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Analysis of switching on selected electrical high voltage circuits

Physical phenomena occurring in high-current contact systems of electric switches, when switching on unloaded transformers and capacitor banks, are much more dangerous than the phenomena occurring in the contact switch systems installed in other electric power systems. Switching on unloaded transformers may be accompanied by significant over-currents, greatly exceeding the nominal currents of the transformer. Connecting the capacities of capacitor banks causes transients in the circuit, leading to significant, fast over-currents and over-voltages. High-frequency currents may be transmitted by electromagnetic couplings to control circuits and other low-voltage circuits. The subject of the paper is the analysis of transient processes during switching on unloaded transformers and the capacities of capacitor banks. Additionally, the authors assess the impact of the power switching phase in particular circuits on the over-currents which arise there.

Keywords: *switching on unloaded transformers and capacitor banks, power switching phase, synchronized switching.*

1. INTRODUCTION

Switching on or off currents in both high- and low-voltage electric power circuits takes place with the use of electric mechanical switching contacts. The process of connecting an electric circuit is accompanied by transient states of voltage and current, resulting from the circuit inductance and capacity [1, 5, 10]. The occurring over-voltages and over-currents have significantly high values and high rates of rise. Therefore they can be dangerous to the connected receivers and to the switch as such. These phenomena speed up the wear of contact systems and quenching devices. They also stimulate erosion and contact welding. The erosion process gets more intensive with the increasing arc temperature and its burning time [6, 8, 9]. The impact of these phenomena on mining operations is of considerable importance too [11].

When the contacts are closed in any environment, which acts as isolation between the contacts of the switch, the isolation layer is punctured and an electric arc occurs between the converging contacts. Thus, switching on the current in an electric circuit occurs, most frequently, not as a result of the adhering contacts but due to the punctured isolation of the given environment. The time of arc burning depends on the voltage value of the electric field in the contact area and on the converging speed of the contacts [7, 9].

While switching on alternating currents, particularly short-circuit currents, an electric arc, which appears at the moment the contacts get separated, dies down when the current passes through zero. Immediately after that, the dielectric strength increases. Its rate of increase depends on the neutralization speed of charges which are in the area between contacts. The number of these charges depends on the current which was flowing in the arc previously. At the same time, the transient state, initiated in the circuit by switching off breaking current, results in the occurrence of recovery voltage between the diverging contacts. The recovery voltage contains the basic component with the pulsation of the power supply source and the free component with much bigger pulsation. The voltage wave is influenced, first of all, by the arc voltage, post-arc channel, quenching system of the switch [1, 5].

The analysis of the operating conditions of high-voltage switches demonstrates that in normal working conditions one can assume to have 80 switching operations annually. This corresponds to the mechanical endurance of the switch of at least 2,000 operations during 25-years exploitation. In special cases, e.g. while connecting parallel banks, reactors, filters in pump-storage plants and wind farms, the number of annual connections can be much bigger, therefore the switching endurance is estimated at 10,000 operations minimum.

The paper features the issues related to the analysis of the process of switching on unloaded transformers and capacitor banks. It also takes up the evaluation of the properties of transient processes which accompany the processes of switching on currents. Finally, the authors focus on the selection of a proper current switching phase in the concerned circuits with a view to limit negative properties of the transient processes.

2. SELECTED ISSUES RELATED TO SWITCHING ON ALTERNATING CURRENTS

The analysis of transient switching processes related to switching on alternating currents includes the following:

- switching on unloaded transformers,
- switching on capacitor banks.

2.1. Switching on unloaded transformers

The process of switching on unloaded transformers to the network is accompanied by a transient state. During this state there are over-currents which may achieve significantly high values [3, 4, 9]. The values depend both on the parameters of the transformer and the features of the switch. The transient processes which accompany the process of switching on current are related to the non-linear quality of the transformer magnetic circuit and the possibility to have residual magnetism in the core. This magnetism is a remnant of previous exploitation of the transformer. This means that the next switch-on of the transformer can occur at the stream value in the core different from zero. It is important to note here that similar switching processes occur while switching on parallel reactors [1, 9].

The analysis is focused on physical phenomena occurring while switching on an unloaded single-phase transformer whose substitute diagram is presented in Fig. 1.

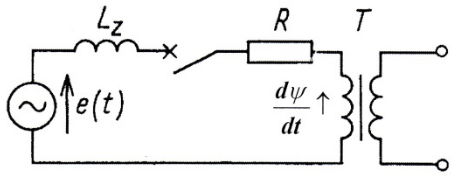


Fig. 1 Substitute diagram of the circuit

Time wave of current for the transient state of switching on a substitute circuit of the transformer (Fig. 1), when skipping the inductance of the primary winding (L_z = 0) is determined from the following equation [9]:

$$e(t) = Ri + \frac{d\psi}{dt} = E_m \cos(\omega t + \varphi) \qquad (1)$$

where:

e(t) – instantaneous value SEM of the power supply source;
ω – pulsation of the power supply source;
Ψ – instantaneous value of magnetic association of the primary winding during the transformer switch-on;
φ – SEM phase in the moment of switching on;
i – instantaneous value of the transformer switching current;
R – resistance of the switched-on circuit.

After the integration of equation (1) we obtain the following:

$$\psi(t) = \frac{E_m}{\omega}\sin(\omega t + \varphi) - R\int_0^t i dt + C_1 \qquad (2)$$

The constant of integration C_1 for boundary conditions t = 0, i = 0, $\Psi = \Psi_0$, association resulting from residual magnetism) is:

$$C_1 = \psi_0 - \frac{E_m}{\omega}\sin\varphi \qquad (3)$$

Thus the equation solution has the following form:

$$\psi(t) = \psi_0 + \frac{E_m}{\omega}\left[\sin(\omega t + \varphi) - \sin\varphi\right] - R\int_0^t i dt \qquad (4)$$

The highest instantaneous values of magnetic association can be achieved when:

- $\Psi(0) > 0$ and is big, i.e. when residual magnetism is big;
- $\varphi = -\pi/2$, initial SEM phase in the moment of switching on corresponds to SEM passing through zero.

The highest value of the associated stream Ψ_m occurs after the time of $t = \pi / \omega$ and is:

$$\psi_m = \psi_0 + 2\frac{E_m}{\omega} - R\int_0^t idt \approx \psi_0 + 2\psi_{um} - R\int_0^t idt \qquad (5)$$

where:
Ψ_{um} – maximum value of magnetic association in the steady state.

Assuming, in turn, that the resistance value of the winding $R = 0$ in equation (1), we have the following:

$$e(t) = E_m \cos(\omega t + \varphi) = \frac{d\psi_u}{dt} \qquad (6)$$

Therefore, the magnetic association in a steady state is described by the following dependency:

$$\psi_u = \frac{E_m}{\omega}\sin(\omega t + \varphi) = \psi_{um} \sin\ (\omega t + \varphi) \qquad (7)$$

A sample waveform of the transformer switching current, for the set magnetization curve, is demonstrated in Fig. 2.

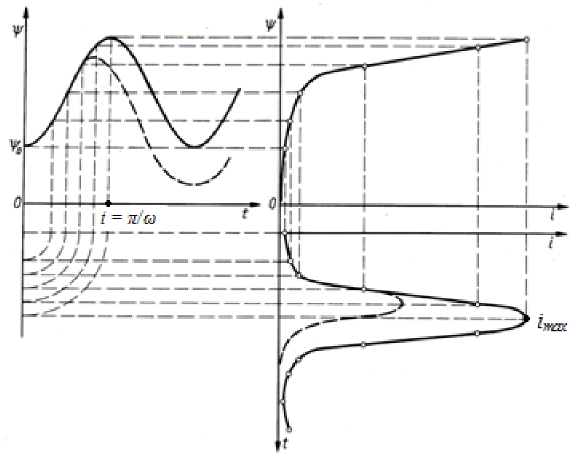


Fig. 2 Current waveform while switching on an un-loadded transformer, for the set magnetization curve; R = 0 (solid line) and R > 0 (dashed line) [9]

As it can be seen in Fig. 2, due to the flat waveform of the $\Psi(i)$ characteristic, the achieved peak values of current can be quite significant. The higher are these values, the higher is the value of magnetic association $\Psi(0)$ as a result of residual magnetism and the higher is the saturation of the steady state which corresponds to the magnetic association Ψ_{um}.

In the process of uncontrolled switch-on of a transformer, particularly a high-power transformer, one has to take into account switching currents whose values are from 8 to 15 times higher than the values of their rated current, thus the rated current has a value similar to that of short-circuit current. Such current values have mechanical impact on the transformer windings. Additionally, they can stimulate protection circuits and cause unplanned switch-offs. What is more, one has to consider the possibility to have inductance of extra currents and voltages in control circuits and low-voltage circuits. They may be inadmissible, particularly for electronic devices.

Therefore, it is considered to be fully justifiable to use synchronized (controlled) switching for transformers, particularly high-power ones. This process is accompanied by lowering residual magnetism of the core and switching on the transformer at its maximum voltage [2, 4, 9, 12, 13].

Thus it is justifiable to use synchronized switching of transformers and to switch them on at their maximum voltage values in order to limit over-currents in the circuit [2, 4, 9, 12, 13].

2.2. Switching on capacitor banks

Connecting the capacities of capacitor banks causes transient states which are very important in the switching technology. Such states lead to significant over-currents and over-voltages. Similar problems can be encountered while connecting unloaded long lines [2, 5, 9, 10].

Most frequently, capacitor banks are installed as three-phase elements, connected in the form of an ungrounded star due to the simplicity of protection measures against internal short circuits in the bank. If we assume that the three phases are switched on simultaneously, and in the light of the circuit symmetry, the star points can be connected resistance-free and the three-phase circuit can come down to a single-phase one [2, 6, 9].

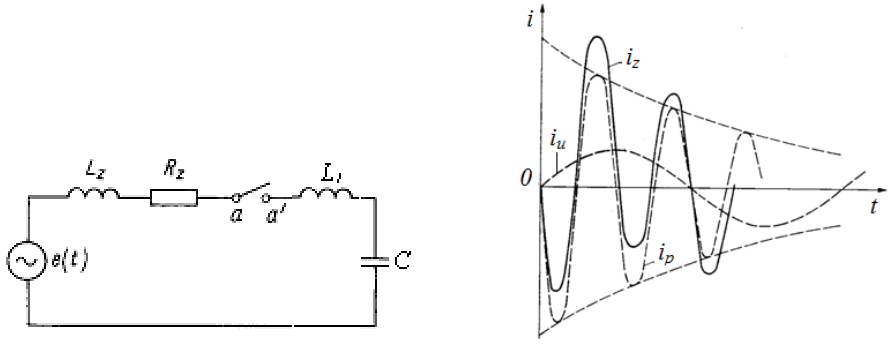
The following boundary switching moments are characteristic of capacitor banks switching:

- when the instantaneous value of the power supply network voltage is equal to the maximum value,
- when the instantaneous value of the power supply network voltage is equal to zero.

The switching processes for other time moments are included between these boundary cases. The most frequent case is when a capacitor is switched on to the network at the maximum value of the power supply voltage. When the gap between contacts is punctured, an electric arc occurs between the switch contacts. The transient current which flows then has the highest over-current possible in the circuit.

While analyzing transient processes which occur while switching the lumped capacity of capacitor banks, it is necessary to consider the case when single capacitors are switched on to the network in which there are not any other capacitors connected in a parallel manner (Fig. 3). What is more, one has to consider another case which is even more dangerous in terms of over-currents occurring in the circuit, i.e. connecting extra capacitors to the circuit which already has some live capacitors.

a) *b)*



Rys. 3. Switching on batteries with the capacity C and connections inductance L_1, in a power supply circuit with the inductance L_z (L_z » L_1) and resistance $R_z \approx 0$: a) substitute diagram of the circuit; b) waveforms of switching current iz and its components [6]

Assuming sinusoidal supply voltage *s(t)*, insignificantly small resistance of the supply circuit R_z and not taking into account the inductance L_1 of connections with the capacitor bank (as it is much smaller than the supply inductance L_z), the value of switching current $i_z(t)$ is calculated from the following dependency:

$$i_z = I_m(\sin\omega t - \frac{\omega_0}{\omega} e^{\alpha t} \sin\omega_0 t) \qquad (8)$$

where:

I_m – maximum value of steady-state current i_u, $I_m = E_m \omega C$;

ω – pulsation of the power supply source;

ω_0 – pulsation of free vibrations; $\omega_0 = \sqrt{\frac{1}{L_z C}}$

The amplitude of switching current in the most inconvenient moment, i.e. when the voltage of the power supply source is at its maximum value $e(t_0) = E_m$, is calculated from the following:

$$i_{z\max} = I_m(1 + \frac{\omega_0}{\omega}) = I_m(1 + \sqrt{\frac{S_k}{Q_k}}) \qquad (9)$$

where:

S_k – short-circuit computing power in the place where a capacitor bank is connected;

Q_k – capacitor bank power.

When single low- or medium-voltage banks are switched on, the amplitude value of switching current can be 5 – 20 times higher than the peak value in a steady state. While the voltage on the capacitor can reach only the double maximum value of the power supply source voltage. In real circuits the transient processes of currents and voltages are suppressed due to the circuit resistance and enlarged skin effect.

Connecting an extra capacitor bank to a previously switched on bank, with a view to have better adjustment of the total capacity to the given reactive power, may produce serious connection problems. While connecting particular sections of the capacitors to live sections, the value of over-current in the circuit results from the capacities of particular sections (groups) of capacitors (Fig. 4). Due to small inductance values in the branches (connections) of the given bank when it is switched on by means of the C_2 bank switch, the C_1 bank is practically shortened [2, 5, 9]. Then the transient process of the current is suppressed to a small extent.

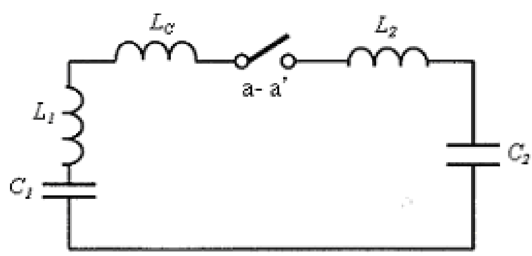


Fig. 4 Substitute diagram of a circuit for analyzing the connection of the capacity C_2 to a group of capacitors with the capacity C_1; L_1, L_2, L_C – inductances of connections [6]

If, while switching on the bank C_2, there is a flashover between the contacts *a – a'* of the switch, at the maximum value of power supply voltage, then the transient current will have the highest initial rate of rise and amplitude. Its value can be determined from the following:

$$i_2(t) = u_{aa'}(0)\frac{1}{\sqrt{(L_1+L_2+L_c)(\frac{1}{C_1}+\frac{1}{C_2})}}\sin\omega_{02}t \qquad (10)$$

where:

$$\omega_{02} = \sqrt{\frac{1}{L_1+L_2+L_c}(\frac{1}{C_1}+\frac{1}{C_2})} \qquad (11)$$

The highest value of the current amplitude $i_2(t)$ may sometimes exceed the value of maximum aperiodic short-circuit current in the given place of the network. However, the rates of rise of switching currents are much bigger than those of short-circuit currents. In addition, high-frequency currents may propagate through electromagnetic couplings into control circuits and other low-voltage circuits, exerting unfavourable impact on different electronic circuits and microprocessors of control and automatic systems [6, 10, 12].

There are some measures which can efficiently reduce over-currents in capacitor banks [2, 9, 10]:

- two-step switch-on of capacitor banks with the use of a switch equipped with a resistor, closed with the delay which is enough to suppress the transient process of current;
- synchronized switch-on when power supply voltage passes through zero.

3. WYBÓR FAZY ZAŁĄCZANIA PRĄDU

Limited dielectric strength of the environment, surrounding the contacts of the closed electric high-voltage switch, has certain consequences, i.e. switching on the current in an electric circuit is not a result of the contacts contraction but happens due to the electric breakdown of the given environment, e.g. SF_6. The puncture of the gap between contacts occurs when the value of the gap dielectric strength $u_p(t)$ equals the instantaneous value of voltage applied to the gap $u(t)$ (Fig. 5).

Generally, the higher is the speed value v_s of converging contacts of the electronic switch, the shorter is the opening time of the switch. As a result of that, shorter time of electric arc burning positively impacts the durability of electric switches.

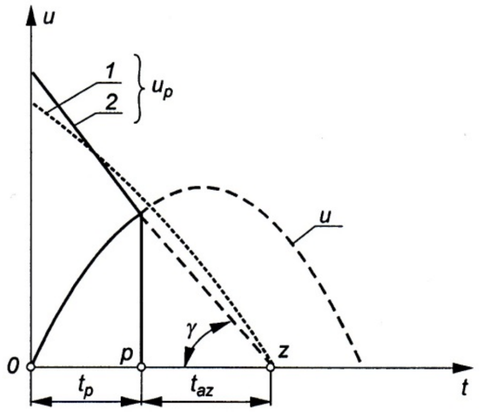
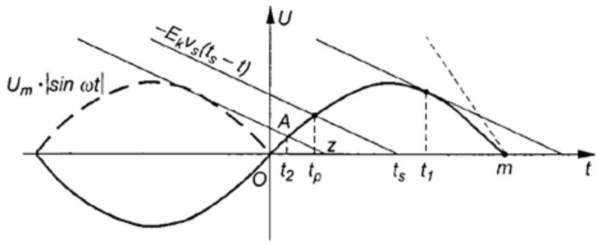


Fig. 5 Graphic determination of pre-arc time t_p and arc time t_{az} while switching on current [7]



Rys. 6. Determining the moment of the arc ignition while switching on alternating current [6]

Assuming that breakdown voltage is proportional to the size of the gap between contacts (Fig. 6) and that it does not depend on the contacts polarity, it is possible to determine the moment t_p when a breakdown occurs while switching on current, at the voltage $u = U_m \sin \omega t$. This can be determined by means of the following dependency:

$$U_m|\sin\omega t| = E_k n v_s (t_s - t_p) \qquad (12)$$

where:

E_k – value of the electric field strength at which the puncture occurs;

v_s – speed value of converging contacts (decreasing gap between contacts), at the moment of electric arc ignition in the gap,

n – number of gaps in the pole,

t_p – moment of the gap puncture,

t_s – moment of the contacts meeting.

Thus switching on current is possible at any voltage circuit angle, including the circuit angle corresponding to the moment when voltage passes through zero, provided that the following condition is fulfilled:

$$k = \frac{nE_k v_s}{\omega U_m} \geq 1 \qquad (13)$$

The minimum speed value of the contacts at the moment when they meet, which guarantees no puncture of the gap during current switch-on in an electric circuit, can be determined from the following dependency:

$$v = \frac{\omega U_m}{n E_k} \tag{14}$$

The higher is the speed value v_s of converging contacts, the shorter is the opening time of the switch $(t_s - t)$ and, obviously, the shorter is the time of electric arc burning. In the case of synchronized switching it is required to adjust the switch in such a way that, depending on the load character, the beginning of current flow in particular phases should occur when the instantaneous value of the given phase voltage is the most convenient from the point of view of switching processes. This means that when the inductive load is switched on by an ideal switch, the impulse generation should occur in such a moment that the contacts meet at the maximum instantaneous value of voltage and when capacitive load is switched on – at the voltage value equal to zero.

Switches used to make three-phase connections should, as a matter of fact, have separate drives for particular poles. The selection of a given current switching phase requires to apply an electronic circuit which controls the process of the switch closing.

4. CONCLUSIONS

Based on the conducted analysis and tests described in this paper, the following conclusions can be drawn:

1. In the process of switching on an unloaded transformer there may be significant over-voltages in its primary circuit, up to 8-15 times of the value of their rated current. As a result of that, the switching apparatus, particularly control and protection devices, can be exposed to hazards.
2. Significant over-voltages occurring while switching on capacitor banks can lead to damages of particular capacitors and may cause switch contacts to weld.
3. High-frequency switching currents in capacitive circuits are transmitted through electromagnetic couplings into control circuits and other low-voltage circuits.
4. The switch-on phase of current in an electric circuit, speed of the switch contacts convergence and distribution of opening times have significant impact on over-currents and over-voltages in the circuit.
5. Synchronized current switch-on/off makes is possible to reduce significantly over-currents and over-voltages in an electric power system.

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