Digital model of a vacuum circuit breaker for the analysis of switching waveforms in electrical circuits^{*}

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Abstract. The article presents a method of modelling a vacuum circuit breaker in the ATP/EMTP package, the results of the verification of the correctness of the developed digital circuit breaker model operation and its practical usefulness for analysis of overvoltages and overcurrents occurring in commutated capacitive electrical circuits and also examples of digital simulations of overvoltages and overcurrents in selected electrical circuits.

1 Introduction

Alternating current vacuum circuit breakers are currently the most dynamically developing constructions of low and medium voltage electro-energetic circuit breakers. Particularly in the field of medium voltage, there is a rapid increase in their participation in the global production of the circuit breakers of this voltage (Fig. 1) and in some industrialized countries (e.g. Japan, Germany) it already exceeds 50% [1]. There is a belief that it will soon be the dominant switched technique in the field of medium voltage.

The reason for such a dynamic development of vacuum circuit breakers is the number of very good technical parameters of such circuit breaker constructions which are superior when compared to other types of circuit breakers. The most important are: high durability parameters, high reliability, small size, high resistance to environmental exposures, no hazard impact of an electric arc on the environment and a significantly lower amount of required maintenance compared to other types of circuit breakers.

Apart from the aforementioned advantages, vacuum circuit breakers also have some disadvantages. Their main drawback, which in some cases limits their usage or makes them also require the use of overvoltage limiters, is the tendency to generate excessive switching overvoltages in commutated electrical circuits with large rising slopes.

Theoretical methods of determining the transition states in switching processes of these circuits enable only a very rough estimation of overvoltage values which

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Fig. 1. The participation of selected types of 3–38 kV medium voltage circuit breakers on the world market according to Eaton company [1].

may occur in these processes. This is due to the difficulty of creating an appropriate mathematical model of both a commutated circuit and also processes occurring in a circuit breaker. In turn, the laboratory tests of the physics of a vacuum arc are laborious and time-consuming and also require complicated laboratory posts and specialized measuring apparatus which makes them very expensive and limits their number. Consequently, the results enable a more qualitative than quantitative analysis of the examined phenomena. It is often necessary to conduct these studies on a wide range of changes in the external circuit parameters (e.g. in a function of the switching off of current amplitude, return voltage parameters, etc.), and also in various variants of vacuum circuit breaker constructions (with different material,

constructional, technological parameters, etc.). This is connected with the necessity of making a number of long and very expensive modifications of both the laboratory post and the vacuum circuit breaker itself.

These restrictions nearly never occur in studies based on a numerical simulation of phenomena occurring in a vacuum arc, which is carried out on the basis of mathematical and physical models describing them, and provides the ability of changing values of all the examined parameters and multi-criteria analysis of their impact on the waveforms of considered phenomena.

In the modeling of transient phenomena occurring during commutation of electrical circuits with the use of vacuum circuit breakers, the most important and the most difficult circuit element to model is a vacuum circuit breaker. The most common models of a vacuum circuit breaker which can be found in literature present it as a resistance variable [2–4] or an “ideal circuit breaker” [5]. These models provide a significant simplification of calculations, but at the same time, also provide a reduction of their accuracy and mapping fidelity of simulated transient waveforms of currents and voltages, which limits the scope of their application to qualitative analysis rather than quantitative. The main disadvantage of these models is the inability of mapping transient phenomena occurring in a very short time after the switching off of the arc, including among others: re-ignition of the arc which is a very dangerous phenomenon for both the circuit breaker and other devices installed in a commutated electrical circuit.

In the literature more complex models that more accurately map the real vacuum circuit breaker [6,7] can be found. However, even these models are not free of some disadvantages which decrease their accuracy. The most important of them is the lack of sufficiently precise relations of the modeled phenomena with specific, only for vacuum circuit breakers, technical, material and technological parameters.

Analysis of this issue also shows that, due to the significant differences in waveforms of switching phenomena occurring during the switching on of an electrical circuit and also during its switching off, more reasonable than developing one universal model of a circuit breaker for analysis of both these states of operation, is to develop two separate but much more accurate models for each of them individually. These models mainly differ in the algorithms that control the operation of the circuit breaker.

The digital model of the vacuum circuit breaker presented in the article was modelled in the package ATP/EMTP on the basis of the complex model presented in references [6,7], in which the algorithm controlling the operation of the circuit breaker was modified in a way to ensure the possible accurate mapping of the behaviour of the real vacuum switch during the switching off of an electrical circuit and considering, specific for vacuum circuit breakers, mechanisms of generating overvoltage (mechanism of natural current interruption, mechanism of forced current interruption, escalation of voltage and late re-ignitions [8,9]). An important advantage of this model is the ability to carry out with its usage a multi-criteria analy-

Fig. 2. Simplified scheme of the vacuum circuit breaker [7].

sis of switching off phenomena in electrical circuits with different configurations and parameters. The article presents the results of sample simulations of the switching off of waveforms in the selected medium-voltage capacitive circuits obtained with the use of this model.

2 Model of a vacuum circuit breaker in ATP/EMTP software

The developed digital model of a vacuum circuit breaker consists of an “ideal switch”, which is an element taken from the library of ATP/EMTP software and also a controlling algorithm which was programmed in the MODELS block of ATP/EMTP software (Fig. 2). The controlling algorithm controls the current and voltage at contacts of the “ideal switch” during switching operations and causes an appropriate response of this switch to changes in accordance with guidelines established by the author and placed in the algorithm.

These guidelines were developed by the author with regards to various parameters characterizing the properties of the vacuum circuit breaker which have a significant impact on the waveforms of switching phenomena generated during commutation of an electrical circuit, including in particular the following parameters and quantities:

- the speed of recovery of the dielectric strength of a gap between contacts in a vacuum immediately after arc extinguishing;
- the value of chopping currents of a circuit breaker;
- the conditions of re-ignition of an arc in a circuit breaker;
- material, constructional and technological parameters of the vacuum chamber of a circuit breaker;
- the way of conducting the course of the phenomenon of current chopping in the MODELS block.

The further part of the article presents a brief way of modeling the values of these parameters in the controlling algorithm. The values of these parameters were determined considering the following assumptions which result from the theory and practice of vacuum switching technology.

2.1 The speed of recovery of the dielectric strength of a gap between contacts in a vacuum immediately after arc extinguishing

The arc electrical strength of a gap between contacts in a vacuum and also the speed and slope of recovering its full

Fig. 3. Waveform of the recovery of electrical strength of the contact gap in the vacuum circuit breaker with contacts made of Cu and with a diameter of 30 mm [10].

value (the strength of the “cold break” in a vacuum) in dynamic conditions occurring immediately after the interruption of the vacuum arc between the opening contacts of the circuit breaker, before and after they reach the fully open state, depend on many factors (including those with random character), but mainly depend on the material from which the contacts are made, their dimensions and shape and also the speed of other particles present in the gap decay (ions, electrons, neutral particles, metal microdroplets) and thermal phenomena on the surface of contacts whose presence determines the emergence and development of mechanisms leading to a breakthrough of a contact gap. The literature from the subject gives results of experimental studies of these issues, including the rate of recovery of the electrical strength of a contact gap in a circuit breaker with contacts made of various metals, usually copper. Therefore, in order to ensure the greatest possibility of comparing the simulation results obtained using the present digital model of the circuit breaker with the results of tests taken from the literature, in the controlling algorithm of a circuit breaker, the laboratory designated strength curve of a contact gap in the vacuum circuit breaker was used with contacts made of Cu (Fig. 3).

It should be noted that the controlling algorithm was built in a way which ensures easy exchange of the strength curve of the contact gap on the curve corresponding to other materials of the contact. It is important to remember that the choice of characteristics are also affected by the voltage and the size and shape of the contacts, including for example, as shown in Figure 4 and described by the following formula [10]:

$$U_w = A_1 d^b \quad (1)$$

where: A_1 , b – are coefficients which depend on the contact material, d – is the distance of the gap between contacts.

It should also be mentioned that simulations of switching waveforms of currents and voltages which were carried out with the use of, the presented in the article, model

Fig. 4. Electrical strength of the gap between contacts in a vacuum, with copper contacts and with regards to the diameter of contacts and length of the gap between contacts d [mm] [10].

of a circuit breaker for which the controlling algorithm uses linear characteristics of the speed of recovering the strength of the contact gap, often significantly differ from the corresponding waveforms presented in the literature. This may indicate that the use of the linear characteristic in models for modelling the phenomenon of recovering the strength of a contact gap which is found in the literature, is a major simplification which leads to excessively large estimation errors of considered switching waveforms.

2.2 Chopping current in the controlling algorithm of the circuit breaker model

One of the most important parameters which have a major impact on the switching waveforms of currents and voltages in a commutated electrical circuit is the *chopping current of a circuit breaker* I_u [11].

It depends primarily on the material of contacts and also constructional and technological features of the circuit breaker and it results from processes occurring in a

Fig. 5. Values of the I_u chopping current of some alloys and sintered contact materials used for contacts of vacuum circuit breakers depending on their percentage composition [12].

vacuum arc next to the natural current passage through zero. When the instantaneous value of the periodic component of switching off the arc current is reduced below the value of the *minimum stable current of the burning of an arc* I_{min} , the arc starts to burn in an unstable way (due to the minus energy balance which is supplied and dissipated in the arc), which is manifested by the appearance of a high-frequency i_{uf} current in a circuit which imposes the basic component of mains frequency current. As a result of the imposition of these currents, the instantaneous values of the arc current periodically reach values close to zero. With the next rapprochement, the arc switches off with the i_{uh} instantaneous value of the arc current and interruption of the circuit appears at a non-zero instantaneous value of the basic component of the current I_u , which is called the chopping current (shearing, breaking). The lack of distinction between these values which can be found in the literature can lead to errors in estimating values of the chopping current and switching overvoltages generated by the vacuum circuit breakers. Chopping currents, present in the catalogues of currently produced vacuum circuit breakers, do not exceed several amperes (Fig. 5) [12].

In the developed controlling algorithm the value of the chopping current of the considered vacuum circuit breaker which was taken, for example from its catalogue data sheet, is applied directly to the algorithm in the MODELS block. The possibility of implementation of several different chopping current values, which correspond to different circuit breakers, is also provided which enables the comparison of the overvoltage propensities of those circuit breakers. In the presented computational examples a chopping current equal to $I_u = 3$ A was assumed.

2.3 Verification of vacuum circuit breaker ability to switch off high-frequency currents

The ability of a vacuum circuit breaker for interrupting i_{hf} high-frequency current occurring in the arc current before its natural passage through zero in the phase of unstable

Fig. 6. Exemplary oscillogram of the waveform of the switching off of the i current in the vacuum chamber of the vacuum circuit breaker [11].

Fig. 7. Waveforms of i_o current, u_l arc voltage, u_p return voltage and u_{wp} return strength with diverging contacts of the vacuum circuit breaker; τ – burning time of the arc, τ_{gr} – boundary burning time of the arc, t_0 – moment of arc ignition, φ – current interruption phase [12].

burning of the arc (Fig. 6) is in the developed controlling algorithm of the vacuum circuit breaker model characterized by the slope of oscillations of this di/dt current. The control of this slope was applied in the algorithm, and it was assumed, as in many other publications [6,7], that the vacuum circuit breaker is able to switch off the high-frequency current with slopes of descent to zero not greater than $150 \text{ A}/\mu\text{s}$. In the algorithm it is possible to easily change the implemented values of the slope of a current [13].

2.4 Verification of the condition of re-ignition of the arc in the model of a vacuum circuit breaker

The formation of re-ignition of the arc between contacts of the opening vacuum circuit breaker is usually limited to cases in which the switching off of the current (interruption) occurs after the loss of contact between contacts, i.e. when the time of arc τ is very short ($\tau \leq \tau_{gr}$, Fig. 7) and

the electrical strength of the still small gap between contacts is too small in relation to the rapidly rising return voltage. As a result of multiple re-ignition of the arc, an increase of the energy stored in the commutated electric circuit occurs, and due to this there is also an increase of expected voltages in the next arc ignitions (escalation of voltage).

Another, less commonly occurring cause of re-ignition of the arc could be the emergence of the phenomenon of forced current interruption in the circuit breaker during the switching off of the circuit. This phenomenon can happen only in three-phase circuits with an isolated neutral point as a result of the existence of capacitive and inductive couplings of individual phases.

The verification of the conditions of occurrence of re-ignitions of the arc in the circuit breaker and their effective switching off was carried out in the developed controlling algorithm by applying the decisive loop in which for each moment in time, return voltage values at contacts of opening the “ideal switch” are compared with corresponding voltage values in certain moments in time which were determined due to characteristics of electrical strength adapted in the algorithm. In the case when the value of return voltage reaches or exceeds the value of electrical strength of a gap between contacts, the “ideal switch” closes, which represents the occurrence of the phenomenon of re-ignition of the arc.

2.5 Implementation of parameters of the contact and extinguishing chamber system of a vacuum circuit breaker

The following material and constructional parameters of the contact and extinguishing chamber system of a vacuum circuit breaker are implemented into the controlling algorithm of the circuit breaker: contact material, the diameter of contacts, the maximum opening distance of contacts and also the time of opening contacts for maximum distance. These parameters in the algorithm are not permanently declared values but can be modified and adjusted according to conducted analysis. The change of data is carried out with the use of the panel shown in Figure 8 [14] which was created in order to improve the implementation of changes.

Thanks to the panel there is no need to change the MODELS block for each simulation and instead the new values of the parameters are entered and then used in the algorithm during the simulation.

The described model of a vacuum circuit breaker is designed as a model of the three-phase vacuum circuit breaker but after the application of small adjustments it can also be used in single-phase circuits.

2.6 The results of digital simulation of overvoltages and overcurrents in selected electrical circuits

A lot of simulations of current and voltage waveforms occurring during the switching off of various electrical capacitive circuits with different configuration and various parameters were carried out with the use of the

MODEL: ModelDef

Attributes		
DATA	UNIT	VALUE
dmax	mm	4
t_styku1	s	0.06
t_styku2	s	0.06
t_styku3		0.06
t_otwierania	s	0.006

Copy Paste entire data grid Reset Order:

Fig. 8. Panel of implementing data to the model in ATP/EMTP software: dmax – the maximum distance of opening contacts; t_styku1, t_styku2, t_styku3 – times in which begins the dissipation of individual contacts; t_otwierania – time of opening contacts to maximum distance [14].

presented digital model of a vacuum circuit breaker. For individual cases of these circuits, digital models, separate and optimal for their analysis, have been developed in ATP/EMTP software. Several examples of them and obtained waveforms of analyzed values with their usage are presented below.

2.7 Switching waveforms during the switching off of single capacitor banks

To simulate overvoltages and overcurrents occurring in an electrical circuit during the switching off of the three-phase capacitor bank with the vacuum circuit breaker, the digital model of such a circuit which is shown in Figure 9 and developed in the ATP/EMTP software can be used. In this model there is a possibility to obtain voltage and current waveforms in each place of the circuit with the use of current and voltage probes. Knowledge of the value of overvoltages on the capacitor bank which is being switched off and also the value of overvoltages on clamps of the vacuum circuit breaker can be seen as the most important for the assessment of the overvoltage hazard which occurs in this circuit.

This model enables the carrying out of simulations of current and voltage waveforms which occur during:

- the switching off of the triple-phase capacitor bank with an insulated and grounded neutral point [15] and also the switching off of the triple-phase capacitor bank with the use of a circuit breaker with variable values of the contact and extinguishing chamber system;
- the switching off of the triple-phase capacitor bank with changes of their capacity, changes in the values of voltage supply and changes of circuit parameters (RLC elements – which map power cables) [16];

Fig. 9. Model of the capacitive circuit with an isolated (a) and grounded (b) neutral point of the capacitor bank in ATP/EMTP software.

Fig. 10. Voltage waveforms on the clamps of the capacitor bank with power equal to $Q = 50$ kVar, rated voltage equal to 6 kV and an isolated neutral point (a) and voltage on the vacuum circuit breaker (b) during asynchronously opening contacts of a circuit breaker with a delay of 0.02 s.

- the switching off of the triple-phase capacitor bank in conditions of re-ignition of arc occurrence in the vacuum circuit breaker [17];
- the switching off of the triple-phase capacitor bank with an isolated neutral point with asynchronicity of opening contacts in the vacuum circuit breaker, Figure 10 [14].

Exemplary waveforms obtained from these simulations are presented in Figures 11 and 10.

Fig. 11. Waveforms of voltage (a) and current (b) between the contacts of a circuit breaker during the switching off of a capacitor bank with an isolated neutral point with power equal to 50 kVar [16].

Fig. 12. Model of a capacitive circuit with an isolated neutral point of a capacitor bank and triangular varistor system of surge arresters in ATP/EMTP software [16].

2.8 Switching waveforms in capacitive circuits with surge arresters

The electrical circuit modelled in ATP/EMTP software and presented in Figure 12 can be used for the analysis of overvoltages and overcurrent occurring during the switching off of the capacitive circuit with a vacuum circuit breaker in which surge arresters are installed. In this circuit it is possible to easily change the system of connections of surge arresters and the way the neutral point of the source and commutated circuit work.

Fig. 13. Waveforms of voltage (a) and current (b) on contacts of a circuit breaker during the switching off of the capacitor bank with an insulated neutral point and a triangular surge arrester system (Fig. 12).

Exemplary current and voltage waveforms on the contacts of the vacuum circuit breaker which were obtained from simulations with the use of this model are presented in Figure 13. Figure 14 shows the voltage waveform on the clamps of the capacitor bank which is being switched off with surge arresters attached in a triangular shape, as shown in Figure 12.

In the [5] study there is a detailed description of this issue and also a presentation of other solutions of using the surge protection measures and also analysis of the effectiveness of their operation.

2.9 Switching waveforms during the switching off of the successive stages of a capacitor bank

The model of the circuit which is used to analyze waveforms of overvoltages and overcurrents during the switching off of successive stages of a capacitor bank with vacuum circuit breakers is shown in Figure 15 [18]. As was revealed from computational experiments, because in this circuit numerical oscillations appear which disturb the functioning of the model, an anti-aliasing filter was used in order to eliminate them. Sample voltage and current waveforms which were obtained with the use of it are shown in Figure 16.

Fig. 14. The voltage on the capacitor bank with an insulated neutral point and triangular surge arrester system during switching off (Fig. 12).

Fig. 15. The circuit modeled in ATP/EMTP software which is used for current and voltage transient waveform simulations occurring during the switching off of the successive stages of a capacitor bank; VS – a vacuum circuit breaker, C1, C2, C3 – capacitors, RL – load, E – power supply, FA – anti-aliasing filter.

Carried out simulations have shown that the circuit from Figure 10 may also be useful for analyzing the switching off of capacitor banks with a bigger number of stages, and connected with this a larger number of vacuum circuit breakers. Circuit breakers in this circuit interact with their own work during simulations.

3 Conclusion

The presented digital model of a vacuum circuit breaker enables multi-criteria analysis of current and voltage

Fig. 16. Phase voltage waveforms at the clumps of a capacitor bank (a) C_1 , (b) C_2 , (c) C_3 during the switching off of the C_1 and C_2 capacitor bank; t_1 – moment of the switching off of the C_1 capacitor bank, t_2 – moment of the switching off of the C_2 capacitor bank.

switching waveforms occurring during commutation of capacitive electrical circuits using vacuum circuit breakers to be conducted. The adaptation to new parameters of a circuit and circuit breaker is relatively easy. It could therefore be useful in the design, modernization and operation of such circuits.

Digital simulation results of current and voltage switching waveforms in the studied electrical circuits with the use of vacuum circuit breakers which were obtained using this model presented a large, sufficient for practical assessments, comparison with the results of empirical research, which confirms the correctness of the developed digital model of a vacuum circuit breaker and its practical utility.

The developed model, and corresponding with it computational algorithms, can be seen as an efficient research tool which enable the replacement of very complex, time-consuming and expensive laboratory research which require complicated research posts and specialized measuring equipment, with a digital simulation which does not possess such restrictions.

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