COMAR CONDENSATORI S.p.A
Via del Lavoro, 80 – Loc. Crespellano
40053 VALSAMOGGIA (BOLOGNA)
Tel. +39 / 051 / 733.383 - Fax. +39 / 051 / 733.620

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Title: **Choice of Power Factor Correction equipment in the presence of Harmonics**

Level: **BASIC**

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Author: Engineering Department of COMAR Condensatori SPA

1 Summary

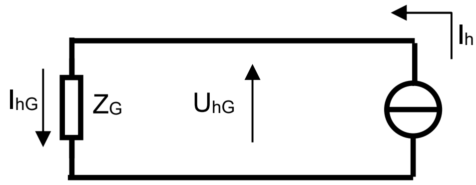
The criteria for choosing a P.F.C. equipment from the COMAR catalog based on the information collected on the electrical network are described below, on which it is necessary to reduce the reactive power absorbed by the electrical network, relative to the harmonics present.

If there is a risk of resonance with one of the harmonics present in the network, it is necessary to adopt a bank of capacitors with series inductance. The preferable resonance frequency is that which reduces the harmonic content on the capacitors, to guarantee a long life. It should be noted that a low tuning frequency (for example of 138 Hz) reduces more the harmonics flowing on the bank of capacitors, with respect to a higher frequency (for example of 189 Hz).

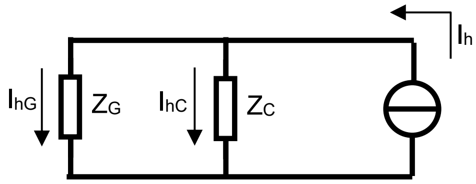
Finally, emphasis is placed on the method of measuring the THDu value, which identifies the harmonic voltage level present on the electrical network. Being the thermal inertia of the inductances of the order of 30 .. 60 min, the measurements of the THDu can be averaged over a time of 30 min.

2 Notes on harmonics

In an electric network without capacitors, the harmonics produced by the distorting loads (rectifiers, overloaded electric machines, etc.) flow mainly on the element of the network with the lowest equivalent impedance, ie mainly on the transformer.



If we consider the equivalent circuit of a network with distorting loads, like the one shown in the figure, where Z_G is the equivalent impedance of the network without the distorting loads, the harmonic currents produced ($I_h \equiv I_{hG}$) generate harmonic voltages U_{hG}, easily measurable in every point on the network.



In an electrical network where there are also capacitors, the lowest impedance becomes that of the capacitor, so the harmonic currents tend to flow even on the capacitors.

The impedance of the capacitor becomes lower and lower, the more the order of the harmonic increases, in practice it becomes lower than that of the transformer already for the first orders of more common harmonics produced by distorting loads.

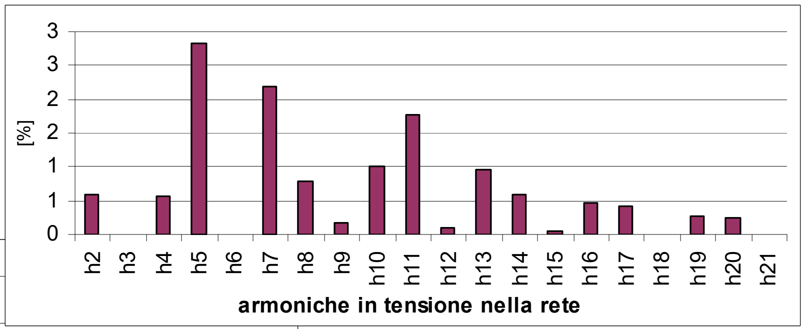
The life of the capacitors is strongly influenced by the presence of harmonic currents, to reduce the quantity of harmonics flowing in the capacitors an inductance is inserted in series, to create an LC load that presents a high impedance as the harmonic order increases. With this solution the load of the harmonic currents on the capacitors is considerably reduced.

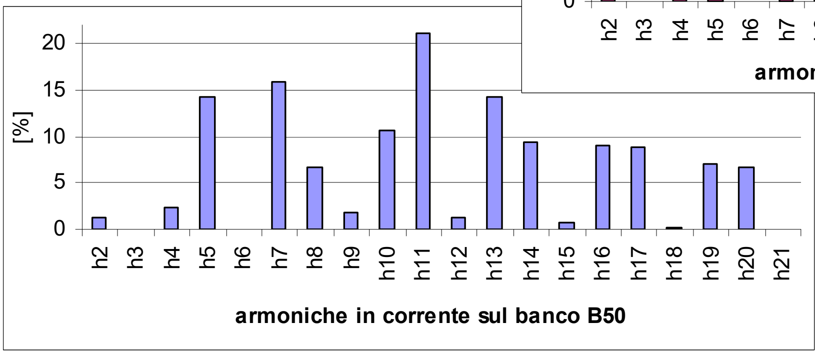
For the higher, or equal, harmonics at the 5th a bank of capacitors tuned to the 138 Hz frequency has a higher impedance than a capacitor bank tuned to the 189 Hz frequency. Therefore, less harmonics flow on the capacitors if the tuning frequency is 138 Hz, safeguarding it more life.

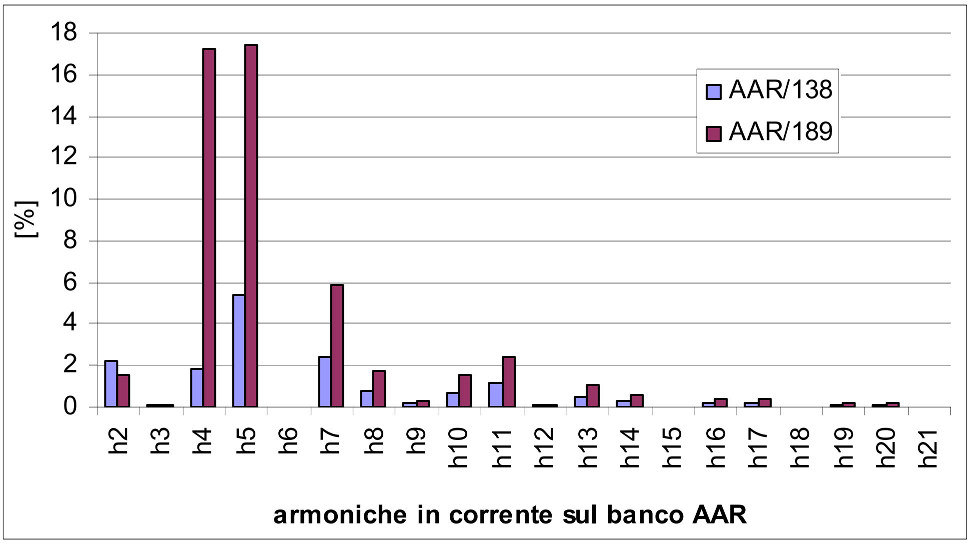
Another phenomenon to consider is the reduction of the transformer impedance, as its transformer power increases, so the greater the transformer power, the less harmonics will flow on the capacitor bank.

2.1 A practical example

A practical example to compare the harmonics that would flow in the capacitors with and without series inductances.







It can be seen that the harmonics flowing on the condenser are lower overall:

A. in the case of banks with series inductances (AAR/138 and AAR/189([1])) if compared to the harmonics that would flow in a bank B50 without series inductances;
B. in banks with series inductances tuned to 138 Hz, if compared to the harmonics that would flow in a bank with inductances tuned to 189 Hz.

Note:
([1]) the AAR / 189 series is also called AAR / 100

3 Impedance of the capacitor banks compared

3.1 Comparison between the impedance calculated at the 5th harmonic and that of a transformer

Considering the voltage value of the harmonics unchanged, analyzing the 5th harmonic, it results that the impedance of the bench in comparison is the following.

Capacitor banks	Impedance |Z(250Hz)| [Ω]
B50 – 25 kvar	1.4
B50 – 50 kvar	0.7
B50 – 75 kvar	0.5
AAR ft=189Hz – 25 kvar	1.0
AAR ft=189Hz – 50 kvar	0.5

Capacitor banks	Impedance |Z(250Hz)| [Ω]
AAR ft=189Hz – 75 kvar	0.3
AAR ft=138Hz – 25 kvar	3.4
AAR ft=138Hz – 50 kvar	1.7
AAR ft=138Hz – 75 kvar	1.1
Trasformatore da 400kVA	0.08

3.2 Comparison between the impedance calculated at the 7th harmonic and that of a transformer

Considering the voltage value of the harmonics unchanged, analyzing the 5th harmonic, it results that the impedance of the bench in comparison is the following.

Capacitor banks	Impedance |Z(350Hz)| [Ω]
B50 – 25 kvar	1.0
B50 – 50 kvar	0.5
B50 – 75 kvar	0.3
AAR ft=189Hz – 25 kvar	2.4
AAR ft=189Hz – 50 kvar	1.2

Capacitor banks	Impedance |Z(350Hz)| [Ω]
AAR ft=189Hz – 75 kvar	0.8
AAR ft=138Hz – 25 kvar	5.7
AAR ft=138Hz – 50 kvar	2.9
AAR ft=138Hz – 75 kvar	1.9
Trasformatore da 400kVA	0.11

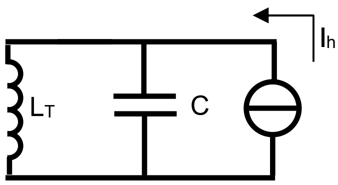
4 Risk of malfunctioning of the equipment connected to the electricity grid, having stages with a power electronics turned towards the electric network

The presence of capacitor banks without series inductances on the electrical network can lead to a radical change in the impedance of the electric network at high frequencies.

If we consider the impedance to the 11th harmonic, the impedance of a network with a 100 kVA transformer into which a 75 kvar bank is inserted is reduced to less than 1/3. For example, this can cause an overload of the power stage of an inverter for the photovoltaic system present on the network.

5 Resonance risk analysis with the upstream transformer

The life of the capacitors is negatively influenced by the quantity of harmonics that circulate there. In the case of parallel resonance between the upstream transformer (L_T) and the capacitor bank (C), the amount of harmonics circulating in the capacitors is amplified, drastically reducing the life of the capacitors.



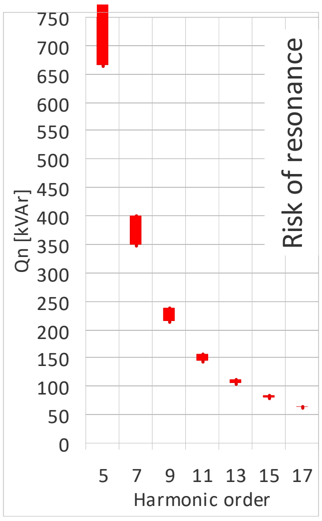
5.1 For an automatic Power Factor Correction equipment

If there is the presence of harmonics, perform the resonance risk analysis, as indicated below. If the risk of resonance exists, equipment with series inductances must be installed (ie filter not tuned or detuned).

To analyze the resonance risk the formula is used:

$$h_r = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{P_{SC}}{Q_C}} \approx \sqrt{\frac{1}{Q_C} \cdot \frac{S_{tr}}{\frac{Z_{tr}\%}{100}}}$$

h_r resonance order
P_{SC} Short circuit power at the insertion point of the capacitor bank
Q_C Reactive power of the capacitor bank
X_C capacitor bank reactance @ f_1
X_{SC} reactance to the short-circuit of the transformer
S_{tr} Apparent power of the transformer
Z_{tr} transformer impedance % ≡ Ucc%



To identify when an installation is at risk of resonance, it must be checked whether the resulting resonance order h_r is close to a harmonic.

To facilitate this verification, a spreadsheet has been developed that automatically generates a graph like the one on the side.

The risk of resonance is present when the black horizontal line intersects the red bar.

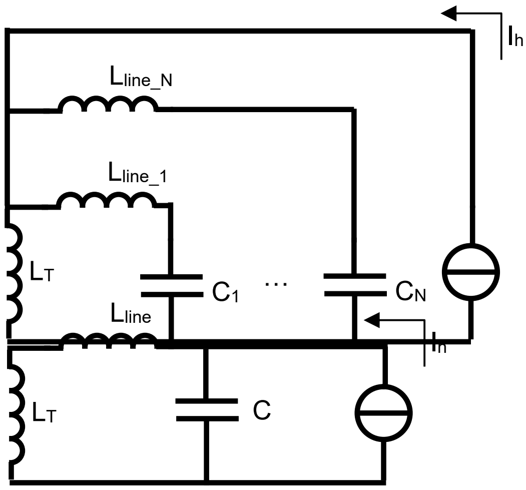
The horizontal lines correspond to the reactive power values that the power factor correction board can produce (example with steps of 50 kvar in the graph to the side).

5.1.1 When to perform risk analysis

Perform the analysis described above at least if one of the following conditions is true

- if the power factor correction panel is installed in the cabin where the MV / LV transformer is present;
- if upstream there is at least one dedicated transformer for the user to be corrected;
- if the available active power of the user to be corrected is greater than 200 kW.

5.2 For N fixed P.F.C. equipment



If there is a large number of P.F.C. equipment on the electricity network, the risk of resonance could exist, considering the sum of all the P.F.C. powers.

If the risk of resonance exists, decentralized fixed equipment with series inductances must be installed (filter not tuned or detuned), or the hypothesis of adopting centralized power factor correction equipment with series inductors must be evaluated.
To apply the criteria described in the previous chapter 5, the simplification shown opposite can be performed.

Where

C – capacity equivalent to all individual power factor correction equipment C_1 .. C_N
L_T – equivalent inductance of the transformer
L_{line} – equivalent inductance of the connection line to the transformer

In practice it is possible to consider in the calculations increases of the equivalent impedance of the transformer such as to incorporate the contribution of the connection lines between power factor correction equipment and the upstream transformer. In practice, it can be seen that the insertion of the cable in series with the distributed equipment lowers the reactive power values at which resonance could occur.

5.3 What COMAR needs to know about the electrical system

To perform the resonance risk analysis, the information described in par. **Errore. L'origine riferimento non è stata trovata.** summarized below:

Hypothesis A – single power factor correction equipment with single upstream transformer
Reactive power of the capacitor bank Q_C
Apparent transformer power S_{tr}
Short-circuit voltage percentage Ucc% (alternatively, impedance percentage Z_{tr}% of the transformer)

Hypothesis B – multiple P.F.C. equipment

For each power factor correction equipment, request the information described in hypothesis A, with the distance between the equipment and the upstream transformer and the type of connection cable (only if greater than 20 m).
Hypothesis C – multiple transformers

For each transformer the information described in hypothesis A must be requested, with the distance between the transformers and the type of connection cable between the different transformers (only if greater than 20 m)

In any case, it is necessary to know the harmonic spectrum of the electrical network.

6 Scelta in funzione del livello delle armoniche

Consider the following parameters

$THDi_{Cat}$ – THD in current on the capacitor bank declared in the catalog
Gn – power of distorting loads [kW]
Sn – apparent power of the transformer [kVA]
$THDi_C$ – THD in current on the capacitor bank considered in this technical documentation
$THDi_G$ – THD in current on the transformer declared on the catalog
THDu – THD in voltage of the network corresponding to $THDi_C$, or minimum value taken from the project datasheets
ft – resonance frequency

The following is a selection table of the series of power factor correction equipment according to some of these parameters more easily available to customers:

Gh/Sn – this ratio can be estimated without taking measurements
THDu – this parameter can be easily measured or estimated on the system during the design phase

Gh/Sn	≤0.1	≤0.15	≤0.3	≤0.4	>0.4	>0.4	>0.4	>0.4
THDu [%]	≤ 5	≤ 9	≤ 10	≤ 11	≤ 3	≤ 7, ≤ 11 (3)	≤ 21	≤ 4, ≤ 8 (3)
$THDi_{Cat}$ [%]	≤ 50	≤ 70	≤ 80	≤ 90	-	-	-	-
$THDi_C$ [%]	≤ 50	≤ 70	≤ 85	≤ 85	≤ 67	≤ 67	≤ 67	≤ 67
$THDi_G$ [%]	≤ 15	≤ 25	≤ 35	≤ 40	≤ 100	≤ 100	≤ 100	≤ 100
ft [Hz]	-	-	-	-	189	189	189	135
Model	B15	B35	B50	DMP	AAR/100	AAR/6xx	AAR/D20	AAR/138

Note:

(3) not using the 75 kvar rack, but only the 25 and 50 kvar racks

6.1 Choice of tuning frequency

Referring to the description in the chapter **Errore. L'origine riferimento non è stata trovata.**, you can choose the tuning frequency f_t taking into account the following.

All harmonic currents with harmonic order ≥ 5 are mostly attenuated by a bank of capacitors with a tuning frequency of 138 Hz, compared to one with 189 Hz or higher, so

- if the transformer power is very low, a tuning frequency of 138 Hz is preferable
- if the transformer power is medium / high you can opt for cheaper LC banks, for example tuned to 189 Hz (in low voltage), or 215 Hz (in medium voltage)

Finally, when choosing the tuning frequency, also consider that the 3rd harmonic, if present on all 3 phases in a balanced way, will never enter the capacitor bank, if not neutral. On the bank of capacitors, only unbalanced 3rd harmonic currents can flow: those between phase and phase.

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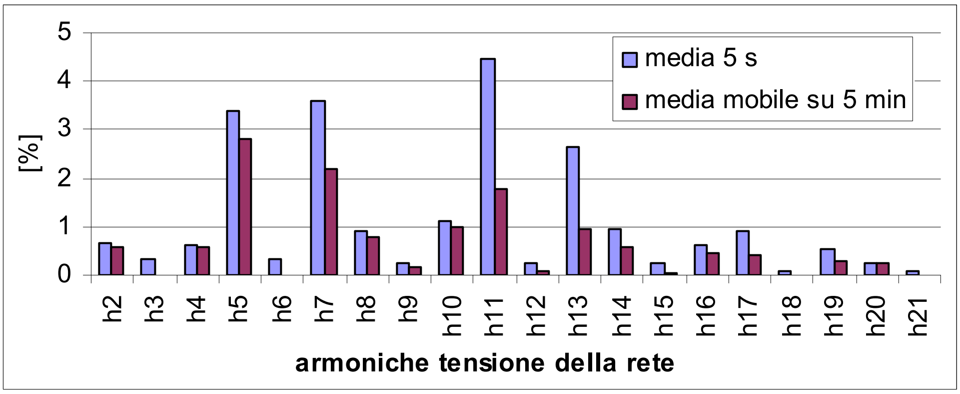
6.2 Analysis of measures to derive the maximum THDu of a network

Considering the thermal time constants of the inductances (of the order of 30-60 min) the values of the measured harmonics must be analyzed with a comparable integration period (ie the period of the measurement average).

An example that shows the values of the compared measurements, with average at 5 s, or at 5 min.



In conclusion, considering the peak values of the harmonics there is the risk of over-dimensioning the picture.
If instead we consider equipment with inductances having a linearity (L> 0.9 Ln)

$\frac{I_{sat}}{I_{h1}} > 1.5$, where I_{sat} is the saturation current, I_{h1} is the fundamental current

it can be considered to use values averaged over a period of at least 30 minutes to have a good cost performance ratio.