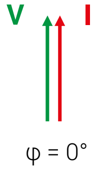
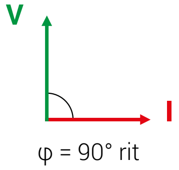
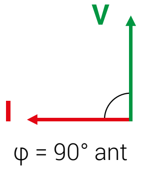
TECHNICAL NOTES

Power factor correction: why?

In electrical circuits the current is in phase with the voltage whenever are in presence of resistors, whereas the current is lagging if the load is inductive (motors, transformers with no load conditions), and leading if the load is capacitive (capacitors).

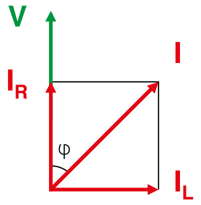






The total absorbed current, for example, by a motor is determined by vector addition of:

- I_R resistive current;
- I_L inductive reactive current;

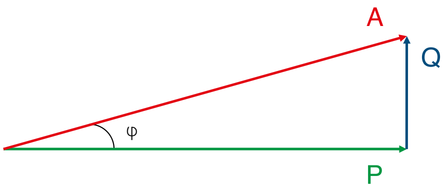


$$\cos\varphi = \frac{I_R}{I}$$

These currents are related to the following powers:

- **Active power** linked to I_R;
- **Reactive power** linked to I_L;

The reactive power doesn't produce mechanical work and it is an additional load for the energy supplier.
The parameter that defines the consumption of reactive power is the power factor.
We define power factor the ratio between active power and apparent power:



$$FP = \frac{P}{A}$$

$$A = \sqrt{P^2 + Q^2}$$

As far as there are not harmonic currents power factor coincides to cosφ of the angle between current and voltage vectors.
Cosφ decreases as the reactive absorbed power increases.

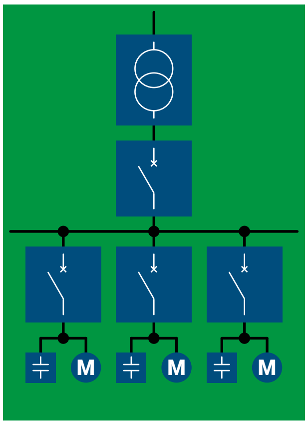
Low cosφ, has the following disadvantages:

- High power losses in the electrical lines.
- High voltage drop in the electrical lines.
- Over sizing of generators, electric lines and transformers.

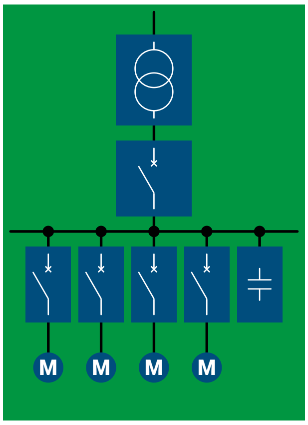
From this we understand the importance to improve (increase) the power factor.
Capacitors need to obtain this result.

Power factor correction: how?

By installing a capacitor bank it is possible to reduce the reactive power absorbed by the inductive loads in the system and consequently to improve power factor. It is suitable to have cosφ a little in excess of 0.95 to avoid paying the penalties provided for by the law.
The choice of the correct power factor correction equipment depends on the type of loads present and by their way of working.
The choice is between **individual compensation** and **central compensation**.
Nel caso di rifasamento distribuito, le unità rifasanti sono disposte nelle immediate vicinanze di ogni singolo carico che si vuole rifasare.
Individual compensation: power factor correction is wired at each single load (i.e. motor terminals).
Central compensation: there is only one bank of capacitors on the main power distribution switch board or substation.



Individual compensation



Central compensation

The individual compensation is a simple technical solution: the capacitor and the user equipment follow the same sorts during the daily work, so the regulation of the cosφ becomes systematic and closely linked to the load. Another great advantage of this type of power factor correction is the simple installation with low costs.
The daily trend of the loads has a fundamental importance for the choice of most suitable power factor correction. In many systems, not all the loads work in the same time and some of them work only a few hours per day. It is clear that the solution of the individual compensation becomes too expensive for the high number of capacitors that have to be installed. Most of these capacitors will not be used for long period of time.
The individual compensation is more effective if the majority of the reactive power is concentrated on a few substatios loads that work long period of time.
Central compensation is best suited for systems where the load fluctuates throughout the day. If the absorption of reactive power is very variable, it is advisable the use of automatic regulation in preference to fixed capacitors.

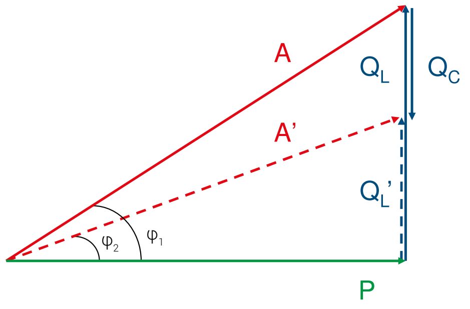
Power factor correction: How many?

The choice of capacitor bank to install in a system is closely depended from:

- $\cos\varphi_2$ value that we would obtain;
- $\cos\varphi_1$ starting value;
- installed active power.

By the following equation:

$$Q_C = P \cdot (\tan\varphi_1 - \tan\varphi_2)$$



Can be also written $Q_C = k \cdot P$

where the parameter k is easily calculated using Table 1 (in APPENDIX).
As example if we have installed a load that absorbs an active power of 300 kW having a power factor 0.7 and we want to increase it until 0.97.
From the table 1 we find: k = 0,770.
and therefore:

$$Q_C = 0{,}770 \cdot 300 = 231 \text{ kvar}$$

where:
Q_C = required capacitors reactive output (kvar);
P = active power (kW);
Q_L, Q_L' = inductive reactive output before and after the installation of the capacitor bank;
A, A'= apparent power before and after the power factor correction (kVA).

A typical example of power factor correction, sometimes not much considered but surely important, concerns the power factor correction of transformers for the distribution of energy.
It is essentially a fixed power factor correction that must compensate for the reactive power absorbed by the transformer in its no load condition (this happens often during the night). The calculation of the needed reactive output is very easy and it bases itself on this equation:

$$Q_C = I_0\% \cdot \frac{A_N}{100}$$

where
I_0% = magnetising current of the transformer
A_N = apparent rated power in kVA of the transformer

If we don't have these parameters, it is convenient to use the following table.

Power transformer [kVA]	Oil [kvar]	Resin [kvar]
10	1	1,5
20	2	1,7
50	4	2
75	5	2,5
100	5	2,5
160	7	4
200	7,5	5
250	8	7,5
315	10	7,5
400	12,5	8
500	15	10
630	17,5	12,5
800	20	15
1000	25	17,5
1250	30	20
1600	35	22
2000	40	25
2500	50	35
3150	60	50

Another very important example of power factor correction concerns asynchronous three-phase motors that are individually corrected.
The reactive power likely needed is reported on following table:

Motor power		Required reactive power [kvar]				
HP	KW	3000 rpm	1500 rpm	1000 rpm	750 rpm	500 rpm
0,4	0,55	–	–	0,5	0,5	–
1	0,73	0,5	0,5	0,6	0,6	–
2	1,47	0,8	0,8	1	1	–
3	2,21	1	1	1,2	1,6	–
5	3,68	1,6	1,6	2	2,5	–
7	5,15	2	2	2,5	3	–
10	7,36	3	3	4	4	5
15	11	4	5	5	6	6
30	22,1	10	10	10	12	15
50	36,8	15	20	20	25	25
100	73,6	25	30	30	30	40
150	110	30	40	40	50	60
200	147	40	50	50	60	70
250	184	50	60	60	70	80

Be careful: the capacitor output must not be dimensioned too high for individual compensated machines where the capacitor is directly connected with the motor terminals. The capacitor placed in parallel may act as a generator for the motor which will cause serious overvoltages (self-excitation phenomena). In case of wound rotor motor the reactive power of the capacitor bank must be increased by 5%.

Power factor correction: technical reasons

Recent energy market deregulation, along with new potential energy supplier rising, had lead to many and different type of invoicing which are not very clear in showing Power Factor up. However as energy final price is steady growing, to correct power factor is becoming more and more convenient. In most of the cases power factor improvement device prime cost is paid back in few months.
Technical-economical advantages of the installation of a capacitor bank are the following:

- Decrease of the losses in the network and on the transformers caused by the lower absorbed current.
- Decrease of voltage drops on lines.
- Optimisation of the system sizing.

The current I, that flows in the system, is calculated by:

$$I = \frac{P}{\sqrt{3} \cdot V \cdot \cos\varphi}$$

where
P = Active power.
V = Nominal voltage.

While cosφ increases, with the same absorbed power we can obtain a reduction in the value of the current and as a consequence the losses in the network and on the transformers are reduced.
Therefore we have an important saving on the size of electrical equipment used on a system. The best system sizing has some consequence on the line voltage drop. We can easily see that looking at the following formula:

$$\Delta V = R \cdot \frac{P}{V} + X \cdot \frac{Q}{V}$$

where
P = Active power on the network (kW).
Q = Reactive power on the network (kvar)
while R is the cable resistance and X its reactance (R<<X).

The capacitor bank installation reduces Q so we have a lower voltage drop. If, for a wrong calculation of the installed capacitor bank value, the reactive part of the above equation becomes negative, instead of a reduction of the voltage drop we have an increasing of the voltage at the end of the line (Ferranti Effect) with dangerous consequence for the installed loads.

Some examples clarify the concepts set out above:

cosφ	Power loss[1] [kW]	Supplied active power[2] [kW]
0,5	3,2	50
0,6	2,3	60
0,7	1,6	70
0,8	1,3	80
0,9	1	90
1	0	100

1. In function of cosφ, from a copper cable 3 x 25mm² 100m long carrying 40kW at 400Vac
2. By a 100kVA transformer, in function of cosφ

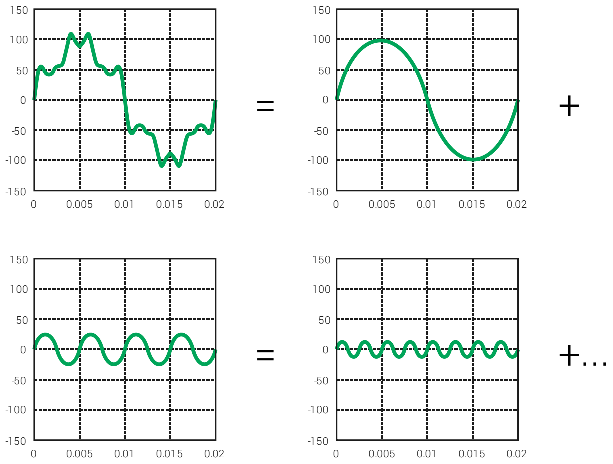
As we can see as the power factor increases we have fewer losses in the network and more active power from the same KVA. This allows us to optimise on the system sizing.

Power factor correction: Harmonics in the network

The distortions of the voltage and current waveforms are generated by non-linear loads (inverter, saturated transformers, rectifier, etc.) and produce the following problems:

- On the AC motors we find mechanical vibration that can reduce expected life. The increase of the losses creates overheating with consequent damaging of the insulating materials.
- In transformers they increase the copper and iron losses with possible damaging of the windings. The presence of direct voltage or current could cause the saturation of the cores with consequent increasing of the magnetising current.
- The capacitors suffer from the overheating and the increasing of the voltage that reduce their life.

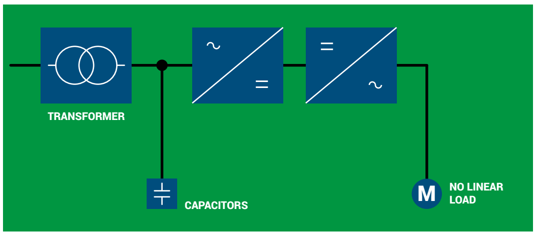
The waveform of the current (or voltage) generated by a nonlinear load being periodical, could be represented by the sum of many sinusoidal waves (a 50Hz component called fundamental and other components with multiple frequency of the fundamental component so called **harmonics**).

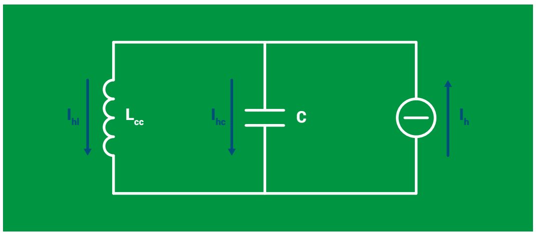


$$I = I_1 + I_2 + I_3 + ... + I_n$$

It is not advisable to install the power factor correction without considering the harmonic content of a system. This is because, even if we could manufacture capacitors that can withstand high overloads, capacitors produce an increase of harmonic content, with the negative effects just seen.
We speak about resonance phenomena when an inductive reactance is equal to the capacitive one:

$$2\pi f\, L = \frac{1}{2\pi f\, C}$$





Ideal current generator represents motor as harmonic current components generator I_h, these are independent from circuit inductance, while L_{CC} is obtainable by capacitor upstream short circuit power (in general it is equal to transformer short-circuit inductance).

The resonance frequency is obtained as follows:

$$N = \sqrt{\frac{S_{CC}}{Q}} \cong \sqrt{\frac{A \cdot 100}{Q \cdot V_{CC}\%}}$$

where
S_{cc} = short-circuit power of the network (MVA)
Q = output of power factor correction bank (kvar)
A = rated power transformer (kVA)
$V_{cc}\%$ = transformer short-circuit voltage
N = resonance harmonic order

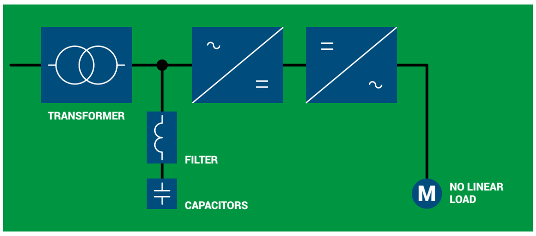
In parallel resonance conditions the current and the voltage of the circuit L_{CC} - C are heavily amplified as well as the nearby harmonic currents.

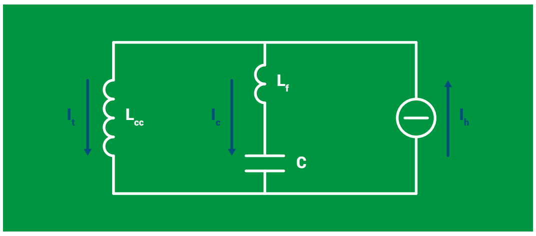
Hereinafter an example:
A = 630kVA (rated power transformer)
$V_{CC}\%$ = 6 (transformer short-circuit voltage %)
Q = 300kvar (output of power factor correction bank)

$$N = \sqrt{\frac{A \cdot 100}{Q \cdot V_{CC}\%}} = \sqrt{\frac{630 \cdot 100}{300 \cdot 6}} \cong 6$$

The result shows that in these conditions the system transformer-capacitor bank has the parallel resonance frequency of 300Hz (6x50Hz). This means likely amplification of 5th and 7th harmonic current.

The most convenient solution to avoid this is the detuned filter, formed introducing a filter reactor in series with the capacitors, making this a more complex resonant circuit but with the desired feature of having a resonance frequency below the first existing harmonic.





With this type of solution, the parallel resonance frequency is modified from

$$f_{rp} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{cc} \times C}}$$

to

$$f_{rp} = \frac{1}{2 \cdot \pi \cdot \sqrt{(L_{cc} + L_f) \times C}}$$

Normally the resonance frequency between the capacitor and the series reactance is shifted lower than 250Hz and it is generally between 135Hz and 210Hz. The lower frequencies correspond to higher harmonic loads.
The installation of a reactance in series with the capacitor bank produces a series resonance frequency:

$$f_{rs} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_f \times C}}$$

If a harmonic current I_h with the same frequency of the resonance in series exists, this one will be totally absorbed by the system capacitors - reactors without any effect on the network. The realisation of a tuned passive filter is based on this simple principle.
This application is required when we want the reduction of the total distortion in current (THD) on the system:

$$THD = \frac{\sqrt{I_3^2 + I_5^2 + I_7^2 + \ldots + I_n^2}}{I_1}$$

where
I_1 = component at the fundamental frequency (50Hz) of the total harmonic current
I_3 - I_5 - ... = harmonic components at the multiple frequency of the fundamental (150Hz, 250Hz, 350Hz, ...)

The dimensioning of tuned/passive filters is linked to the circuit parameter:

- Impedance of the network (attenuation effect less as the short-circuit power on the network increases: in some cases could be useful to add in series with the network a reactance to increase the filtering effect).
- Presence of further loads that generate harmonics linked to other nodes on the network.
- Capacitor types.

On this last point we have to make some considerations.
It is known that the capacitors tend to decrease capacity over time: varying the capacity inevitably varies the resonance series frequency

$$f_{rs} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_f \times C}}$$

and this drawback can be very dangerous because the system could lead in parallel resonance conditions. In this case, the filter does not absorb more harmonics but even amplifies them.
In order to have a constant capacity guarantee over time we need to use another type of capacitors made in bimetallized paper and oil impregnated polypropylene.
In addition to the passive absorption filter realized with capacitors and inductances is possible to eliminate the network harmonics, with another type of absorption filter: the Active Filter. The operation principle is based on the in-line injection of the same current harmonics produced by non-linear loads, but out of phase.

Power factor correction in presence of distorted voltage

In many industrial electrical systems or in the tertiary sector, the presence of non-linear loads (inverter, welding, filament free lamps, computers, drives, etc..) causes a distortion of the current, which is synthesized by the THDI% numeric parameter: if the current is sinusoidal his THDI% is zero, more the current is deformed so much higher is its THDI%.
In electrical currents with very deformed currents, the power factor correction equipment are carried out in a "filter banks" (or "block" or "blocked" or "detuned" if you prefer), or rather with inductors that prevent harmonic current to reach and damage the capacitor.
Usually the supply voltage remains sinusoidal even if a very deformed current flows in the plant; however, if the MV/LV transformer impedance is high, the voltage may also be affected by deformation: this impedance, crossed by a distorted current, will create a voltage drop equally distorted, causing on LV users a non-sinusoidal supply voltage (or with a certain $THDV_R$%).
It is rare that the $THDV_R$% reaches 8% (limit of IEC 50160), this happens for example when the MV/LV transformer is characterized by a high series impedance and/or is overloaded (saturation).
In a plant with distorted voltage there will be problems of various types, depending on the utilities (breakage or malfunction of electronic parts such as relays, plc, controller, computers; production beyond the acceptable tolerances, etc.).
Regarding the power factor correction, a high $THDV_R$% creates problems for the blocking reactors used in power factor correction banks. These can saturate and overheat for overload up to be damaged, causing the out of service of the power factor correction bank and/or problems to the capacitors.
This will result in an economic loss (payment of penalties for low cosφ) and technical, because the plant will run through by a higher current, resulting in conductors additional overhead (cables, bars) and the transformer.
For this problem, ICAR has developed a dedicated solution: the MULTImatic FD25V (for 400V network) and FD70V (for 690V network) power factor correction ranges. They are made with sound heavy dutybimetallized paper capacitors with high performance electronic instrumentation for the electrical parameters control; high linearity reactance allow them to bear up to 8% $THDV_R$ continuously.

Power factor correction in the presence of a photovoltaic system in spot trading

If on electrical plant of an industrial user is added a photovoltaic system, the active power drawn from the supply is reduced because of the power supplied by the photovoltaic system and consumed by the plant (consumption).
Therefore, it changes the relationship between reactive power and active energy drawn from the network and, consequently, the power factor is lower than the same system without photovoltaic.
We must therefore pay particular attention to the power factor correction not to have any penalties for low cosφ that could seriously erode the economic benefits of the photovoltaic system.
The power factor correction will be reviewed both for installed capacity, both for construction type. In fact, increasing the power factor corrector power, you will modify the resonance conditions with the MV/LV transformer which supply the system.
When the photovoltaic system has more power than the users one, or if it is possible that power is introduced to the network, the power factor corrector must also be able to run on the four quadrants. The two "standard" quadrants are related to the plant operation as a user that absorbs from the network both active and inductive reactive power, while the two quadrants related on the plant functioning as a generator, it provides the network active power, but it absorbs the inductive reactive power (quadrants of generation.

All ICAR range of cosφ electronic controllers are able to operate in four quadrants, running two different cosφ targets to optimize the system economic performance.
To manage the cogeneration quadrants you can alter some parameters settings. It is advisable to enter a value equal to 1, to optimize the yield of the PFC Bank. Refer to the manuals of the controllers for more details.
To get the maximum benefit in the time allowed by the PFC Bank, we recommend to use bimetallized paper capacitors, the only ones that guarantee a useful life comparable to the photovoltaic system one.