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# Harmonics Generation, Propagation and Purging Techniques in Non-Linear Loads

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## 1. Introduction

Industrial revolution has transformed the whole life with advanced technological improvements. The major contribution in the industrial revolution is due to the availability of electrical power that is distributed through electrical utilities around the world. The concept of power quality in this context is emerging as a “Basic Right” of user for safety as well as for uninterrupted working of their equipment. The electricity users whether domestic or industrial, need power, free from glitches, distortions, flicker, noise and outages. The utility desires that the users use good quality equipment so that they do not produce power quality threats for the system. The use of power electronic based devices in this industrial world has saved bounties in term of fuel and power savings, but on the other hand has created problems due to the generation of harmonics. Both commercial and domestic users use the devices with power electronics based switching that draw harmonic current. This current is a dominant factor in producing the harmonically polluted voltages. The “Basic Right” of the user is to have a clean power supply, whereas the demand of utility is to have good quality instrument/equipment. This makes power quality a point of common interest for both the users as well as the utility. Harmonics being a hot topic within power quality domain has been an area of discussion since decades and several design standards have been devised and published by various international organizations and institutions for maintaining a harmonically free power supply. In a wider scenario, the harmonically free environment means that the harmonics generated by the devices and its presence in the system is confined in the allowable limits so that they do not cause any damage to the power system components including the transformers, insulators, switch-gears etc. The deregulation of power systems is forcing the utilities to purge the harmonics at the very end of their generation before it comes to the main streamline and becomes a possible cause of system un-stability. The possible three stage scheme for harmonics control is

- Identification of harmonics sources
- Measurement of harmonics level
- Possible purging techniques

To follow the above scheme the power utilities have R&D sections that are involved in continuous research to keep the harmonics levels within the allowed limits. Power frequency harmonics problems that have been a constant area of research are:

- Power factor correction in harmonically polluted environment
- Failure of insulation co-ordination system
- Waveform distortion
- De-rating of transformer, cables, switch-gears and power factor correction capacitors

The above mentioned research challenges are coped with the help of regulatory bodies that are focused much on designing and implementing the standards for harmonics control. Engineering consortiums like IEEE, IET, and IEC have designed standards that describe the allowable limits for harmonics. The estimation, measurement, analysis and purging techniques of harmonics are an important stress area that needs a firm grip of power quality engineers. Nowadays, apart from the traditional methods like Y- $\Delta$  connection for 3<sup>rd</sup> harmonic suppression, modern methods based on artificial intelligence techniques aids the utility engineers to suppress and purge the harmonics in a better fashion. The modern approaches include:

- Fuzzy logic based active harmonics filters
- Wavelet techniques for analysis of waveforms
- Sophisticated PWM techniques for switching of power electronics switches

The focus of this chapter is to explain all the possible sources of harmonics generation, identification of harmonics, their measurement level as well as their purging/suppression techniques. This chapter will be helpful to all electrical engineers in general and the utility engineers in particular.

## 2. What are harmonics?

In electrical power engineering the term harmonics refers to a sinusoidal waveform that is a multiple of the frequency of system. Therefore, the frequency which is three times the fundamental is known as third harmonics; five times the fundamental is fifth harmonic; and so on. The harmonics of a system can be defined generally using the eq. 1

$$f_h = hf_{ac} \quad (1)$$

Where  $f_h$  is the  $h^{\text{th}}$  harmonic and  $f_{ac}$  is the fundamental frequency of system.

Harmonics follow an inverse law in the sense that greater the harmonic level of a particular harmonic frequency, the lower is its amplitude as shown in Fig.1. Therefore, usually in power line harmonics higher order harmonics are not given much importance. The vital and

the most troublesome harmonics are thus 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup>. The general expression of harmonics waveforms is given in eq. 2

$$V_n = V_m \sin(n\omega t) \tag{2}$$

Where,  $V_m$  is the rms voltage of any particular frequency (harmonic or power line).

The harmonics that are odd multiples of fundamental frequency are known as Odd harmonics and those that are even multiples of fundamental frequency are termed as Even harmonics. The frequencies that are in between the odd and even harmonics are called inter-harmonics.

Although, the ideal demand for any power utility is to have sinusoidal currents and voltages in AC system, this is not for all time promising, the currents and voltages with complex waveforms do occur in practice. Thus any complex waveform generated by such devices is a mixture of fundamental and the harmonics. Therefore, the voltage across a harmonically polluted system can be expressed numerically in eq. 3,

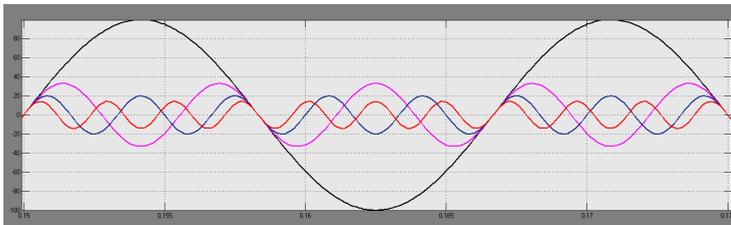
$$V = V_{fp} \sin(\omega t + \phi_1) + V_{2p} \sin(2\omega t + \phi_2) + V_{3p} \sin(3\omega t + \phi_3) + V_{np} \sin(n\omega t + \phi_n) \tag{3}$$

Where,

$V_{fp}$  = Peak value of the fundamental frequency

$V_{np}$  = Peak value of the n<sup>th</sup> harmonic component

$\phi$  = Angle of the respected frequency



**Figure 1.** Fundamental and harmonics frequency waveforms

Similarly, the expression for current through a given circuit in a harmonically polluted system is given by the expression given in eq. 4

$$I = I_{fp} \sin(\omega t + \phi_1) + I_{2p} \sin(2\omega t + \phi_2) + I_{3p} \sin(3\omega t + \phi_3) \dots + I_{np} \sin(n\omega t + \phi_n) \tag{4}$$

Harmonic components are also termed as positive, negative and zero sequence. In this case the harmonics that changes with the fundamental are called positive and those that have phasor direction opposite with the fundamental are called negative sequence components. The zero components do not take any affect from the fundamental and is considered neutral in its behavior. Phasor direction is pretty much important in case of motors. Positive sequence component tends to drive the motor in proper direction. Whereas the negative

sequence component decreases the useful torque. The 7<sup>th</sup>, 13<sup>th</sup>, 19<sup>th</sup> etc. are positive sequence components. The negative sequence components are 5<sup>th</sup>, 11<sup>th</sup>, 17<sup>th</sup> and so on. The zero component harmonics are 3<sup>rd</sup>, 9<sup>th</sup>, 15<sup>th</sup> etc. As the amplitude of harmonics decreases with the increase in harmonic order therefore, in power systems the utilities are more concerned about the harmonics up to 11<sup>th</sup> order only.

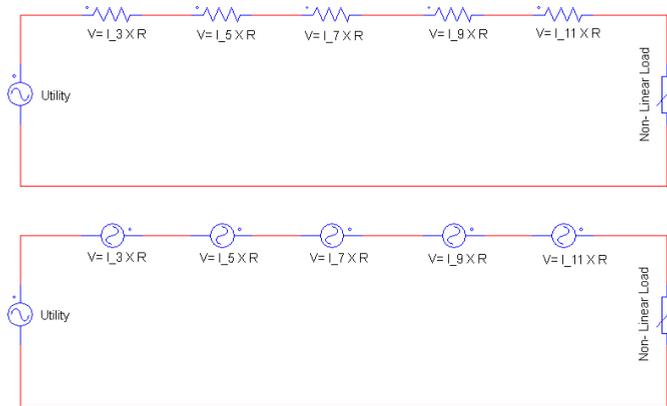
### 3. Harmonics generation

In most of the cases the harmonics in voltage is a direct product of current harmonics. Therefore, the current harmonics is the actual cause of harmonics generation. Power line harmonics are generated when a load draws a non-linear current from a sinusoidal voltage. Nowadays all computers use Switch Mode Power Supplies (SMPS) that convert utility AC voltage to regulate low voltage DC for internal electronics. These power supplies have higher efficiency as compared to linear power supplies and have some other advantages too. But being based on switching principle, these non-linear power supplies draw current in high amplitude short pulses. These pulses are rich in harmonics and produce voltage drop across system impedance. Thus, it creates many small voltage sources in series with the main AC source as shown in Fig.2. Here in Fig.2  $I_3$  refers to the third harmonic component of the current drawn by the non-linear load,  $I_5$  is the fifth harmonic component of the load current and so on. R shows the distributed resistance of the line and the voltage sources are shown to elaborate the factor explained above. Therefore, these short current pulses create significant distortion in the electrical current and voltage wave shape. This distortion in shape is referred as a harmonic distortion and its measurement is carried out in term of Total Harmonic Distortion (THD). This distortion travels back into the power source and can affect other equipment connected to the same source. Any SMPS equipment installed anywhere in the system have an inherent property to generate continuous distortion of the power source that puts an extra load on the utility system and the components installed in it. Harmonics are also produced by electric drives and DC-DC converters installed in industrial setups. Uninterrupted Power Supply (UPS) and Compact Fluorescent Lamp (CFL) are also a prominent source of harmonics in a system. Usually high odd harmonics results from a power electronics converter. In summary, the harmonics are produced in an electrical network by [2, 16, 26, 42]

- Rectifiers
- Use of iron core in power transformers
- Welding equipment
- Variable speed drives
- Periodic switching of voltage and currents
- AC generators by non-sinusoidal air gap, flux distribution or tooth ripple
- Switching devices like SMPS, UPS and CFL

It is worth mentioning here that voltage harmonics can emerge directly due to an AC generator, due to a non-sinusoidal air gap, flux distribution, or to tooth ripple, which is caused by the effect of the slots, which house the windings. In large supply systems, the greatest care is taken to ensure a sinusoidal output from the generator, but even in this case

any non-linearity in the circuit will give rise to harmonics in the current waveform. Harmonics can also be generated due to the iron cores in the transformers. Such transformer cores have a non-linear B-H curve [37].



**Figure 2.** Voltage distortion due to non-linear current

#### 4. Problems associated with harmonics

Harmonically polluted system has many threats for its stability. It not only hampers the power quality (PQ) but when a current is rich in harmonics, is drawn by some device, it overloads the system. For example third harmonic current has a property that unlike other harmonic component it adds up into the neutral wire of the system. This results in false tripping of circuit breaker. It also affects the insulation of the neutral cable. Overloading of the cables due to harmonically polluted current increases the losses associated with the wires. It should also be kept in mind that only the power from fundamental component is the useful power, rest all are losses. These additional losses make the power factor poor that results in more power losses. The overall summarized effects of harmonics in the power system include the following [9, 18, 39]

- Harmonic frequencies can cause resonant condition when combined with power factor correction capacitors
- Increased losses in system elements including transformers and generating plants
- Ageing of insulation
- Interruption in communication system
- False tripping of circuit breakers
- Large currents in neutral wires

The distribution transformers have a  $\Delta$ -Y connection. In case of a highly third harmonic current the current that is trapped in the neutral conductor creates heat that increases the heat inside the transformer. This may lead to the reduced life and de-rating of transformer. The different types of harmonic have their own impact on power system. For instance let us

consider the 3<sup>rd</sup> harmonic. Contrary to the balanced three phase system where the sum of all the three phases is zero in a neutral system, the third harmonic of all the three phases is identical. So it adds up in the neutral wire. The same is applicable on triple-n harmonics (odd multiples of 3 times the fundamental like 9<sup>th</sup>, 15<sup>th</sup> etc.). These harmonic currents are the main cause of false tripping and failure of earth fault protection relay. They also produce heat in the neutral wire thus a system needs a thicker neutral wire if it has third harmonic pollution in it. If a motor is supplied a voltage waveform with third harmonic content in it, it will only develop additional losses, as the useful power comes only from the fundamental component.

## 5. Harmonics monitoring standards

The identification of harmonics as a problem in AC power networks, has forced the utilities and regulatory authorities to devise the standards for harmonics monitoring and evaluation. The standards for harmonic control thus address both the consumers and the utility. Therefore, if the customer is not abiding by the regulations and is creating voltage distortion at the point of common coupling the utility can penalize him/her. Various renowned engineering institutes like IEEE, IEC and IET have devised laws to limit the injection of harmonic content in the grid. These standards are mostly helpful to achieve a user friendly healthy power quality system. IEEE standards are widely cited for their capability to address all the regions in the world. There are more than 1000 IEEE standards on electrical engineering fields. IEEE standards on power quality, however, are our main inspiration here. IEEE standard on harmonic control in electrical power system was published in 1992 and it covers all aspects related to harmonics [7]. It defines the maximum harmonics distortion up to 5 % on voltage levels  $\leq 69\text{kV}$ . However, as the voltage levels are increased the allowable limits for harmonics in this standard are decreased to 1.5 % on all voltages  $\geq 161\text{ kV}$ . It is also worth mentioning that individual voltage distortion starts from 3 % and ends at 1.0 % for voltage levels of  $\leq 69\text{kV}$  and  $\geq 161\text{ kV}$  respectively. Besides the standards that are designed keeping in view the global requirements, regional authorities devise their own standards according to their load profile and climatic conditions. Most of the standards are made according to the regional requirements of the country whereas few are based on the global needs and requirements. In Saudi Arabia there exists a regulatory body that defines the permissible limits and standard operational procedures for electricity transmission, distribution and generation. This body is known as electricity and co-generation regulatory authority [38]. Apart from devising standards they also follow some standards defined by UAE power distribution companies. One such standard defined by Saudi Electric Company (SEC) in 2007 and is known as "Saudi Grid Code". Harmonics limit set by the Saudi authorities is almost the same as IEEE standard but with a bit flexible limit of 3% THD for all networks operating within the range of 22kV-400kV [35, 38]. Table 1 compares the IEEE standard, the Abu Dhabi distribution company and the SEC standard for the harmonics limit in the electric network. It is interesting to mention that IEEE standard for controlling harmonics is silent for the conditions where a system is polluted with inter-harmonics (non-integer frequencies of fundamental frequency). For such conditions power

utilities use IEC standard number 61000-2-2. The IEC also defines the categories for different electronic devices in standard number 61000-3-2. These devices are then subjected to different allowable limits of THD. For example, class A has all three phase balanced equipment, non-portable tools, audio equipment, dimmers for only incandescent lamp. The limit for class A is varied according to the harmonic order. So for devices of class A the maximum allowable harmonic current is 1.08 A for 2<sup>nd</sup>, 2.3A for 3<sup>rd</sup>, 0.43A for 4<sup>th</sup>, 1.14A for 5<sup>th</sup> harmonics. The beauty of this IEC standard is that it also caters for power factor. For example all devices of class C (lighting equipment other than the incandescent lamp dimmer) have 3<sup>rd</sup> harmonic current limit as a function of circuit power factor.

	SEC Standard	Abu Dhabi Distribution Company	IEEE Limits
Harmonics	THD limit is 5% for 400 V system, and 4% and 3% for 6.6-20kV and 22kV-400kV respectively	THD limit is 5% for 400 V system, and 4% and 3% for 6.6-20kV and 22kV-400kV respectively	5% for all voltage levels below 69kV and 3% for all voltages above 161 kV

**Table 1.** Comparison of Harmonic Standards [7, 35, 38]

The modern systems based on artificial intelligent techniques like Fuzzy logic, ANFIS and CI based computations are reducing the difficulty of data mining that helps in redesigning the standards for power quality harmonics [24, 25]. In developed countries like Australia, Canada, USA the power distribution companies are already partially shifted to smart grid and they are using sophisticated sensors and measuring instruments.

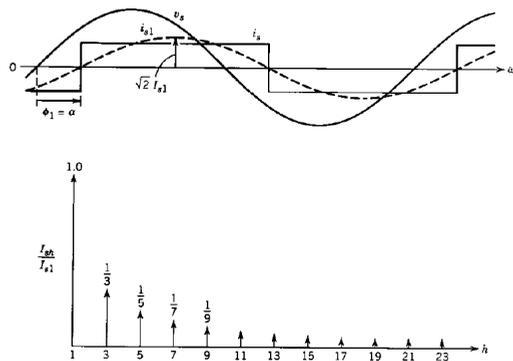
In terms of smart grid environment these sensors will help in mitigating the problems by predicting them in advance. Smart grid, by taking intelligent measurements and by the aid of sophisticated algorithms will be able to predict the PQ problems like harmonics, fault current in advance. It is pertinent to mention that the power quality monitoring using the on-going 3G technologies has been implemented by Chinese researchers. They used module of GPRS that is capable of analyzing the real time data and its algorithm makes it intelligent enough to get the desired PQ information [22].

## 6. Harmonics measurement

The real challenge in a harmonically polluted environment is to understand and designate the best point for measuring the harmonics. Nowadays the revolution in electronics has messed up the AC system so much that almost every user in a utility is a contributor to the harmonics current. Furthermore, the load profile in any domestic area varies from hour to hour within a day. So in order to cope with the energy demand and to improve the power factor, utilities need to switch on and off the power factor correction capacitors. This periodic and non-uniform switching also creates harmonics in the system. The load information in an area although, provide some basic information about the order of harmonic present in a system. Such information is very useful as it gives a bird eye view of

harmonic content. But for the exact identification of the harmonics it is necessary to synthesize the distorted waveform using the power quality analyzer or using some digital oscilloscope for Fast Fourier Transform (FFT). For example Fig.3 shows a general synthesis of the current drawn by a controlled rectifier. Once identified, the level and type of harmonics (3<sup>rd</sup>, 5<sup>th</sup> etc.) the steps to mitigation can be devised. It should be kept in mind that proper measurement is the key for the proper designing of harmonic filters. But the harmonics level may differ at different points of measurement in a system. Therefore, utilities need to be very precise in identifying the correct point for harmonic measurement in a system. Among the standards, it is IEEE standard 519-1992 that outlines the operational procedures for carrying out the harmonic measurements. This standard however does not state any restriction regarding the integration duration of the measurement equipment with the system. It however, restricts the utility to maintain a log for monthly records of maximum demand [5]. Various devices are used in support with each other to carry out the harmonic measurements in a system. These include the following

- Power Quality Analyser
- Instrument transformers based transducers (CT and PT)



**Figure 3.** Typical line current of a controlled converter [26]

Various renowned companies are designing and producing excellent PQ analyzers. These include FLUKE, AEMC, HIOKI, DRANETZ and ELSPEC. These companies design single phase and three phase PQ analyzers that are capable of measuring all the dominant harmonic frequencies. The equipment that is used for harmonic measurement is also bound to some limitations for proper harmonic measurement. This limitation is technical in nature as for accurate measurement of all harmonic currents below the 65<sup>th</sup> harmonic, the sampling frequency should be at least twice the desired input bandwidth or 8k samples per second in this case, to cover 50Hz and 60Hz systems [5]. Mostly, the PQ analyzers are supplied along with the CT based probes but depending on the voltage and current ratings a designer can choose the CT and PT with wide operating frequency range and low distortion. The distance of equipment with the transducer is also very important in measuring harmonics. If the distance is long then noise can affect the measurement therefore properly shielded cables like coaxial cable or fiber optic cables are highly recommended by the experts [5]. In short,

the measurement of harmonics should be made on Point of Common Coupling (PCC) or at the point where non-linear load is attached. This includes industrial sites in special as they are the core contributors in injecting harmonic currents in the system.

## 7. Harmonics purging techniques

Techniques have been designed and tested to tackle this power quality issue since the problem is identified by the researchers. There are several techniques in the literature that addresses the mitigation of harmonics. All these techniques can be classified under the umbrella of following

- i. Passive harmonic filter
- ii. Active harmonic filter
- iii. Hybrid harmonic filter
- iv. Switching techniques

### 7.1. Passive harmonic filters

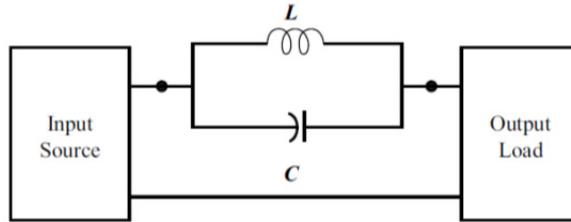
Passive filter techniques are among the oldest and perhaps the most widely used techniques for filtering the power line harmonics. Besides the harmonics reduction passive filters can be used for the optimization of apparent power in a power network. They are made of passive elements like resistors, capacitors and inductors. Use of such filters needs large capacitors and inductors thus making the overall filter heavier in weight and expensive in cost. These filters are fixed and once installed they become part of the network and they need to be redesigned to get different filtering frequencies. They are considered best for three phase four wire network [18]. They are mostly the low pass filter that is tuned to desired frequencies. Giacoletto and Park presented an analysis on reducing the line current harmonics due to personal computer power supplies [10]. Their work suggested that the use of such filters is good for harmonics reduction but this will increase the reactive component of line current. Various kind of passive filter techniques are given below [18, 19].

- i. Series passive filters
- ii. Shunt passive filters
- iii. Low pass filters or line LC trap filters
- iv. Phase shifting transformers

#### 7.1.1. Series passive filters

Series passive filters are kinds of passive filters that have a parallel LC filter in series with the supply and the load. Series passive filter shown in Fig.4 are considered good for single phase applications and specially to mitigate the third harmonics. However, they can be tuned to other frequencies also. They do not produce resonance and offer high impedance to the frequencies they are tuned to. These filters must be designed such that they can carry full load current. These filters are maintenance free and can be designed to significantly high

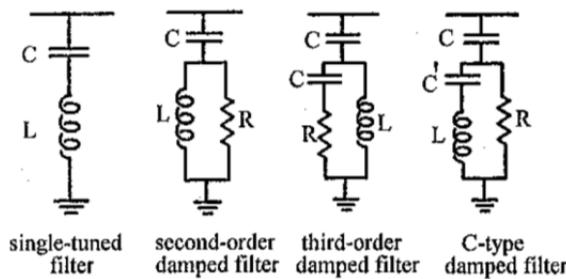
power values up to MVARs [4]. Comparing to the solutions that employ rotating parts like synchronous condensers they need lesser maintenance.



**Figure 4.** Passive Series Filter [18]

7.1.2. Shunt passive filters

These type of filters are also based on passive elements and offer good results for filtering out odd harmonics especially the 3<sup>rd</sup>, 5<sup>th</sup> and 7<sup>th</sup>. Some researchers have named them as single tuned filters, second order damped filters and C type damped filters [3]. As all these filters come in shunt with the line they fall under the cover of shunt passive filters, as shown in Fig.5. Increasing the order of harmonics makes the filter more efficient in working but it reduces the ease in designing. They provide low impedance to the frequencies they are tuned for. Since they are connected in shunt therefore they are designed to carry only harmonic current [18]. Their nature of being in shunt makes them a load itself to the supply side and can carry 30-50% load current if they are feeding a set of electric drives [13]. Economic aspects reveal that shunt filters are always economical than the series filters due to the fact that they need to be designed only on the harmonic currents. Therefore they need comparatively smaller size of L and C, thereby reducing the cost. Furthermore, they are not designed with respect to the rated voltage, thus makes the components lesser costly than the series filters [33]. However, these types of filters can create resonant conditions in the circuit.



**Figure 5.** Different order type shunt filters [3]

7.1.3. Low pass filter

Low pass filters are widely used for mitigation of all type of harmonic frequencies above the threshold frequency. They can be used only on nonlinear loads. They do not pose any

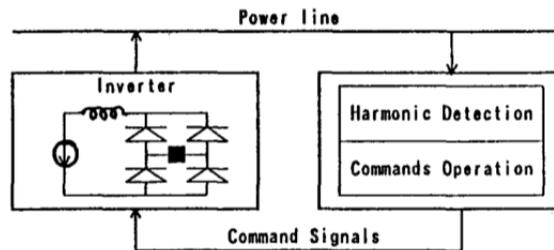
threats to the system by creating resonant conditions. They improve power factor but they must be designed such that they are capable of carrying full load current. Some researchers have referred them as line LC trap filters [19]. These filters block the unwanted harmonics and allow a certain range of frequencies to pass. However, very fine designing is required as far as the cut off frequency is concerned.

#### 7.1.4. Phase shifting transformers

The nasty harmonics in power system are mostly odd harmonics. One way to block them is to use phase shifting transformers. It takes harmonics of same kind from several sources in a network and shifts them alternately to  $180^\circ$  degrees and then combine them thus resulting in cancelation. We have classified them under passive filters as transformer resembles an inductive network. The use of phase shifting transformers has produced considerable success in suppressing harmonics in multilevel hybrid converters [34]. S. H. H. Sadeghi et.al. designed an algorithm that based on the harmonic profile incorporates the phase shift of transformers in large industrial setups like steel industry [36].

## 7.2. Active harmonic filters

In an Active Power Filter (APF) we use power electronics to introduce current components to remove harmonic distortions produced by the non-linear load. Figure 6 shows the basic concept of an active filter [27]. They detect the harmonic components in the line and then produce and inject an inverting signal of the detected wave in the system [27]. The two driving forces in research of APF are the control algorithm for current and load current analysis method [23]. Active harmonic filters are mostly used for low-voltage networks due to the limitation posed by the required rating on power converter [21].



**Figure 6.** Conceptual demonstration of Active filter [27]

They are used even in aircraft power system for harmonic elimination [6]. Same like passive filters they are classified with respect to the connection method and are given below [40].

- i. Series active filters
- ii. Shunt active filters

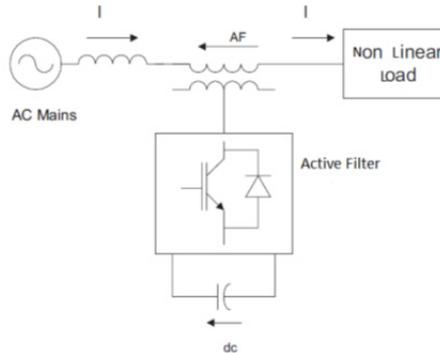
Since, it uses power electronic based components therefore in literature a lot of work has been done on the control of active filters.

### 7.2.1. Series active filter

The series filter is connected in series with the ac distribution network as show in Fig.7 [33]. It serves to offset harmonic distortions caused by the load as well as that present in the AC system. These types of active filters are connected in series with load using a matching transformer. They inject voltage as a component and can be regarded as a controlled voltage source [33]. The drawback is that they only cater for voltage harmonics and in case of short circuit at load the matching transformer has to bear it [31].

### 7.2.2. Shunt active filter

The parallel filter is connected in parallel with the AC distribution network. Parallel filters are also known as shunt filters and offset the harmonic distortions caused by the non-linear load. They work on the same principal of active filters but they are connected in parallel as stated that is they act as a current source in parallel with load [21]. They use high computational capabilities to detect the harmonics in line.



**Figure 7.** Series active filters [33]

Mostly microprocessor or micro-controller based sensors are used to estimate harmonic contents and to decide the control logic. Power semiconductor devices are used especially the IGBT. Some researchers claim that before the advent of IGBTs active filters were seldom use due to overshoot in budget [11]. However, despite of their usefulness shunt active filters have many drawbacks. Practically they need a large rated PWM inverter with quick response against system parameters changes. If the system has passive filters attached somewhere, as in case of hybrid filters then the injected currents may circulate in them [28].

## 7.3. Hybrid harmonic filters

These types of filters combine the passive and active filters. They contain the advantages of active filters and lack the disadvantages of passive and active filters. They use low cost high power passive filters to reduce the cost of power converters in active filters that is why they are now very much popular in industry. Hybrid filters are immune to the system impedance, thus harmonic compensation is done in an efficient manner and they do not

produce the resonance with system impedance [29]. The control techniques used for these types of filters are based on instantaneous control, on p-q theory and  $i_d-i_q$ . K.N.M.Hasan et.al. presented a comparative study among the p-q and  $i_d-i_q$  techniques and concluded that in case of voltage distortions the  $i_d-i_q$  method provides slightly better results [12]. They are usually combined in the following ways [21]

- i. Passive series active series hybrid filters
- ii. Passive series active shunt hybrid filters
- iii. Passive shunt active series hybrid filters
- iv. Passive shunt active shunt hybrid filters

### 7.3.1. *Passive series active series hybrid filters*

These type of hybrid filters have both kind of filters connected in series with the load as shown in Fig.8 and are considered good for diode rectifiers feeding a capacitive load [32]

### 7.3.2. *Passive series active shunt hybrid filters*

This breed of hybrid filter has passive part in series with load and active filter in parallel. AdilM. Al-Zamil et al. proposed such type of filters in their paper and used the high power capability. of passive filter by placing them in series with the load. They used an active filter with space vector pulse with modulation (SVPWM) and implemented it on micro-controller. They used only line current sensors to compute all the parameters required for reference current generation. Their proposed system worked satisfactorily up to the 33<sup>rd</sup> harmonic and the results shown are based on a system with line reactance of 0.13 pu. In their system the bandwidth required for active filter is relatively less due to the passive filter that takes care of the rising and falling edges of load current. They proposed that while designing hybrid system the line filter L and capacitance C of active filter needs a compromise in selection depending on the acceptable level of switching frequency ripple current and minimum acceptable ripple voltage [1].

### 7.3.3. *Passive shunt active shunt hybrid filters*

These types of filters have both the passive and active filters connected in shunt with the load as shown in Fig.9 [21]. In a comparative study J.Turunen et al. claimed that they require smallest transformation ratio of coupling transformer as a result they need a fairly high power rating for a small load and in case of high power loads the problem of dc link control results in poor current filtering [43].

### 7.3.4. *Passive shunt active series hybrid filters*

As its name implies it is a kind of hybrid filter that has an active filter in series and a passive filter in shunt as shown in Fig.10. J. Turunen et al. in a comparative study stated that this breed of hybrid filter utilizes very small transformation ratio therefore for same rating of load their power rating required is large compared to the load [43].

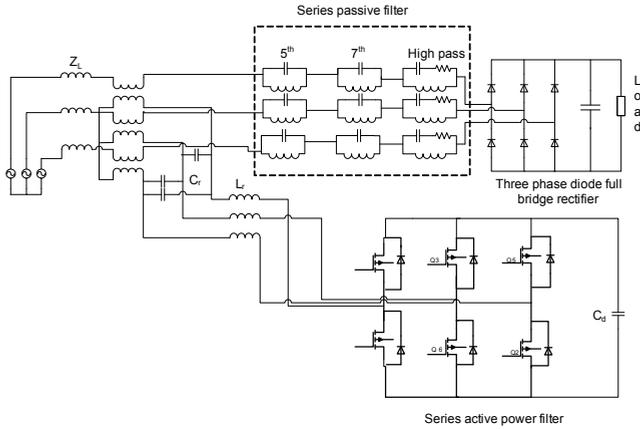


Figure 8. Passive series active series hybrid filters [32]

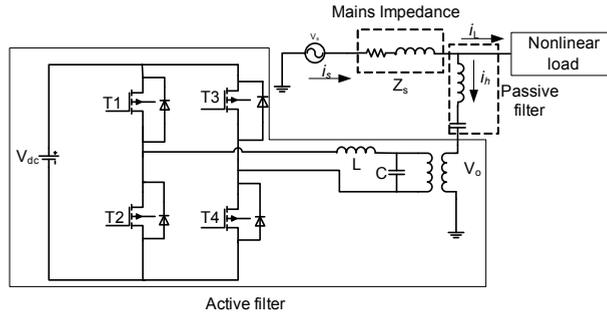


Figure 9. Passive shunt active shunt hybrid filters [21]

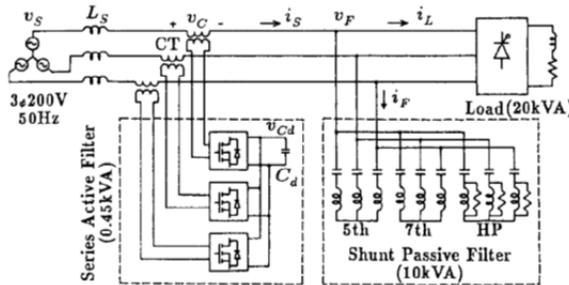


Figure 10. Active series passive shunt hybrid filters [29]

### 7.4. Switching techniques

Besides using the method of installing filters, power electronics is so versatile that up to some extent harmonics can be eliminated using switching techniques. These techniques may vary from the increasing the pulse number to advance algorithm based Pulse Width

Modulation (PWM). The most widely used sine triangle PWM was proposed in 1964. Later in 1982 Space Vector PWM (SVPWM) was proposed [20]. PWM is a magical technique of switching that gives unique results by varying the associated parameters like modulation index, switching frequency and the modulation ratio. The frequency modulation ratio ' $m$ ' if taken as odd automatically removes even harmonics [17, 26]. Here the increase in switching frequency reduces the current harmonics but this makes the switching losses too much. Furthermore, we cannot keep on increasing switching frequency because this imposes the EMC problems [15]. D.G.Holmes et al. presented an analysis for carrier based PWM and claimed that it is possible to use some analytical solutions to pin point the harmonic cancelation using different modulation techniques. Sideband harmonics can be eliminated if the designer uses natural or asymmetric regular sampled PWM [14]. The output can be improved by playing with the modulation index. One specialized type of PWM is called Selective Harmonic Elimination (SHE) PWM or the programmed harmonic elimination scheme. This technique is based on Fourier analysis of phase to ground voltage. It is basically a combination of square wave switching and the PWM. Here proper switching angles selection makes the target harmonic component zero [26, 30]. In SHE technique a minimum of 0.5 modulation index is possible [41]. But even the best SHE left the system with some unfiltered harmonics. J. Pontt et al. presented a technique of treating the unfiltered harmonics due to the SHE PWM. They stated that if we use SHE PWM for elimination of 11<sup>th</sup> and 13<sup>th</sup> harmonics for 12 pulse configuration then the harmonics of order 23<sup>th</sup>, 25<sup>th</sup>, 35<sup>th</sup> and 37<sup>th</sup> are one that play vital role in defining the voltage distortions. They proposed the use of three level active front end converters. They suggested a modulation index of 0.8-0.98 to mitigate the harmonics of order 23<sup>rd</sup>, 25<sup>th</sup> and 35<sup>th</sup>, 37<sup>th</sup> [30]. With some modifications researchers have shown that SHE PWM can be used at very low switching frequency of 350 Hz. Javier Napoles et al. presented this technique and give it a new name of Selective Harmonic Mitigation (SHM) PWM. They used seven switching states and results makes the selective harmonics equal to zero [8]. This is excellent since in SHE PWM the selective harmonic need not to be zero. It is sufficient in conventional PWM to bring it under the allowable limit. Siriroj Sirisukprasert et al. presented an optimal harmonic reduction technique by varying the nature of output stepped waveforms and varied the modulation indexes. They tested their proposed technique on multilevel inverters that are better than the two level conventional inverters. They excluded the very narrow and very wide pulses from the switching waveform. Unlike SHE PWM as discussed above they ensured the minimum turn on and turn off by switching their power switches only once a cycle. Contrary to traditional SHE PWM, in this case the modulation index can vary till 0.1. The output is a stepped waveform for different stages they classify the production of modulation index as high, low and medium and the real point of interest is that for all these three classes of modulation indexes the switching is once per cycle per switch [41]. Some researchers used trapezoidal PWM method for harmonic control. This kind of PWM is based on unipolar PWM switching. Here a trapezoidal waveform is compared with a triangular waveform and the resulting PWM is supplied to the power switches. Like other harmonic elimination techniques in PWM based techniques researchers have proposed the use of AI based techniques including FL and ANN.

## 8. Conclusion

This chapter summarizes one of the major power quality problems that is the reason of many power system disturbances in an electrical network. The possible sources of harmonics are discussed along with their effects on distribution system components including the transformers, switch gears and the protection system. The regulatory standards for the limitation of harmonics and their measurement techniques are also presented here. The purging techniques of harmonics are also presented and various kind of harmonic filters are briefly presented. To strengthen the knowledge base, this chapter has also discussed the control of harmonics using PWM techniques. By this chapter we have attempted to gather the technical information in this field. A thorough understanding of harmonics will provide the utility engineers a framework that is often required in the solution of research work related to harmonics.

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