n° 142

control equipment for MV capacitor banks

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In 1984, he joined the Medium Voltage Equipment Division in the technical department and since 1986 is responsible for the technical management of medium voltage circuit breakers and contactors. He specializes in switching low inductive currents (IEEE publications).

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summary

1. reactive energy compensation

introduction

The location of the capacitors in an electrical network constitutes what is known as the "compensation mode".
This is determined by:
■ the objective desired (penalty suppression, cable relief, transformers..., increasing the voltage level),
■ the electrical distribution mode,
■ the loading rate,
■ the predictable influence of the capacitors on the characteristics of thenetwork
■ the cost of the installation.
Reactive energy compensation can be (see fig. 1):
■ overall, for example:
□ HV network for EDF 1
□ MV network for a medium voltage subscriber 2
□ LV network for a low voltage subscriber 3 on fixed type bank.
■ by sector, for example:
□ by distribution center for EDF (primary substation) 4
□ by workshop or building for a low voltage subscriber 5
■ individual

This compensation is technically ideal since it produces reactive energy at the point where it is consumed, and in quantities strictly adjusted according to the demand.

However, this solution is costly and generally leads to overcompensation since it does not include combining possibilities for load increases.

Example: large medium and low voltage motors.

It is more economical to install capacitor banks for MV and HV for power ratings exceeding about 1,000 kVAr. However, analysis of different countries networks shows that there is no universal rule.

The compensation mode depends on the country's and company's distributors energy policy. In the U.S.A. compensation is essentially in MV for tariff policy reasons. In contrast in Germany, compensation is done in LV, because it is logical to compensate exactly at the reactive energy consumption point.
■ in France, EDF installs fixed banks on the 63 and 90 kV networks and multiple banks in its HV/MV substations on its 10, 15, and 20 kV networks.
The power on the latter can reach 4.8 MVAr at 20 kV.

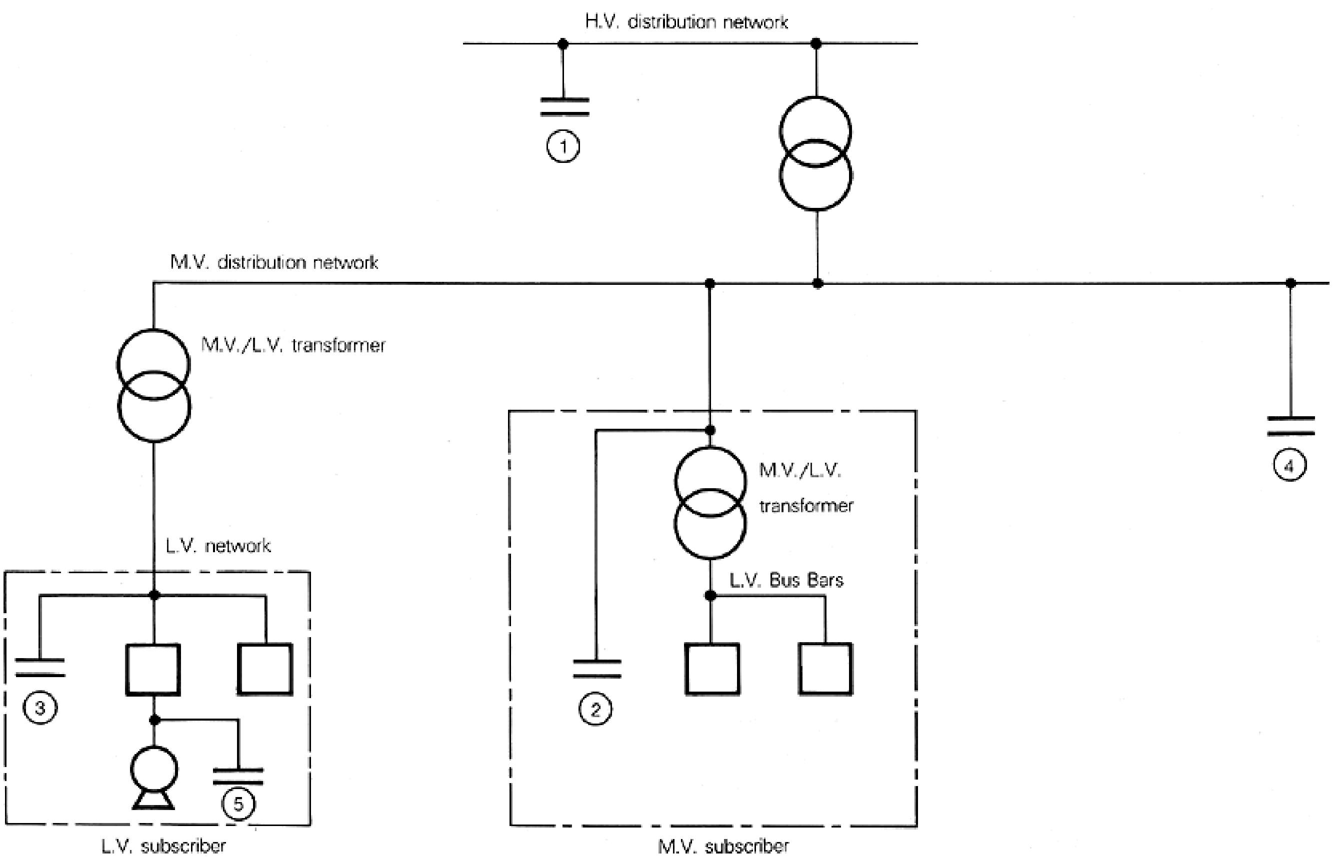


fig. 1

■ MV or LV subscribers must compensate their installations, to obtain a power factor value at the connection point to the main network of not less than 0.928.
This document covers only medium voltage compensation.

MV compensation techniques

Standards compensation

The capacitor banks are connected in parallel to the network.

They can be:
■ single (see fig. 2)
When their reactive power is low and the load relatively stable.

■ multiple (see fig. 3)
This type of compensation is commonly called "back to back".

This type of bank is widely used in heavy industry (high power load) and power suppliers (EDF in the primary substations).
It allows step by step reactive energy regulation.
Switching on or off multiple banks can be controlled by varmeter type relays.

Special compensations

Note: these systems are briefly covered for information.

■ instantaneous static compensators
When continuous and variable compensation is required (industries with very variable high loads and regulation on some EHV networks), installations combining capacitors, variable inductances and power electronics are set up (see fig. 4). The system generally comprises:
□ fixed bank of capacitors,
□ a set of harmonic filters absorbing network harmonics and harmonics generated by the installation itself (power electronics),
□ a variable inductance connected through thyristors. This inductance absorbs the excess reactive energy generated by the capacitors,
□ some of these capacitors can be switched themselves by thyristor.

■ series bank
In the case of large networks with long lines, capacitor banks can be mounted in series on the line (see fig. 5).
This circuit arrangement allows permanent compensation adapted to the requirements since the reactive energy provided depends on the line current.
Such systems exist on the American continent, but this technology is not used in Europe.
A sophisticated short circuit system is required to avoid the destruction of the capacitors when a short circuit current flows in the line.

symbol definitions used

Foreword: **only three phase circuits are covered in this study**.

The notations are as follows:

■ power supply source
□ U: rated voltage,
□ Icc: network short circuit current,
□ Scc: network short circuit power

$$Scc = \sqrt{3}\ U\ Icc = \frac{U^2}{Lo\ \omega},$$

□ Lo: network short circuit inductance,
□ f: industrial frequency,
□ ω: pulsation at industrial frequency.

■ the connections
□ L: connection inductance (series), with the bank (single bank case),
□ *l* : connection inductance (series) with each bank step (multiple capacitor bank),
□ *L*: surge inductance.

■ load
□ C: bank capacity,
□ Q: bank power,
($Q = U^2\ C\ \omega = \sqrt{3}\ U\ Icapa$),
□ Icapa: capacitive current flowing in the bank.

■ transient phenomena
□ Ie: inrush current,
□ fe: inherent oscillation frequency of Ie,
□ S_A: overvoltage factor (supply side).
S_A in p.u. = maximum peak voltage value divided by

$$\frac{U\sqrt{2}}{\sqrt{3}},$$

□ S_B: overvoltage factor (capacitor side)

■ switchgear
□ In: rated normal current,
□ Iencl. max: maximum making capacity (peak).

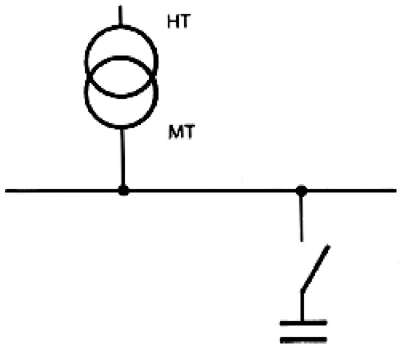


fig. 2

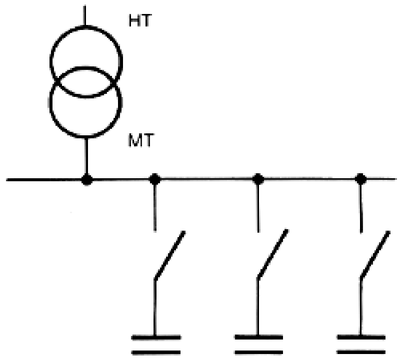


fig. 3

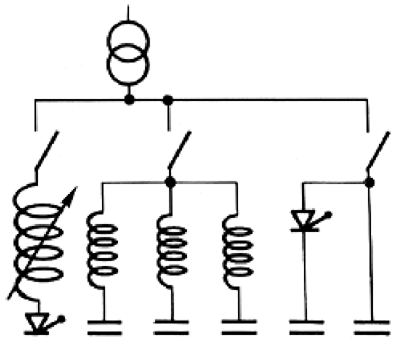


fig. 4

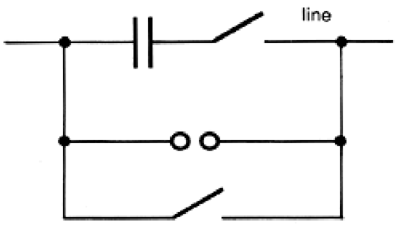


fig. 5

2. switching capacitor banks

electrical switch-on phenomena

Switching-on a bank of capacitors which is connected in parallel to the network causes transient phenomena resulting from bank charging.

As far as the current is concerned, the oscillating load provokes an overcurrent with an amplitude which is a function of the network and bank characteristics.

At the point of consideration, switching-on is equivalent in practical terms to the setting up of a short circuit with short duration (high frequency in relation to the network frequency).

From the voltage side, the load is followed by the propagation of a shock wave. These transient phenomena depend on network characteristics and on the timing of contact closing or prestrike.

There are two possible cases: a single bank and a bank divided into several capacitors to be switched independently to the supply system.

Single capacitor banks (see fig. 6)

Note: $L \leq Lo$

L is thus ignored with respect to Lo in the following calculations.

The switching-on of an isolated bank in a network (wiring diagram with current and voltage curves showing the inrush current and the overvoltages on supply side and load side which follow closing) is shown in figure 7.

The inherent oscillation frequency is

$$fe = \frac{1}{2\,\pi\sqrt{Lo\,C}}$$

The overvoltages supply side and load side are equal to: $S_A = S_B = 2$ p.u.

The closing peak current is given by:

$$Ie = \frac{U\sqrt{2}}{\sqrt{3}}\sqrt{\frac{C}{Lo}} = Icapa \times \sqrt{2}\sqrt{\frac{Scc}{Q}}$$

Scc: short circuit power of the source in MVA at the connection point

Q: capacitor power rating in MVAr.

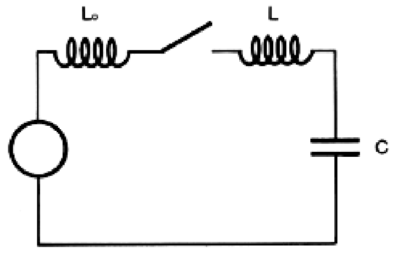


fig. 6

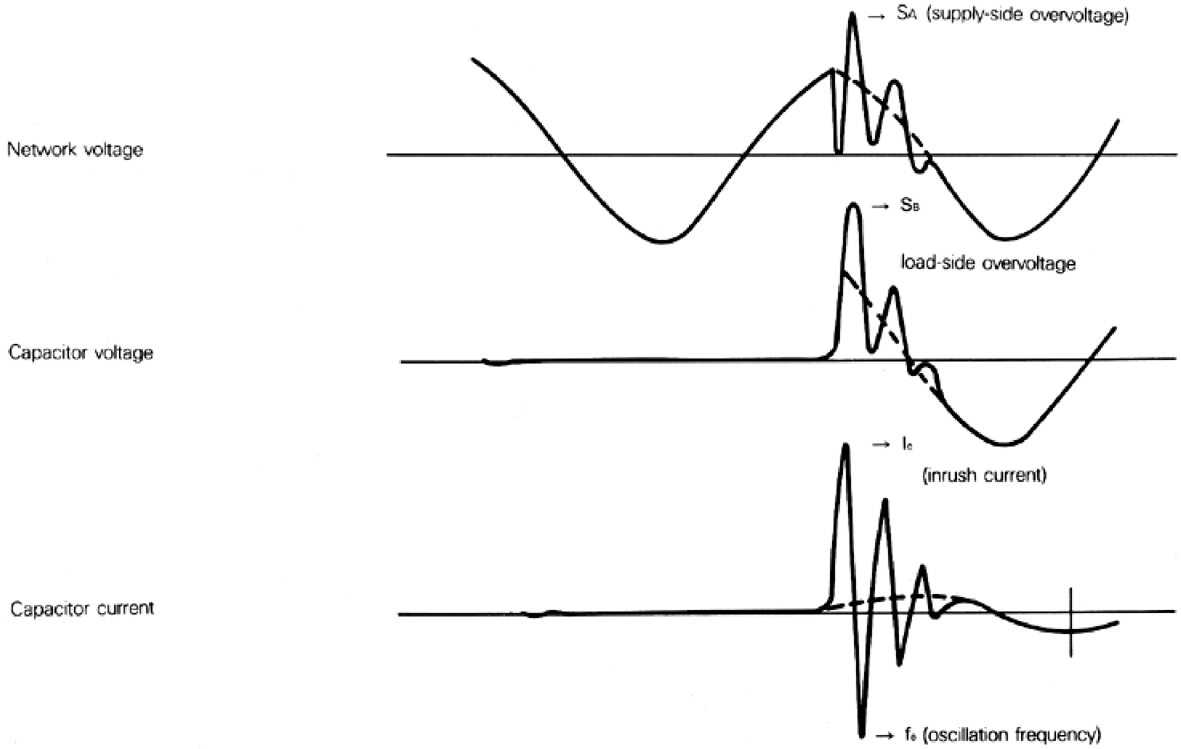


fig. 7

Multiple capacitor banks (see fig. 8)

Remark: we only consider the case of identical bank units. Calculations are more complex for the general case (see IEC standard 56. 1987 Appendix BB).

Lo: source inductance

l : series link inductance

n: number of steps operating when the n + 1th is closed.

The switch-on of one step, made with on line charged capacitors, provokes two superimposed transient phenomena.

The first very fast in frequency

$\frac{1}{2\pi\sqrt{l\,C}}$ corresponds to the discharge of the connected capacitors into the switched-on capacitor; the second, with slower frequency

$\frac{1}{2\pi\sqrt{Lo\,C}}$ thus very negligible in relation to the other (Lo much higher than *l*) corresponds to the discharge of all the bank units into the network, equalizing the banks potential.

The switch-on of the n + 1th bank of a multiple bank (schematic diagram and current and voltage curves showing inrush current, overvoltages appearing at the switch-on by distinguishing both phenomena) is shown in figure 9.

It should be noted that the overvoltage propagated on the network S_A decreases as the number of banks units in service increases. On the other hand, the inrush current is all higher since the number of units is high.

$$Ie = \frac{n}{n+1}\,\frac{U\sqrt{2}}{\sqrt{3}}\,\sqrt{\frac{C}{l}}$$

$$= Icapa\,\sqrt{2}\,\frac{n}{n+1}\,\frac{fe}{f}$$

inherent oscillation frequency

$$fe = \frac{1}{2\pi\sqrt{l\,C}}$$

Supply side overvoltage:

$$S_A = \frac{n+2}{n+1}\ \text{p.u.}$$

capacitor side overvoltage:

$$S_A = \frac{2n}{n+1}\ \text{p.u.}$$

These **overvoltages** never exceed twice the network voltage and generally do not cause problems, all the units being constructed to tolerate this level. On the other hand, the inrush currents require appropriate methods to avoid damage to the capacitors and the switchgear.

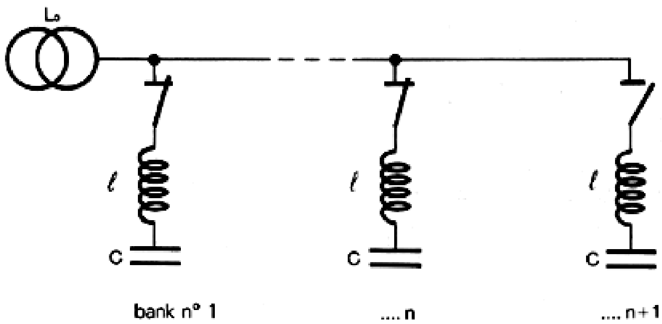


fig. 8

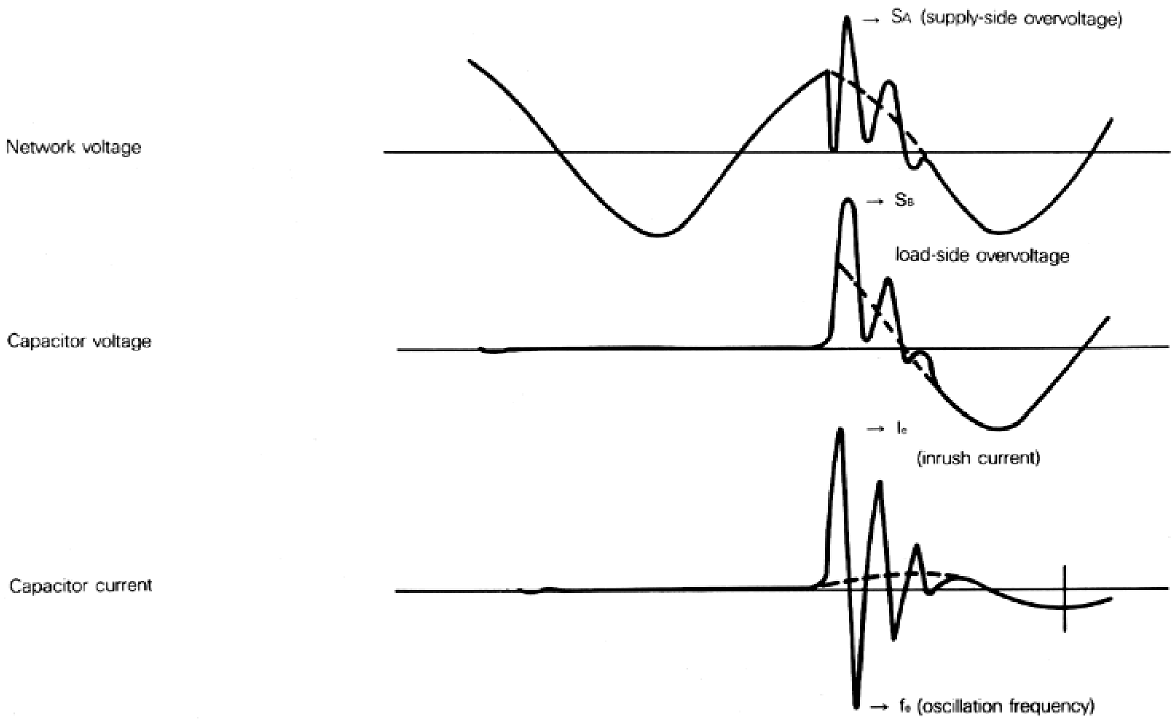


fig. 9

electrical switch-off phenomena

When the arc of the switching device is extinghished at a zero current, the separated bank remains charged at peak voltage.

The bank is then discharged through the discharge resistors fitted with each capacitor (time: 1 to 5 minutes).

The Transient Recovery Voltage at the switch terminals reaches 2 U_M after a half cycle (assuming a very short arc time). If the switch dielectric regeneration increases faster than the TRV, the current interruption occurs normally.
On the contrary if it increases less quickly than the TRV, then a breakdown occurs (see fig. 10 C).

The Standards distinguish between **reignition** (breakdown before the quarter of cycle after clearing) which does not cause a rise in voltage, and **restrike** (breakdown after the quarter of cycle).

In this case (see fig. 10 D), the phenomena are similar to those during switch-on, but can be amplified by the fact that energizing can occur under a voltage equal to the double of the closing one.

From a theoretical point of view, if several energizings happen, the following occurs:

- increasing shock waves: 2 U_M; 4 U_M; 6U_M...
- increasing overvoltages: 3 U_M; 5 U_M; 7 U_M...
- increasing TRV: 2 U_M; 4 U_M...

In practice, voltages do not increase so quickly and so regularly at each restrike because restrikes do not always appear when the difference of voltage is maximum and there is also some damping. Nevertheless, successive restrikes during the switching off of a bank can lead to high overvoltages, which are dangerous for the network and for the capacitors.

In addition, resulting inrush currents are proportional to the difference of voltage between the network and the bank before energizing.
Consequently, the inrush current amplitudes are always greater than those during switch-on and are thus more dangerous for all the equipment.

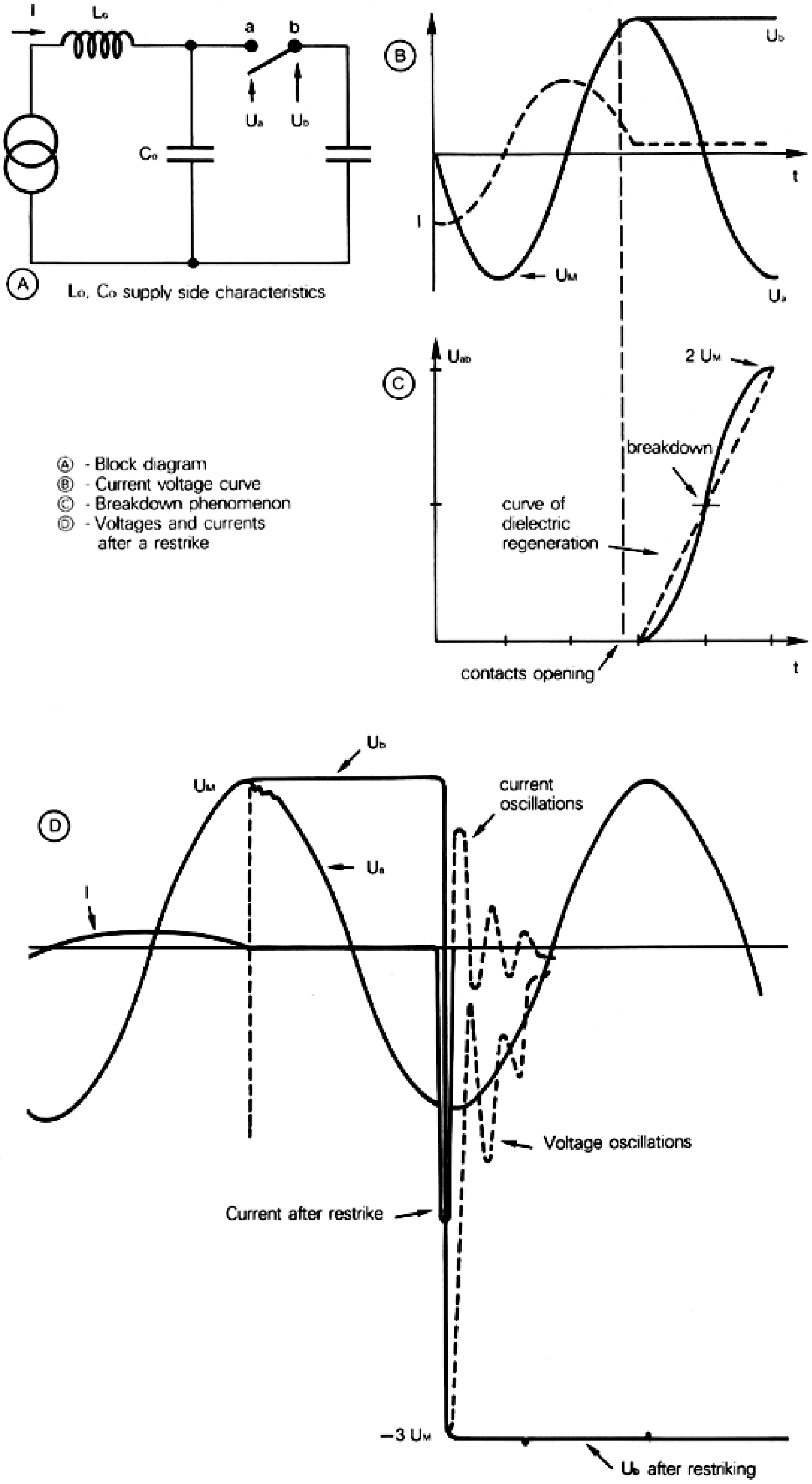


fig. 10

It is therefore of prime importance to use operating switchgear with rapid dielectric regeneration to avoid restrikes.

some values

The inrush currents during closing vary considerably according to the network configuration.

■ in the case of a **single bank**, the transient peak current depends on the short circuit power at the connection point.

Figure 11 shows the ratio:

$$\frac{Ie}{Icapa}$$

as a function of Scc and of the bank power Q.

In the existing installations, inrush current never exceeds 100 times the current flowing in the bank (Icapa).

On average, the inrush current is of the order of 10 to 30 times Icapa.

The frequency related to the transient phenomena is from 300 to 1,000 Hz

$$\left(fe = \frac{1}{2\,\pi\sqrt{Lo\,C}} = \frac{\omega}{2\,\pi\sqrt{2}}\,\frac{Ie}{Icapa}\right)$$

■ in the case of a **multiple banks** the transient current is much higher as the linking inductance is very weak in relation to the source inductance.

Without any particular limitation (surge inductances), the inrush currents are 30 to 50 times higher than in the previous case. These inrush currents are generally larger than the values tolerated by the switchgear. Limiting inductances (called surge inductances) are thus necessary in most cases (see § 5).

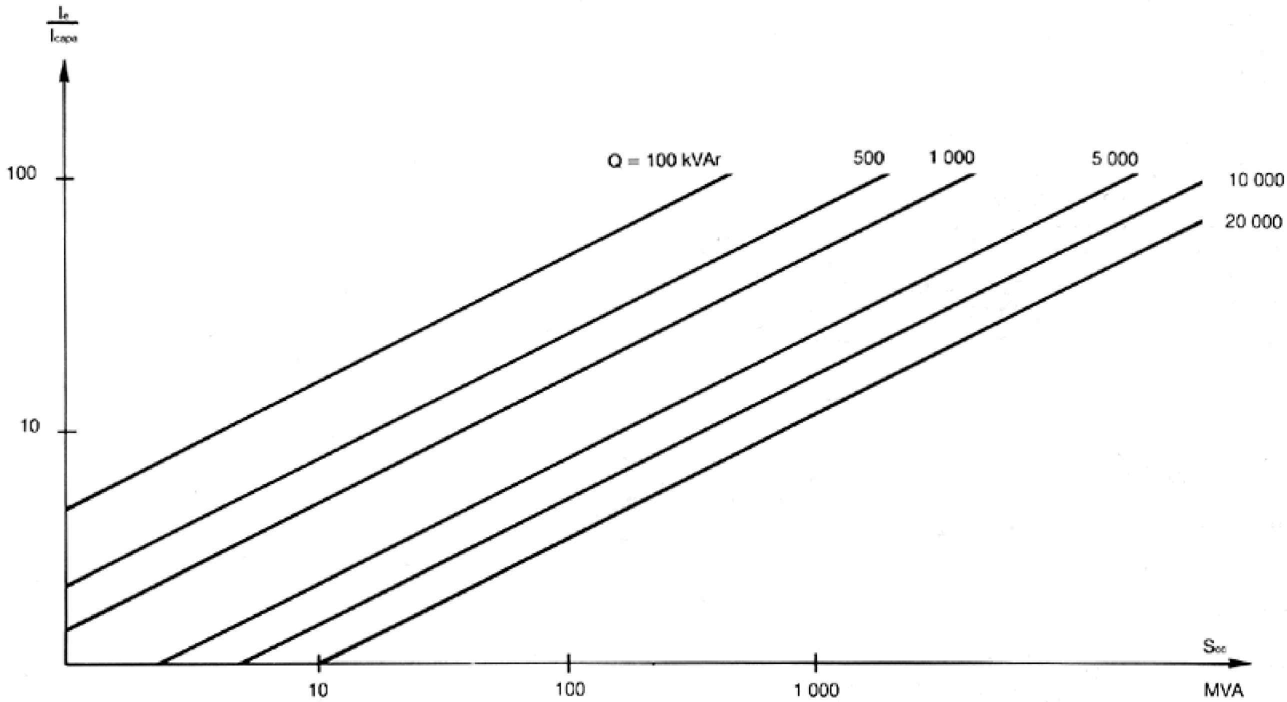


fig. 11

3. problems concerning capacitors and solutions

electrical stresses

Switchgear has to withstand inrush currents and overvoltages during capacitor switching operations.
If the switchgear is designed for normal ratings, precautions must be taken when the performances of the operating equipment are not high enough.

Capacitors

The transient overvoltage of 2 U_M at the terminals is normally carried out without any particular ageing provided that it does not occur more than 1,000 times yearly. The inrush currents during switch-on must never exceed 100 times the capacitor bank nominal current rating.
Such an inrush current can be withstood 1,000 times yearly. An inrush current of 30 times Icapa can be accepted 100,000 times yearly.
In case of higher inrush currents, limit inductances commonly called surge inductance are connected in series with the capacitor banks.

capacitor bank design

There are two cases:
■ single bank (see fig. 12),
■ multiple banks (see fig. 13),

Single bank

The equipment is usually of simple design because:
■ the networks Scc does not cause inrush currents greater than 100. Icapa,
■ the number of operations is small since there is no reactive energy regulation.
Therefore there is no need for surge inductance. The capacitor bank is directly connected to the network through its protection device, chosen according to the voltage, short circuit current, and thermal current characteristics (capacitive current + 30 %).

■ Ie must be lower than the making capacity of the protection device, for the number of operations concerned.

Multiple banks

The linking inductances are generally very low between the different capacitor banks.

Making currents must be limited by surge inductance in series with the bank:
■ to avoid exceeding the 100 Icapa admissible for the capacitors,
■ to avoid exceeding the making capacity of the switchgear.

switchgear thermal rating

One switchgear characteristic is its permanent heating condition which corresponds to its nominal current rating.

When this switchgear switches and/or protects capacitors, the real current in the bank must be taken into account, and this can be higher than the assigned current. This permanent overload is generally due to current harmonics with frequencies higher than the industrial frequency.

Power capacitors can accept 1.3 times the assigned current value.
Thus the maximum capacitive current assigned at 50 Hz for all equipment will be 0.7 In.

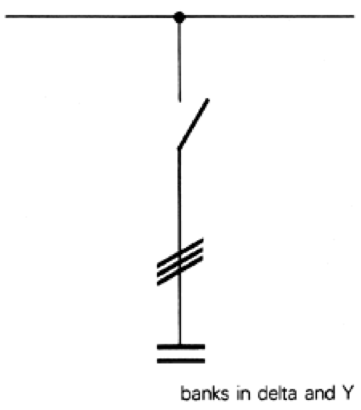


fig. 12

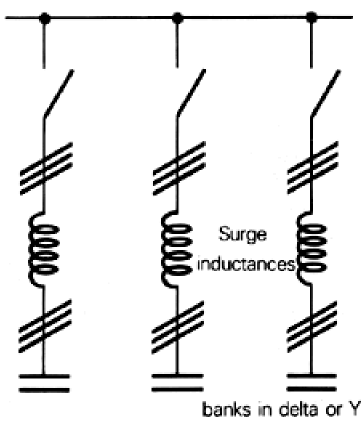


fig. 13

4. switchgear problems and technical solutions

The switchgear consists of (see fig. 14):
■ the operating control devices (switches, contactors) used in multiple banks cases,
■ protection devices (circuit breakers) which are always used for single banks and also relatively often for the multiple banks.

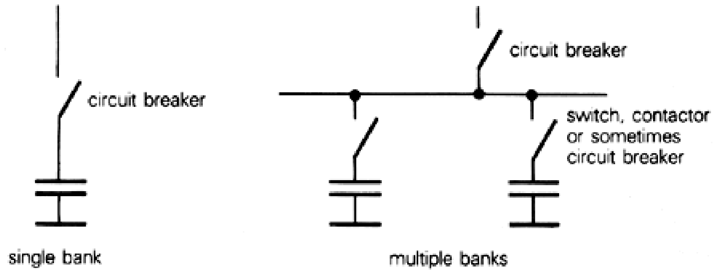


fig. 14

problems involved

The main problems concerning the switchgear are:

Inrush current

■ at nominal frequency (50 or 60 Hz), the circuit breaker has not to respond to the peak value of the current during the prestrike period (< 3 ms).

■ at a frequency of about 1 kHz, the circuit breaker has to withstand a series of current peaks during the prestrike. This indicates that contact wear is much bigger at higher frequencies than at nominal frequency, for an equivalent current.

Breaking

The principal phenomena involved are described in the paragraph "Electrical switch off phenomena" (essentially a dielectric problem: be careful on restrikes).
In addition, in case the protection function must be ensured, the stresses related to the short circuit breaking must also be considered.

Overloading due to harmonics

Generators and receivers in which the magnetic circuits are saturated (static converters) cause voltage wave distorsions, resulting in significant current harmonics, since in the case of capacitors, current I is proportional to the frequency, i.e. for the harmonic rank n, of relative value x. %

$$I = UCn\,\omega = I_{50\,Hz}\sqrt{1 + (n\,x)^2}$$

with $U = U_{50\,Hz}\sqrt{1 + x^2}$

The overload factor is

$$\frac{\sqrt{1 + (n\,x)^2}}{\sqrt{1 + x^2}} \approx 1 + x^2\,\frac{n^2 - 1}{2}$$

Standards UTE 127, C54.100, CEI 70, CEI 871 for capacitors, indicate an overload factor of 30 % (corresponding to n = 5 and x = 17 %).
If In is the rated nominal current of the switchgear, the maximum capacitive current which can be carried at 50 Hz, is thus Icapa = 0.7 In.

In (A)	Icapa (A)
630	400
1,250	875
2,500	1,750
3,150	2,200

Mechanical endurance

Switching and protecting capacitor banks occur several times a day, there-fore good electrical and mechanical endurance are also required for switchgear.

Merlin Gerin solutions

In response to all these problems Merlin Gerin has chosen the SF6 breaking technique. The dielectric rigidity of this gas being much higher at equal pressure than most of those known, the capacitive current breaking is ensured **without restrikes** and at a relatively low pressure of SF6 (≤ 2.5 bar). The opening dielectric witthstand is not related to the previous closing current peak. Closing operation brings inrush current which is the main cause of contact wear (wear during opening is negligible) because this inrush current occurs at each operation.

It is thus the value of this peak current and the number of operations which must be considered with respect to electrical endurance. Good electrical endurance is obtained by using tungsten alloys at the arcing contacts extremities, and using SF6 with activated alumina, to limit the rate of gas decomposition during breaking to negligible values.
The robustness and the mechanical simplicity of the switchgear allow, in general, 5 times more operations than required by standards IEC 56. 1987, i.e. 10,000 operations.

The entire MG switchgear range is capable of operating capacitor banks in compliance with IEC and ANSI standards. Performance data are given in the technical leaflets. As an example, some characteristics are given (valid in 1988) for circuit breakers, contactors and MV switches in appendix 1.

standards

IEC standards

Standards 56. 1987 specifies the test methods for closing and breaking capacitive currents. Two supply circuits are described.
■ circuit A: impedance such as the short circuit current does not exceed 10 % of the ciricuit current is of the same order as the circuit breaker nominal short circuit.
■ circuit B: impedance such as the short circuit current is of the same order as the circuit breaker's nominal short circuit.

If Icapa is the nominal capacitive current, there are four test sequences (see fig. 15).

Each test sequence must include 10 tests (three phase case) or 12 tests (single phase case). Concerning back to back switching, the IEC Standards cover the methods for inrush currents and indicates an approximate value of the inherent frequencies of these currents: 2 to 5 kHz.

ANSI standards

Related documents:
ANSI C37-073-1972
ANSI C37-0732-1972
ANSI C37-06 version Dec. 85.
Parameter definitions of this standard:

- V: maximum nominal voltage
- Isc: short circuit current
- $A = \dfrac{Isc}{Isc - Icapa}$

See adjoining fig. 16

In each sequence, one breakdown is accepted provided that it does not occur more than 1/3 cycle after clearing (5.5 ms).
Number of operations: 24 openings distributed as follows:

- 12 O from 0° to 180° with 2 O every 30°,
- 6 O with an arc time 1st phase to clear the shortest (at ± 7.5°),
- 6 O with an arc time 1st phase to clear the longest (at ± 7.5°)

Value of Icapa (see fig. 17).
Test parameters for back to back switching (see fig. 18).

EDF regulation

Standards: UTE C64 102 (circuit breakers) and UTE C64 132 (switches).
EDF uses MV multiple capacitor banks in metal-enclosed switchgear with integral switch. MG switch used is the FLUARC IFB4.
Bank power: 4.8 MVAr or 160 A capacitive under 20 kV.
EDF defines 2 classes of switch (see fig. 19).

During type testing, IFB4 Switch has achieved in the Renardieres laboratory 10,000 CO in electrical endurance (Ie = 11.5 kAp and Icapa = 160 A) and 10,000 CO in mechanical endurance.These tests show that the MG SF6 switchgear gives the perfect control of electrical phenomena which occur during switching on and switching off, capacitors in the network, and have a high mechanical endurance.

test sequences	supply circuit	test current in % of Icapa
1	A	20 to 40
2	A	over 100
3	B	20 to 40
4	B	over 100

fig. 15

sequences for three phase switchgear

test duty	sequ. No	voltage	% capa	No of operations
isolated capacitor bank or cable switching	1 A	$\dfrac{2\,V}{1 + A}$	30	24 O
isolated capacitor bank or cable switching	1 B	$\dfrac{2\,V}{1 + A}$	100	24 CO
back to back capacitor bank	2 A	$\dfrac{2\,V}{1 + A}$	30	24 O
back to back capacitor bank	2 B	$\dfrac{2\,V}{1 + A}$	100	24 CO

fig. 16

In (A)	Icapa max (A)	
	circuit breaker for metalclad application	outdoor circuit breaker
1,200	630	400
2,000	1,000	400
3,000	1,600	400

fig. 17

	circuit breaker for metalclad application		outdoor circuit breaker	
In (A)	Ie (kÂ)	fe (kHz)	Ie (kÂ)	fe (kHz)
≤ 2,000	15	≤ 2.0	20	4.2
3,000	25	1.3	20	4.2

fig. 18

class	test order			
	mechanical oper.	electrical oper.	mechanical oper.	electrical oper.
1	3,000 CO	2,000 CO		
2	5,000 CO	5,000 CO	5,000 CO	5,000 CO

fig. 19

selection table for the use of MG medium voltage switchgeear

Electrical endurance (on closing)
The various tests made in the laboratory, and the theoretical contact wear calculations using Weibull's law, give for each switchgear the maximum number of operations, as a function of the inrush current.

The oscillation frequency has little impact on contact wear and thus on the switchgear performance (except Rollarc contactor 1.6 kHz max).
The curves for each switchgear are shown in **appendix 2**, with test references, and a table for each item of switchgear indicating.

- inrush corresponding to the mechanical endurance of the switchgear
- maximum inrush current and the corresponding number of operations.

Note: the curves in appendix 2 correspond in fact to a close/open endurance, with "normal" opening current values: for opening currents higher than 300 A, phase consult MG.

5. inrush current calculations and surge inductances

Preliminaries:

■ symbol definitions used: see paragraph 2 page 5.

■ as a function of nominal voltages and currents (with Icapa = 0.7 In), short-circuit power, etc... it is assumed the switchgear has been already selected for the following calculations.

single bank

■ power $Q = U^2 C \omega = \sqrt{3}\ U\ \text{Icapa}$,

■ inrush current:

$$\text{Ie} = \frac{1}{\sqrt{\text{Lo C}}} \times \frac{1}{\omega} \text{Icapa} \sqrt{2}$$
$$= \text{Icapa} \sqrt{2} \sqrt{\frac{\text{Scc}}{Q}}$$

Lo: source inductance

Scc: network short circuit power,

■ corresponding oscillation frequency:

$$\text{fe} = \frac{1}{2 \pi \sqrt{\text{Lo C}}}$$

In general, no surge inductance is necessary, except in cases where Scc is high and Q low; peak current must then be limited:

□ either for the capacitors:
(Ie > 100 Icapa),

□ or either for the switchgear (Ie incompatible with the appendix curves).

■ surge inductance calculations (added to Lo).

1st case

Ie > 100 Icapa (capacitor limit)

$$\text{Take } L = \frac{U^2}{\omega} \left(\frac{200}{Q} - \frac{10^6}{\text{Scc}}\right)$$

With	*L* in	µH
	U	kV
	Q	MVAr
	Scc	MVA

2nd case

Ie > Iencl max, maximum inrush current of the switchgear (indicated in appendix 2).

$$\text{Take } L = \frac{10^6}{\omega} \left(\frac{2\,Q}{3\,(\text{Iencl. max})^2} - \frac{U^2}{\text{Scc}}\right)$$

With	*L* in	µH
	Q	MVAr
	Iencl max	kAp
	U	kV

3rd case

Combine 1st and 2nd case.
Take the biggest value of *L*.

multiple banks

■ n banks (identical) switched on when n + 1th is switched on,

■ unit power :

$Q = U^2 C\omega = \sqrt{3}\ U\ \text{Icapa}$

■ inrush current:

$$\text{Ie} = \sqrt{\frac{2}{3}}\, U \frac{n}{n+1} \sqrt{\frac{C}{l}}$$
$$= \text{Icapa} \sqrt{2} \frac{n}{n+1} \frac{\text{fe}}{f}$$

l : link inductance:
0.5 µH/m is a good approximation for bars or cables in medium voltage.

■ oscillation frequency:

$$\text{fe} = \frac{1}{2 \pi \sqrt{l\ C}}$$

Link inductances between the banks are generally very low (a few µH), that is why a limitation of inrush currents by a surge inductance in series with each bank is generally necessary
(see fig. 20).

■ surge inductance calculation *L*.
The value of *l* added to *L* is neglected.

1st case:

Ie > 100 Icapa (capacitor limitation)

$$\text{Take } L = \left(\frac{n}{n+1}\right)^2 \frac{2\,.\,10^2}{\omega} \frac{U^2}{Q}$$

2nd case :

Ie > (Iencl.max.) maximum peak current for the switchgear (indicated in appendix 2)

$$\text{Take } L = \left(\frac{n}{n+1}\right)^2 \frac{2\,.\,10^6}{3\,\omega} \frac{Q}{(\text{Iencl. max})^2}$$

With:

n:	number of switch-on banks when n + 1th is switched on,
Q:	bank power MVAr,

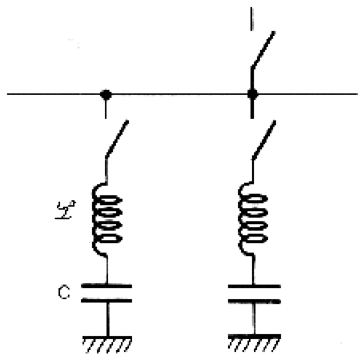


fig. 20

Iencl.max.:	maximum switchgear making current: kAp,
U:	voltage kV,
L:	surge inductance in µH,

3 rd case:

Combine 1st and 2nd case.
Take the biggest value of *L*.

Note: to summarize the inrush current calculations for single or multiple banks, see appendix 3.

surge inductances

The inductances must be adapted as a function of the manufacturer's capabilities and economic considerations.
Installation: internal - external
Nominal permanent current.
1.3 to 1.5 In.

Inductance value: 0 + 20 %
Thermic witchstand to transient inrush currents: 30 to 50 In.

Electrodynamic withstand: Icc at the connection point.

It is an inductance without magnetic core. The most frequently used values are those with inductances of 50, 100 or 150 µH.

For example: EDF 50 µH 200 A for 3 banks of 4.8 MVAr under 20 kV.

6. appendices

appendix 1: medium voltage switchgear characteristics

switchgear designation	short circuit performance	rated normal current	capacitive current switched
circuit breaker (1)			
FG1	25 kA/12 kV 20 kA/15 kV	630 and 1,250 A	440 and 875 A
FG2	50 kA/12 kV 40 kA/17.5 kV	630 to 3,150 A	440 to 2,200 A
FG3	31.5 kA/25.8 kV	630 to 2,500 A	440 to 1,750 A
FG4	40 kA/38 kV 31.5 kA/40.5 kV	630 to 2,500 A	440 to 1,750 A
FB4	25 kA/40.5 kV	630 and 1,250 A	440 and 875 A
SF1	25 kA/38 kV	630 and 1,250 A (2)	440 and 875 A
contactor (2)			
Rollarc R 400	10 kA/7.2 kV 8 kA/12 kV	400 A	240 A
switch for capacitors			
IFB4	24 kV		160 A
VM6	24 kV		135 A

(1) This switchgear can be used as capacitor switch.
(2) SF1 1,250 A available in 1993.

All updated characteristics are given in the technical specifications.

A summary is given here (valid in 1992).

Some test references

■ electrical closing endurance

□ **IFB4**

- EDF standard for capacitor banks of 4.8 MVAr switch.
- 10,000 closing and opening under 23 kV with closing current: 11.5 kAp, oscillation frequency 3.4 kHz and opening current: 160 A.
- 10,000 closing and opening unloaded.

EDF report HM 51-02-201.

□ **FG1**

- 700 single phase closing at 25 kAp under 2 kHz that is 1,400 in three phase.
- 1,000 single phase closing at 20 kAp under 2.5 kHz that is 2,000 in three phase.

Volta report AR 113 A.

□ **FB4**

- 4,500 single phase closing at 10 kAp under 4.1 kHz that is about 2,000 in three phase.

Volta report E74.

□ **VM6**

- 4,000 closing/opening under 25 kV
- closing 8 kAp; opening 100 A.

EDF report HM 51-07-929.

■ Other tests closing/opening

□ **FG3**

at 24 kV single phase voltage, closing 15 kAp under 2.5 kHz and 880 A opening.
CESI-GPS 1540 report.

□ **FG4**

at 30 kV single phase voltage, closing 15 kAp under 2.5 kHz and 880 A opening.
CESI-GPS 1543 report.

□ **FB4**

at 30 kV single phase voltage, closing 15 kAp under 2.5 kHz and 880 A opening.
CESI-GPS 1544 report.

□ **VM6**

at 24 kV three phase voltage, opening 135 A.
Volta report AB 2430.

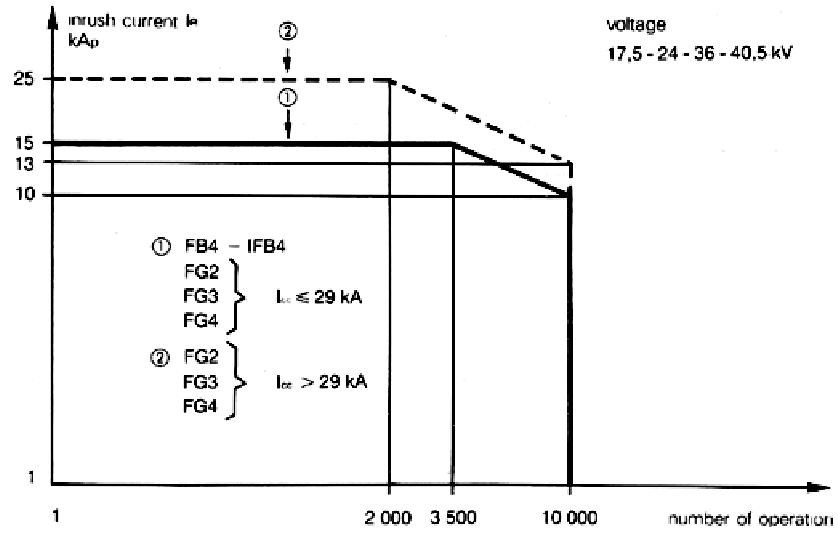
□ **SF1 630 A**

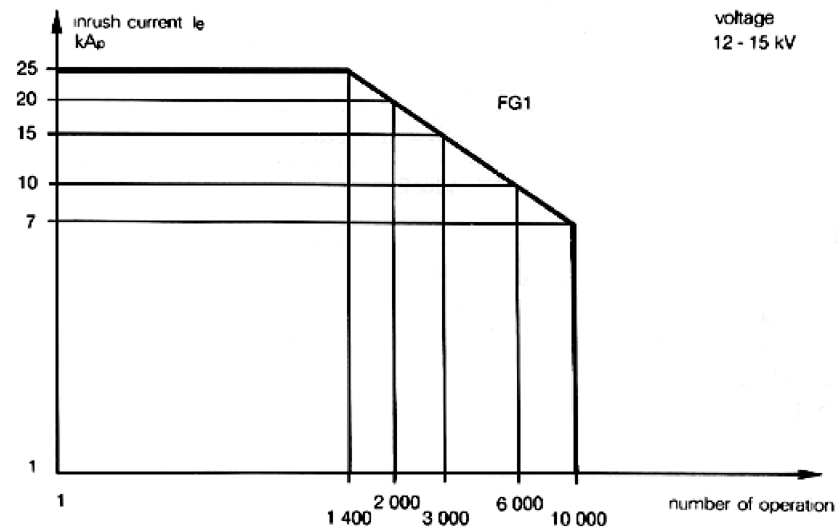
at 24 and 36 kV three phase, 440 A.
CESI-GPS 1952 A and B.

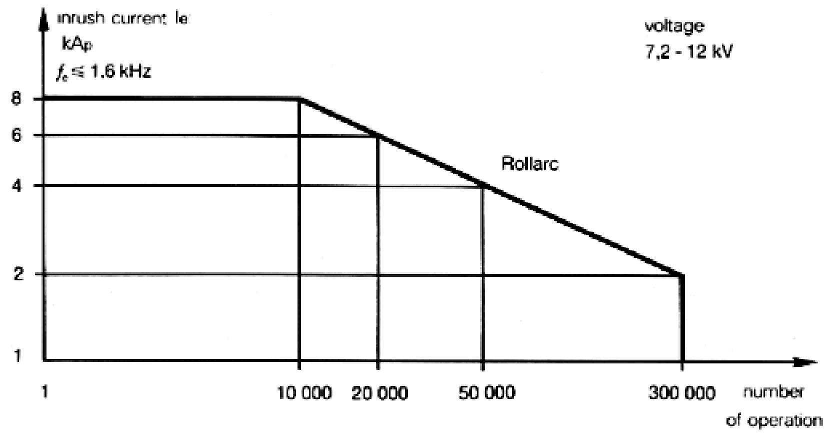
appendix 2: selection table for the use of medium voltage switchgear

switchgear designation	Icc	max No of operations: Nmax	Ie correspond'g to Nmax.-kAp	No of operations at Iencl.max	Iencl.max kAp
circuit breaker					
FB4		10,000	10	3,500	15
FG1		10,000	7	1,400	25
FG2	< 29 kA	10,000	10	3,500	15
	> 29 kA	10,000	13	2,000	25
FG3	< 29 kA	10,000	10	3,500	15
	> 29 kA	10,000	13	2,000	25
FG4	< 29 kA	10,000	10	3,500	15
	> 29 kA	10,000	13	2,000	25
SF1	1,250 A	10,000	10	3,500	15
contactor					
ROLLARC		300,000	2	10,000	8
switch					
IFB4		10,000	10	3,500	15
VM6		4,000	8		

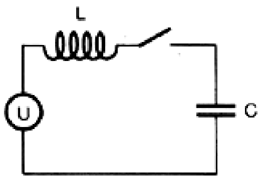
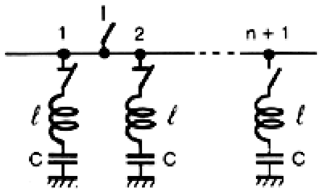
appendix 3: inrush current function of number of operations







appendix 4: switching on capacitor banks: inrush current calculations summary table

	single bank	multiple banks (identical)
		
	Lo = short circuit network inductance Scc = $\sqrt{3}$ U Icc with U/$\sqrt{3}$ = LoωIcc	n banks switched on when n + 1 switched on l = link inductance (0.5 μH/m)
bank power	$Q = U^2 C\,\omega = \sqrt{3}\,U\,Icapa$	$Q = U^2 C\,\omega = \sqrt{3}\,U\,Icapa$; Q = Power of each bank
inrush frequency	$Ie = \frac{1}{\sqrt{Lo\,C}} \times \frac{1}{\omega}\,Icapa\sqrt{2} = Icapa\sqrt{2}\sqrt{\frac{Scc}{Q}}$	$Ie = \sqrt{\frac{2}{3}}\,U\,\frac{n}{n+1}\sqrt{\frac{C}{l}} = Icapa\sqrt{2}\,\frac{n}{n+1}\,\frac{fe}{f}$
oscillation frequency	$fe = \frac{1}{2\pi\sqrt{Lo\,C}}$	$fe = \frac{1}{2\pi\sqrt{l\,C}}$
max. bank peak	Imax. peak bank = 100 Icapa	Imax. peak bank = 100 Icapa
electrical switchgear	cf curve appendix 2	cf curve appendix 2
switchgear nominal endurance	$Inominal \geq \frac{Icapa}{0.7}$	$Inominal \geq \frac{Icapa}{0.7}$
supply side current	2 p.u.	$\frac{n+2}{n+1}$ p.u.
load side overvoltage	2 p.u.	$\frac{2n}{n+1}$ p.u.
surge inductance overvoltage	generally, surge induct not reqd (unless Scc high and Q low)	generally, surge induct reqd
surge inductance calculations *L*	$L \geq \frac{10^6}{\omega}\left(\frac{2\,Q}{3\,(Imax.\,peak)^2} - \frac{U^2}{Scc}\right)$	$L \geq \frac{2.10^6}{3}\,\frac{Q}{\omega}\left(\frac{n}{n+1}\right)^2 \times \frac{1}{(Imax.\,peak)^2}$

Note: for definitions of symbols used: see para 1 page 3.
L: μH
Q: MVAr
Scc: MVA
Imax. peak: kAp (*)
(*) Imax. peak is the smallest of the two following switched on values:
- the bank maximum peak current (100 Icapa)
- the switchgear maximum peak current Iencl. max. (see appendix 2: curves or 2nd column summary table).

7. bibliography

Standards
IEC 56, 1987
UTE C64 102 and C64 132
ANSI C37-073-1972 and
C37-073-1972

Merlin Gerin's "Cahiers Techniques"

■ Economic optimization of capacitor banks.
(Optimisation économique des batteries de condensateurs).
Cahier Technique n° 100
(C.G. POUZOLS)

■ Contactor-fuse combinations for the protection of high voltage receivers - 2nd part - The case of capacitors and transformers.
(Association contacteurs - Coupe circuit pour la commande et la protection des récepteurs haute tension - 2e partie - Cas des condensateurs et des transformateurs).
Cahier Technique n° 108
(SAPUTO)

Publications

■ Revue Generale de l'Electricité
(General review of Electricity)
October 1958:
Switching and protection switchgear for capacitor banks in a medium voltage network.
(L'appareillage de manœuvre et de protection pour les batteries de condensateurs sur un réseau MT).

■ Merger Magazine Number 43-
Switching on and off capacitor banks, pages: 1 to 21.
(Enclenchement et déclenchement des batteries de condensateurs, p. 1 à 21).
DUCLUZAUX-HENNEBERT

■ Electra Number 62
Circuit-breaker stresses when switching back-to-back capacitor banks.
(Contraintes sur les disjoncteurs des batteries de condensateurs couplées "dos à dos" lors des manœuvres).

■ Electra Number 87
Requirements for capacitive current switching tests employing synthetic test circuits for circuit-breakers without shunt resistors.

Réal. : Illustration Technique Lyon - Photo : IPV
IPV 09-92 - 2500 - Imp. Léostic