harmonic trap filters.
Passive filters are working on the basis of selection of impedance values. If a passive filter is connected in series with a system, it should possess high impedance value to reduce the harmonics. If it is connected in parallel the harmonics are diverted to the ground through a minimum impedance value and mostly capacitors are connected in shunt connected filters. Based on the connection of resistors, inductors and capacitors in the main circuit the passive filters are classified as series and shunt filters.

4.4.1 Series Passive Filter

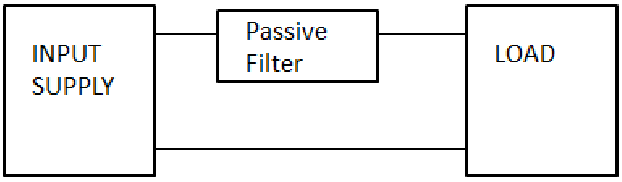

Fig.8 Series Passive Filter

Fig.8 represents a series passive filter with the combination of parallel connected inductance and capacitance connected in series with the supply and the load. They are applicable to single phase supply to reduce third harmonic of the system. They can also be utilized for the reduction of other tuned frequency distortion. It is easy to maintain and should be designed carefully for higher current ratings.

4.4.2 Shunt Passive Filter

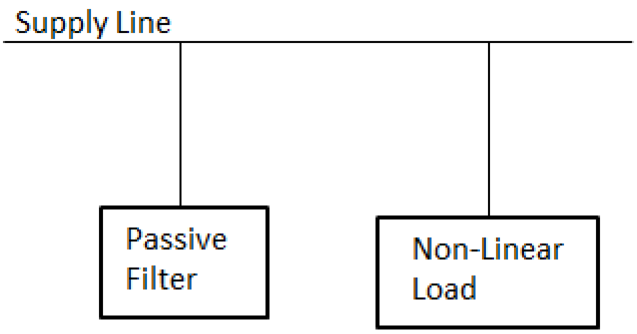

Fig.9 Shunt Passive Filter

Fig.9 shows a shunt passive filter which is nothing but the combination of resistors, inductors and capacitors connected either in series or parallel combination suitable for the specified application. They are capable of reducing mostly odd harmonics from the system. They are connected in shunt connection so it can control mainly the distortions caused by the current. The impedance value is very low to transfer the harmonics to the ground. So they require only smaller size for capacitor and inductor which in turn reduces the cost of filter. But they are affected by resonance problem.

Merits:

1. Design and construction is simple.
2. Cheaper system.
3. Maintenance free system.
4. Utilized for power factor correction

Demerits:

1. Designed carefully for higher current ratings.
2. Chances for occurrence of resonance.
3. Only odd harmonics got eliminated by these filters.

4.5 Active Filters

Active filter is also called as active power filter or active line conditioner. Active filters are connected with the system in a way that it generates current or voltage which is 180° out of phase with the system generating disturbed voltage or current. So, active filter injects the required parameters in line to reduce the harmonic contents. The active filter uses power electronics circuitry to produce counter harmonic currents to be injected into the system so it requires control techniques to tune it efficiently [43 – 47]. Like passive filter active filters are also classified as series active filter and shunt active filter.

4.5.1 Series Active Filter

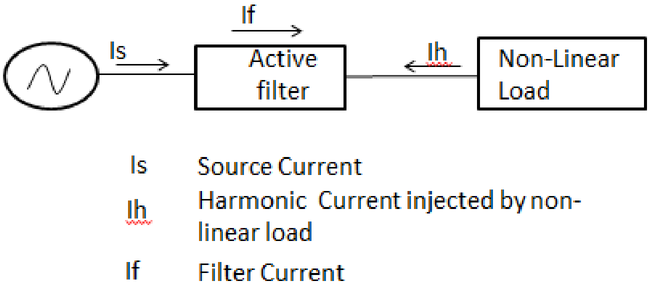

Fig.10 Series Active Filter

Fig.10 represents the series active filter which is connected in series with the system. The series active filter has to be connected through an impedance matching transformer. The active filter generates filter current which is in out of phase with the harmonic current produced by non-linear load. This in turn reduces the level of harmonics introduced in the system. The main draw-back here is the matching transformer has to withstand during short circuit occurrence on load side.

4.5.2 Shunt Active Filter

Fig.11 shows the shunt active filter which is connected in parallel with the power system line. It acts as a controlled current source. It produces the harmonic currents with equal magnitude but direct in opposition to the current introduced by the non-linear load. Thus we can say that the shunt active filter with non-linear load is completely turned into a linear load system. Here the active filter is conditioning the line rather than eliminating the distortions in voltage and current quantities. It can be operated for any tuned frequency ratings. So, it is widely used in power system when compared with Passive filters.

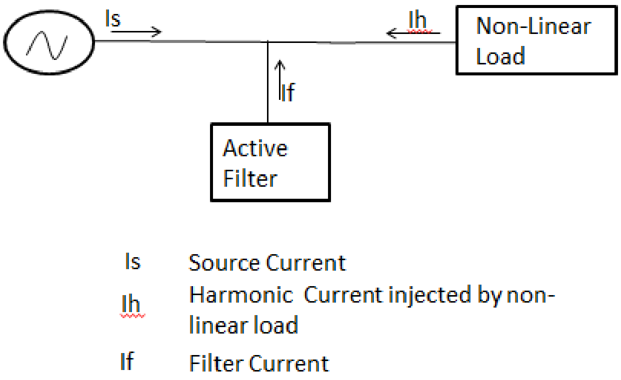

Fig.11 Shunt Active Filter

Merits:

1. Active power filters are designed to satisfy the IEEE standard limits for harmonic mitigation.
2. It can also be loaded with excess harmonic loads to be added in future.
3. Resonance problem is eliminated.
4. Improves system power factor.
5. Used to eliminate harmonics in the order of 2 to 50.

Demerits:

1. Expensive technique for mitigating harmonics.
2. Special control is required for active filters.
3. Regular maintenance is required.

4.6 Hybrid Filters

Based on the studies on passive and active filters it is economical if both the filters should operate together for mitigating harmonics of power system. This type of filter is termed as hybrid filter. This filter enhances the performance of passive filter. Hybrid filters consists of high power low cost passive filter which in turn reduces the power converters cost required for active filters [48]. Based on the connection of active and passive filters we can classify hybrid filters into parallel / series type hybrid filter and series / parallel type hybrid filter.

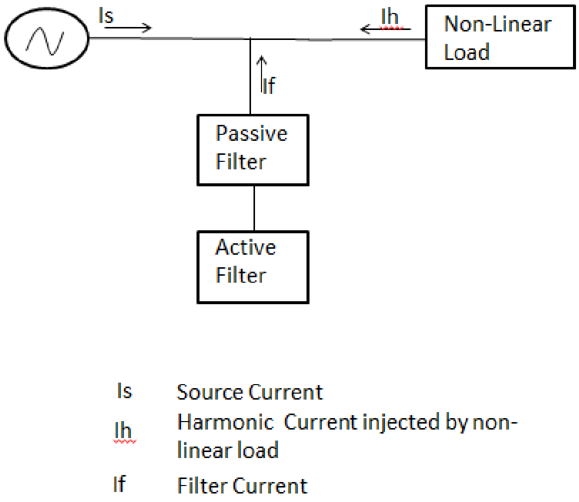

Fig.12 Parallel / Series hybrid filter

Fig.12 shows the parallel / series hybrid filter. In this technique hybrid filter consists of both passive and active filters. The total combination is connected in parallel with the system and the passive and active filters are connected in series. The passive filter is the combination of L and C connected in series and the active filter has to be connected through a matching transformer.

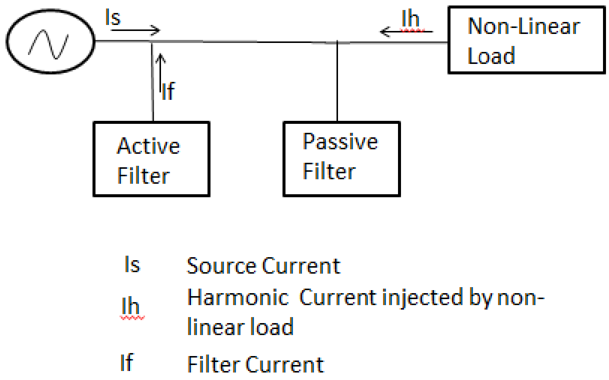

Fig.13 Series / Parallel hybrid filter

Fig.13 shows series / parallel hybrid filter for harmonic reduction. Here the active and passive filters are connected in series with the line but both active and passive are connected in shunt connection. The passive filter is the combination L and C connected in series and the active filter should be connected through a matching trans former with the system. The passive filter portion provides power factor correction parameters whereas the active filter is tuned to remove all the harmonics in the order of 2 to 50 in the system.

Merits:

1. Wide harmonic frequency elimination is achieved here.
2. Reactive power compensation is done by passive filter.
3. Power factor is improved.

Demerits:

1. Expensive method.
2. Maintenance is difficult.
3. Passive portion should not be overloaded..

5. Comparison Between Various Harmonic Mit Igation Techniques

Table no. 4 gives the comparison between the harmonic mitigation techniques [49 – 50]. Here all the discussed mitigation techniques are compared based on their performance and their complexity in injecting into the system.[51]

Table.4 Comparison of mitigation techniques

S.No.	parameters	Line reactors	Transformers	Pulse Rectifiers	Filters
1	IEEE std Limits	Rarely	Rarely	Rarely	Active and hybrid filters achieves it completely than passive filters
2	Power Factor Correction	No	No	No	Yes
3	Resonance Problems	No	No	No	Yes –passive and hybrid filters No-Active filters.
4	Injection	Hard	Hard	easy	Active-Easy
5	Efficiency	Moderate	Moderate	High	Passive-Moderate
6	Connection	Series	series	Series	Hybrid Series +Shunt
7	Complication	Simple	Simple	Simple	Passive – Moderate Active hybrid- complex
8	Cost	Low	Low	Low	Passive – Moderate Active, Hybrid - Expensive

6.Conclusion

This survey paper explains about various harmonic mitigation techniques for power system to enhance the power quality and power factor of the load. These harmonic techniques are followed to avoid equipment failure and increase the reliability of the system. Above all discussed techniques each and every system follows different methodology to reduce the harmonics and supply the utility with reliable power. Each method is applicable for a specified system. For example, active and hybrid filters can be used to reduce vast harmonic frequency range. So, based on the harmonic study parameters the consumer can select a prescribed method to prevent their utility from harmonic pollution as well as from paying electric penalty.

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