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Modeling of switching effects in capacitive circuit with a vacuum switch and varistor surge protection

Abstract. *Analysis of transient phenomena occurring in the capacitive circuit with a vacuum switch. Paper presents the simulation results performed in ATP/EMTP. The analysis applies to the overvoltage and overcurrent during re-ignitions of arc when surge protection installed is. An assess of the practical suitability and effectiveness of examined system's connections. The results obtained during the modeling are consistent with the theoretical analysis and empirical research described in the literature.*

Streszczenie: *Artykuł przedstawia analizę zjawisk stanów nieustalonych zachodzących podczas łączenia łącznikiem próżniowym obwodów o charakterze pojemnościowym. Zamieszczono wyniki symulacji przeprowadzonych w programie ATP/EMTP. Przeanalizowano skuteczność, a także przydatność ochrony przeciwprzepięciowej w tychże obwodach. Analiza wyników uzyskanych podczas modelowania jest zgodna z analizami teoretycznymi i badaniami empirycznymi zamieszczonymi w fachowej literaturze.* (***Analiza zjawisk stanów nieustalonych zachodzących podczas łączenia łącznikiem próżniowym obwodów o charakterze pojemnościowym***)

Keywords: overvoltage, overcurrent, capacitive circuit, simulation, ATP/EMTP, vacuum switch
Słowa kluczowe: przepięcia, przetężenia, obwody pojemnościowe, symulacje, ATP/EMTP, łącznik próżniowy

Introduction

During switching capacitive currents there can appeared significant values of overcurrent and overvoltage, which may hinder switching processes and make a threat for circuit insulation and all installed electrical devices. This threat can be more dangerous when vacuum switch is used to connect circuits with capacitor bank. Vacuum switch have a lots of advantages like a very good technical parameters but also have some disadvantages like the tendency to generate excessive overvoltage characterized by chopping current I_u. I_u is defined as the instantaneous values of periodic component of switching current in its times goes out (fig. 1).

a) .... .b)

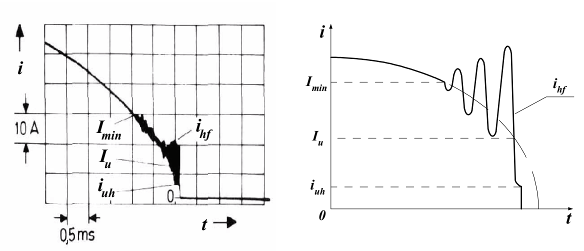

Fig. 1. Course of switching current in vacuum switch chamber extinguishing: a) sample oscillogram, b) stylized course [9]: I_{min}-current minimum stable arc burning, i_{hf}-high-frequency current,i_{uh}-instantaneous value of the current arc goes out

This tendency stems directly from the specific mechanism of interrupting the electric current in a vacuum, mainly consisting of faster than in other media (which lasted only a few milliseconds) the diffusion of all the ionized plasma particles from space between contacts, after passing the arc current through zero and high –speed of recovery strength in vacuum of up to several kilovolts per microsecond. Because of this, vacuum circuit breaker interrupt AC before its first natural passage through zero (fig.1) and arc burning time does not exceed one half period of time, what minimizes the negative impact of the arc (erosion contacts) and increases the durability of contacts but at the same time can be source of dangerous overvoltage, which value can be determined from depending:

(1) $$U \approx I_u Z_0$$

where:

(2) $$Z_0 = \sqrt{\frac{L}{C}}$$

is characteristic impedance of the circuit and L, C are inductance and capacitance circuit to be disabled.

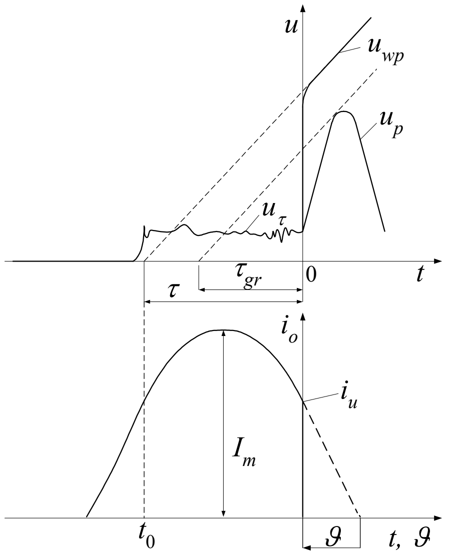

Fig 2. Course of current i_0 voltage of arc u_l,return voltage u_p, and recovery strength u_{wp}, t-arc burning time,t_{ogr}-boundary arc burning time, t_0-moment of ignition of the arc, V- phase of chopping current

Even greater overvoltages can appear when the re-ignitions of arc appear during switching effects. There may occur mechanism generating overvoltages caused by forced (virtual) chopping current or escalation of returned voltage. Fortunately, cases of re-ignitions of the arc in real circuits are not frequent (fig.3) and limited in very short time ($t \leq t_{gr}$, fig.2) and recovery strength is too small in relation to the rapidly growing return voltage.

Under certain circumstances, overvoltages generated by the vacuum switch can be harmful for isolation and all devices in the switched circuit. In such cases there is used surge protection. Proper selection of such equipment requires authoritative analysis of switching processes in capacitive circuit.

Transients in capacitive circuit get more complicated under the influence the specific mechanisms of generation of vacuum switch (natural cut off arc, virtual cut of arc, escalation of voltage [11]). The result is that the analytical analyses are very pressure vices and require a number of simplifying assumptions. The obtained results are not satisfying, because the waveforms are not very accurate and allow for more qualitative than quantitative analysis. In this situation, the digital method gives the best results. It allows analyzing the impact of a number of parameters in a wide range and tested their effect on the appearance of dangerous phenomena of the transition.

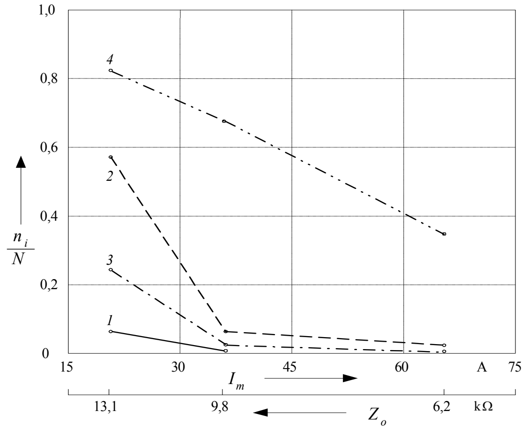

Fig.3. Dependence of the incidence of single re-ignitions of the arc in chamber extinguishing vacuum contactor four foreign companies (line 1-4) the current amplitude I_m and wave impedance Z_0 switched circuit; n_i -number of trials that have experienced the re-ignition of the arc, N-the total number of trials

The article presents the results of digital simulation of current and voltage waveforms during switching off by vacuum switch when the neutral point of three-phase capacitor bank is insulated. What is the most important is that in simulation was analyzed surge protection with varistors and in each case the re-ignition of the arc in the vacuum circuit breaker used to form. There were also considered the effectiveness analysis of surge and assessed their practical usefulness. In this analysis, there was adopted simplifying assumption that the damping effect and the voltage drop on the arc can be omitted

Varistor surge

Oxide ZnO varistors, and surge that are built with their usage have much better protective and performance properties than the protection against overvoltages .previously used (RC or Zener diode). This is caused their specific properties. They have highly non-linear, usually symmetrical, voltage-current characteristics. Characteristic for them are large changes of resistance with relatively small changes in voltage (fig. 4). They are also distinguished by a high nonlinearity coefficient (α = 40-60), short duration of action, ability of absorbing large surges of current in relation to their small mass and size.

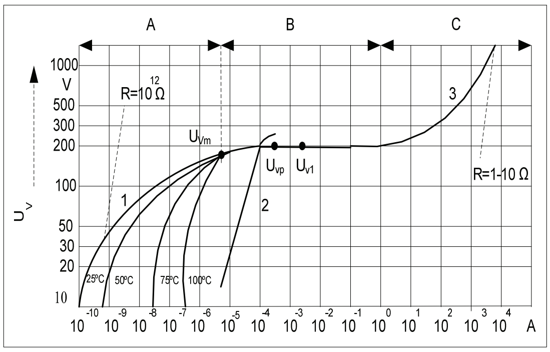

Fig 4. Sample voltage-current characteristics of varistor :1-removed part of the characteristics at constant voltage, 2-removed some characteristics with a voltage alternating, 3-removed some characteristics with a impulse voltage, A- range prior to puncture, B- range of relevant work, C- saturation range, U_{Vm}- continuous operating voltage, U_{Vp}- proper voltage,U_{V1}- varistor voltage flowing through the current 1mA [7]

Varistors have also some drawbacks like uninterrupted high voltage of main switch in relation to rapidly increasing switching transients, relatively large capacity (hundreds to thousands of pikofarad) and lack of ability to reduce the steepness of surges rise(that limit the possibility of self-use varistors in high frequency circuits). In characteristics $U_V=f(I_V)$ there can be distinguished three ranges of varistors:

1. Range A - Varistor behaves like an insulator with a specific capacity and very low steepness. In this range, the varistor is about 99% of the whole of its use time because in normal operation conditions, the varistor operates continuously with a voltage less than varistor's voltage U_{Vm}, of permanent work. This voltage is defined as the maximum voltage, when the appearing on the varistor in steady state power does not cause overheating and damage. In this range varistor has a high resistance value which comparatively slightly decreases with increasing voltage. Characteristic $U_V=f(I_V)$ in range A is depended on temperature (fig.4).
2. Range B - proper range of varistor's work. It is the large non-linearity in relation to the current-voltage that makes a slight increase in voltage on the protected by varistor device which can increase the value of current flowing through the varistor by several orders. In situation, the varistor is exposed to a variety of casual or switching surges. Therefore it should have a high energy endurance and ability to absorb large heat. In this section, the characteristics of the relationship between current and voltage can be specified by a model:

(3) $$I = k_V U^{\propto}$$

where: k_V- factor depending on the dimensions and material properties varistor.

3. Range C - where the nonlinearity coefficient rapidly decreases its value (α<10), and the resistance of the varistor is set at 1÷10Ω. At high currents varistor passes into the so-called saturation condition, where the current-voltage characteristic becomes linear again and can be described as dependency:

(4) $$U = r_V I$$

where: r_V is the internal resistance of the ZnO grains, characterized by a resistivity ρ≈1Ωm.

Parameters of under test circuit at switch accepted in the simulation

Computer simulation of currents and voltages waveforms generated during the off-phase vacuum switch with power capacitor 50 MVAr with isolated neutral point (fig.5) was performed in case of occurrence of re-ignitions of the arc in switch and in case of application varistor surge of different systems connections (Fig.6) for the battery protection. Simulations were performed by use the ATP / EMTP and found in its library varistor's model as a type MOV (Metal Oxide Varistor English) element, allowing to a good reflection of the voltage- currents characteristics of real varistor (Fig. 4), and using the block MODELS modeling vacuum switch.

Simulation of the considered circuits in this case is realized by building their ATPdraw schemas in the module with usage of ready-made items from the library and then by introduction of preset values for each parameter and analysis of the results presented by numbers or figures, graphs or their timing, derived from the module PlotXY.

MODELS block action, which was modeled according to figure 7.Vacuum switch works by sending signals closure or opening of a switch (taken from the library) and analysis of the return voltage and electrical recovery strength characteristics in real vacuum switch (fig. 8) carried by the following algorithm:

- Stage 1-there follows simulation of the opening of the contacts.
- Stage 2-there is made a comparison of the return voltage value on the contacts switch with electrical recovery strength. If the return voltage exceeds the strength there follows send of the signal to close contacts vacuum switch what models the occurrence of re-ignition of the arc and initializes a high-frequency current's flow and the formation of overvoltage and overcurrent.
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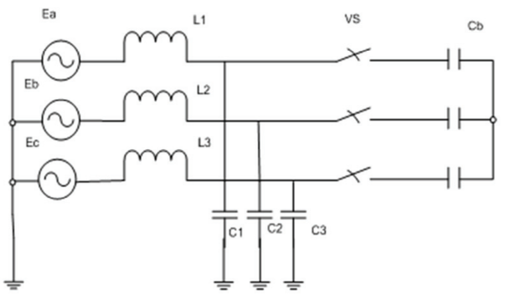


Fig.5 Modeled in ATP / EMTP circuit for the analysis of switching overvoltage generated by switching off vacuum switch during the three-phase capacitor bank with isolated neutral point:L_1,L_2,L_3-power circuit inductance, C_1,C_2,C_3 - capacity power circuit, C_b-capacitor bank, E_1,E_2,E_3-voltage.

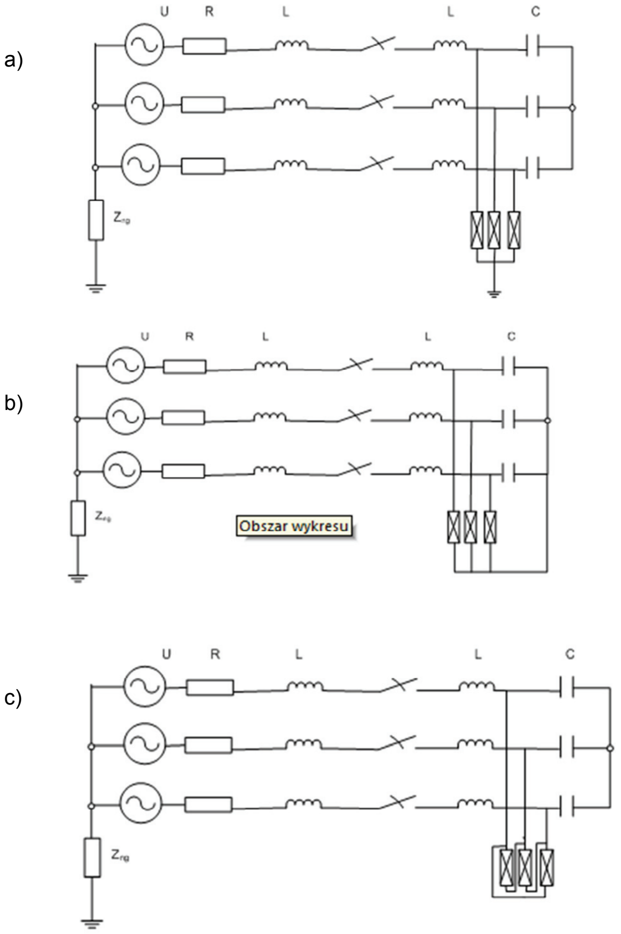


Fig.6 Circuits surge in the circuit with a battery of capacitors with insulated neutral point used in computer simulation: a) the star with neutral point grounded, b) the star with neutral point connected to the neutral point of capacitor bank, c) delta connection [1].

- Stage 3-there is checked condition of the ability of vacuum switch to cut the high frequency current. If the switch is able to interrupt high-frequency current generated in step 2, there is sent signal of the opening of switch contacts modeling the interruption of the flow of this current.
- Stage 4- there is checked the condition from step 2 and the loop is repeated until the return voltage is lower than the electrical recovery strength. The switch contacts remain open and can be admitted that the circuit has been successfully disabled.

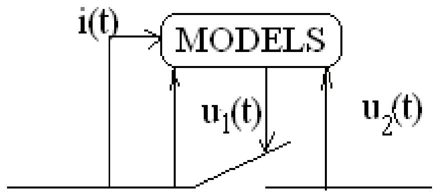


Fig. 7 Model vacuum switch in a package of programs ATP / EMTP with a diameter of 30 mm by 5 depending

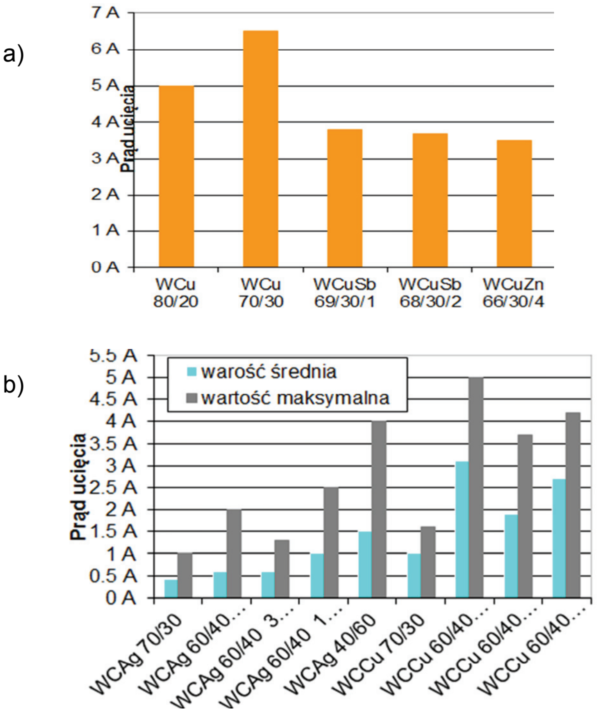


Fig. 8 The average values a) and the average and maximum b) chopping currents I_u alloys and sintered materials of contacts connecting the vacuum switch

Computational experiments presented in the article were performed for vacuum switch with contacts that open simultaneously and different times with the adoption of the following parameters characteristic for the switch affecting on the switching waveforms of currents and voltages in electrical circuits under consideration:

- Chopping current I_u=3A (fig. 8),
- Electrical recovery strength for Cu contacts with a diameter of 30 mm, determined by the formula 5:

$$U_w = A_1 \cdot d^b \tag{5}$$

where: A_1, b- factors depend on the contacts material, d-distance between contacts

- Maximum distance between contacts d_{max}=3 mm,
- nominal voltage adapter and power supply circuit U = 6kV,

- Maximum steepness and high frequency current i_{hf} at which switch is able to turn off the circuit s=150 A/μs.

More over in these calculations were also adopted the following simplifying assumptions:

- arc resistance is negligibly small (with sufficient accuracy for practical calculations,)
- power source is without resistance (ideal),
- all circuit elements are presented in the concentrated form.

In the simulations presented in the article there was adopted in the formula 5, such values A_1, b when designated using this model the steepness of the rise in the strength characteristics of the modeled switch was lower than the actual steepness of the real switch characteristics. Such procedure was used to obtain the re-ignitions of the arc occurrence in the switch in realized simulations. To better assess the practical usefulness and effectiveness of individual systems connections surge (Fig. 2) and their impact on the number of re-ignitions of the arc. Characteristics modeled as a real adapter would not provide such opportunities because in the vacuum switch re-ignition of the arc appear really rare and have a random nature (Fig.3).

Transient simulation results during the disconnection of capacitor bank with insulated neutral point by a vacuum switch with the simultaneous opening of the contacts

Simulation performed in electrical circuit from Fig.6 have shown (under the assumed parameters of the vacuum switch and switched circuit with the simultaneously opening of contacts in each pole switch) incidence of cases in the formation of the arc re-ignition in a vacuum switch extinguishing chambers. In Figures 9-11 are examples of considered transients values obtained in one such simulation.

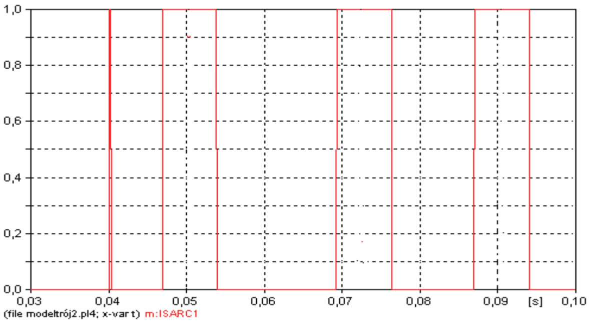
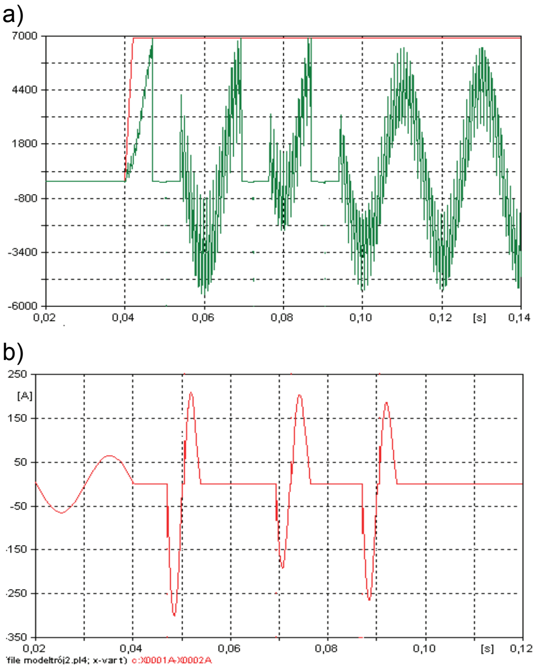


Fig.9 The number and times of occurrence of re-ignitions of the arc during the shutdown of Fig.5

From the analysis of the changes of these values in function of elapsed time since the opening of switch contacts due to that the first turning off the vacuum arc was cut before its natural zero crossing (I_u = 3A) after a period of 0.04 s, and then re-ignition of the arc occurred in the moments: 0.047, 0.07, 0.087 s after opening the vacuum contacts. The re-ignition were created in times exceeding the amplitude of the return voltage appearing on switch contacts, the values of strength, despite the fact that at that time there was already full strength this break equals 7 kV. Burning time of the arc and switching off the circuit where in this case after the time 0.095 s.

The re-ignition of the arc used to cause overcurrents's values achieving 300 A (Fig. 10b), threatening both the capacitors and other elements. They were also reason of connection overvoltage on the side of switched off capacitor equal 8kV (Fig. 11), dangerous for the isolation of these batteries. It should be noted that by the actual switching circuits it should be expected appearing of a smaller, but still dangerous, overvoltage and overcurrent values, because of occurring in them generated transient damping, that in the presented simulations have been omitted.


a)

b)

Fig.10 The course of recovery of strength (red curve) and the recovery voltage (green curve) on the vacuum switch contacts (a) and course of current (b) of the capacitor with a capacity of 50 MVAr in the circuit of Figure 5

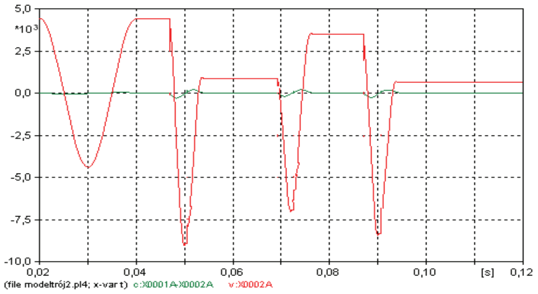


Fig.11 The course of current (green curve) and voltage (red curve) on the side of the battery switched off with 50 MVAr in the circuit Fig.5

Transient simulation results during the disconnection of capacitor bank with insulated neutral point by a vacuum switch with the different time opening of the contacts

In the real vacuum switches the contacts (in each of their poles) open at different times. To determine the effect of asynchronicity on switching waveforms there were processed digital simulations out for switch which contacts in phase A use to open 0.02 seconds faster than the phase B and C. To ensure comparability of results (that were with previously presented results obtained for the simultaneously opening of switch contacts), these simulations were carried out in the same circuit of Figure 5. and with the same parameters of circuit and switch. Their results are shown by the sample waveforms in Figures 12-15.

These waveforms show that the switching off considered capacitor bank by switch vacuum with difference time of opening contacts results higher overvoltage than voltage occurring during realized switches with simultaneously opening of contacts. It should be noted that overvoltage and overcurrent in both compared cases reach values that threaten the battery and the other elements of switched circuit.

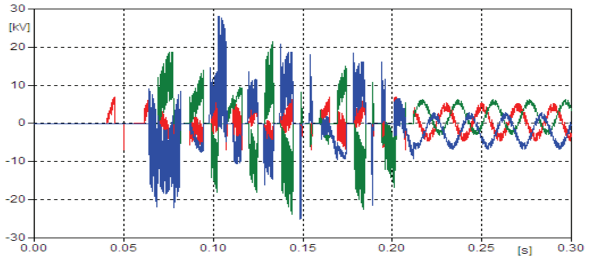


Fig.12 Voltage at the terminals of capacitors with insulated neutral point (Fig. 5) during the shutdown of the vacuum switch contacts opening not simultaneous

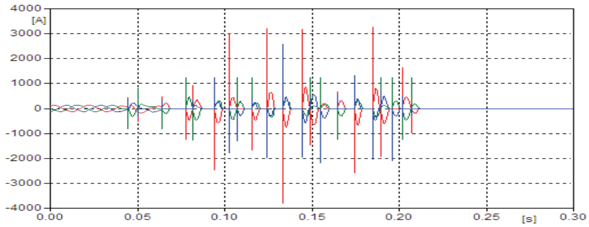


Fig.13 Currents during off capacitors with insulated neutral point (Fig.7) with the vacuum switch contacts opening not simultaneous

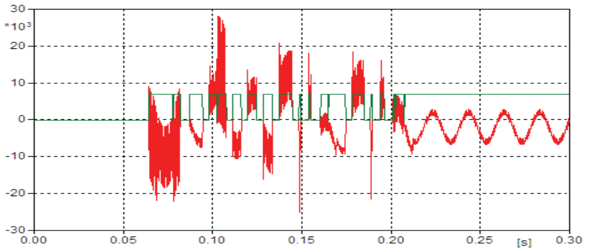


Fig.14 Recovery strength (green curve) and the return voltage on switch contacts in phase C (red curve) when only the battery of capacitors with insulated neutral point (Fig. 5) connecting the vacuum switch with different contacts opening time

Electrical recovery strength of the opening switch in case of simultaneous opening of contacts was punctured with two short bursts re-ignitions which ended in less time than re-ignition in the circuit with different time opening switch contacts.

Overcurrents during re-ignitions of the arc used to reach in both cases (Fig.11, 16) comparable maximum values of 300 A, however various intervals and with different intensity.

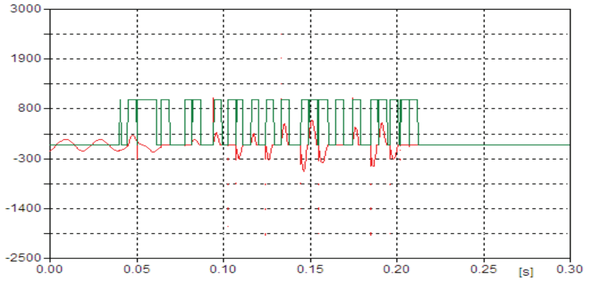


Fig.15 Current (red curve) and the moments of appearance of the arc (on a scale of 1:1000, green curve) when lamps repeatedly capacitor with insulated neutral point (Fig. 5)switch the vacuum switch with different contacts opening time

In the circuit commutated by switch with simultaneously opening contacts the maximum overcurrent has occurred only once in the initial phase of re-ignitions of the arc, while the frequency of ignitions of the arc and time of their concurrency where smaller than in circuit with switch with difference time of contacts opening.

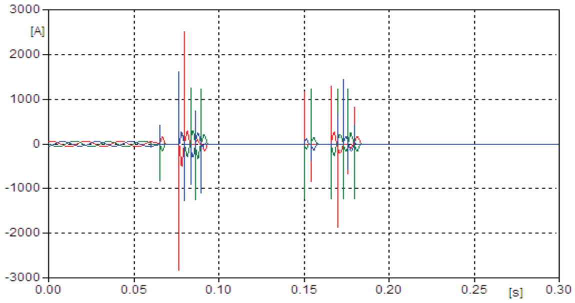


Fig. 16 Current when lamps repeatedly capacitors with insulated neutral point (Fig. 5) connecting the vacuum switch with the simultaneous opening of contacts

Transient simulation results during the turning off three-phase capacitor circuit with varistor surge, by a switch with simultaneous opening of contacts

In Figures 19-20 there are shown the waveforms of observed values that were obtained during the switching of circuits with different connections varistor surge (Fig.6).In Figure 17, 18 there are shown for purposes of verification, voltage waveforms obtained in the circuit without the surge (Fig. 5).

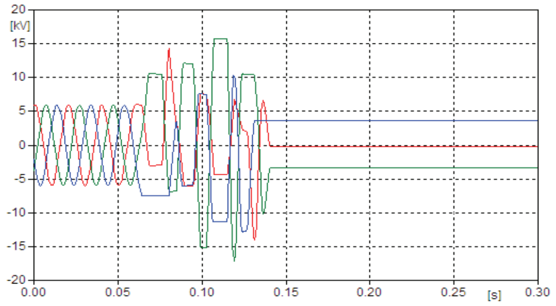


Fig.17 Terminal voltage capacitors switched off by an isolated zero point without the surge

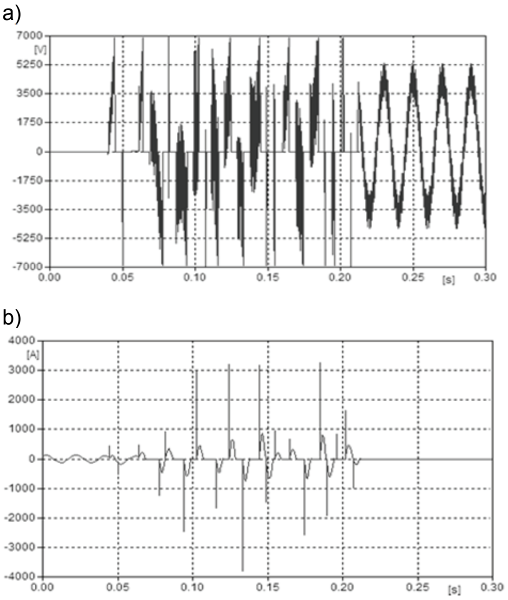


Fig.18 Waveform voltage (a) and current (b) between the contacts during switching the capacitors with insulated neutral point without the surge.

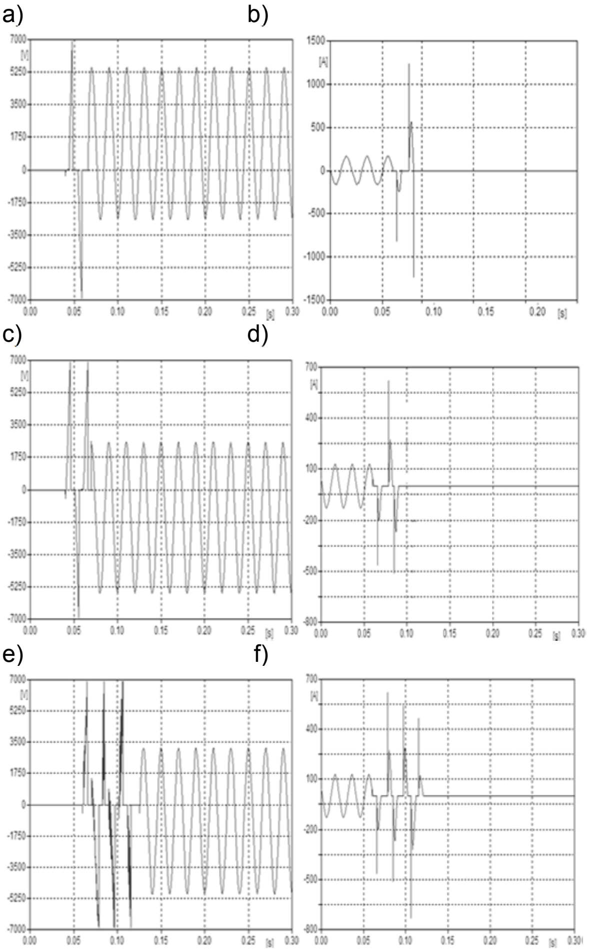


Fig 19 Waveforms (a, c, e) and current (b, d, f) on switch contacts when switch off capacitor with insulated neutral point and connected in surge: a, b-star with grounded neutral point (Fig. 6 a) , c, b-star with neutral point connected to the neutral point of capacitors (rys.8b), e, f – delta connection

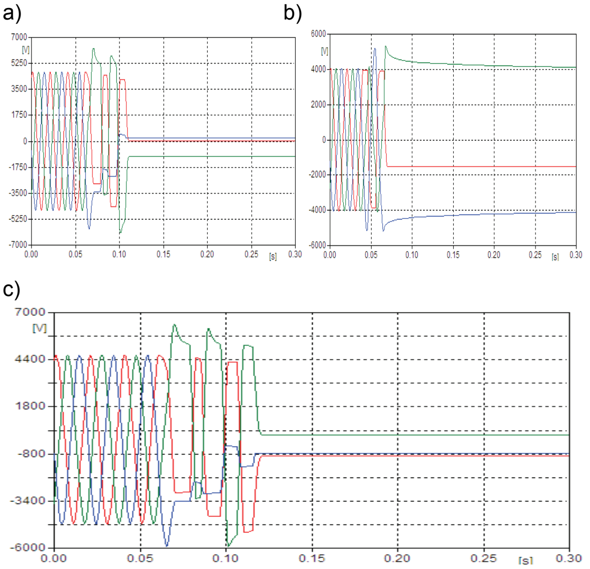


Fig. 20 Terminal voltage capacitors switched off by an isolated neutral point of the system surge a) star connection grounded neutral point b) of the star connection neutral point connected to the neutral point capacitor c) delta connection

Results obtained from the simulation of waveforms of the circuit without switching surge protection (Fig. 17, 18) show that the resulting overvoltage are dangerous, reached values three times greater than the rated working voltage capacitors.

The obtained simulation results show that in all cases of exemptions of capacitors, the re-ignition of the arc are formed and the accompanying overvoltage and overcurrent reach the values threatening to commutated circuits and the vacuum switch. Application varistor's systems shown in Figure 6 reduces the amplitude of existing exposure (overvoltage, overcurrent) and their frequency (the number of re-ignitions of the arc), what has a positive effect on the durability and reliability of switched circuit and installed in it devices. The biggest effect of pending varistor's systems restricting surge shows a star system with grounded neutral point (Fig. 6).

Conclusion

1. The model is a result of the initial stage of work developing model for waveforms simulation during commutation by vacuum switch capacitive circuit.
2. A number of computational experiments were carried out with taking this model. There were included different configurations and parameters of the switched circuit and vacuum switch what allowed obtaining results in good agreement with the results of theoretical analysis and empirical research. This confirms the correctness and validity of used in its construction simplifying assumptions and their possibility of use in later stages of model development.
3. All shown surge protection limited created overvoltages to the safe for capacitor bank value. They also decrease number of re-ignition of the arc what had a positive impact on vacuum switch and capacitor bank durability. The most effective and also the easiest in realization is star system with grounded neutral point.

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