Impact of De-Energization of 33kV Harmonic Filter on TRV of Vacuum Circuit Breakers

P. Marini

***Abstract*—In some oil & gas plants, 33 kV large harmonic filters are needed for the aim of both compensating the overall power factor of the plant and for filtering the harmonic current distortion caused by the variable speed drives.**

In case of the de-energization of the filter bank by means of the switching of a vacuum circuit breaker, the vacuum interrupter is subject to a great dielectric stress when the voltage recovers at its terminals: the reason of this particularly high stress lies in the series connection of the reactor coil with the capacitor in order to realize the proper harmonic filter order. Consequently, it can happen that the rated peak value of the transient recovery voltage (TRV) of the vacuum circuit breaker is exceeded.

Useful considerations, based on IEC standards for high voltage circuit breakers as well as on laboratory tests performed on vacuum interrupters by switchgear manufacturer, are carried out in order to specify the vacuum circuit breaker's rated voltage which is most suited for handling the filter switching duty.

***Keywords*: harmonic filter, switching, de-energization, TRV, vacuum circuit breaker.**

I. Introduction

IT is quite common in oil and gas plants that large synchronous motors fed by line commutated inverter drives (e.g. motors rated 5 to 30 MW) are used to drive compressor machines required by this type of industrial process [1]. These line commutated drives generate a high content of current harmonic distortion with very low power factor (usually 0.8 lagging, at 50Hz) towards the 33 kV switchgear from which they are supplied: therefore, several large harmonic filters made of capacitor banks equipped with de-tuned type series reactors [2], are needed for the aim of both improving the overall power factor of the plant to a higher value (usually 0.95 lagging, at 50Hz), as well as for attenuating the harmonic voltage distortion caused by the harmonic currents injected by the drives into the supply network.

The harmonic filters can be switched - on or off - several times during each year of normal plant operation, due to the frequent variation of loading for the compressors. The de-energization of one harmonic filter, although it does not correspond to the same condition as the clearing of a short circuit fault, can pose anyway a huge stress on the terminals of the vacuum circuit breaker used to switch the harmonic filter [3]: especially for low order (e.g. the 3rd) harmonic filters, it can happen that the minimum 36 kV rated insulation level commonly foreseen by IEC standards [4], is no longer sufficient to guarantee that the TRV of the circuit breaker be not exceeded, but it is necessary to select 40.5 kV as rated insulation level: a new study approach, non existing in the literature, is here presented in order to assess the filter de-energization and to ensure that the insulation rating of the vacuum circuit breaker is correctly determined.

Paolo Marini is with the Department of Electrical Engineering, Maire Tecnimont Group, Milan, Italy (e-mail: p.marini@tecnimont.it).

Paper submitted to the International Conference on Power Systems Transients (IPST2019) in Perpignan, France June 17-20, 2019

II. System Data and Modeling

A. System Data

The electrical distribution scheme of a typical industrial plant, in which large harmonic filter banks are applied, is shown in Fig. 1.

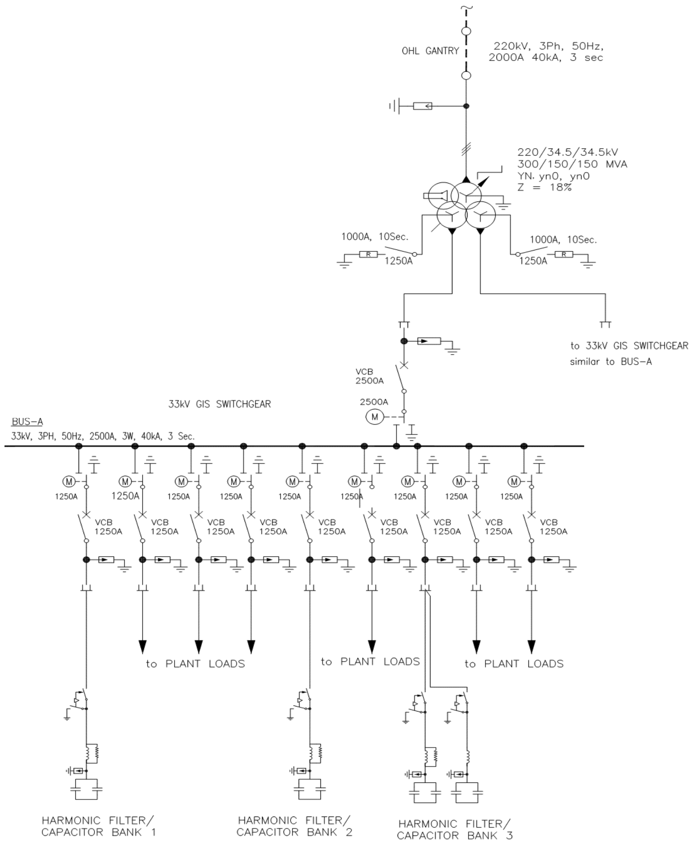


Fig. 1. Single-line diagram of a typical industrial scheme with filters

Main electrical parameters, for the main network components of the actual plant configuration being object of the study, are reported in the Appendix.

B. Modeling

For the aim of numerical simulation by ATP (Alternative Transient Program) [5], [6], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [7].

All equivalent impedances of the network components are referred to the harmonic filter bank operation voltage (33 kV).

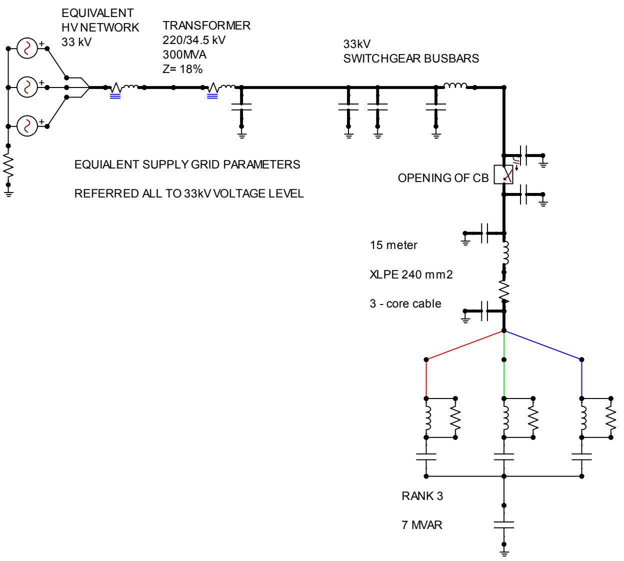


Fig. 2. ATP model of the electrical system under study

Only the filter bank being tuned to the lowest harmonic order (3rd) is taken into consideration, because it will give the worst effect on the circuit breaker TRV during the de-energization switching operation. The filter bank is modeled as a series connection between the harmonic current blocking reactor (L component) and the capacitor (C component) for the power factor improvement, hence as a first order filter made of an L-C series connection. An additional damping resistor (R) is connected in parallel to the capacitor to attenuate the voltage amplification effect due to harmonic resonance between L-C filter and supply network in steady state conditions.

Main transformer is modeled by means of its short circuit impedance.

Supply cable feeding the filter bank is modeled with as a lumped parameter Π circuit, since it is an electric short line due to its small route length of few tens of meters.

The equivalent impedance of the supply network is derived from the corresponding value of available minimum short power at the point of common coupling of the industrial plant to the supply grid.

The capacitance to earth values of main equipment (transformer, switchgear busbars, instrument transformers, circuit breaker) are taken from reference standard [8].

The vacuum circuit breaker of the capacitor feeder is modeled as time controlled ideal switch, i.e. a switch that opens at a pre-determined time, by considering also a non-simultaneity between poles. The arc quenching behavior of the vacuum circuit breaker is not modeled, because the intention of this work is not to study the phenomena of reignitions, restrikes and non-sustained disruptive discharges which could occur inside the vacuum interruption chamber during the breaking, and since the vacuum circuit breaker is of type C2 (i.e. with very low probability of restrikes) as per relevant IEC standards [4]. Hence the aim of this study is to evaluate the inherent TRV at breaker terminals, occurring during a normal opening operation of the harmonic filter bank.

III. Pre-Analysis and Assumptions

Before performing numerical simulations, few theoretical considerations are first discussed to evaluate the TRV during the de-energization switching duty and to define the rated insulation level for the vacuum circuit breaker.

A. Phenomenon of capacitor de-energization

It is well known from technical literature [9], [10], [11], that a capacitor de-energization gives rise to a circuit breaker TRV having typically an initial small voltage jump with high rate-of-rise as transient contribution, followed by a (1 - cosine) continuation of the recovery voltage with much lower rate-of-rise being practically at power frequency.

The initial very steep rate-of-rise of the TRV could give rise to reignitions at relatively low levels of voltage, i.e. breakdowns occurring shorter than a quarter of the power frequency cycle (5 ms at 50 Hz), but the energy involved in this reignition breakdown event is usually very limited and is generally of no concern [10]. Also laboratory type tests performed by switchgear manufacturer confirmed that the initial TRV does not influence the breaking capability of the vacuum circuit breaker.

For a three-phase non-effectively earthed capacitive load, the recovery voltage of the first-pole-to-clear can reach theoretically a peak of 2.5 times the supply voltage peak if the two last poles interrupt 90 electrical degrees (5 ms at 50 Hz) after the first, or even a peak of 3 times the supply voltage peak if the interruption occurs after 180 electrical degrees (10 ms at 50 Hz) [3], [11]. This peak could instead exceed the reference standard test values of TRV peak, thus causing restrikes being harmful for the interrupting chamber, since now the breakdown occurs more than a quarter of the power frequency cycle after current interruption and the energy involved in the breakdown is more significant than in case of reignitions [10].

B. Effect of harmonic filter on voltage stress

When harmonic filter banks are interrupted, the stress on the circuit breaker when the voltage recovers at its terminals is greater than on circuit breakers feeding other loads. The reason for this lies in the series connection of the reactor coil and the capacitor which created a series resonance condition in order to realize a filter properly tuned to the needed harmonic order.

When the switching circuit breaker is in closed condition, the filter voltage and the supply system voltage (U_N) are equal.

As the capacitor stores electrical charge, the capacitor voltage (U_C), being higher than system voltage, is applied to the circuit breaker after switching-off. The filter voltage after interruption is equal to the capacitor voltage (U_C), which is found simply by calculating the voltage divider between capacitor and reactor and by normalizing the result as a function of the harmonic number (n) used as parameter:

$$U_C = U_{N\max} \frac{n^2}{n^2 - 1} \quad (1)$$

where:
U_C = voltage at capacitor
$U_{N\max}$ = maximum system operating voltage
n = harmonic number
= √(capacitor reactance / inductor capacitance).

The ratio ($U_C/U_{N\max}$) can be seen as an overvoltage factor for the normal operating voltage of the filter capacitor. By plotting the ratio ($U_C/U_{N\max}$) as a function of the harmonic number (n), the trend shown in the following figure is found:

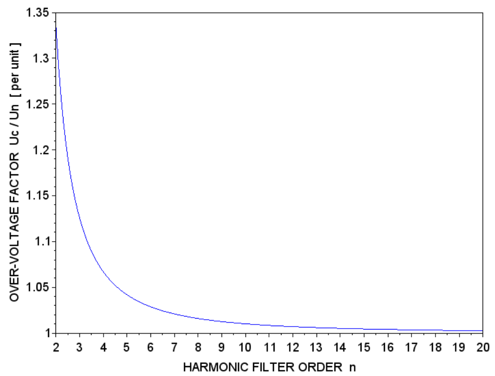


Fig. 3. Overvoltage factor of the filter capacitor vs. harmonic order

C. Simplified Evaluation of TRV

The TRV on the breaker (first-pole-to-clear) depends on the load side voltage line-to-earth and the line side (bus bar) voltage line-to-earth [9]. All these voltages can be computed as follows.

$$U_{N\max} = 1.1 * U_N = 1.1 * 33kV = 36.3kV \quad (2)$$

where:
$U_{N\max}$ = maximum system operating voltage
1.1 = factor to account for both voltage variation due to supply voltage variation and to the voltage increase due to harmonic currents which flow in the 33kV system
U_N = rated system operating voltage.

$$U_C = U_{N\max} \frac{n^2}{n^2 - 1} = 36.3kV * \frac{3^2}{3^2 - 1} = 40.84\,kV \quad (3)$$

where:
U_C = filter capacitor voltage
$U_{N\max}$ = maximum system voltage as per (2)
n = harmonic number (3^{rd}, 3*50 Hz = 150 Hz)

$$U_L = U_C * \sqrt{\frac{2}{3}} * 1.5 = 40.84kV * \sqrt{\frac{2}{3}} * 1.5 = 50.02kV \quad (4)$$

where:
U_L = load side voltage of circuit breaker
U_C = filter capacitor voltage as per (3)
√(2/3) = factor to get the peak phase-to-earth value
1.5 = first pole-to-clear factor, as per [3], [4]

$$U_S = U_{N\max} * \sqrt{\frac{2}{3}} = 36.3kV * \sqrt{\frac{2}{3}} = 29.64kV \quad (5)$$

where:
U_S = system side (bus) voltage of circuit breaker
$U_{N\max}$ = maximum system voltage as per (2)
√(2/3) = factor to get the peak phase-to-earth value

As the system side voltage alternates between positive and negative maximum peak value, and since the loads side remains charged at the peak value of the capacitor bank because discharging may last for up to 5 minutes maximum, the TRV on the first-pole-to-clear results then equal to the following peak value:

$$U_{TRV,1pole} = U_L + U_S = 50.02kV + 29.64kV = 79.7kV \quad (6)$$

where:
$U_{TRV,1pole}$ = TRV on first-pole-to-clear
U_L = load side voltage as per (4)
U_S = system side voltage as per (5).

IV. Results

The results of numerical simulations are shown graphically in the following figures. Voltages across circuit breaker terminals are chosen as the most significant magnitudes which will be compared with the reference laboratory tested TRV.

A. De-energization with 5 ms pole non-simultaneity

Capacitor is switched-off by giving the opening command to the first circuit breaker pole at 10 ms, while the opening command to last two poles is triggered 5 ms later.

The next figure shows the resulting actual TRV across the circuit breaker, for each phase:

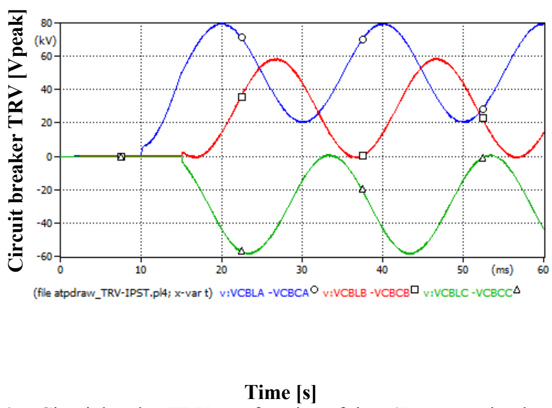


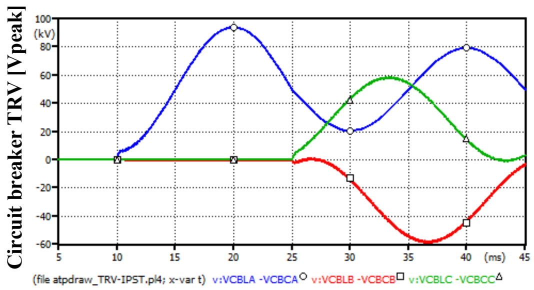
Fig. 4. Circuit breaker TRV as a function of time (5 ms non-simultaneity)

It can be seen that the TRV is mostly made of a recovery voltage waveshape at power frequency (in reality there is also a higher frequency ripple superimposed on the power frequency but it is practically negligible), while the most significant transient effect occurs mainly in the initial small voltage jump having a steeper rate of rise than the subsequent recovery voltage shape. The worst peak value of recovery voltage is reached on phase A and it is equal approximately to 80 kV: this peak value is quite in line with the result (79.7 kV) calculated though the simplified numerical procedure being treated previously.

B. De-energization with 10 ms pole non-simultaneity

Worse effects on TRV can be obtained in case the opening command to the last two poles is triggered with further delay, being equal in this case to 10 ms instead of 5 ms.

The next figure shows the resulting actual TRV across the circuit breaker, for each phase:



Time [s]

Fig. 5. Circuit breaker TRV as a function of time (10 ms non-simultaneity)

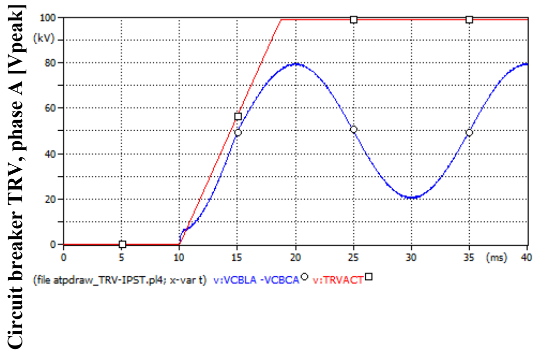
The worst peak value of recovery voltage is reached on phase A and it is equal approximately to 94 kV.

C. Simulations versus Manufacturer laboratory tests

Since no international IEC standards exist for the switching-off duty of harmonic filter equipment, with respect to what is instead standardized for the terminal fault, the short-line fault, and the out-of-phase duties, of reactors and capacitors considered separately [3], [4], it is strictly necessary to require the Manufacturer of vacuum circuit breaker to perform special type tests which assess the switching duty also for this new scenario and to define a reference test TRV.

The Manufacturer was obviously not in the condition to test exactly the same electrical circuit configuration as the one installed in the industrial plant, but he conservatively decided to consider a harmonic filter tuned at the 2^{nd} harmonic order which is the worst theoretical condition for the capacitor over-voltage as it was shown in previous Fig. 3 of subsection B of Section III.

The next figure shows the comparison between the simulated first-to-pole clear TRV, for the case of 5 ms non-simultaneity between poles, and the reference laboratory test TRV:

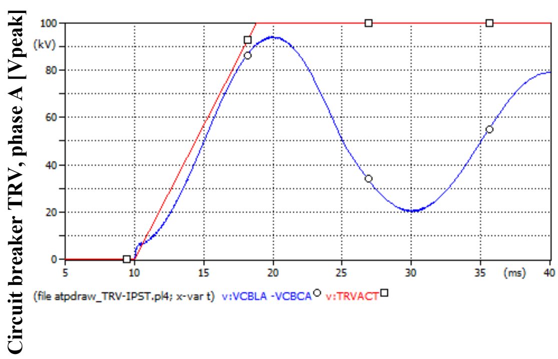


Time [s]

Fig. 6. Simulated TRV (5 ms non-simultaneity) vs. laboratory tested TRV

The laboratory tested two-parameter TRV has a peak value of 100 kV, with a time to peak value of 8.7 ms, and it is referred to a rated insulation voltage of 40.5 kV for the vacuum circuit breaker. Hence, in order to access properly the switching duty of the vacuum circuit breaker feeding the harmonic filter, the Manufacturer deemed suitable to select the next available IEC insulation coordination level [12], with respect to the minimum available level of 36 kV which was the insulation rating initially selected for the 33 kV gas insulated switchgear where the vacuum circuit breakers were installed.

The next figure shows the comparison between the simulated first-to-pole clear TRV, for the case of 10 ms non-simultaneity, and the reference laboratory test TRV:



Time [s]

Fig. 7. Simulated TRV (10 ms non-simultaneity) vs. laboratory tested TRV

It can be seen that also in this worst case, the simulated recovery voltage is still within the reference test TRV of 40.5 kV vacuum interrupter.

V. CONCLUSIONS

The resonance effect given by the series connection between reactor and capacitor and which is needed to realize a certain tuning for the harmonic filter, introduces a permanent over-voltage on the filter capacitor during its normal steady state operation, and this over-voltage then badly impact the TRV across breaker poles after their separation. This scenario is not yet standardized into IEC standards for high voltage circuit breakers, therefore final user of the industrial plant should always require switchgear manufacturers to perform special tests in order to assess the switching-off duty of the vacuum interrupters.

The lower the harmonic order to which the filter is tuned, the greater the voltage stress imposed on the circuit breakers terminals after contacts separation. In the case study, the 5th harmonic order was the most significant for the VSD equipment installed in the plant, and the filter capacitor was tuned at the 3rd order in such a way that the injected 5th harmonic current flows partly into the 33 kV supply network and partly into the harmonic filter.

The insulation level of 40.5 kV is not yet recognized by IEC standards as a standard insulation coordination level [12]: anyway, it is mentioned in the same IEC standard that it is a current practice insulation level used in some countries, like most European countries. The adoption of 40.5 kV insulation level in lieu of 36 kV allowed the manufacturer of vacuum circuit breakers to use only one interrupter chamber, while with 36 kV insulation level manufacturer should have used two breakers in series in order to handle the resulting TRV in presence of the worst theoretical 2nd order harmonic filter, with consequent complication in the management of control logics of breakers during the normal operation of capacitor banks requested to compensate the power factor under load variations.

Numerical simulations carried out by EMTP-ATP software proved to be very useful tool to correctly assess the proper insulation level of vacuum circuit breakers used for the switching of harmonic filters, especially for the condition of non-simultaneity among breaker poles. For circuit breakers feeding harmonic filters, as confirmed also by the experience of manufacturer of circuit breakers, it is not sufficient to verify only the fault duties due to terminal faults, like test types T10, T30, T60, T100 as per IEC standards [4], but it is always necessary to study additionally the de-energization of the harmonic filter bank: in fact, for harmonic filter equipment their normal switching-off operation becomes the key factor to select the proper insulation rating of vacuum circuit breaker.

VI. APPENDIX

A. Equipment stray capacitance parameters

The capacitance to earth typical values of main equipment are estimated on the basis of technical literature [8], and they are shown in the following table:

TABLE I
CAPACITANCE TO EARTH VALUES OF MAIN EQUIPMENT

Parameter	Capacitance
Transformer bushing	0.03 µF
Potential transformer	125 µF
Current transformer	75 µF
Gas insulated switchgear busbar	164 µF
Vacuum circuit breaker open-gap	2 x 0.02 µF
Filter bank cable feeder	2 x 0.00165 µF

B. Electrical Network Components Data

TABLE II
DISTRIBUTION TRANSFORMER

Equipment	Parameters
Transformer dedicated to the supply of main distribution 33 kV switchgear bus bar	300 MVA rated power
	220 / 34.5 rated voltage ratio
	Z_T = 18% short circuit impedance (referred to rated power)
	L_T = 2.08 mH inductance/phase (at 33 kV)
	R_T = 0.022 Ω resistance/phase (at 33 kV)

TABLE III
HARMONIC FILTER BANK

Equipment	Parameters
Capacitor: - improves the power factor - regulating step with lowest tuning harmonic order	33 kV Rated operating voltage
	7 MVAR Rated operating reactive power
	123 A Rated operating current
	C = 20.5 µF capacitance/phase
	X_C = 155.6 ohm Capacitor reactance/phase
	Cn = 0.015 µF Capacitance between star neutral point and earth
	Double-Star phase connection
Series reactor: - limits the capacitor inrush current - filters the harmonic currents generated by distorting non-linear equipment	L_L = 55 mH Reactor inductance/phase
	R_L = 583 Ω parallel damping Resistance/phase
	X_L = 17.3 Ω Reactor reactance/phase
	$n = \sqrt{(X_C/X_L)} = 3$ harmonic tuning factor (3*50Hz = 150Hz) of the L-C filter
	Air-core reactor type

TABLE IV
SUPPLY NETWORK

Equipment	Parameters
Equivalent Network at the point of common coupling for the industrial plant	220 kV rated voltage
	50 Hz rated frequency
	2668 MVA min. 3-phase short circuit power
	7 kA min. 3-phase sub-transient short circuit current at rated voltage
	X/R = 10 reactance to resistance ratio
	L_N = 1.3 mH inductance/phase (at 33 kV)
	R_N = 0.0408 Ω resistance/phase (at 33 kV)
	R_G = 19 Ω 33 kV neutral earth

VII. ACKNOWLEDGMENT

The author gratefully acknowledges the Electrical Department of Maire Tecnimont Group, for the consultation of the available technical literature.

VIII. REFERENCES

[1] L. Moran, C. Albistur, R. Burgos, "Multi-Mega VAR Passive Filters for Mining Applications: Practical Limitations and Technical Considerations," *Industry Applications Society Annual Meeting, 2015 IEEE,* 18-22 Oct. 2015.

[2] Industrial a.c. networks affected by harmonics - Applications of filter and shunt capacitors, IEC Standard 61642, September 1997.

[3] High-voltage switchgear and controlgear, Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating current circuit-breakers, IEC/TR Standard 62271-306, December 2012.

[4] High-voltage switchgear and controlgear, Part 100: Alternating current circuit-breakers, IEC Standard 62271-100, April 2013.

[5] E. Haginomori, T. Koshiduka, J. Arai, H. Ikeda, *Power System Transient Analysis. Theory and Practice using Simulation Programs (ATP-EMTP)*, John Wiley & Sons, 2016.

[6] *Alternative Transient Program (ATP) - Rule Book*, Canadian/American EMTP User Group, 1987-92.

[7] H. W. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, Canada, 1992.

[8] IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers, IEEE Standard C37.011, 2005.

[9] L. van der Sluis, *Transients in Power Systems*, John Wiley & Sons, 2001.

[10] R. Smeets, L. van der Sluis, M. Kapetanovic, D. Peelo , *Switching in Electrical Transmission and Distribution Systems*, John Wiley & Sons, 2015.

[11] D. F. Peelo, *Current Interruption Transients Calculation*, John Wiley & Sons, 2014.

[12] Insulation co-ordination, Part 1: Definition, principles and rules, IEC Standard 60071-1, January 2006.