INTRODUCTION

The inappropriate installation of reactive energy compensation equipment in industrial facilities gives rise to a great variety of technical problems. These problems cause significant differences in relation to the usual problems in distribution networks.

The differences start at the very approach to reactive power compensation and extend to the characteristics of the compensation units, the loads or the influence of the standards.

Iberdrola has been collaborating for many years with its customers, by working inside their facilities. Thanks to this experience, characteristic problems have been observed in industrial facilities, which are presented in the article that follows.

INDUSTRIAL COMPENSATION vs. DISTRIBUTION NETWORKS COMPENSATION

Power factor correction is a common practice both in distribution networks and in industrial facilities. However, the motives for compensating reactive power in an industrial installation and the problems that usually arise after this installation are different from the usual ones in distribution networks.

The reasons for which an electric utility installs capacitor banks might be technical, such as to avoid overloads in transformers and lines; or economic, such as, for example, to reduce energy losses or, depending on the legislation, to avoid penalties.

Nevertheless, the main reason, and in most cases the only one, why a customer installs a capacitor bank is to avoid penalisation in the electricity bill.

On the other hand and in general, the installation of capacitor banks in medium or high voltage substations does not usually cause great problems for electric utilities, beyond the normal problems of capacitor and breaker maintenance. In fact, when technical problems occasionally exist after the installation of capacitor banks in substations, it is more frequent for these to affect those customers whose facilities are not appropriate, rather than the distribution network itself.

However, industrial customers often suffer serious problems caused by their own reactive power compensation system. The most common and better known are those related with harmonics, although there are others related with interharmonics, high frequency surges and even EMC problems.

As a result, the appreciation of the person responsible for an industrial installation is different from that of the personnel of an electric utility. For the former, reactive power compensation does not usually solve any problems but the opposite, it causes problems such as damage to equipment or defects in the production process, which, in extreme cases, might even lead to fires.

Therefore, for a customer, reactive power compensation is no more than a necessary evil, something which has to be installed because it pays for itself within less than one year due to the application of the electricity rate, but not a solution to a problem, as it can be for an electric utility.

In fact, in the first stage of liberalisation of the Spanish electric market, the penalty for reactive power consumption was eliminated and, as a result, a large number of industrial customers disconnected or stopped updating their capacitor banks. After a new change in legislation, penalties were brought back in 2002 and a strong campaign took place for the installation of capacitor banks. As a result of this sudden and massive introduction of capacitor banks, a great deal of problems related with “power quality” are arising in numerous industrial installations.

REACTIVE POWER COMPENSATION FOR MEDIUM AND HIGH VOLTAGE

In order to compensate power ratings above 1 MVAr, the connection of capacitors in medium voltage systems might be the cheapest option. In view of the fact that customers value mainly the economic facet, it is usual for them to opt for simple solutions that do not have regulation systems in order to connect or disconnect the capacitors. In fact it is common, in medium voltage capacitor banks with not very high power ratings, for customers to reduce costs by connecting the capacitors through fuses, without a breaker, without doing any calculations of harmonics. In the capacitor banks of distribution substations, the most habitual problems are due to switching transients. However, as most customers usually keep their capacitors permanently connected, they do not usually have problems of this kind.

It is advisable to differentiate between two types of industrial compensation in MV or HV:

- Customers who connect capacitors directly at the PCC.
- HV customers who connect capacitors at MV bus bars.

In both cases, a technical particularity of compensation in MV or HV must be taken into account, the resulting circuit
forms a predominantly reactive system, with very little damping in comparison with low voltage systems. This means that resonances, especially those that are produced at high order harmonics, are more important than usual in low voltage systems.

Connection of capacitor banks at the PCC

To analyse the problems of capacitor banks connected at the Point of Common Coupling, they must not be considered as a part of the installation but simply as one more element in the distribution network.

Variable resonances. In these circumstances, we deal with a capacity which is connected in parallel with the capacitor banks of the distribution network or with the capacity of the lines and which, additionally, will have a parallel resonance with the network inductance. There are, therefore, different variable configurations depending on the hour of the day and on the maintenance work on the network.

In the case of untuned capacitor banks, the most frequent because they are the cheapest, this gives rise to different resonance frequencies which gradually change throughout time. As a result, there is a high possibility that a resonance with harmonics takes place in some of these configurations. These harmonics might come from the customer itself or from any other source in the proximity.

It must be taken into account that the capacitor banks of this type of customers are small in comparison with the power of the network, which gives rise to high resonance frequencies, which are hardly damped.

Connection of capacitor banks at intermediate MV bus bars

At customers connected to high and very high voltage networks, it is common to have intermediate medium voltage bus bars. In view of the fact that these are customers with high consumption levels, the most economic reactive correction scheme consists of connecting the capacitors at medium voltage.

This type of system has the following peculiarities:
- It is an LC system with very low damping.
- The power of the capacitor bank can be between 10% and 70% of the power of the transformer.
- In some types of industries, the power of the non-linear loads is about 3 times greater than the power of the capacitor bank.

Untuned capacitor banks. The cheapest option is to use capacitor banks without an inductance to filter or reject harmonics.

The first problem of this configuration is due to the connection transients of the capacitor banks which, in view of the previously mentioned characteristics, are very strong and might cause damage at the capacitor banks or tripping in the production process. The habitual practice in these cases is to keep the capacitor bank permanently connected. The second problem is the inevitable resonance at some harmonic frequency, although this is easy to calculate or, otherwise, easy to detect at the time of commissioning. The most serious problems usually occur when the customers enlarge the capacitor bank or change the factory loads on their own, without making calculations about harmonics.

Tuned capacitor banks. Tuning of the capacitor banks avoids the problems indicated in the previous point, although some other kinds of problems have been detected. Arc furnaces emit interharmonics, which must be considered when designing the capacitor bank, as they might mean a severe overload of the capacitor bank components, even leading to their destruction. In fact, the use of second order filters for arc furnaces requires a greater oversizing of their components than for other uses. Another option is the use of higher order filters.
Another problem is the attraction of harmonics coming from the distribution network. The tuning of a capacitor bank is usually calculated in order to avoid problems with the harmonics emitted by the customer itself. Nonetheless, it must be taken into account that the tuned capacitor bank presents a series resonance in relation to the HV network at a lower frequency than the series resonance in relation to the MV network.

The resonance in relation to the HV network is more difficult to calculate, since factors beyond the customer’s control also affect.

In any case, the most serious cases of damage have occurred, once again, at customers who have modified the power of their capacitors on their own, also inadvertently altering the tuning of the capacitor bank. It is typical to increase the power at the capacitors of a tuned filter to the 5th harmonic and for this filter to start to absorb the 3rd harmonic present in the network.

**REACTIVE POWER COMPENSATION FOR LOW VOLTAGE**

The most frequent case at industrial customers is to compensate the reactive power at low voltage. To do this, there are on the market a large number of manufacturers that offer standardised products with power ratings up to and even exceeding 1000 KVAR.

This is a very well known and widespread product and, as a result, on many occasions it is installed without enough study. Therefore, it is very common to find industrial installations where responsible for maintenance consider that it is normal for capacitors to become damaged and that they have to be replaced regularly, in spite of the fact that these products are designed for long-term use.

**Peculiarities of low voltage industrial systems**

In order to implement a reactive power compensation system in a low voltage industrial system, it must be taken into account that this might cause great differences with regard to the correction of reactive power in a distribution network.

**Larger capacitor banks, in proportion to the transformer.** The capacitor bank needed in many industrial installations can be almost as powerful as the transformer. There are loads that have power factors of 0.7 and even lower. One extreme case takes place when there is a generator connected to the low voltage system. In this case, the capacitor bank can be larger than the transformer. As a result, the resonance frequencies in industrial installations can become noticeably lower than the typical resonance frequencies of distribution networks.

**Greater number of switching operations and configurations.** Precisely due to the large size of the capacitor banks and the variable nature of consumption levels, the use of automatic capacitor banks has spread. This circumstance has two consequences. The first is the high number of switchings of the contactors, as many as hundreds of switchings daily, which means a greater stress on materials.

On the other hand, as there are multiple capacitor bank configurations, depending on the number of capacitors connected, there are the same number of different types of behaviour in the presence of harmonics, in spite of its being the same installation. In addition to complicating calculations, this circumstance increases the possibility of the existence of an inappropriate configuration.

**Greater proportion of disturbing loads.** Nowadays, most of high power industrial loads generate harmonics. It is not unusual to find a transformer that supplies rectifiers which add up to a similar power rating to the total power of the transformer.

In fact, in cases in which the production equipment is oversized, or when there is a low voltage generator, the power of the rectifiers can exceed the power of the transformer.

The result is that the transformer suffers a harmonic current several times higher to that suffered by a distribution transformer.

**Different summation laws for harmonics.** Distribution transformers supply a large number of loads. However, an industrial transformer supplies a much smaller number of loads.

It is even common to find a transformer dedicated to supplying a single load, such as an induction furnace or a large motor. In these cases, the power of the load is similar to the power of the transformer. Therefore, the exponential summation laws habitually applied in distribution networks in accordance with the second summation law contained in the Technical Report IEC 61000-3-6 [1] are not complied with, but rather values...
closer to the direct addition are reached, which is closer to the first summation law.

**Reactive power compensation methods in low voltage**

Although there are more or less advanced custom-made solutions, the great majority of capacitor banks used in low voltage are standardised designs by a manufacturer. Manufacturers usually recommend the use of capacitor banks connected permanently for small power ratings, typically lower than 10 or 20% of the power rating of the transformer. For higher power ratings, automatic compensation units are used, which connect steps depending on requirements. Most units use contactors for the connection of steps, whereas in some cases thyristors are used. Moreover, there is another more important divisions, from the point of view of harmonics problems, which concerns the type of capacitors or the tuning used.

**Standardised capacitors.** These are untuned capacitor banks, with capacitors that withstand 1.3 times the nominal current, in accordance with standard EN 60831-1. The paradox exists that fulfillment of this standard is not sufficient to guarantee the operation of capacitors in industrial plants in general, in accordance with the levels of compatibility defined in standard EN 61000-2-4 class 2; or in accordance with standard EN 50160 [4] in case of low voltage distribution networks. In fact, the manufacturers themselves recommend that this type of capacitors should not be used when there are loads that generate harmonics.

**Oversized capacitors.** These are untuned capacitor banks, with capacitors that habitually withstand 1.5 times their nominal current. This is usually the minimum required to withstand what is indicated in standards EN 61000-2-4 or EN 50160. Nevertheless, two points must be emphasised. On the one hand, the resonance caused by the use of untuned capacitors might be the cause of non-fulfillment of the said standards. On the other hand, this type of standards are not taken into account in industrial installations and, in fact, the limits are frequently exceeded, without this necessarily meaning a problem for the production equipment. As in the previous case, the manufacturers of capacitors themselves recommend that this type of capacitor banks not be used when the levels of harmonics get close to the limits.

**Tuned capacitor banks.** A reactance in series is included with the capacitors, so that resonances are avoided at certain frequencies. Although these are sometimes called filters, in fact the majority of the equipment units standardised by manufacturers are not worthy of this name, since they are not designed to absorb harmonics but simply to protect the capacitors.

**Problems in reactive power compensation at low voltage**

**Problems in capacitor banks.** Precisely because of the weakness of the capacitors in the presence of harmonics, the capacitor banks themselves are usually the first to suffer problems. The most habitual of these problems is overloading of the capacitors due to harmonics in untuned capacitor banks, normally caused by a resonance. However, another cause of overloading must also be pointed out, namely the circulation of high level harmonics in spite of the fact that there is no resonance. This case takes place when the disturbing loads have a good power factor or when tuned capacitor banks coexist with untuned capacitors.

Another typical problem is the excess temperature in tuned capacitor banks, due to the losses in the inductances.

Finally, the contactors are very stressed elements. It must be taken into account that in an automatic capacitor bank, they perform hundreds or thousands of switching operations annually. In untuned capacitor banks, this significantly shortens the service life of the contactors and makes it necessary to use special contactors. In tuned capacitor banks the ageing of the contactors is lower but, if it takes place, the effects are more serious. The switching of a large inductance with a contactor in bad condition gives rise to extremely severe overvoltages, sufficient to break the insulation of such robust equipment items as the electrical installation, the inductances or the capacitors themselves.

**Problems in other equipment units.** These are usually the typical ones caused by harmonics, such as control or switching failures. It is interesting to point out that they normally affect the control equipment more than the power equipment. Transformer overheating deserves special mention. A resonance, with its resulting increase of harmonic currents through the MV/LV transformer means a significant temperature growth. In the case presented in figures 3 and 4, a transformer suffered a serious overheating, despite of the air forced cooling. After installing a filter, in order to reduce the harmonic content, the transformer temperature was reduced by more than 20º C, even though the production and the reactive compensation systems where maintained.

The problem in industrial systems is extremely extensive. So much so that really strange cases occasionally occur, such as the case of a customer whose control systems were being disturbed by a strong radiated field. After an investigation it was discovered that the origin of the disturbance was the auxiliary current transformer wires of a capacitor bank that had been left out of service. The current transformer had remained connected, generating such
overvoltages in its wires that they were radiating until it caused high frequency transients in a factory control system.

Figure 3: Voltage and current through a overheated transformer

![Graph showing voltage and current through a overheated transformer](image1)

Figure 4: Voltage and transformer current after filter installation

![Graph showing voltage and transformer current after filter installation](image2)

REFERENCES


[2] CENELEC, 1996, EN 60831-1 “Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1kV”. Part 1, General”.


CONCLUSIONS

Most of the Industrial Customers use capacitor banks in LV

or in MV to correct their power factor, which seems to be a similar approach used by utilities. However, in practice, the problems within industrial sites are different from those experienced by utilities.

While actual problems in MV utilities are related to switching, and less frequently to harmonics or other PQ issues, within industrial sites we can find a very complete list of problems regarding different disturbances. Thus, we have found harmonic resonances, as expected, but also damages due to high order harmonics or interharmonics, or due to high frequency overvoltages and even EMC problems.

Some differences are based on technical reasons. Thus, in contrast to utilities, the nominal power of capacitor banks in some industries can be even higher than the transformer power. Moreover, we can find a single load with the same power as the transformer. Other loads consume more reactive power than active power. Other factors affect the harmonic contents or give rise to addition laws different from those generally used in networks.

Other differences come from common practices in industry, which are not usually associated to standards. In fact, the voltage levels where capacitor banks are connected are the first difference, since switching LV or MV capacitors represent different EMC problems, and harmonic treatment differs as well. However, customers will chose a LV or a MV capacitor bank taking into account mainly short term reasons, like paying-off, existing space, etc.

The effects of disturbances are suffered mostly by the owner of the capacitor bank. Nevertheless, capacitor banks connected to the Point of Common Coupling are cases that must be considered carefully. In this case, harmonics can affect the whole MV system, especially when there are changes in the network impedance. Another problem of this configuration is the unexpected presence of high frequency currents that can cause damages to the breaker of the utility’s capacitor bank.