Guidelines for Applying Capacitors to Low Voltage Systems

-controlling power factor and distortion-

[This article is extracted from a paper developed by the authors, entitled "Harmonic Considerations on Low Voltage Systems". The paper was prepared for the Textile, Fiber, and Film Industry Technical Conference - May 1991. A copy of this paper can be obtained by checking the box on the enclosed post card and returning it to Qual-Tech Engineers.]

INTRODUCTION

Over the past decade there has been a significant increase in the use of shunt capacitors and harmonic producing loads on low voltage systems (up to 1000 volts). When used properly, this combination of capacitors and harmonic producing devices can result in a significant increase in the efficiency of the operation of the electrical system. When they are not used properly, harmonic distortion can become excessive and this can negatively affect the operation of the facility. The biggest concern is harmonic distortion. On low voltage systems, the standards have recommended a voltage distortion limit of 5% with a 3% maximum for sensitive loads such as hospitals and airports. When these limits are met, problems rarely occur. In this article guidelines are provided for controlling distortion while still using harmonic producing loads and capacitors.

THREE PHASE HARMONIC PRODUCING LOADS

At low voltages most three phase harmonic producing devices are 6-pulse and, therefore, exhibit the following harmonics: 5, 7, 11, 13, 17, 19, etc. (This includes all of the odd harmonics, except for multiples of three.) Examples of such devices are variable speed and variable frequency ac drives, dc drives, three phase power controlled furnaces, UPS systems, dc chemical processes, welders, and many other types of equipment.

The harmonic content of such devices is generally highest at the fifth harmonic and continually decreases as the harmonic number increases. Example harmonic currents for such devices are given in Table 1 for operation near full load. When the harmonic content on the system is excessive, some of the common problems that occur are overheating of transformers, overheating of motors, unexplained fuse blowings or breaker trips, misoperation of electronic devices, and other similar problems. Excessive distortion for these types of loads can generally be controlled by using higher pulse number devices or adding filter banks to the system.

Table 1
Harmonic Currents for Developing Guidelines

Harmonic	Harmonic Current (%)
1	100.0%
5	20.0%
7	12.0%
11	8.0%
13	7.0%
17	4.5%
19	4.0%
23	3.0%
25	3.0%

OTHER TYPES OF HARMONIC PRODUCING LOADS

The vast majority of 3-phase harmonic producing loads on low voltage systems consists of 6-pulse rectifiers, but there are other types of harmonic producing loads. The next most common are probably 12-pulse and 3-pulse loads. At low voltage, 12-pulse is relatively rare, although examples could include UPS systems and sensitive welding operations. From a harmonic point of view, 12-pulse reduces the distortion compared to 6-pulse above. 3-pulse is also relatively rare. It exhibits even harmonic characteristics, including the 2nd and the 4th. These even harmonics cause transformer saturation and significant heating, and consequently, they are seldom used at significant kVA ratings and, in fact, should be avoided.

Single phase loads are usually low power and are commonly associated with zero sequence currents and the overheating of the neutral. This problem is usually mitigated by over sizing the neutral and rating the supplying transformer to handle the harmonic duty. (Ungrounded three phase capacitor banks do not affect zero sequence harmonics.)

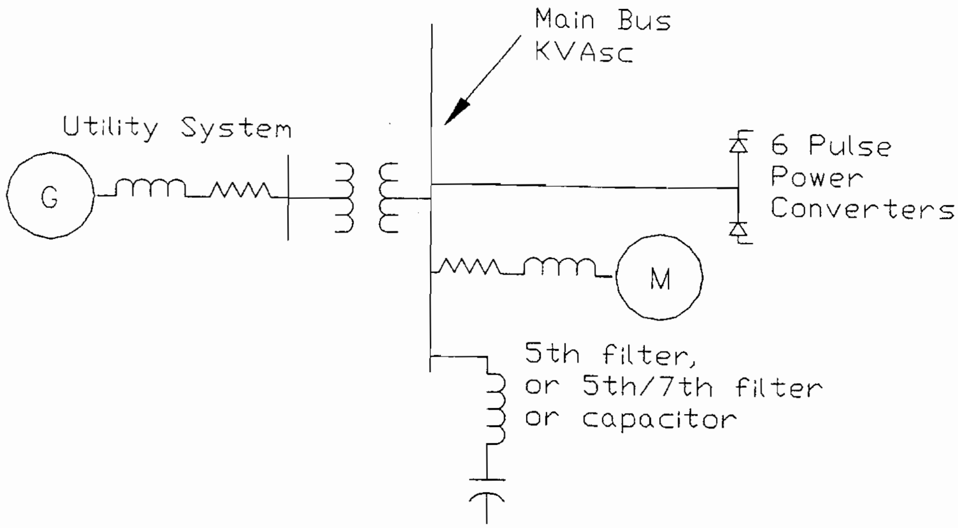

Figure 1
Typical Industrial Plant

SYSTEM CONFIGURATION

Figure 1 illustrates a simplified one line diagram of a typical industrial plant consisting of a mixture of linear and nonlinear loads with a capacitor bank used for power factor correction. This example system is general enough to apply to a very high percentage of the low voltage systems which are in service and is the basis for the derivation guidelines given in this article. The key factors associated with this example system are summarized as follows:

> The nonlinear loads are six pulse converters with the harmonic currents given in Table 1.
>
> For plants that contain many drives that operate at random speeds and operating conditions, it is reasonable to determine the harmonic content of all the drives by taking the square root of the sum of the squares of the individual drive kVA values and then determining the harmonic content per the values in Table 1. This method should be applied with discretion since it decreases the total harmonic current injection and can yield optimistic results.

In most cases, capacitors are usually applied to an industrial system to reduce a power factor tariff imposed by the utility or to release system capacity. In either case a predetermined amount of kvar is determined without regard to harmonics. In the following pages a step by step procedure is outlined that will facilitate the plant engineer in predicting the total harmonic voltage distortion (Vthd) when the addition of capacitors or variable speed drives is planned. In situations where the Vthd is over the IEEE recommended limit of 5%, a minimum harmonic filter size can be determined.

HARMONIC DISTORTION WITHOUT CAPACITORS

Since the harmonic currents are considered as a constant percentage of the total drive current, a relationship relating the Vthd to the drive kVA (kVA6p) and the short circuit duty (kVAsc) can easily be developed. The Vthd without capacitors or filters on the system illustrated in Figure 1 can be determined by the following equation using the harmonic current values given in Table 1:

$$\%Vthd = 2.35 \times (KVA6p/KVAsc) \times 100\% \qquad (1)$$

The plot of this equation is shown in Figure 3. It is apparent that a kVAsc/kVA6p ratio of less than 47 will result in a Vthd of greater than 5%. For a typical 2000 kVA transformer with a 1% system impedance and 5.75% transformer impedance, this equates to approximately 30% of the total transformer load consisting of 6-pulse power converters. If the kVAsc/kVA6p is less than 47, it is recommended that filters be applied to minimize voltage distortion and risk of equipment damage.

HARMONIC DISTORTION WITH CAPACITORS

The application of power factor correction capacitors to the system in Figure 1 may cause the Vthd to increase. This is due to the formation of resonance between the capacitor bank and the system impedance. Figure 2 illustrates an impedance scan of an industrial plant viewed from the drive which shows a high impedance near the seventh harmonic due to the addition of the capacitor bank. When no capacitors are energized on the power system, a purely inductive impedance is seen. The resonance causes an increase in impedance and, therefore, the injected current from the 6-pulse drives causes an increase in the harmonic voltage. The harmonic at which the resonance occurs can be determined by the following equation:

$$h = \sqrt{KVAsc/kvar} \qquad (2)$$

In general, if "h" is determined to be close to one of the harmonic currents listed in Table 1, significant harmonic distortion can occur. In Figure 3, the maximum Vthd is plotted for the example system for the condition where "h" is equal to one of the frequencies listed in Table 1. From Figure 3 it is evident that if kVAsc/kVA6p is less than 175 and capacitors are applied on the system, Vthd may exceed 5%. For a typical 2000 kVA transformer with a 1% system impedance and 5.75% transformer impedance, this equates to approximately 10% of the total transformer load consisting of 6-pulse power converters. In power systems containing many small drives operating at different phase angles, the total higher order harmonic currents will be less than the values shown in Table 1 and therefore the Vthd predicted by Figure 3 will also be less. When multi-step switched capacitor banks are used, the resonant frequency will decrease as steps come on. If the 6-pulse load is greater than 10% of the total, it is very likely that resonance and high distortion will occur at one or more of the capacitor values.

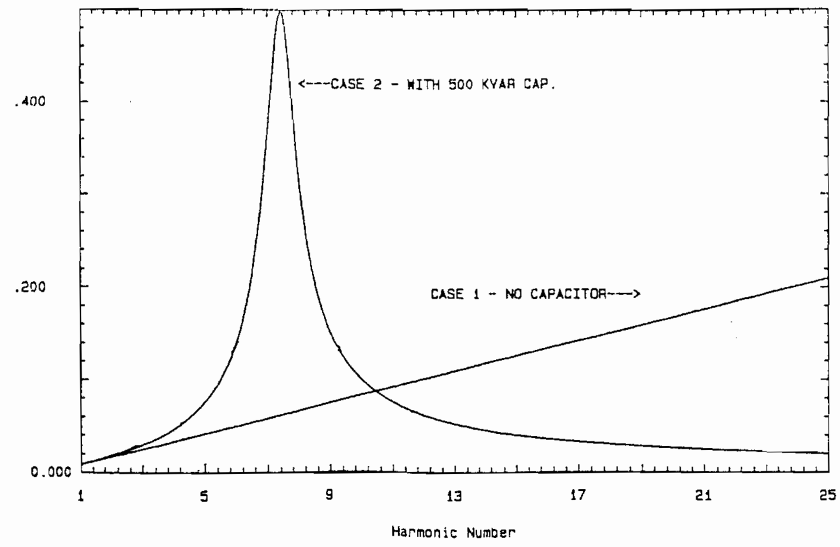

Figure 2
System Impedance Scan vs. Harmonic Number

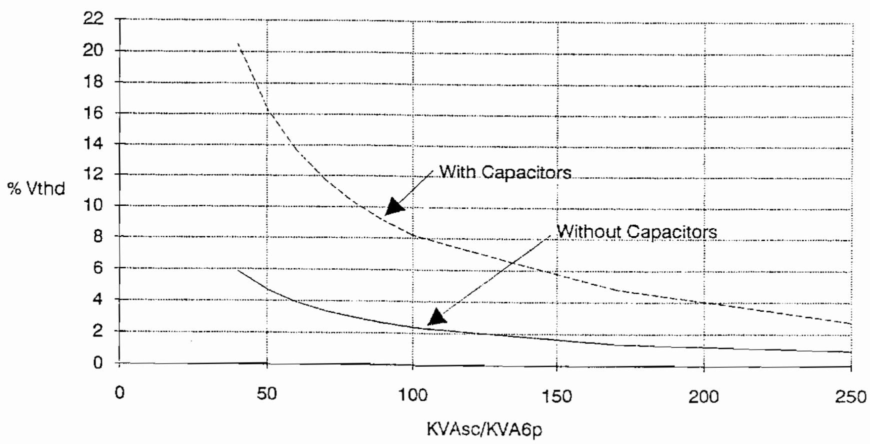

Figure 3
Maximum %Vthd vs. KVAsc/KVA6p

HARMONIC DISTORTION WITH FILTERS

If voltage distortion is determined to be a problem, a filter may be applied to the system. Figure 4 illustrates how a 5th harmonic filter reduces the system impedance near the 5th harmonic: this will in turn reduce the voltage distortion. The filter, when tuned to the 5th harmonic, will force the system resonance to exist below the 5th where usually no significant harmonic currents exist. A minimum filter size can be determined from Figure 5 to limit the voltage distortion on the main bus to 5%. Figure 5 shows four curves; two curves for filters applied at the main bus and two corresponding to filters applied on the secondary of an isolation transformer or a series reactor with 5.75% impedance serving a large drive or group of drives. The kvar size of the filters on the secondary side of the isolation transformer are smaller, but isolation transformers are not always used. The kvar size of the 5th/7th filter is smaller, but it requires an additional set of reactors and, therefore, may be more expensive. The specific filter design is usually determined by both system requirements and economics. If the filter requirements are less than the power factor requirements, a larger filter can be applied.

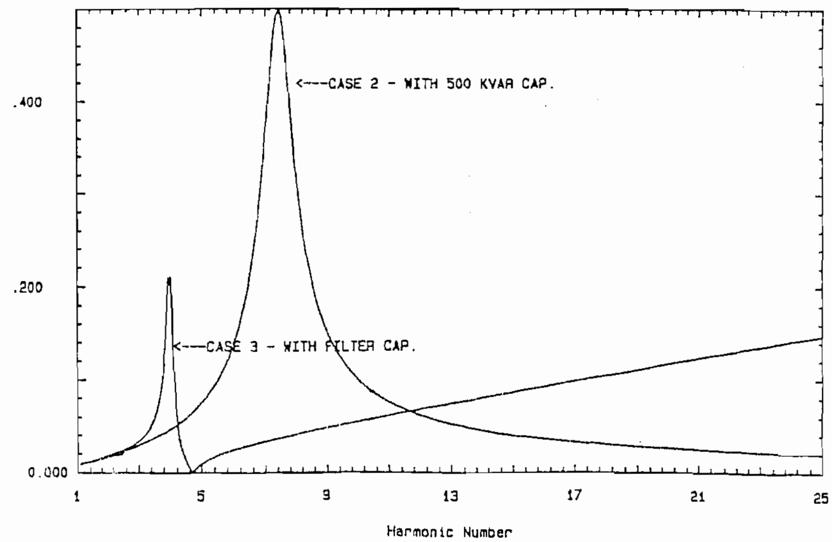

Figure 4
System Impedance Scan vs. Harmonic Number

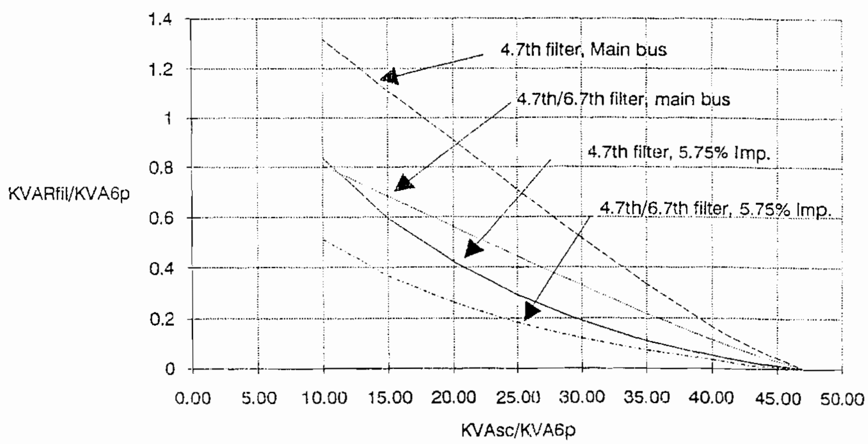

Figure 5
Minimum Filter Design to Limit Vthd to to 5%

CONCLUSIONS

In most low voltage installations, the following guidelines can be followed:

1. If the kVA of harmonic producing load is less than 10% of the transformer kVA rating, capacitors can be applied without concern for excessive distortion.

2. If the kVA of harmonic producing load is less than 30% of the transformer kVA rating and the capacitor kVAR is less than 20% of the transformer kVA rating, capacitors can be applied without concern for excessive distortion.

3. If the kVA of harmonic producing load exceeds 30% of the transformer kVA rating, capacitors should be applied as filters. See Figure 5 for guidance.

These guidelines are generally applicable when transformers with a 5.75% impedance are used and the system impedance behind the transformer is less than 1% on the transformer base.

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