INTRODUCTION

Capacitor bank switching is one of the most demanding operations in MV networks, due to its frequency and the associated transients. It is both an important maintenance concern, since strong currents affect breakers and capacitors, and a frequent power quality issue, as its voltage transients can have a relevant effect on customers and, less often, on other elements of the distribution network.

CAPACITOR SWITCHING AND POWER QUALITY

The most common power quality aspect of capacitor switching is the characteristic LC transient in the course of the capacitor bank energization. It can result into a moderate overvoltage transmitted through the network. An example can be seen in figure 1, which shows the voltages and capacitor bank currents during this operation. Its effects on customers -magnification, equipment malfunction, etc.- are fairly known. Thus, the Voltage Quality Working Group of Cigrè–Cired summarized these aspects [1].

Switching transients

Although the transient is complex and includes several frequencies, highest frequencies are rapidly damped and line impedance limits its effect to the substation proximity. Thus, transient transmitted by distribution networks have usually frequencies of some hundred Hertz, while peak values do not reach normally 2.0 times the normal system peak voltage.

Even without important overvoltages, capacitor switching causes steep voltage gradients which are transmitted to LV, where some customer loads can convert this dv/dt into leakage currents (figure 4).
Mitigation techniques

Mitigation techniques to be applied in LV and specially series reactors for Adjustable Speed Drives (figure 3) are commonly used. In this figure it can be observed how the series reactor reduces the voltage in the d.c. bus, preventing the overvoltage trip.

In contrast, solutions to be applied in HV and MV systems - which involve important changes in capacitor bank breakers, tuning inductances or damping resistors - are not frequently applied since they present problems of cost, losses, maintenance and space.

SUBSTATION EQUIPMENT

Breaker reignitions

Breaker technology - or more precisely its dielectric strength - is one of the fundamental issues regarding high frequency switching transients. Breaker mechanical limitations as well as maintenance are other factors that have an effect on breaker reignitions.

The reignition that takes place during the de-energization operation it is also called restrike, while the ignition that takes place before the energization is completed is called pre-strike.

Figure 5 shows an example of pre-strikes. It can be seen how the currents of the three phases start simultaneously during a energization operation. However all the currents are interrupted at their first zero crossing, for starting again some instants later.

From the power quality point of view, the first consequence of these undesirable events is the repetition of the LC transient or the dv/dt. Moreover, the transient becomes more complex. Firstly due to the addition of transients, which can lead to peak voltages higher than normal. And secondly because transients can be repeated in consecutive cycles, due to the fact that the arc into the breaker appears and disappears.

This incorrect behaviour of the breaker results also in a higher stress on breaker contacts, specially because the current flows through the gap between the open contacts. In these circumstances, the probability of breaker damage increases dramatically, aggravated by the daily repetition of switching operations.

The de-energization operation is not particularly harmful for the breaker contacts, since it involves lower currents. However, voltage across the open contacts can rise up to 2 times the system peak voltage.

As a consequence, a restrike can take place in case of damaged breakers, as shown in figure 6. The restrike is equivalent to a energization transient and it is usually very short, due to the arc extinction system of the breaker. However the appearance of this event is a sign of a problem, either damaged contacts or an inappropriate type of the switching device.

Effect on capacitors

Capacitors themselves are quite sensitive to current transients, since they are designed to withstand transient current peaks up to 100 times their nominal current, according to IEC 60871-1 standard [2].

In case of reignition, the peak value of the transient can be as high as 2 times the normal energization peak current, due to the difference between the instantaneous voltage in the network and the voltage that remains in the capacitors. Consequently, any reignition implies an additional stress for the capacitors, which reduces their lifetime.

In case of breaker malfunction, multiple reignitions take place in a few milliseconds, making possible - in some extreme cases - immediate damages in capacitors.
Other effects

In case of important damages in the breaker contacts, severe high frequency transients -in the range of some tens or hundreds of KHz- appear as figures 7 and 8 show. In some cases, these transients can cause electromagnetic compatibility problems in the substation, even reaching overvoltages exceeding the isolation of auxiliary circuits.

CAPACITOR BANK MONITORING

Bearing all this conditions in mind, Iberdrola has developed monitoring process, particularly designed for capacitor banks. It will lead to an important improvement, since it allows to adapt maintenance works to actual needs, in order to improve breaker behaviour and, consequently, to reduce switching transients severity.

Protection based monitoring

Up to now, two kind of tools have typically been used in order to assess capacitor switching transients and their transmission: wave-form recorders designed for transient analysis and transient simulation programs which work in the time domain. These methods allow a comprehensive analysis of a particular capacitor bank or site, but they are too complex for being applied in a big network with hundreds of capacitor banks, since each analysis would require extensive dedication of skilled engineers and sophisticated tools.

In contrast, the widespread application of specific protections for capacitor banks and the flexibility of digital technology make possible the inclusion of new detection functions, which can be applied systematically to capacitor banks.

In this case, it is required a protection relay able to detect breaker malfunctions such as restrikes -or reignitions-, pre-strikes or contact delays.

Since these events -associated to contact arcing- are really fast, a first hardware requirement becomes clear: the sampling rate of the protection relays must be fast enough for detecting transients. Normally protections take only into account the fundamental frequency and, for certain applications, low order harmonics. With this basis, fast sampling is not necessary, so even the most advanced protections are not usually able to detect the high frequency transients –like those represented in figure 8- associated to restrikes.

Even the evolution of capacitor currents requires a fast response, as can be seen in figure 9, which gives detailed information on the energization represented in figure 5. During this event, the current I2 appears during 700 microseconds, while currents I1 and I3 last 1.5 milliseconds. However, current I3 remains at zero only during 240 microseconds, before currents I2 and I3 start again.

These sampling requirements are too demanding for many existing protections. Nevertheless, some recent hardware platforms used for protection relays are able to detect events clearly shorter than one millisecond, which is enough to detect modifications on normal breaker behaviour.

In addition, some changes with regard to protection strategies are required. Usually, protection relays algorithms work in the frequency domain using a Fourier transform. Hence, although the repetition of the FFT -or DFT- analysis several times per cycle allows a quick response, all the relays decisions are based on a one cycle period. On the other hand, a reliable identification of restrikes based on Fourier transform results extremely complex, taking into account the variability of wave-forms.

Therefore, for this particular application, a time domain algorithm has been developed for detecting breaker malfunctions. The algorithm determines the number of ignitions of each phase. An alarm signal is activated when a restrike or pre-strike, either in one phase or in several phases.

In order to avoid miscalculation due to transients coming from other sources, such as nearby capacitor banks, the algorithm is only active during switching operations, either energization or de-energization.
Reignition detection

Logically, in those capacitor banks connected in delta or in isolated wye, the current requires at least 2 phases to flow, so single phase reignition is only possible, in grounded-wye capacitor banks.

However, the ignition detection algorithm is applied to each phase independently, as shown in figures 10 and 11. This first figure illustrates a reignition detection using the same energization event that was shown previously in figures 5 and 9. Since it is an energization, one ignition per phase is the normal value. However, as soon as the second ignition—in other words, the first reignition—appears in any of the three phases, the alarm is activated indicating a pre-strike.

In contrast, no ignitions are expected during a de-energization operation. For that reason, the first ignition give rise to the alarm, as can be seen in figure 11, where a reignition that affects only to phases 2 and 3 can be observed.

These alarms can be stored in the protection memory for local use, or transmitted to the disturbance analysis centre. A repetitive alarm indicates that an early breaker maintenance would be advisable.

The waveform record and the number of ignitions are stored for later analysis, as they can provide additional information on the state of each phase and the urgency of the maintenance needs.

CONCLUSIONS

The development of new digital protection algorithms will enable permanent bank monitoring to be carried out.

This new system can be extended to an important amount of MV and HV capacitor banks, and will allow a more effective preventive maintenance.

Thus, consequent breaker improvements will also lead to a significant power quality benefit, as transient magnitudes are limited and the behaviour of LV mitigation equipment is facilitated.

REFERENCES
