SWITCHING VOLTAGES IN M.V. NETWORKS

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SWITCHING VOLTAGES IN M.V. NETWORKS:

their natures, characteristics and methods to prevent their occurrence or to limit their values.

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SUMMARY

In M.V. cable networks as applied in the Netherlands, the insulation co-ordination is in principle defined by the potential occurrence of switching overvoltages. These overvoltages have different origins. Harm can be caused to the installation by either the amplitude or rising time or both. In this article, the basic phenomena are reviewed, such as normal current chopping, virtual current chopping, multiple restrikes and pre-ignitions.
The probability of their occurrence in practice is discussed and possible precautions are mentioned. The paper includes a description of a special method to prevent the most severe overvoltages, i.e. those caused by virtual current chopping. The method involves a patented design of breaker mechanism in which one pole opens some milliseconds before the other two. The theoretical background for reduced overvoltages due to this advanced opening pole is described in detail. A method of surge limitation, namely zinc-oxide arresters is dealt with too. Results of tests with several configurations are covered.

A summary of the situations where arrestors are needed whether or not using the advanced opening pole is presented in tabular form.

DIFFERENT KINDS OF SWITCHING OVERVOLTAGES

Pre-ignitions

When switches are closing, pre-ignition is unavoidable, no matter what type of switch is used. A part of the resulting voltage jump V goes as a surge wave in the direction of the load. A plausible assumption is that 80% of V goes in the direction of the load, depending on the source and load impedance.
On arrival, when relatively high impedance prevails, such as an inductive load, a voltage increasing effect will occur because the wave is reflected.
Practical values for this increasing effect are 1.5 to 1.8.

The voltage jump of the first igniting pole is at the most 1 p.u. ($\sqrt{2}\,.U/\sqrt{3}$). As a result of an oscillation after ignition of the first pole and the voltage on the source-side of -0.5 p.u. a voltage jump of 2.5 p.u. is possible on the two other poles, when ignited.

The maximum overvoltage that can be reached on the terminals of an inductive load therefore amounts to 0.8 x 1.8 x 2.5 = 3.6 p.u.

The rising time of the surge wave at the front, which can be 0.2 to 1 μs, is the determining factor for the severity for the (inductive) load on the first windings. When, for instance, the rising time is 1 μs, 60 to 80% of the resulting voltage appears over the first winding.
The above mentioned phenomenon occurs when the time taken for a wave (travelling at approximately half the speed of light) to pass along the cable is longer than the time needed by the wave to rise i.e. for cable lengths of 20 m or more.

Normal current chopping

When opening a switch, the current can be interrupted before it reaches its natural current zero point due to instabilities in the arc. The energy ½ Li^2 present at that moment in the inductive load will oscillate via the ever present (parasitic) capacitance, so that the overvoltage amounts to approximately $i\sqrt{\frac{L}{C}}$.

The frequency range is up to 20 kHz. The overvoltage on both cable ends occurs simultaneously and therefore no surge waves occur. With chopping currents of a maximum of 6 A, the overvoltages are limited in practice to 3 or 4 p.u. and can therefore cause no damage to the installation.

Multiple restrikes

In principle, multiple restrikes may occur during both closing and opening operations. Switches with a very fast recovering dielectric such as vacuum or SF6, can interrupt the instantaneous current after a pre-ignition when closing the switch. Because the contacts keep moving towards each other, the next pre-ignition occurs when a smaller voltage prevails over the gap, so that escalation is practically impossible. When opening the switch, the transient recovery voltage (TRV) can exceed the dielectric strength of the increasing gap, so that restriking occurs.

This will be mainly the case when the contact separation occurs around the current zero in an inductive series circuit. The occurring current can be interrupted again when it reaches its high frequency current zero, by switches with a fast recovering dielectric. Due to the larger distance between the contacts that has in the meantime arisen, restriking will occur when higher voltages appear over the gap, after which a new interruption can take place. This phenomenon can be repeated several times. As a result of the multiple restrikes, the power frequency current through the load can also increase again after current zero. When high frequency interruption occurs, this instantaneous load current will be chopped up to relatively high values. The resulting overvoltages due to this voltage escalation can be higher than possible with normal current chopping.

The frequency at which the restrike repeats itself lies roughly between 25-250 kHz. The frequency range of the TRV, in which the overvoltage occurs, is up to 20 kHz. The restrike itself causes a surge wave as described under pre-ignitions.

Overvoltages up to 17 p.u. are possible.

Virtual current chopping

When in a 3-phase circuit a restrike occurs in the last opening pole, the instantaneous value of the arc-current in the other poles is forced down to zero, due to the high frequency equalising currents. Switches with a fast recovering dielectric can extinguish at these high-frequency current zeros.

This phenomenon is called virtual current chopping because the instantaneous value of the power frequency current ($\sqrt{2}$ .i sin60º) is abruptly interrupted in the phases concerned. This value can be much higher than possible with multiple restrikes and therefore the overvoltages are much higher too. The overvoltages can (theoretically) exceed 40 p.u.

Resonance

The resonance frequency of transformers with small ratios such as 10/2 and 10/6 kV can be present in the same area as repeating frequencies of occurring multiple restrikes (25-250 kHz). With these transformers, overvoltages can occur on the secondary side of 3 to 5 times the primary overvoltage, as a result of the resonance. With transformers with a larger ratio, e.g. 10/0.4 kV, no harmful overvoltages as a result of resonance can occur in practice.

PROBABILITY OF OCCURENCE IN PRACTICE WHEN USING VACUUM CIRCUIT-BREAKERS OR SWITCHES

For vacuum switchgear, the contact material has a definite influence on the value of the chopping current. A distinction can be made between switches with a high chopping level (Cu contacts: 17 A) and switches with a low chopping level (CuCr contacts: 5 A). The contact material has also an influence on the repeating frequency and duration of the multiple restrikes and also therefore on the chance of virtual current chopping. In table 1 a summary of measurements of the duration of multiple restrikes, gap-opening and overvoltages of vacuum circuit-breakers is given..

TABLE 1 - Summary of measurements on vacuum circuit-breakers

high chopping level				Low chopping level			
U_n kV	t_r µs	gap mm	U_{max} kV	U_n kV	t_r µs	gap mm	U_{max} kV
10-12	2000	2	85	10-12	1700	1.7	75
6-7.2	1300	1.3	60	6-7.2	600	0.6	40
3-3.6	1000	1	50	3-3.6	200	0.2	35

U_n	rated voltage
t_r	duration of multiple restrikes
gap	contact opening
U_{max}	maximum switching overvoltage limited by the contact opening

The probability of multiple restrikes and virtual current chopping for vacuum circuit-breakers with high and low chopping levels are set out in figure 1. The results of a large number of tests are incorporated in this figure.
It is based on:

- controlled opening
- inductive series circuits with current values up to 400 A
- cable lengths of 5, 30 and 123 m
- voltages of 10-12: 6-7.2: 3-3.6 kV

Multiple restrikes over the switch gap occur when the contact separation lies close to a current zero. In vacuum circuit-breakers with a high chopping level, this is from approx. 15° before the current zero, and for circuit-breakers with a low chopping level from approx. 6°.

In a 3-phase circuit, a current zero occurs every 60°, whereby the possibility of multiple restrikes and virtual current chopping is reduced to respectively 25% (15/60 x 100%) and 10% (6/60 x 100%), with switching in practice (not controlled).
A study has been made to determine in which situations a circuit with a series character (L and R in series) and a power factor of ≤ 0.3 occurs.
For distribution networks, the probability of harmful situations is summarised in table 2 and for industrial networks in table 3 for vacuum circuit-breakers with low chopping level.

Because the switching frequency in industrial networks can be high, the probability of overvoltages cannot be discounted. In addition, the fairly large risk of damage in industrial applications should be taken into account. For industrial networks it is assumed that the probabilities of overvoltages occurring are equivalent to respectively 25% (Cu contacts) and 10% (CuCr contacts) of the risk of occurring with controlled switching.

POSSIBLE PRECAUTIONS AGAINST OVERVOLTAGES

Of the possible precautions such as RC-networks, Zorc-suppressors, reactors, spark gaps, varistors with or without gap (SiC, ZnO) and the advanced-opening pole, only the last two are discussed in this article.

a) Application of ZnO varistors.

ZnO is extremely suitable as an overvoltage arrester because of its:

- speed of operation
- constant protection characteristic
- capacity to absorb energy

- high operating reliability
- series and parallel application

In table 4 a summary is given of the amount of energy to be absorbed. This energy is produced by virtual current chopping and multiple restrikes at the various voltage levels.

b) Advanced-opening pole. Holec's patented solution for the prevention of virtual current chopping is to use an advanced-opening pole on its vacuum circuit-breakers. During current breaking, this advanced pole opens 8-10 ms earlier than the other two.
This is explained with reference to fig. 2, in which the S-pole is chosen to be the advanced one.

In fig. 2, the difference in time between contact separation of the advanced and the other poles, (t_1-t_0) must be considered to be the minimum advance or lead time to ensure that virtual current chopping is avoided.

Due to the symmetry it is sufficient to consider the contact separation of the advanced pole in one half period. That half period is assumed to be the one before current zero 1.

In the first .instance, the interruption of I_s is assumed to be single phased:

- when the S-pole is opened before $t = t_o$, the vacuum circuit breaker will always definitely interrupt the current I_s at current zero 1. Before the definite break takes place there could have been breaking attempts followed by restrikes inside the vacuum interrupter.
- when the S-pole opens between t_0 and current zero 1, it is possible that the vacuum interrupter does not interrupt the current I_s definitely at current zero 1, despite possible breaking attempts. The current I_s will then continue to flow until it is definitely interrupted at current zero 2 (without restrikes).

Now consider the 3-phase circuit. If the contact separation of the S-pole takes place very closely before current zero 1 (i.e. the S-pole opens just before, or just after t_0), restrikes are possible and two situations can occur:
Either; I_s will he definitely broken at current zero 1, possibly with preceding restrikes. For both other poles it is not so critically important where they are opened, as long as it happens after current zero 1. The circuit is then changed to a 2-phase circuit. Both currents decay together to zero and cannot give rise to large virtual chopping currents.
Or; I_s will be definitely broken without restrikes at current zero 2. This situation is shown in fig. 2 by the thick line. It can only occur if the S-pole contacts separate between t_0 and current zero 1. When-the contacts of the R- and T-poles open just before current zero A of the R-pole or current zero B of the T-pole, virtual current chopping can still arise as a result of restrikes in the R- or T-pole. Thus it must be ensured that the current through the S-pole has been definitely broken before the arcs of the other poles start extinguishing at their respective current zeros.

From the above it follows that the R- and T-poles should not be opened until after current zero B. The time between t_0 and current zero B is thus the minimum time that the advanced pole must open before the other two in order to prevent virtual current chopping. This advance time is therefore the sum of the minimum arcing time t_m plus one third of the periodic time of the power frequency, T/3 (T=20 ms for 50 Hz). Practice has shown that 8-10 ms is a good choice.

TESTS ON 3-PHASE VACUUM CIRCUIT-BREAKERS

Circuit-breakers which have been provided with special facilities for the prevention or limitation of the highest overvoltages (as a result of virtual current chopping) are compared with a circuit breaker without these special facilities. Breaking tests have been carried out on:
a) conventional circuit-breaker without special facilities.
b) conventional circuit-breaker with ZnO arrestors.
c) circuit breaker with advanced opening pole.
The following ratings were valid for all circuit-breakers U_n = 12 kV, I_n = 1600 A, I_{sc} = 25 kA;
contact material CuCr.

The-test circuit is shown in fig. 3. It shows a practical situation as switching off stalled motor currents. The Inductive load is connected by means of PILC cables 3 x 95 mm^2, in lengths of 30 and 123 m. The test voltage is 12 kV 50 Hz. Power frequency currents of 25 up to 400 A have to be interrupted. The test-circuit protection (spark gaps) were set at a peak value of 60 kV. This coincides with an overvoltage of approx. 6 p.u. in 12 kV-circuits.

a) Conventional circuit-breaker without facilities.

when switching off currents of up to 250 A, overvoltages were observed when contact separation was effected close to current zero. These overvoltages were so high, that the spark gaps were activated. These high overvoltages were due to virtual current chopping, as is apparent from the registered current and voltage signals in fig. 4.

Restrikes in phase S cause virtual-current chopping in the R and T phases of 150 A.

b) Conventional circuit-breaker with ZnO arrestors.

Ratings ZnO arrestor: U_{cov} = 12 kV, max. discharge voltage = 35 kV at 5 kA (8/20 µs). An oscillogram of a representative breaking test is shown in fig. 5. Due to the limitation of the 8-channel X-t recorder, I_r has been omitted. As in fig. 4, virtual current chopping occurs in the R- and T-phases. The chopping current is 227 A. The limitation of the overvoltages by the ZnO arreators at 28 kV is clearly visible in fig. 5. The absorbed energy is approx. 2700 J for the ZnO's in the R- and T-phases.

c) Circuit-breaker with advanced opening pole.

Virtual current chopping never occurred with the circuit-breaker with advanced opening pole. An oscillogram of a representative test is shown in fig. 6. The repetitive restrikes in the (advanced opening) S-pole cause transient currents which pull down the power frequency current to zero in the R- and T-phases. Since these are still closed, no virtual current chopping can occur. Eventually the S-phase extinguishes at its first current zero after opening so that the circuit changes into a two phase (R-T) circuit. The two phase current is smoothly broken at its first current zero after opening of the R- and T-poles.

Conclusions:

- Pre-ignitions cause in practice a heavy burden on inductive loads such as motors. They occur during each closing operation and are independent of the type of switching medium.
- Virtual current chopping causes the most severe overvoltages.
- If virtual current chopping cannot occur, overvoltage arrestors are only needed in those few cases where voltage escalation due to multiple restrikes can occur. These arrestors can be very compact because of the low energy absorption capacity required.
- in table 5 the situations are given where arrestors are still needed despite the advanced opening pole. The energy to be absorbed can be a factor of 10 lower with an advanced opening pole.

TABLE 2 - Summary of situations in distribution networks in which harmful overvoltages can occur.

function	load condition	high surges due to	probability of occurrence
- main circuit-breaker (supply side)	- transformer secondary short-circuited $\leq$300 kVA	virtual current chopping	not known
- transformer circuit-breaker	- no-load inrush current	virtual current chopping	negligible
- transformer circuit-breaker of control station	- transformer earth fault or internal fault	virtual current chopping	negligible
- transformer circuit-breaker of generator plant	- no-load inrush current - transformer secondary short-circuited $\leq$ 300 kVA - transformer earth fault or internal fault	virtual current chopping	negligible
- circuit-breaker of frequency controlled devices	- short-circuited frequency-controlled devices - transformer earth fault or internal fault	virtual current chopping	negligible
- circuit-breaker of artificial neutral point transformer	- earth fault < 450 A in a system with no star connected neutral point	virtual current chopping	negligible

TABLE 3 - Summary of situations in industrial networks (6-12 kV) in which harmful overvoltages can occur

function	load condition	high surges due to	probability of occurrence
- transformer circuit-breaker	- inrush of transformers	virtual current chopping	not known
	- transformer secondary short-circuited $\leq$300 kVA	virtual current chopping	negligible
	- transformer earth fault	virtual current chopping	negligible
- circuit-breaker	- inductive load current	virtual current chopping	1 – 8 %
	- inductive load current of a generator	virtual current chopping	negligible
	- inductive load current with low ratio transformer	resonance	3 – 10 %
	- switching of motors (inching and jogging)	virtual current chopping	1 – 8 %
	- switching on motors with cables $\geq$20 m	pre-ignition	100 %
	- converters	virtual current chopping resonance	1 – 8 % 3 - 10 %

TABLE 4 - Summary of the amount of energy to be dissipated by the arrestors.

circuit-breaker			with high chopping level		with low chopping level	
U_n kV	U_{cov} kV	U_d kV	dissipated energy due to		dissipated energy due to	
			virtual chopping J	multiple restrike J	virtual chopping J	multiple restrike J
10-12	12	29.4	7408	692	4111	386
6-7.2	7.2	17.6	4445	416	2467	232
3-3.6	3.6	8.8	2222	208	1233	116

Where: U_n = power frequency voltage
U_{cov} = Continuous operating voltage
U_d = Discharge voltage

TABLE 5. – Recommendations for Zno surge arrestors and vacuum circuit-breakers with a low chopping level where arrestors are still needed

voltage level kV	load condition kV	continuous operating Voltage U_{cov}	voltage of arrestor U_d	dissipated energy	
				without advanced opening J	with advanced opening J
10 - 12	Motors ≤ 720 kW	12 kV	30 kV	8200	820
	Motors > 720 kW	12 kV	30 kV	820	820
	Generators and converters	12 kV	30 kV	8200	820
	Inductive loaded transformers	12 kV	30 kV	8200	820
	Inductive loaded transformers with low ratio 10/3 or 10/6 kV	12 kV secondary side voltage	30 kV crest value of 50 Hz 1 minute voltage	8200 820	820 820
6 – 7.2	Motors ≤ 450 kW	7.2 kV	18 kV	5000	500
	Motors > 450 kW	7.2 kV	18 kV	500	500
	Generators and converters	7.2 kV	18 kV	5000	500
	Inductive loaded transformers	7.2 kV	18 kV	5000	500
3 – 3.6	Motors ≤ 220 kW	3.6 kV	10 kV	2500	250
	Motors > 220 kW	3.6 kV	10 kV	250	250
	Generators and converters	3.6 kV	10 kV	2500	250
	Inductive loaded transformers	3.6 kV	10 kV	2500	250

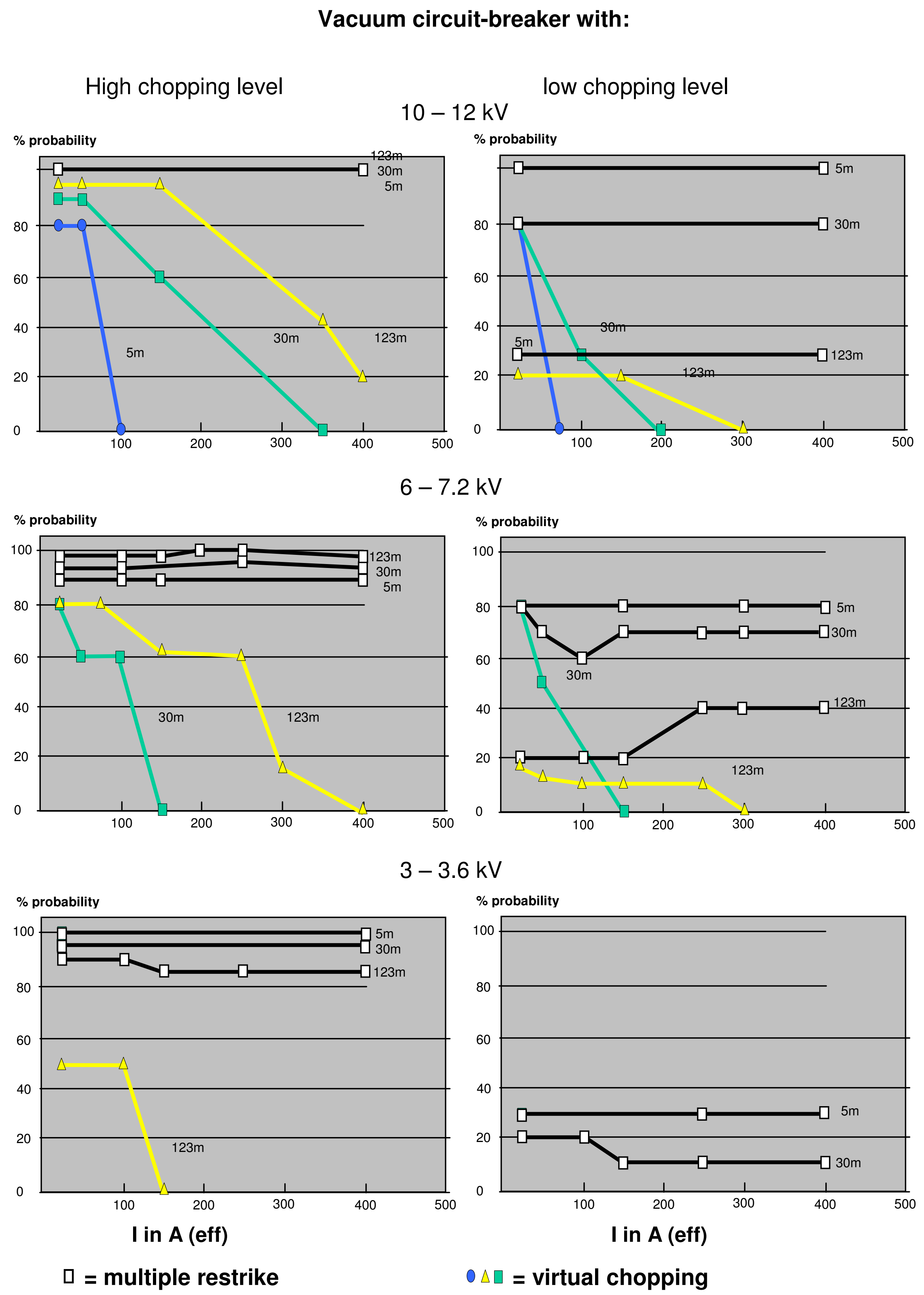

Figure 1 Probability of occurrence on switching overvoltages with vacuum circuit-breaker and controlled switching

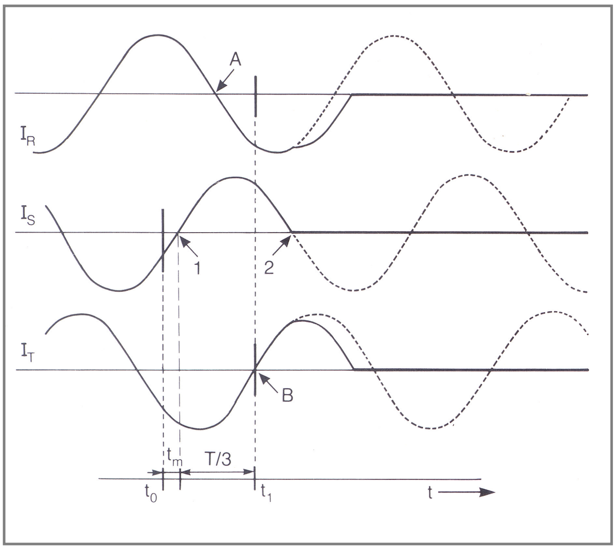

Figure 2 Principle of 3-phase current breaking with advanced opening pole

I_r, I_s, I_t : power frequency currents of R, S and T phases to be interrupted.

Points 1 and 2 : current zeros in the advanced pole (S-phase)

Points A and B: current zeros in the R and T phases

T : periodic time of power frequency

t_0 : moment of opening of advanced pole (S)

t_1 : moment of opening of two other poles (R,T)

t_m: minimum arcing time

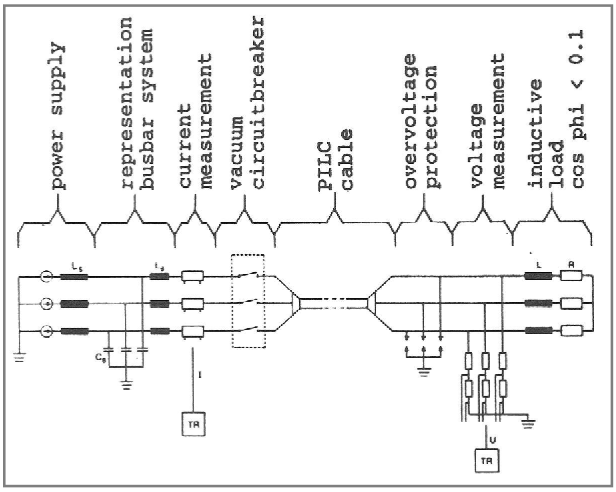

Figure 3 Test circuit

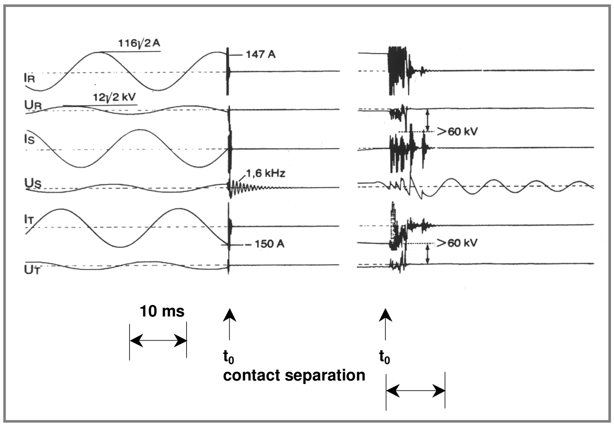

Figure 4 Breaking of an inductive current by vacuum circuit-breaker without facilities

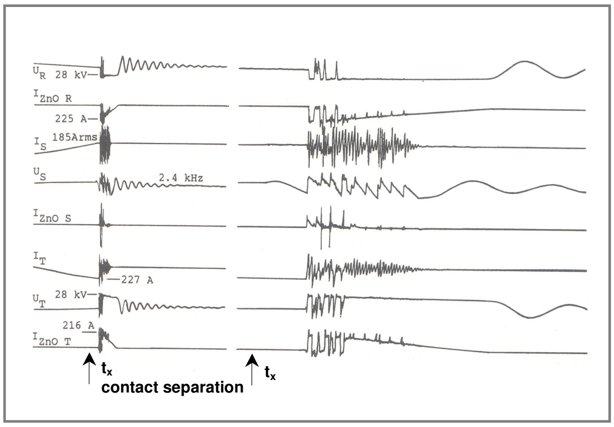

Figure 5 Breaking of an inductive current by vacuum circuit-breaker with ZnO arrestors

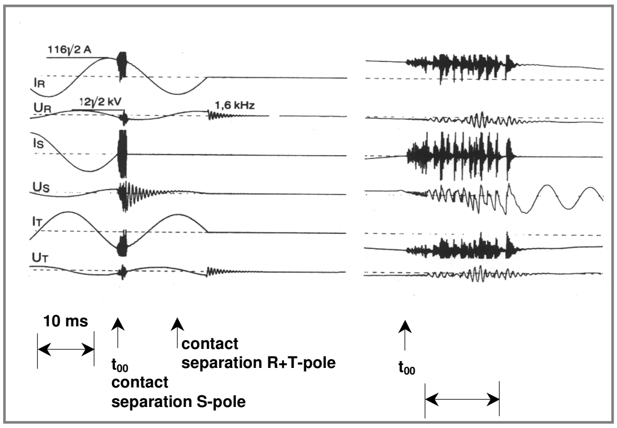

Figure 6 Breaking of an Inductive current by vacuum circuit-breaker with advanced opening pole