n° 143

behaviour of the SF6 - MV circuit-breakers Fluarc for switching motor starting currents

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Engineer, graduated from the I.E.G. in 1952. He started work at Merlin Gerin in 1953 where he embarked on a long career in the switchgear engineering branch of which he became head in 1972. He participed in developing all the high voltage products from the fuse to the circuit-breaker and became particularly involved in SF6 circuit-breakers. From 1978 onwards he turned towards marketing and high voltage circuit-breakers where he has the job of product manager.

E/CT 143 up dated july 1992

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summary

1. Historics		p. 4
2. Auto compression technique		p. 5
3. Rotating arc technique		p. 7
4. Switching of small inductive currents		p. 8
5. Motor insulation		p. 8
6. Propagation of steep fronted waves in motor windings		p. 9
7. Motor insulation according to IEC and practice	Interturn insulation	p. 11
	Ground insulation	p. 11
	Summary	p. 11
8. Overvoltages and steep fronted voltage waves	The steep fronted voltage waves	p. 12
	Current chopping	p. 15
	Prestrikes	p. 15
9. Results with Fluarc CB	Test circuit	p. 17
	Test results	p. 18
	Experience	p. 18
10. Conclusions		p. 20

1. historics

Many years ago, oil circuit-breakers (OCB) and air magnetic circuit-breakers (AMB) were the main breaking techniques for MV applications.
OCB, mainly in Europe, i.e. bulk oil CB and minimum oil CB, were the single technology in the catalogue of the majority of world-wide CB manufacturers.
But the qualities of AMC were very appreciated by the users in the field of the industrial distribution for 6.6 and 11 kV in Asia, Europe and 5 or 15 kV in America.

With AMB, from low voltage applications to MV ones, the users did not worry about voltage surges and, mostly were unawared of the existence of such phenomena.

Thanks to the magnetic blowing, the cooling of the arc depends on the value of the breaking current, leading to a very smooth breaking.

Since 1970 or 1975 (depending on the different countries) SF6 and vacuum breaking techniques appeared on the MV market, for the primary substations firstly.

The success of these new breaking techniques is well known. The advantages are:

- a longer life time, in comparison with OCB,
- a better behaviour for rapid reclosing, capacitor switching etc... in comparison with OCB and AMB,
- a smaller volume in comparison with AMB.

To take the place of AMB for industrial application, and particulary for starting motor switching, SF6 CB is the good response, giving:

- the advantage of a smooth breaking,
- and, in comparison with AMB, the compactness.

For these reasons, Merlin Gerin has led AMB technology, after 35 years of manufacturing AMB type Solenarc, in favour of SF6 technology, which is developped and manufactured since 1970 in the MV field.

2. auto compression technique

Merlin Gerin range of SF6 MV circuit-breakers is called Fluarc. All the Fluarc are self extinguishing CB. That means that the same mass of SF6 gaz is working during the whole life - more than 20 or 30 years - of the CB, in a sealed for life enclosure.

During the arcing period the arc is cooled by convection in that a certain quantity of hot gas is replaced by cold gas. This is not a surface phenomenon; the cold gas is brought in perpendicularly to the direction of flow to promote the mixing of hot gas and cold gas. Heat exchange by radial conduction is very low compared with this. We could also expect heat exchange by radiation, on account of the high temperature of the arc. In fact, the exchanges are small because radiation is from the peripheral layers only. Finally the heat exchanges during arcing take place chiefly by convection. The energy supplied by the system in time dt to a mass dm of gas is:
dw = VI dt = h dm,
V being the arcing voltage and
h the enthalpy per unit of mass.

We again have VI dt = hρ sdx,
ρ being the density, s the cross section of the arc and
dx the path taken by the mass dm in the time dt.
Hence VI = hρ su, u being the velocity of the gases.

The power transmitted is directly dependent on this velocity. The laws of gas flow teach us that this velocity cannot be indefinitely increased to increase the mass flow of the hot gas. It is advantageous to stay in the vicinity of the speed of sound in the gas. This speed can only be obtained by suitable structural arrangements and sufficient switching energy. The hollow tubular contacts facilitate the rapid flow of hot gases and causes instability of the arc root, preventing wear on the arcing contacts. The puffer technique is remarkably effective, as it is sufficient to inject only a small quantity of gas between the contacts.

With the Fluarc FB and FG, the quantity of compressed gas injected at the throat of the nozzle is 5 grammes during breaking; to limit the temperature of the arc to 10 or 15,000 °K, it must be possible to evacuate the heat produced by the arc which is approximately 30,000 joules when interrupting a current of 25 kA.
The gas enthalpy curve shows that one gramme of gas is sufficient to carry this energy (fig. 1).

During arcing, the space occupied by the arc at the throat of the nozzle depends on the instantaneous current value. The cross section of the arc is proportional to this and consequently is subject to the same sinusoidal variation. At high current values, the arc may occupy the whole of the available space, blocking the flow of gas.
Indeed, the mass flow in the arc is very low compared with the flow of cold gas around the arc, as the gas density is low at the temperature of the arc. This is what is known as the "clogging" effect (fig. 2).

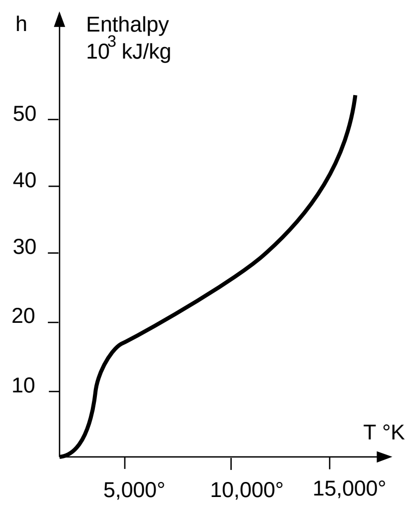


fig. 1: enthalpy of SF6 as a function of temperature.

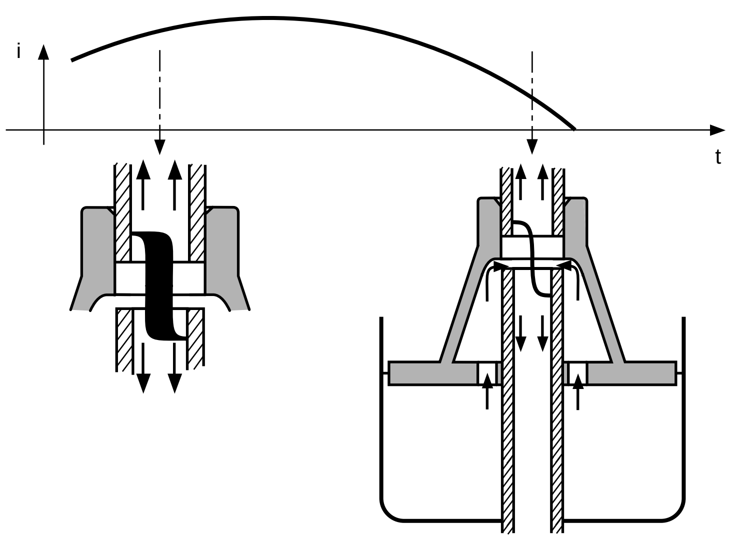


fig. 2: clogging effect.

The total mass flow at the nozzle throat is thus low when instantaneous current values are high, but it rises very quickly as soon as the current falls, and shortly before current zero it is greater than that which would occur on opening without current (fig. 3, fig. 4).

The clogging effect is beneficial for two reasons:

■ when the circuit-breaker opens on a high current it keeps a larger amount of gas in reserve than when it interrupts lower currents.
It does not act "blindly" whatever the current;
it is better prepared for the passage through current zero in heavy currents, and it avoids brusquely interrupting low currents, as the mass flow on non load is modest.

■ interruption of a heavy current causes braking in the opening movement.
This braking limits the distance between contacts, that is, the length of the arc and thus the energy dissipated in the arc.
It is therefore important to stress that the arc is relatively short, in the order of 15 mm for a 12 kV, 24 kV, or 36 kV equipment, that is, smaller than the contact diameter.

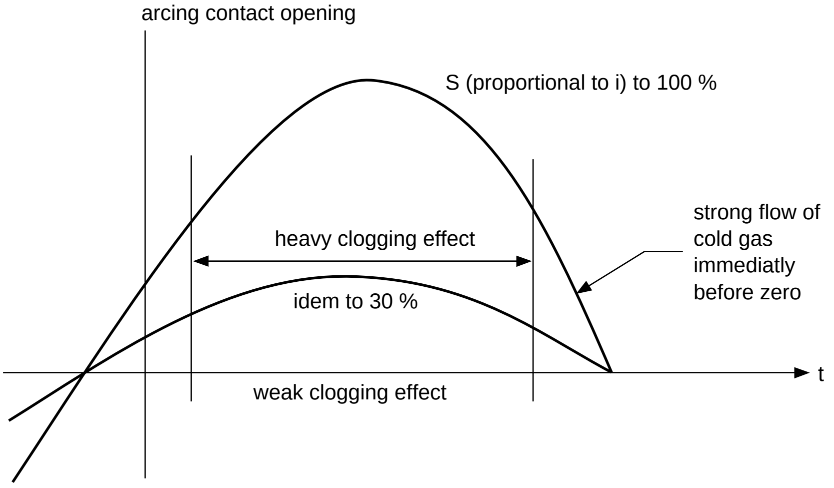


fig. 3: variation of the arc cross sections at 30 % and 100 % of the breaking capacity.

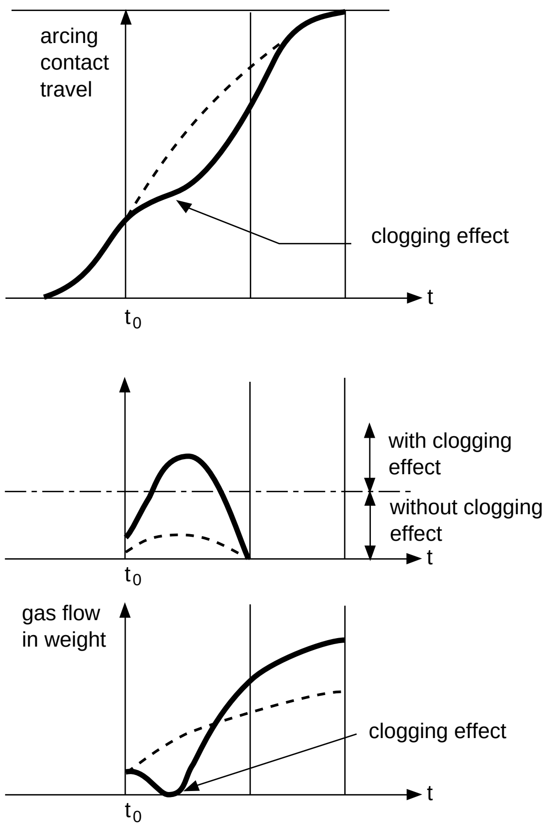


fig. 4: contact travel.

3. rotating arc technique

The motion of the arc is caused by a magnetic field produced by the load current itself, and applied on to the arc.

The process is clearly illustrated in figure 5.
As the main contacts separate, the current to be broken is diverted through a solenoid down to the arcing rings, an arc appears between the two rings, perpendicular to its own magnetic field B produced through the solenoid.
The current I is flowing into a conductive plasma. Simultaneously, the magnetic field B perpendicular to I.

The effect of this combination is a force F exerted upon the arc, which is consequently accelerated into a circular motion along the arcing ring.
The solenoid is designed in such a way that the resulting arc speed is high during the arcing period. This have several advantages:
■ the cooling of the arc is effective in the surrounding SF6.
■ hot spots creating metallic vapors and excessive wearing are avoided through the motion of the arc roots.
This rotation of the arc will proceed no more than half a period, until a current zero.
The speed of rotation of the arc has been measured. It varies with the intensity of the current to be interrupted and can reach the speed of sound in the gas for the highest currents (fig. 6).
When short-circuit currents are interrupted, the speed slightly before the current zero is high enough to keep the arc in rotation. The field is out of phase with the current and the product of the two is still significant.
On the other hand, the speed is very low just before the current zero when small current are interrupted. This is the reason for the smooth breaking made possible by this technique and the absence of switching surges.

	during arcing period	**just before current zero**
high currents	very high (speed of sound)	high
low currents	high	low

fig. 6 speed of arc rotation in the magnetic field.

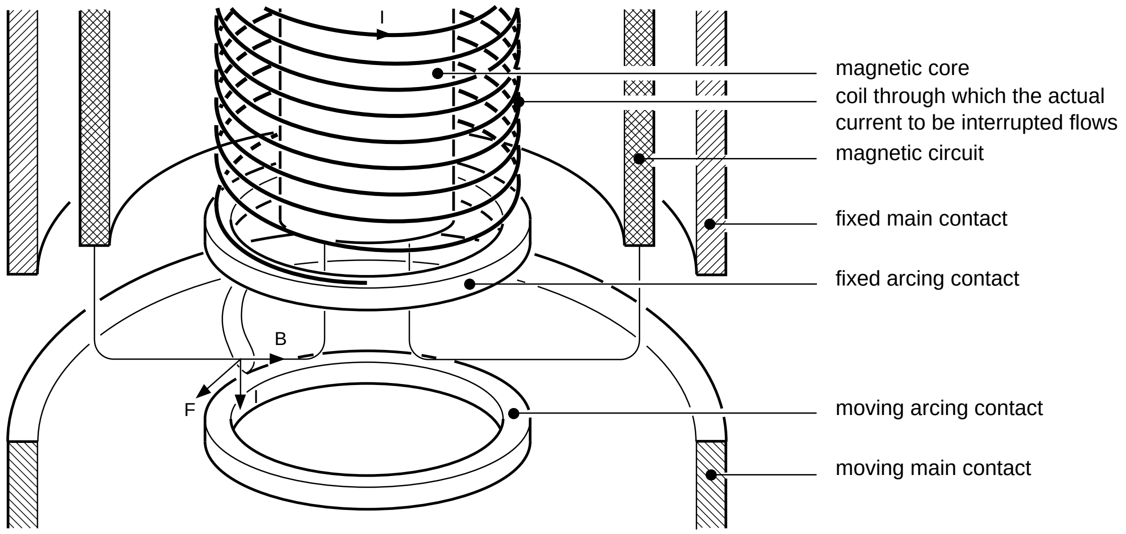


fig. 5: example: rotating arc contactor (Rollarc).

4. switching of small inductive currents

Switching of motor starting currents is the most frequent and the most severe case:

- the switching of small inductive currents, as unloaded transformers switching, is easier, thanks to the dumping factor of the transformers,
- the motor insulation is lower than the insulation of the rest of the circuit. Due to the large number of medium voltage motors used in industry and their relative importance, it is necessary to ensure their continuous reliable operation.

The price of these motors is much higher than the price of the switchgear, leading the users to be prudent and sometimes anxious.
During their lifetime, these machines are subject to many forms of voltage surges with varying magnitudes and wavefronts. Surges which originate on the machine voltage system are likely to be most severe due to their short propagating distances and no intervening transformers. The most common sources of these surges are restriking during interruption and prestriking during energisation and current chopping.

Switching overvoltages have recently undergone much investigation due to the discovery of motor failures and the introduction of new switching technologies. To determine the effects of switching overvoltages on motor insulation, it is necessary to investigate the characteristics of the overvoltage waveforms generated by switching operations and the effect of the waveforms on the various forms of insulation.
Previous studies of motor overvoltages have proved that for all types of switching devices the overvoltages injected at the terminals of a motor running at speed, whether it be under load or unloaded, are in almost all cases, not of sufficient magnitude to damage motor insulation.

This is because the low surge impedance and the back EMF present in the winding of a rotating machine are sufficient to reduce the net switching overvoltage seen by the motor insulation to an insignificant level. For motors under starting conditions however, the rotor is stationery and therefore no back EMF has been generated.

5. motor insulation

Most stator windings of AC machines are composed of form wound coils which are joined together to form a phase winding. The coils consist of several turns in series, each of which must be insulated from each other and the earthed steel laminations. Thus the insulation can be divided into "winding to earth" and interturn insulation types.
To achieve magnetic and thermal performance, the coils are placed close together near the air gap in slots in the grounded stator core laminations, with several turns in the same slot. This results in thin, dry-type insulation between turns and thicker insulation to earth to withstand the machine voltage. The construction results in large capacitances between turns and between coils and the slot. This in turn results in a slow surge velocity in motor windings.
The machine winding to earth insulation or main insulation, is normally subjected to high dielectric stress which only increases by a factor of three to ten times during surges. The interturn insulation however, is normally subjected to very low stress levels which may increase 100 to 1,000 times under surge conditions. This makes interturn insulation very difficult to test. It also leads to varying opinions on testing conditions. Consequently, there exists no standards for normalisation on the subject.

6. propagation of steep fronted waves in motor windings

As previously described, the motor winding consists of many turns connected in series. The exact distribution of voltage stress placed on interturn insulation by a steep fronted wave is very difficult to determine, due to the many parameters involved with the winding construction. Many models have been developed to approximate the phenomena, the most popular being a capacitor model, or a ladder network of coils and shunt capacitors.

Using the ladder network, the winding can be considered to have travelling wave properties with a given surge impedance and transit time. Thus a steep fronted wave will take a certain time to travel through each turn. This time (Tt) is usually much smaller than the wave-front time (Tf) as shown in figure 7.

If the wave amplitude is Vmax, then the voltage developed across the turn V2 = Vmax. (Tt/Tf). Thus, for a particular motor with a fixed wave propagation characteristic (Tt) the voltage appearing across the first turn is dependent on the magnitude and front time of the surge (i.e. rate of change of surge voltage).

Results of experimentations, have revealed that wave front times in excess of 3 µs result in a negligibly small voltage build up across the first turns however for waves with front times less than 10 µs voltage distribution across initial turns is significant, in particular for very fast front times of 0.2 to 0.5 µs a major percentage of the wave front magnitude can appear across the line end coil. This is illustrated in figure 8.

It must be remembered that the duration of such overvoltages is very short so the energy accumulated in this time is very small. As a result the damage to insulation is very limited and usually undetectable.

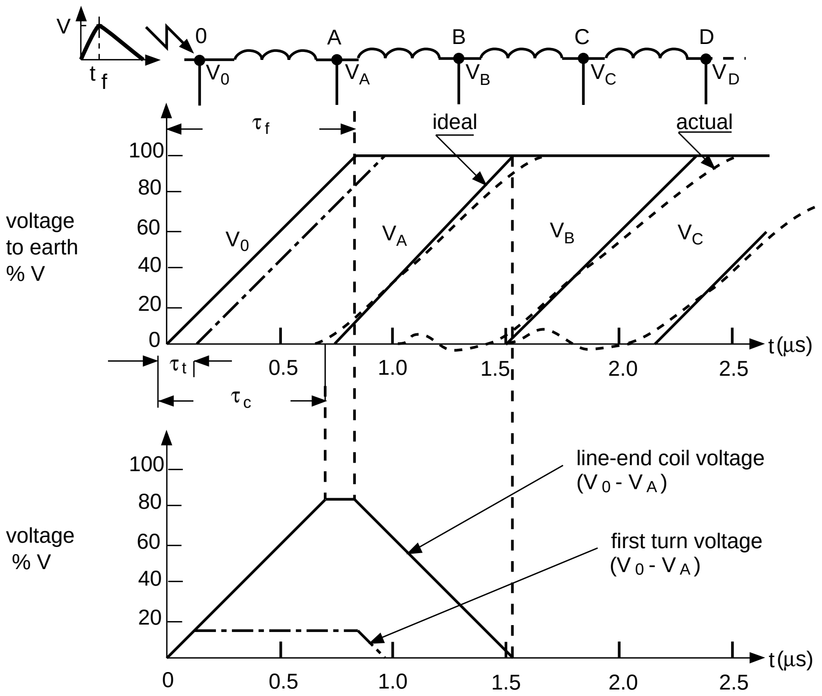


fig. 7: interturn and intercoil voltages developed in a winding subject to steep fronted voltage transients (time in microseconds).

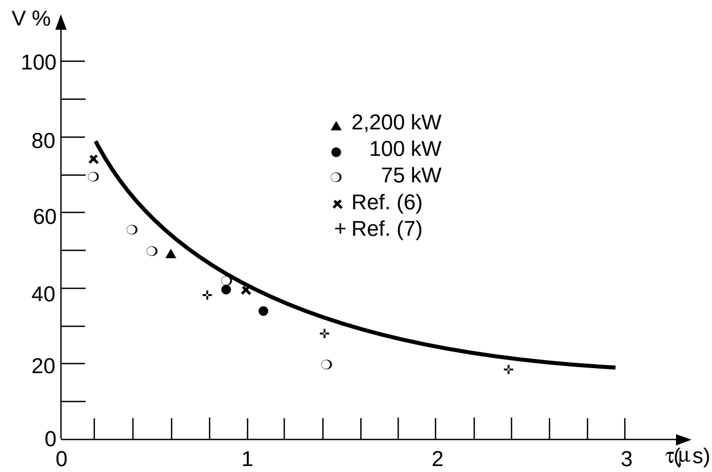


fig. 8: % of wave front magnitude as a function of wave front time.

Damage to insulation from steep fronted waves occurs in the form of microscopic holes in the insulation medium termed "pinhole" failure. A single pinhole causes very little change in the insulation characteristic and normally remains undetected. If the steep-fronted surge occurs regulary then the pinholes will accumulate and cause hotspots leading to gradual degradation of the insulation characteristics limiting the motor life.

This degradation is usually a slow cumulating process which may remain undetected until the coilslot insulation fails. Recent discussion of high voltage motor failures has led to the production of curves of suggested motor withstand surge voltages. The graph of the figure 8 illustrates the motor impulse withstand curve published by an IEEE committee which takes aging into account. This curve illustrates the excellent capability of motor insulation to withstand surges of long wavefront duration. However they also indicate their susceptibility to failure for surges with front times between 0.2 and 1.0 microseconds.

From the above explanation, it can be seen that, for a given motor insulation, stressing is a function of the magnitude and rise time of the voltage surge. In practise, the wave enters the motor at the terminals, undergoes reflection depending on cable and motor surge impedances and proceeds to propagate through the windings. The first coil encountered is the line-end coil and it is in the first few turns or the inner end of this coil where the highest interturn stressing occurs. The magnitude of the voltage appearing across this turn is a function of wavefront steepness reaching the coil, velocity of propagation within the winding and the motor core length, the most onerous conditions being small front duration, slow wave velocity and a long core.

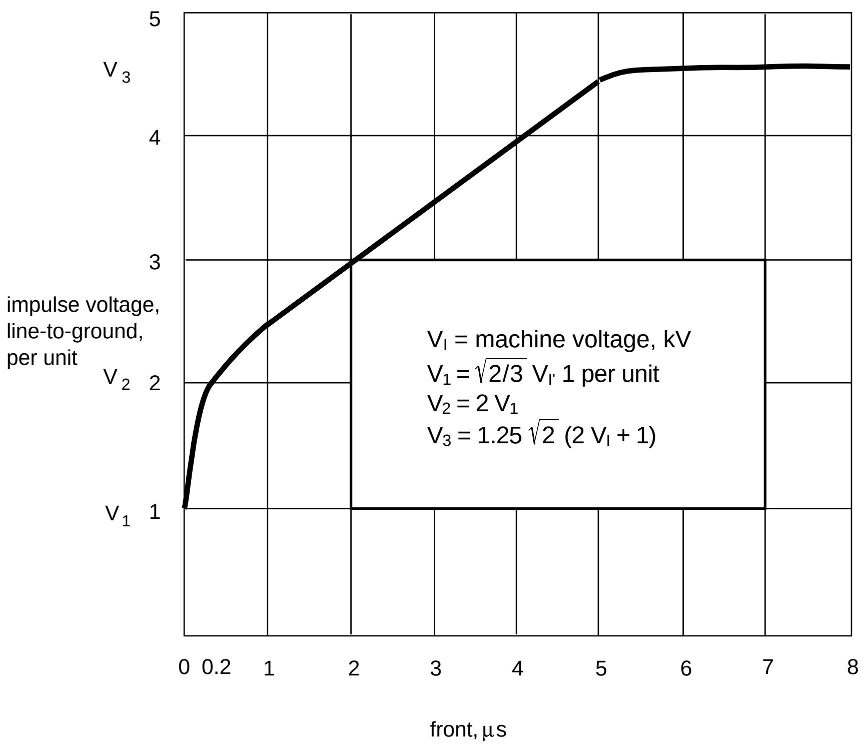


fig. 9: machine impulse voltage withstand envelope.

7. motor insulation according to IEC and practice

The technical comittee of rotating machinery (working for IEC) and the different authors of the technical litterature agree on the rated insulation levels for rotative machines.

The future IEC is today the 2 (secretariat) 688 document, stipulating the following levels.

interturn insulation

The rated lighting impulse withstand voltage is:
$4\ U_N + 5\ U_N$ = rated voltage, for the type test.

In terms of p. u $(1\ \text{p. u} = U_N \sqrt{2} / \sqrt{3})$ this level is:
4.9 p. u + 5 kV (peak) = 31 kV

for $U_N = 6.6$ kV.

This voltage is to apply between the terminals. A model of the line end coil is tested at 50 % of this value, which is a compromise due to the non linear distribution of the voltage along the winding. The front time should not be shorted than 0.5 microsecond.

ground insulation

Power frequency voltage test
The r.m.s. voltage $(2\ U_N + 1)$ kV shall be applied for 1 min between coil terminals and earth, shall then be increased at the rate of 1 kV/s up to $2\ (2\ U_N + 1)$ kV and shall then immedialety be reduced at a rate of at least 1 kV/s to zero, without failure.

The rated impulse level $4\ U_N + 5$ is lower than the peak value:

$2\sqrt{2}\ (2\ U_N + 1)$ kV

derived from this test because the impulse level of a machine is determined by the interturn voltage due to longitudinal voltage distribution.

The purpose of the higher a.c. test level is to produce a voltage gradient at the slot end more nearly equivalent to that obtained by the impulse test. In terms of p. u, this peak value is:

$2\sqrt{2}\ (2\ U_N + 1) = 6.9\ \text{p. u} + 2.8.$

Impulse test
The test voltage is the same than for the interturn insulation
4.9 p. u + 5 kV (peak)
with a front time of 1.2 miscrosecond.

summary

rated insulation levels for rotative machines

insulation	50 (60) Hz test rms value	impulse
interturn insulation		4.9 p. u + 5 = 31 kV at 6.6 kV (50 % on the model) front time: 0.5 µs
ground insulation	$2\ U_N + 1 \rightarrow 2\ (2\ U_N + 1) \rightarrow 0$ 14 kV → 28 kV → 0	4.9 p. u + 5 = 31 kV at 6.6 kV front time: 1.2 µs

8. overvoltages and steep fronted voltage waves

The overvoltage problem accompanying small inductive currents breaking is one which has received a large amount of publicity and undergone much research. To understand the problem it is necessary to examine the phenomena which give rise to different overvoltages. The three main phenomena associated with small inductive current switching overvoltages are prestrikes, restrikes and current chopping.

Thus all three phenomena have a statistical basis.
Successive prestrikes and restrikes, during closing and opening operations, are due to multiple reignitions of the CB.

The prestriking phenomenon occurs during every closing operation but its severety depends upon the point on wave on which the process is initiated (among other things).

Restriking and current chopping which can occur when opening also depend on the point of wave of switching for their initiation.

the steep fronted voltage waves

They are created by the reignitions:
■ when opening (successive restrikes) and
■ when closing (successive pretrikes) with certain types of CB or contactors.

A reignition can occur when the contacts separate juste before the current zero: the CB interrupts a first time the current at the 50 Hz zero, the voltage raises between the contacts which are too close, leading to a reignition. The inrush current is a high frequency current which the CB is capable to interrupt a second time, if its recovery strength velocity is very high. Then, the same phenomenon starts again: the voltage raises and a lot of reignitions can happen, more than 50 or 100 in the worst case.
These reignitions create travelling waves, moving dowstream. The amplitude of these waves depend on the voltage difference across the CB contacts, just before the break down. When the motor is connected by a cable, the amplitude of the incoming wave can almost double at its terminals. To summarize this phenomenon, the CB can cause repetitive HF transients if the CB is capable to interrupt the HF transients currents, corresponding to the multiple reignitions. The vacuum CB are capable to interrupt HF currents, due to the very high recovery strenght velocity: only one microsecond after the current zero, the gap between contacts can reach 75 % of the full dielectric insulation. This behaviour depends on the type of contact alloy, but it remains still different of the SF6 CB behaviour, which need roughly ten microsecond to reach 75 % of the full dielectric insulation.

Reignitions according to IEC
In I.E.C. document, multiple reignitions created by the switchgear is qualified of "abnormal events", in such case, the windings (of the motor) should:
■ either be designed to withstand other impulse levels
■ or be protected in an appropriate way.

That means that the users have two solutions to avoid failures of MV motors:
■ either using motors with a very good interturn insulation in compliance with the characteristics (front, amplitude) of the travelling waves,
■ or using voltage surge absorbers (for voltage amplitude limiting) and R-C devices (for transient currents shunting).
The IEC document illustrates these phenomena with figure 10.

Reignitions are defined not only by U_{lf} but also by the peak-to-peak value U_s. The number of reignitions is a basic data, because the repetition of excessive interturn voltages can lead to the definitive damage of the interturn insulation.

With the SF6 breaking technique, a single reignition is possible and frequent when contact separate just before the current zero (50 Hz), exceptionnaly a few ones and never a high number.

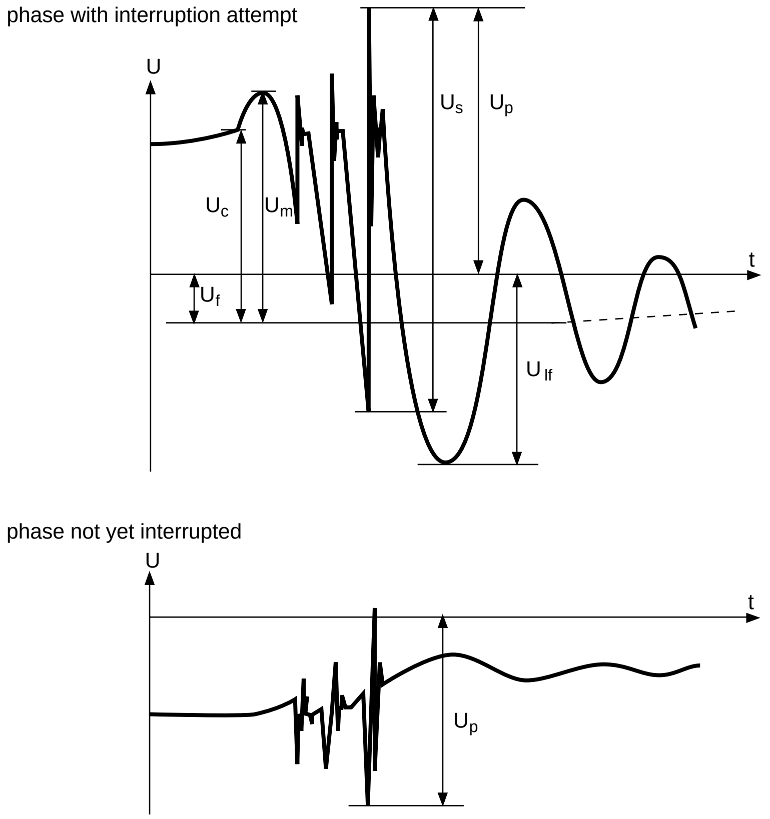
Restrike transients
Following interruption of current, whether it be at a normal current zero or whether it be chopped, the voltage across the load oscillates between the load side inductance and capacitance causing an overvoltage as previously described. If the voltage rise momentarily exceeds the dielectric voltage withstand capability of the separating contacts, a reignition occurs across the contacts. This reignition results in the flow of an oscillating current through the circuit-breaker. This phenomena is described in the following paragraphs with reference to the circuit of figure 11.

This circuit is identical to the single phase circuit in which however an internal loop around the circuit-breaker consisting of C_{p1} and L_{p1}, has been included. This internal circuit includes the inherent parallel capacitance of the circuit-breaker and connecting leads plus the capacitance to earth. It also includes the equivalent inductance in the circuit of "first parallel oscillation". On interruption, the source and load side parallel LC circuits oscillate practically independently at frequencies fs and f_L as given previously. The very small parasitic values of C_{p1} and L_{p1} result in a first parallel oscillation of very high frequency, 1 to 10 MHz, during which C_{p1} is discharged through the circuit-breaker.

$$f_{p1} = \frac{1}{2\pi\sqrt{L_{p1} C_{p1}}}$$

The next phenomena, termed the second parallel oscillation involves the next circuit loop as illustrated in figure n° 10.

During this period of time, energy transfer occurs between the source and load capacitances through stray inductance L_0. Thus the oscillation occurs with a frequency:



U_l : instantaneous value of the remaining power frequency voltage
U_c : initial voltage
U_m: suppression peak voltage
U_{lf} : low frequency overvoltage (to earth)
U_p : maximum overvoltage (to earth)
U_s : maximum peak-to-peak voltage excursion at reignition

fig. 10: illustration of load side voltages.

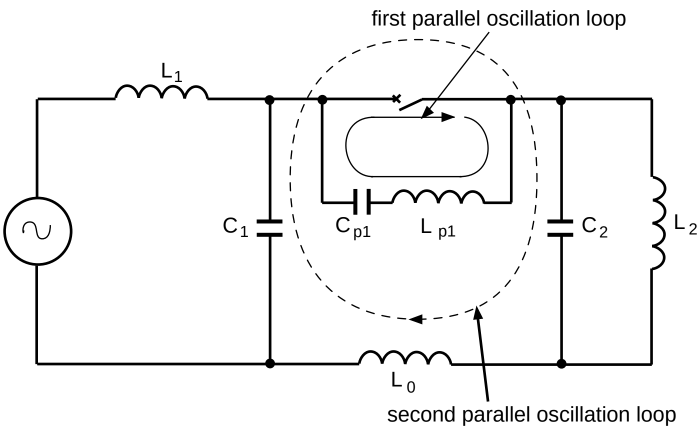


fig. 11: equivalent circuit
where C_{p1} = C.B. stray capacitance
L_{p1} = C.B. stray inductance.

$$fp2 = \frac{1}{2\pi} \frac{C_1 + C_2}{L_0 C_1 C_2} \quad (100 - 500 \text{ kHz})$$

Due to the large inductive values of the source and load inductances the remainder of the circuit does not become involved in second parallel oscillations. The third phenomenon is termed main circuit oscillation and involves the total circuit with a frequency of:

$$fm = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 (C_1 + C_2)}} \quad (5 - 20 \text{ kHz})$$

which for highly inductive load may be simplified to

$$fm = \frac{1}{2\pi \sqrt{L_1 (C_1 + C_2)}} \text{ as } L_1 < L_2$$

These phenomena occur simultaneously after reignition and the resultant overvoltage is therefore a super-imposition of the three waveforms however actual development of the waveforms depends on circuit-breaker characteristics, damping and circuit values.

Single reignition

Immediately following reignition across the circuit-breaker the first parallel oscillation occurs at a rapid frequency discharging Cp1. The second parallel oscillation then predominates causing an oscillating current which may or may not cause a current zero and if so may or may not be interrupted by the circuit-breaker. If not then the oscillation continues until it is sufficiently damped at which time the main circuit oscillation predominates.

Multiple reignitions

"Multiple reignitions" is a phenomena which may occur during the opening sequence of a circuit-breaker. For highly inductive circuits the current leads the voltage by almost 90°. Thus after current interruption near the current zero the voltage is almost at a peak value. On the load side the voltage begins to oscillate at frequency f_L while on the source side the osillation occurs at fs. If the momentary difference in the oscillating voltages exceeds the rate of rise of dielectric strength a reignition of the arc takes place at time t1. The load side now experiences first and then second parallel oscillations.

These second parallel oscillations cause a high frequency current to flow through the circuit-breaker. This current, when superimposed on the power frequency current, may produce several high frequency current zeros. The circuit-breaker will attempt to interrupt at these current zeros. Whether or not the circuit-breaker can interrupt the current successfully is determined by the $\frac{di}{dt}$ of the current as it crosses the zero point and the ability of the breaker to interrupt this $\frac{di}{dt}$

This is determined by the dielectric recovery rate of the circuit-breaker. For breakers with high dielectric recovery rates interruption may occur at the first high frequency current zero where as circuit-breakers with slower dielectric recovery rates may take several oscillations or may not be able to interrupt the high frequency current at all.

The high frequency current is initiated by second parallel oscillations and therefore it flows in the internal circuit illustrated previously in figure 10. Its frequency is governed by the components in this loop. Thus the current flowing through the load inductance L_2 is unaffected by the second parallel oscillation loop apart from small perturbations.

During the period of reignition the load terminal oscillates about a voltage level determined by its value at the time of the first interruption. The average voltage level during this period causes the load current to increase.

During the period of interruption the transient recovery voltage rises until it exceeds the dielectric strength of the electrode space causing a restrike. It must be remembered that during the opening sequence of the circuit breaker the contacts are separating and therefore the dielectric strength of the gap and consequently the breakdown voltage increases with each restrike.

During this time the load current will increase and then decrease depending on whether the instantaneous value of the load terminal voltage exceeds the voltage level-E/2 as shown in figure 12. The additional magnetic energy from the power frenquency source which accumulates in the load inductance and the increasing value of breakdown voltage permit the second reignition to occur at a higher mean voltage than the first reignition.

The sequence of successive regnitions and high frequency current interruptions which makes up the multiple restrike process can occur several times as the increasing amount of energy in the load inductance and the increasing contact spacing enable each successive reignition to occur at a higher mean voltage.

The reignition/interruption process can terminate in either of two ways:

■ the first way involves cessation of the reignition phenomena. As the contact spacing increase the minimum transient recovery voltage required for breakdown also increases. The magnitude of the TRV is dependent upon the value of chopped current which is given by the value of current flowing through the load. After a certain number of restrikes the load current and therefore the chopped current increases more slowly. When the rate of rise of TRV is overtaken by the rate of rise of dielectric strength, the interruption is definitive.

■ the second method involves cessation of the current interruption phenomena. If the high frequency current continues for several cycles without interruption by the circuit breaker it will be quickly damped to zero and the circuit breaker will have to wait for the next power frequency zero before it can interrupt the current. This occurs if the magnitude of the high frequency current component is not sufficient to cause the net current to reach the current zero or if the circuit breaker does not have a sufficient dielectric recovery rate to enable it to successfully interrupt the high frequency current as it crosses the current zero point.

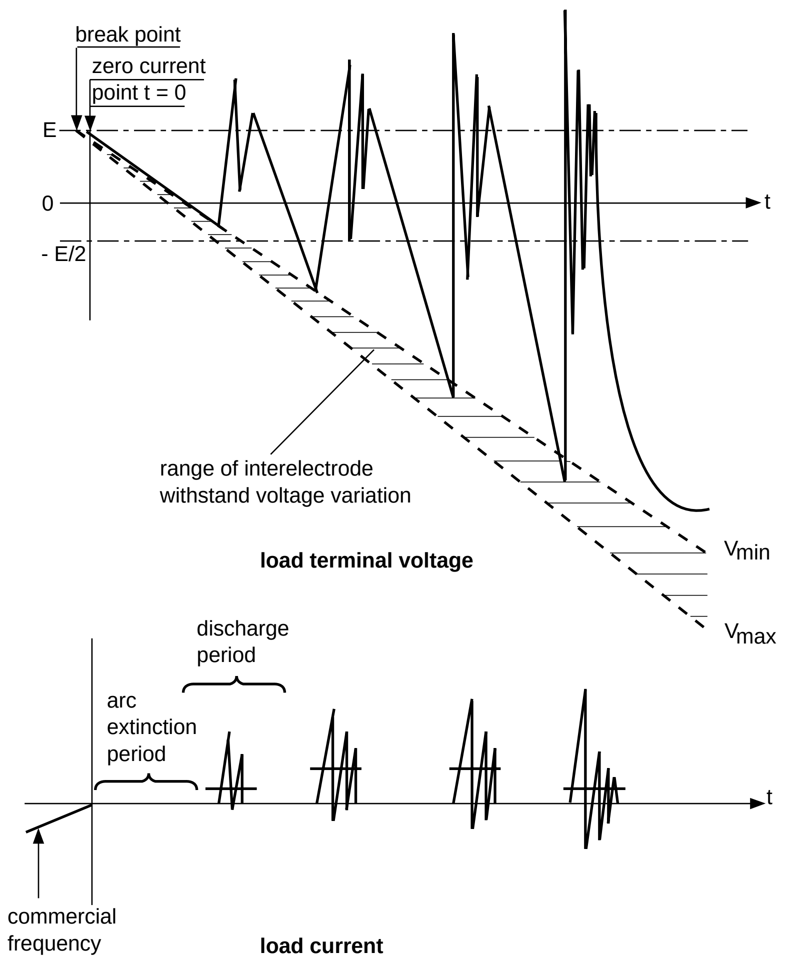


fig. 12: multiple reignitions.

The prospective restriking overvoltage is governed by the circuit and circuit-breaker characteristics. The slope of the reignition wave is a function of the frequency of the second parallel oscillation circuit while the prospective magnitude is determined by the available energy, that is the energy stored in the circuit inductance and capacitance at the time of interruption. In practise the magnitude is restricted by the dielectric strength of the contact gap which is increasing during opening. Thus the actual restriking voltage magnitude is a function of available energy and dielectric recovery so a general maximum value cannot be given. The phenomenon of multiple restrikes depends on the ability of the circuit-breaker to interrupt high frequency current. Vacuum circuit-breakers exhibit excellent dielectric recovery rates and are therefore able to interrupt high frequency currents. Therefore when vacuum circuit-breakers and contactors interrupt circuits where sufficient energy is available to initiate a restrike, an interruption/restrike process (multiple restriking) often results.

current chopping

It is defined as "an abrupt current interruption in the circuit-breaker away from the natural power-frequency current zero of the circuit connected to the circuit-breaker".

Although the current in a circuit-breaker can chop to zero almost instantaneously the current in the load inductance requires time to dissipate the stored magnetic energy and allow the magnetic field to collapse. When a current is chopped by the circuit-breaker the energy stored in the load inductance is transfered to the load side capacitance and produces an overvoltage.

The mathematic relation between the chopped current I_a and the over voltage value is well know. Thank's to the conservation of energy:

$$1/2\ C_2\ U^2\max = 1/2\ C_2\ U_c^2 + 1/2\ L_2\ I_a^2$$

$$U_{max} = \sqrt{U_c^2 + L_2 / C_2 \times I_a^2}$$

where

U_c = voltage across downstream capacitor

C_2 = value of downstream capacitor

L_2 = value of downstream inductance

If the load side neutral is not earthed, as is the case for most motors, a voltage displacement will occur in the neutral after interruption of the first phase (fig. 13) and the resulting overvoltage will be:

$$U_{max} = 0.5 + \sqrt{(1.5\ V)^2 + 1.5\ L_2 / C_2\ I_a^2}$$

The above equation neglects damping and in practice the oscillations will decay progressively depending on circuit damping which is governed primarily by the nature of the load.
If we take into account the actual circuits, it is necessary to introduce the damping factor K.
The lowest value of U_{max} is obtained without current chopping:

$$K = 1 + \frac{X}{1.5\ V}$$

$$\begin{aligned}(U_{max})\ \text{mini} &= 0.5\ V + X \\ &= 0.5\ V + (K - 1)\ 1.5\ V \\ &= 1.7\ V \text{ with } K = 1.8 \\ &= 1.4\ V \text{ with } K = 1.6\end{aligned}$$

With a non negligeable current chopping, U_{max} is, of course, higher.

The highest values can be obtained when interruption of the first phase causes interruption of the remaining phases almost simultaneously. This phenomenon is called virtual current chopping.
The process of virtual current chopping is entirely dependent on specific circuit conditions and interphase coupling. It can therefore occur with any circuit-breaker type. Similar to other phenomena involving high frequency current interruptions, virtual current chopping is much more likeky to occur in vacuum circuit-breakers than circuit-breakers which use other interruption techniques. Due to the high values of chopped current which may occur, the energy stored in the load circuit at the time of interruption can be very high leading to excessive overvoltages.

prestrikes

During the closing operation of all switches a position is reached where the dielectric strength between the closing contacts falls below the voltage across the contacts.

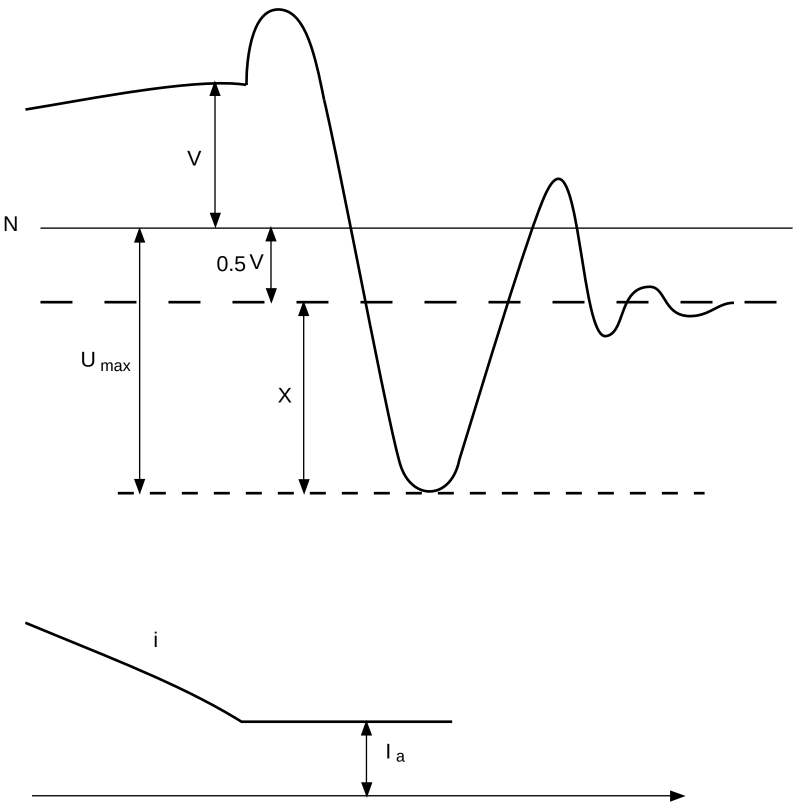


fig. 13: interruption of the first phase with current chopping I_a.

At this point a flashover, termed a prestrike, will occur. The source and load side voltages will reach some intermediate voltage very rapidly and the voltage across the terminals of the switch falls to a very low value. This rapid change of voltage results in the injection of a steep fronted voltage wave into both load and source sides. The magnitude of this wave can be as high as the crest value of the system line to neutral voltage.

The high frequency current now flows as an arc across the closing contact gap. Both current and voltage waves flow down the cable to the load where reflection takes place. The reflected wave returns to the breaker terminals where its effect depends on relative surge impedance magnitudes. The prestriking arc may then be interrupted at or near to a current zero. Interruption depends on the rate of change of current as it passes through the current zero.

If interruption does occur the dielectric strength will recover until once again the voltage across the contacts overcomes the dielectric strength of the decreasing gap. The process may repeat several times until the contacts touch.

In practise most motor surge impedance are within the range of 200 - 8,000 Ω while most cable surge impedances fall within the range 20 - 50 Ω. Thus the voltage appearing at the motor terminals experiences a "doubling effect" due to reflection (usually in the order of 1.8 times the injected voltage). After reaching a crest value Vn, the voltage wave will decay slowly due to travelling waves in the cable. A discontinuity then occurs on arc interruption and the wave decays as a function of circuit RC values. The voltage across the contact gap will then increase again and the process may repeat itself.

The process consists of prestrike followed by high frequency current flow and current interruption and is therefore similar in nature to the restrike phenomena already described. However the prestriking process occurs during circuit-breaker closure and the dielectric profile of the closing contacts is decreasing. Thus the magnitude of prestriking transient wavefronts is limited to a progressively decreasing envelope.

In practise the ability of vacuum circuit-breakers to interrupt high frequency currents makes them much more susceptable to mlutiple prestriking than other types of circuit-breakers.

On prestriking of the first pole a steep fronted wave of 1.8 p. u can be injected at the motor terminals as explained above. This voltage propagates through the windings and will be seen at the terminal of the second winding as a "slow" oscillation of magnitude 1.8 p. u.

At this point in time (with source voltage of phase "A" at maximum) the source voltage of phases "B" and "C" will be 0.5 p. u. Thus in the worst case, when reignition of the second pole occurs at a time when the motor terminal voltage of the second pole phase is 1.8 p. u, a circuit breaker terminal voltage of 2.3 p. u is injected into load and source sides as a steep fronted wave in a similar fashion to the first pole. This wave also undergoes reflection at the motor terminals resulting in a steep fronted wave of up to 4.14 p. u (2.3 x 1.8) at the motor terminals.

In practise, the prestrike phenomena is very complex and difficult to predict. The resulting overvoltages depend on many factors including circuit-breaker characteristics, dielectric properties, high frequency current interruption capability and pole scatter, circuit characteristics (surge impedances and natural frequencies) and point of wave of closing. The inability of the SF6 circuit-breaker to interrupt high frequency current usually results in a single prestriking transient.

9. results with Fluarc CB

A lot of test campaigns has been performed in different laboratories for some years, directly with MV motor or with motor circuit subtitutes.
Recently, according to IEC draft which is about to be adopted the following tests have been performed in Volta laboratory (test report AC 1239 and 1240).

test circuit (fig. 14)

Drawing of the test circuit:
100 A 7.3 kV and 280 A 7.3 kV

Cable characteristics:
the two extremities of the screen of the radial field cable are earthed.

lenght:	100 m
voltage:	12/20 kV
current:	295 A
type:	Pirelli X 23
insulation:	polyethylene
capacitance by metre:	0.22 nF/m
characteristic impedance:	40 Ω

Circuit motor parameters

current:	280 A
power factor:	< 0.2
oscillation frequency:	27 kHz
current:	100 A
power factor:	< 0.2
oscillation frequency:	11.7 kHz

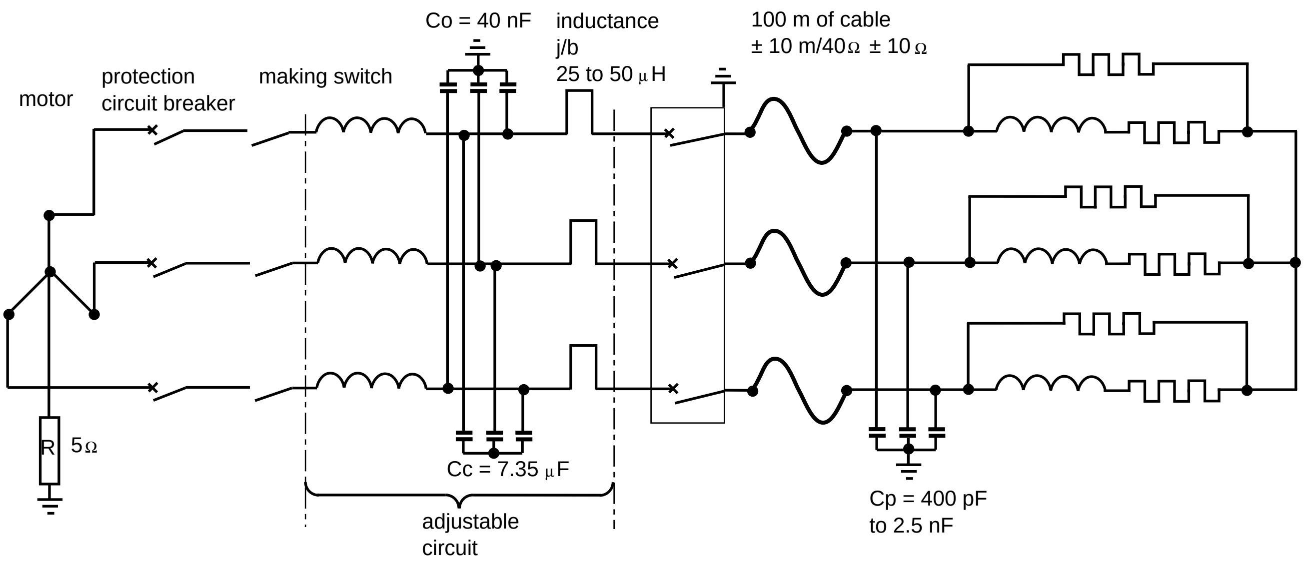


fig. 14

test results

Fluarc CB were FG2/40 kA and FG1/25 kA.

Test voltage: 7.3 kV

These results are based on 20 tests at each value of current and capacitance. This summary takes into account the statistical aspect.

Example with FG2 CB: see figure 15.
Example with FG1 CB: see figure 16.

experience

The first Fluarc CB were energized in 1971. Since that time, more than 50,000 units have been installed for different applications and especially for the industrial distribution worldwide:

- power plant auxilliaries,
- heavy industries (process),
- off shore platforms, etc...

Where motor switching has to be perfect to secure expensive installations.

CB type	**I**	**Cc** µF	**K** (damping)	**overvoltage** (pu) average	average + standard deviation	**multiple reignitions**
FG2	100 A		1.77	2.96	3.43	no
	100 A	7.35	1.77	2.94	3.41	no
	280 A		1.54	1.91	2.09	no
	280 A	7.35	1.54	1.87	2.14	no
FG1	100 A		1.77	1.63	1.81	no
	100 A	7.35	1.77	1.79	2.14	no
	280 A		1.54	1.69	1.78	no
	280 A	7.35	1.54	1.43	1.64	no

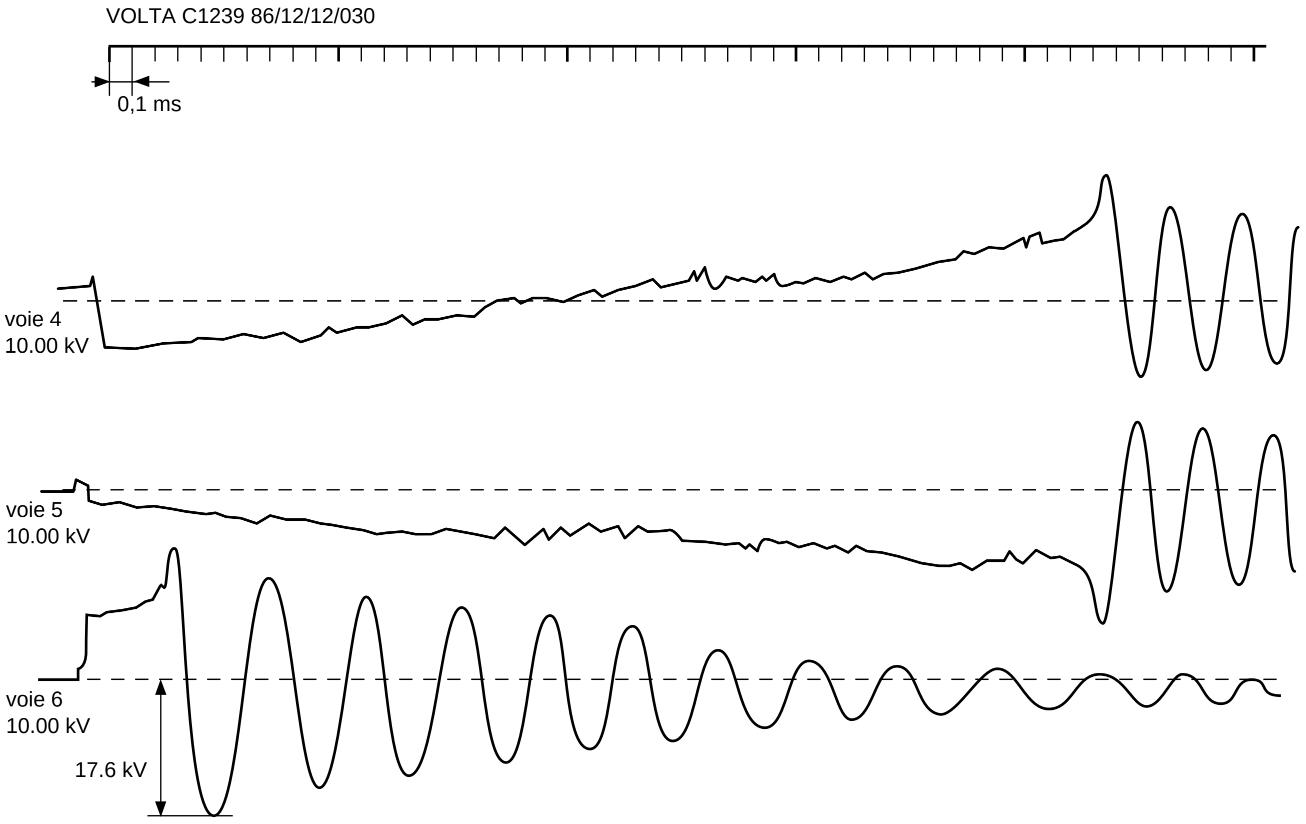


fig. 15: 3 phase interruption of 100 A with FG2 CB at 7.3 kV with IEC motor subtitute circuit.

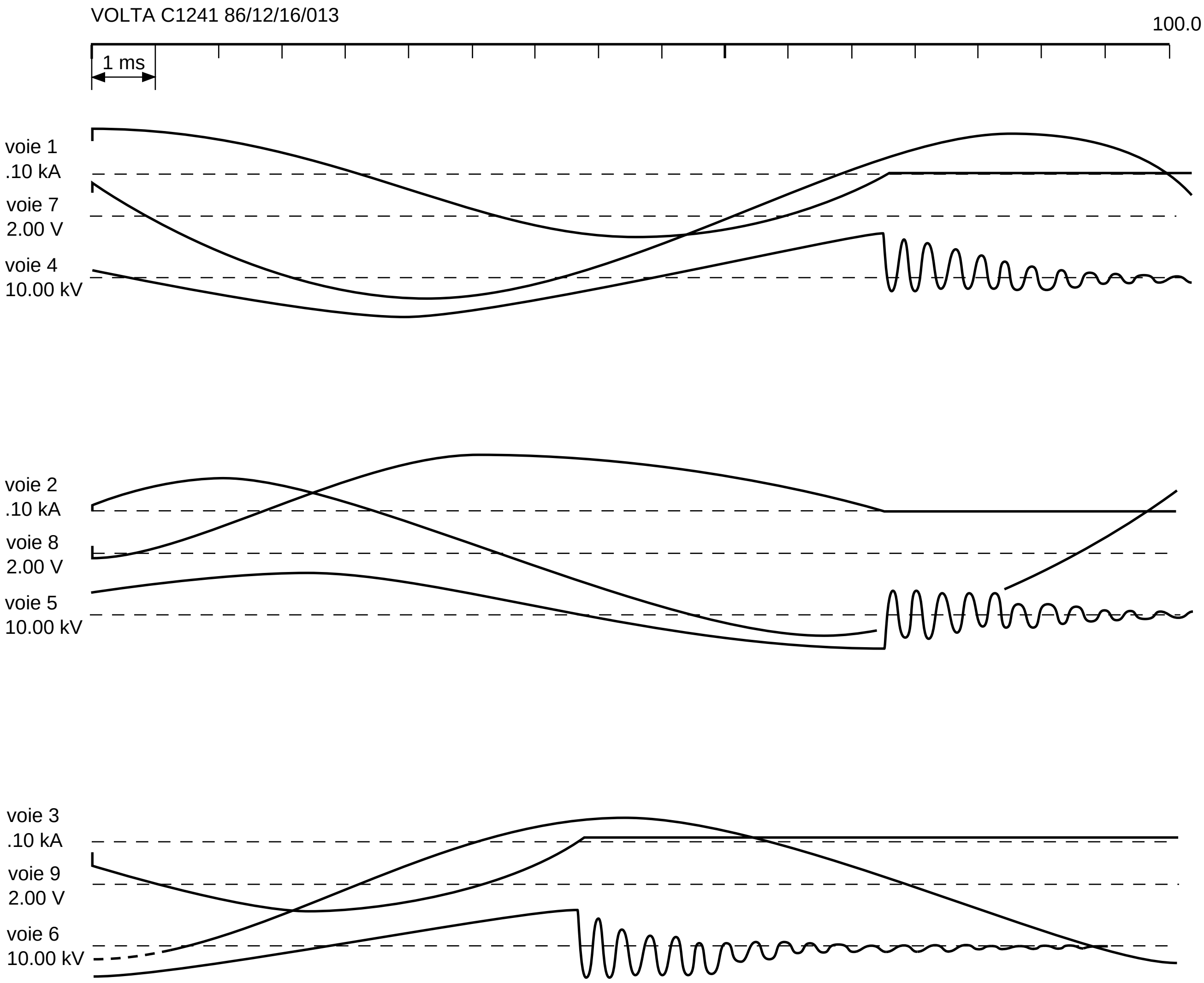


fig. 16: 3 phase interruption - 100 A with FG1 7.3 kV without current chopping.

10. conclusions

Fluarc CB and Rollarc contactor are suitable for MV motor switching. When comparing the motor insulation and the performances of these apparatus, a great margin of security does exist.

More precisely, the main conclusions are:

- at 6.6 kV, the most popular motor voltage, the BIL of the circuit is 60 kV (peak value), the motor insulation between line and earth is 31 kV (peak value).

The overvoltage due to the current chopping is compatible with this motor insulation for many types of CB. In this field Fluarc FG2 is a good response in a large range of rated currents, voltages and breaking capacities.

Sometimes, taking into account the low insulation of old motors and/or the aging of these motors, we recommand the best solution for the smallest sizes of motor (below 250 kW): the rotating arc technique (Fluarc FG1 or contactor-fuses Rollarc).

- on the other hand, the interturn insulation of the motor has to be saved thank's to restrike free CB. All the types of Fluarc CB and Rollarc contactor do not create multiple reignitions.
- protection devices as Zno surge arresters (for overvoltage limiting) and capacitor resistance (for HF current-shunting) are not necessary with Fluarc CB and Rollarc contactor.
- a great experience, based on the servicing time and on the quantity, can confirm these conclusions.

Réal. : Illustration Technique Lyon
IPV 07-92 - 2500 - Imp. : Léostic