Interruption of small, medium-voltage transformer current with a vacuum circuit breaker

Alain Xemard, Bruno Jurisic, Michel Rioual, Arthur Olivier, Eric Selin

Abstract--Vacuum circuit breakers are known to potentially cause voltage escalation when interrupting small currents. Consequently, their installation in electrical systems may require the use of specific means aiming at reducing overvoltages. In this paper, the subject is explored in a configuration of an industrial plant. A medium-voltage transformer is connected to the electrical feeding system using a cable equipped with a breaker on the opposite terminal. The risk of voltage escalation is studied when the transformer loaded with a small inductive load is switched off. The study is conducted with an EMTP-like software program; a detailed high-frequency model of the transformer is used as well as a VCB model able to represent current chopping and restriking. The protection provided by surge arresters and a filter is also studied.

***Keywords*: EMTP-like software program, vacuum circuit breaker, current chopping, high frequency transformer model, voltage escalation, insulation coordination.**

I. INTRODUCTION

Vacuum Circuit Breakers (VCBs) have been widely used in the medium-voltage systems of industrial plants because of their performance, competitive price and cheap maintenance. Today according to [1], 80% of new medium-voltage systems make use of vacuum switching technology. A well-known important issue with vacuum circuit breakers is that the overvoltages occurring at the interruption of small inductive currents can lead to the failure of some apparatuses if appropriate measures are not taken to limit them [1][2][3]. The paper explores the subject for a configuration in which a VCB switches a lightly loaded transformer located at the terminal of a cable. Based on a detailed electromagnetic representation of the system, it determines if a risk of high overvoltages exists when opening the VCB and studies the efficiency of various solutions aimed at reducing these overvoltages.

The 2nd paragraph briefly presents the behaviour of VCBs regarding overvoltages and voltage escalation. The 3rd paragraph details the configuration considered in the study and its modelling with an EMTP-like program. The last paragraph presents an analysis of the overvoltages based on numerical simulations. The paper ends with conclusions.

The main idea of the paper is to evaluate the performance of different solutions aimed at limiting the risk of voltage escalation on a real, industrial configuration based on a detailed high-frequency representation of the transformer.

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II. VACUUM CIRCUIT BREAKERS AND VOLTAGE ESCALATION

Vacuum circuit breakers are common in an industrial environment at nominal voltage system levels up to 72 kV. They are reliable and generally cheaper than other technical solutions. As with other circuit breakers, their operating principle is to separate two contacts in order to interrupt the current. After separation of the contacts an electrical arc is created and quenched in order to open the circuit. The VCB uses vacuum as it has high insulation properties: theoretically, vacuum is the best insulation component as there is no material to carry charges if it is absolute (in a vacuum circuit breaker, the pressure can reach a typical value of 10^{-4} P [4]) .The principle of current interruption by a VCB is the following: at the separation of the contacts, metal vapour is created in the vacuum chamber constituted of ions liberated from the contacts. The arc existing between both contacts can disappear before reaching the natural zero-current crossing. This phenomenon is known as current chopping [5] and exists when interrupting small currents (typically lower than 600 Amps).

This current chopping can be at the origin of significant overvoltages when small inductive currents are interrupted [6] [7]. In the configuration presented in fig. 1, an inductive load is connected to the feeding network via a cable. When the current through the VCB is interrupted the energy stored in the inductive load oscillates between the inductive load and the capacitance C (which is constituted of the stray capacitance of the load associated with the capacitance of the cable connecting the VCB to the load).

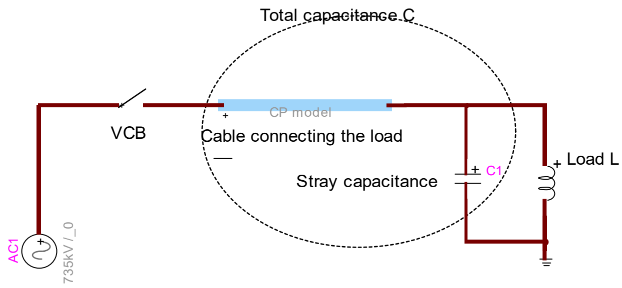

Fig. 1. Opening of an inductive load with a VCB.

In a single phase configuration, the overvoltage at the load, following the interruption of the breaker current, is sinusoidal with a frequency f, and a value V_{ch} respectively given by:

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$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

$$V_{ch} = I_{break}\sqrt{L/C} \quad (2)$$

This overvoltage creates a fast increase of the Transient Recovery Voltage (TRV) between the contacts of the VCB. If these contacts are not distant enough to have a sufficient withstand strength, a reignition occurs which generates a high frequency current inside the VCB.

A specific characteristic of VCBs compared to other types of breakers is their ability to interrupt high frequency currents [1]. Therefore, this high frequency current following a reignition can be chopped leading once again to the existence of overvoltages. The same cycle can take place several times, generating each time higher overvoltages. This phenomenon is called voltage escalation and can be at the origin of dangerous overvoltages. It appears only when the separation of the contacts takes place close to the natural zero-current crossing. If the separation takes place far from the natural zero-current crossing, at the interruption of the current, the distance between the contacts is sufficient to withstand the TRV between the terminals of the breaker.

Moreover, in a three-phase system, the induction between the phases can cause "virtual current chopping". In case of chopping / reignition on one phase, the capacitive and magnetic coupling with the other phases which conduct the power-frequency current can generate a high-frequency current on these phases which superimposes on the power-frequency current and can lead to current chopping.

All of these phenomena have to be considered because they can generate high frequency overvoltages which can damage the load, especially inductive loads (like a transformer) and whose reduction may often necessitate the use of overvoltage limiters [15]. Voltage escalation cannot exist if the current to be interrupted exceeds 600 A. The arc does not extinguish at the first current zero when the contacts are open, and at the next current zero the distance between the contacts has increased and consequently the dielectric strength between the contacts is sufficient to withstand the TRV [6].

III. Description of the Configuration Under Study

This study focuses on a 10 kV three-phase system with a feeding network delivering power to a lightly loaded MV / LV 630 kVA Dy11 transformer through a 25 m long cable.

A VCB is installed at the beginning of the cable on the side of the feeding network. The LV side of the transformer supplies a star connected load whose neutral is solidly grounded (L= 4 mH, R = 0.2 Ω).

The system considered in the study is presented in the fig. 2. below.

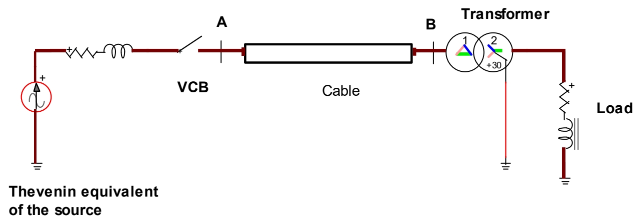


Fig. 2. System considered in the study.

IV. Modelling of the System

The system was modelled with the software program EMTP-RV [4] according to [9] in order to represent fast front overvoltages. The modelling of each component is presented in the following subparagraphs.

A. *Representation of the VCB*

The VCB modelled according to [6], [7] is based on the following characteristics:

- The chopping current is a parameter of the model; it was chosen equal to 5 Amps in the study;
- The maximum value of the variation of the current which the VCB can interrupt is an affine function of the time following the separation of the contacts;
- The withstand voltage of the VCB is an affine function of the time following contacts separation (this approximation is valid for a distance up to a few millimeters between the contacts [6]);
- The minimum time which can occur between two re-ignitions of the VCB; physically, two re-ignitions cannot occur within this delay, the ionized gas takes time to restore and re-ionize.

The statistical variation of the parameters [14] is not taken into account, nor is the impedance of the arc, contrary to [6].

The control of the switch representing the breaker was developed with the control library of the software program based on the rules listed above.

B. *Representation of the transformer*

The grey box model used in this study has been presented in detail in [10] and this paragraph recalls its main characteristics. It is based on a lumped RLCG network and a segmentation of the transformer geometry. Its parameters are deduced from the transformer geometry and properties of material. Each RLCG element represents a physical part (segment) of the transformer's windings. As an example, Fig. 3 represents an

RLCG network, which corresponds to one phase of a two-winding transformer with only one segment per winding.

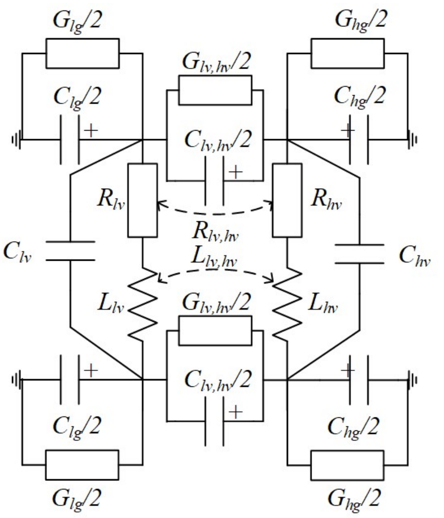


Fig. 3. RLCG network for one phase of a two-winding transformer.

The transformer model is constituted of the inductances, capacitances and resistances of the windings themselves, the mutual inductances and resistances (related to proximity effect), capacitances and conductances between the windings and the capacitances and conductances to the ground. It is valid up to a few hundred kHz. It is considered that, in this frequency range, the capacitances are constant versus frequency, while conductances, resistances and inductances vary versus frequency. To calculate them the field calculation program FEMM is used. The concept of complex permeability is used to calculate the inductance and resistance in order to limit the calculation time [11]. In FEMM, magnetic and electrostatic solvers for a 2D axisymmetric geometry are used to calculate respectively both the RL and CG parameters. The transformer geometry is segmented into "electrical elements" according to the frequency range of interest. When calculating RL elements, the transformer core is represented as a nonconductive linear magnetic material with the complex magnetic permeability. As the magnetic flux is shielded from the transformer core at high frequencies, it acts as a linear magnetic material [16].
The main steps for the establishment of the model and its inclusion in the software program utilized are recalled in fig. 14 of appendix B. More details about the transformer model and parameter calculation can be found in ref. [17].

C. *Representation of the other elements*

The source is represented as a 10 kV Thevenin equivalent whose impedance leads to a three phase short-circuit current of 4.75 kA RMS. The source is connected to the transformer with 3 630 mm2 single core cables, whose sheaths are grounded at both ends, represented with a FDQ model [9].

V. CALCULATION OF THE OVERVOLTAGES AT THE OPENING OF THE VCBS AND EVALUATION OF SOLUTIONS AIMING AT MITIGATING OVERVOLTAGES

A. *Case without overvoltage limiting device*

The opening of the VCB was studied when no overvoltage limiting device is used. Fig. 4 below shows an example of the phase to ground overvoltages which appear at the HV terminals of the transformer after opening of the VCB. The results presented in this figure are similar to results already available in the relevant literature [2][3][6][14][15].

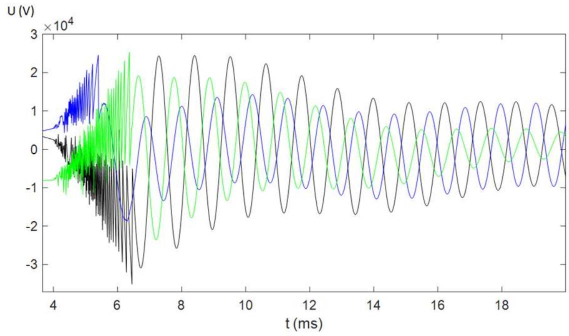


Fig. 4. Overvoltage (V) at the HV terminals of the transformer.

In the simulation, the separation of the contacts of the VCB had been chosen at a time when the current circulating in the VCB is close to zero on phase c (green). This means that the current interruption takes place at a time when the separation of the contacts is not sufficient to withstand the transient recovery voltage occurring after separation (see II). The opening of the VCBs produces, during arc time, a phenomenon of voltage escalation due to current extinctions and reignitions (see fig. 5), which ends when the breaker contacts are distant enough to withstand the TRV.

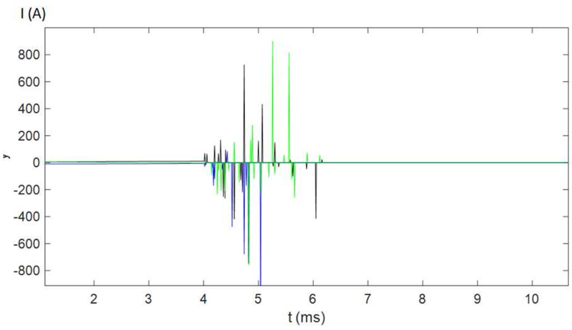


Fig. 5. Current (A) circulating in one phase of the VCB. It is constituted of a series of impulses due to the successive arc interruptions and reignitions.

The maximum value of this overvoltage during voltage escalation is 4.3 p.u. (with 1 p.u. = 8.163 kV). It should be noted that, because of the coupling between phases, the electromagnetic transient on one phase is able to create zero current crossing on the other phases (and, consequently, current chopping followed by restrikes). The voltage escalation is followed by severe oscillations lightly damped at a frequency of 910 Hz. This oscillation is related to a resonance frequency of the system seen from the HV terminals of the transformer (as shown in the figure below), which represents the input impedance Zaa of the phase a of the system versus frequency (seen from the HV terminal of the transformer when it is loaded as indicated in IV.C).
A frequency scan study conducted with the software program has shown that this resonance frequency is directly related to the presence of the inductive load. When this load is

disconnected, this specific resonance disappears.

It has to be discussed whether or not this strong oscillation is related to the existence of the series of reignition after the separation of the VCBs' contacts.

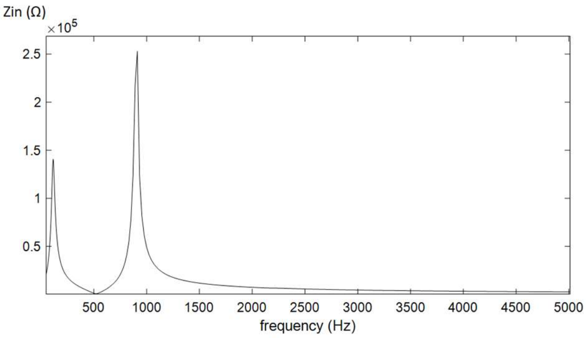


Fig. 6. Input impedance of the phase a of the system versus frequency at the HV terminal of the transformer when the transformer is loaded.

Simulations were performed without current chopping and without reignitions. They have shown that, even if the oscillation does exist, the overvoltages are significantly less severe. Fig. 7 below shows the phase to ground overvoltages at the HV terminals of the transformer when the contacts of the breakers (which do not chop current and do no restrike) separate at 4 ms (time similar to the one used for the VCBs). It can be seen that the crest value of the overvoltages is significantly lower than the crest value obtained when opening the restrike-free breakers: 1.85 p.u.

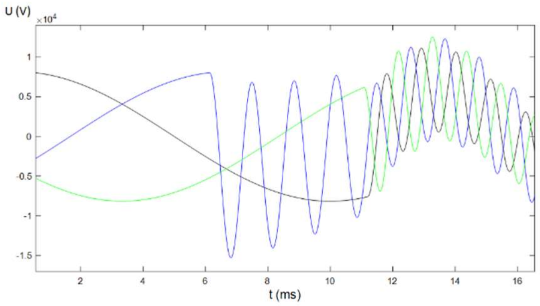


Fig. 7. Phase to ground overvoltages (V) at the HV terminals of the transformer when the restrike-free breakers are opened at 4 ms.

As the crest value of the overvoltages might depend on the time at which the breakers open, a systematic study was conducted in order to determine the crest value of the overvoltage versus time when the breakers do not chop current and do not reignite. The maximum value of the overvoltages found was 2.6 p.u., much less than in the case of voltage escalation.

B. Case with surge arresters at the load terminals

As the overvoltages obtained when opening the VCBs are too severe to be withstood by the equipment, a protection with arresters (the characteristic is given in appendix A) at the transformer terminals is studied (location B of Fig. 2. above). Fig. 8 below shows that the overvoltage obtained when the VCB contacts separate at 4 ms are reduced to 2.64 p.u. (21 kV). This severe overvoltage occurs during voltage escalation. According to IEC 60071-1 [12], the standard-rated short duration power frequency withstand voltage and the minimum rated lightning-impulse withstand voltage are respectively 28 kV (r.m.s value) and 60 kV (minimum) for 12kV equipment. These values are higher than the overvoltages but the differences between the simulated overvoltages and the standard voltage shapes for tests [12] should prompt caution. These overvoltages can potentially cause internal damage to the transformer [13]. If it is planned to disconnect the transformer frequently, the risk of damaging it should be studied carefully.

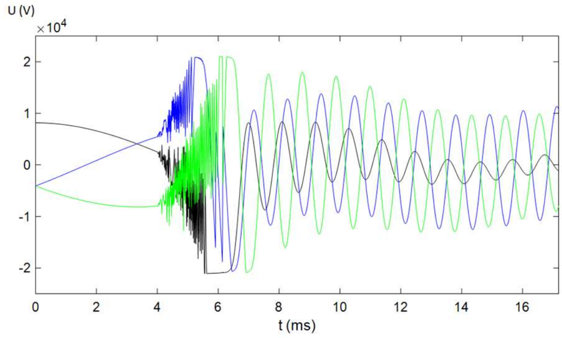


Fig. 8. Phase to ground overvoltages (V) at the transformer MV terminals when arresters are installed directly at the transformer.

Fig. 9 below shows the phase to ground overvoltages at the other side of the cable, after the breaker (location A of Fig. 2.). It can be seen that these overvoltages are similar to the ones experienced at the terminals of the transformer. This is due to the short length of the cable between the VCBs and the transformer (25m).

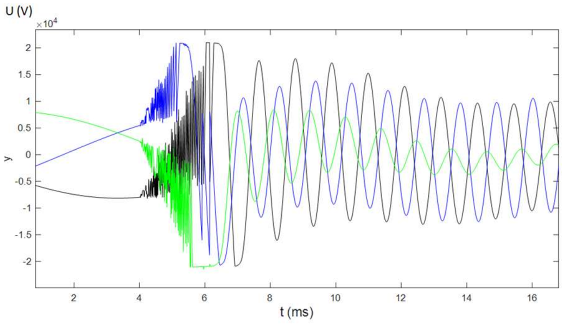


Fig. 9. Phase to ground overvoltages (V) at the source terminals, after the VCBs, when the arresters are installed at the transformer.

C. Case with surge arresters at the source side

In this paragraph the surge arresters are installed on the source side after the VCBs (location A of Fig. 2.). The phase to ground overvoltages at the terminal of the transformers and on the source side of the cable are respectively shown in the fig. 10 and fig. 11 below.

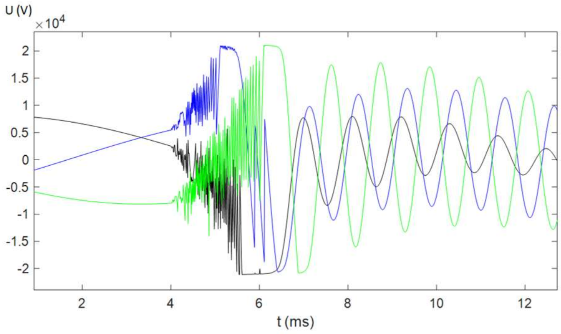


Fig. 10. Phase to ground overvoltages (V) at the transformer's terminals, after the VCBs when the arresters are installed at the source side.

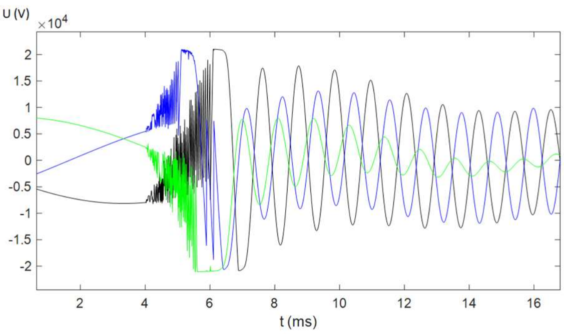


Fig. 11. Phase to ground overvoltages (V) at the source terminals, after the VCBs, when the arresters are installed at the source side.

It can be seen that the position of the surge arresters does not have a significant influence on the overvoltages because of the short length of the cable.

D. *Case with a filter close to the VCBs*

The installation of a RC filter close to the VCBs (location A of Fig. 2.), instead of arresters is studied. R and C have respectively the value 30 Ω and 200 nF. The goal of the filter is to reduce the velocity of increase of the TRV and therefore limit the risk of having a reignition. Figure 12 below shows the phase to ground overvoltages at the transformer when opening the VCBs at 4 ms.

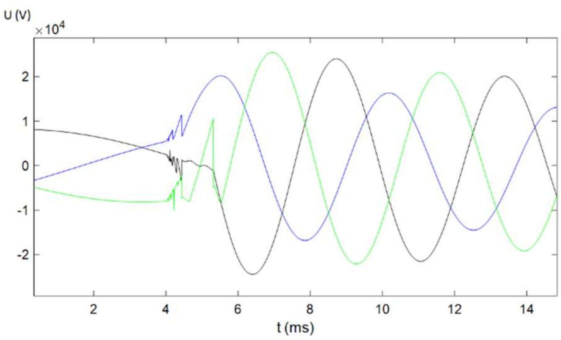


Fig. 12. Phase to ground overvoltages (V) at the transformer's MV terminals when a RC filter is placed close to the VCB

It can be seen that the number of reignitions is reduced. Moreover, these reignitions do not cause severe overvoltages. A systematic study of the overvoltages versus the opening time of the VCBs confirms this result.

VI. Conclusions

VCBs are known to potentially cause voltage escalation when interrupting small inductive currents. This paper studies a configuration in which a lightly loaded MV / LV transformer is switched off. A detailed modelling of the system is used, including a high-frequency transformer model.

It is shown that a voltage escalation phenomenon (due to a series of breakers reignitions followed by severe resonance overvoltages) is generated when the separation of the contacts takes place close to the natural zero current. These overvoltages require the installation of overvoltage limiters. The study of the installation of arresters indicates that they are an adequate solution to reduce the amplitude of the overvoltages, and that their location (close to the transformers or in the vicinity of the source) does not have a significant influence on the protection they provide in this particular configuration. However, care should be taken that the shape of the overvoltages generated by the opening of the VCBs is significantly different from the standard wave shapes (during voltage escalation as well as during the resonance part) used for testing transformers and consequently if the transformer has to be switched off frequently the risk of damaging the equipment or the risk of premature aging of the transformer should be considered carefully. These overvoltages can be at the origin of internal damage inside the transformer. The study of the stress due to voltage escalation on windings is complex because of the difficulty to accurately model VCBs.

An RC filter installed close to the VCBs seems to be an efficient solution for reducing the risk of voltage escalation in the configuration considered in the paper, even if reignitions are still present.

Considering that voltage escalation takes place when the contacts separate close to the natural zero-current crossing, the use of synchronized switching seems to be an appealing solution for frequent switching of critical loads.

VII. Appendix

A. *(V,I) characteristic of the arrester*

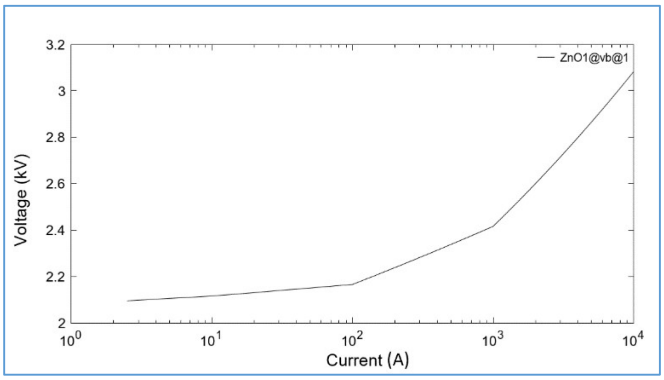
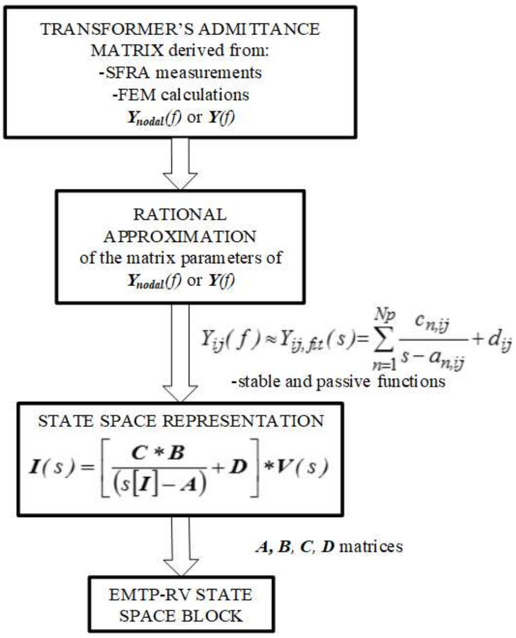


Fig. 13. Characteristic of the arrester.

B. *Outline of the procedure for establishing the transformer model and inputting it in EMTP-RV*

Fig. 14. Characteristic of the MV/LV transformer



VIII. Acknowledgment

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