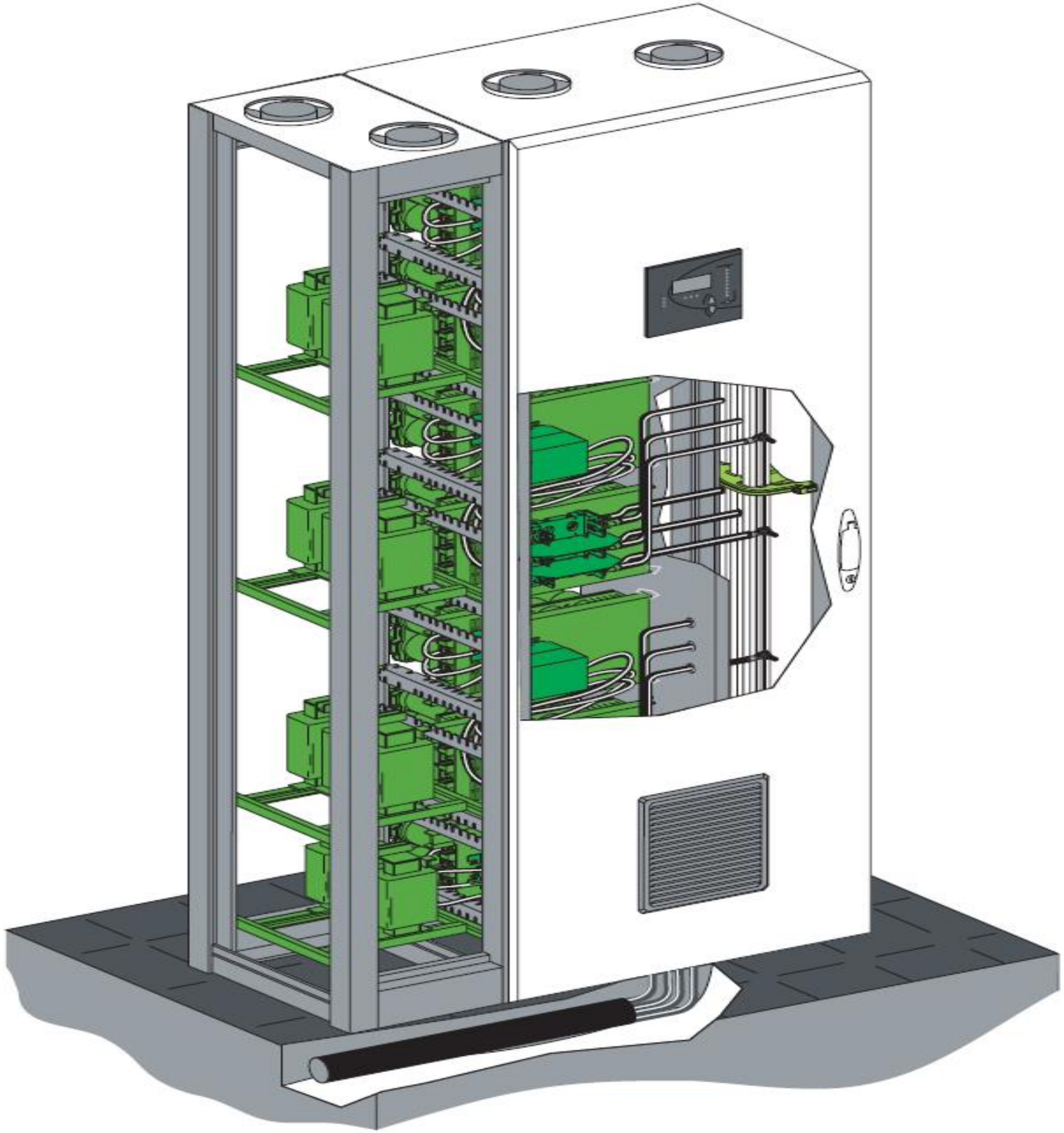


Power Factor and Power Factor Correction

Power Factor Correction

- Power Factor and reactive power.
- How to improve power factor.
- Where to install power factor correction capacitors?
- How to determine the optimum level of compensation?
- Compensation at the terminals of a transformer.
- Power factor correction of induction motors.
- The effects of harmonics.

Practical design Guide

Practical Exercise

Power Factor and reactive power

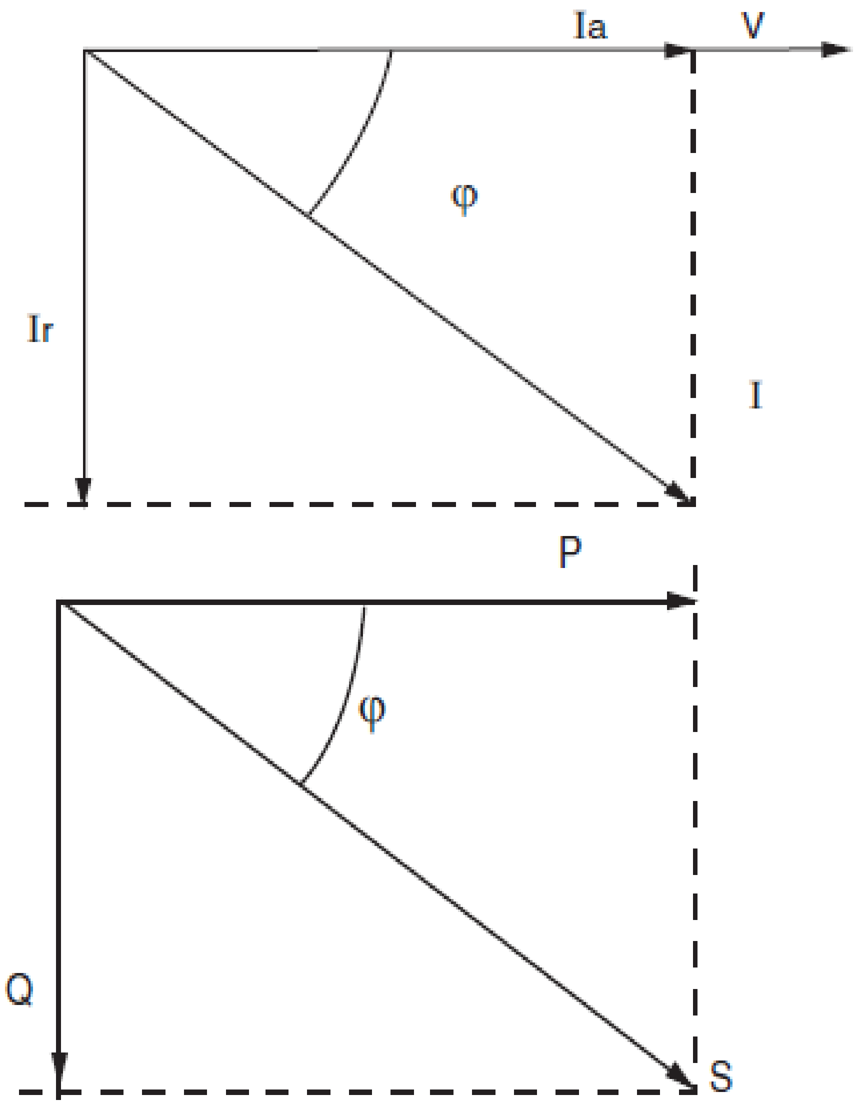
Definition

The **Power Factor λ is the ratio of the active power P (kW) to the apparent power S** (kVA):

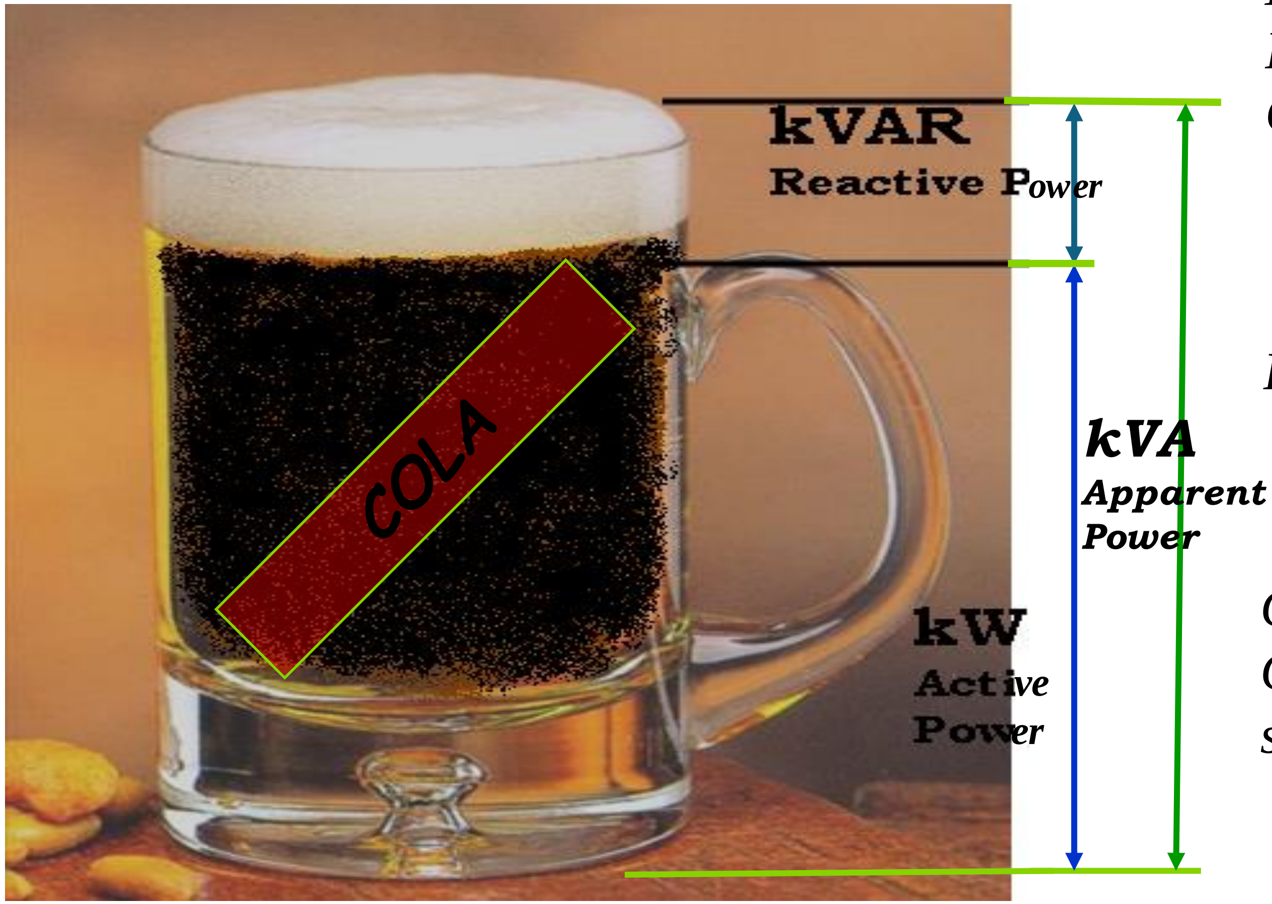
$$\lambda = \frac{P(kW)}{S(kVA)}$$

Power Factor: P/S = cos θ

This formula is applicable for sinusoidal voltage and current. This is why the Power Factor is then designated as **"Displacement Power Factor".**



What is Power Factor ?



> Power Factor : The Cola Analogy

Mug Capacity = Apparent Power (KVA)
Foam = Reactive Power (KVAR)
Cola = Real Power (kW)

$$\text{Power Factor} = \frac{\text{Cola (kW)}}{\text{Mug Capacity (KVA)}}$$

Capacitors absorb the Foam (KVAR), freeing up Mug Capacity so you don't have to buy a bigger mug and/or so you can pay less for your Cola!

An example of power calculations:

Motor Pn = 51 kW cos **θ** = 0.86 ζ = 0.91 (motor efficiency)

Pn = delivered shaft power = 51 kW

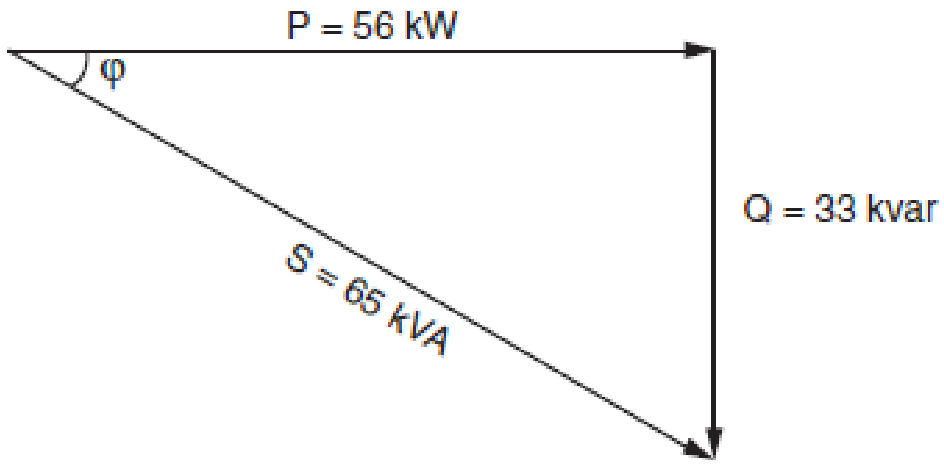
P = active power consumed

$$P = \frac{Pn}{\rho} = \frac{51}{0.91} = 56 \text{ kW}$$

S = apparent power

$$S = \frac{P}{\cos\varphi} = \frac{56}{0.86} = 65 \text{ kVA}$$

$$Q = \sqrt{S^2 - P^2} = \sqrt{65^2 - 56^2} = 33 \text{ kvar}$$



Nature of reactive power

> All inductive (i.e. electromagnetic) machines and devices that operate on AC systems convert electrical energy from the power system generators into mechanical work and heat. This energy is measured by kWh meters, and is referred to as **"active"** energy.

> In order to perform this conversion, magnetic fields have to be established in the machines. The magnetic field is created by the circulation of current in coils, which are mainly inductive. The current in these coils is therefore lagging by 90° relative to the voltage, and represent the **reactive** current absorbed by the machine.

> It should be noted that while reactive current does not draw power from the system, it does **cause power losses in transmission and distribution systems** by heating the conductors and produces **the worst possible conditions of voltage drop**

Equipment and appliances			cos φ	tan φ
Common induction motor	loaded at	0%	0.17	5.80
		25%	0.55	1.52
		50%	0.73	0.94
		75%	0.80	0.75
		100%	0.85	0.62
Incandescent lamps			1.0	0
Fluorescent lamps (uncompensated)			0.5	1.73
Fluorescent lamps (compensated)			0.93	0.39
Discharge lamps			0.4 to 0.6	2.29 to 1.33
Ovens using resistance elements			1.0	0
Induction heating ovens (compensated)			0.85	0.62
Dielectric type heating ovens			0.85	0.62
Resistance-type soldering machines			0.8 to 0.9	0.75 to 0.48
Fixed 1-phase arc-welding set			0.5	1.73
Arc-welding motor-generating set			0.7 to 0.9	1.02 to 0.48
Arc-welding transformer-rectifier set			0.7 to 0.8	1.02 to 0.75
Arc furnace			0.8	0.75

Penalty Of Low Power Factor Calculation

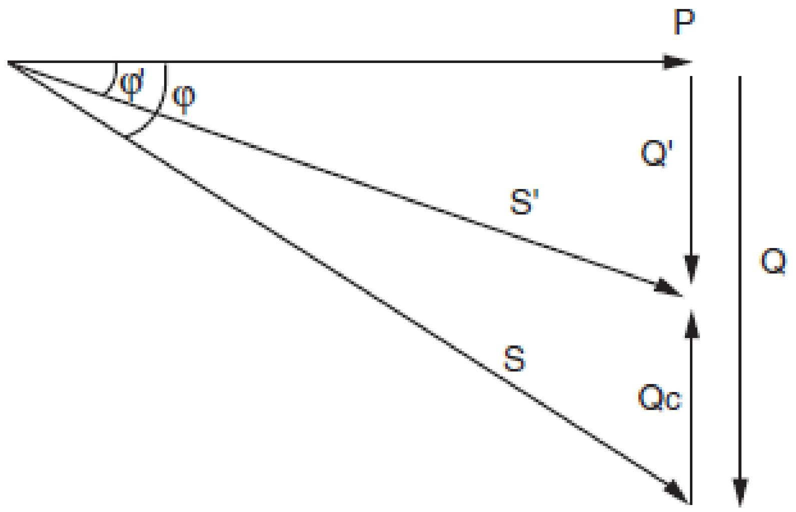
- $$\text{Average Annual PF} = \frac{\text{Annual kWh}}{\sqrt{\text{Annual kWh}^2 + \text{Annual kVARh}^2}}$$
- **PF** Penalty Is A Percent Multiplier To The Annual Electrical Bill
- No Penalty or bonus For **PF** of **0.92**
- **PF** Penalty Multiplier **0.5%** For Every **0.01** Drop (For **0.72 < PF < 0.92**)
- **PF** Penalty Multiplier Is **1%** For Every **0.01** Drop (For **PF < 0.72**)
- **PF** Bonus For **0.92 < PF < 0.95**
- **PF** Bonus multiplier **0.5%** for every **0.01** rise above **0.92** (up to **0.95**)
- *Thousands Of Customers Across The Country Are Currently Unaware That They Are Being Penalized For Low Power Factor!!!*

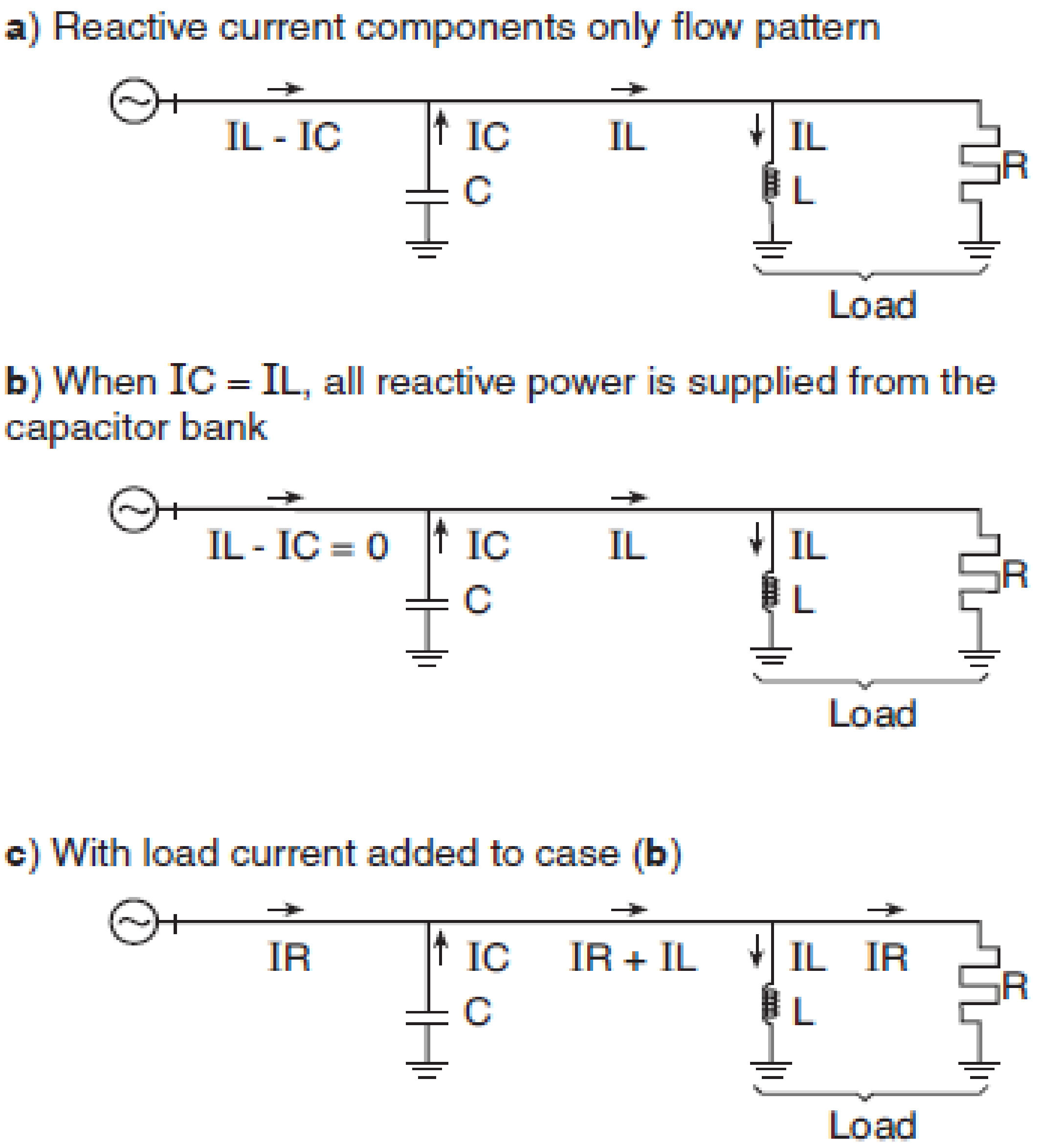
How to improve power factor

How to improve the power factor

Example:
A motor consumes 100 kW at a power factor of 0.75.
To improve the power factor to 0.93, the reactive power of the capacitor bank must be :

Qc = 100 (0.88 - 0.4) = 48 kvar





Before compensation		kvar rating of capacitor bank to install per kW of load, to improve cos φ (the power factor) or tan φ, to a given value													
		tan φ	0.75	0.59	0.48	0.46	0.43	0.40	0.36	0.33	0.29	0.25	0.20	0.14	0.0
tan φ	cos φ	cos φ	0.80	0.86	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
2.29	0.40		1.557	1.691	1.805	1.832	1.861	1.895	1.924	1.959	1.998	2.037	2.085	2.146	2.288
2.22	0.41		1.474	1.625	1.742	1.769	1.798	1.831	1.840	1.896	1.935	1.973	2.021	2.082	2.225
2.16	0.42		1.413	1.561	1.681	1.709	1.738	1.771	1.800	1.836	1.874	1.913	1.961	2.022	2.164
2.10	0.43		1.356	1.499	1.624	1.651	1.680	1.713	1.742	1.778	1.816	1.855	1.903	1.964	2.107
2.04	0.44		1.290	1.441	1.558	1.585	1.614	1.647	1.677	1.712	1.751	1.790	1.837	1.899	2.041
1.98	0.45		1.230	1.384	1.501	1.532	1.561	1.592	1.628	1.659	1.695	1.737	1.784	1.846	1.988
1.93	0.46		1.179	1.330	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
1.88	0.47		1.130	1.278	1.397	1.425	1.454	1.485	1.519	1.532	1.588	1.629	1.677	1.758	1.881
1.83	0.48		1.076	1.228	1.343	1.370	1.400	1.430	1.464	1.497	1.534	1.575	1.623	1.684	1.826
1.78	0.49		1.030	1.179	1.297	1.326	1.355	1.386	1.420	1.453	1.489	1.530	1.578	1.639	1.782
1.73	0.50		0.982	1.232	1.248	1.276	1.303	1.337	1.369	1.403	1.441	1.481	1.529	1.590	1.732
1.69	0.51		0.936	1.087	1.202	1.230	1.257	1.291	1.323	1.357	1.395	1.435	1.483	1.544	1.686
1.64	0.52		0.894	1.043	1.160	1.188	1.215	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
1.60	0.53		0.850	1.000	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
1.56	0.54		0.809	0.959	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
1.52	0.55		0.769	0.918	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
1.48	0.56		0.730	0.879	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.480
1.44	0.57		0.692	0.841	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
1.40	0.58		0.665	0.805	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202	1.263	1.405
1.37	0.59		0.618	0.768	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
1.33	0.60		0.584	0.733	0.849	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1.192	1.334
1.30	0.61		0.549	0.699	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096	1.157	1.299
1.27	0.62		0.515	0.665	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1.123	1.265
1.23	0.63		0.483	0.633	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030	1.091	1.233
1.20	0.64		0.450	0.601	0.716	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1.058	1.200
1.17	0.65		0.419	0.569	0.685	0.713	0.740	0.774	0.806	0.840	0.878	0.918	0.966	1.007	1.169
1.14	0.66		0.388	0.538	0.654	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	0.996	1.138
1.11	0.67		0.358	0.508	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	0.966	1.108
1.08	0.68		0.329	0.478	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	0.937	1.079
1.05	0.69		0.299	0.449	0.565	0.593	0.620	0.654	0.686	0.720	0.758	0.798	0.840	0.907	1.049
1.02	0.70		0.270	0.420	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.99	0.71		0.242	0.392	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.96	0.72		0.213	0.364	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.94	0.73		0.186	0.336	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.91	0.74		0.159	0.309	0.425	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.88	0.75		0.132	0.82	0.398	0.426	0.453	0.487	0.519	0.553	0.591	0.631	0.673	0.740	0.882

Schneider Electric

How to improve the power factor

Compensation at LV:

At low voltage, compensation is provided by:

- Fixed-value capacitor
- Equipment providing automatic regulation, or banks which allow continuous adjustment according to requirements, as loading of the installation changes

Note: When the installed reactive power of compensation exceeds 800 kvar, and the load is continuous and stable, it is often found to be economically advantageous to install capacitor banks at the medium voltage level.

How to improve the power factor

1. Fixed Capacitors

This arrangement employs one or more capacitor(s) to form a constant level of compensation.

Control may be:
- •Manual: by circuit-breaker or load-break switch
- •Semi-automatic: by contactor
- •Direct connection to an appliance and switched with it

These capacitors are applied:
- • At the terminals of inductive devices (motors and transformers)
- • At bus-bars supplying numerous small motors and inductive appliance for which individual compensation would be too costly
- • In cases where the level of load is reasonably constant.

•Where the kvar rating of the capacitors is **less than, or equal to 15% of the supply transformer rating**, a fixed value of compensation is appropriate. Above the 15% level, it is advisable to install an automatically-controlled bank of capacitors.

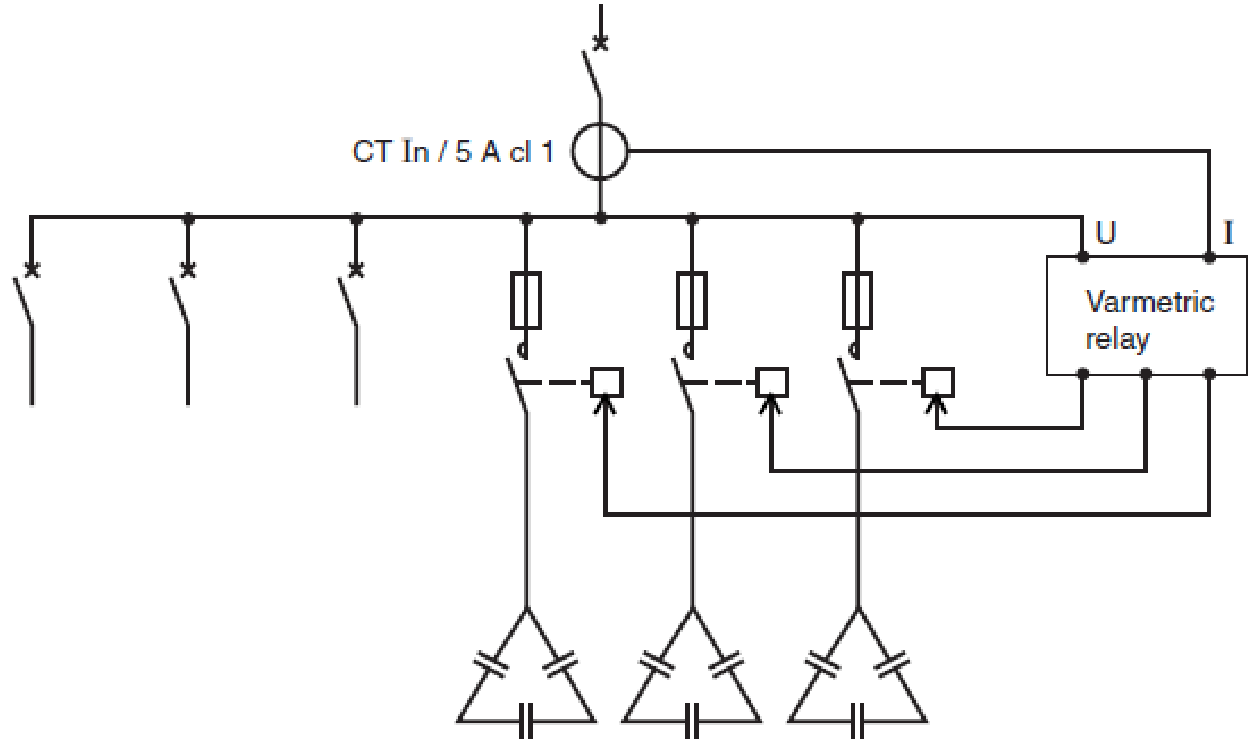
How to improve the power factor

2. Automatic Capacitors bank

This kind of equipment provides automatic control of compensation, maintaining the power factor within close limits around a selected level. Such equipment is applied at points in an installation where **the active-power and/or reactive-power variations are relatively large**,

for example:

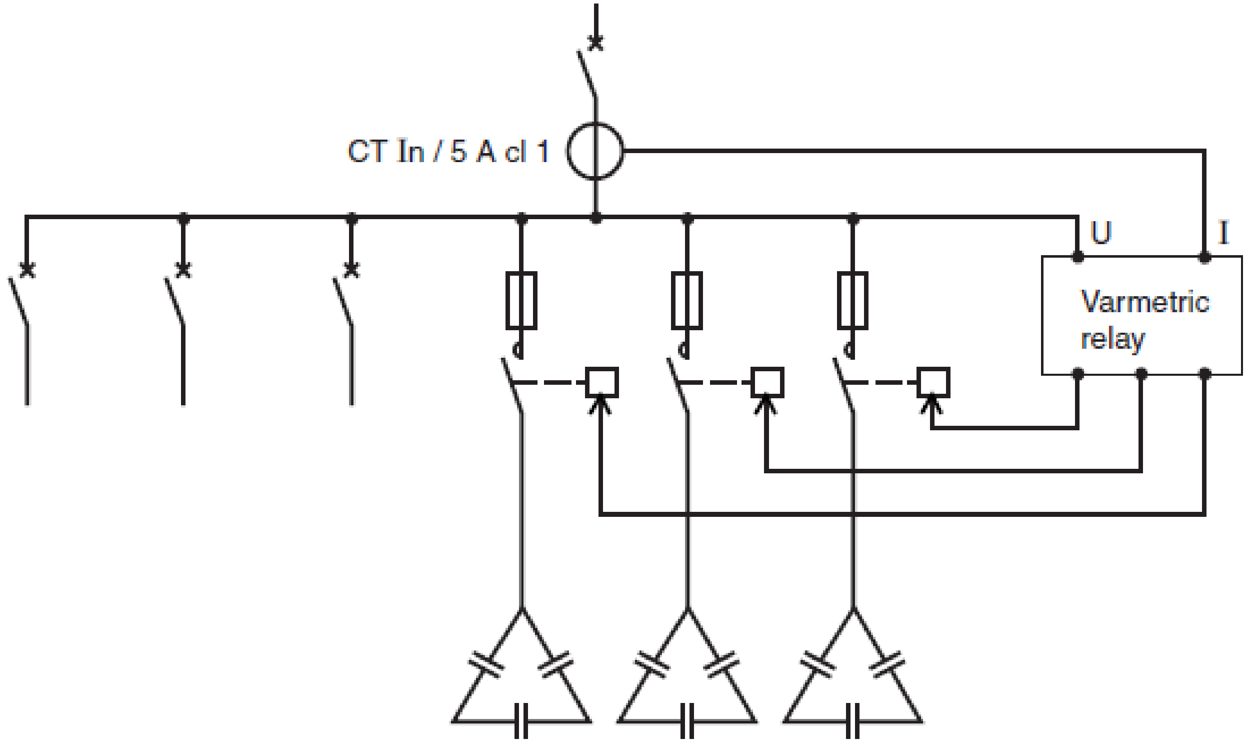
- At the bus-bars of a general power distribution board
- At the terminals of a heavily-loaded feeder cable



How to improve the power factor

2. Automatic Capacitors bank

Power factor correction equipment including **<u>static contactors (thyristors)</u>** instead of usual contactors is particularly suitable for a certain number of installations using equipment with fast cycle and/or sensitive to transient surges.



<u>The advantages of static contactors are :</u>

- Immediate response to all power factor fluctuation (response time as low as 40 ms according to regulator option)
- Unlimited number of operations
- Elimination of transient phenomena on the network on capacitor switching
- Fully silent operation

Where to install power factor correction capacitors?

Global Compensation

Advantages

•Reduces the tariff penalties for excessive consumption of kvars

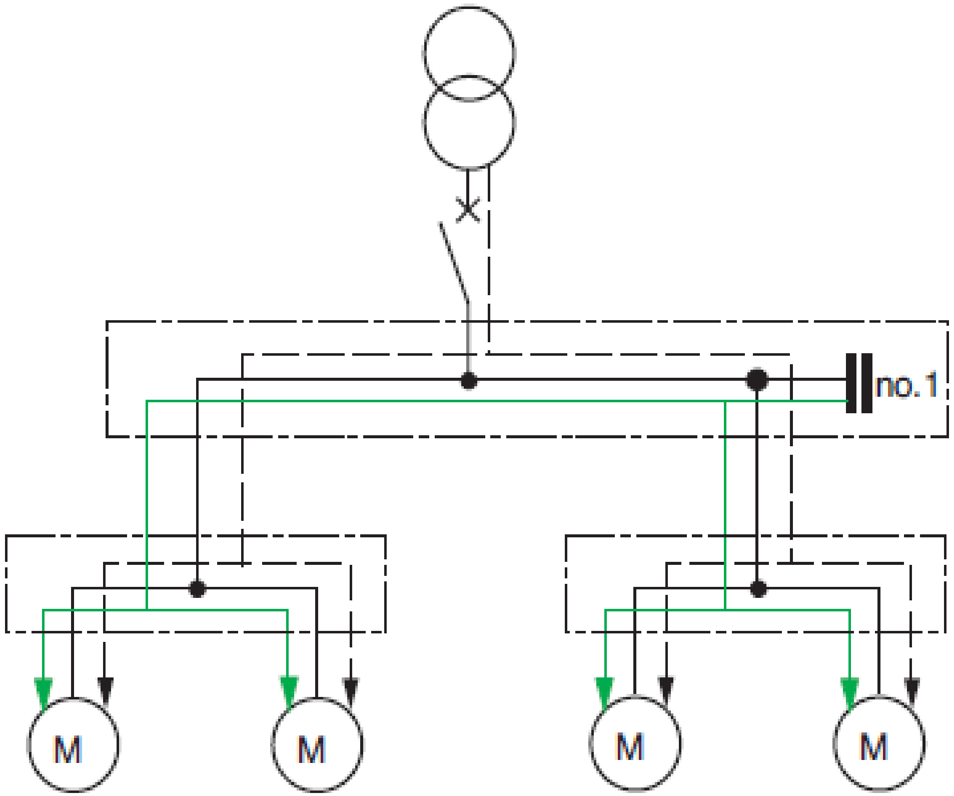
•Reduces the apparent power kVA demand, on which standing charges are usually based

•Relieves the supply transformer, which is then able to accept more load if necessary

Comments

•Reactive current still flows in all conductors of cables leaving (i.e. downstream of) the main LV distribution board

•For the above reason, the sizing of these cables, and power losses in them, are not improved by the global mode of compensation.



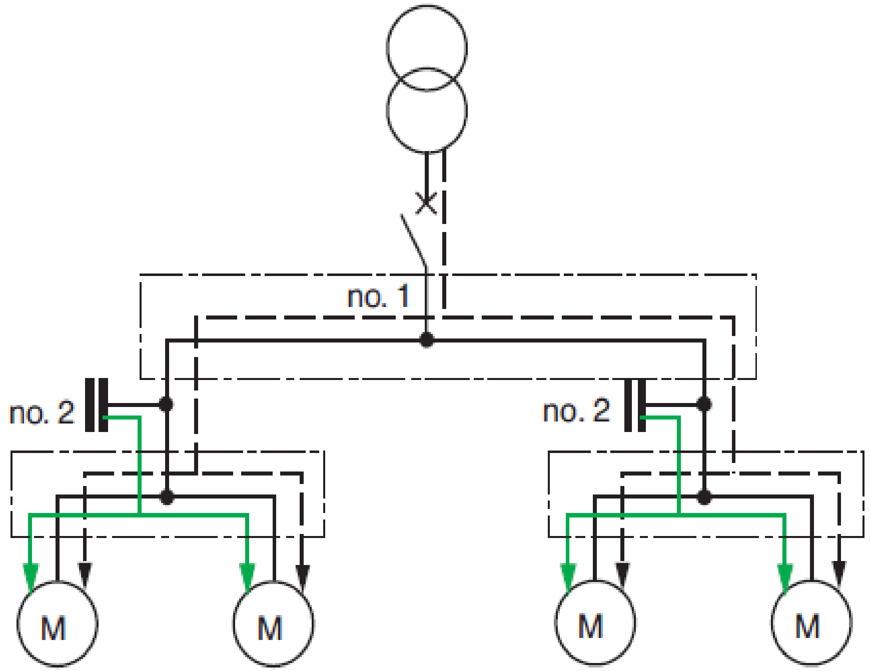
Compensation by sector

Advantages

- Reduces the tariff penalties for excessive consumption of kvars
- Reduces the apparent power kVA demand, on which standing charges are usually based
- Relieves the supply transformer, which is then able to accept more load if necessary
- The size of the cables supplying the local distribution boards may be reduced, or will have additional capacity for possible load increases

Comments

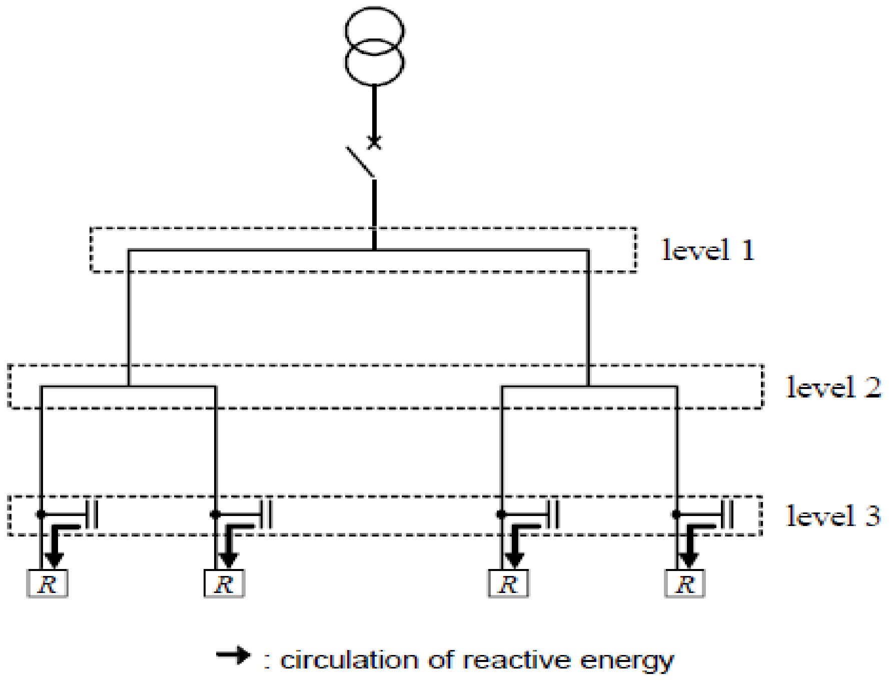
- Reactive current still flows in all cables downstream of the local distribution boards
- For the above reason, the sizing of these cables, and the power losses in them, are not improved by compensation by sector
- Where large changes in loads occur, there is always a risk of overcompensation and consequent overvoltage problems



Individual Compensation

Individual compensation should be considered when the power of the motor is significant with respect to the declared power requirement (kVA) of the installation.

The kvar rating of the capacitor bank is in the order of 25% of the kW rating of the motor. Complementary compensation at the origin of the installation (transformer) may also be beneficial.



Advantages

- Reduces the tariff penalties for excessive consumption of kvars
- Reduces the apparent power kVA demand
- Reduces the size of all cables as well as the cable losses

Comments

- Significant reactive currents no longer exist in the installation

Compensation at the terminals of a transformer

Compensation to increase the available active power output

An installation is supplied from a 630 kVA transformer loaded at 450 kW (P1) with a mean power factor of 0.8 lagging. The apparent power $S1 = \frac{450}{0.8} = 562$ kVA

The corresponding reactive power

$$Q1 = \sqrt{S1^2 - P1^2} = 337 \text{ kvar}$$

The anticipated load increase P2 = 100 kW at a power factor of 0.7 lagging.

The apparent power $S2 = \frac{100}{0.7} = 143$ kVA

The corresponding reactive power

$$Q2 = \sqrt{S2^2 - P2^2} = 102 \text{ kvar}$$

What is the minimum value of capacitive kvar to be installed, in order to avoid a change of transformer?

Total power now to be supplied:

P = P1 + P2 = 550 kW

The maximum reactive power capability of the 630 kVA transformer when delivering 550 kW is:

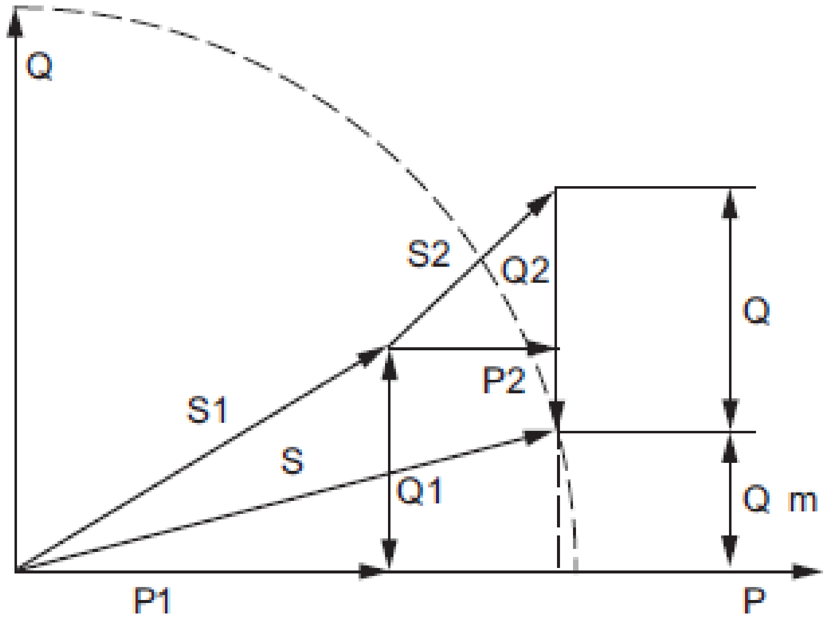
$$Qm = \sqrt{S^2 - P^2} \qquad Qm = \sqrt{630^2 - 550^2} = 307 \text{ kvar}$$

Total reactive power required by the installation before compensation:

Q1 + Q2 = 337 + 102 = 439 kvar

So that the minimum size of capacitor bank to install:

Qkvar = 439 - 307 = 132 kvar



Compensation of reactive energy absorbed by the transformer

Where metering is carried out at the MV side of a transformer, the reactive-energy losses in the transformer may need to be compensated (depending on the tariff)

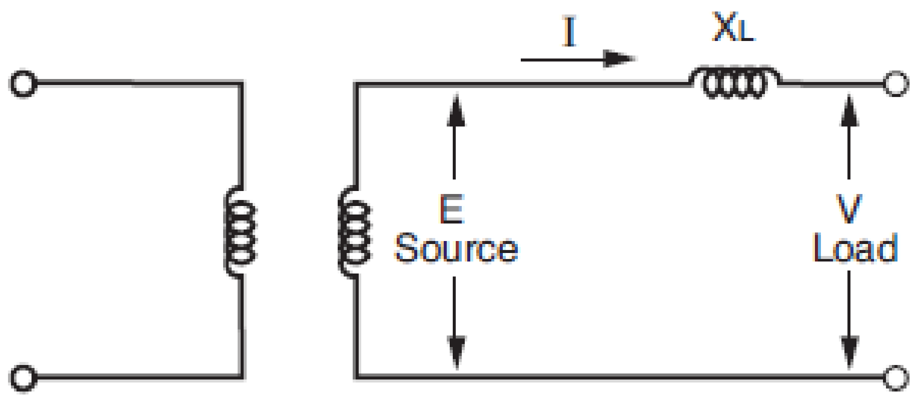
The reactive power absorbed by a transformer cannot be neglected, and can amount to (about) 5% of the transformer rating when supplying its full load. Compensation can be provided by a bank of capacitors. In transformers, reactive power is absorbed by both shunt (magnetizing) and series (leakage flux) reactances. Complete compensation can be provided by a bank of shunt-connected LV capacitors

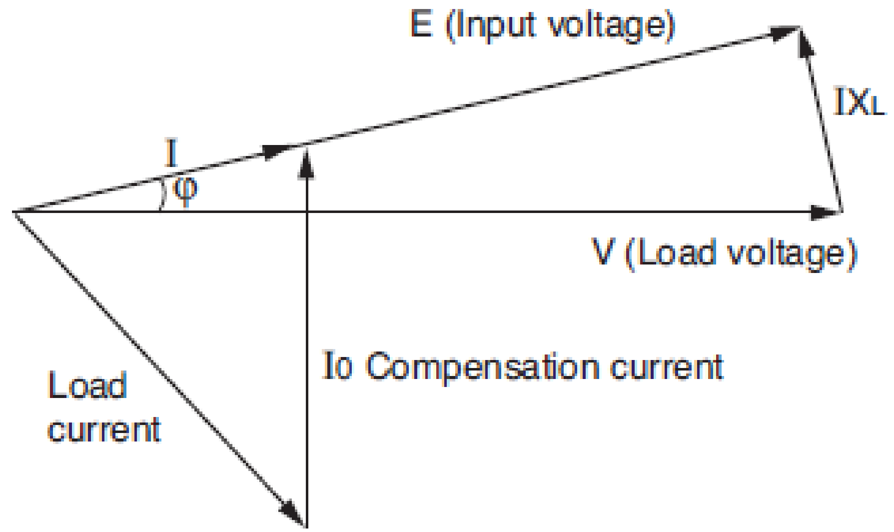
Rated power (kVA)	Reactive power (kvar) to be compensated	
	No load	Full load
100	2.5	6.1
160	3.7	9.6
250	5.3	14.7
315	6.3	18.4
400	7.6	22.9
500	9.5	28.7
630	11.3	35.7
800	20	54.5
1000	23.9	72.4
1250	27.4	94.5
1600	31.9	126
2000	37.8	176

Compensation of reactive energy absorbed by the transformer

As a matter of interest, the kvar losses in a transformer can be completely compensated by adjusting the capacitor bank to give the load a (slightly) leading power factor.

In such a case, all of the kvar of the transformer is being supplied from the capacitor bank, while the input to the MV side of the transformer is at unity power factor,





Power factor correction of induction motors.

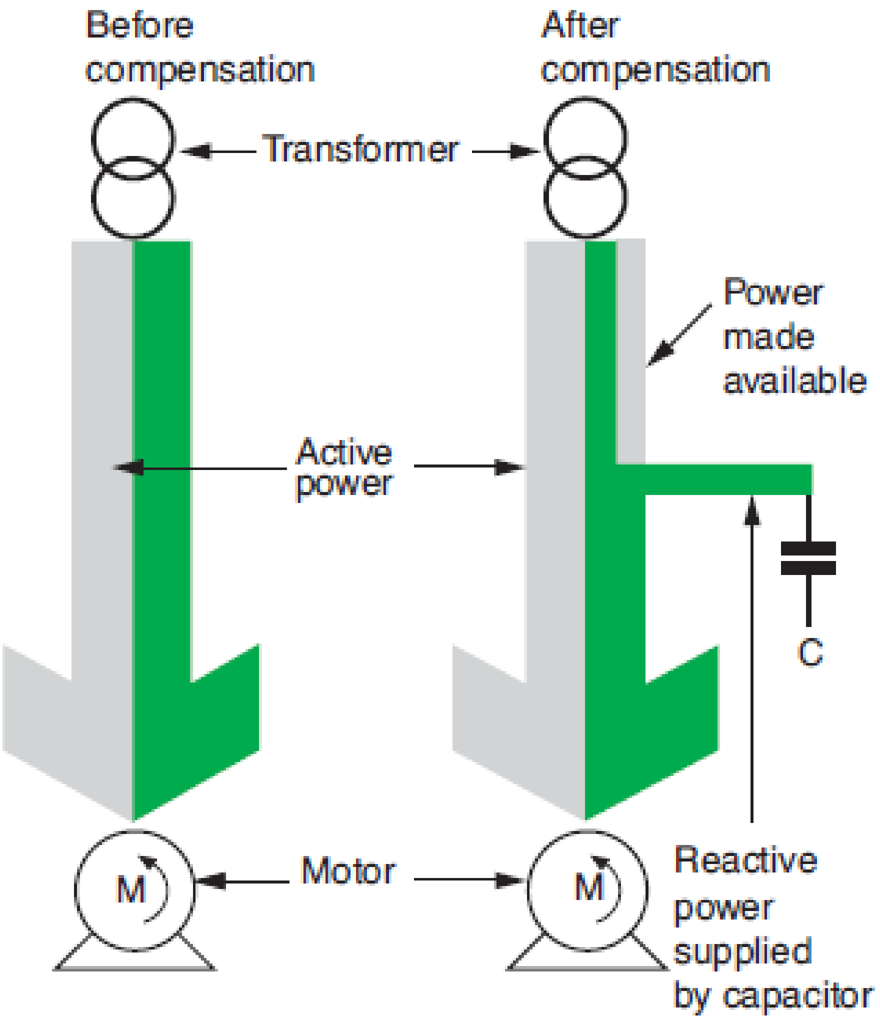
Connection of Capacitor bank and protection setting

Individual motor compensation is recommended where the motor power (kVA) is large with respect to the declared power of the installation

After applying compensation to a motor, the current to the motor-capacitor combination will be lower than before, assuming the same motor-driven load conditions. This is because a significant part of the reactive component of the motor current is being supplied from the capacitor.

Where the over-current protection devices of the motor are located upstream of the motor capacitor connection (and this will always be the case for terminal-connected capacitors), the over-current relay settings must be reduced in the ratio:

cos θ before compensation / cos θ after compensation



The effects of harmonics.

Risk of resonance

$$h_0 = \sqrt{\frac{S_{SC}}{Q}}$$

Where:

S_{SC} = the level of system short-circuit power (kVA) at the point of connection of the capacitor

Q = capacitor bank rating in kvar

h_0 = the order of the natural frequency f_0 , i.e. $f_0/50$ for a 50 Hz system, or $f_0/60$ for a 60 Hz system.

For example:

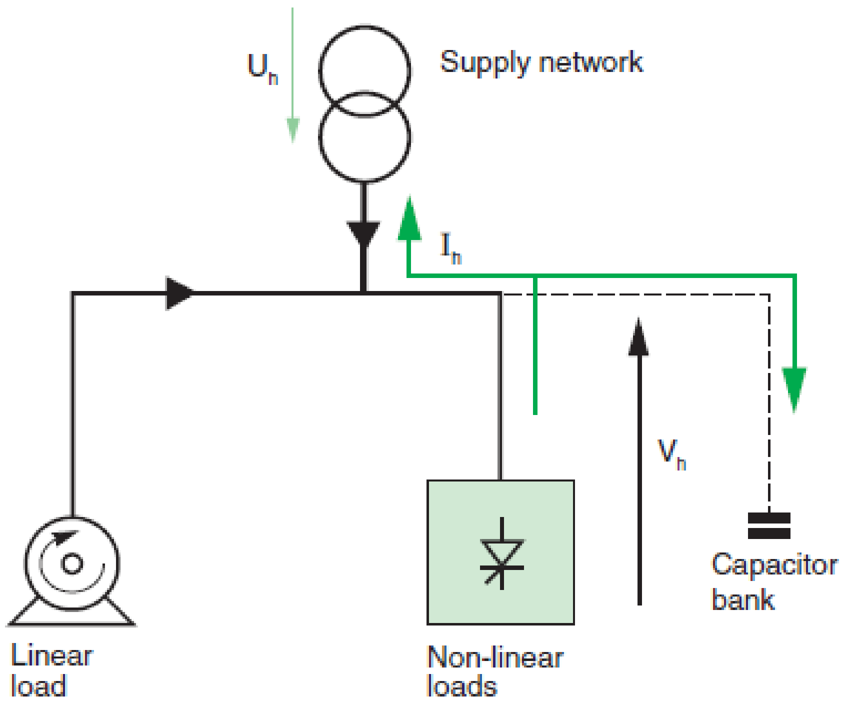
Transformer power rating:	S = 630kVA
Short-circuit voltage:	u_{SC} = 6%
Short-circuit power at the busbar level:	S_{SC} ~ 10 MVA
Reactive power of the capacitor bank:	Q = 350 kvar

Then:

$$h_0 = \sqrt{\frac{S_{SC}}{Q}} = \sqrt{\frac{10.10^3}{350}} = 5.5$$

The natural frequency of the capacitor/system-inductance combination is close to the 5th harmonic frequency of the system.

For a 50Hz system, the natural frequency f_0 is then equal to $f_0 = 50 \times h_0 = 50 \times 5.5 =$ 275 Hz



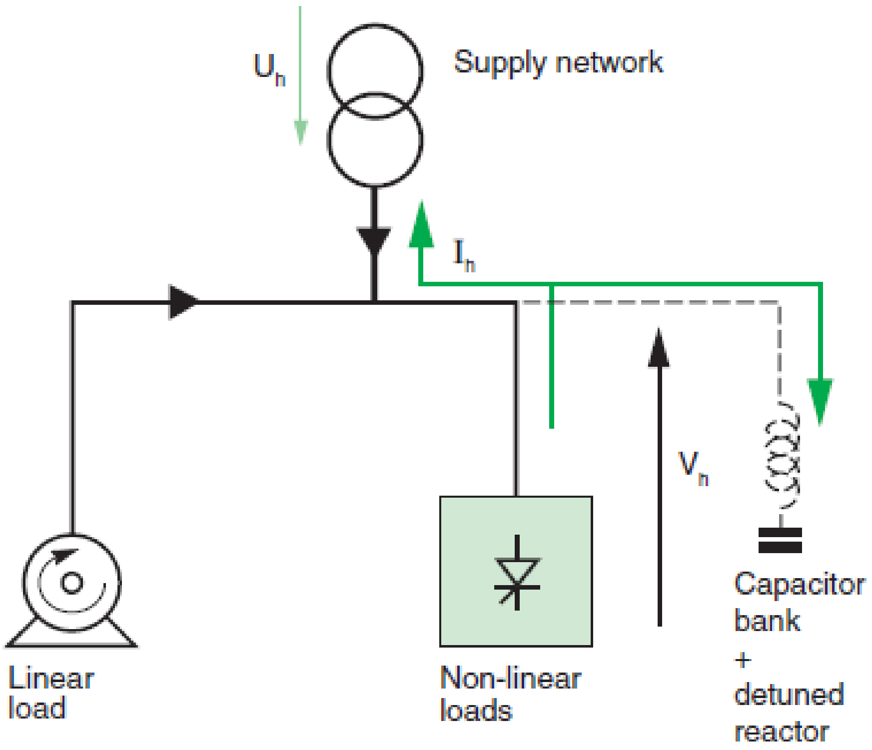
Possible Solutions

$G_h \leq 0.1 \times S_n$	$0.1 \times S_n < G_h \leq 0.2 \times S_n$	$0.2 \times S_n < G_h \leq 0.5 \times S_n$	$G_h > 0.5 \times S_n$
Standard capacitors	Heavy Duty capacitors or capacitors with voltage rating increased by 10%	Heavy Duty capacitors or capacitors with voltage rating increased by 20% + detuned reactor	Harmonic filtering necessary

- S_{SC} = 3-phase short-circuit power in kVA at the busbar level
- S_n = sum of the kVA ratings of all transformers supplying (i.e. directly connected to) the busbar
- G_h = sum of the kVA ratings of all harmonic-generating devices (static converters, inverters, variable speed drives, etc.) connected to the busbar. If the ratings of some of these devices are quoted in kW only, assume an average power factor of 0.7 to obtain the kVA ratings

Connection of Power Factor Correction capacitors with detuned reactors

In order to attenuate the effects of harmonics (significant increase of capacitor current as well as high current and voltage distortion), reactors should be associated to capacitors. Reactors and capacitors are configured in a series resonant circuit, tuned so that the series resonant frequency is below the lowest harmonic frequency present in the system.



Relative impedance (%)	Tuning order	Tuning frequency @50Hz (Hz)	Tuning frequency @60Hz (Hz)
5.7	4.2	210	250
7	3.8	190	230
14	2.7	135	160

Harmonic Management

Harmonic Management

1. Why is it necessary to manage harmonics.

Harmonic Disturbances

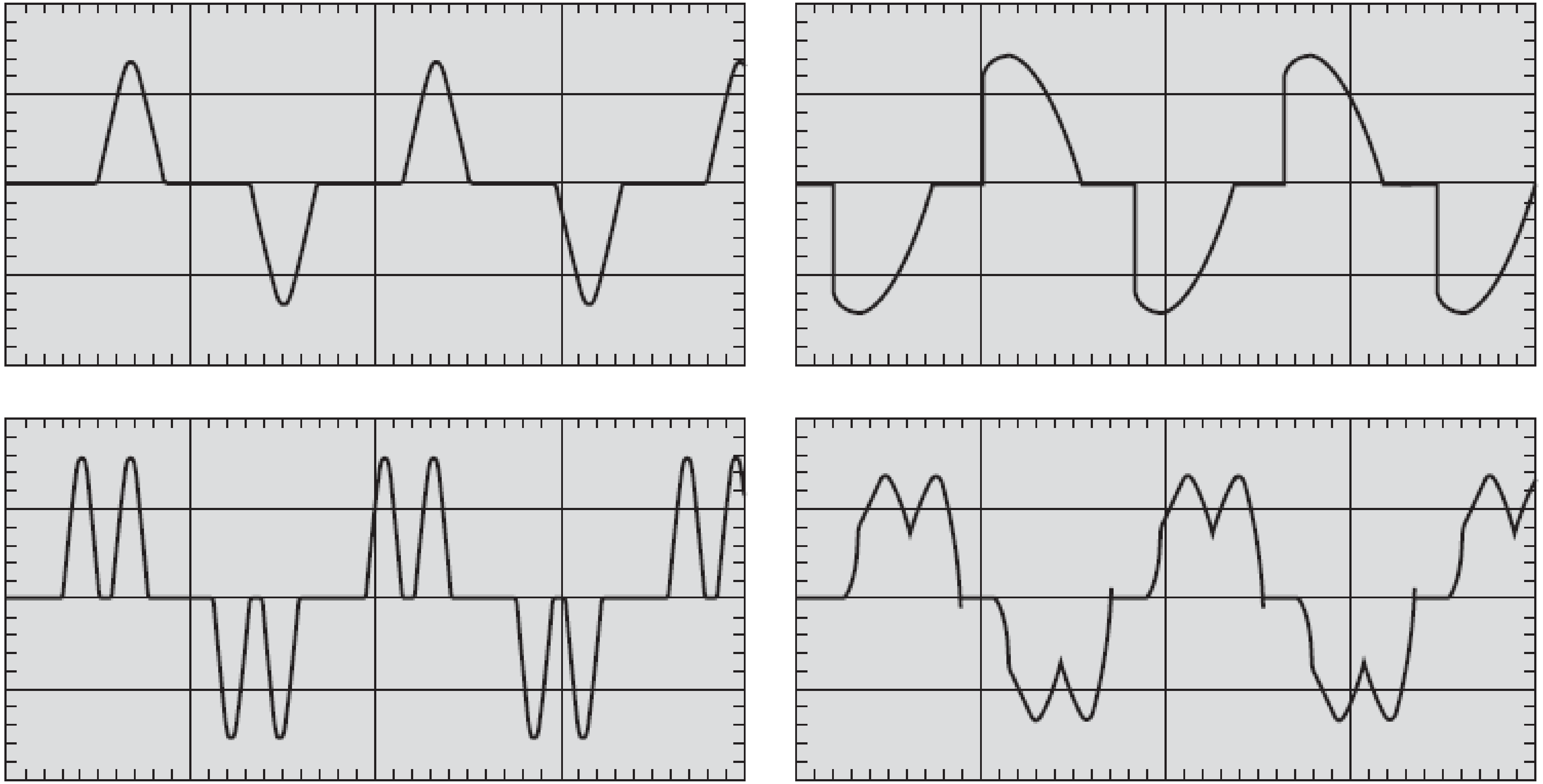
- Overload of distribution networks due to the increase of r.m.s. currents
- Overload of neutral conductors, which current can exceed the phase currents,
- Overload, vibration and premature ageing of generators, transformers and motors
- Overload and premature ageing of Power Factor Correction capacitors,
- Distortion of the supply voltage that can disturb sensitive loads,
- Disturbance in communication networks and telephone lines.

Economic impact of Disturbances

- Premature ageing of equipment means it must be replaced sooner, unless oversized right from the start,
- Overload on the distribution network means higher equipment rating, increased
- subscribed power level for the industrial customer, and increased power losses,
- Unexpected current distortion can lead to nuisance tripping and production halt.

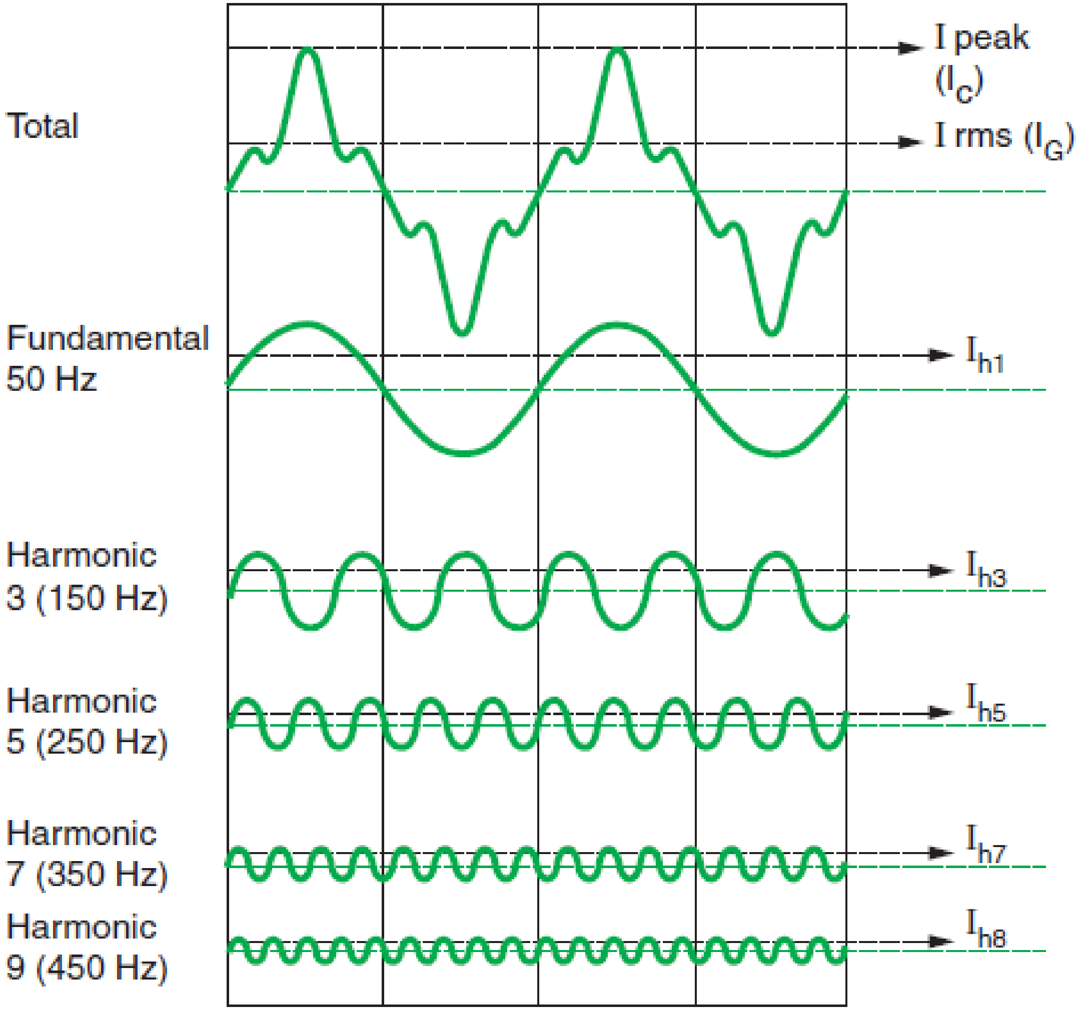
2. Definition and origin of harmonics.

Definition



A load is said to be non-linear when the current it draws does not have the same waveform as the supply voltage. The flow of harmonic currents through system impedances in turn creates voltage harmonics, which distort the supply voltage.

Definition



$$y(t) = Y_0 + \sum_{h=1}^{h=\infty} Y_h \sqrt{2}\sin(h\omega t - \varphi_h)$$

where:

- Y_0: value of the DC component, generally zero and considered as such hereinafter,
- Y_h: r.m.s. value of the harmonic of order h,
- ω: angular frequency of the fundamental frequency,
- φ_h: displacement of the harmonic component at t = 0.

Total Harmonic Distortion: THD

The Total Harmonic Distortion (THD) is an indicator of the distortion of a signal. It is widely used in Electrical Engineering and Harmonic management in particular.

Current or voltage THD

For current harmonics, the equation is:

$$THD_i = \sqrt{\sum_{h=2}^{h=H} \left(\frac{I_h}{I_1}\right)^2}$$

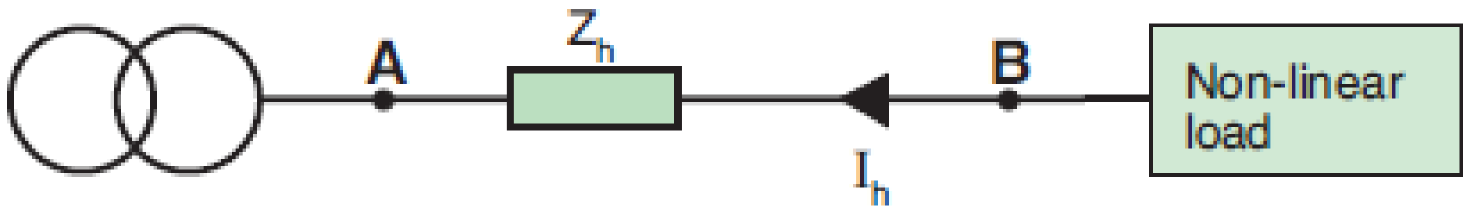
By introducing the total r.m.s value of the current: $I_{rms} = \sqrt{\sum_{h=1}^{h=H} I_h^2}$ we obtain the following relation:

$$THD_i = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2 - 1}$$

equivalent to: $I_{rms} = I_1 \sqrt{1 + THD_i^{\,2}}$

Origin of harmonics

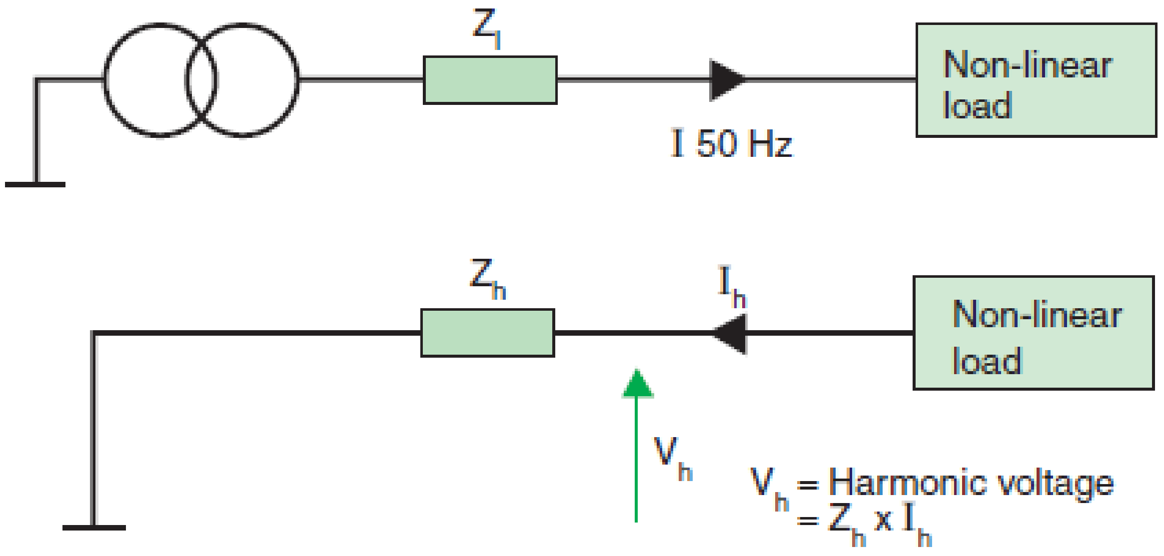
- Industrial equipment (welding machines, arc and induction furnaces, battery chargers),
- Variable Speed Drives for AC or DC motors,
- Uninterruptible Power Supplies,
- Office Equipment (PCs, printers, servers, etc.),
- Household appliances (TV sets, microwave ovens, fluorescent lighting, light dimmers).



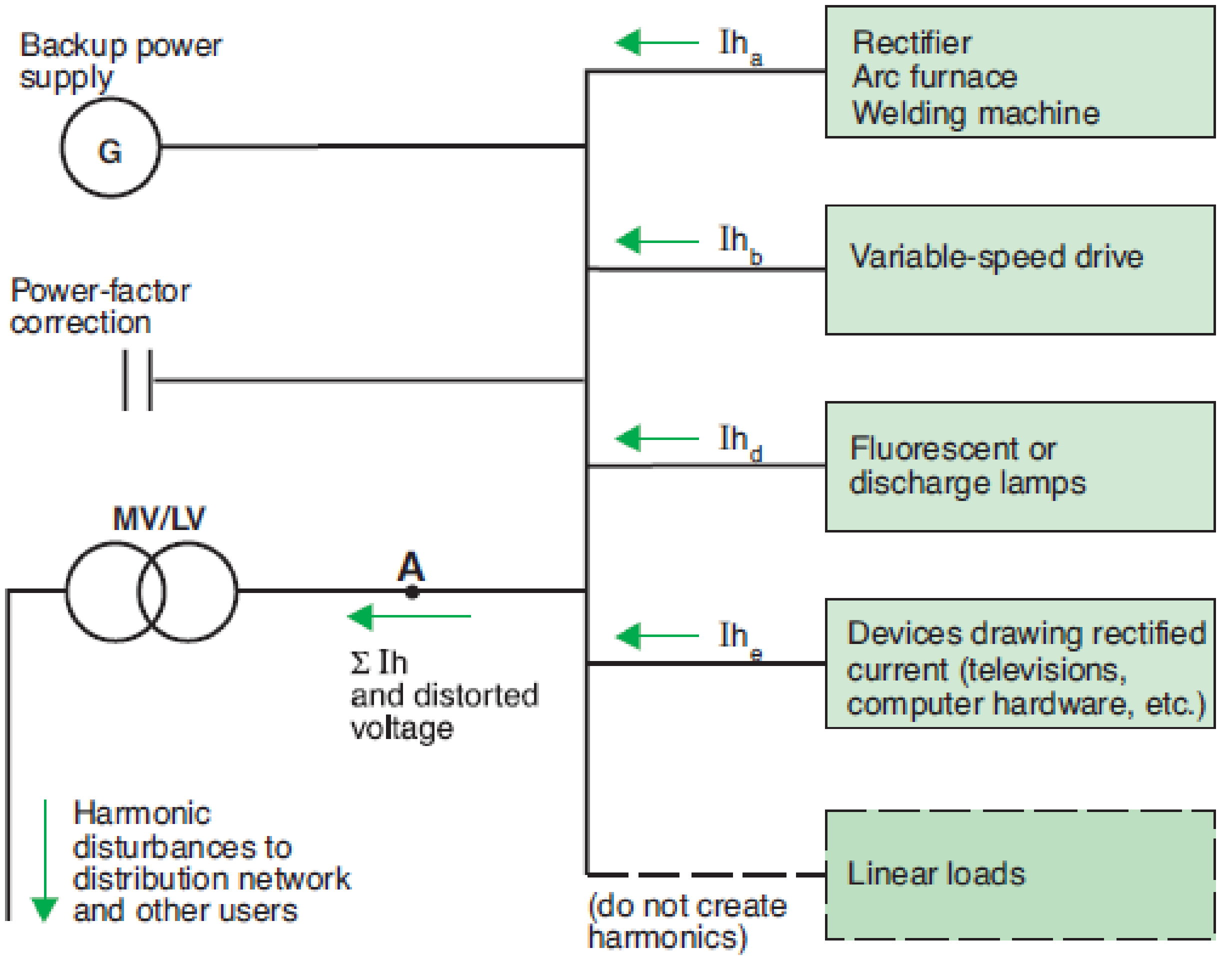
Origin of harmonics

The total system can be split into different circuits:

•One circuit representing the flow of current at the fundamental frequency,
•One circuit representing the flow of harmonic currents.



Flow of harmonic current in distribution network



3. Essential indicators of harmonic distortion

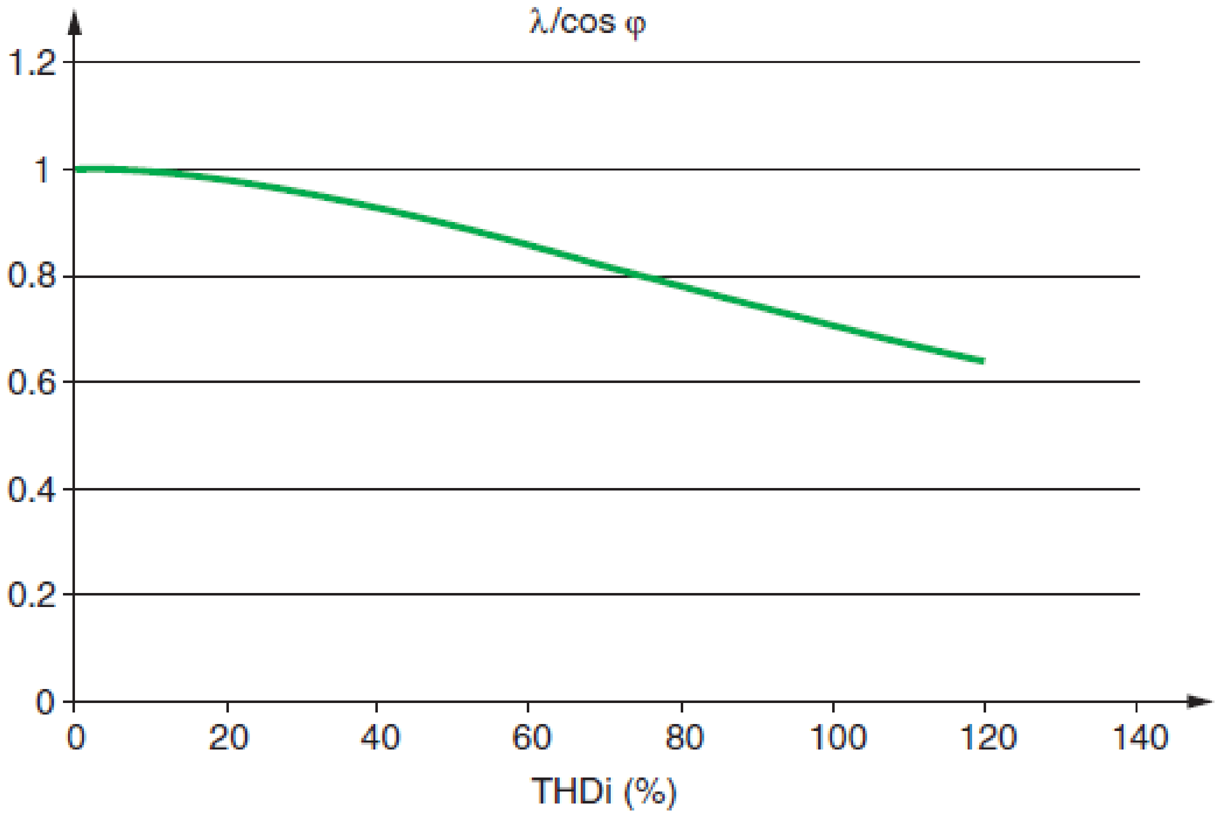
A. Power Factor

The Power Factor must not be mixed-up with the Displacement Power Factor (cos θ), relative to fundamental signals only.

$$\lambda = \frac{P}{S} = \frac{U_1 I_1 \cos\varphi}{U_1 I_{rms}}$$

As: $$\frac{I_1}{I_{rms}} = \frac{1}{\sqrt{1 + THD_i^2}}$$

hence: $$\lambda \approx \frac{\cos\varphi}{\sqrt{1 + THD_i^2}}$$

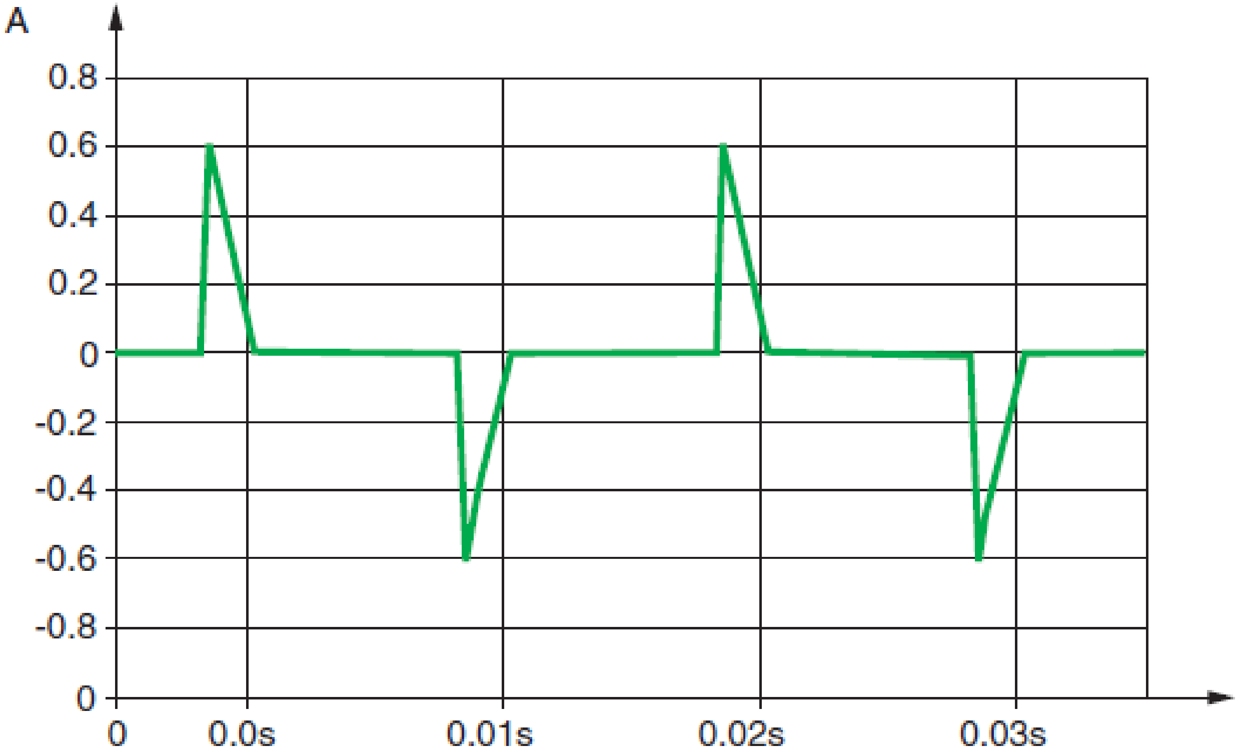


B. Crest Factor

The crest factor is the ratio between the value of the peak current or voltage (I_M or U_M) and its r.m.s. value.

- For a sinusoidal signal, the crest factor is therefore equal to √2.
- For a non-sinusoidal signal, the crest factor can be either greater than or less than √2.

$I_{r.m.s.}$:	0.16A
I_M :	0.6A
THD_i :	145%
Crest factor:	3.75

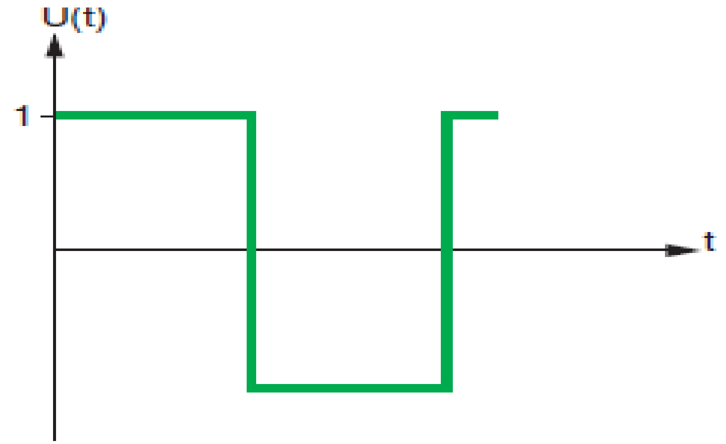


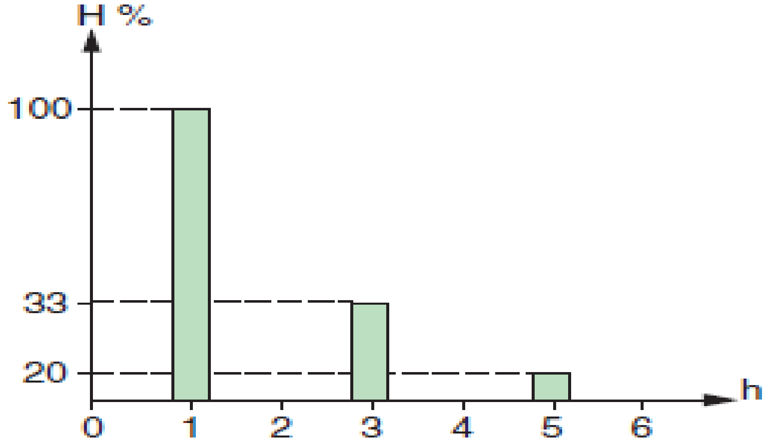
C. Harmonic Spectrum

The harmonic spectrum is the representation of the amplitude of each harmonic order with respect to its frequency.

$$I_{rms} = \sqrt{\sum_{h=1}^{H} I_h^2} = \sqrt{I_1^2 + I_2^2 + \ldots + I_H^2}$$

$$V_{rms} = \sqrt{\sum_{h=1}^{H} V_h^2} = \sqrt{V_1^2 + V_2^2 + \ldots + V_H^2}$$





D. Usefulness of the various indicators

THD_u is an indicator of the distortion of the voltage wave.

- 5%: normal situation, no risk of malfunctions,
- 5 to 8%: significant harmonic distortion, some malfunctions are possible,
- 8%: major harmonic distortion, malfunctions are probable. In-depth analysis and the installation of mitigation devices are required.

THD_i is an indicator of the distortion of the current wave.

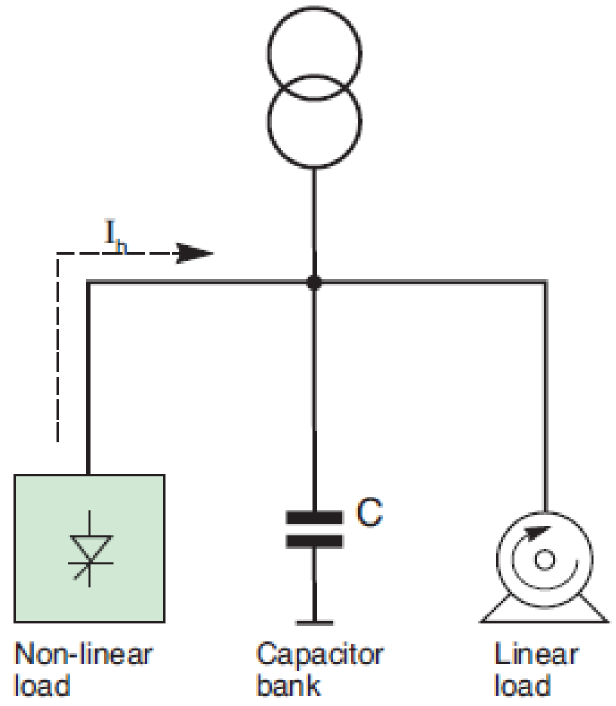
- 10%: normal situation, no risk of malfunctions,
- 10 to 50%: significant harmonic distortion with a risk of temperature rise and the resulting need to oversize cables and sources,
- 50%: major harmonic distortion, malfunctions are probable. In-depth analysis and the installation of mitigation devices are required.

4. Main effects of harmonics in electrical installations

A. Resonance

an installation made up of:

- A supply transformer,
- Linear loads
- Non-linear loads drawing harmonic currents
- Power factor correction capacitors



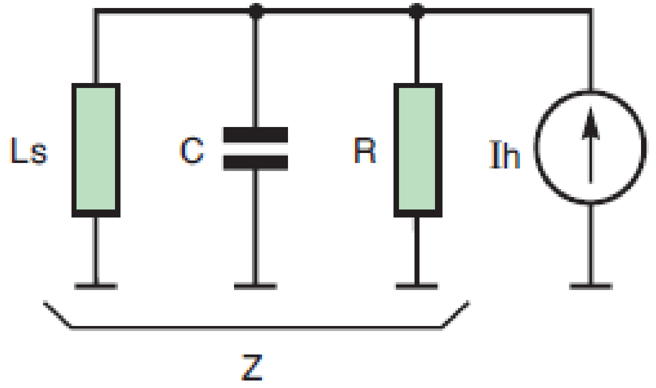
For harmonic analysis:

LS = Supply inductance (upstream network + transformer + line)

C = Capacitance of the power factor correction

R = Resistance of the linear loads

Ih = Harmonic current

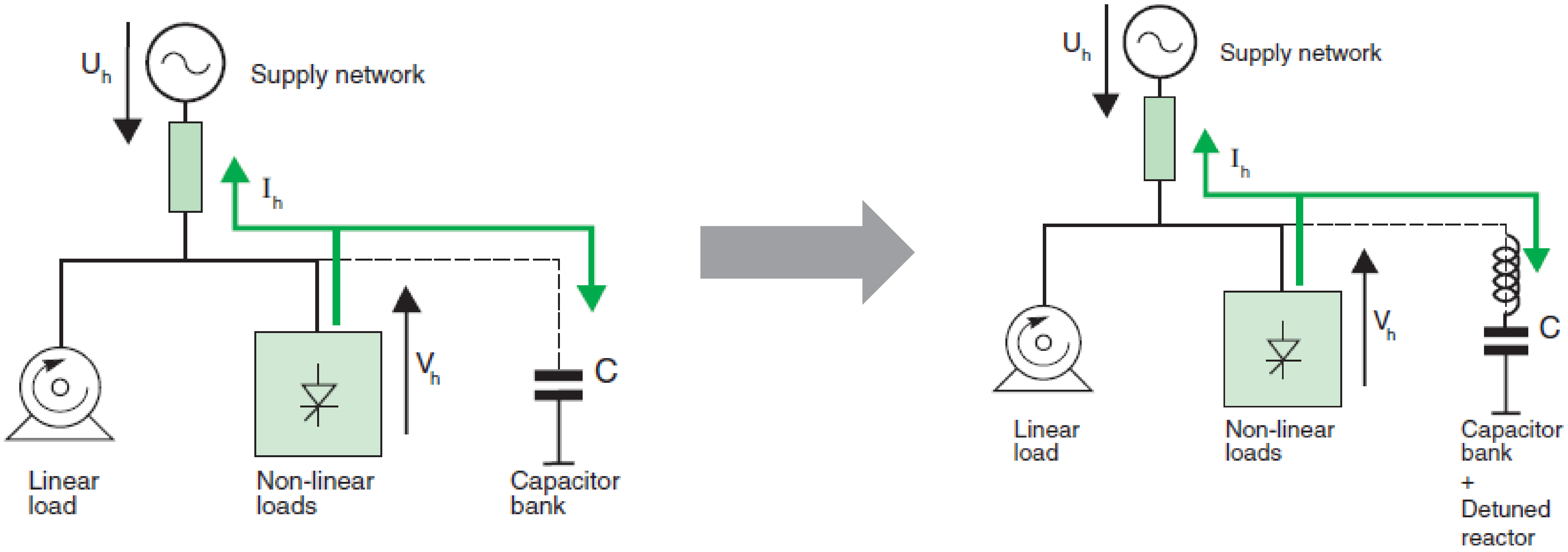


$$Z = \frac{jLs\omega}{1-LsC\omega^2}$$

A. Resonance

At the resonance frequency, impedance is at its maximum and high amounts of harmonic voltages appear because of the circulation of harmonic currents. This results in major voltage distortion.

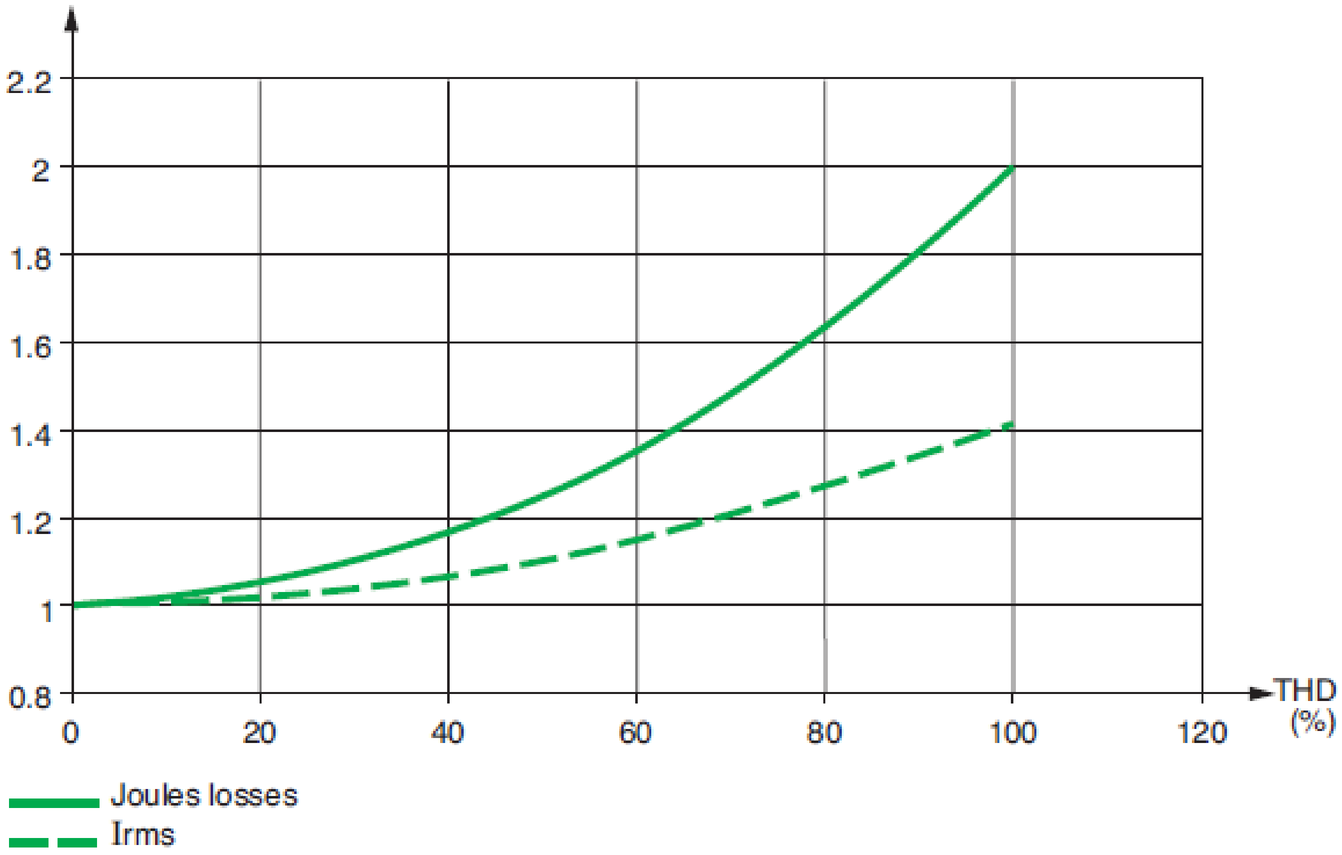
The distribution network and the power factor correction capacitors are subjected to high harmonic currents and the resulting risk of overloads. To avoid resonance, antiharmonic reactors can be installed in series with the capacitors.



B. Increased Losses

$$THD_i = \sqrt{\left(\frac{I_{r.m.s.}}{I_1}\right)^2 - 1}$$

$$I_{r.m.s.} = I_1 \cdot \sqrt{1 + THD_i^2}$$

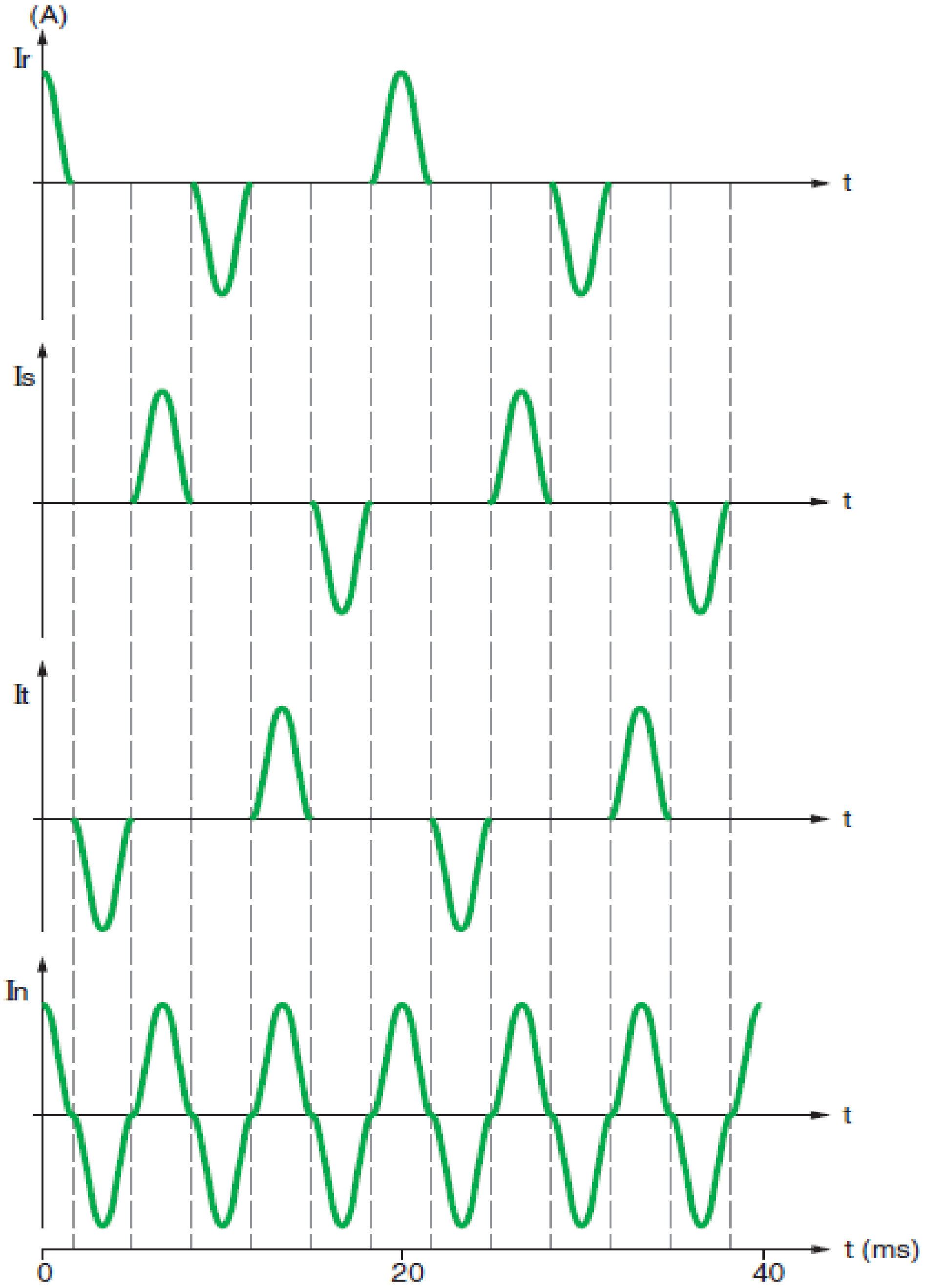


The harmonic currents cause an increase of the Joule losses in all conductors in which they flow and additional temperature rise in transformers, switchgear, cables.

C. Neutral Conductor

In this example, the current in the neutral conductor has a rms value that is higher than the rms value of the current in a phase by a factor equal to the square root of 3.
<u>The neutral conductor must therefore be sized accordingly.</u>

The current in the neutral may therefore exceed the current in each phase in installation such as those with a large number of single-phase devices (IT equipment, fluorescent lighting). This is the case in office buildings, computer centers, Internet Data Centers, call centers, banks, shopping centers, retail lighting



C. Neutral Conductor

Harmonic current

The current-carrying capacity of three-phase, 4-core or 5-core cables is based on the assumption that only 3 conductors are fully loaded.

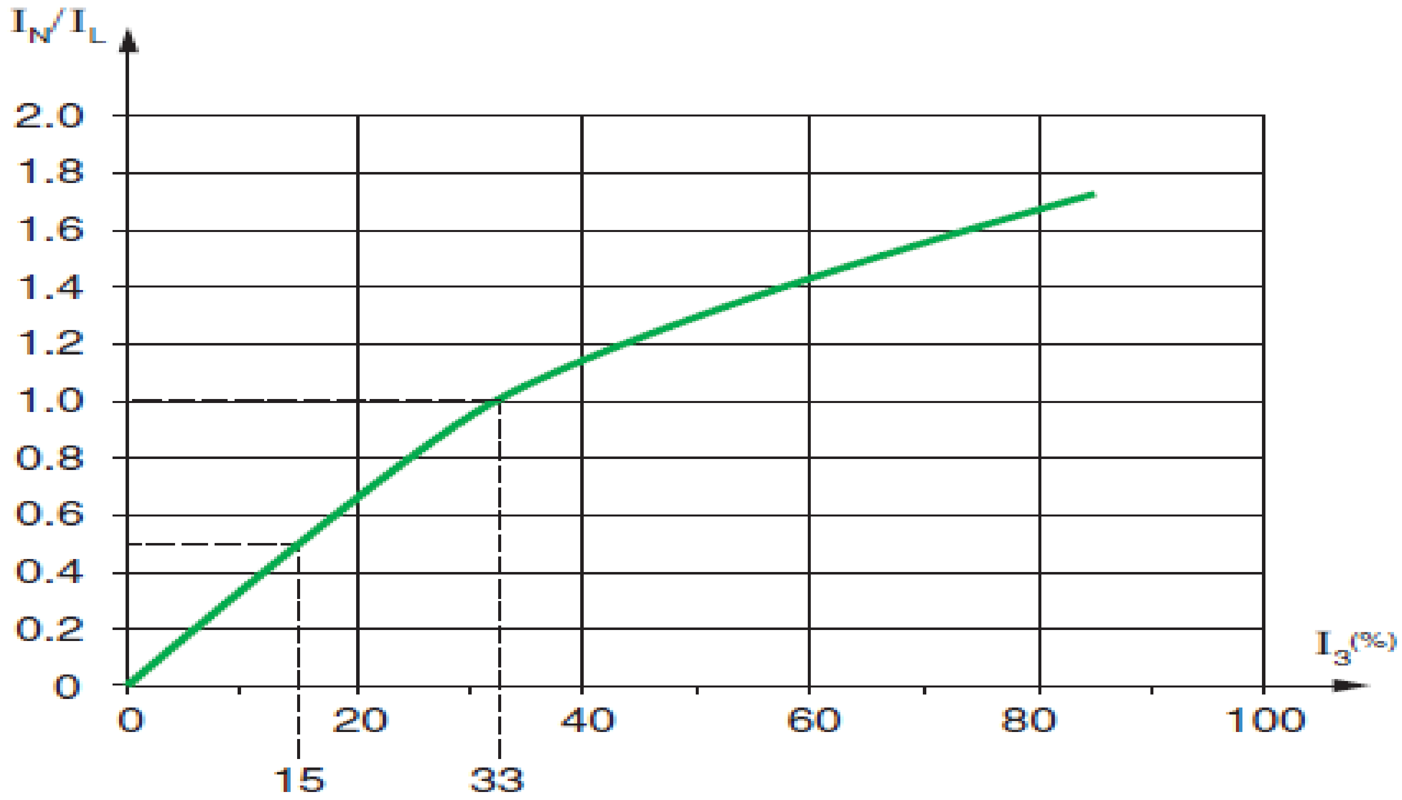
However, when harmonic currents are circulating, the neutral current can be significant, and even higher than the phase currents. This is due to the fact that the 3rd harmonic currents of the three phases do not cancel each other, and sum up in the neutral conductor.

This of course affects the current-carrying capacity of the cable, and a correction factor shall be applied.

In addition, if the 3rd harmonic percentage h3 is greater than 33%, the neutral current is greater than the phase current and the cable size selection is based on the neutral current..

C. Neutral Conductor

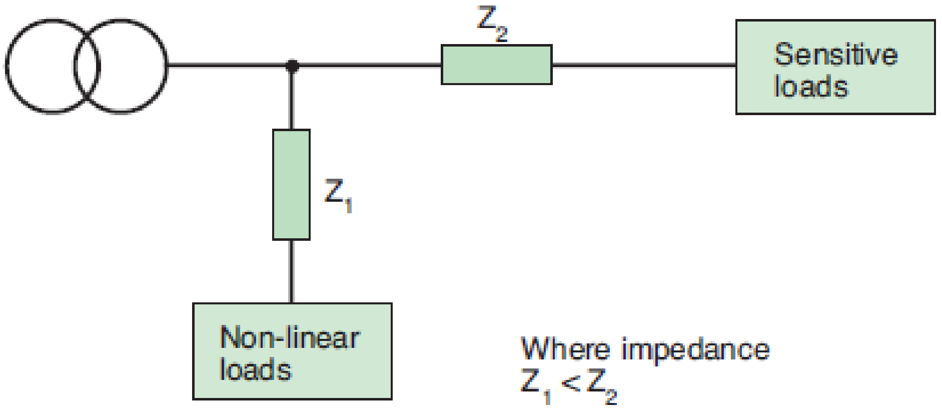
Third harmonic content of phase current %	Correction factor	
	Size selection is based on phase current	Size selection is based on neutral current
0 - 15	1.0	
15 - 33	0.86	
33 - 45		0.86
> 45		1.0 (1)



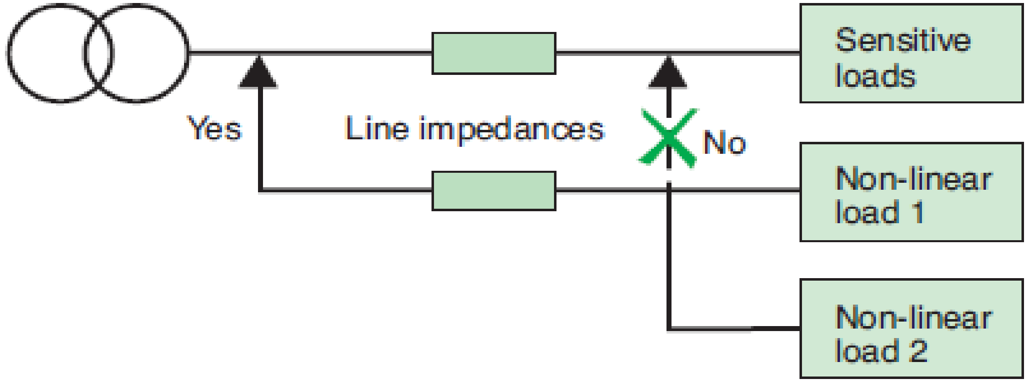
5. Solutions to mitigate Harmonics

A. Basic Solutions

Position the non-linear loads upstream in the system

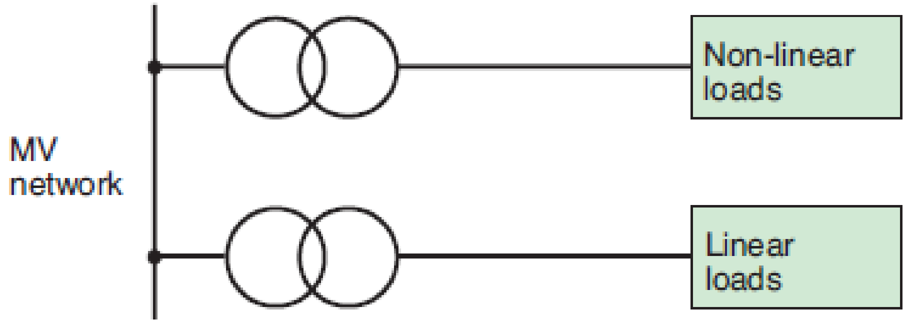


Group the non-linear loads

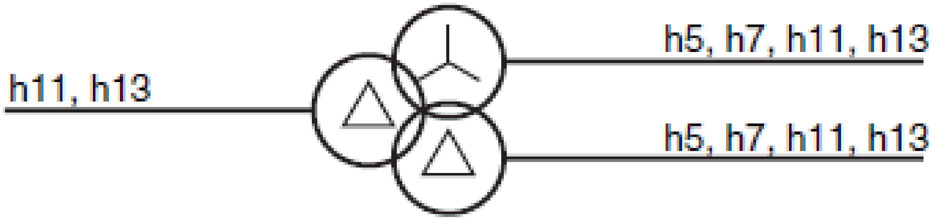


A. Basic Solutions

Create separate sources



Transformers with special connections



- Dyd connection suppresses 5th and 7th harmonics
- Dy connection suppresses the 3rd harmonic
- DZ 5 connection suppresses the 5th harmonic

B. Harmonic Filtering

Passive Filters

Typical applications:

•Industrial installations with a set of non-linear loads representing more than 500 kVA (variable-speed drives, UPSs, rectifiers, etc.)

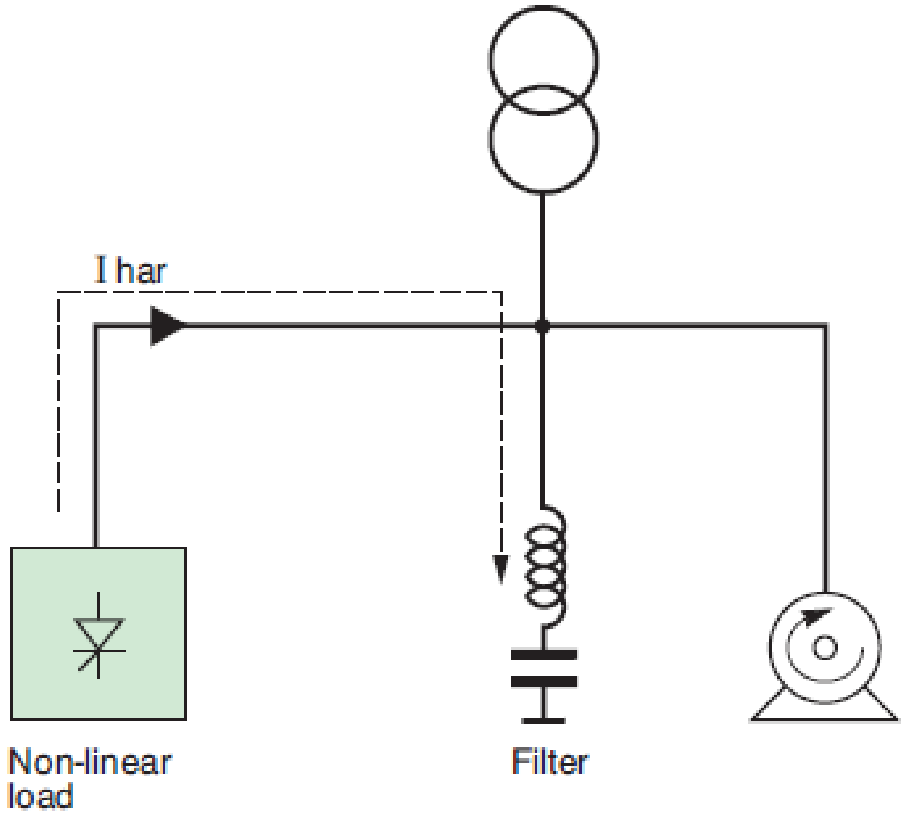
•Installations requiring power-factor correction

•Installations where voltage distortion must be reduced to avoid disturbing sensitive loads

•Installations where current distortion must be reduced to avoid overloads

Operating principle:

An LC circuit, tuned to each harmonic order to be filtered, is installed in parallel with the non-linear load**. This bypass circuit absorbs the harmonics, thus** avoiding their flow in the distribution network.



B. Harmonic Filtering

Active Filters

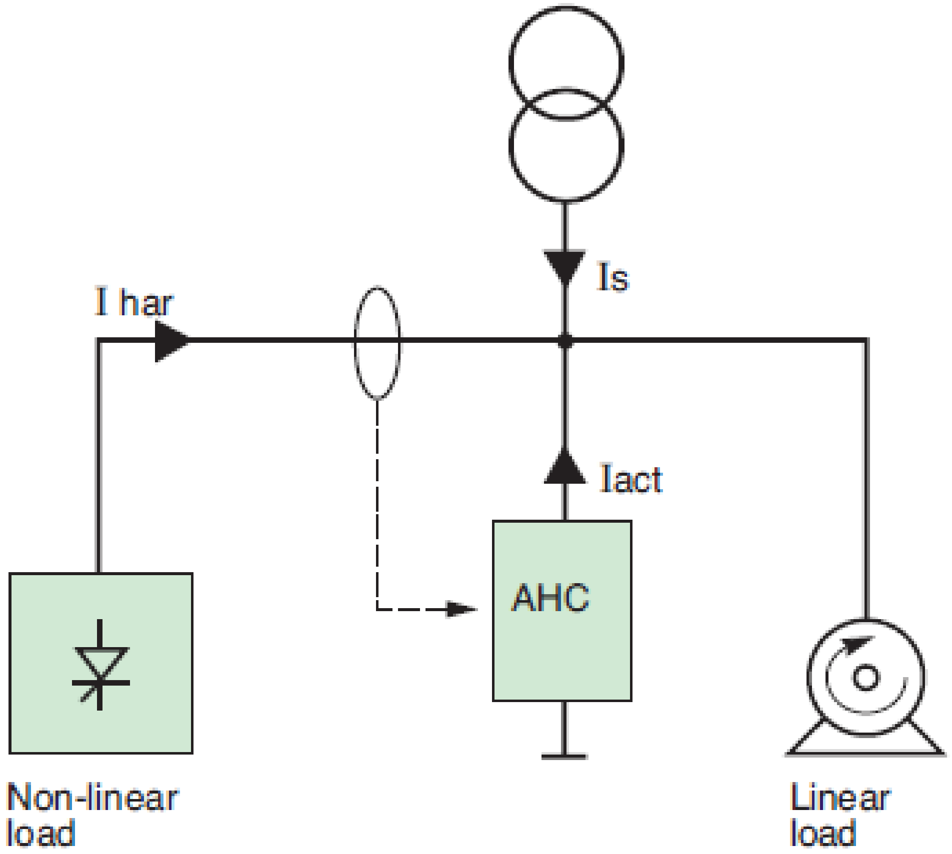
Typical applications

•Commercial installations with a set of non-linear loads representing less than 500 kVA (variable-speed drives, UPSs, offi ce equipment, etc.)

•Installations where current distortion must be reduced to avoid overloads.

Operating principle

These systems, comprising power electronics and installed in series or parallel with the non-linear load, compensate the harmonic current or voltage drawn by the load. The AHC injects in opposite phase the harmonics drawn by the non-linear load, such that the line current Is remains sinusoidal.



B. Harmonic Filtering

Hybrid Filters

Typical applications

•Industrial installations with a set of non-linear loads representing more than 500 kVA

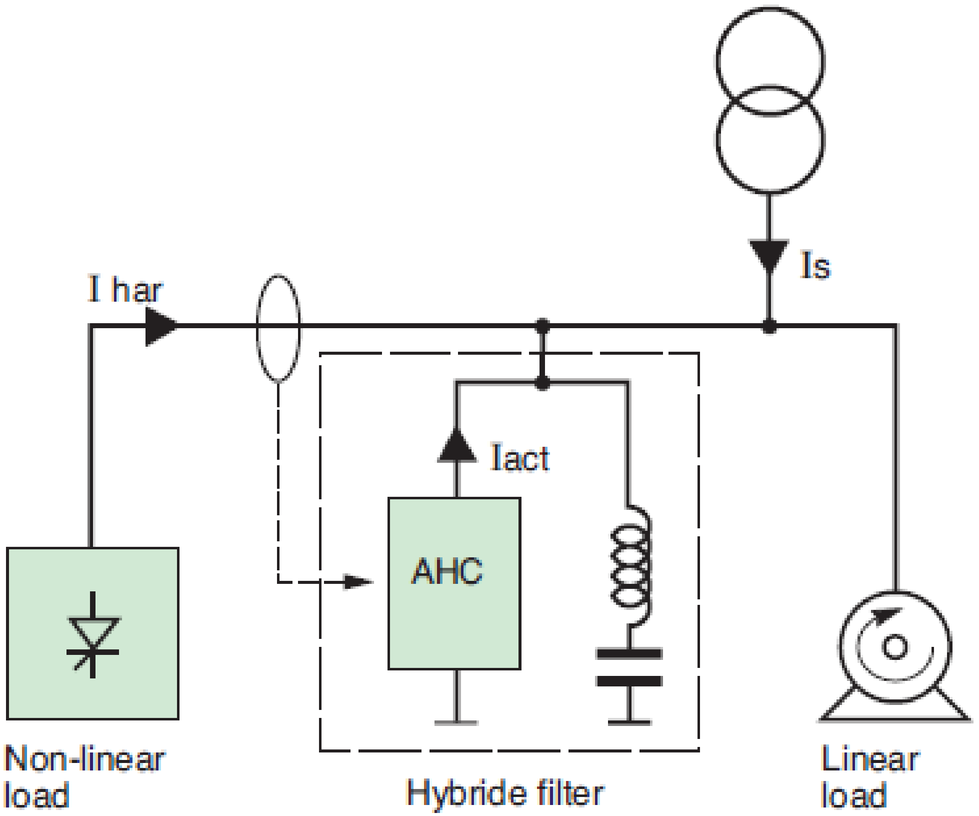
•Installations requiring power-factor correction

•Installations where strict limits on harmonic emissions must be met.

Operating principle

Passive and active filters are combined in a single system to constitute a hybrid filter.

This new filtering solution offers the advantages of both types of filters and covers a wide range of power and performance levels.



6. Choice of Solutions

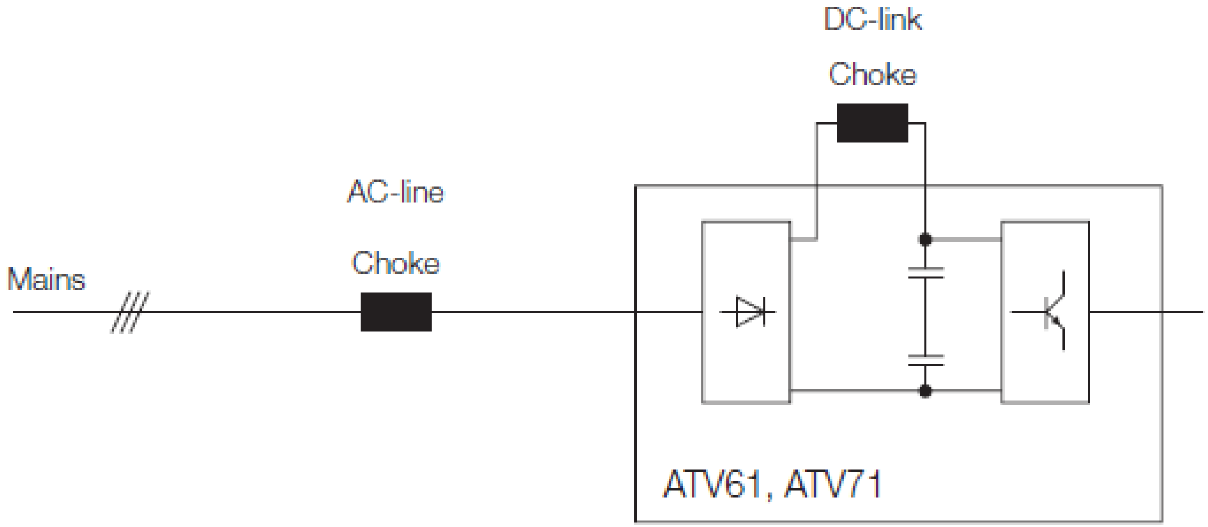
Schneider Product offer

C-less technology

This technology combined with the advanced control algorithm decreases the THDi down to 35%. This solution has been adopted for Altivar ATV21 which is dedicated to centrifugal pumps, fans and HVAC machines.

AC-Line or DC-link chokes for Drives

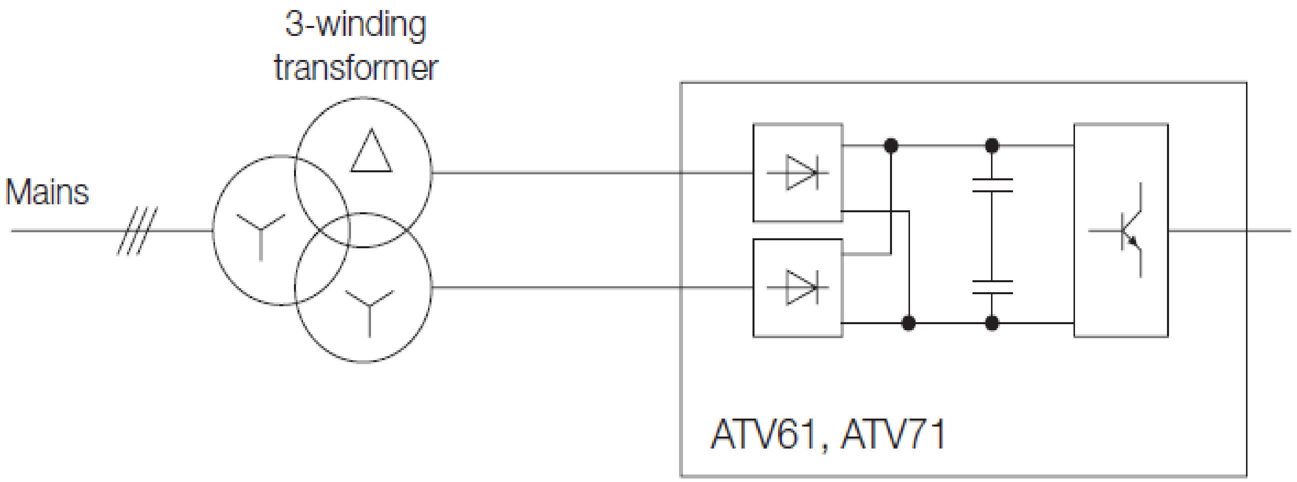
They are commonly used up to about 500kW unit power or 1,000kW total drives power.
In this power range the transformer should be at least 2.5 times the drives load. Depending on the transformer size and cabling, the resulting THDu will be up to ~6%. This could give possible nuisance, but is usually well accepted in industrial networks.



Schneider Product offer

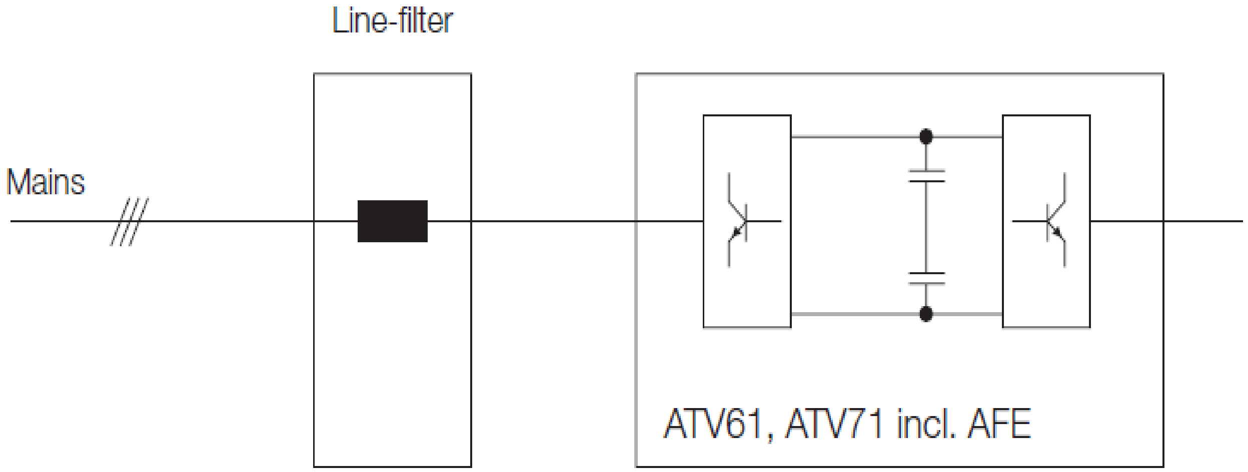
Multi-pulse arrangement

This is usually used for drives above 400 kW, but could also be reasonable for smaller power ratings. Precondition is a dedicated transformer directly supplied from the MV network. Standard is the use of a 3-winding transformer providing a 12-pulse supply for the drive.



Active Front End (AFE)

An AFE is the best performing solution concerning harmonic mitigation, limiting the THDi below 5%. All the applicable standard requirements can be met. No detailed system evaluation is necessary, making this solution the easiest to implement.



Schneider Product offer

Hybrid filter

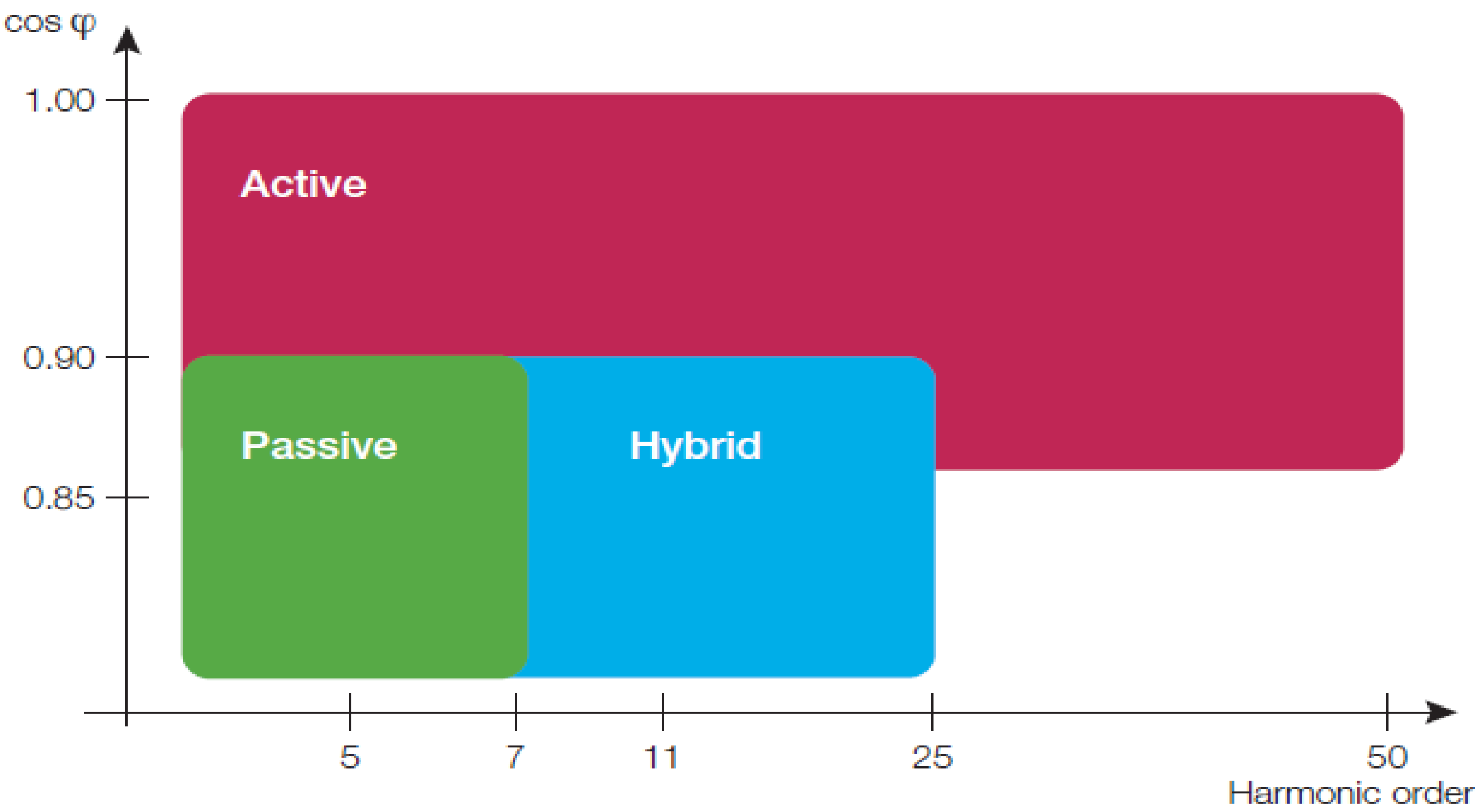
A hybrid filter is a system including a passive filter tuned on the 5th harmonic and a SineWave active filter in a single unit.

Main characteristics:

- supply voltage: 400V,
- Passive filter tuned to the 5th harmonic order,
- Active filter rated current: 20 to 180A,
- Reactive energy compensation: up to 265 kvar,
- Total harmonic current: up to 440A.

Schneider Electric Solutions

At installation level



<u>The selection of the filter technology is based on 2 parameters:</u>

- Requirement for reactive energy compensation (improvement of Displacement Power Factor)
- Maximum harmonic order to be treated. When the DPF is lower than 0.85 – 0.9, a passive or hybrid solution is preferred.

Schneider Electric Solutions

Guidance for a Solution

- If harmonic mitigation is necessary, global mitigation should be considered first. This is because single large mitigation equipment at the installation level is usually more cost effective than several small ones at equipment level.

- When large drives are present, (≥400kW), local mitigation is recommended. Typical solutions include multi-pulse configurations, Active Front End (AFE), and active filter.

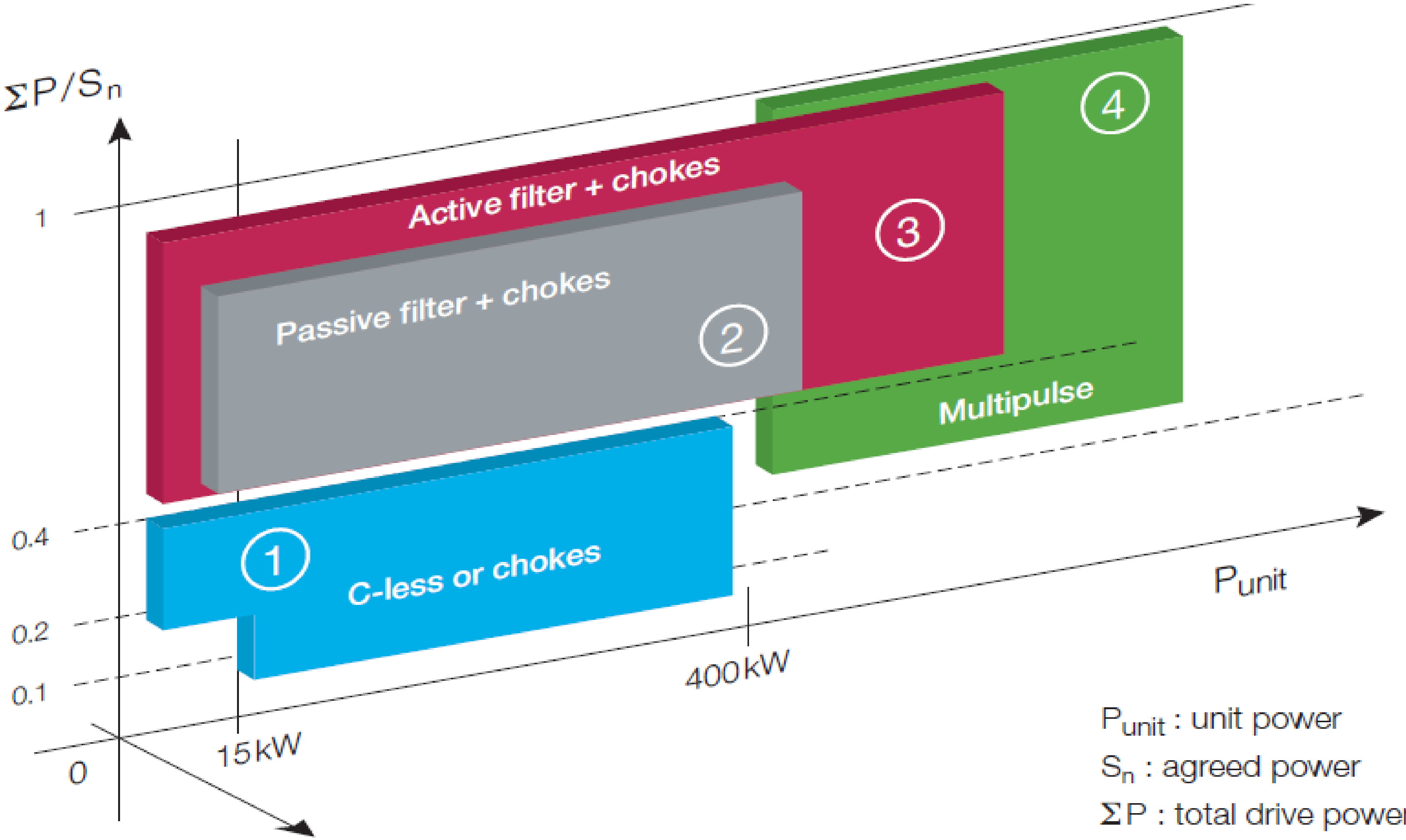
- When a large number of drives are present, the implementation of chokes is recommended (AC-line or DC-link chokes).

- When PFC capacitors are present, detuned banks should be preferred, with active filter if further attenuation is needed. This will ensure capacitor protection and avoid resonance.

- When PFC capacitors are not present, an active filter is the preferred solution.

Schneider Electric Solutions

Guidance for a Solution



P_{unit} : unit power

S_n : agreed power

ΣP : total drive power

Schneider Electric