Power Quality Application Guide

LEONARDO POWER QUALITY INITIATIVE

Capacitors in Harmonic-Rich Environments

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Capacitors in Harmonic-Rich Environments

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Capacitors in Harmonic-Rich Environments

Old plant in a new environment

Capacitor banks, used for the compensation of fundamental reactive power, are essential for the economic operation of systems that include resistive-inductive loads. In fact resistive-inductive loads have been omnipresent since the beginning of electrical power engineering. However, since substantial non-linear loads are now becoming similarly omnipresent, there are two new risks emerging around and inside the capacitor banks:

- ◆ Current overload of capacitors

- ◆ Parallel resonance of capacitances with inductances in their (electrical) proximity.

Compensation capacitors continue to be indispensable, and it is fairly easy to design or upgrade them to cope with the new challenges. This Guide identifies the optimal approach when selecting new plant and upgrading existing capacitor banks in order to prevent problems caused by harmonics.

Basics: Characteristics of inductances and capacitances

Electrically, inductance is analogous to the inertia of mass in a mechanical system. A reactor, i.e. a component with a defined and intentional inductance value, represents the electrical equivalent of a flywheel which would have a defined inertia. Of course, anything that has a mass also has inertia and, in the same way, any piece of conductor has a parasitic inductance.

Both the inductance L and the capacitance C represent reactive components with a reactance and a reactive power intake/output, whereas capacitive reactive power input is the equivalent of inductive reactive power output and vice versa. Reactive power has, in effect, no clearly definable direction of flow. The reactances are calculated as follows:

$$X_L = 2\pi f L \quad \text{and} \quad X_C = \frac{1}{2\pi f C}$$

So the inductive reactance X_L is proportional to frequency f, while the capacitive reactance X_C is inversely proportional to frequency f. For any parallel combination of L and C there will be a frequency f_0, at which the reactances are equal – this is the resonant frequency. This frequency, at which the LC combination oscillates, is calculated as:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

With respect to leading currents, it may seem a bit difficult to imagine how a capacitive current can be intelligent enough to know in advance what the voltage that drives it will do a quarter of a period later but, in a way, this does actually happen. To be precise, it is any **change** of current that is lagging or leading in relation to the corresponding voltage **change**, e.g. the zero crossing. It originates from the energy being stored in the capacitance and from the special characteristics of the waveform.

Electrical capacitance corresponds to the resilience (elasticity) of a mechanical component. A capacitor can be produced with a defined capacitance, corresponding to a spring in a mechanical system, but, just as any material is resilient (elastic) to some extent, so there is a certain amount of parasitic capacitance between any two pieces of conducting material.

The question is whether these parasitic reactances are large enough to play a role in practical engineering. At high voltages or high frequencies they often are, but this is not normally the case at low voltage levels and mains frequency.

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The energy content in each of the two energy stores is given by:

$$W_{spring} = \frac{D}{2} * s^2, \quad W_{mass} = \frac{m}{2} * v^2$$

where:

$D =$ elasticity constant (elongation per force, Hooke's Law)

$s =$ elongation (instantaneous distance from point of relaxed state)

$m =$ mass

$v =$ speed of movement of this mass

in which s and v could be, and should be, written as functions of time $s(t)$ and $v(t)$, for that is what they are, periodically changing with time.

Now combining the two, the inertial mass and the resilient spring, provides a system with two energy stores. Energy that is released from one of the components may flow right into the other one. If the spring is extended and released, the mass will be accelerated, with the force to do so coming from the relaxing spring. At the zero crossing of the force the spring is in its relaxed state and the mass is moving at maximum velocity. Since the mass has inertia it will continue to move, now compressing the spring, so that energy is transferred from the moving mass back to the spring. When the energy stores are a capacitor and an inductor, the tension in the extended/compressed spring correlates with the positive/negative voltage in the capacitor and the speed of the mass is the current, also swapping polarity at regular intervals. All polarity swaps occur alternately and at constant intervals, first the voltage, then the current, every quarter period (or every 90° because all changes of the two dimensions, tension and velocity in the mechanical, voltage and current in the electrical model, follow a sine function). On account of the 90° phase shift, it can also be said that one of the dimensions follows a cosine function and, since assuming linear and loss-free components, at any point of time within the oscillation

$$\sin^2(\omega t) + \cos^2(\omega t) = 1$$

then the internal energy

$$W = \frac{C}{2} * u^2(t) + \frac{L}{2} * i^2(t) = const$$

at any point of time. With real components losses occur and the phase displacement of current against voltage in an inductive/capacitive component becomes a little bit less than ±90° but, if operated within the specified range, losses are low, and the influence of non-linearity in reactor core materials is largely negligible for technical purposes if the reactor is properly designed.

What is special about the sine wave?

Sine voltages drive sine currents, and sine currents produce sine voltage drops. Is this true for the sine waveform only or for any function? To answer directly, it is a peculiarity of the sine wave. See the examples for other waveforms in Figures 1 and 2. Only for resistive elements are the instantaneous voltage values proportional to the instantaneous current values, so that any voltage curve produces a current curve of the same shape and vice versa. For reactive loads (e.g. in the case of an inductance L) the instantaneous voltage is proportional to the rate of **change** of current with respect to time (di/dt), or (in the case of a capacitance C) current is proportional to the rate of **change** of instantaneous voltage with respect to time (du/dt). The same goes for a sine and a cosine wave.
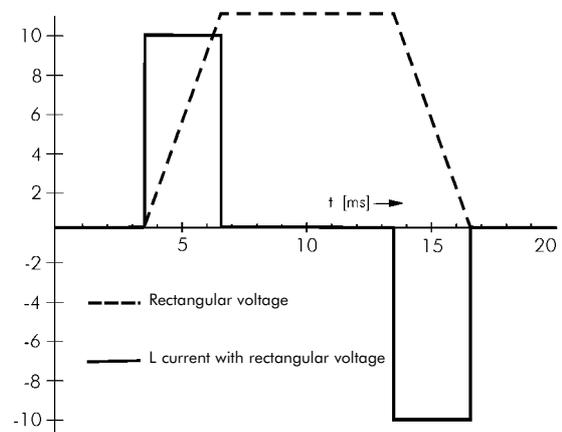

Figure 1 - Rectangular voltage causes trapezium current in an ideal (loss free) reactor

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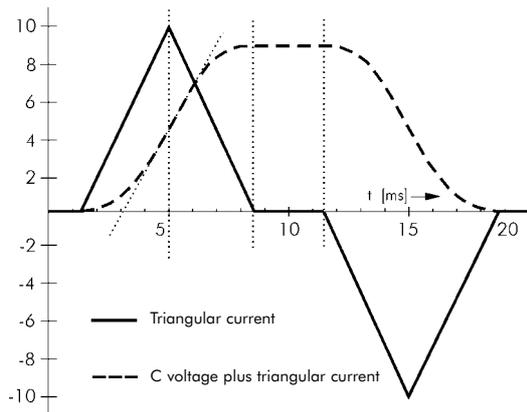
Figure 2 - Triangular current flowing
through a capacitor
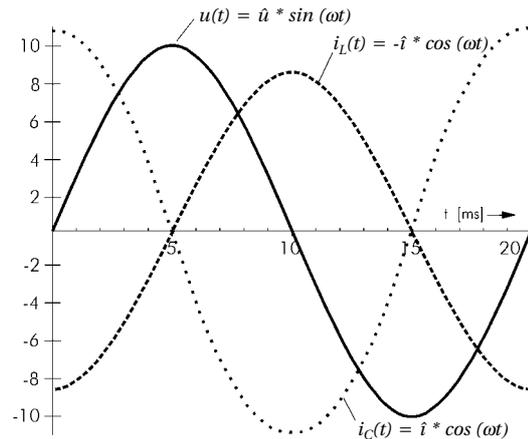
Figure 3 - Sine voltages drive cosine currents
in reactive components

The sinusoidal voltage and current curves have the same shape for resistive and reactive components, but with a phase shift. For reactive components, the voltage is proportional to the **rate of change** of current. But the rate of change of a sinusoid is described by a cosinusoid, which has the same shape and merely a different start point. Since the starting point of mains voltages and currents lies somewhere in the past, where it is no longer of interest, it appears as though sine voltages drove sine currents and sine currents caused sine voltage drops with just a phase shift between them.

What is reactive power?

In resistive loads, the instantaneous values of voltage and current are proportional to each other (Figure 4), in reactive components they are not (Figure 6). In the latter case, if one of the dimensions has a sinusoidal waveshape, so does the other, but with a phase shift between the two; hence, during two sections of every AC period they have the same sign, but during the other two sections their signs are different. During these periods of opposite voltage and current polarities the product of them, the power, is negative, so a power consumer in fact temporarily turns into a power "supply". The electrical energy absorbed a quarter period before was not consumed (e.g. converted into another form of energy, such as heat), but was stored and is now recovered and fed back into the network. The real "active" energy transferred during each full period equals the integral of power, that is the area below the voltage multiplied by current curve (shaded areas in the figures), with the parts below the abscissa to be subtracted from those above. So fundamental reactive power is an oscillation of energy.
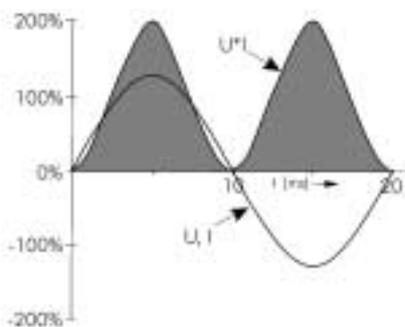
Figure 4 - Resistive load
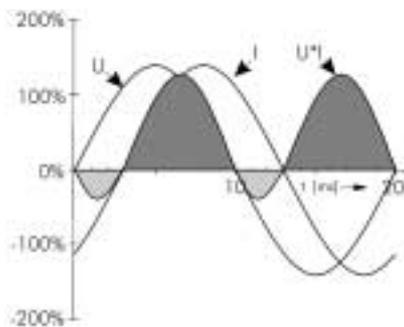
Figure 5 - Resistive-inductive load
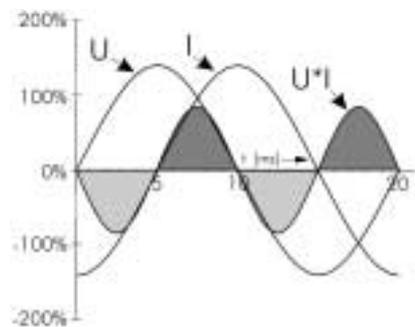
Figure 6 - Inductive load

So far, the definition of reactive power, as it relates to sinusoidal voltages and reactive loads, is still relatively simple. However, reactive power is also present in phase angle controlled resistive loads. In a German electrical engineering journal, an author claimed that such a load (e.g. an incandescent lamp with a dimmer) does not cause fundamental reactive power, since there are no periods of time within a full wave where voltage and current have opposite polarities. He provoked a flood of disagreement among readers, pointing out that in the Fourier analysis of such phase-angle controlled current the fundamental wave **did**

have a lagging phase shift against the voltage, so it was evident that there **was** fundamental reactive power. Both viewpoints sound logical but which one is correct?

Figure 7 provides the explanation. Looked at from the simple point of view of the load (top row in Figure 7), there is no reactive power – current is in phase with voltage (despite the distorted waveshape) and the displacement power factor is unity. But all loads exist in a common system, and should be examined from the system perspective, shown in the lower row of Figure 7. Now the voltage waveform is again sinusoidal and the displacement power factor is now 0.8 lagging (see the W, VA and VAR measurements).
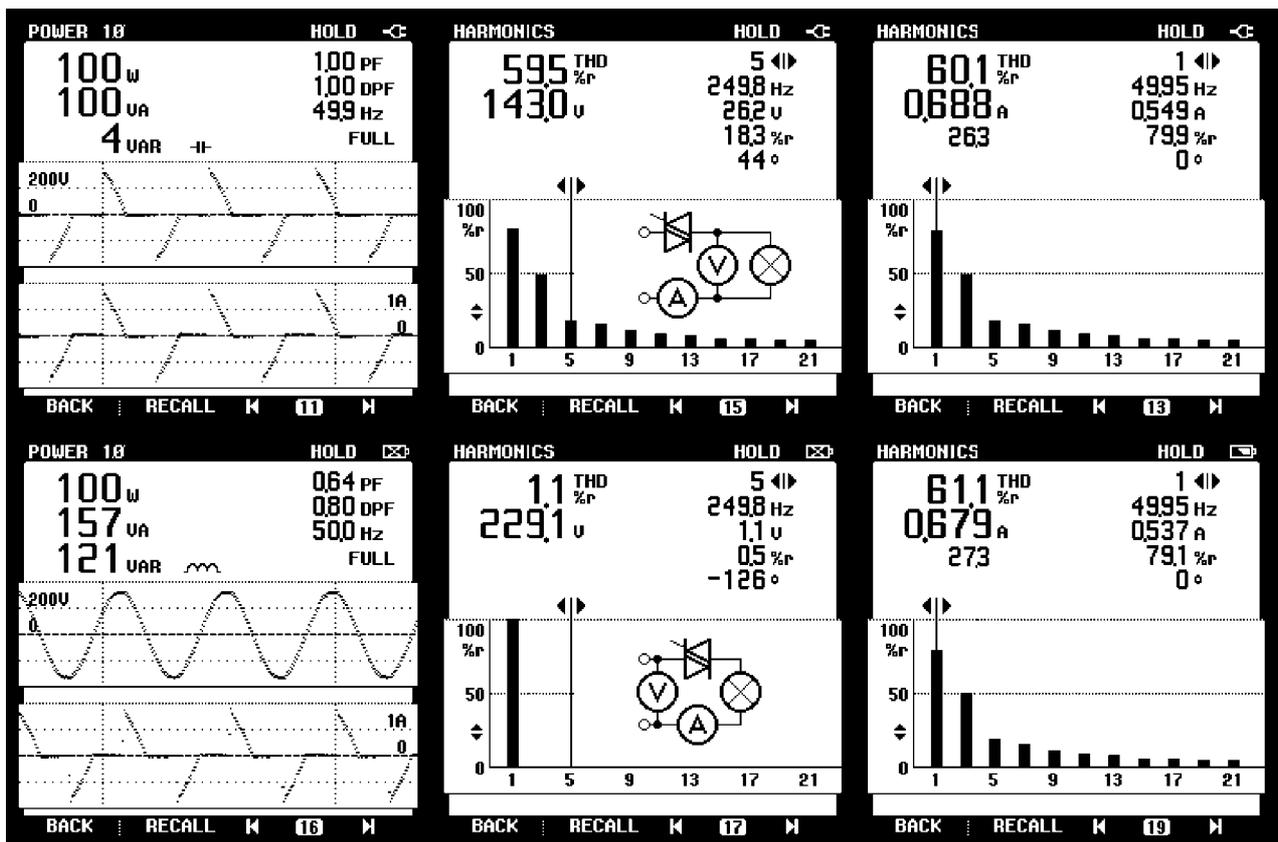
Figure 7 - Does a phase-angle controlled resistive load cause fundamental reactive power or not? From the utility viewpoint the additional impact on the mains is indeed there, while energy oscillation, which some experts see as a prerequisite for the existence of reactive power, does not take place

Why compensate?

In a normal network there are many simultaneously active loads. Many will be resistive while some have a capacitive component, where the current curve hurries a bit ahead of the voltage curve (leading), and others have an inductive component where the current lags behind the applied voltage. In most networks the resistive-inductive loads prevail so that the overall current will have a resistive-inductive nature (Figure 5). This incessant, but undesired, oscillation of energy means an additional flow of current in cables and transformers that adds to their loading, causes additional resistive-losses and uses a potentially large part of their capacity. Therefore the basic reasons for compensating are to avoid:

- ◆ the undesired demand on transmission capacity
- ◆ the energy losses caused by such
- ◆ the additional voltage drops the additional currents cause in the distribution system.

These extra voltage drops in the system are important; a reactive current flowing in a resistance causes a real power loss. Even where the impedance is largely reactive, rapid changes in the reactive current may cause flicker. A good example of this is a construction crane connected to a relatively small distribution transformer when a new home is erected in a residential area. The cranes are usually driven by relay-controlled three-phase induction motors which are quite frequently switched from stop to start, from slow to fast and from downwards to upwards. The start-up currents of these motors are very high, several times the rated current, but these start-up currents have a very high inductive component, the power factor being around cos $\varphi \approx$ 0.3, or even smaller with bigger machines. The voltage drop in the transformer is also largely inductive, so this voltage drop has more or less the same phase angle as the start-up current of the motor and adds very much more to the flicker than the same current drawn by a resistive load (Figure 8). However, this also means that this flicker can easily be mitigated by adding a capacitor to compensate the inductive component of the motor's start-up current.
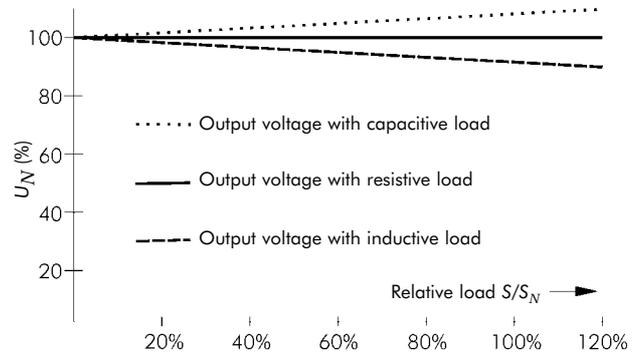

Figure 8 - Voltage drop in a transformer (here 630 kVA according to HD 428 list C) is minor under resistive load, major with inductive load and negative with capacitive load

How to compensate under today's conditions

Control and regulation of reactive power

It is normally desirable to compensate reactive power. This is quite easy to achieve by adding an appropriate capacitive load parallel with the resistive-inductive loads so that the inductive component is offset. So, while the capacitive element is feeding its stored energy back into the mains, the inductive component is drawing it, and vice versa, because the leading and the lagging currents flow in opposite directions at any point in time. In this way, the overall current is **reduced** by **adding** a load. This is called parallel compensation.

To do this properly requires knowledge of how much inductive load there is in the installation, otherwise over-compensation may occur. In that case, the installation would become a resistive-capacitive load which in extreme cases could be worse than having no compensation at all. If the load – more precisely its inductive component – varies, then a variable compensator is required. Normally this is achieved by grouping the capacitors and switching them on and off group-wise via relays. This of course causes current peaks with the consequent wear of the contacts, risk of contact welding and induced voltages in paralleled data lines. Care must be taken in timing the switch-on; when voltage is applied to a fully discharged capacitor at the instance of line voltage peak, the inrush current peak is equal to that of a short circuit. Even worse, switching-on a short time after switch-off, the capacitor may be nearly fully charged with the inverse polarity, causing an inrush current peak nearly twice as high as the plant's short circuit current peak! If there are many switch-mode power supply loads (SMPS) being operated on the same system, then a charged compensation capacitor, reconnected to the supply, may feed directly into a large number of discharged smoothing capacitors, more or less directly from capacitance to capacitance with hardly any impedance in between. The resulting current peak is extremely short but extremely high, much higher than in a short circuit! There are frequent reports about the failure of devices, especially the contacts of the relays controlling the capacitor groups, due to short interruptions in the grid which are carried out automatically, e.g. by auto-reclosers, to extinguish a light arc on a high or medium voltage overhead line. It is often suggested that this doubling of peak value cannot occur with capacitors that are equipped with discharge resistors in accordance with IEC 831. However, the standard requires that the voltage decays to less than 75 V after 3 minutes, so they have little effect during a short interruption of a few tens of milliseconds up to a few seconds.

If, at the instant of re-connecting the capacitor to the line voltage, the residual capacitor voltage happens to equal the supply voltage, no current peak occurs. At least this is true if the compensator is viewed as a pure capacitance and the incoming voltage as an ideal voltage source, i.e with zero source impedance. But if the self-inductance of the system is taken into account, certain resonances between that and the capacitance may occur. Assume the following case: the residual voltage of the capacitor is half the peak value and equal to the instantaneous line voltage, which would be the case 45° after the last voltage zero crossing, i.e.

$$u_C = u(\frac{\pi}{4}) = 400V \frac{\sqrt{2}}{2} = 283V$$

At this point in time the current in the capacitor would be expected to be:

$$i_C = -\frac{\hat{i}}{2}$$

but it is not because the capacitor has been disconnected from the supply up to this point in time. At the instant of connection, neglecting the system's inductance, the current would rise up to this value immediately, and nothing would happen that would not have happened anyway in the steady state. But a real system is not free of inductance, so the current will assume this value only hesitantly at first, then speed up and – again due to the inductance, its 'inertia' – shoot beyond the target nearly way up to double the expected value. Then it will come down again and so on and thus perform a short period of oscillation that may be attenuated down to zero well within the first mains cycle after connection. The frequency of such oscillation may be rather high, since the mains inductance is low, and may cause interference to equipment in the installation. Only if the instantaneous line and residual capacitor voltages are both at their positive or negative peaks, at which point in time the instantaneous current would be zero anyway, will the resistive-inductive current start without oscillation.

More precisely, there are two conditions to be fulfilled. Firstly, the sum of voltages across the capacitance and its serial reactance (be it parasitic or intentional detuning) must be equal to the line voltage. Secondly, the supposed instantaneous current, assuming connection had already taken place long before, has to equal the actual current, which of course is zero until the instant of switching. This second condition is fulfilled only at line voltage peak, which therefore has to equal the capacitor voltage. To achieve this, the capacitor is pre-charged from a supplementary power source. This practice has a secondary minor advantage in that it makes sure that there is always the maximum possible amount of energy stored in the capacitor while not in use, so that at the instant of turn-on it may help to mitigate some fast voltage dip and subsequent flicker which otherwise might occur.

Relays, however, are too slow and do not operate precisely enough for targeted switching at a certain point of the wave. When relays are used, measures have to be taken to attenuate the inrush current peak, such as inrush limiting resistors or detuning reactors. The latter are frequently used anyway for other reasons (see Section 3.3.1 of this Guide), and are sometimes required by utilities. Although this series reactor replaces the inrush current peak at switch-on with a voltage peak (surge) at switch-off, it is still the lesser evil, since the reactive power rating of the reactor is just a fraction of the capacitor rating and so the energy available is less.

Electronic switches, such as thyristors, can be easily controlled to achieve accurate point-on-wave switching. It is also possible to control switching so as to mitigate a fast flicker caused by a large unstable inductive load, such as the crane motor mentioned previously, an arc furnace or a spot welder.

An alternative option frequently applied in some parts of Europe is FC/TCR compensation, the paralleling of a Fixed Capacitor with a Thyristor Controlled Reactor.

Centrally or dispersed?

The reason why commercial electricity users normally compensate is because some utilities charge for reactive power – not such a high charge as active power but still a significant charge – so that they are compensated for "useless use" of the distribution system. In some countries, the practice of charging for reactive power is declining and power factor compensation is becoming less common. Electricity users see this as an advantage, but in fact it places an increased load on a system that is often working quite close to the maximum.

The traditional approach is to place one large static compensator at the point of common coupling, the utility entry, and correct the power factor there to the level required to avoid charges,

usually cos φ = 0.90 or cos φ = 0.95. The alternative approach is to disperse compensation near to resistive-inductive loads and, in the extreme, to an individual appliance that draws reactive current.

Centralised compensation is often believed to be cheaper because the central unit is less costly to purchase than spreading the same reactive power rating across the plant in dispersed small units. The installed compensation capacity can also be lower because it can be assumed that not every reactive current consumer will be simultaneously active. However, it must be remembered that reactive currents cause real losses within the installation – the voltage drop in a resistive element, such as a cable, is in phase with the current, so the product, the power loss, is always positive. Central compensation does nothing to reduce these losses, it merely reduces the power factor charge levied by the utility. On the other hand, when compensation is dispersed the total cost of the individual units will be greater than the cost of a single large centralised unit and the total installed compensation capacity will usually be greater – every device has compensation, whether in use or not. Losses are reduced because reactive current flows only between compensation and appliance, rather than back to a centralised compensator at the point of common coupling.

Apart from efficiency, there are technical arguments for and against centralised compensation. For example, if the aggregate load on a transformer is capacitive, the output voltage rises above nominal. This effect is sometimes used to offset the voltage drop in a heavily loaded transformer. The load is simply overcompensated so that the overall load appears capacitive to the transformer, so reducing the inductive voltage drop in the transformer [1]. In cases where a frequently switched heavy load causes a flicker problem, this may be a more sturdy and reliable solution than electronic flicker compensators and may also be considerably more cost-efficient in cases where a degree of compensation would be needed in any case.

However, in general terms, the overvoltage of a transformer under capacitive load is a risk that should be avoided or must be adequately dealt with by, for example, using a slightly higher than nominal voltage rating ($\approx$6%). Sometimes it is necessary or desirable to apply compensation at MV level and it is attractive to connect LV capacitors via a MV/LV transformer rather than paying the higher price for MV capacitors. In such a case, the transformer load is capacitive and the output voltage higher than expected. This can be dealt with by proper selection of components with adequate voltage rating or by selecting the transformer ratio, by the use of taps, to normalise it. The latter is preferable since it avoids running the transformer in an over excited state with consequently higher losses. The idea may turn out to be a false economy because, although the installation cost is reduced, the running costs are increased. Reactive current in the installation is transformed twice – from the installation LV to the system MV and from system MV to capacitor LV – with two load losses to be paid for by the customer.

The other disadvantages of reactive power, transmission capacity demand and voltage drop, also occur inside the plant on any line and in any transformer between the inductive load and the compensator. It is better to spend 100% of the budget on 100% of the use than 75% of the budget on only 50% of the use.

In a decentralisation scheme, each and every – even small – resistive-inductive load may be compensated by integrating a capacitor into it. This has been done quite successfully, for instance, in luminaires with one or two fluorescent lamps and magnetic ballasts. In Germany and Switzerland this is frequently implemented as serial compensation, where one out of every two lamp-and-ballast circuits is left uncompensated and the other one is (over-) compensated by means of a series capacitor, dimensioned in such a way as to draw precisely the same amplitude of current as the uncompensated branch, but with the inverse phase angle.

Decentralisation, however, has its limits in situations where an asynchronous induction machine is individually locally compensated. If the capacitor is located before the motor switch, then it may easily remain connected when the motor is off, leaving the system overcompensated. If the capacitor is located after the motor switch, so it is disconnected with the motor, then there is a risk of self-excitation in the machine as it decelerates. Voltage is generated although the device has been isolated from the supply, even overvoltage in case the capacitance is wrongly dimensioned.

It should be evident at this point that reactive power is not always undesired. Rather, the proper amount of capacitive reactive power needs to be generated to offset the inductive reactive power and, in cases where resistive-capacitive loads prevail, vice versa. Capacitive reactive power is also quite advantageous and loss-reducing e.g. for exciting asynchronous generators such as wind turbines and cogeneration plants if these are connected directly to the system without an inverter. It even becomes an absolute necessity in situations where such generators are supposed to feed an island network, otherwise there is no excitation, no voltage and no supply, even while the machine is running.

Detuning

Detuning refers to the practice of connecting each compensation capacitor in series with a reactor. One reason for detuning, the attenuation of inrush currents, has already been mentioned. However, the basic reason why detuning is recommended by all compensator suppliers and most utilities – and why many consumers have already adopted it - is the problem of voltage disturbances on the network. Modern electronic loads draw harmonic currents, cause harmonic voltage disturbance (see Section 3.1 of this Guide) and impose high frequency noise on the network. As the reactance of a capacitor is inversely proportional to the frequency, these high frequencies can cause the current rating of the capacitor to be exceeded. This is prevented by the presence of a detuning inductor. The reactive power rating of the detuning reactor is usually 5%, 7% or 11% of the reactive power of the compensation capacitor. This percentage is also called the "detuning factor".

When talking about ratings, there is scope for substantial confusion as to whether the reactive power indicated on the rating plate of a compensator refers to the rated mains voltage or to the rated capacitor voltage (which is higher), and whether or not the detuning factor has been taken into account. In fact, the stated reactive power should always refer to the combined unit - compensator plus detuning reactor - at the supply voltage and fundamental frequency.

As the reactance of a reactor rises proportionally with the frequency while that of the capacitor drops, an 11% detuning factor at 50 Hz already becomes ≈100% at 150 Hz[1], meaning that the inductive and capacitive reactances are equal (in resonance with each other) and cancel out. This provides an option to design detuning factors in such a way as to "suck out" a particular harmonic from the network, while performing the basic compensation function as well. This is described in more detail in Section 3.3.1. Generally, however, in order to prevent capacitor (and reactor) overload, it is preferable to avoid detuning factors that place the resonant frequency on one of the predominant harmonic frequencies. Rather, the detuning factor is chosen so that the capacitor / inductor combination becomes inductive for frequencies just below the lowest occurring harmonic and above (Figure 9). This avoids resonances (Figure 10) that might otherwise occur between the capacitor and other elements of the system, especially the stray inductance of the nearest transformer, being excited by one or another harmonic. In the figures the amplification factors are plotted against the frequency. The amplification factor here is to be understood as the ratio of the system's behaviour as it is, compared to the same system's behaviour in the absence of the compensator.

But this is not the only reason for detuning. Nowadays capacitors may also easily be overloaded by the higher frequencies omnipresent in the networks, higher than the most common harmonics. Even small high frequency voltages superimposed on the supply voltage - so small that they are not visible in the voltage recordings of a high-class network analyser (Figure 11), can drive high currents through the capacitors.
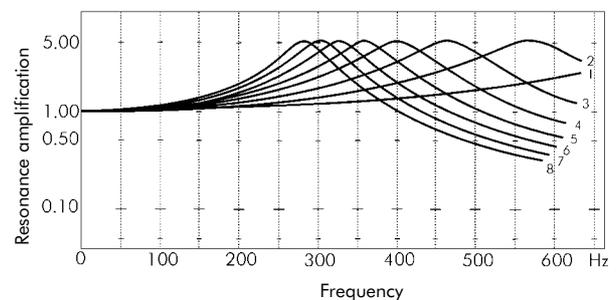

Figure 9 - Resonance curves of different compensators ranging from 50 kvar (curve 1) to 400 kvar (curve 8), operated on a 1 250 kVA transformer (Frako)
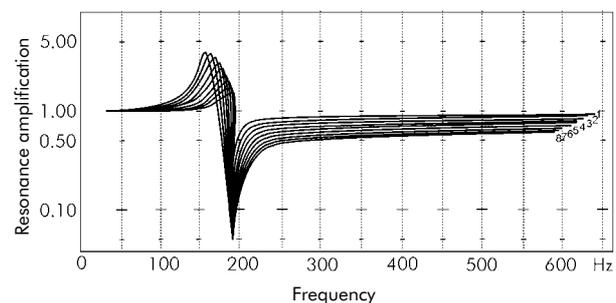

Figure 10 - Resonance curves of different detuned compensators ranging from 50 kvar (curve 1) to 400 kvar (curve 8), operated on a 1 250 kVA transformer (Frako)

[1] *X_L at 50 Hz = 11%, so X_L at 150 Hz = 33% (wrt X_C at 50 Hz). X_C at 150 Hz = 33%. Both are equal in magnitude, hence a 'detuning' factor of 100%.*
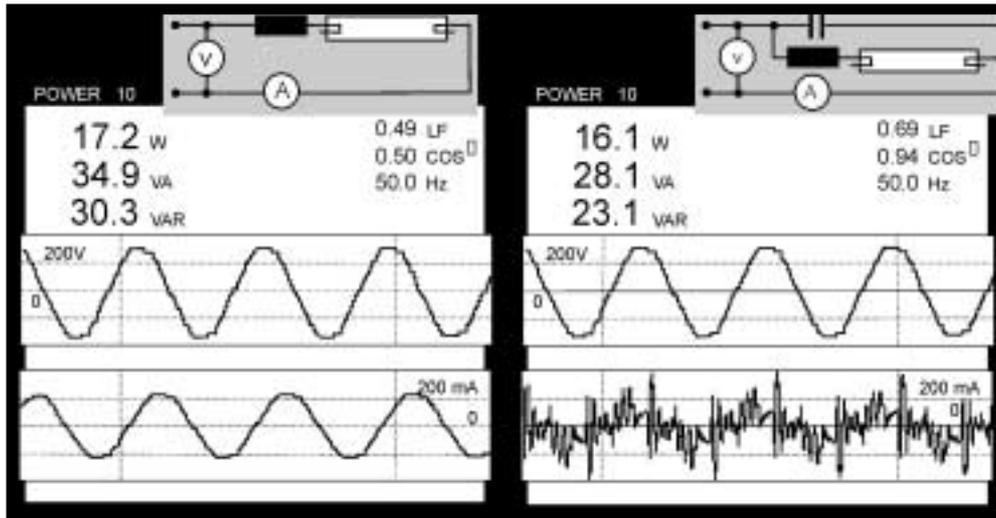
*Figure 11 - 11 W fluorescent lamp without (left) and
with parallel compensation (right)*

On the left is an 11 W fluorescent lamp operated with a magnetic ballast but without compensation. However, the very high amount of reactive power requires compensation by capacitors. On the right, the lamp system current, (the serial connection of lamp and ballast, paralleled with the appropriate capacitor) is a bizarre zigzag rather than an approximate sinewave. This additional mixture of higher frequency currents must be flowing through the capacitor, since nothing else has changed in the wiring. The measurements confirm this. As the current is almost sinusoidal on the left, the difference between the power factor, (also called load factor *LF)* and the *cos* φ (also called displacement factor) is small, while on the right it is significant. The reason is that the power factor is the ratio of real (50 Hz) power to apparent power, including fundamental reactive power, harmonic power and noise power, while the good old *cos* φ - displacement factor - only includes the fundamental reactive power caused by a phase shift between voltage and fundamental current. The capacitor is intended to carry reactive current (left), but is also a sink for harmonic currents (right) if not detuned. This is the second reason for the widespread detuning practice today and reveals how important it may be for the life of a capacitor designed for 50 Hz. The experiment can be repeated with similar results in nearly all modern networks. Simply connecting a capacitor to the line voltage and recording the current will give similar readings everywhere. It may be very impressive to make the capacitor current flow through an appropriately dimensioned loudspeaker. The noise is truly awful, but it changes back again to a calm and quiet 50 Hz hum as soon as the capacitor is "detuned" with a reactor.

The present example also makes the above mentioned serial compensation practice for fluorescent lamps appear quite advantageous, as it represents a compensating capacitance with a detuning factor of 50%, and this even with a reactor that is already there and need not be added.

Summary

It is important first of all to understand the complementary behaviour of *L* and *C* elements in order to understand the business of compensation. Compensation capacitors should always be detuned in order to avoid resonance with harmonics and overload by high frequency current. Variable compensation units should be designed for rapid switching using semiconductor switches and intelligent control algorithms. The optimum placement of compensation, whether it should be centralised or distributed, has been discussed.

References and Bibliography

[1] *Wolfgang Hofmann, Wolfgang Just: Blindleistungs-Kompensation in der Betriebspraxis, VDE Verlag, Offenbach, Germany, 4th edition, 2003*

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