ALPES TECHNOLOGIES

Capacitor department

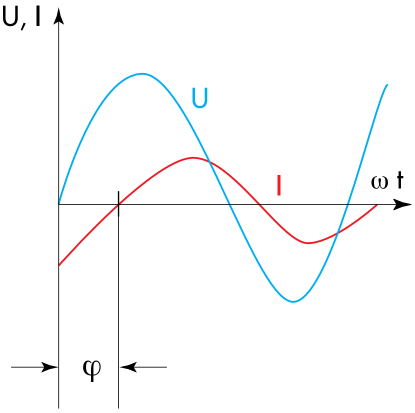
GENERAL INFORMATION

Reactive energy compensation with capacitors

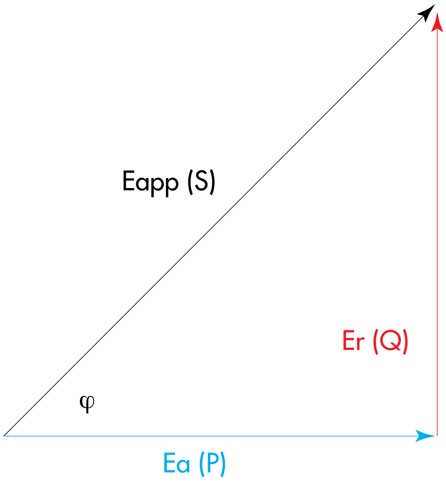
CONTENTS

I - DEFINITIONS

1) PHASE SHIFT - ENERGIES - POWERS



Phase shift between current and voltage (angle φ)



Energies

$$\text{Eapp} = \overrightarrow{\text{Ea}} + \overrightarrow{\text{Er}}$$
$$\text{Eapp} = \sqrt{(\text{Ea})^2 + (\text{Er})^2}$$

Powers

$$\overrightarrow{S} = \overrightarrow{P} + \overrightarrow{Q}$$
$$S = \sqrt{(P)^2 + (Q)^2}$$

- **for three-phase supply :**

$$S = \sqrt{3}\ UI$$
$$P = \sqrt{3}\ UI \cos\varphi$$
$$Q = \sqrt{3}\ UI \sin\varphi$$

* for a single-phase supply, the term √3 disappears.

An alternating current electrical installation, including receivers such as transformers, motors, welding machines, power electronics, etc., and in particular any receiver for which the current is out-of-phase in relation to the voltage, absorbs a total energy called the apparent energy (E app).

This energy, which is generally expressed in kilovolt-ampere-hours (kVAh), corresponds to the apparent power S (kVA) and can be broken down as follows:

- Active energy (Ea) : expressed in kilowatt hours (kWh). It can be used, after being transformed by the receiver, in the form of work or heat. This energy corresponds to the active power P (kW).

- Reactive energy (Er) : expressed in kilovar hours (kvarh). It is particularly used in motor and transformer windings to create the magnetic field which is essential for operation. This energy corresponds to the reactive power Q (kvar). Unlike the previous energy, this energy is said to be "unproductive" for the user.

2) POWER FACTOR

By definition, the power factor, or the cos φ, of an electrical device is equal to the ratio of the active power P (kW) over the apparent power S (kVA) and can vary from 0 to 1.

It can thus be used to identify the level of reactive energy consumption of devices easily.

$$\cos\varphi = \frac{P(\text{kW})}{S\ (\text{kVA})}$$

- a power factor equal to 1 will result in a zero reactive energy consumption (pure resistance).
- a power factor less than 1 will result in reactive energy consumption which increases as it approaches 0 (pure inductance).

In an electrical installation, the power factor may be different from one workshop to another depending on the devices installed and the way in which they are used (off-load, full-load operation, etc.).

Since energy metering devices measure the active and reactive energy consumptions more easily, EDF, the French electricity supply board, has chosen to use the term tg φ on the electricity bills of its customers.

$$\text{tg}\ \varphi = \frac{Er\ (\text{kvarh})}{Ea\ (\text{kWh})}$$

Tg φ is the quotient between the reactive energy Er (kvarh) and the active energy Ea (kWh) used during the same period.

Unlike cos φ, it is easy to see that the value of tg φ must be as low as possible in order to have the minimum reactive energy consumption.

The relationship between Cos φ and tg φ is given by the following equation:

$$\cos\varphi = \frac{1}{\sqrt{1 + (\text{tg}\varphi)^2}}$$

but a simpler method consists of referring to a conversion table (see section VII).

II - POWER FACTOR OF MAIN RECEIVERS

The receivers which consume the most reactive energy are :

- low-load motors
- welding machines
- arc and induction furnaces
- power rectifiers

RECEIVER		COS φ	TG φ
Ordinary asynchronous motors 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		approx. 1	approx. 0
Fluorescent lamps		approx. 0.5	approx. 1.73
Discharge lamps		0.4 to 0.6	approx. 2.29 to 1.33
Resistance furnaces		approx. 1	approx. 0
Compensated induction furnaces		approx. 0.85	approx. 0.62
Dielectric heating furnaces		approx. 0.85	approx. 0.62
Resistance welding machines		0.8 to 0.9	0.75 to 0.48
Single-phase static arc welding stations		approx. 0.5	approx. 1.73
Rotating arc welding units		0.7 to 0.9	1.02 to 0.48
Arc welding transformers-rectifiers		0.7 to 0.8	1.02 to 0.75
Arc furnaces		0,8	0,75
Thyristor power rectifiers		0.4 to 0.8	2.25 to 0.75

III - ADVANTAGES OF A GOOD POWER FACTOR

A good power factor is :

A high cos φ (close to 1)
or low tg φ (close to 0)

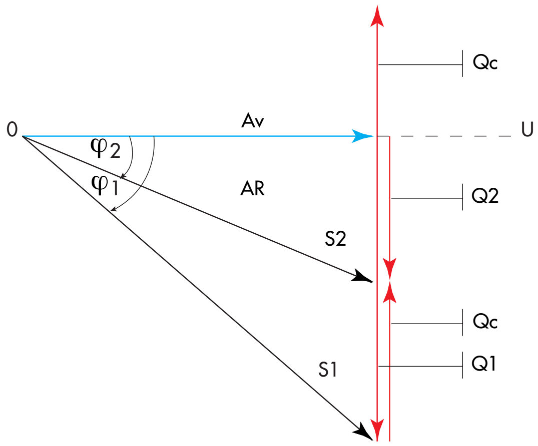
A good power factor makes it possible to optimise an electrical installation and provides the following advantages:

- no billing for reactive energy (EDF "Tarif Vert" rate subscribers),
- decrease in the subscribed power in kVA (EDF "Tarif Jaune" rate subscribers)
- limitation of active energy losses in cables given the decrease in the current conveyed in the installation,
- improvement in the voltage level at the end of the line,
- additional power available at the power transformers if the compensation is performed in the secondary winding.

IV - HOW TO IMPROVE THE POWER FACTOR

By installing capacitors or capacitor banks.

Power diagram



P : active power
S1 and S2 : apparent powers (before and after compensation)
Qc : Reactive power of capacitor
Q1 : Reactive power without capacitor
Q2 : Reactive power with capacitor

Equations :

$Q2 = Q1 - Qc$
$Qc = Q1 - Q2$
$Qc = P.\text{tg}\,\varphi\,1 - P.\text{tg}\,\varphi\,2$

$$\boxed{Qc = P(\text{tg}\,\varphi\,1 - \text{tg}\,\varphi\,2)}$$

* φ 1 phase shift without capacitor
* φ 2 phase shift with capacitor

Improving the power factor of an electrical installation consists of giving it the means to produce a varying proportion of the reactive energy that it consumes itself.

Different systems are available to produce reactive energy, particularly phase advancers and shunt capacitors (or serial capacitors for major transport networks).

The capacitor is most frequently used given:
. its non-consumption of active energy,
. its purchasing cost,
. its easy use,
. its service life (approximately 10 years),
. its very low maintenance (static device).

The capacitor is a receiver composed of two conducting parts (electrodes) separated by an insulator. When this receiver is subjected to a sinusoidal voltage, it shifts its current, and therefore its (capacitive reactive) power, by 90° forward the voltage.

Conversely, all other receivers (motors, transformers, etc.) shift their reactive component (inductive reactive power or current) by 90° backward the voltage.

The vectorial composition of these (inductive or capacitive) reactive powers or currents gives a resulting reactive power or current below the existing value before the installation of capacitors.

In simpler terms, it can be said that inductive receivers (motors, transformers, etc.) consume reactive energy, while capacitors (capacitive receivers) produce reactive energy.

V - ELECTRICITY RATES FOR REACTIVE ENERGY

(description based on the french system)

1) "TARIF VERT" RATE (ABOVE 250 kW)

By installing capacitors, you can produce the reactive energy you require yourself and reduce the cost of your electricity bill considerably.

A capacitor bank is an investment which is paid off in a few months mainly due to :

- **the cancellation of the kvarh billed ("tarif vert" rate subscribers)**
- **the decrease in the subscribed power in kVA ("tarif jaune" rate subscribers)**

For this rate, EDF bills the reactive energy for the period from 1st November to 31st March inclusive during day-tariff and peak hours directly.

This billing applies to all subcribers with a primary winding tg φ greater than 0.4 (or primary winding cos φ less than 0.928) and is defined as follows:

- Let Ea (kWh) be the active energy consumed every month during the period and hours defined above.
- Let Er (kvarh) be the reactive energy consumed every month during the period and hours defined above.

The quantity of the billed reactive energy Er bill will be equal to:

$$\text{Er bill} = \text{Er} - 0.4.\text{Ea}$$

The total of the bill will be :

$$\text{Er bill} \times a$$

(where a is the cost of the reactive energy given in the current scale).

2) "TARIF JAUNE" RATE (36 TO 250 kVA)

For this rate, the power is subscribed in apparent power, i.e. in KVA. Therefore, it accounts for the power factor, but the subscriber is not billed directly for reactive energy.

However, if the installation has a poor power factor, the kVA subscription is increased excessively and this results in a significant increase in the fixed basic rate which may be up to 40% or even 60%.

By measuring the power factor (cos φ), it is very easy to define the reactive energy compensation requirements and reduce the kVA subscribed power considerably.

VI - HOW TO CALCULATE THE POWER OF CAPACITORS

1) CALCULATION FROM ELECTRICITY BILLS (LV or MV metering EDF "Tarif Vert" rate subscribers)

ÉNERGIE RÉACTIVE P + HP	ÉNERGIE RÉACTIVE P + HP au niveau du comptage	TANGENTE phi			
		secondaire		primaire	
120.000	125.000			0	96

kvar h en franchise	kvar h en consommés
	120.000

kvar h à ristourner	kvar h à facturer
	70.000

	PUISSANCES SOUSCRITES					PUISSANCES RETENUES POUR CALCUL DE PRM					PR		PRM		Dépassement à facturer
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5					
	525	590	590	590	590						560	1			

From 1st November 1987, in France, the reactive energy billing limit changed for all "tarif Vert" rate subscribers (LV or MV metering) to:

* tg $\varphi = 0.4$ or cos = 0.928: on the primary winding,

* tg $\varphi = 0.31$ or cos = 0.955: on the secondary winding.

For the calculation of the capacitor banks to be installed, proceed using the following method:

- analyse the 5 electricity bills from November to March,
- select the month for which the bill is the highest (kvarh to be billed),
- evaluate the number of hours of operation of the installation every month in day-tariff and peak hours (generally 6 a.m. to 10 p.m. excluding Sundays),

- calculate the capacitor power Qc to be installed

$$Qc = \frac{\text{kvarh to be billed (monthly)}}{\text{Nb.of working hours (monthly)}}$$

* for LV metering, in the calculation of the kvarh to be billed, EDF introduces a fixed rate transformer consumption by applying a coefficient of 0.09 on the secondary winding tg φ calculated to obtain the primary winding tg φ.

Example

Take the subscriber SMITH :

. highest reactive energy bill : December 87,

. number of kvarh to be billed : 70,000,

. monthly number of hours of operation : 350 hours (day-tariff + peak)

$$Qc \text{ (bank to be installed)} = \frac{70.000}{350} = 200 \text{ kvar}$$

2) CALCULATION FROM MEASURING ELEMENTS READ ON THE HV/LV TRANSFORMER SECONDARY WINDING/ PkW - COS φ

Example :

Take a plant powered from an 800 kVA HV / LV subscriber station which would like to change the power factor of its installation to :

* Cos φ = 0.928 (tg φ = 0.4) on the primary winding

* or Cos φ = 0.955 (tg φ = 0.31) on the secondary winding

with the following readings :

- voltage: 400 V three-phase 50 Hz
- P = 475 kW
- Cos (secondary) = 0.75 (or tg φ = 0.88)

Qc (bank to be installed) = Pkw (tg φ measured - tg φ to be obtained)

Qc = 475 (0.88 - 0.31) # 270 kvar

Note: the coefficient K = (tg φ measured - tg φ to be obtained) is obtained easily from the Cos φ values using the conversion table on page 9.

3) CALCULATION FOR FUTURE INSTALLATIONS :

For future installations, compensation is frequently requested from the commissioning stage. In this case, it is impossible to calculate the bank using conventional methods (electricity bill or measurements on-site).

For this type of installation, it is recommended to install a capacitor bank equal to approximately **25% of the nominal power of the corresponding HV / LV transformer.**

Example:
1000 kVA transfomer => Q capacitor = 250 kvar

Note : this type of ratio corresponds to the following operating conditions:

- 1000 kVA transformer
- real transformer load = 75%
- Cos φ of load = 0.80
- Cos φ to be obtained = 0.95

} k = 0.421 (table on page 9)

Qc = 1000 x 75% x 0.80 x 0.421 = 250 kvar

4) CALCULATION FOR INDEPENDENT PRODUCERS (SMALL POWER STATIONS)

For this type of installation, the independent producer must supply the electricity company with a quantity of reactive energy equal to at least 40% of its active energy production during WINTER day-tariff and peak hours.

In this case, the calculation of the capacitor bank should account for:

- the on-load reactive consumption of the generator
- the on-load consumption of the LV / HV transformer (if applicable)
- the reactive energy to be supplied, or 40% of the active energy produced

VII - CAPACITOR POWER CALCULATION TABLE

1) Conversion table

Using the power of a receiver in kW, this table can be used to calculate the power of the capacitors to change from an initial power factor to a desired power factor. It also gives the equivalence between cos φ and tg φ.

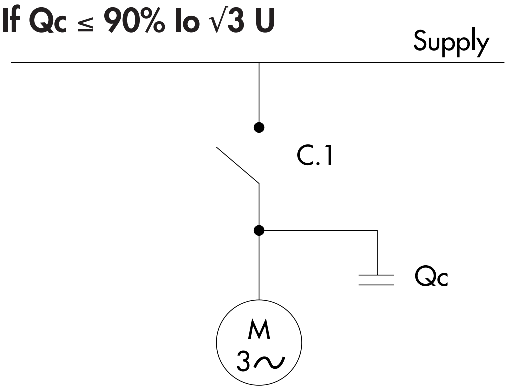
Final power factor		Capacitor power in kvar to be installed per kW of load to raise the power factor to :										
cos φ		0,90	0,91	0,92	0,93	0,94	0,95	0,96	0,97	0,98	0,99	1
	tg φ	0,48	0,46	0,43	0,40	0,36	0,33	0,29	0,25	0,20	0,14	0,0
0,40	2,29	1,805	1,832	1,861	1,895	1,924	1,959	1,998	2,037	2,085	2,146	2,288
0,41	2,22	1,742	1,769	1,798	1,831	1,840	1,896	1,935	1,973	2,021	2,082	2,225
0,42	2,16	1,681	1,709	1,738	1,771	1,800	1,836	1,874	1,913	1,961	2,002	2,164
0,43	2,10	1,624	1,651	1,680	1,713	1,742	1,778	1,816	1,855	1,903	1,964	2,107
0,44	2,04	1,558	1,585	1,614	1,647	1,677	1,712	1,751	1,790	1,837	1,899	2,041
0,45	1,98	1,501	1,532	1,561	1,592	1,626	1,659	1,695	1,737	1,784	1,846	1,988
0,46	1,93	1,446	1,473	1,502	1,533	1,567	1,600	1,636	1,677	1,725	1,786	1,929
0,47	1,88	1,397	1,425	1,454	1,485	1,519	1,532	1,588	1,629	1,677	1,758	1,881
0,48	1,83	1,343	1,730	1,400	1,430	1,464	1,467	1,534	1,575	1,623	1,684	1,826
0,49	1,78	1,297	1,326	1,355	1,386	1,420	1,453	1,489	1,530	1,578	1,639	1,782
0,50	1,73	1,248	1,276	1,303	1,337	1,369	1,403	1,441	1,481	1,529	1,590	1,732
0,51	1,69	1,202	1,230	1,257	1,291	1,323	1,357	1,395	1,435	1,483	1,544	1,686
0,52	1,64	1,160	1,188	1,215	1,249	1,281	1,315	1,353	1,393	1,441	1,502	1,644
0,53	1,60	1,116	1,144	1,171	1,205	1,237	1,271	1,309	1,349	1,397	1,458	1,600
0,54	1,56	1,075	1,103	1,130	1,164	1,196	1,230	1,268	1,308	1,356	1,417	1,559
0,55	1,52	1,035	1,063	1,090	1,124	1,156	1,190	1,228	1,268	1,316	1,377	1,519
0,56	1,48	0,996	1,024	1,051	1,085	1,117	1,151	1,189	1,229	1,277	1,338	1,480
0,57	1,44	0,958	0,986	1,013	1,047	1,079	1,113	1,151	1,191	1,239	1,300	1,442
0,58	1,40	0,921	0,949	0,976	1,010	1,042	1,073	1,114	1,154	1,202	1,263	1,405
0,59	1,37	0,884	0,912	0,939	0,973	1,005	1,039	1,077	1,117	1,165	1,226	1,368
0,60	1,33	0,849	0,878	0,905	0,939	0,971	1,005	1,043	1,083	1,131	1,192	1,334
0,61	1,30	0,815	0,843	0,870	0,904	0,936	0,970	1,008	1,048	1,096	1,157	1,299
0,62	1,27	0,781	0,809	0,836	0,870	0,902	0,936	0,974	1,014	1,062	1,123	1,265
0,63	1,23	0,749	0,777	0,804	0,838	0,870	0,904	0,942	0,982	1,030	1,091	1,233
0,64	1,20	0,716	0,744	0,771	0,805	0,837	0,871	0,909	0,949	0,997	1,058	1,200
0,65	1,17	0,685	0,713	0,740	0,774	0,806	0,840	0,878	0,918	0,966	1,007	1,169
0,66	1,14	0,654	0,682	0,709	0,743	0,775	0,809	0,847	0,887	0,935	0,996	1,138
0,67	1,11	0,624	0,652	0,679	0,713	0,745	0,779	0,817	0,857	0,905	0,966	1,108
0,68	1,08	0,595	0,623	0,650	0,684	0,716	0,750	0,788	0,828	0,876	0,937	1,079
0,69	1,05	0,565	0,593	0,620	0,654	0,686	0,720	0,758	0,798	0,840	0,907	1,049
0,70	1,02	0,536	0,564	0,591	0,625	0,657	0,691	0,729	0,796	0,811	0,878	1,020
0,71	0,99	0,508	0,536	0,563	0,597	0,629	0,663	0,701	0,741	0,783	0,850	0,992
0,72	0,96	0,479	0,507	0,534	0,568	0,600	0,634	0,672	0,721	0,754	0,821	0,963
0,73	0,94	0,452	0,480	0,507	0,541	0,573	0,607	0,645	0,685	0,727	0,794	0,936
0,74	0,91	0,425	0,453	0,480	0,514	0,546	0,580	0,618	0,658	0,700	0,767	0,909
0,75	0,88	0,398	0,426	0,453	0,487	0,519	0,553	0,591	0,631	0,673	0,740	0,882
0,76	0,86	0,371	0,399	0,426	0,460	0,492	0,526	0,564	0,604	0,652	0,713	0,855
0,77	0,83	0,345	0,373	0,400	0,434	0,466	0,500	0,538	0,578	0,620	0,687	0,829
0,78	0,80	0,319	0,347	0,374	0,408	0,440	0,474	0,512	0,552	0,594	0,661	0,803
0,79	0,78	0,292	0,320	0,347	0,381	0,413	0,447	0,485	0,525	0,567	0,634	0,776
0,80	0,75	0,266	0,294	0,321	0,355	0,387	0,421	0,459	0,499	0,541	0,608	0,750
0,81	0,72	0,240	0,268	0,295	0,329	0,361	0,395	0,433	0,473	0,515	0,582	0,724
0,82	0,70	0,214	0,242	0,269	0,303	0,335	0,369	0,407	0,447	0,489	0,556	0,698
0,83	0,67	0,188	0,216	0,243	0,277	0,309	0,343	0,381	0,421	0,463	0,530	0,672
0,84	0,65	0,162	0,190	0,217	0,251	0,283	0,317	0,355	0,395	0,437	0,504	0,645
0,85	0,62	0,136	0,164	0,191	0,225	0,257	0,291	0,329	0,369	0,417	0,478	0,602
0,86	0,59	0,109	0,140	0,167	0,198	0,230	0,264	0,301	0,343	0,390	0,450	0,593
0,87	0,57	0,083	0,114	0,141	0,172	0,204	0,238	0,275	0,317	0,364	0,424	0,567
0,88	0,54	0,054	0,085	0,112	0,143	0,175	0,209	0,246	0,288	0,335	0,395	0,538
0,89	0,51	0,028	0,059	0,086	0,117	0,149	0,183	0,230	0,262	0,309	0,369	0,512
0,90	0,48		0,031	0,058	0,089	0,121	0,155	0,192	0,234	0,281	0,341	0,484

Example :
200 kW motor
cos φ = 0.75
Desired cos φ = 0.93
Qc = 200 x 0.487 = 98 kvar

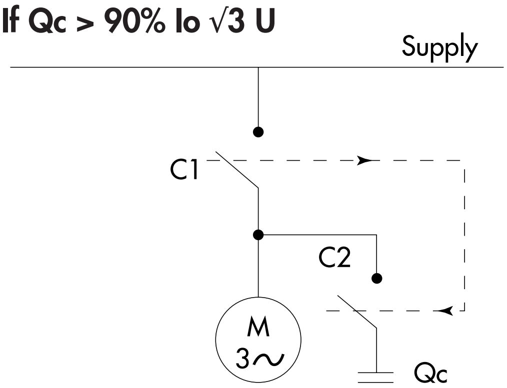
2) REACTIVE COMPENSATION OF ASYNCHRONOUS MOTORS

(COMPENSATION AT MOTOR TERMINALS)

If Qc ≤ 90% Io $\sqrt{3}$ U



If Qc > 90% Io $\sqrt{3}$ U



* Io: Off-load current of motor
* U: Network voltage

The table below gives a rough guide of the maximum capacitor power which can be connected **directly to the terminals of an asynchronous motor without a risk of self-excitation.** In any case, it will be necessary to check that the maximum capacitor current does not exceed 90% of the magnetising current (off-load) of the motor.

Maximum motor power		Maximum speed rpm		
		3.000	1.500	1.000
HP	kW	Max. power in kvar		
11	8	2	2	3
15	11	3	4	5
20	15	4	5	6
25	18	5	7	7,5
30	22	6	8	9
40	30	7,5	10	11
50	37	9	11	12,5
60	45	11	13	14
100	75	17	22	25
150	110	24	29	33
180	132	31	36	38
218	160	35	41	44
274	200	43	47	53
340	250	52	57	63
380	280	57	63	70
482	355	67	76	86

However, if the capacitor power required to compensate the motor is greater than the values indicated in the above table or if, more generally:
If Qc > 90% Io $\sqrt{3}$ U, compensation at the motor terminals remains possible by inserting a contactor (C.2) controlled by an auxiliary motor contactor contact (C.1) in series with the capacitor.

3) REACTIVE COMPENSATION OF TRANSFORMERS

To guarantee its operation, a transformer needs internal reactive energy required for the magnetisation of its windings. The table below gives a rough guide of the value of the fixed bank to be installed according to the powers and loads of the transformer. These values may change according to the technology of the device. Each manufacturer is able to give their precise values.

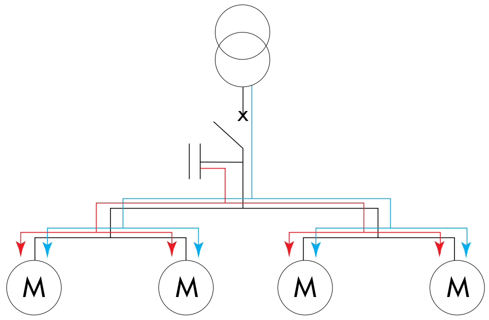
Nominal kVA transformer power	Kvar power to be provided for internel transformer consumption		
	off-load	**75% load**	100% load
100	3	**5**	6
160	4	**7,5**	10
200	4	**9**	12
250	5	**11**	15
315	6	**15**	20
400	8	**20**	25
500	10	**25**	30
630	12	**30**	40
800	20	**40**	55
1000	25	**50**	70
1250	30	**70**	90
2000	50	**100**	150
2500	60	**150**	200
3150	90	**200**	250
4000	160	**250**	320
5000	200	**300**	425

When defining a reactive energy compensation installation, it is recommended to provide a fixed capacitor corresponding to the internal reactive consumption of the transformer at a 75% load.

VIII - DIFFERENT POSSIBLE CAPACITOR BANK INSTALLATIONS

In an L.V. electrical installation, capacitor banks can be installed at 3 different levels:

1) GLOBAL INSTALLATION



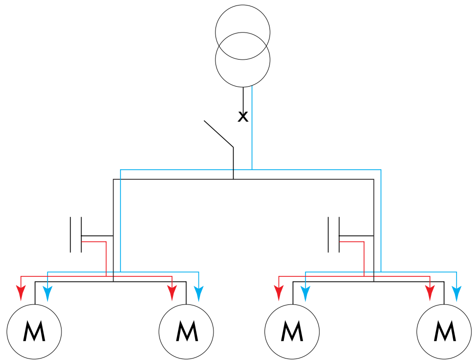
Advantages:

- No reactive energy bill.
- Represents the most economical solution since all the power is concentrated at one point and the expansion coefficient makes it possible to optimise banks.
- Relieves the transformer.

Remark:

- The losses in the cables (RI^2) are not reduced.

2) SECTOR INSTALLATION



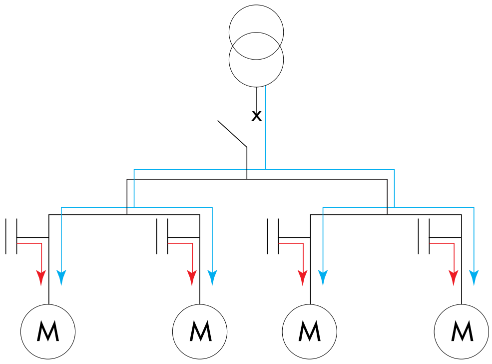
Advantages:

- No reactive energy bill.
- Relieves most of the line feeders and reduces Joule's heat losses (RI^2) in these feeders.
- Incorporates the expansion of each sector.
- Relieves the transformer.
- Remains economical.

Remark:

- Solution generally used for a very large plant network.

3) INDIVIDUAL INSTALLATION



Advantages:

- No reactive energy bill.
- From a technical point of view, the ideal solution since the reactive energy is produced in the same place as where it is consumed; therefore, the Joule's heat losses (RI^2) are reduced in all the lines.
- Relieves the transformer.

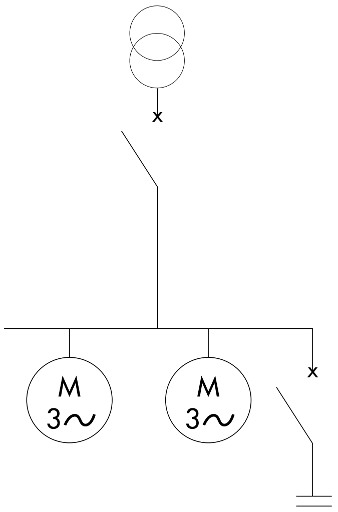
Remark:

- Most costly solution given:
  - . The high number of installations,
  - . The non-incorporation of the expansion coefficient.

IX - DIFFERENT COMPENSATION SYSTEMS OR TYPES

To select a capacitor bank, there are two major compensation systems or types.

1) FIXED TYPE CAPACITOR BANKS :



■ The reactive power supplied by the bank is constant irrespective of the variations of the power factor and load of the receivers and, therefore, of the reactive energy consumption of the installation.

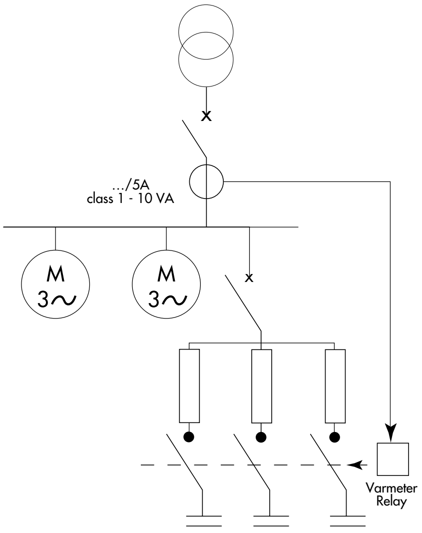
■ These banks are switched on:

- either manually by a circuit breaker or switch,
- or semi-automatically by a remote-controlled contactor.

■ This type of bank is generally used in the following cases:

- constant load electrical installations operating 24 hours a day,
- internal reactive compensation of transformers,
- individual compensation of motors.

2) AUTOMATIC TYPE CAPACITOR BANKS :



■ The reactive power supplied by the bank can be modulated according to the variations of the power factor and the load of the receptors and, therefore, of the reactive energy consumption of the installation.

■ This type of bank is composed of a parallel combination of capacitor steps (step = capacitor + contactor). Switching all or part of the bank on and off is controlled by a incorporated varmeter regulator.

■ These banks are generally used in the following cases:

- variable load electrical installations,
- compensation of main switchboards (LVMS) or major outlets,
- installation of a bank with a power greater than the transformer power by 15%.

Qc bank > 15% transformer PkVA

X - CONTROL, PROTECTION, CONNECTION OF CAPACITORS

1) CONTROL DEVICE

In the case of high-speed cycle loads (welding machines, etc.), conventional systems (electro-mechanical contactors) are no longer suitable for controlling capacitors. High-speed switching compensation systems with solid state contactors are required.
ALPES TECHNOLOGIES offers this type of equipment.

The engagement current of a capacitor depends on:

- the power of the capacitor,
- the short-circuit power of the network to which it is connected,
- whether capacitor banks already engaged are present or not.

Given these parameters, it is essential to use quick opening and closing control devices (switches, contactors, etc.).

When selecting the switch gear, the user must be made aware of the choice of equipment (capacitor control).

Contactors are specially designed by contactor manufacturers for capacitor control, particularly for automatically controlled banks.

These contactors are equipped with auxiliary contacts combined with preload resistors used to limit the current requirement during engagement.

If these contactors are not equipped with these preload resistors, an inductance (shock self-induction coil) of a minimum value of 5 microH must be produced with the cable connecting the contactor to the capacitor.

2) PROTECTION

In addition to the internal protective devices incorporated in the capacitor:

- self-healing metallized polypropylene film,
- internal fuses,
- overpressure disconnecting device ;

it is essential to provide an external protective device on the capacitor.

This protection will be provided either:

- by a circuit breaker:
  - . thermal relay, setting between 1.3 and 1.5 In,
  - . magnetic relay, setting between 5 and 10 In.

- by GI type HRC fuses, rating 1.5 to 2 In.

In = Nominal capacitor voltage,

$$\text{In} = \frac{Qc}{\sqrt{3}\,U}$$

E.g.: 50 kvar - 400 V three-phase

$$\text{In} = \frac{50}{1{,}732 \times 0{,}4} = 72\ \text{A}$$

3) CONNECTION (CABLE DESIGN)

Applicable capacitor standards are defined so that capacitors can withstand a permanent excess current of 30%.

These standards also authorise a maximum tolerance of +10% on the nominal capacitance.

Therefore, the cable should be designed at least for:
I cable = 1.3 x 1.1 . (I nominal capacitor)

i.e. I cable = 1.43 . I nominal

XI HARMONICS

INTRODUCTION

The modernisation of industrial processes, the sophistication of electrical machines and equipment has, in recent years, led to significant development in power electronics :

These semi-conductor-based systems (transistors, thyristors, etc.) designed to produce :

- solid state power converters : AC/DC
- rectifiers
- inverters
- frequency converters
- and many other wave train or phase setting control devices. For electrical supplies, these systems represent "non-linear" loads. A "non-linear" load is a load for which the current consumption is not the reflection of the power supply voltage (even though the source voltage on the load is sinusoidal, the current consumption is non-sinusoidal).

Other "non-linear" loads are also present in electrical installations, in particular:

- variable impedance loads, using an electric arc: arc furnaces, welding stations, fluorescent tubes, discharge lamps, etc.
- loads using strong magnetising currents: saturated transformers, inductors, etc.

The FOURIER series breakdown of the current consumption of a non-linear receiver reveals:

- a sinusoidal term at the supply 50 Hz frequency, the fundamental.
- sinusoidal terms for which the frequencies are multiples of the frequency of the fundamental, the harmonics.
  According to the equation:

$$I_{rms} = \sqrt{I_1^2 + \sum_{h=2}^{n} I_h^2}$$

Σ: Sum of all the harmonic currents from rank 2 (50 Hz x 2) to the last rank n (50 Hz x n).

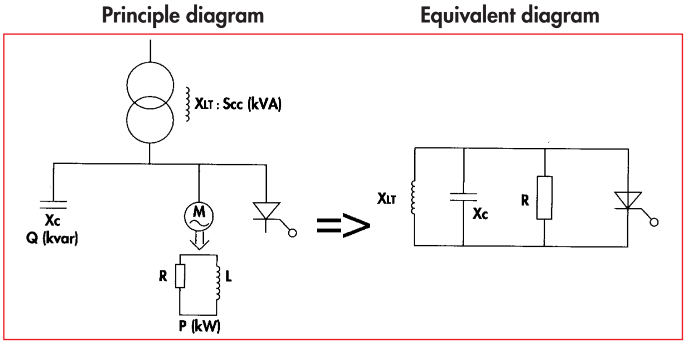
These harmonic currents circulate in the source and the harmonic impedances of the source produce harmonic voltages according to the equation $U_h = Z_h \times I_h$.

Harmonic currents induce most of the harmonic voltages which cause the overall harmonic distortion of the supply voltage.

$$U_{rms} = \sqrt{U_1^2 + \sum_{h=2}^{n} U_h^2}$$

Note : The harmonic distortion of the voltage generated by manufacturing defects of the alternator and transformer windings is generally negligible.

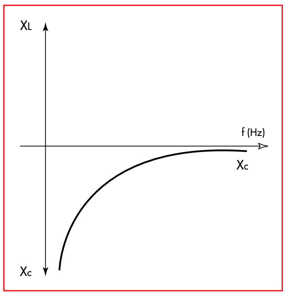
INFLUENCE OF HARMONICS ON CAPACITORS



Note: since the inductance of the motor is much higher than that of the source, it becomes negligible in a parallel assembly.

- Scc (kVA) : Short-circuit power of source
- Q (kvar) : Capacitor bank power
- P (kW) : Non-interfering load power

a) Decrease in capacitor reactance

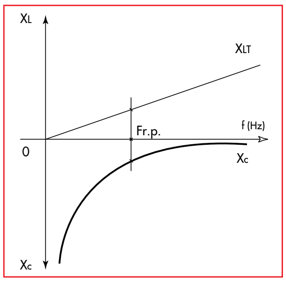


The reactance of the capacitor

$$Xc = \frac{1}{C\omega} = \frac{1}{C \cdot 2 \cdot \pi \cdot f}$$

is inversely proportional to the frequency, its curve is reciprocal and its ability to block harmonic currents decreases considerably when the frequency increases.

b) Parallel resonance or anti-resonance between the capacitors and the source



- the reactance of the source X_{LT} is proportional to the frequency.
- the reactance of the capacitors XC is inversely proportional to the frequency.
  At the frequency Fr.p., there is parallel resonance or anti-resonance (since the two reactances are equal but opposite) and amplification (F.A.) of the harmonic currents in the capacitors and in the source (transformer) where:

$$\text{Fr.p.} = \text{F Supply} \sqrt{\frac{Scc}{Q}} \qquad \text{F.A.} = \frac{\sqrt{Scc.\ Q}}{P}$$

It is important to note that :

- the higher the short-circuit power of the source (Scc) is, the further the resonance frequency moves away from the dangerous harmonic requencies.
- the higher the power (P) of the non-interfering loads is, the more the amplification factor of the harmonic currents is reduced.

Main harmonic currents :

The main harmonic currents present in electrical installations are produced by semi-conductor based systems, i.e.:

harmonic 5 (250 Hz) - I5 - 20% I1
harmonic 7 (350 Hz) - I7 - 14% I1
harmonic 11 (550 Hz) - I11 - 9% I1
harmonic 13 (650 Hz) - I13 - 8% I1

* I1 Current of semi-conductor system at 50 Hz

INSENSITIVITY OF CAPACITORS TO HARMONICS

By design and in compliance with applicable standards, capacitors are capable of withstanding a continuous rms current equal to **1.3 times the nominal current** defined at the nominal voltage and frequency values.

This excess current coefficient has been defined to account for the combined effects of the presence of harmonics and excess voltage (with the capacitance variation parameter being negligible).

It can be noted that according to the degree of harmonic interference SH (power of harmonic generators), this coefficient generally proves to be insufficient and that the parameter Scc (short-circuit power) directly related to the power of the source ST is preponderant in the value of the parallel resonance frequency (Fr.p.).

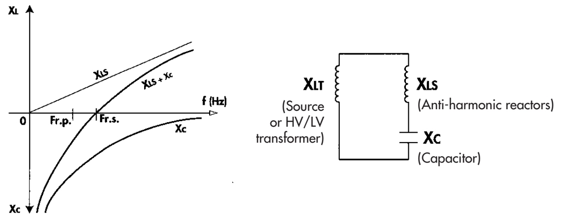
By combining these two parameters SH and ST, three types of networks can be defined with a corresponding "type" of capacitor to be installed:

Type of supply	Pollution criterion	Type of capacitor to be used
Low level of interference	if $\frac{SH}{ST} \leq 15\%$	Standard type
Moderate level of interference	if $15\% < \frac{SH}{ST} \leq 25\%$	H type
High level of interference	if $\frac{SH}{ST} > 25\%$	*SAH type anti-harmonic reactors *FH type harmonic filters

* SH: expanded power in kVA of harmonic generators present in the secondary winding of the MV/LV transformer(s) to be compensated.
* ST: power in kVA of the MV/LV transformer (or MV/LV transformers for two or more transformers in parallel).

PROTECTION OF CAPACITORS WITH ANTI-HARMONIC REACTORS

For supplies with a high level of harmonic interference, installing an anti-harmonic reactors connected in series with the capacitor proves to be the only effective solution.
The anti-harmonic reactors has two purposes:
* to increase the impedance of the capacitor against harmonic currents
* to shift the parallel resonance frequency (Fr.p.) of the source and the capacitor to below the main frequencies of the interfering harmonic currents.



* Fr.p.: Anti-harmonic reactors/capacitor/MV/LV transformer parallel resonance frequency
* Fr.s.: Anti-harmonic reactors/capacitor serial resonance frequency,
(most common values used 190 - 210 and 225 Hz. Other typical values 205 Hz and 215 Hz).

* for frequencies below Fr.s., the reactors/capacitor system behaves like a capacitance and compensates for the reactive energy.
* for frequencies above Fr.s., the reactors/capacitor system behaves like an inductance which, in parallel with the inductance XLT, cancels any risk of parallel resonance at frequencies above Fr.s., particularly at the main harmonic frequencies.

HARMONIC FILTERS

For installations with a high level of harmonic pollution, the user may be confronted with two requirements:

- compensating for reactive energy and protecting the capacitors
- reducing the voltage distortion rate to acceptable values compatible with the correct operation of most sensitive receivers (automatic control systems, industrial computer hardware, capacitors, etc.).

For this application, **ALPES TECHNOLOGIES** is able to offer "passive type" harmonic filters. A "passive type" harmonic filter is a serial combination of a capacitor and an inductive coil for which each combined frequency corresponds to the frequency of an interfering harmonic voltage to be eliminated.

For this type of installation, ALPES TECHNOLOGIES offers services including :

- analysis of the supply on which the equipment is to be installed with measurements of harmonic currents and voltages
- computer simulation of the compatibility of the harmonic impedances of the supply and the different filters
- calculation and definition of the different components of the filter
- supply of capacitors, inductive coils, etc.
- measurement of system efficiency after installation on site

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