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The model of a vacuum circuit breaker for switching on capacitor bank

Streszczenie. *W pracy przedstawiono metodę tworzenia modelu w oprogramowaniu Matlab wyłącznika próżniowego, który służy do modelowania procesów łączeniowych w obwodach pojemnościowych. W modelu wyłącznika próżniowego uwzględniono zjawisko odbijania styków (które jest nowym rozwiązaniem), zjawisko przerwania prądu, a także rekonstrukcję siły między stykami, podczas sterowania procesem przełączania. Istnieją różne metody modelowania wyłącznika dla układów łączeniowych zaproponowane w literaturze, ale żaden z nich nie uwzględnia zjawiska odbijania styków. Rozwiązanie przedstawione przez autora nie jest idealne. Jednak w prosty i przystępny sposób uwzględnia to zjawisko w procesach przełączania. Dokument wskazuje, że zastosowane rozwiązanie jest ważne i wpływa na przebiegi prądów i napięć w obwodach podczas procesów przełączania. W artykule przedstawiono również przebiegi napięcia i prądu, które pokazują metodę działania modelu podczas przepięć i przetężeń. W artykule przedstawiono analizę pojawiających się przepięć i przetężeń oraz ich wpływ na zjawiska łączeniowe w obwodzie z bateriami kondensatorów. Najważniejszym i nowym rozwiązaniem w modelowaniu łączników próżniowych jest uwzględnienie zjawiska odbicia styków w procesie załączania obwodu pojemnościowego.* ***Model wyłącznika próżniowego w obwodach pojemnościowych***

Abstract*. The paper presents the method of creating a model in Matlab software of a vacuum circuit breaker that is used for modelling the switching processes of capacitive circuits. In the model of the vacuum circuit breaker, the phenomena of contact bounces (which is a new solution), the phenomenon of the current interruption and also the reconstruction of the strength between the contacts were taken into account during control of the switching process. There are different methods of modelling a circuit breaker for switching circuits proposed in literature, but none of them consider the phenomenon of contact bounces. The solution presented by the author is not ideal. However, in a simple and accessible way it takes into account the aforementioned phenomenon in switching processes. The paper indicates that the used solution is important and influences the waveforms of currents and voltages in circuits during switching processes. The paper also presents voltage and current waveforms that show the method of the model operating during overvoltages and overcurrents. An analysis of emerging overvoltages and overcurrents, and their influence on switching phenomena in the circuit with switching capacitor banks, can also be found in the paper. The most important is included a new version of a model of vacuum circuit which is an answer to simulate a switch on process in capacity MV circuit. In the literature can usually be found the model when we can simulate a switch off MV inductive circuit, so presented model is new version of modelling such capacity circuits.*

Słowa kluczowe: wyłącznik próżniowy, obwód pojemnościowy, model Matlab, przepięcia, przetężenia, bateria kondensatorów
Keywords: vacuum circuit breaker, vacuum switch, capacity circuit, Matlab model, overvoltage, overcurrent, capacitor bank

Introduction

The development of the industry and the steady increase in the demand for electricity has forced electrical equipment manufacturers to seek new technological solutions in the areas of switching processes and environmental protection. Vacuum circuit breakers are one of the dynamically developing branches of low and medium voltage circuit breakers. The reasons for their popularity can be found in their better technical parameters when compared to other types of circuit breakers. Vacuum circuit breakers are characterized with having small dimensions, a low failure rate, resistance to environmental exposure and a reduced need for maintenance [1].

The use of vacuum circuit breakers as an alternative to devices that use a sulphur hexafluoride quench chamber (SF6) was forced, among other things, by the need to take care of the natural environment. Fluorinated greenhouse gases represent 1.5% of all greenhouse gases emitted by highly developed countries. They are 22 thousand times more effective at binding heat than CO2, and their presence in the atmosphere is estimated at thousands of years [2].

The interruption of current in a vacuum is characterized by a very fast diffusion of ionized particles from the contact gap, which lasts a few microseconds, and also a high speed of increase in arc strength [1]. The very fast increase in the strength of the contact gap is a direct cause of overvoltages and overcurrents, the values of which depend on mechanisms that are characteristic for vacuum circuit breakers e.g. natural current interruption, forced current interruption and voltage escalation. Moreover, the nature of a circuit affects the values of overvoltages and overcurrents. Inductive circuits are characterized by the occurrence of high values of overvoltages. In turn, capacitive circuits are characterized by lower values of overvoltages, but increased values of overcurrents.[3,4]

Analysis of the phenomena occurring in vacuum circuit breakers is very complex due to the complexity of the mathematical models that describe these physical processes. The complexity of the models increases in the case of simulations that allow for e.g. asynchronous opening of contacts. The basic difficulty in using digital machines to calculate switching overvoltages is the long calculation time and high demand regarding the memory capacity of a machine. Calculations made using electronic analogue machines are more efficient. However, in practice this is possible in the case of more simple issues. Due to the above-mentioned difficulties during mathematical modelling, it has to be stated that the vast majority of intermediate studies on switching overvoltages are made on real models" [1].

The current state of the development of digital technology allows for the most complicated systems to be modelled. In the academic environment, several models of vacuum circuit breakers [5] were developed in the ATP/EMTP environment [6,7]. Models of such circuit breakers were also created in MATLAB Simulink software [8]. Electric arc models based on a controllable current source[9,10,11], and also simulations that connect a circuit breaker model with an arc model [5],were also developed.

Until now, most of the research on the development of the vacuum circuit breaker model were related to the situation of closing inductive or capacitive circuits [12,13,14].As of today, there has probably not been a model developed that would enable the phenomena occurring during the opening of a circuit to be simulated.

Model of a vacuum circuit breaker

The vacuum circuit breaker model consists of an "ideal switch" (Fig.1) from the MATLAB software library and the control block with trajectory poles (Fig.2).

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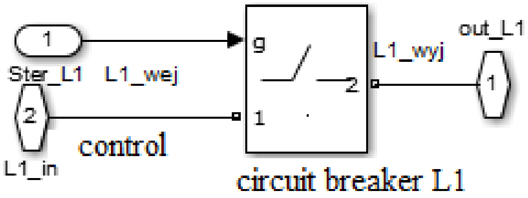

Fig.1 Scheme of one of the poles of a circuit breaker

The operation of the control block is based on mathematically described conditions that determine the operation of the vacuum circuit breaker during circuit switching. Switching operations are initiated on the basis of three criteria (Fig. 3), which were proposed in paper [3]:

- the condition of current interruption defined at a constant value of Iu = 3A,
- the condition of an increase in high frequency current defined as s = 150A/μs,
- the condition of the electrical strength of a contact gap U_w. This parameter is currently being analysed according to formula (1). The fixed values that are dependent on the contact material were assumed for the copper contacts according to literature [1].

$$U_{wy} = A_1 * d^b \tag{1}$$

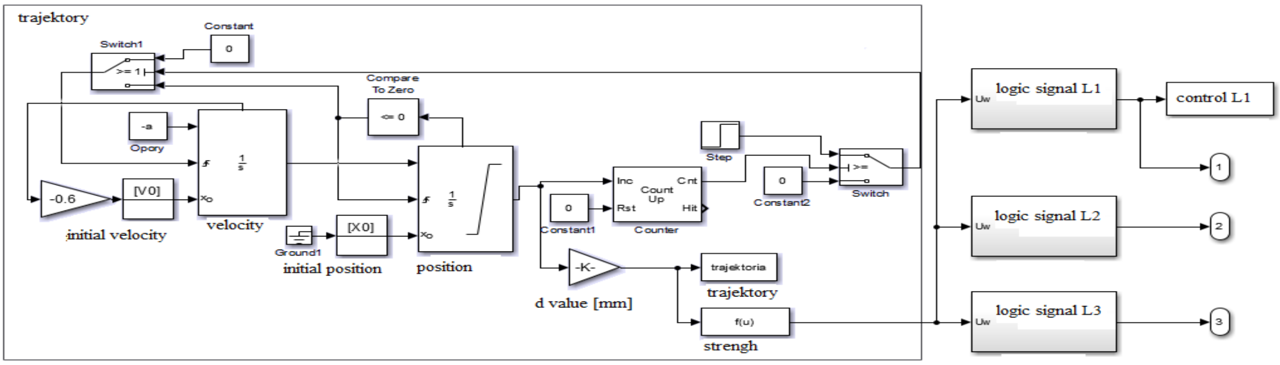

Fig.2 Control system of the trajektory poles of a circuit breaker

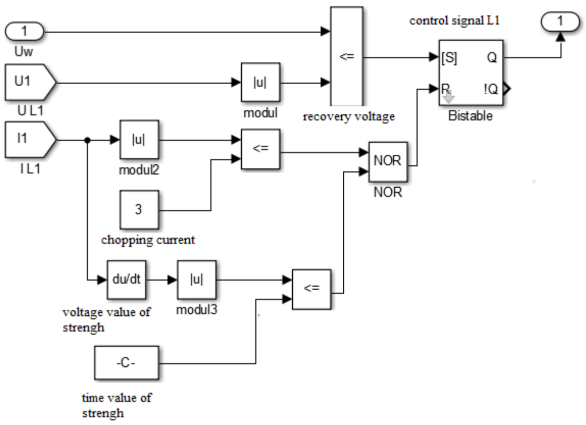

Fig.3 Voltage and current conditions for controlling the pole of a circuit breaker

An important element in the analysis of the phenomena that occurs during the switching on of circuits using a vacuum circuit breaker is the phenomenon of the bouncing of contacts of the circuit breaker. In the presented work, this phenomenon was simulated in a purely physical way - the algorithm of elastic bounces was used [15] which takes into account parameters such as the elasticity of a contact, its position, initial velocity or resistance of movement (e.g. gravity effect) (Fig.4, Fig.5).

The presented solution is taken from the MATLAB software library and is described in detail in the materials published on websites under the name "sldemo_bounce". Due to the fact that it is a fixed solution, it does not have characteristic built-in processes for switching on. Therefore, the proposed solution suffers from errors resulting from a lack of parameters, such as the actual attenuation that distorts the trajectory of a contact, or re-ignition as a result of the breakdown of a small contact gap.

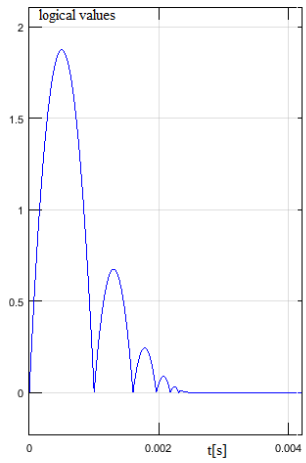

Fig.4 Simulation of the bounces of a movable contact in a vacuum circuit breaker

This type of simplification is the main reason for obtaining errors during research. However, it should be noted that after a series of simulations, similar results to those obtained during actual measurements or to those found in the cited literature were achieved. Therefore, the control block operates according to the following algorithm (Fig. 6):

- After starting the software, the part of the model that is responsible for determining the trajectory of the movable contact starts working (Fig.4).

- This allows the function d=f(t) - of a contact gap d at time t, to be obtained.
- The function d=f(t) is converted into the dependence of the electric strength of the contact gap as a function of time U_w=f(t) on the basis of formula (1).

The current and voltage conditions that are described above are verified. Their control is cyclical according to the trajectory of the contact that was set earlier.

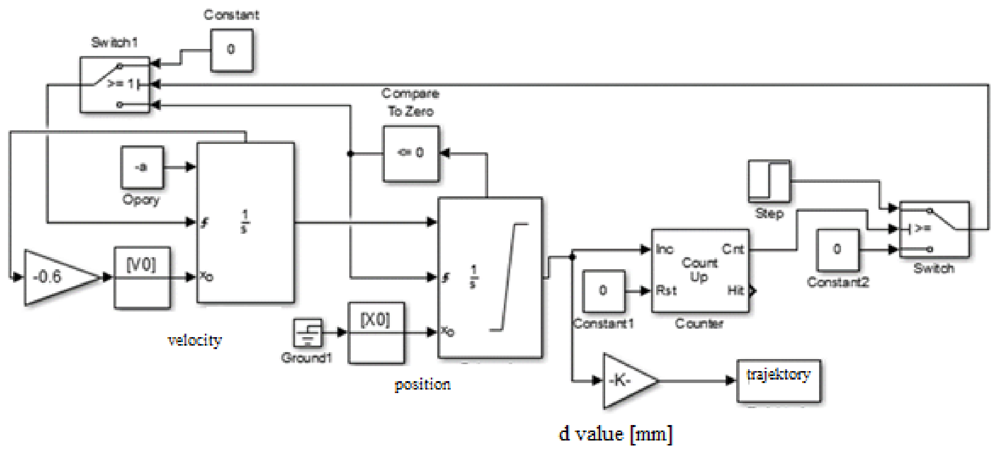

Fig.5 Algorithm simulating the elastic bounces of a contact

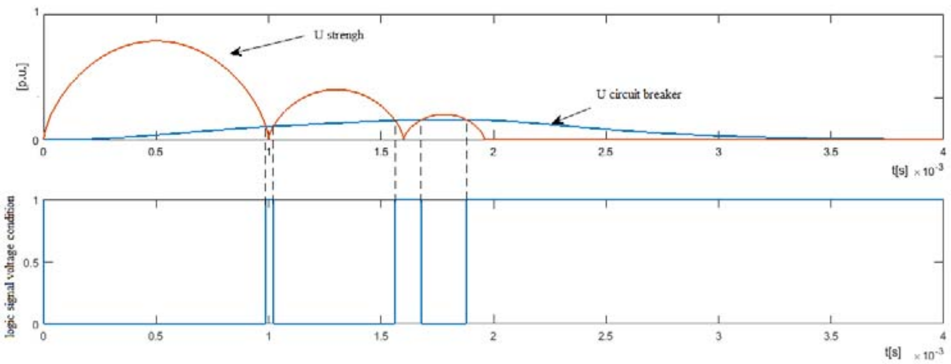

Fig. 7 Scheme of operation of the voltage element of the algorithm that generates the signal that controls the poles of the circuit breaker

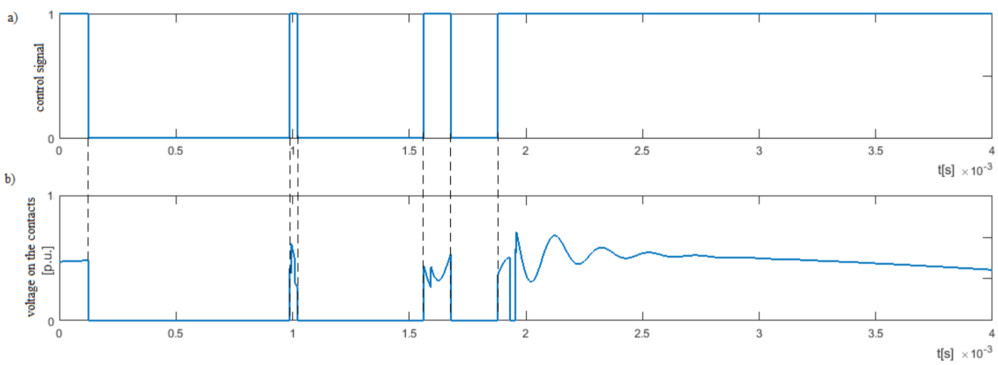

Fig. 8. Influence of the control signal (a) on the voltage at the capacitor clamps (b

Figure 7 shows how to generate a logic signal for voltage conditions. The calculated value of the electrical strength of the contact gap is compared with the actual value of the potential difference at the clamps of the circuit breaker. If the control condition of U_{out}-U_{min}>U_w is fulfilled, a logic signal is generated, which in the next step is compared to the sum of the current conditions.

The signals generated on the basis of the electricalstrength of the contact gap condition (Fig.6), and also the current conditions, are delivered to the bistable switch of the set/reset type. The logical one levels formed in the voltage element are given to the "SET" input, which is set as a priority, while the current conditions provide a signal to the "RESET" input (Fig. 3).

The result of the comparison of individual results is the generation of the control signal (Fig. 8a) directly onto the circuit breaker (Fig. 1).

The resulting control signal has a decisive influence on the operation of the system with a vacuum circuit breaker.

The capacitive circuit in MATLAB software

The capacitive circuit with a vacuum circuit breaker (Fig. 9) is powered by a three-phase programmable voltage source block, the parameters of which, such as supply voltage, frequency or phase shift between individual phases, can be regulated during the simulation. The following parameters were assumed:

- Supply voltage: U_z= 6÷17kV
- Frequency: f=50Hz
- Phase shift φ=120°

The blocks that simulate the capacity and inductance of the supply circuit were also used. The parameters of the power supply network were chosen according to subject literature. The configuration of these parameters is constant for all types of simulations and is equal to:

the inductance of the power supply network of Lz=20mH,

the capacity of the power supply network of Cz=0,27μF.

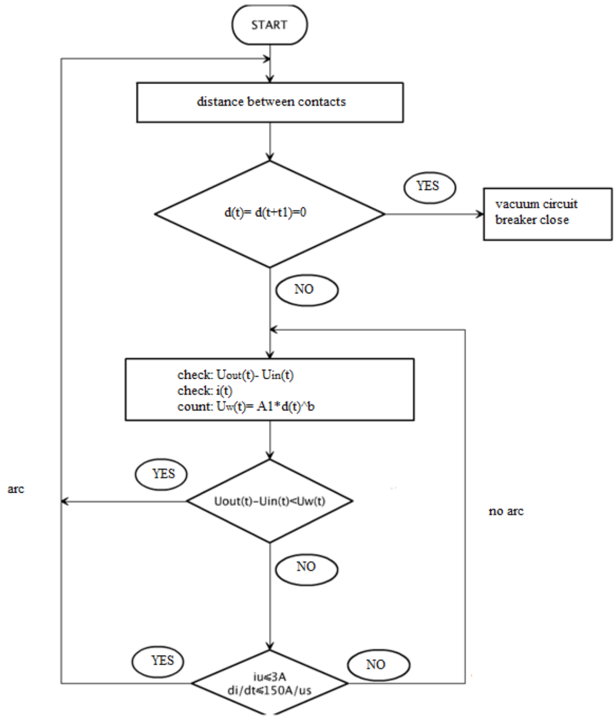

Fig.6. Algorithm of the system controlling the poles of a circuit breaker

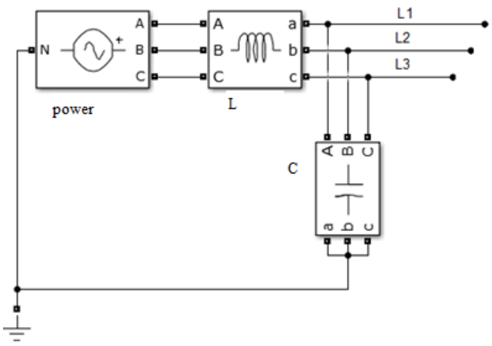

Fig.9 The software block that represents the power supply network

During the conducted tests, the following parameters required constant control:

the waveforms of a control signal (Fig.8a);

the waveforms of a trajectory generating signal (Fig.4);

the voltage at the contacts of the circuit breaker (Fig.12);

the power supply current (Fig. 9);

the voltage on the contacts of the capacitor bank (Fig.8b, 11a,b,c);

the current at the capacitor bank (Fig. 10 a,b,c).

In the case of these types of measurements, it is necessary to use a lowpass filter in order to remove noise from the measuring signal or to separate measured signals with different frequencies. The "2an-Order Filter" block (a ready-made element from the MATLAB library [12]) was used for this purpose, the appropriate configuration of which allows reliable results to be obtained.

The capacitor banks in the following three configurations were used as passive elements:

- the star-connected capacitor bank;
- the star-connected capacitor bank with a grounded neutral point;
- the delta-connected capacitor bank.

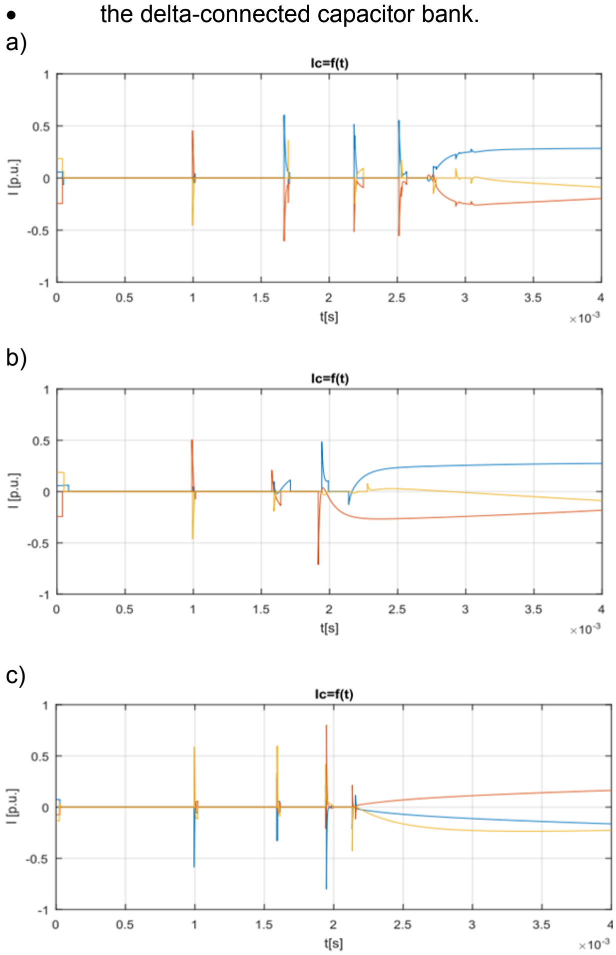

Fig. 10. Waveforms of I_c current that flows through a capacitor bank. Circuit parameters: bank power Q = 50MVAr, supply voltage Uz = 8kV. Capacitor bank connection systems: a) star b) star with a grounded neutral point c) delta

For each of the analysed groups of capacitor bank connections (star, grounded star, delta), a series of simulations were performed for the supply voltage that varied between 6 and 17kV, and for the bank power that ranged from 50 to 2050kVAr. These parameters were selected in order to show the width of the actual use of medium voltage vacuum circuit breakers. The other parameters of the circuit did not change. The multitude of investigations allowed for both the evaluation of the correctness of the operation of the model control algorithm, and the drawing of conclusions about the operation of a particular capacitor bank.

Discussion

The paper presents the model of a vacuum circuit breaker (including the phenomena and processes that are characteristic for vacuum circuit breakers, e.g. contact bounces) and analysis of its operation during capacitive circuit switching processes.

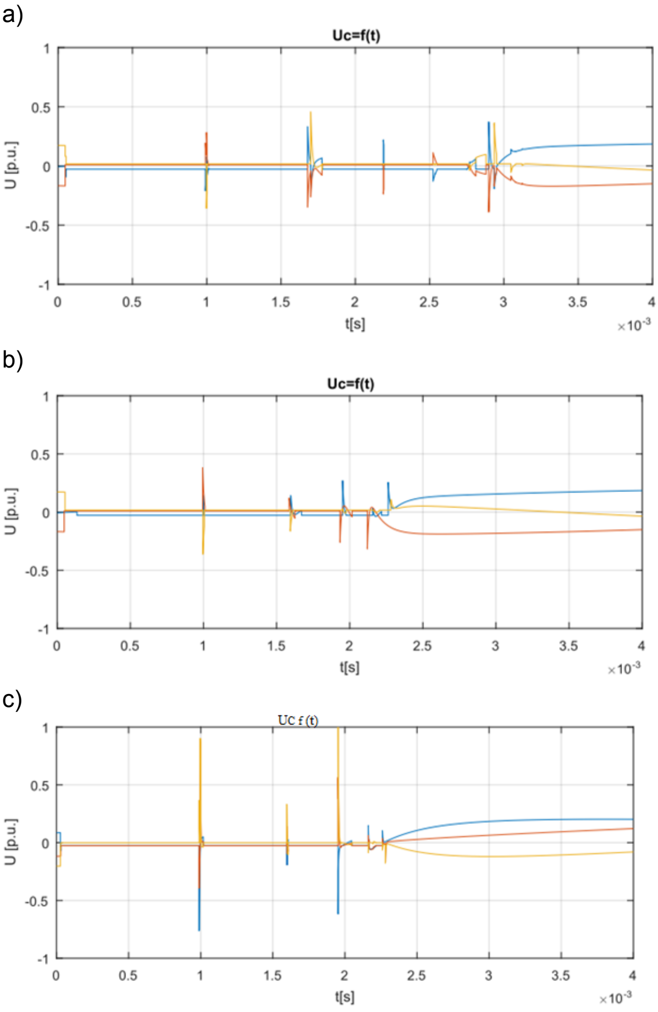

Fig. 11. Waveforms of U_c voltages on the capacitor clamps. Circuit parameters: bank power Q = 50MVAr, supply voltage Uz = 6kV. Capacitor bank connection systems: a) star b) star with a grounded neutral point c) delta

The digital model that was created for this purpose can be used to analyse transient phenomena for supply voltages in the range of Uz = 6 ÷ 17kV, and for bank power in the range of Q = 50 ÷ 2050kVAr when capacitor banks are star-connected with a grounded neutral point, star-connected with insulated neutral point and delta-connected.

The digital model algorithm is based on phenomena that are characteristic for a vacuum arc and which take into account parameters such as: the gap between contacts and the electrical contact gap strength associated with it, interrupted current and high-frequency currents.

The effect of the supply voltage and the power of capacitor banks on the values of overvoltages and overcurrents were widely analysed. The obtained results were verified by comparing them with laboratory tests published in scientific literature [1,3] and [16]. The following conclusion was drawn: the proposed algorithm adequately simulates phenomena that occur during switching on capacitive circuits with a vacuum circuit breaker. The used simplifications do not allow for a comprehensive analysis of commutation phenomena, however, the model satisfactorily reflects overvoltages and overcurrents.

The presented computational algorithm and the digital model developed on its basis significantly simplify the analysis of commutation phenomena in capacitive circuits with vacuum circuit breakers. First and foremost, it enables costly and complex laboratory tests to be either limited or reduced to a situation in which the results of the digital simulation hold promise for their research or economical usage.

Conclusion

Analysis of the simulation of results provides the following conclusions:

- a star-connected capacitor bank with a grounded neutral point has the smallest value of overvoltages and overcurrents. This is consistent with the calculations obtained from literature and it confirms that a three-phase circuit can be treated as a single-phase circuit in calculations. The maximum values in such a circuit do not exceed the double value of the nominal voltage and are therefore not dangerous.

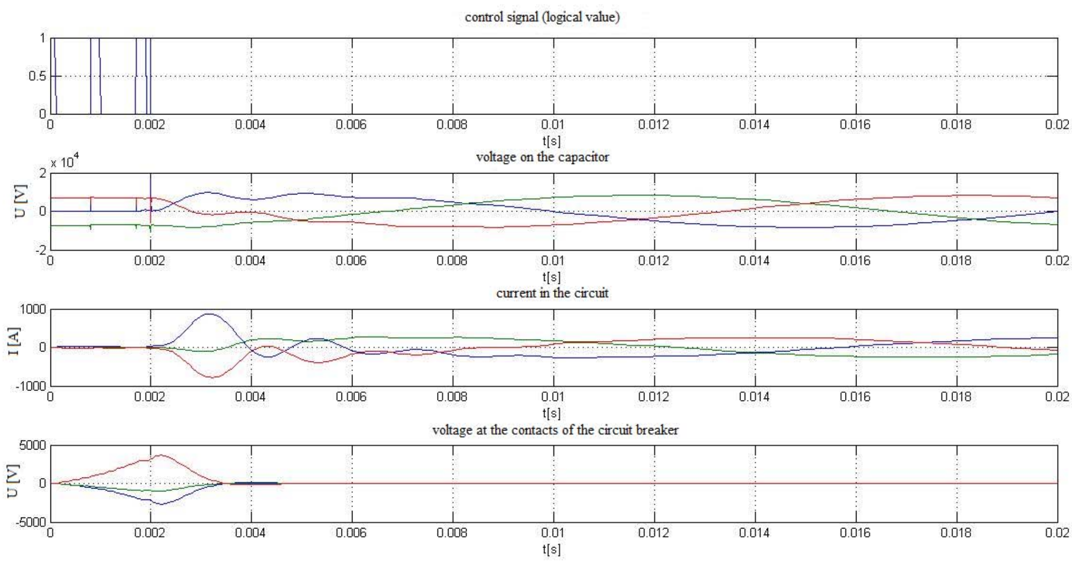

Fig. 12. Waveforms of control signal, voltage on the capacitor, current in the circuit and voltage at the contacts of the vacuum circuit breaker from summary results

- in a star-connected system with a grounded neutral point, the highest value of overvoltages and overcurrents was recorded during the odd contact bounces, i.e. during bounces No. 1 and 3.
- a star-connected system with an insulated neutral point is characterized by overvoltages and overcurrents of comparable amplitude during each bounce. However, increased amplitude was observed during the second contact bounce during some simulations.
- a star-connected system with an insulated neutral point has the longest cessation time of transient processes after the complete closure of a circuit breaker.

The circuit in which the capacitor bank is delta-connected is characterized by the worst parameters. The values of overvoltages reach five times the values of supply voltage (at peak), and the values of overcurrents reach seven times the values of the set current (at peak).

The maximum amplitudes of overvoltages and overcurrents for both a star-connected system with a grounded neutral point and star-connected system with an insulated neutral point are at a comparable level, whereas the average value is lower for a system with a grounded neutral point.

It can be concluded from the analysis of the presented circuits that switching on the capacitive circuit with a vacuum circuit breaker is not dangerous for capacitor banks and the obtained values of voltages and currents are smaller than during the phenomenon of switching off capacitive circuits.

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