SWITCHING OF SMALL INDUCTIVE CURRENTS USING VACUUM CIRCUIT-BREAKERS

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ABSTRACT

This paper presents the main results of a comparison of motor current switching tests according to IEC 62271-110, performed by a medium voltage vacuum circuit-breaker and a simulation of this breaker and the test circuit.

The obtained curves were analyzed and the characteristic parameters of the vacuum interrupter as chopping current, voltage withstand curve and high-frequency current interrupting capability were determined. Based on these parameters, a model of the vacuum interrupter as well as the tested circuits were adapted and simulated in the ATP-EMTP program. By implementing the relevant network segment these simulations were compared with the effective measurements. It can be shown, that the robustness and the accuracy of the simulation model covers the requirements of reproducing the measurements with high accuracy.

INTRODUCTION

Inductive switching becomes more and more important as a normal duty of medium voltage switchgear. The medium voltage circuit-breakers are in most cases specified and selected according to requirements other than inductive current switching. So far this duty generally represents no difficulties. In comparison with the circuit-breaker's rated short-circuit breaking current the inductive breaking current is insignificant. However the inductive current is usually interrupted before its natural zero by a phenomenon known as current chopping.

Taking into consideration the equivalent inductance and capacitance of the load, an oscillating circuit is acting. The magnetic energy stored in the inductance is transferred at the moment of current chopping as electric energy to the capacitor. Therefore the chopping current creates over-voltages characterized by very steep rates of rise, able to exceed the rise of the withstand voltage of the interrupting unit. The subsequent multiple re-ignitions and the virtual current chopping phenomenon can reach voltage levels far above the insulation withstand level of the network components. This is due to capacitive and inductive phase couplings of the overlaid network.

Guaranteeing a generic qualification of the products covering all possible network configurations, a high number of expensive tests would have to be performed. Therefore the possibilities of using simulation and calculation instruments were investigated.

The main goal was to establish a simulation tool for network analyses including the switching of inductive loads. As a necessary consequence of the simulation the appropriate overvoltage protection, as RC snubbers and surge arresters, shall be dimensioned.

STANDARDS AND APPLICATION GUIDES

Medium voltage circuit-breakers are designed and type tested according to IEC 62271-100 [1]. This standard describes the mandatory test duties, mainly to demonstrate the short-circuit switching capabilities. For inductive switching no mandatory test is required.

In 1994 the Technical Report IEC TR 61233 summarized the switching conditions of circuit-breaker in circuits with inductive loads. This TR was replaced by IEC 62271-110 [2], introduced in 2005. Here the mandatory testing requirements were defined applicable to circuit-breakers used to switch high-voltage motor currents and shunt reactor currents. No-Load switching of transformers to break magnetizing currents was not considered. The reason is the impossibility to define a correct model for the non-linear characteristics of the transformer core in a test laboratory. Therefore such a test would only be valid for the individual tested transformer and can not be transferred to other transformers of the same or similar design.

Based on the IEC TR 61233, a CIGRE Guide for the application of IEC 62271-100 and IEC 62271-1 [3] was introduced in 2006. Among others, this technical brochure analyzes the inductive switching based on field experience and results of simulation models.

In 2009 the board of IEC decided to establish a new project team, PT50, to create an IEC Application Guide under IEC 62271-306 [4] This work is based on the mentioned CIGRE guide. The working status was published 18.06.2010 under 17A/927/CD. Presently, 17A/941/CC is now working on the revision and review of comments.

MOTOR SWITCHING TEST WITH VACUUM CIRCUIT-BREAKER

Due to the standard there are special requirements for inductive switching. These are special test circuits and test duties, which have to be fulfilled.

Test circuit

IEC 62271-110 defines the motor switching test, representing the switching of small inductive currents, i.e. at motor starting phase. The test circuit is shown in Figure 1 and described in Table 1. However, it must be noted, that due to hysteresis of the motor magnetic field, it is not possible to represent the exact circuit in a test laboratory. The test circuit should in fact reproduce equivalent field conditions.

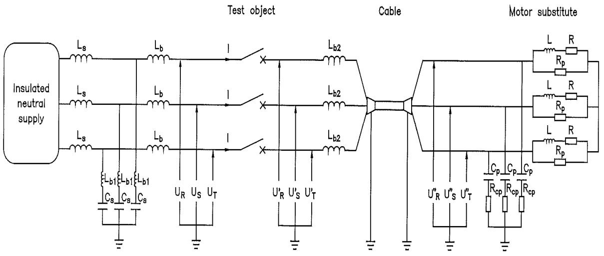


Figure 1: Motor switching test circuit

Table 1: Electrical parameters

Supply circuit	**connections (Busbar)**	**Load circuit (Motor substitute)**
U = 12,0kV phase to phase f = 50Hz I_{sc} = 10kA cos φ <0,1 L_s = 2,2mH C_s = 0,04µF / 1,75µF L_b = -µH	L_{b2} = 15µH	I = 115A / 275A cos φ <0,15 L = 170mH/ 83mH R = 7,5Ω / 3,75Ω C_p = 500pF f = 4,0kHz U_c=27kV; t3=35µs

The referred switching test was performed with cable length of 25m between the circuit-breaker and the motor substitute. The equivalent capacitance C_p represents the capacitances of the motor windings and the cable connection. The corresponding frequencies of the load circuit were determined in an equivalent way. On the other hand the parameters of the transient recovery voltage are based on prospective values without the influence of the cable.

Test duties

The circuit-breaker was tested in four configurations of two motor substitute circuits with motor currents of 115A and 275A, and in two supply circuits with capacitances C_S of 0,04µF and 1,75µF. A total number of 80 (4 x 20) close-open operations were performed. The phase position of the tripping impulses was adjusted at intervals of 9 degrees in every variant of the circuit. Therefore thus could be uniformly distributed over the period of a cycle (9 x 20 = 180).

Test object

The test in the described test circuit was performed with a three phase vacuum circuit-breaker type HVX 12-50-31-E in an air isolated medium voltage switchgear type PIX-H. In addition the test was carried out with surge arresters installed in the switchgear and connecting the phases to earth. The technical data are summarized in Table 2.

Table 2: Technical data of tested circuit-breaker

	Circuit Breaker	**Surge Arrester**
Type	HVX 12-50-31-E	HE15
Rated Voltage	12 kV	15 kV
Rated Current	3150 A	-
Rated Frequency	50 Hz	50 Hz
BIL	75 kV	110 kV
PFWV	28 kV	-
Short-circuit making current	128 kA	100 kA
Short-circuit breaking current	50 kA	-
Minimum opening time	35 ms	-
Transient recovery voltage		-
Frst-pole-to-clear factor	1,5	-
Peak value (U_C)	20,6 kV	-
Rate of rise (U/t)	0,34 kV / µs	-
Operating sequence	O-0,3s-CO-3min-CO	-
Vacuum interrupter	VG5	-
Line discharge class	-	1
Nominal discharge current	-	10 kA

Test results

No mandatory overvoltage factors are defined in IEC 62271-110, as these are only relevant to the specific test condition. The circuit-breaker must fulfil the conditions given in IEC 62271-100 during and after the motor switching tests. Re-ignitions shall take place between the arcing contacts. The aim of the test is to gain the characteristics of the circuit-breaker at several cases with respect to overvoltages and to cover the majority of service applications. The mentioned characteristics are the chopping current distribution, voltage recovery withstand (1) and high frequency (2) arc quenching capability.

$$U = L\frac{di}{dt} \tag{1}$$

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

The chosen test object was able to withstand the test procedure and to pass the test successfully.

SIMULATION MODEL

To reproduce the test results, the tested circuit was implemented into the ATP-EMTP software. The model of the circuit-breaker was developed using its MODELs section. The obtained tested results were analysed and the circuit-breaker characteristics were implemented in the model. The function unit is using an ideal circuit-breaker, with an single duty: to open or to close. The circuit-breaker is controlled by a circuit logic program, using FORTRAN code. The decision matrix is shown in Figure 2.

In every time step the circuit currents and voltages are calculated. Based on the comparison with the tested characteristics of the vacuum interrupter, the logic decides the switching operation of the circuit-breaker. Following parameters of the vacuum interrupter are considered:

- The capability to interrupt the current before its natural current zero (current chopping)
- The voltage withstand characteristics (re-ignitions)
- The capability to interrupt high frequency equalising currents as result of re-ignitions (HF arc quenching).

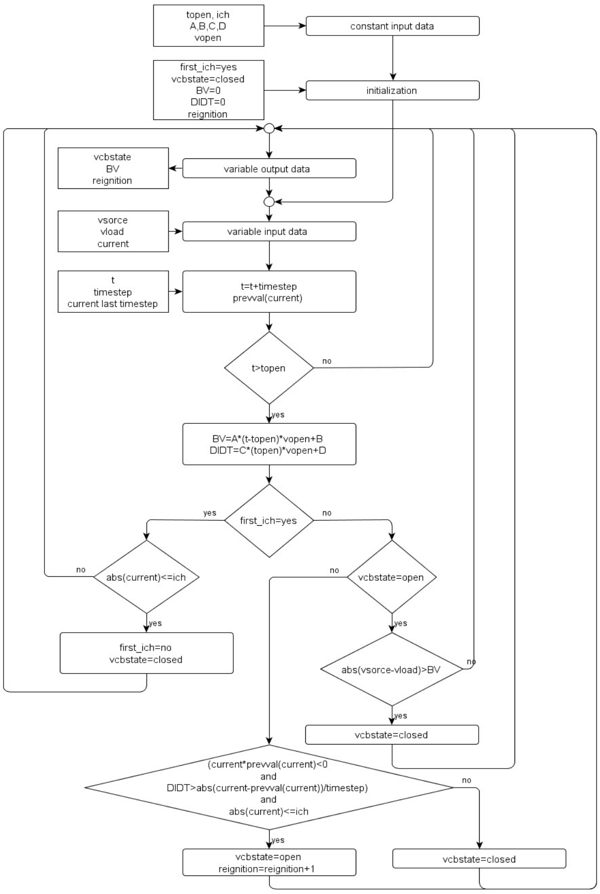


Figure 2: Structure of decision matrix

The model input parameters are summarized in Table 3. These values have to be known for simulating the inductive switching behaviour of the circuit breaker.

Table 3: Electrical parameters

Parameter	**Instruction**
t_{open} [ms]	Opening time of the circuit-breaker
i_{ch} [A]	Chopping current
A [kV/ms]	Slope of the recovery withstand voltage
B [kV]	Initial recovery withstand voltage
C [A/µs^2]	Curvature of the high frequency arc quenching capability
D [A/µs]	Slope of the high frequency arc quenching capability
v_{open} [m/s]	Opening speed of the contacts

Simulation results

The simulations have been done in accordance to the four various configurations given by the test duties of IEC 62271-110. With the developed models it was able to simulate the circuit breaker and also the whole test circuit. Therefore different cases of re-ignition could be investigated. The results of the simulation are analysed in the next chapter in comparison to the test results.

COMPARISON OF TEST RESULTS AND SIMULATION

The simulation performance is demonstrated by a comparison with the obtained test curves. The overvoltages on the circuit-breaker contacts could be determined for the following four cases.

Interruption without re-ignition

This is a standard case for inductive switching. In all three phases the circuit breaker is able to open without any re-ignition due to the overvoltage caused by the chopping current.

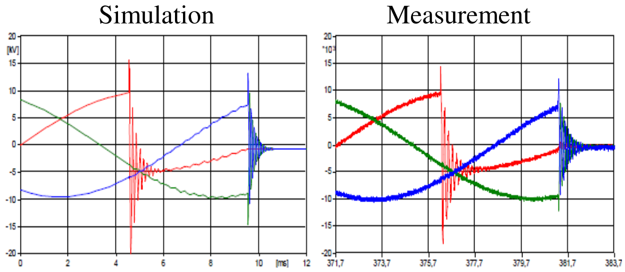

Simulation Measurement

Figure 3: Interruption without re-ignition

This case can be exactly reproduced by the simulation. The overvoltage peak depends only on the chopping current value i_{ch} and on the equivalent parameters of the load side, i.e. the cable connection and the motor.

Interruption with multiple re-ignitions

This case describes the opening time nearly the natural current zero of the first-phase-to-clear. The overvoltage exceeds the recovery withstand voltage of the still small opening contact gap.

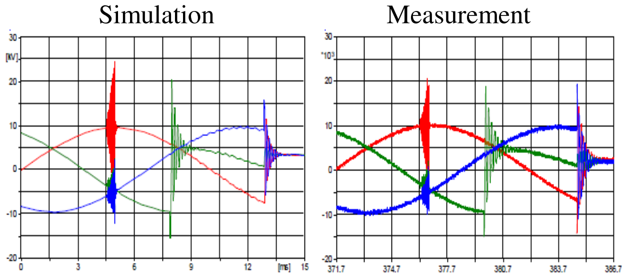
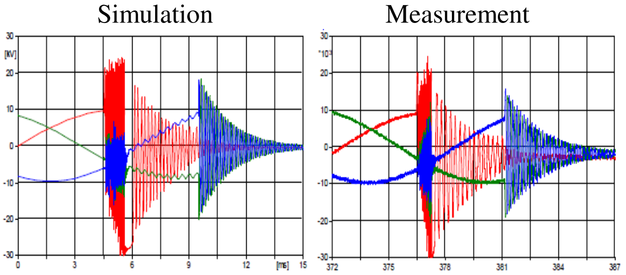

Simulation Measurement

Figure 4: Interruption with multiple re-ignitions

As a result multiple re-ignitions occur in this situation and the peak overvoltages are below the response value of the surge arresters. The simulation results show the same behaviour than the test results.

Multiple re-ignitions with single phase limitation

In this case the surge arrester in the first-phase-to-clear limits the overvoltage escalation due to multiple re-ignitions. The overvoltages in the other phases are lower than the response values of their surge arresters.


Simulation

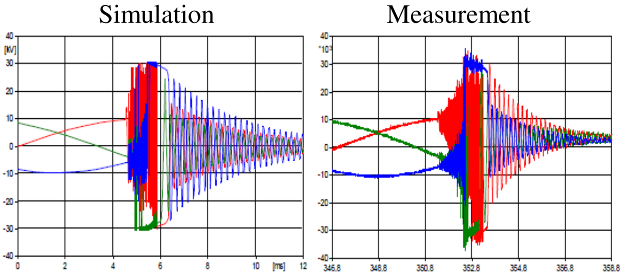
Measurement

Figure 5: Single phase limitation of surge arrester

The comparison of test results and simulation shows also the same behaviour. The single small difference is the duration of the re-ignitions in the first phase to clear due to the higher damping in the real test circuit.

Multiple re-ignitions with virtual current chopping

This situation shows the worst case of switching overvoltages, caused by the phenomenon of virtual current chopping. The high frequency current, due to multiple re-ignitions in the first-phase-to-clear, superposes the power frequency currents in the other phases, causing a current zero in these. Surge arresters response in all phases.


Simulation

Measurement

Figure 6: Virtual current chopping

Also here the simulation shows a good correlation with the test results. The small difference in the duration of the re-ignition in the first-phase-to-clear is similar to the single phase limitation.

Simulation of various network configurations

With a number of simulations the influences of the variable parameters of supply and load side on the occurring overvoltages were investigated. The probability of re-ignition decreases with the increasing length of cable, the probability of the virtual current chopping is therewith not affected. Even one re-ignition can cause virtual current chopping phenomena. Same simulation results have been obtained in [5]. For this reason RC snubbers are used to limit firstly the rate of rise of transient recovery voltages and secondly to damp its peak value. Figure 7 shows the difference of installations with or without RC snubber.

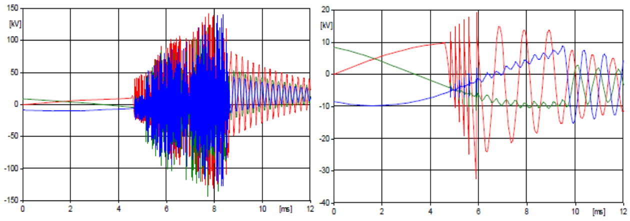


Figure 7: Overvoltages without and with RC snubber

By using a properly dimensioned RC snubber the overvoltage can be significantly reduced. An outstanding advantage of the developed ATP model is the possibility to calculate the RC components and to simulate the behaviour in interaction with the circuit breaker.

CONCLUSION

In this paper the model of vacuum circuit-breaker for inductive switching was presented, based on the test according to IEC 62271-110. The test results were analyzed and the characteristic parameters of the vacuum interrupter were implemented in the ATP-EMTP model. Frequencies, occurring in those circuits, can reach ranges of hundreds of MHz. This fact makes the simulation more complex, as in the majority of the network installations the high frequency couplings between the phases are not known.

The developed model can reproduce the switching behaviour of a vacuum circuit-breaker in a circuit with inductive load. The simulation curves match with good reliability the results obtained with the measurement. Therefore the circuit-breaker model can be used in similar applications with inductive loads for further simulation of the switching behaviour. Due to this expensive tests can be saved.

REFERENCES

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[4] IEC 62271-306, under work, *High voltage switchgear and controlgear – Part 306: Guide for application of IEC 62271-100, IEC 62271-1 and related standards*

[5] Penkov, D., et al., 2008, "Overvoltage protection study on vacuum breaker switched mv motors", *Petroleum and Chemical Industry Conference Europe – Electrical and Instrumentation Applications*