Modeling of repetitive ignitions in switching devices: case studies on Vacuum Circuit Breaker and GIS disconnector

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Abstract. Repetitive ignitions of electric arc during switching operation may result in generating Fast and Very Fast Transients (FT and VFT) and thus require analyses to ensure reliable system operation. The paper presents a common approach for modeling and simulation of such phenomenon for two types of switching devices: Vacuum Circuit Breakers (VCB) and GIS disconnectors. In each case, the associated (VFT) are modeled with the use of a case-specific Breakdown Voltage Characteristic (BDV), characterizing the switching process, and with the use of case-specific power system conditions. Two case studies are presented. For Vacuum Circuit Breaker, a switching operation of un-loaded transformer is presented. For GIS disconnector, switching of short bus-bar during the disconnector type testing is presented.

Keywords: Vacuum Circuit Breaker, Gas Insulated Switchgear, GIS disconnector, Very Fast Transient overvoltages.

1 Introduction

Very steep wavefront transients in power networks characterized by high dU/dt are often a result of switching events using various types of HV and MV switching apparatus. The transients overvoltage is often of a repetitive nature, which means that multiple overvoltages may be generated during a single switching operation. Those repetitive overvoltage characterized by high rate of rise values may pose significant risks as they can destroy motors, transformers, and other electrical equipment due to highly non-uniform potential distribution and internal resonant phenomena resulting in local voltage amplification. Overstressing the insulation system reduces significantly the equipment lifetime and often leads to an internal short-circuit.

The existing standards specifying testing procedures for HV and MV equipment do not cover the phenomena mentioned above as the nature of the generated transients depends very strongly not only on the specific parameters of the given piece of equipment, but also on parameters of the network and the physical processes within the switching device. Therefore the analysis of the transients which occur during the switching operation often requires case by case studies, for which are needed.

Two types of Very Fast Transients (VFT) are recognized in power system [1] as requiring high attention to ensure the system reliable operation: 1) VFT originating

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from operation of Vacuum Circuit Breakers (VCB), and 2) VFT originating from operation of Gas Insulated-Switchgear (GIS) disconnectors.

Despite of the fact that the two types of VFT are associated with physically different switching devices and operating conditions, repetitive ignitions of the electric arc in a contact gap can be analyzed in a similar way. The ignitions occur when voltage across the gap is higher than dielectric withstand characteristics of the gap (Breakdown Voltage Characteristics, BDV). In each case the transients associated with the switching operation are characterized with high frequency and have repetitive character. As such, they can pose a threat to power equipment insulation system, such as when they interact with resonant frequencies of power transformers [2]. In some cases this requires mitigation methods [2, 3], the first evaluation of which being done with the use of modeling and simulation approach.

In this paper a common approach is presented for modeling and simulation of two different types of switching operations: VCB and GIS disconnector. In the two cases a method is used which was initially proposed for modeling of Vacuum Circuit Breakers, as described e.g. in [4, 5].

The paper is organized in the following way. After introduction in Section 1, Section 2 follows with description of the method originally proposed for modeling of Vacuum Circuit Breakers, with indicated differences between modeling of VCB and GIS disconnector. In Section 3 and Section 4, application of the method is presented for typical VFT-related system studies: Section 3 presents VCB operation when switching of an unloaded transformer and Section 4 presents GIS disconnector operation when switching of a short bus-bar during the disconnector type testing. Finally, the summing-up section with conclusions is given.

The system studies presented in this paper are typically performed as a part of the system configuration analyses in the course of insulation coordination studies or for the design process related to the insulation system design of the switching device and power equipment. The objective of such analyses is to evaluate reliable power system operation in presence of VFT.

2 Modeling of repetitive re-ignitions in switching devices

2.1 General approach

The approach for modeling of repetitive ignitions was first presented for modeling of Vacuum Circuit Breakers operations, e.g. in [4, 5]. The approach is to use a controlled switch which is switched on and off after specific criteria are checked. This approach is illustrated in Figure 1. As it can also be used to simulate GIS disconnectors, additional capacitor was applied as indicated in a green frame in Figure 1.

In this approach, after the opening operation of the breaker's contacts starts, the dielectric withstand voltage between the contacts increases as a function of time. When the Breakdown Voltage Characteristics is exceeded by Transient Recovery Voltage (TRV), a control signal is generated to close the switch. In this way the ignition is simulated, being called a restrike for the opening operation and a prestrike for the closing operation. When quenching capability of the contact gap is high enough, the arc is effectively extinguished, which is simulated by means of a control signal generated to open the switch in Figure 1. The theme is repeated during the switching device operation until the dielectric strength of the contact gap is higher than the TRV for the opening operation, or until contacts mating for the closing operation.

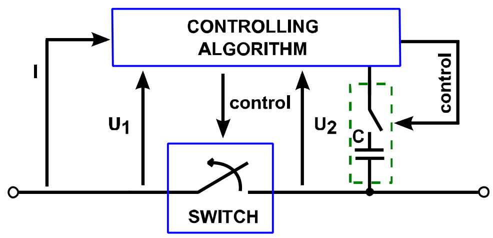

Fig. 1. Model of Vacuum Circuit Breaker based on ideal switch; capacitor for GIS disconnector modeling marked with green frame

The model can be further advanced by considering the arc voltage characteristics. This is modeled with the use of a variable resistor which value is changed in each simulation step. This approach is illustrated in Figure 2 [4]. The variable arc resistance is implemented according to the model assumptions, based on the switch voltage, switch current and other model specific parameters [5].

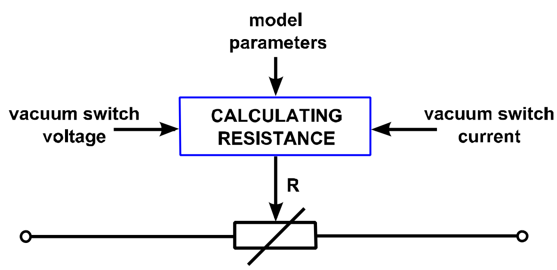

Fig. 2. Model of arc ignition based on variable arc resistance

The approach presented in Figure 1 and Figure 2 was used to perform simulations presented further in this paper. The models were implemented in EMTP-ATP software [6].

2.2 Modeling of Vacuum Circuit Breaker

Several specific phenomena are implemented in a mathematical model of a Vacuum Circuit Breaker, among which the major ones are: arcing time, current chopping, dielectric strength of the contact gap, and quenching capability of high frequency current.

Arcing time is an interval between the first and the last occurrence of the arc ignition in the process of contacts separation for opening and contacts mating for closing. Typical values of the arcing time are in the range of hundreds microseconds. A Gaussian distribution is used to represent the random nature of this phenomena.

Chopping current is also a random phenomenon. The mean value of the chopping current in the Vacuum Circuit Breaker can be estimated by dependence [4, 5]:

$$I_{ch} = (\omega \cdot i \cdot \alpha \cdot \beta)^{q} \tag{1}$$

where: $\omega = 2 \cdot \pi \cdot 50$ Hz, i – amplitude of the 50/60 Hz current, α – constant (e.g. $\alpha = 6.2 \cdot e\text{-}16$ in [5]), β – constant (e.g. $\beta = 14.3$ in [5]), $q = (1- \beta)\text{-}1$.

The value of the chopping current depends on the contact material properties, but also on the separation time of the contacts and is lower for the situation when the contacts start to separate in a closer vicinity of a current zero crossing.

For modeling of Breakdown Voltage Characteristics, the two breakdown mechanisms are considered. The first one is the breakdown of a cold gap, which is for when the arc ignites for the first time during an opening or a closing operation process. The second breakdown mechanism is related to the gap which has already ignited. In that case, a residual charge carriers exist near a cathode. The charge causes that the breakdown occurs at lower voltage values. A typical relation of the breakdown voltage for the cold gap is given by the linear formula:

$$U = A \cdot (t - t_{open}) + B \tag{2}$$

where: A, B – values of constants, given e.g. in [4], t_{open} – time of contact separation.

When Transient Recovery Voltage exceeds the dielectric strength of the breaker's contact system, the reignition occurs. The reignition is characterized with the high frequency current related to the arc stability and to the external circuit parameters (inductance and capacitance and associated energy balance).

2.3 Modeling of GIS disconnector

In principle the same approach as described above for modeling of Vacuum Circuit Breakers is utilized for modeling of GIS disconnectors. Specific conditions include: 1) Breakdown Voltage Characteristic, being specific to the breakdown in SF6 gas and to the design of the disconnector contact system, and 2) simulated circuit diagram, being specific to a typical disconnector configuration within the test set-up and substation. As the disconnector is installed together with an associated circuit breaker, and during the disconnector operation the circuit breaker has opened contacts, an additional voltage condition at the load side of the disconnector is associated with the Trapped Charge accumulated on the busbar between and disconnector and the circuit breaker, represented by capacitor C in Figure 1. The capacitor serves to simulate the voltage condition associated with a Trapped Charge in the busbar between the operated disconnector and an open contact system of an associated circuit breaker. Also, the disconnector specific Breakdown Voltage Characteristics is in use, which in its basic form is given by a linear function, having zero value at the time of the contacts mating and the power system withstand voltage at the time of full contact separation.

The breakdown time in SF6 is even shorter than in vacuum, which leads to even higher frequencies of transients when interaction between the disconnector and the system elements occurs. In the presence of very high frequencies, shorter elements have to be considered as lines with distributed parameters.

The arc resistance is modeled by the exponential formula with a time constant leading to the arc duration which is specific to the breakdown time in SF6 gas [7]:

$$R = R_a + R_0 \cdot e^{-t/\tau}, \tag{3}$$

where: R_a – arc static resistance, R_0 – resistance of the gap while disconnector is opened, τ – time constant.

Case study: Switching of unloaded transformer with Vacuum Circuit Breaker

In this section an exemplary case study is presented which involves Vacuum Circuit Breaker switching off event in a medium voltage (MV) network. The studied circuit consists of an external grid which supplies the MV/LV distribution transformer through HV/MV power transformer, as presented in Figure 3. Medium voltage cables are also considered in the network diagram.

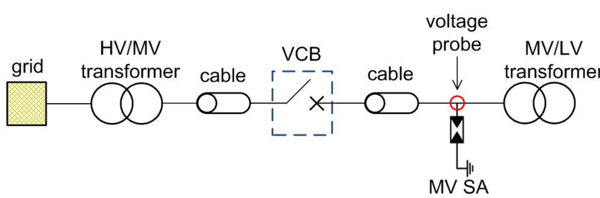

Fig. 3. Vacuum Circuit Breaker switching study – network diagram

The goal of the study was to illustrate the effect of the Vacuum Circuit Breaker opening operation on transient behavior for the following conditions:

- Breakdown Voltage Characteristic (BDV): simulations performed for 20 kV/ms and 5 kV/ms
- Cable length between VCB and MV/LV transformer: simulations performed for 15 m and 200 m

The objective was to present the impact of the above listed parameters on transient overvoltages at the MV/LV transformer terminals (see Figure 3). Based on simulation results it was presented that in order to achieve credible simulation results, detailed input data has to be assumed, both in terms of the system (cables lengths in the case presented) and switching device (BDV of the Vacuum Circuit Breaker in the case presented).

In the studied case the medium voltage network is at 15 kV voltage level. Single-core cables with cross sectional area equals to 95 mm^2 were modeled by means of surge impedance Z = 30 Ω and wave propagation speed v = 200 m/μs (lossless distributed line). The unloaded MV/LV transformer was modeled according to the data in Table 1.

Table 1. MV/LV transformer input data

Parameter	Value
Power, S	630 kVA
Voltage ratings, U_{N1}/U_{N2}	15 / 0.4 kV
Short circuit voltage, $u_{k\%}$	6%
No load current, I_0	1%
Load losses, ΔP_{Cu}	7 kW
No load losses, ΔP_{Fe}	0.8 kW
Primary side capacitance (phase to phase)	0.9 nF
Primary side capacitance (phase to ground)	1.35 nF

Four scenarios were simulated. The simulation results are presented in Figures 4 to Figure 6 in the form of voltage waveforms presenting phase-to-ground voltages at the operated transformer's primary side according to Figure 3. The results are presented for the assumed BDV (20 kV/ms and 5 kV/ms) and for the two cable lengths (15 m and 200 m).

As it is illustrated in the Figures 4 to Figure 6, the system configuration as well as the rate of rise of the assumed VCB's dielectric withstand strength have significant influence on the simulation results. At longer cables multiple arc reignitions do not occur due to the highly capacitive component of the switched off circuit, which decreases the TRV (see Figure 6). In the case of short cable connections, for the BDV with lower rate-of-rise value, arc restrikes last longer and their count number is significantly higher.

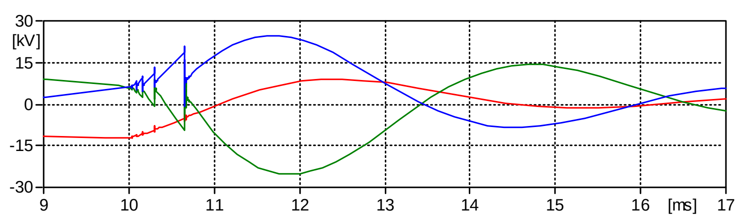

Fig. 4. MV side voltage; BDV = 20 kV/ms, 15 m cable

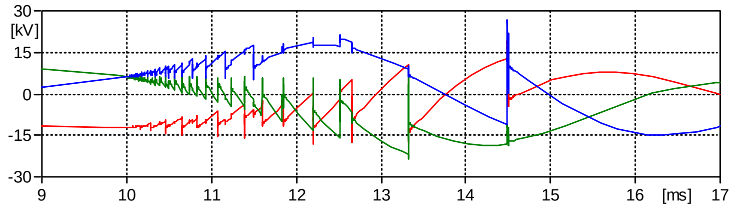

Fig. 5. MV side voltage; BDV = 5 kV/ms, 15 m cable

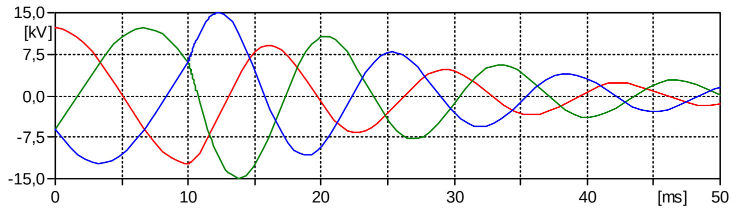

Fig. 6. MV side voltage; BDV = 5, 20 kV/ms, 200 m cable

Case study: switching of short bus-duct with GIS disconnector

In this section an exemplary case study is presented which involves GIS disconnector opening operation in type test set-up. The studied circuit, as presented in Figure 7, consists of an *AC* 50 Hz voltage source, a *DC* voltage source, and two disconnectors: *DS* – disconnector under test, and DA – auxiliary disconnector. The *AC* voltage RMS value is equal to the rated voltage of the disconnector under test, multiplied with factor 1.1. The *DC* voltage value is -1.0 p.u., where p.u. is the amplitude of the phase-to-ground rated voltage.

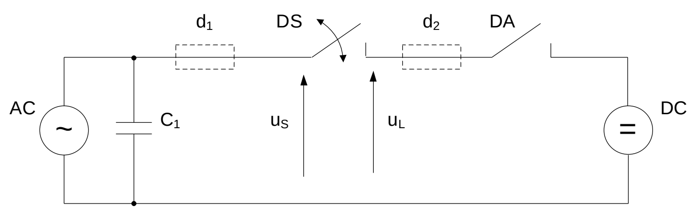

Fig. 7. Test Duty 1 set-up according to IEC 62271-102 [8]

The type test procedure according to IEC 62271-102 [8] assumes that initially a short bus-duct d_2 is charged to the *DC* value with the use of auxiliary disconnector *DA*. During the operation of the disconnector under test *DS*, the auxiliary disconnector *DA* remains opened.

During the disconnector *DS* operation, the voltage on the disconnector source side changes with the AC 50/60 Hz frequency, while the voltage on the load side remains at a certain DC level, as presented in Figure 8. In Figure 7 and Figure 8, the disconnector source and load side voltages are indicated as: u_S – the source side voltage (sinusoidal waveform in Figure 8, in green), and u_L – the load side voltage (step-wise waveform in Figure 8, in blue). A breakdown occurs every time when the voltage between the disconnector contacts exceeds the breakdown voltage related to the actual contact gap length, as presented in Figure 8. Due to the very short breakdown time in SF_6 (a few ns), transients originating from arc ignitions in GIS have very steep fronts (Very Fast Transients).

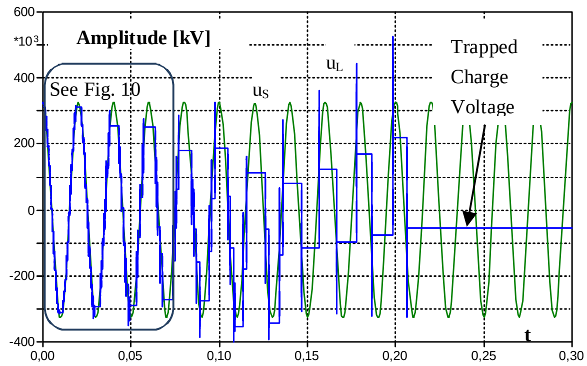

Fig. 8. Very Fast Transient process during type testing according to Figure 7; u_S – source side voltage, u_L – load side voltage, for disconnector opening operation

When the disconnector opening operation is completed, after the occurrence of the last restrike, Trapped Charge Voltage (TCV) remains on the load side of the disconnector. The Trapped Charge Voltage is an initial condition for the closing operation of the disconnector, which starts after the opening operation is completed. The relation between the overvoltage and the voltage drop across the contact system at the time of the arc ignition is linear and thus depends on the Trapped Charge Voltage at the time of the arc ignition [9].

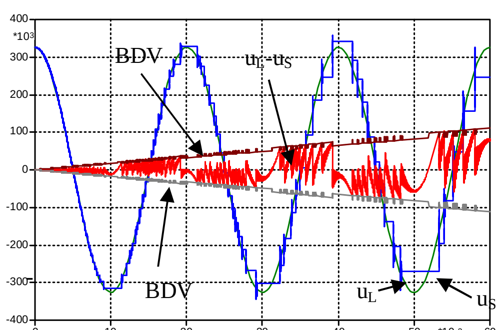

Fig. 9. Breakdown Voltage Characteristics, source side voltage u_S, load side voltage u_L, voltage across the contacts u_S-u_L during disconnector opening operation

For design of the disconnector insulation system, it is thus important that the value of the Trapped Charge Voltage reflects the real conditions during type testing. It is visible in Figure 8 that none of the restrikes reaches the most unfavorable condition of -2.0 p.u. voltage drop on the contact system at the time of the arc ignition. Also, for the first arc ignition during the closing operation, the Trapped Charge Voltage is significantly lower than the most severe condition of -1.0 p.u.

In Table 2 the values of Trapped Charge Voltages are calculated for four rates-of-rise of Breakdown Voltage Characteristic assumed for calculation. The BDV are related to the speed of the disconnector moving contact, which was varied from 0.1 m/s (low speed disconnector) to 3.0 m/s (high speed disconnector). It is shown that for low speed disconnectors the Trapped Charge Voltage conditions are lower.

Table 2. Trapped Charge Voltage calculated for different speed of disconnector moving contact

Contact speed [m/s]	**Trapped Charge Voltage [p.u.]**
0.1	-0.24
1.0	-0.55
1.5	-0.68
3.0	-1.00

3 Conclusions

Although Vacuum Circuit Breakers (VCB) and GIS disconnectors are governed with different physical principles and are operating in different network conditions, the repetitive process of the arc ignition during operation of both switching devices can be modeled based on a common approach.

In the paper the approach was presented together with two simulation case studies: the VCB operation of an un-loaded transformer, and the GIS disconnector operation during the disconnector type testing.

Parameters associated with the internal switching process can be modeled with the use of Breakdown Voltage Characteristics (BDV). It was presented that the BDV has an impact on time instances when the breakdowns occur. However, for a given breakdown (strike event), the associated voltage waveform depends on the external circuit (here energy oscillation takes place).

4 References

1. CIGRE JWG A2-A3-B3.21, “Electrical Environment of Transformers – Impact of Fast Transients”, Electra No. 218, Feb. 2005, pp. 25-37
2. IEEE PC57.142/D8.3 Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformer, Switching Device, and System Interaction, Transformers Committee and the Switchgear Committee WG, IEEE PES, 2012
3. U. Riechert, M. Bösch, J. Smajic, A. Shoory, M. Szewczyk, W. Piasecki, S. Burow, S. Tenbohlen, Mitigation of Very Fast Transient Overvoltages in Gas Insulated UHV Substations, CIGRE 2012
4. J. Helmer, M. Lindmayer, Mathematical Modeling of the High Frequency Behavior of Vacuum Interrupters and Comparison with Measured Transients in Power Systems (IEEE XVII th International Symposium on Discharges and Electrical Insulation in Vacuum, Berkeley 1996).
5. Wong S. M., Snider L. A., Lo E. W. C.: “Overvoltages and reignition behaviour of vacuum circuit breaker”, International Conference on Power Systems Transients (IPST), New Orleans, USA, 2003
6. H. W. Dommel, W. S. Meyer: “Computation of Electromagnetic Transients,” Proceedings of the IEEE, vol. 62, no. 7, July 1974, pp. 983-993
7. D. Povh, H. Schmitt, O. Volcker, et al., “Modeling and Analysis Guidelines for Very Fast Transients”, IEEE Power Engineering Review, Volume: 17, Issue: 13, 1996
8. IEC 62271-102, “High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches”
9. M. Szewczyk, W. Piasecki, M. Stosur, U. Riechert, J. Kostovic, “Impact of Disconnector Design on Very Fast Transient Overvoltages in Gas-Insulated UHV Switchgear”, Proceedings of 17th International Symposium on High Voltage Engineering (ISH), August 22nd – 26th, Hannover, Germany