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UNDERSTANDING AND SOLVING HARMONIC PROBLEMS CAUSED BY 3-PHASE NON-LINEAR LOADS

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Over the last thirty years a major change has occurred in the type of electrical loads found in industrial and commercial facilities. The advent of affordable and reliable high-current capable electronic components has resulted in the replacement of gearboxes, variable belt drives, motor generators, etc. with solid-state devices that carry out the same functions in a more efficient and controllable manner. In the HVAC (heating, ventilating, air conditioning) market, adjustable speed fans and compressors have replaced shutters and on-off switches for controlling air flow and temperature.

SCR rectifiers have taken the place of motor-generators to supply DC for elevator and pump motors, and AC adjustable-speed drives have almost eliminated the use of gear boxes on large industrial machines. However, the widespread use of solid-state devices has resulted in electrical system problems that must be addressed.

ELECTRONIC LOADS AND HARMONICS

Electronic loads, called “non linear loads” do not draw sine-wave current, but instead draw current with waveforms that do not look like sine waves. These waveforms require harmonic currents. Thus non-linear loads draw harmonic currents along with the 60 Hz current that provides power to the load. (Harmonics are defined as continuous integral multiples of the fundamental frequency. If the fundamental (or 1st harmonic) frequency is 60 Hz, the 5th harmonic would equal 300Hz (5 x 60), the 7th harmonic would equal 420Hz, etc.)
The particular harmonic currents drawn by a non-linear load depend on how the load is connected to the electrical system and the operating conditions of the load. In this paper we will deal with loads connected phase-to-phase in a 3-phase distribution system. Such loads draw 5th and 7th, 11th and 13th, and higher order harmonic pairs. (Single-phase loads connected phase-to-neutral are discussed in a separate paper.[1])
Operating conditions determine the relative amount of each harmonic drawn by the load. The amount of harmonic current drawn by a load can range from 10-50% of the fundamental 60 Hz current for 3-phase loads

such as adjustable speed motor drives and even higher for some battery charger and rectifier loads.

EFFECTS OF NON-LINEAR LOADS

Non-linear loads have both direct and indirect effects on facility operation. Direct effects are those items which directly impact operation of the electrical distribution system while indirect effects generally increase operational costs.

Direct Effects

Power factor. Induction motors and other magnetic equipment within a facility draw a type of current called “reactive current.” This current does no work, but provides the magnetic field necessary for a motor to operate. Harmonic currents drawn by non-linear loads also do no work, but enable the load to operate, and are often called, by analogy, “harmonic reactive currents.” Both reactive and harmonic reactive currents flowing in an electrical distribution system increase rms current. A single value which describes the result of this increased current is the *power factor*. Power factor is defined as real power (the power that does work) divided by apparent power (the power that must be delivered in order to do the work.) Symbolically, $F_p = kW/kVA$. For linear loads the power factor thus calculated is called “displacement power factor.” When harmonic currents are present, the apparent power is increased by these currents, and a new expression is used to calculate power factor: $F_p = kW/kVA_{rms}$, where kVA_{rms} includes harmonic currents.
This power factor, which includes all the non-working currents, is called the ”true or total power factor.”

Another way to state this definition is, “power factor is a measure of the efficiency of utilization of a power distribution system’s capacity.” Since reactive and harmonic currents do no real work but require that the system carry these currents, the presence of harmonic reactive currents lowers the power factor. Switchgear, breakers, transformers, and wires are all current limited, so the presence of harmonic currents (lowered power factor) reduces the capacity of the system to carry 60 Hz current.

For example, the secondary of a 1000 kVA 480 volt transformer is rated to carry 1200 amps rms per phase. If the phases are carrying 800 amps of harmonic current, not an unusual number for a transformer serving adjustable speed drives, with the rms current limited to 1200 amps, the transformer can only supply 894 amps of 60Hz current. The power factor is 0.75 and 25% of the transformer’s capacity is wasted carrying harmonic currents.[2] Non-linear loads drawing harmonic currents can cause overheated switchgear, buses, and transformer, to the point that transformers have “burned up.” Circuit breakers will often trip, even though they are properly sized for the 60Hz load, resulting in lost production.

Notching. In addition to harmonics, non-linear loads utilizing SCR rectifiers (typically rectifiers, battery chargers, and dc drives) can produce notching in the ac voltage sine wave. Voltage notching can lead to failure of sensitive electronic controls or timing circuits, resulting in lost production and, in some cases, destruction of both instruments and product.

Indirect Effects

Production limitation. Electrical system problems caused by non-linear loads have a direct effect on operational costs. If output is to be maintained or even increased, the electrical distribution system must be oversized. If production is limited by electrical capacity, and operating costs are constant, the per-unit cost of goods goes up. Failure of controls resulting in damaged equipment and lost production both increase cost of goods. Two other indirect problems caused by harmonics also affect operational costs.

Power factor penalties. Low power factor, in addition to reducing the usable capacity of the facility distribution system, also reduces the utility's useable capacity. In order to supply the billable kilowatts of electricity, the utility must also supply un-billable reactive and harmonic power. Many utilities respond to this by charging a "power factor penalty." This penalty compensates them for the extra capacity they must build. Power factor penalties can be quite severe. A typical penalty structure might be as follows: F_p > 90% = no penalty; F_p 85-90% = 5% of the kWh-hour charge; F_p 80-85% = 7.5% of the kWh-hour charge; F_p < 80% = 25% of kWh-hour charge. It is evident that a low power factor, can have a significant impact on power costs, and harmonic currents contribute greatly to reducing power factor.

Regulations. Regulations on harmonic distortion can also influence the cost of power. The most common harmonic regulation imposed by utilities is IEEE 519-1992. This document is often used by utilities to limit the amount of harmonic current customers are permitted to draw from the utility system.

IEEE 519. IEEE 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," addresses both current distortion and voltage distortion. The regulatory portion of this document is found in chapters 10 and 11.

Chapter 10 is entitled, "Recommended Practices for Individual Consumers." In section 10.1, general, the following words are found: *"This section describes the current distortion limits that apply to individual consumers of electrical energy. Section 11 describes the quality of electrical power that the producer should furnish to the consumer. These limitations are for the benefit of all parties involved."* The reason individual consumers are limited in harmonic current distortion is due to the recognition by the authors of the standard that the consumer's loads were directly responsible for the producer's voltage distortion.

By limiting currents drawn by a customer, distortion of the voltage delivered to other customers would be limited. Table 10.3 contains data showing the maximum current distortion which a customer's facility is permitted to draw from the utility distribution system.

Uniform measurements are required to ensure compliance with regulatory limits, so a standard measuring point was needed. The concept of the "PCC" or point of common coupling was introduced. This point of measurement was specified as the place where the utility and customer interface and both current and voltage standards were to be applied at this point.

Chapter 11 is entitled, "Recommended Practices for Utilities." Quoting from section 11.1, General, *"The distortion limits recommended in this section establish the maximum voltage distortion at the point of common coupling (PCC) with each consumer."* Table

11.1 contains the voltage distortion limits for utilities. It is in this table that the familiar 5% number for voltage distortion, at bus voltages up to 69kV, is found.

As mentioned, in order to ensure that they do not exceed the 5% voltage distortion limitation at the PCC, thus ensuring the quality of power delivered to all customers, the utilities impose harmonic current limitations on the customer, also at the PCC. (Note that IEEE519 limitations are applied only at the point of common coupling, not within the user's electrical distribution system.) Utilities either charge power users for high harmonic distortion or require them to take mitigating action to remove the distortion.

IMPROVING POWER FACTOR

Linear loads – no harmonic currents. Improving low displacement power factor caused by motors and other inductive loads is a matter of supplying the reactive current from an alternate source. Power capacitors connected phase to phase provide this current and raise the power factor. However, when non-linear loads are present in the system, the harmonic currents can destroy power capacitors. Thus a different means of improving power factor is needed.

Non-linear loads – harmonic currents. Improving total power factor in the presence of harmonics caused by non-linear loads requires a means of supplying reactive current and removing the harmonic currents from the system.[3] A number of harmonic filtering devices can be supplied. These devices are discussed briefly here and in more detail in another paper.[4]

PASSIVE HARMONIC FILTERS

Passive harmonic filters are RLC tuned filters which either remove harmonic currents from the distribution system or, in the case of the series blocking filter, prevent harmonic currents from being drawn by the system. Filters are tuned to the lowest harmonic produced by 3-phase loads, the 5th, and are broad band enough to remove significant quantities of 7th and higher harmonics as well. In addition to removing harmonic currents the capacitors in the filter provide reactive current to improve displacement power factor. The end result is the total power factor is improved.

These filters can be sized to handle the harmonic current produced by a single load, or can incorporate multiple switched filter steps enabling the removal of harmonic currents produced by a number of loads. Multiple step filters are switched by an electronic controller which senses the need for filtering and switches steps in and out as the load changes.

Single Filters

Series blocking filters. Series blocking filters consist of an RLC tank tuned to have an almost infinite impedance at the 5th harmonic. A tuned tank is placed in series with each of the three phases supplying the non-linear load, preventing the load from drawing any 5th harmonic current. The load, which obtains its power from the 60Hz current, draws the same amount of this current with or without the filter. Thus the load continues to operate, only without 5th harmonic currents. By blocking 5th harmonic current, the filter changes the way in which the load draws its current. Instead of a high peak waveform, the current waveform drawn by the load is more trapezoidal in shape. Since the harmonic content of any waveform is determined by the shape of the waveform, it is clear that the harmonic spectrum of current drawn by the power supply will change when the filter is installed.
In addition to containing almost no 5th harmonic the spectrum is lower in 7th, and higher order harmonics as well.

Series blocking filters can be manufactured for 208, 240, 480, and 600 volt systems. They are rated for the horsepower of the drive and are available for adjustable drives up to 15 hp. For drives larger than this, shunt filters become more cost effective.

Shunt filters. Shunt filters are RLC circuits tuned to have a minimum impedance at a frequency just below the 5th harmonic, normally 282 Hz. They are connected phase-to- phase across the line and serve to shunt harmonic currents. Since they appear as the lowest impedance in the system to 5th harmonic currents, the filters can be said to “trap” harmonic currents, preventing their flow in the rest of the system. (These filters are often called “trap filters.”) Shunt filters also provide reactive current to improve displacement power factor, and are rated in kVAR as are power capacitors. Shunt filters are available for 208, 240, 480, and 600 volt systems. Non-linear loads from 20 Hp to the largest loads available at these voltages can be accommodated. Shunt filters can be installed for a specific load or can be sized to handle all the loads on a bus or system.

Detuned capacitors. In many situations displacement power factor improvement is the major concern and harmonic removal is secondary. Ordinary power capacitors cannot safely be used for displacement power factor improvement when non-linear loads are present. Instead, a special detuned capacitor is available. This filter is an RLC circuit tuned to have a minimum impedance near the 4th harmonic, usually about 252 Hz. At this tuning the filter is not as effective at removing harmonics as the shunt filter, but still removes some harmonic currents. However, the tuning enables this unit to be safely used in the presence of harmonics. Thus displacement power factor can be improved in situations where capacitors cannot be connected. Detuned capacitors, rated in kVAR, have lower cost than shunt filters and are appropriate for power factor improvement where harmonic removal is not the major concern.

Multi-Step Filters

Multi-step filters can be provided either as shunt filters or detuned capacitors. These units consist of a number of RLC tuned steps switched in and out by a controller. Each step in the multi-step shunt filter is a complete self-contained tuned filter. Each step in a multi- step detuned capacitor is a complete self-contained detuned capacitor. Such units are usually placed on a distribution bus or at a transformer serving multiple non-linear loads. As loads are switched on or off during facility operation, the controller switches filter steps in and out to maintain a target power factor. There are two different switching methods available depending on the type of load.

Ordinary switching. The most common type of switching for multi-step filters uses a standard var controller to initiate switching, and electromagnetic contactors to connect or disconnect each step. The controller is set to maintain a particular power factor and a current transformer is used to sense the reactive and harmonic current flowing to the load. As the load changes, the controller switches steps in or out to follow the change. To avoid “searching” as the load varies slightly, the controller is set to switch when the power factor is outside of a window, often ± 20%. In order to protect the capacitors and contactors from excessive switching, a built-in time delay holds the switching repetition rate to about 1 minute per step. This is more than adequate for most industrial situations, since loads do not change very rapidly.

Electronic switching. In some situations, loads change rapidly and ordinary step switching is not satisfactory. This is the case for example, where multiple elevators are in operation in high-rise buildings. The starting and stopping of the elevators results in rapidly varying demands for power factor correction. To make matters worse, in emergency operation on a generator, ordinary step switching could result in a period of leading power factor, which could destroy the generator. Therefore a switching method is need which will enable the filter to closely track the load. Electronic filters, both shunt and detuned capacitors can be manufactured with rapid electronic switching of steps.

Although a standard var controller is used, the actual switching is accomplished with solid state relays which operate instantly and have no limitation on the rate of switching operations.

These electronically switched filters can track power factor changes on a half to full cycle basis, providing almost instantaneous correction with no danger of developing a leading power factor when the load is on generator operation. These filters are designed for elevators, welders, cranes, ski lifts, and other loads which have rapidly changing harmonic or reactive current requirements.

ACTIVE FILTERS

Active filters utilize an entirely different technology from passive filters. In operation an active filter looks at the harmonic waveform being drawn by a non-linear load, analyzes that waveform and then injects harmonic currents into the line that are of equal amplitude and 180° out-of-phase to each harmonic current being drawn by the load. The injected currents cancel each harmonic current and the load, as seen by the utility, appears to be an almost perfect sine wave. The filters are sized to cancel a certain number of amperes of harmonic current and can be set to cancel any percentage of any combination of harmonics. They can also provide reactive current for displacement power factor. The limitation is the total ampere capacity of the filter. The filters are constructed in modular fashion and the addition of extra current modules will enable the filter to handle almost any amount of harmonic or reactive current. The filter can track changes in harmonic current demand instantaneously. While quite expensive, active filters are finding a market in areas where absolute harmonic control is required and loads vary rapidly and frequently.

SOLVING HARMONIC AND POWER FACTOR PROBLEMS

Harmonic and power factor problems can be readily solved by the proper application of the various mitigating devices discussed above. However, before any problem can be solved one musts carefully define the problem. It is not enough to say that the presence of adjustable speed drives causes harmonics which are a problem. As we have shown, the real problem may be a utility regulation, and while the harmonics may be causing this problem, the way in which they are handled is determined by the end result which is desired. The first question that must be answered before any filtering is considered is, "Why is this problem being addressed?" A sampling of problems will be examined and the most suitable solution will be outlined.

Utility power factor penalty

If the problem to be addressed is a penalty from the utility for poor (low) power factor, and non-linear loads are present, then the solution is to get the greatest number of vars for the least amount of money. The least expensive filter in this instance is a fixed detuned capacitor sized to improve the power factor of the entire facility. This filter could be connected on a bus or at the service entrance switchgear and would be protected either by a switchgear circuit breaker or a breaker built in to the filter. If a single large load (for instance a 500 hp drive) was to be switched off during normal operating periods, the filter might be large enough to drive the power factor leading. In this case, two filters might be used; one floating on the line for the majority of the facility and one sized for the large drive to be switched on and off with the drive.

This type of installation would require that the filters be turned off during plant shutdown, such as nights or weekends, to avoid leading power factor. If the facility load changed frequently in normal operation, a switched detuned capacitor would be the most cost-effective solution to this power factor penalty problem. Either of these solutions will reduce the utility power factor penalty. An added benefit is reduced transformer loading. If the transformer is anywhere near loaded, improving the power factor will reduce transformer temperature.

Utility harmonic limitation

If the utility requires that a facility containing non-linear loads meet IEEE 519 harmonic current limitations, a switched shunt filter, sized to remove sufficient harmonic current from the facility, can be connected at the service entrance switchgear. In normal operation the loads will not vary enough to require fast switching and this type of filter may be the most cost effective. However, if the facility contains only a few large non- linear loads which do not operate continuously (for example a number of 350 hp dc drives for plastic extruders) it might be better to connect a filter at each drive, sized to handle the harmonic and reactive requirements of that drive, and switched on and off with the drive.

Increased transformer capacity and lifetime.

Hot distribution transformers are another type of problem often encountered when non- linear loads are being powered. A transformer that is more than 50% loaded and is carrying significant harmonic currents is likely to be running extremely hot. Since heat is the major cause of transformer failure, reducing the temperature will reduce the chance of failure. Also, removing harmonic currents from the transformer will increase the amount of useable load. A switched shunt filter located at the transformer will provided the needed harmonic reduction, thereby reducing temperature and freeing up capacity. This solution is always more cost effective than increasing transformer size.

Increased internal capacity.

In many facilities the need to supply harmonic and reactive currents reduces useful system capacity to the extent that needed equipment cannot be connected. If the choice is either to increase the size of the system with larger transformers and buses or remove the excess current, the latter is always more cost effective. In this case, adding filters at the service entrance will not increase capacity within the facility since the harmonic currents will still flow through the distribution buses. Fixed filters at each load make the most sense since removing harmonic currents at the load provides increased capacity throughout the facility. If loads are changed frequently, each filter can be switched on and off with its load. If new non-linear loads are to be installed, a properly sized filter should be included with each new load. In addition to increasing internal capacity, this type of filter installation will reduce transformer heating and free up transformer capacity.

More cost effective design.

When a new facility is being designed or major renovations to an existing facility are being considered, it is fruitful to consider harmonic mitigation from the beginning of the design process. With the proper filtering design, major cost savings can result from a reduction in the required size of the electrical distribution system. Utilizing a smaller system to its capacity, rather than over-designing a system to handle wasted current capacity, is always the most cost effective way to design such systems.

CONCLUSIONS

Problems encountered in powering 3-phase non-linear loads have been discussed. The presence of these loads introduces harmonic currents into the electrical distribution system, leading to lowering of the total power factor with the resultant reduction in useable system capacity. A number of harmonic filters have been examined.

The most important question to answer when 3-phase harmonic filtering is being considered is, “Why is this project being undertaken?” A number of answers to this question are given as examples. From these examples it can be seen that, although there are numerous reasons for removing harmonic currents, the results are always the same. Power factor is increased, transformer heating is decreased, and wasted capacity is made available. With the proper filtering method matched with the problem, harmonic mitigation in 3-phase electrical distribution system can be readily and economically accomplished.

1. *Harmonic Currents and Voltages, Causes, Problems and Solutions,* White paper, M.Z. Lowenstein, 1999.
2.
$$I_{rms} = \sqrt{I_{60\ Hz}^2 + I_{harmonics}^2}$$
$$1200 \text{ amps} = \sqrt{I_{60\ Hz}^2 + (800)^2}$$
$$I_{60\ Hz} = \sqrt{(1200)^2 - (800)^2}$$
$$I_{60\ Hz} = 894 \text{ amps}$$
3. *Knocking out Harmonics and Improving Power Factor,* M.Z.Lowenstein, J. Holley, M Zucker, Electrical System Design, March, 1988.
4. *Design and Application of 3-phase Harmonic Filters,* M.Z. Lowenstein, White paper, 2000.

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