Harmonics & Its Mitigation Technique by Passive Shunt Filter

Kuldeep Kumar Srivastava, Saquib Shakil, Anand Vardhan Pandey

Abstract*— *This paper presents the study of harmonics present in the system & harmonics filter of primarily used in electrical system & worldwide. Through this paper we come to know about the harmonics & their significance effect on the system regarding the harmonics distortion caused by non- linear load such as computers, Variable frequency drives, & rectifier circuit. In this presentation we presented some of simple but not the least harmonics filter which is given as PASSIVE SHUNT FILTERS are also introduced with their respective designing methods. The basic object of this paper is to study about the designing of passive shunt type filter for the distribution system. These filters are very much affective in reduction of harmonics & distortion in voltage caused by non linear load. Here we studied design process of single tuned & high pass filter. The major objective in this study will tell us the use of shunt passive filter, their designing criteria.

Key words: Fundamental frequency, Harmonics, Harmonics filter, linear load, Non-linear load, Passive shunt filter

I. INTRODUCTION

In recent days power quality in electrical energy system has become a major challenge for engineers to maintain the sinusoidal waveform in the system if there is any distortion come in the waveform is known as Harmonic in the system. Harmonic is a problem arises due to use of Non-linear load or in other word we can say that from solid state component. In electrical system harmonics is a seen for long time but major of problems related to harmonics are come in frame from past few years. In electrical power system distribution traditional equipment such as rotating machine produces harmonics due to uneven distribution of flux in air gap of rotating machine this tends to no sinusoidal voltage & current generation in rotating machine such as synchronous machine. If we talk about traditional electrical equipment transformer overloading of transformer is a cause of harmonic generation. Harmonics in power system is defined as current or voltage which is defined as multiple integer of system frequency or fundamental frequency. Today most of load are producing are producing except of incandescent bulb light the magnitude of harmonic is varies from load to load. The arise of harmonic current in system is going to further distorted the system voltage that increasingly affect the system performance & give undesirable situation such of them are as overheating problems, mechanical & electrical oscillation in alternator & prime movers, failure of insulation problems, failure of control system & unpredictable behavior of protection & relay connected in system etc.

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Since all these above said problems are severe for the electrical system, so the harmonic mitigation is important for both point of view of utilities & consumers end. Harmonic filtering technique using passive filters is the one of the most used & earliest technology present in the system used to address the harmonic mitigation. The filters have been used very widely because of its very simple designing process & low cost factor.

II. HARMONICS & ITS EFFECTS

Today in modern age fashion of electronics load increased rapidly. These electronics component are very much responsible for change in the electrical characteristics which are if when analyzed with analyzer become the evident of change of line voltage & line current waveform from pure sinusoidal to some other signal form, this distortion in waveform is given as Harmonic Distortion

The harmonic distortion is a very old problem but previously it was not so severe as today. in the past harmonic distortion represented the less no of problem due conservative design of power system & equipment & too common use of delta grounded & wye connection in distribution transformers[1]. Previously it was arose by the saturation of transformers, by industrial arc furnaces, some other electrical devices which are a kind of product of arc such as large welding machine, telephone interference, & increased risk of fault from the overvoltage condition which are developed due to use of power factor correction capacitors.

Basics of Harmonics Theory

Basically Harmonics in power distribution system is defined as harmonic current or harmonic voltage which is multiple integer of system frequency or fundamental frequency. Harmonic component must have sinusoidal waveform same as of fundamental power component say the waveform of voltage & current. In harmonic there is change arises in total voltage or current waveform & also frequency distortion come in picture, this total distortion disturb whole the system & give failure of system.

A harmonic component of a sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple of fundamental frequency or line frequency of system harmonic in power or say voltage or current can then be conceived as perfectly sinusoidal component of frequency multiple of fundamental frequency which can be seen in figure[1]

Harmonic Order

In the electrical system various type of harmonics are present which are given by their order.

Harmonic order or **harmonic number** is a reference to the frequency of the harmonic component.
The order of harmonics are decided by formula as shown below [2]

Fh = (h) * fundamental frequency or line frequency

Where h = Integer value

So if we talk about first harmonics of system will be same as the line frequency. Now for the 3rd harmonics the harmonic component is given by above formula for the system having frequency of 50 Hz

F3 = 3 * 50 = 150 HZ

Fifth harmonic is similary given by

F5 = 2 * 50 = 250 HZ

& seventh harmonic can be given as

F7 = 7 * 50 = 350 HZ

So now if we had considered ideal condition that system has frequency of 50 Hz is with a peak value of 100 Amp current along the system. This 100 Amp value is also consider as one per unit. Likewise this per unit the harmonics would have same waveform of order of (1/3) (1/5) (1/7) of fundamental waveform or amplitude. This behavior of harmonic shown an inverse law with harmonic component, the system have these harmonics are shown In fig 2 where the whole system frequency is also affected shown in the waveform.

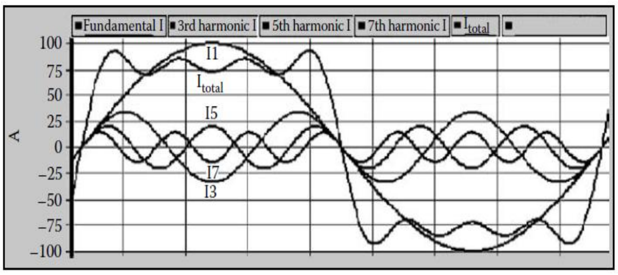


Fig [1] Resultant waveform of system has 3rd 5th & 7th harmonics

In figure the systems current how get impacted by harmonics is shown. The resultant current of the system first of all going to reduced & second one there is fluctuation problem also arise in system which further may give rise problem such as overheating, insulation failure etc.

Causes of HARMONICS

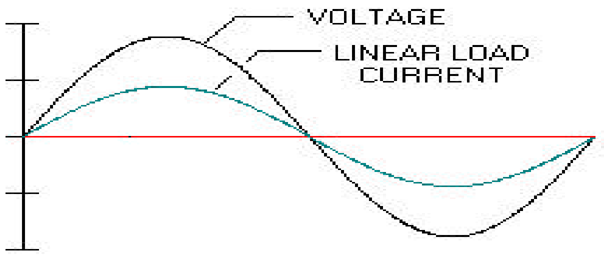
Harmonics are basically arising due to type of load we are using in the system**.** There are in system two type of load are present one is linear load which is characterized by have same waveform identical with the line waveform. In other or very simple way we can say that if there is sinusoidal input given to any load having charectistics of linearity then the resultant output generated by load will also be sinusoidal. It has been seen that up to 1980's the load are of linear type. The other load is given as non- linear load which has different waveform than the supply waveform the simple example of nonlinear load is SMPS (switch mode power supply). In now a day's most of loads are of non-linear type & produces harmonics. Only the load known which fulfill the condition of linear load is given as Incandescent lamp.

Linear load:

A load is said to be linear if the waveform of voltage & current signals follow each other identifiably or very close to each other[3] A very easy way to understand the linear load can be given by the Ohm's law which stated that the current (I) through resistance fed by voltage source (V) is equal to the relation (R) between voltage & resistance which are described by

I (*t*) = V (*t*) / R

This relation proves that current & voltage waveform in electrical circuit with linear load look alike. Therefore if the source is clean or say that there is no distortion in the system then the current waveform will look identical having no distortion as shown in the figure 2



Fig[2] Waveform with Linear Load

Non linear load

Non linear load are type of load in which the voltage waveform & current waveform does not have same waveform & not identical with the applied source [figure 3] due to number of reason present in the system. The much known problem of this is the use of electronic devices & switches. The electronic switches do not conduct load current during the whole power frequency period but only the fraction of that period. This is the main reason that the load voltage & current are not having identical waveform. The other thing which we also can say that the system which does not fulfill the Ohm's law can be said Non-linear load.
Among the all the types of nonlinear load which affects the system most are power converter. Uninterrupted power system (UPS), various type of electric furnaces & etc.

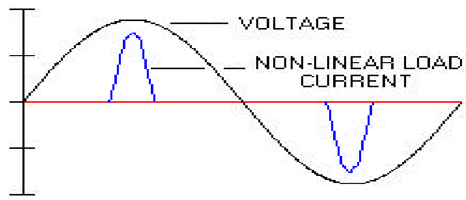


Fig [3] Waveform with Non Linear load

The causes of harmonics which are come in picture broadly are industrial electronics devices. The current drawn by these industries from the distribution system are not remaining longer sinusoidal & the resultant of this waveform causes the occurrence of harmonics in the system.
Basically whatever the harmonics present in the system is due to non-linear load which are the major source of distortion in power system component. The other normally possible causes of presence of harmonics in the system are as follows[4]:

1: In modern technology use of nonlinear loads have increased rapidly resulting from new technologies such as silicon-controlled rectifiers (SCRs), power transistors, and microprocessor controls by which a load-generated harmonics produces in the system.

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2:due to presence of non linear component present in the system such as rectifier, inverter, dc- to - dc converter, Welding machine, & arc furnaces & converters.
3: when there is a sudden change occur in load arise there is some distortion come in flux distribution of synchronous machine
4: speed control device of AC machine which are designed based on semi conductor devices

Effects of Harmonics

Harmonics are a major cause of power supply pollution lowering the power factor and increasing electrical losses. The effect of harmonic results in premature equipment failure and also cause of requirement of equipment of high rating The voltage distortion produced in the system is the major issue with the harmonics distribution. The electronics equipment used in the system usually generate harmonics more than one. In all type of harmonics the tripled harmonics are more severe example of triplet harmonics are 3rd 9th 15th [5]. These harmonics produced bigger problem to engineers because they poses more distortion in voltage. The effect of triplex harmonics come with overheating in wires, overheating in transformer units & also may become the cause of end user equipment failure.

Triplex harmonics overheat the neutral conductor of 4 wire system. the neutral have generally no fundamental frequency or even harmonics but there may be existence of odd harmonics in system neutral conductor & when there is system consist of triplex harmonics it is become additive. these triplex frequency impact on the system can be understand by this way that even under balanced load condition on the account of triplex frequency neutral current magnitude reaches up to 1.75 times of average phase current[6].

Under above discussed case if the load of system increase may become cause of failure of insulation of neutral conductor which further result in the breakdown of transformers winding.

The important & major effect of Harmonics is further discussed as:

Thermal effect on transformers

Transformer is a key device to supply all types of load either for commercial or industrial or residential purpose. As these service transformers are connected with the large end consumer side so they are attached directly or indirectly with the various kind of load say linear & non linear both. In modern age industrial & commercial network are very rapidly influenced by a large or huge amount of harmonic current which produced by variety of nonlinear type loads likes Variable speed drives, electric furnaces different type of converters etc. in addition of that if we take the case of residential user there is a lot of type of personnel & entertaining equipment are which are also a source of harmonic current & harmonic voltage.

Neutral conductor overloading

In single phase power system neutral play a very important role as they carry the return current & complete the circuit. But in case of harmonics it also becomes the return path for the harmonic current to transformer through neutral connection. for an unbalanced system the unbalanced current are passed through the neutral & for this purpose we need to balance the system the size of neutral cable is almost taken equal to its phase cable. Under environment of harmonics the unbalanced current which is passed through the neutral produces a heat loss in the system which again affects the power quality of distribution system.

Effect on lines & cables

Harmonic distortion in a distribution system affect the system current & significantly these increased rms current produces additional heat losses in the system lines & cables

Harmonic distortion in cables affect by increasing the dielectric stress in the cables. This dielectric stress is proportional to the voltage crest factor which represents the crest value of voltage waveform to rms value of waveform. The effect of this increased dielectric stress is such that on the cable is shortens the useful life of cable, causes of increased faults, which ultimately increased the system capital cost & maintenance cost [7].

Thermal effect on rotating machine:

Rotating machine are also affected by harmonics same as transformer. Resistance of rotating machine will goes high if the frequency of system is high. For this if there is harmonic present in the system have a very rich current value which tends to produce a heat loss in the rotating machine [8]. This overall heat loss will again affect the life of transformer & maintenance problems.

Undesired operation of Fuse

In the environment of harmonic the RMS value of voltage & current may increase. This tendency of increased value of RMS voltage & current will lead the problem of unexpected operation of fuse in capacitor banks or other arrangement which are used in the system to make operation of nonlinear load. When if the fuse of one connected phase become fuse then the other remaining fuse is in operation due to this a stress come on the panel capacitor bank. In this type of condition the system other point become unbalanced & this will tends to produce the overvoltage on the system & detune the Passive filter in the system if they are not ready for such type of situation So if we further summarize our above discussion the effect of harmonic affect by the following given means:

- ✓ Equipment overheating
- ✓ Equipment malfunction or operation failure of equipment
- ✓ Equipment failure
- ✓ Communications interference
- ✓ Fuse and breaker operation failure
- ✓ Process problems

III. HARMONIC FILTERING TECHNIQUES

Now days the receiver who utilizes the electrical power is supplied through to various electronic substances say AC- DC converter, Motor speed adjustable unit, various switching mode power supply system & computer process generator. All above discussed terminology are processed on diode, triode, transistor, thyristors which promote the nonlinearity characteristics [9] & due to this non linear function the receiver will be the cause of injecting the harmonic component in the distribution system & will also affect the other consumer by this pollution of harmonic in system. In general harmonic filter technology is quite important for the power quality improvement of the system. The harmonic produce in the system is minimized by the use of various filters that are referring basically as ACTIVE FILTER & PASSIVE FILTER. The simple type of filter is passive filter which is foci in this chapter.

Introduction to PASSIVE FILTER

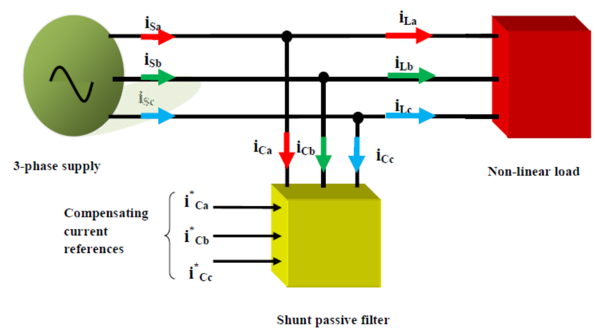
Harmonic distortion in the system is very vast problem for the entire electrical power researcher & they continuously worked on the mitigation of harmonic component in the system to make system neat& clean & consumer avail electrical utilities in very determinant, with high performance & high efficiency. Passive filters are very much helpful for mitigation of harmonic component & used traditionally. Passive filter are used for the mitigation of harmonic in the electrical society for last 3 decades & there is a continuous development has been reported in this technique for the better use of filter & convert the filter more useful to achieve the optimum approach to utilization with reduced rating & cost. The use of passive filter in the mitigation of harmonic in 3 phase system use the utilizing with thyristor controlled reactor & thyristor switched capacitor is the most significant development in the field of harmonic distortion mitigation.
Passive filter are used for the mitigation of harmonic component in six pulse converter & also provide the reactive power compensation in the system to improve the power quality so by mean of this power filter helps the system by two means one is to improve the system power quality & improve reactive power problem so reduced the need of capacitor for supplying extra needed KVAR. The performance of passive filter depends mainly on the system source impedance.

Classification of Passive filter

The classification of Passive filter is done on the type of harmonic generation component source present in the system & passive component sys resistor, inductor & capacitor connected in the system & are given as[10]

1: PASSIVE SERIES FILTER
2: PASSIVE SHUNT FILTER
3: PASSIVE HYBRID FILTER

A very classical type of passive filter [4] is shown in the figure where filter is connected in the parallel with distribution system through power common coupling point having non linear load characteristics



Fig[4] Schematic arrangement of passive filter connected in the system on input side

Passive series filter

The system which come with the voltage source type harmonic which are the bi product of diode rectifier with R-L connected load(figure 5) it is prefer to use the series type passive filter as considered as potential remedy of harmonic mitigation. A passive type series filter has property of purely inductive type or LC tuned characteristics. The main component of passive series filter is AC line reactor & DC link filter.The operating principle of series passive filter is given by these two component connected in series that AC line reactor improve system magnitude of inductance in system that alters the path of current drawn in the rectifier circuit. These whole processes of offering magnitude in the system make system current waveform more continuous compare to without use of filter technology in the system [11]. Therefore system harmonic distortion will be going to reduced compare to previous.

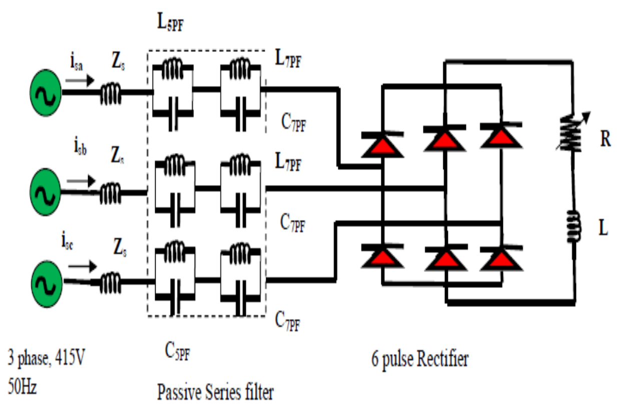


Fig 5 Schematic diagram of series connected passive filter with six pulse rectifier

Passive shunt filter

It is the most common method for the cancellation of harmonic current in the distribution system. Passive harmonic filter are basically designed on principle of either single tuned or band pass filter technology. As the name suggests shunt type filter are connected in system parallel with load. Passive filter offer a very low impedance in the network at the tuned frequency to divert all the related current & at given tuned frequency. Because of passive filter always have tendency of offering some reactive power in the circuit so the design of passive shunt filter take place for the two purpose one is the filtering purpose & another one is to provide reactive compensation purpose of correcting power factor in the circuit at desired level. The advantage with the passive shunt type filter is that it only carry fraction of current so the whole system AC power losses are reduced compare to series type filter.
The given figure[6] shows the schematic diagram of 6 pulse converter system connected with shunt passive type filter which are simply employed ever connection in distribution system have R-L load in system

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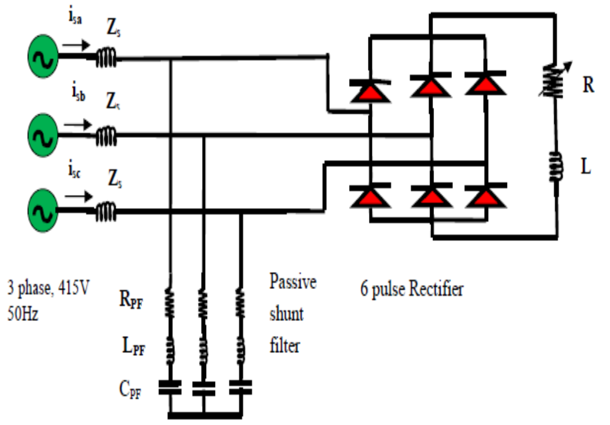
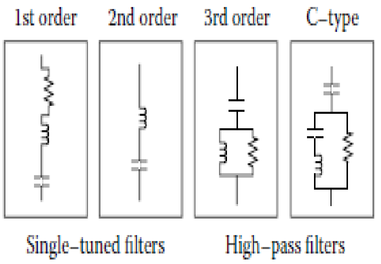


Fig[6]Shunt filter connection with six pulse rectifier circuit at input

IV. DESIGN OF PASSIVE HARMONIC FILTER

In general filter used in distribution system is Passive shunt type filter. In previous discussed chapter we had already studied that shunt passive filter consists of Simple combination of passive component resistor inductor & capacitor in the circuit. The designing of these components should be so well that they will precisely employ for each specified harmonic frequency for which it has been tuned [12]. Passive harmonic filter are used in the society are of single tuned & band pass filter type [13]. Passive filter designed in the same manner in single tuned connection or high pass filter connection which are given in following figure [7]

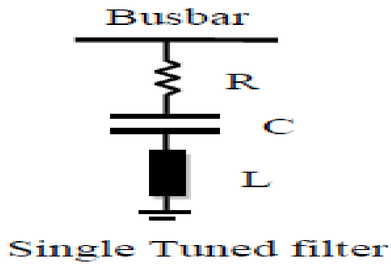


Fig[7] Different type of passive filter

Single tuned filter

Single tuned filters are the probably most common type of filter which is used in industry broadly for the harmonic mitigation. The basic principle of using passive filter is that on the tuned frequency filter will offer low impedance to current through which harmonic current will tends to divert in the system. One more advantage of employing passive filter is that it comes with the property of reactive power compensation [14].

A very simple arrangement of single tuned filter is shown in the figures [8] which also give the connection arrangement used in the single tuned filter designing



Fig[8]Simple connection diagram of single tuned filter

As discussed & easily can seen from the figure that single tuned filter are the simple series connection of R-L-C component & L-C component.

The equation of resonant frequency for single tuned frequency is given by following equation

Where

$$f_0 = \frac{1}{2\pi\sqrt{lc}} \qquad (1)$$

f_0= Frequency at resonant in Hertz
L=inductance of Filter in Hennery
C = Capacitance of Filter in Farads

Other important term which is tentatively necessary to keep in mind is the designing of filter Quality factor. The term quality factor is given by the ratio of reactance at the resonant condition & resistance of the circuit as follows in the equation

$$Q_c = \frac{X_l\, or X_c}{R} \qquad (2)$$

Where

Q_f= quality factor
R = resistance of filter in ohms

For a normal distribution system typical value of quality factor fluctuates in between 15 to 80.

Design equation of Single tuned filter

Impedance of filter branch is given by

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right) \qquad (3)$$

Where

ω=angular frequency ($2\pi f$) of power system & R, L, C are the resistance, inductance, & capacitance of filter branch respectively.

If ***h*** is the ratio between fundamental frequency & harmonic frequency then the value of capacitance & inductance can be found out by following equation which represent the relationship between harmonic and component of filter

$$X_{Lh} = h \times 2\pi f \qquad (4)$$

or

$$X_{ch} = \frac{1}{h \times 2\pi f} \qquad (5)$$

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Again at the tuning of filter the impedance value of filter must be low for which purpose if we see the simple circuit of filter then found that there is only way to minimize the impedance of filter is to make cancel out the two reactance connected in the circuit will eliminate by its own way which is only possible through the resonant condition viz.

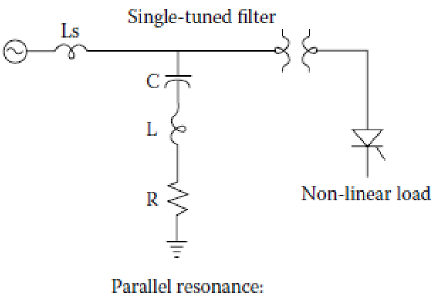
$$X_{Lh} = X_{ch}$$

Now when we put the value of X_{ch} & X_{ch} the equation (6) we can easily get another relationship between harmonic & passive component which is very much important in the designing of filter which is

$$h = \sqrt{\frac{X_C}{X_L}} \qquad (6)$$

Parallel resonant point

Whenever a single tuned harmonic filter is connected with the non linear load will look alike the figure of circuit. As from the figure it is easily seen that there is some inductance present in the system prior to system connected filter which is known as source filter (L_s). This source impedance will always have a tendency of affecting the system resonant condition. This total source impedance will be so much has impact that resonant condition of system will be just before the tune frequency & operate the filter with some neighboring frequency too.

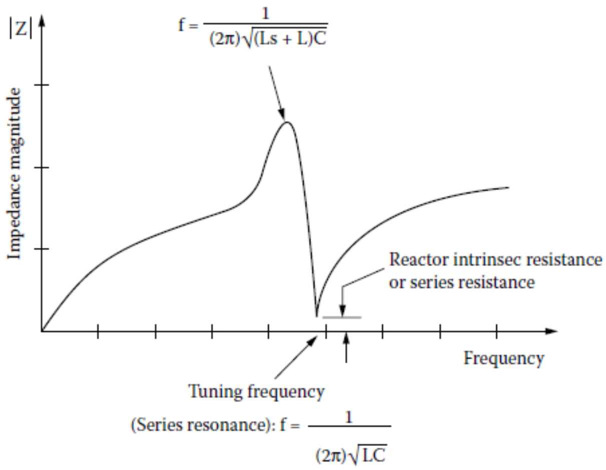


Fig[9] Single tuned filter connected system have source Load

When there are multiple harmonic filters is connected in the system the resonant of filter circuit will be affect for all the harmonic filters. Notice that when there is some source resistance is connected then the filter operation will affect by this additive source impedance with filter own inductance therefore new resonant frequency will be given by as

$$f_{0(parallel\ load)} = \frac{1}{2\pi\sqrt{(Ls+L)/C}} \qquad (7)$$

Now when the graph between frequency & source impedance draw it will be given as figure[10]



Fig[10] Resonant point on a single tuned RLC filter

The frequency will be taken for tuning of filter is normally taken below 3 to 6 percent of desired value [15]. This will come in account of overcoming effect of detuning effect of filter due to higher value of shift & allow providing low impedance path to harmonic current.

Quality factor

When the system have single tune filter the quality factor have property to release the ability of dissipate the absorbed energy at the tuned frequency In an R-L-C series quality factor is defined as ratio of reactance present in the system either capacitive or inductive with resistance of the filter at resonant condition

$$Q_c = \frac{X_L or X_C}{R} \qquad (8)$$

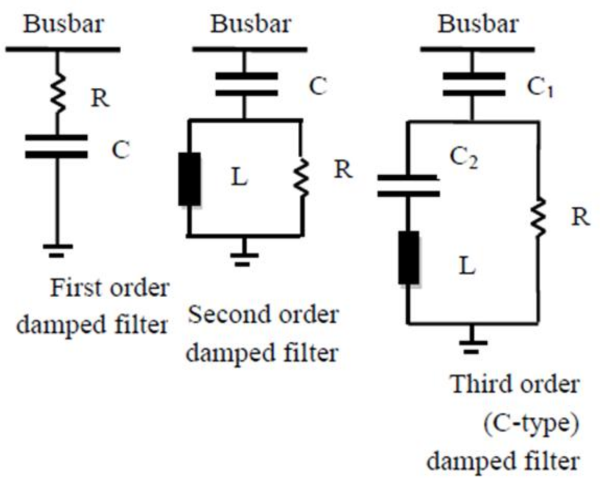
Bandwidth of filter

Bandwidth of filter is given by ratio of harmonic frequency for which it has been designed or tuned frequency & quality factor of the system at fundamental frequency.

$$B = \frac{f_h}{Q_f} \qquad (9)$$

High pass filter

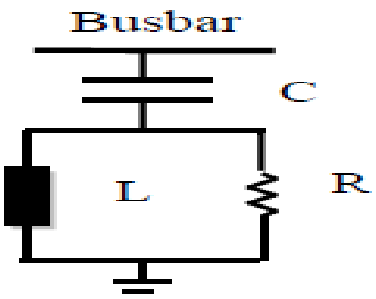
The method used for the mitigation of harmonic currents in electrical system by use of single tuned harmonic filter is not very much give the satisfactorily because of various harmonic frequency operated current are flowing in the circuit this forces in the single tuned filter to design multi single tuned filter for each have specific filtration attitude. For example if there is in system 5^{th}, 7^{th} & 11the harmonic are the major issue for the mitigation then by single tuned methodology will required 3 harmonic filter of each respectively. These all disadvantage of single tuned filter force us to consider on the other alternate of power harmonic current filtering technique, this whole scenario switch us to concentrate on another filtering technique known as ***HIGH PASS FILTER*** various type of High pass filter arrangement is shown in figure [11]



Fig[11] Different types of high pass filter arrangement

Designing of second order high pass filter

A very simple type of second order damped filter is shown in figure [12]



Fig[12] second order damped filter

Impedance

Impedance of filter branch at harmonic cut off harmonic frequency is given by as

$$Z_F(h) = \frac{jRhX_l}{R+jRhX_L} - j\frac{X_c}{h} \qquad (10)$$

Where $\mathbf{X_C}$= capacitor reactance at the fundamental frequency & given by the equationNow the value of the capacitor reactance at fundamental frequency can be found by given formula

$$Xc = \frac{Kv^2}{Q_c} \qquad (11)$$

Now the next step is calculate the reactor size trapping the h_nth harmonic

$$X_l = \frac{Xc}{h_n^2} \qquad (12)$$

Calculate the reactor resistance for a specified quality factor (Q)

$$\boldsymbol{R = X_n * Q}$$

Where Q is vary from 0.5 to 5

The characteristics reactance is given by

$$X_n = X_{cn} = X_{Ln} = \sqrt{X_l} \times X_c$$

Again this can be furtered given as

$$Xn = \sqrt{\frac{l}{c}} \qquad (13)$$

Now the size of filter is given as

$$Q_{filter} = \frac{h_n^2}{(h_n^2 - 1)} Q_c \qquad (14)$$

Now the filter impedance is given by

$$Z_f(h) = \frac{jRhX_l}{R + jRhX_l} - j\frac{X_c}{h}$$

Or

$$Z_f(h) = \frac{jR(hX_l)^2}{R^2 + (hX_l)^2} - j\left[\frac{R^2hX_l}{R^2 + (hX_l)^2} - \frac{X_c}{h}\right] \qquad (15)$$

Above discussed methof are largerely utilized in the pasiive filter designing calculation for the simple system harmonic mitigation process. These method are also useful in power factor correction calculation for the power system where power compensation is required.

V.CONCLUSION

This paper has presented a brief idea about harmonic & their consequences affect on the distribution & transmission system here we also study the basic harmonic mitigation technique which is now a day's applying in fashion. Here we presented a brief idea about the designing process of passive shunt filter for two types of passive filter names single tuned filter & high pass filter for the mitigation of harmonic in the system.

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