HARMONIC REDUCTION USING BROAD BAND HARMONIC FILTERS

Introduction

Events over the last several years have focused attention on certain types of loads on the electrical system that result in power quality problems for the user and utility alike. Equipment which has become common place in most facilities including computer power supplies, solid state lighting ballast, adjustable speed drives (ASDs), and uniterrruptible power supplies (UPSs) are examples of non-linear loads. Non-linear loads generate voltage and current harmonics which can have adverse effects on equipment designed for operation as linear loads (i.e., loads designed to operate on a sinusoidal waveform of 50 or 60 Hz.). Transformers which bring power into an industrial environment are subject to higher heating losses due to harmonic generating sources (non-linear loads) to which they are connected. Harmonics can have a detrimental effect on emergency generators, telephones and other electrical equipment as well. When reactive power compensation (in the form of passive power factor improving capacitors) is used with non-linear loads, resonance conditions can occur that may result in even higher levels of harmonic voltage and current distortion thereby causing equipment failure, disruption of power service, and fire hazards in extreme conditions.

The electrical environment has absorbed most of these problems in the past. However, the problem has now reached a magnitude where Europe, the US, and other countries have proposed standards to responsibly engineer systems considering the electrical environment. IEEE 519-1992 and IEC 555 have evolved to become a common requirement cited when specifying equipment on newly engineered projects. The **broad band harmonic filter** was designed in part, to meet these specifications. The present IEEE 519-1992 document establishes acceptable levels of harmonics (voltage and current) that can be introduced into the incoming feeders by commercial and industrial users. Where there may have been little cooperation previously from manufacturers to meet such specifications, the adoption of IEEE 519-1992 and other similar world standards now attract the attention of everyone.

Harmonic Limit Calculations based on IEEE 519-1992

The IEEE 519-1992 relies strongly on the definition of the point of common coupling or PCC. The PCC from the utility viewpoint will usually be the point where power comes into the establishment (i.e., point of metering). However, the IEEE 519-1992 document also suggests that

Reprinted by permission of MTE Corporation

"within an industrial plant, the point of common coupling (PCC) is the point between the nonlinear load and other loads" [1]. This suggestion is crucial since many plant managers and building supervisors feel that it is equally if not more important to keep the harmonic levels at or below acceptable guidelines within their facility.

In view of the many recently reported problems associated with harmonics within industrial plants [2], it is important to recognize the need for mitigating harmonics at the point where the offending equipment is connected to the power system. This approach would minimize harmonic problems, thereby reducing costly downtime and improving the life of electrical equipment. If one is successful in mitigating individual load current harmonics, then the total harmonics at the point of the utility connection will in most cases meet or better the IEEE recommended guidelines. In view of this, it is becoming increasingly common for specifiers to require non-linear equipment suppliers to adopt the procedure outlined in IEEE 519-1992 to mitigate the harmonics to acceptable levels at the point of the offending equipment. For this to be interpreted equally by different suppliers, the intended PCC must be identified. If this is not defined clearly, many suppliers of offending equipment would likely adopt the PCC at the utility metering point, which would not benefit the plant or the building but rather the utility.

Having established that it is beneficial to adopt the PCC to be the point where the ASD connects to the power system, the next step is to establish the short circuit ratio. Short circuit ratio calculations are key in establishing the allowable current harmonic distortion levels. For calculating the short circuit ratio, one has to determine the available short circuit current at the ASD input terminal. If the short circuit value available at the secondary of the utility transformer feeding the establishment (building) is known, and the cable impedance and other series impedances in the electrical circuit between the secondary of the transformer and the ASD input are also known, then one can calculate the available short circuit at the ASD input. **In practice, it is common to assume the same short circuit current level as at the secondary of the utility transformer feeding the ASD**. The next step is to compute the fundamental value of the rated input current into the ASD. One can rely on the NEC amp rating for induction motors to obtain this number. NEC amps are fundamental amps that a motor draws when connected directly to the utility supply. An example is presented here to recap the above procedure.

A 100-hp ASD/motor combination connected to a 480-V system being fed from a 1500-kVA, 3-Ph transformer with an impedance of 4% is required to meet IEEE 519-1992 at its input terminals. The rated current of the transformer is: 1500*1000/(sqrt(3)*480) which is calculated to be 1804.2 Amps. The short circuit current available at the secondary of the transformer is equal to the rated current divided by the per unit impedance of the transformer. This is calculated to be: 45,105.5 A. The short circuit ratio which is defined as the ratio of the short circuit current at the PCC to the fundamental value of the non-linear current is computed next. NEC amps for 100-hp, 460-V is 124 Amps. Assuming that the short circuit current at the ASD input is practically the same as that at the secondary of the utility transformer, the short-circuit ratio is calculated to be: 45,105.5/124 which equals 363.75. On referring to the IEEE 519-1992 Table 10.3 [1], this short circuit ratio falls in the 100-1000 category.

For this ratio, the total demand distortion (TDD) at the point of ASD connection to the power system network is recommended to be 15% or less. For reference, Table 10.3 [1] is reproduced below:

Current Distortion Limits for General Distribution Systems (120 V through 69,000 V)						
	Maximum Harmonic Current Distortion in percent of I_L					
	Individual Harmonic Order (Odd Harmonics)					
I_{sc}/I_L	**<11**	**$11 \le h \le 17$**	**$17 \le h \le 23$**	**$23 \le h \le 35$**	**$35 \le h$**	**TDD**
< 20*	4.0	2.0	1.5	0.6	0.3	**5.0**
20<50	7.0	3.5	2.5	1.0	0.5	**8.0**
50<100	10.0	4.5	4.0	1.5	0.7	**12.0**
100<1000	12.0	5.5	5.0	2.0	1.0	**15.0**
>1000	15.0	7.0	6.0	2.5	1.4	**20.0**

Even harmonics are limited to 25% of the odd harmonic limits above.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc} / I_L where I_{sc} is the maximum short circuit current at PCC and

I_L is the maximum demand load current (fundamental frequency) at PCC.

TDD is **Total Demand Distortion** and is defined as the harmonic current distortion in % of maximum demand load current. The maximum demand current could either be a 15 minute or a 30 minute demand interval.

Why ASDs Generate Harmonics?

The current waveform at the inputs of an ASD is not continuous. It has multiple zero crossings in one electrical cycle. Hence, the current harmonics generated by ASDs having DC bus capacitors are caused by the pulsed current pattern at the input to the rectifier stage. The DC bus capacitor draws charging current only when it gets discharged due to the motor load. The charging current flows into the capacitor when the input rectifier is forward biased which occurs when the instantaneous input voltage is higher than the steady-state DC voltage across the DC bus capacitor. The pulsed current drawn by the dc bus capacitor is rich in harmonics due to the fact that it is discontinuous as shown in Fig. 1. The voltage harmonics generated by ASDs are due to the flat-topping effect caused by an AC source charging the DC bus capacitor without any intervening impedance. The distorted voltage waveform gives rise to voltage harmonics that could lead to possible network resonance.

PHASE B SNAPSHOT 11:44:19 AM

Phaso B-H VOLTAGE: 406.2 Vrae
1.4 Crust Factor
1.1 Form Factor

Phase B CURRENT: 36.6 A rus
2.9 Crest Factor
2.8 Form Factor

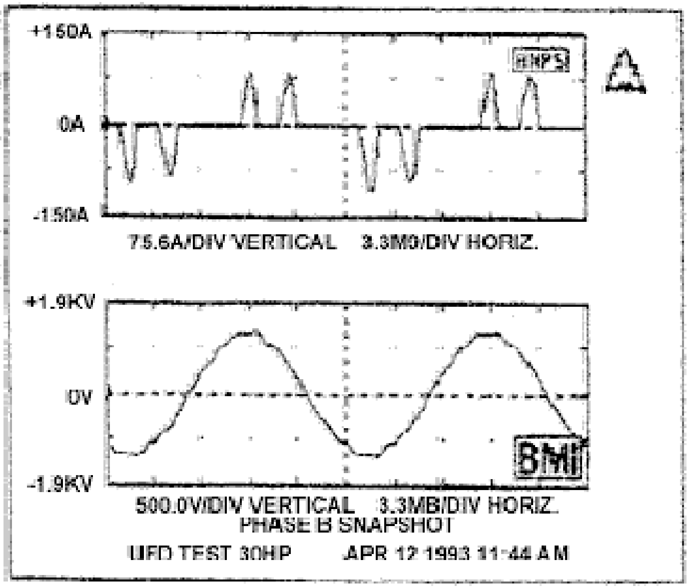


Fig. 1: Typical pulsed current waveform as seen at input of a VFD

The order of current harmonics produced by a semiconductor converter during normal operation is termed as Characteristic Harmonics. In a three-phase, six-pulse converter with **no DC bus capacitor,** the characteristic harmonics are non-triplen odd harmonics (e.g., 5th, 7th, 11th, etc.). In general, the characteristic harmonics generated by a semiconductor converter is given by:

$$h = kq \pm 1$$

where h is the order of harmonics; k is any integer, and q is the pulse number of the semiconductor converter (six for a six-pulse converter). When operating a six-pulse rectifier-inverter system with a DC bus capacitor (Voltage Source Inverter or VSI), one may start observing harmonics of orders other than those given by the above equation. Such harmonics are called Non-Characteristic harmonics. Though of lower magnitude, these also contribute to the overall harmonic distortion of the input current. The per unit value of the characteristic harmonics present in the theoretical current waveform at the input of the semiconductor converter is given by **1/h** where h is the order of the harmonics. In practice, the observed per unit value of the harmonics is much greater than 1/h. This is because the theoretical current waveform is a rectangular pattern made up of equal positive and negative halves, each occupying 120 electrical degrees. The pulsed discontinuous waveform observed commonly at the input of the ASD digresses greatly from the theoretical waveform.

Harmonic Mitigating Techniques

Various techniques of improving the input current waveform are discussed below. The intent of all techniques is to make the input current more continuous so as to reduce the overall current harmonic distortion. The different techniques can be classified into four broad categories:

(a) Introduction of line reactors and/or dc link chokes;

(b) Passive Filters (Series, Shunt, and Low Pass broad band filters);

(c) Phase Multiplication (12-pulse, 18-pulse rectifier systems); and

(d) Active Harmonic Compensation.

The following paragraphs will briefly discuss the available technologies, their relative advantages and disadvantages. The term 3-phase line reactor or just reactor is used in the following paragraphs to denote 3-phase line inductors.

(a) 3-Phase Line Reactors

Line reactors offer significant magnitudes of inductance which can alter the way that current is drawn by a non-linear load such as an input rectifier bridge. The reactor makes the current waveform less discontinuous resulting in lower current harmonics. Since the reactor impedance increases with frequency, it offers larger impedance to the flow of higher order harmonic currents. It is thus instrumental in impeding higher frequency current components while allowing the fundamental frequency component to pass through with relative ease.

On knowing the input reactance value, one can estimate the expected current harmonic distortion.

A table illustrating the expected input current harmonics for various amounts of input reactance is shown below:

Percent Harmonics vs. Total Line Impedance
Total Input Impedance

Harmonic	3%	4%	5%	6%	7%	8%	9%	10%
5th	40	34	32	30	28	26	24	23
7th	16	13	12	11	10	9	8.3	7.5
11th	7.3	6.3	5.8	5.2	5	4.3	4.2	4
13th	4.9	4.2	3.9	3.6	3.3	3.15	3	2.8
17th	3	2.4	2.2	2.1	0.9	0.7	0.5	0.4
19th	2.2	2	0.8	0.7	0.4	0.3	0.25	0.2
%THID	44.13	37.31	34.96	32.65	30.35	28.04	25.92	24.68
True rms	1.09	1.07	1.06	1.05	1.05	1.04	1.03	1.03

Input reactance is determined by the accumulated impedance of the ac reactor, dc link choke (if used), input transformer and cable impedance. To maximize the input reactance while minimizing ac voltage drop, one can combine the use of both ac input reactors and dc link chokes. One can approximate the total effective reactance and view the expected harmonic current distortion from the above chart. The effective impedance value in % is based on the actual loading as derived below:

$$Z_{eff} = \frac{\sqrt{3} * 2 * \pi * f * L * I_{act\,(fnd.)}}{V_{L-L}} \quad X \ 100$$

where $I_{act(fnd.)}$ is the fundamental value of the actual load current and V_{L-L} is the line-line voltage.

The effective impedance of the transformer as seen from the non-linear load is:

$$Z_{eff,x\text{-}mer} = Z_{x\ mer} * I_{act(fnd.)} / I_r$$

where $Z_{eff,x\text{-}mer}$ is the effective impedance of the transformer as viewed from the non-linear load end; $Z_{x\text{-}mer}$ is the nameplate impedance of the transformer; and I_r is the nameplate rated current of the transformer.

On observing one conducting period of a diode pair, it is interesting to see that the diodes conduct only when the instantaneous value of the input ac waveform is higher than the dc bus voltage by at least 1.4 V. Introducing a three phase ac reactor in between the ac source and the dc bus makes the current waveform less pulsating since the reactor is an electrical equipment which impedes sudden changes in current. The reactor also electrically differentiates the dc bus voltage from the ac source so that the ac source is not clamped to the dc bus voltage during diode conduction. This feature practically eliminates flat topping of the ac voltage waveform caused by many ASDs when operated with weak ac systems.

(b) DC Link Choke

Based on the above discussion, it can be noted that any inductor of adequate value placed in between the ac source and the dc bus capacitor of the ASD will help in improving the current waveform. These observations lead to the introduction of a DC link choke which is electrically present after the diode rectifier bridge and before the dc bus capacitor. The dc link choke performs very similar to the three phase line inductance. The ripple frequency that the dc link choke has to handle is six times the input ac frequency for a six-pulse ASD. However, the magnitude of the ripple current is small. One can show that the effective impedance offered by a dc link choke is about 50% of its equivalent ac inductance. In other words, a 3% ac inductor is equivalent to a 6% dc link choke from impedance view point. This can be mathematically derived equating ac side power flow to dc side power flow as follows:

$$P_{ac} = \frac{3 * V_{L-N}^2}{R_{ac}} \qquad P_{ac} = P_{dc}$$

$$V_{dc} = \sqrt{6}\, V_{L-N}$$

$$P_{dc} = \frac{V_{dc}^2}{R_{dc}} \qquad \text{Hence, } R_{dc} = 2 * R_{ac}$$

In the above derivation, it is assumed that the ac to dc semiconductor converter is equipped with a large DC bus capacitor which makes the dc bus voltage equal to sqrt(2) times the input line-line ac voltage. The dc link choke is less expensive and smaller than a 3-phase line reactor and is often included inside an ASD. However, as the derivation shows, one has to keep in mind that the effective impedance offered by a dc link choke is only half its numerical impedance value when referred to the ac side. DC link chokes are electrically after the diode bridge and so they do not offer any significant spike or overvoltage surge protection to the diode bridge rectifiers. It is, thus, a good engineering practice to incorporate both dc link choke and a 3 phase line reactor in an ASD for better overall performance.

(c) Passive Filters

Passive filters consist of passive components like inductors, capacitors, and resistors arranged in a predetermined fashion either to attenuate the flow of harmonic components through them or to shunt the harmonic component into them. Passive filters can be of many types. Some popular ones are: Series Passive filters, Shunt Passive filters, and Low Pass broad band Passive filters. Series and Shunt passive filters are effective only in a narrow proximity of the frequency at which they are tuned. Low Pass broad band passive filters have a broader bandwidth and attenuate almost all harmonics above their cutoff frequency.

Series Passive Filter

One way to mitigate harmonics generated by non-linear loads is to introduce a series passive filter (Fig. 2) in the incoming power line so that the filter offers a high impedance to the flow of harmonics from the source to the non-linear load. Since the series passive filter is tuned to a particular frequency, it offers a high impedance to only its tuned frequency component. Series passive filters are popular for 1-ph application where it is effective in minimizing the 3rd harmonic which is the most offending harmonic in 1-ph systems. The series passive filter offers some impedance to harmonic components around its tuned frequency and as one moves away from the tuned frequency in either direction, the impedance offered keeps diminishing. It is generally designed to offer low impedance at the fundamental frequency. A major drawback of this approach is that the filter components have to be designed to handle the rated load current. Further, one filter section is not adequate to attenuate all the different harmonic spectrum present in the non-linear load current. Unlike the shunt passive filter, the series passive approach when used as a dedicated filter does not introduce any other extraneous resonance circuit. In other words, the dedicated series passive filter does not interfere with an existing power system.

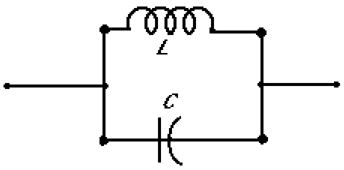


Fig. 2: Series type tuned harmonic filter topology.

Shunt Passive Filter

The second and more common approach is to use a shunt passive filter (Fig. 3). The shunt passive filter is placed across the incoming line and is designed to offer very low impedance to the harmonic currents present in the non-linear load current spectrum. The shunt passive filter processes flow of electrical energy at fundamental frequency from the source but offers a lower impedance path for the flow of harmonic energy needed by the non-linear load. In other words, the harmonic component needed by the non-linear load is provided by the shunt filter rather than the ac source. The fundamental frequency energy component flowing into the shunt filter also provides leading VARs which can be used for power factor correction. Similar to the series tuned filter, the shunt tuned filter is only effective at and around its tuned frequency. In other words, like the series tuned filter, one section of a shunt tuned filter alone is inadequate to provide all the harmonic energy needed by a typical non-linear load (ASD).

The commonly used shunt filter sections comprise of individual sections tuned for the 5th, the 7th, and perhaps a high-pass section typically tuned near the 11th harmonic. Unfortunately, if care is not taken, the shunt filter will try to provide the harmonic energy needed by all non-linear loads connected across the same bus. In this process, it could get overloaded and if it is fused, the fuse could blow. The filter sections could also suffer serious and permanent damage. Such a phenomenon is known as importing of harmonics. In order to avoid import of harmonics, it is important to use series line reactors which impede the harmonic energy flow to other sources from the shunt tuned filter sections. However, the addition of extra line inductance can contribute to a slightly new set of problem. As mentioned earlier, the shunt capacitor in the filter provides leading VARs at fundamental frequency. Leading VAR generation is always associated with a rise in bus voltage. The inductor used in preventing import of harmonics is instrumental in buffering the line voltage from the voltage at the input to the non-linear load (ASD). Thus, the rise in fundamental voltage caused by the filter is now present only at the ASD input which could trip on overvoltage. If not, the overvoltage tolerance margin would be compromised and the ASD could be more vulnerable to fault out on overvoltage thereby causing nuisance trips. The situation could be more serious if the installation happens to be close to a capacitor-switching utility substation.

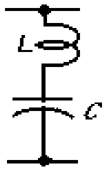


Fig. 3: Shunt type tuned harmonic filter topology.

The shunt passive filter, although used commonly in the industry for harmonic mitigation, has a serious problem of potentially causing power system resonance. The passive filter components introduced in the circuit can interact with existing network impedances and set up other unintended tuned circuit which could get excited due to the presence of appropriate harmonic components at appropriate levels. This would mean that designing and implementing a shunt tuned filter network requires an in-depth study of the existing power system network into which the filters are going to be introduced. The location of the shunt filters is also a very important issue to be considered. A central location could cause more harm than benefit under system resonance conditions, as it would jeopardize the entire system instead of affecting only a localized area. Even if a study is conducted and the tuned filters are designed carefully and are placed strategically to avoid undue system resonance, the problem is not resolved forever. The reason is that any future expansion or change in the electrical network could change the system dynamics and could warrant a newer study and possible relocation and/or redesign of the tuned filter traps.

Low Pass Broad Band Filter

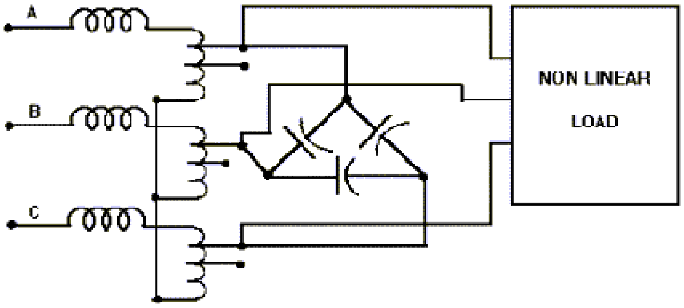
From the preceding discussions on series and shunt passive filters, it is clear that both approaches have certain disadvantages. The low pass broad band filter is however a unique type of filter which incorporates the advantages of both the series and shunt type filters and has neither of their disadvantages. The biggest advantage of the low pass, broad band harmonic filter is that it need not be configured in multiple stages or sections as the shunt and series type do. In other words, one filter section achieves the performance close to the combined effect of a 5th, 7th, and a high-pass shunt tuned filter section. Further, the inherent series impedance present in the filter topology prevents import and export of harmonics from and to other non-linear loads on the system.

The best type of passive filter is a **capacitor**. The impedance of a capacitor reduces as the frequency increases. Hence, a capacitor can effectively supply all the harmonic energy needed by a typical ASD. However, there exist two major drawbacks of using simply a capacitor. The first problem is that of importing harmonics. Any non-linear load that needs harmonic energy will extract it from the capacitor being proposed for use. This will undoubtedly overload the capacitor and can potentially cause irreversible damage to it. The second major problem is that the capacitor behaves like a power factor correction capacitor at fundamental frequency. Power factor correction is generally associated with a rise in ac bus voltage. This can potentially cause an overvoltage condition at the input of an ASD and consequently send it into a fault condition.

Both the above problems can be resolved using existing passive elements. By introducing a large valued line reactor in series with the main ac line and electrically ahead of the shunt capacitor will limit import and export of harmonics to and from the capacitor and ASD network. Introducing the reactor not only impedes the flow of harmonic currents but also electrically differentiates between the input ac supply and the capacitor terminals. The overvoltage caused by the capacitor is now limited to only its terminals and does not show up at the ac input side due to the presence of the large inductor. In order to prevent the ASD from tripping due to overvoltage from the capacitor, a buck transformer is used ahead of the capacitor. In other words the load side of the inductor is connected to a buck transformer which bucks the voltage before it is fed to the capacitors. The capacitor boosts it back up to a nominal value merely due to its power factor corrective action at fundamental frequency. The capacitor is connected right at the input to the ASD. The dc bus capacitor in the ASD draws pulsating current when it is discharged due to the loading effect. This sudden charging current is very effectively and efficiently provided by the ac capacitor of the broad band filter. Any intervening impedance in the form of a dc link choke or an extra ac line inductor in the electrical path between the ac capacitor and the dc bus capacitor hampers the much needed immediate transfer of harmonic energy. Hence, the best performance of the low pass, broad band harmonic filter is achieved when there exists no impedance between the ac capacitor and the dc bus capacitor. The majority of the harmonic energy requirement of the ASD can be met by appropriately sizing the ac capacitor, which is made to provide for it. The ac source is hence required to supply only a part of the harmonic energy requirement of the ASD, which is then reflected as low THD values in the input current spectrum. The 3-phase ac source thus provides energy to the capacitor network at fundamental frequency and the capacitor in turn by virtue of its basic nature provides the bulk of the harmonic energy required by the ASD.

Yet another way of analyzing the performance is by considering the capacitor network to a be a viable ac source. Thus, there exists two ac sources from which the harmonic energy requirement of the ASD can be met - the utility ac source, and the capacitor network. In all likelihood, it will be met by the capacitor since it is electrically closer to the ASD and also it offers a lower impedance at the harmonic order compared to the utility transformer and large series inductor of the broad band filter, when viewed from the ASD side. This is yet one more reason why the inductor of a sufficiently large value is introduced in series with the ac line as part of the broad band harmonic filter. Fig. 4 shows the schematic representation of the patented broad band harmonic filter.

ELECTRICAL SCHEMATIC FOR INPUT BROAD-BAND HARMONIC FILTER



Low Pass Filter Effect on Diode Ripple Current

During the input rectifier diode conduction period, the dc bus capacitor clamps the voltage across the ac capacitor to its existing value. Energy from the ac capacitor is transferred to the dc bus capacitor instantly. The charging current is not impeded and hence the ripple content of this charging current can be high which means that the input diode rectifiers are subject to a larger ripple current magnitude. However, this scenario is true only at light load conditions since the capacitor seems oversized under light load conditions. The magnitude of current being transferred from the ac capacitor to the dc bus capacitor under light load conditions is much lower than the rating of the diodes and so this does not merit any serious consideration. At full rated load, the ac capacitor is almost depleted and the current flowing through the large series reactor into the ac capacitor is also used partially to charge the dc bus capacitor. Flow of current through the large reactor smoothes out the ripples more than what a dc link choke or a 5% line reactor could have provided. Hence, the ripple content in the current flowing through the diode in reality is lower than the case with either a 5% ac reactor or a comparable dc link choke.

Application Issues while using Low Pass Broad band Filter

The probability of harmonic resonance occurring with the broad band harmonic filter in a power system is extremely low. This is because the low pass cutoff frequency is kept deliberately low which is very difficult and improbable to be excited in a 3-phase ac network. A detailed analysis of the interaction between a low pass filter section with a typical existing power system network is discussed in the following paragraphs. The analysis clearly shows that the low pass filter section does not interfere with the existing system and even when it does, it helps in lessening pre-existing potential problems in the network. Hence, the low pass filter renders itself for use without the need to perform complicated, expensive, and time consuming system study. The low pass filter in its original form cannot be used for ASD application since there is an inherent overvoltage across the filter capacitors which is electrically connected to the ASD input. A patented form of the low pass filter section alleviates this problem by making use of a buck transformer, which is strategically placed, in the topology.

The performance of the low pass filter has been found to be consistent through out the load range of the non-linear load (ASD). The overall current harmonic distortion has been found to be reduced from a typical value of 90 to 100% down to 9 to 12% under rated load conditions. Under light load conditions, the current THD has been observed to be in the low 4 to 8% range. This observation leads to a very important aspect of the broad band harmonic filter. **A broad band harmonic filter can now be used to correct harmonic problems created by multiple Drive loads.** In other words, as an example, one 100 hp broad band filter can be used to filter out the harmonics generated by either 10 of 10hp ASDs or 4 of 25hp ASDs or any such combination totaling 100hp of ASD load.

Because of the typical arrangement of passive components in the broad band filter, the patented low pass filter can be used only with non-linear loads and should not be used as a general purpose harmonic filter. It is specifically designed to be used with ASD loads and other non-linear loads having the same topology as the front end of an ASD.

At loads less than the rated load, the broad band harmonic filter generates leading VARs without causing voltage rise on the line side or on the power system side. This feature is similar to that of an idling synchronous motor (also known a synchronous condenser) under over-excited conditions used for providing leading power factor in many industrial applications.

Investigations on Network Interaction with the Broad Band Harmonic Filter

The broad band harmonic filter is basically a low pass LC filter section interposed in between the utility and the ASD. The LC network is tuned in such a way so as not to cause network resonance. In the broad band harmonic filter used by GE, the LC network is tuned to resonate in the neighborhood of 100 Hz. On a 60 Hz. system, it is quite improbable that a low pass LC filter tuned to around 100 Hz. would cause resonance. In order to explain resonance conditions in a network, it is interesting to consider a typical industrial plant layout. Let the industrial location be assumed to have certain power factor correcting capacitors located at the secondary of the main feed transformer. The leakage inductance of the transformer and the power factor correcting capacitor together form a resonant circuit. Let the plant be supplied by a 3000-kVA, 4% main feed transformer, having a secondary line-line voltage of 480-V. Further, let there be power factor correcting capacitor worth 150-kVA, located on the secondary-side (480-V side) of the 3000-kVA transformer. From these assumed data, the leakage inductance and the capacitor together form a resonant circuit with a tuned frequency of around 1341 Hz. This is close to the 22nd harmonic and is rather a high frequency value, which is unlikely to cause any resonance. Further, let there be an existing fifth harmonic filter having a typical tuned frequency of around 280 Hz., supplying a 45-kVA non-linear load. If one assumes that the tuned filter capacitor is about 10% of the size of the power factor correcting capacitors, then an overall network resonance point can be established. The overall network will now have two resonance points of concern - the first is that of the tuned filter itself which is 280 Hz. and a new resonance frequency which after quite a few iterations can be shown to be in the neighborhood of 2000 Hz. The tuned filter can get overloaded if it is not properly protected from importing harmonics in the neighborhood of 280Hz. The new higher frequency point of 2000 Hz. strictly depends on the ratio of the filter capacitor to the power factor correcting capacitor. The larger the filter capacitor, the smaller will be the new resonance point.

Let a broad band filter be introduced into the above network. For sake of argument, let the broad band filter be assumed to be supplying a 45-kVA non-linear load. Because of the different topology of the low pass filter section, the element which would interact with the external network would include the load resistance being supplied by broad band filter. The newly introduced broad band filter network introduces a new resonance point, which is dependent on the loading condition of the broad band filter. On performing a PSpice simulation, it is seen that there exist three distinct resonance points. The first due to the leakage inductance of the power transformer in the neighborhood of 1.1 kHz, the second due to the fifth harmonic tuned filter (trap) close to 300hz, and finally the third one due to the broad band harmonic filter close to 100 Hz. The simulation results clearly show that the broad band harmonic filter does not interact with the rest of the electrical network. Consequently, the network's existing resonance points are not disturbed. This shows that the low pass broad band filter does not even interact with the rest of the electrical network. A simple electrical diagram is helpful in understanding the above argument and is shown below:

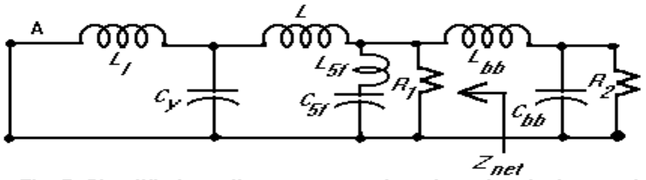


Fig. 5: Simplified one-line representation of an electrical network with a 5th harmonic tuned filter and a broad band harmonic filter.

Phase Multiplication

As discussed previously, the characteristic harmonics generated by a semiconductor converter is a function of the pulse number for that converter. A 12-pulse converter will have the lowest harmonic order of 11. In other words, the 5th, and the 7th harmonic orders are theoretically non-existent in a 12-pulse converter. Similarly, an 18-pulse converter will have harmonic spectrum starting from the 17th harmonic and upwards. The lowest harmonic order in a 24-pulse converter will be the 23rd. The size of passive harmonic filter needed to filter out the harmonics reduces as the order of the lowest harmonic in the current spectrum increases. Hence, the size of the filter needed to filter out the harmonics out of a 12-pulse converter is much smaller than that needed to filter out the harmonics of a 6-pulse converter. However, a 12-pulse converter needs two 6-pulse bridges and two sets of 30^0 phase shifted ac inputs. The phase shift is either achieved using an isolation transformer with one primary and two phase shifted secondary windings or auto-transformer which provide phase shifted outputs. Many different auto-transformer topologies exist and the choice of a topology over the other involves a compromise between ease of construction, performance, and cost. An 18-pulse converter would need three 6-pulse diode bridges and three sets of 20^0 phase shifted inputs; similarly, a 24-pulse converter would need four 6-pulse diode bridges and four sets of 15^0 phase shifted inputs. The transformers providing the phase shifted outputs for multipulse converters have to be properly designed to handle circulating harmonic flux.

(d) Active Harmonic Compensation

Most passive techniques discussed above aim to cure the harmonic problems once they have been created by non-linear loads. However, drive manufacturers are developing drives which do not generate low order harmonics. These drives use Active front ends. Instead of using passive diodes as rectifiers, the active front end ASDs make use of active switches like IGBTs along with parallel diodes.

Power flow through a switch becomes bi-directional and can be manipulated to recreate a current waveform which linearly follows the applied voltage waveform.

Apart from the active front ends, there also exists shunt active filters used for actively introducing a current waveform into the ac network which when combined with the harmonic current, results in an almost perfect sinusoidal waveform.

One of the most interesting active filter topology for use in retrofit applications is the combination of a series active filter along with shunt tuned passive filters. This combination is also known as the Hybrid Structure and was introduced into the market by the authors cited in reference [2]. Manufacturers of smaller power equipment like computer power supplies, lighting ballast, etc. have successfully employed active circuits.

Most active filter topologies are complicated and require active switches and control algorithms which are implemented using Digital Signal Processing (DSP) chips. The active filter topology also needs current and voltage sensors and corresponding Analog to Digital (A/D) converters. This extra hardware increases the cost and component count, reducing the overall reliability and robustness of the design.

Typical Test Results of Low Pass Broad band Filter

This section deals with some typical test results observed on implementing the broad band harmonic filter of Fig. 4. The test results depict the actual operating condition of the load. The true power is seen to be leading under light load condition. However, there is no overvoltage at the input ac supply which shows that the leading power factor due to the filter can be likened to an overexcited synchronous motor connected across the input ac supply.

40-hp ASD with filter

a. Power Input: 26.07 kW

b. True Power Factor: 0.91 (leading)

c. Displacement Power Factor: 0.92 (leading)

d. Average Voltage THD: 2.3%

e. Average Current THD: 7.5%

30-hp ASD with filter

a. Power Input: 20.13 kW

b. True Power Factor: 0.82 (leading)

c. Displacement Power Factor: 0.83 (leading)

d. Average Voltage THD: 2.0%

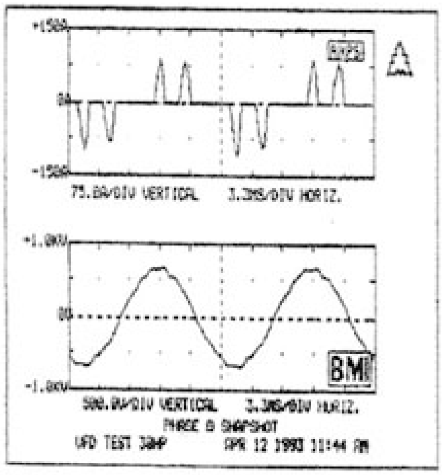
e. Average Current THD: 9.0%

Conclusion

The report discusses generation of current harmonics by non-linear loads and the IEEE-519-1992 standard to limit the quantity of these harmonics. A methodology of applying this standard to a practical industrial site has been discussed. Different harmonic mitigating techniques presently available in the industry has been highlighted. The patented broad band harmonic filter is described. An explanation is provided to show that the broad band harmonic filter does not interfere with the existing power system network to create extraneous resonance points. Experimental test results from various industrial sites show that the broad band harmonic filter is successful in mitigating (limiting) the harmonics generated by ASDs to the IEEE 519-1992 recommended values as applied to the input of an ASD. The improvement in true power factor, transformer de-rate values, and telephone influence factor are important advantages of using the broad band harmonic filter. Further, the ability of the filter to feed multiple ASDs reduces space requirements and increases the cost effectiveness of the filter-drive combination

40 hp VFD AT RATED LOAD WITH NO FILTER; THID=125.2

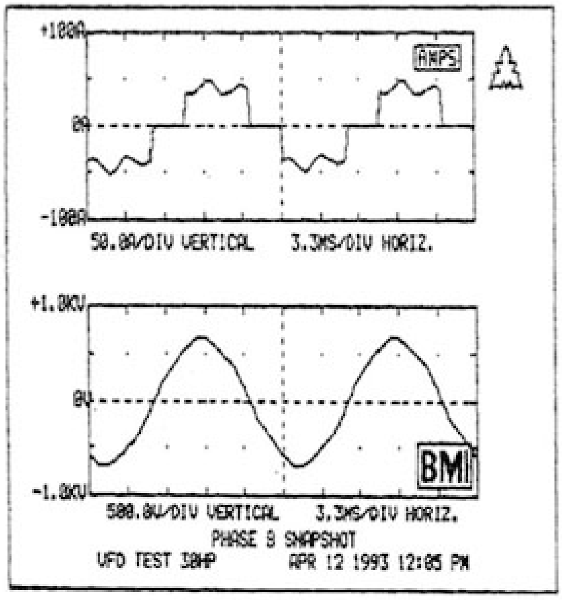
```
PHASE B SNAPSHOT            11:44:18 AM
Phase B-N VOLTAGE:   486.2 Vrms
                       1.4 Crest Factor
                       1.1 Form Factor

Phase B CURRENT:      36.6 A rms
                       2.9 Crest Factor
                       2.0 Form Factor
```



```
Total:              0.62 PF

Total:              1.00 dPF

======================================

Fundamental freq:     60.0 Hz
 VOLTAGE THD              3.1% THD avg
 -----------------------------------
   Phase A-N Volts:   3.0% THD
   Phase B-N Volts:   2.8% THD
   Phase C-N Volts:   3.5% THD
 CURRENT THD            125.2% THD avg
 -----------------------------------
   Phase A Current: 121.5% THD
   Phase B Current: 129.6% THD
   Phase C Current: 124.4% THD
```

40 hp AT RATED LOAD WITH 6% REACTOR; THID=32.4%
(Example: 3% Line Reactor + 6% DC Link Choke)

```
Phase B-N VOLTAGE:   485.3 Vrms
                       1.4 Crest Factor
                       1.1 Form Factor

Phase B CURRENT:      33.0 A rms
                       1.6 Crest Factor
                       1.2 Form Factor
```



```
Total:              0.95 PF

Total:              1.00 dPF

====================================

VOLTAGE THD              2.7% THD avg
-----------------------------------
  Phase A-N Volts:    2.4% THD
  Phase B-N Volts:    2.6% THD
  Phase C-N Volts:    3.2% THD
CURRENT THD             32.4% THD avg
-----------------------------------
  Phase A Current:   34.2% THD
  Phase B Current:   31.5% THD
  Phase C Current:   31.4% THD
```

References

[1] “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”, **IEEE Std. 519-1992.**

[2] Mahesh M. Swamy, Steven Rossiter, et. al, “Case Studies on Mitigating Harmonics in ASD Systems to meet IEEE 519-1992 Standards, **“IEEE IAS Annual meeting, 1994, pp. 685-692”.**

[3] F. Z. Peng, H. Akagi, and A. Nabae, “A New Approach to Harmonic Compensation in Power Systems - A Combined System of Shunt Passive and Series Active Filters, **“IEEE Trans. on Industry Applications, vol. 26, No. 6, Nov./Dec. 1990”.**

[4] Brian Prokuda, “Power Quality Site Surveys for Industrial and Commercial Buildings, “**IEEE A&CPS Conference 1994, pp. 97-103”.**

Author Mahesh M. Swamy; Ph.D

Reprinted by permission of MTE Corporation