Janusz BANDEL
Artur HEJDUK
Andrzej DZIERŻYŃSKI
Piotr KORYCKI
Henryk SIBILSKI

SWITCHING AND LIGHTNING OVERVOLTAGES AND THE REQUIRED WITHSTAND VOLTAGE BETWEEEN THE OPEN CONTACTS OF 245 KV CIRCUIT BREAKERS

ABSTRACT This *paper deals with the surges generated in the network during switching operations and lightning surges. The level of both kinds of surge was compared with the required dielectric strength between the open contacts of 245 kV circuit breakers. Overvoltages greater than the electrical withstand voltage of the circuit breaker can cause arc ignition between the circuit breaker's open contacts and power engineering service s have reported such cases. The results of such failures can be very serious. This is a problem especially for single-break circuit breakers, in which the stresses on the electrical insulation between the open contacts of the breaker are very high. A method for selecting lightning arresters to lower the overvoltages is proposed. The switching of short-circuit currents by a circuit breaker may cause a weakening of the circuit breaker chamber's insulation and reduce its electrical withstand and durability.*

Keywords: *high voltage circuit breakers, switching inductive and capacitive currents, switching and atmospheric overvoltage, lightning arresters*
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1. INTRODUCTION

High voltage circuit breakers in EHV networks are subjected to very high overvoltages during switching and lightning surges. Switching high short-circuit currents

Janusz BANDEL, M.Sc., Artur HEJDUK, M.Sc., Andrzej DZIERŻYŃSKI, Ph.D.
Piotr KORYCKI, Ph.D., prof. Henryk SIBILSKI, Ph.D., D.Sc.
e-mail: [j.bandel; a.hejduk; a.dzierzynski; h.sibilski]@iel.waw.pl

Electrotechnical Institute, ul. M. Pożaryskiego 28, 04-703 Warsaw, Poland

causes ignition between the contacts and the high temperature of the arc and the resulting metal dust particles weaken the insulation strength of the CB vacuum chamber and diminish its switching durability. Power engineering services have reported some cases of arc ignition between the open contacts of circuit breakers [5, 6] and the results of such failures can be very serious. These phenomena are the subject of research and analysis aimed at increasing circuit breaker reliability. We shall discuss the reasons for the occurrence of dangerous overvoltages in circuit breakers, particularly those with EHV circuit breaker with a single interrupting unit. Some recommendations are given for preventing these overvoltages in network operating conditions.

A number of switching scenarios can be specified in which the level of overvoltages is high. These involve switching inductive and capacitive currents. The level of lightning surges will also be discussed depending on the place of the lightning strike relative to the position of the circuit breaker.

IEC National Committees postulate an increase in the switching durability of circuit breakers by increasing the number of switchings which have to be executed during circuit breaker type tests without carrying out any maintenance of the vacuum chamber or the drive.

2. HAZARDS RELATED TO SWITCHING OVERVOLTAGES

High voltage circuit breakers have to withstand the test voltages stipulated in national and international standards [1, 2, 3], which include short duration power frequency voltage withstand tests and impulse voltage tests. For 245 kV circuit breakers the prescribed short duration power frequency withstand voltage across the insulation gap for a network with a grounded neutral is 530 kV, and in the impulse voltage test it is 1200 kV, 1.2/50.

According to IEC standards, when switching short circuits the highest transient recovery voltage at 245 kV CB terminals is 364 kV at 100% of the short circuit current and increases to 500 kV in the out-of-phase test. Switching overvoltages at high currents cause ageing of the circuit breaker chamber's internal insulation, nozzle and contact wear, and a gradual reduction in the circuit breaker's withstand voltage.

Up to now IEC standards accept the maintenance of some chamber elements after undergoing a series of tests, in order to prepare the circuit breaker for subsequent tests. However, in standard operating conditions such actions are not undertaken unless required in the manufacturer's instruction manual.

3. INDUCTIVE AND CAPACITIVE CURRENT SWITCHING

In electrical power systems for voltages of 245 kV and above it is not the level of the atmospheric surges, but switching overvoltages that decide the choice of circuit breakers. Consequently a reduction in switching overvoltages in EHV lines, especially in the vicinity of transformers, is crucial.

The present paper examines the problem of overvoltages assuming equivalent circuits with lumped elements.

To analyze the level of overvoltages that the circuit breaker can be subjected to it is necessary to consider the transients in the system connected with:

- switching off unloaded transformers and reactors;
- switching capacitor banks;
- switching on and off unloaded transmission lines.

3.1. Switching unloaded transformers and reactors

Switching inductive currents in most cases means switching unloaded transformers and reactors [10, 11]. The phenomena of switching inductive currents can most conveniently be analyzed using the single phase equivalent circuit shown in Figure 1.

L_2 and C_2 designate the load inductance and capacitance of the transformer or the reactor that is switched off, and brought to the reference voltage; L_1 and C_1 designate the equivalent load inductance and capacitance of the supply circuit.

When switching off the inductive current, the arc is unstable; it is constantly stretched and at the same time the arc voltage increases. The arc current begins to oscillate due to the influence of the supply circuit and finally a current zero occurs. The capacitances C_1 and C_2 discharge through the inductance of the busbars l_p connecting them. The frequency of the discharge current is:

$$f_3 = \frac{1}{2\pi\sqrt{l_p \cdot \frac{C_1 \cdot C_2}{C_1 + C_2}}}$$

The oscillating current can be switched off by the circuit breaker S at zero current. This phenomenon is called current chopping. The current amplitude depends on the circuit breaker's characteristics and on the circuit parameters, in other words on capacitances C_1, C_2 and inductance l_p.

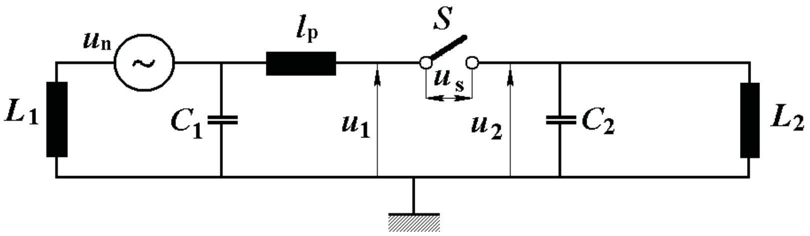
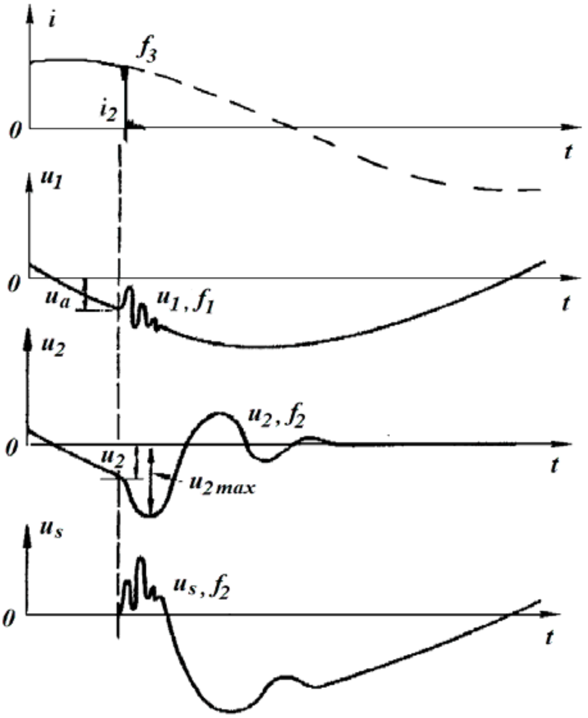


Fig. 1. Switching inductive currents:

u_n – power supply voltage; C_1, L_1 – capacitance and inductance of the power supply; l_p – inductance of the switchgear busbars; S – circuit breaker; u_s – voltage between the CB contacts; u_1 – voltage between phase and neutral on the supply side; u_2 – voltage between phase and neutral on the load side; C_2, L_2 – capacitance and inductance of the load circuit



$$f_3 = \frac{1}{2\pi\sqrt{l_p \frac{C_1 C_2}{C_1 + C_2}}}$$

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

$$f_2 = \frac{1}{2\pi\sqrt{L_2 C_2}}$$

$$u_s = u_1 - u_2, f_2$$

Fig. 2. Current and voltage diagrams at inductive current switching [16]:
u_1, u_2, u_s – instantaneous voltages on, respectively, the supply side, the load side, and between the contacts of the CB, u_a – voltage on the supply side at the beginning of the current interruption; i_2 – current in the supply circuit; f_1 – frequency of the voltage on the supply side at the time of the current interruption, f_2 – frequency of the voltage on the load side at the time of the current interruption, f_3 – frequency of the current at the time of the interruption

The oscillating current can be switched off by the circuit breaker S at current zero. This phenomenon is called current chopping. The current amplitude depends on the circuit breaker characteristics and on the circuit parameters, that is on capacitances C_1, C_2 and inductance l_p. The frequency of the recovery voltage on the supply side depends on L_1, C_1:

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

and is in the range from 1000 Hz to 5000 Hz when this is superposed on the supply side voltage Un, it increases the overvoltage level.

When switching off a transformer T the frequency f_2 is between 200 Hz and 400 Hz; when switching off a reactor it ranges from 900 Hz to 1200 Hz. Between the

CB contacts a voltage occurs, which is the difference between the two voltages of different frequencies. The maximum voltage on the supply side, $U_{2\mathrm{mx}}$ can be calculated from the equation:

$$u_{2mx} = \sqrt{u_a^2 + \beta\, i_a^2 \frac{L_2}{C_2}}$$

where:

u_a, i_a – the voltage and current of the arc,

β – the coefficient representing the influence of the transformer's magnetizing energy.

Due to the arc ignition the magnetic energy of the circuit is reduced. The relatively small current at the first arc ignition is switched off instantly and the voltage increases to such a level when the next arc ignition occurs, which in turn is switched off, and so on. This phenomenon repeats until the final arc extinction occurs (Fig. 2, c).

The level of overvoltages when switching inductive currents, is defined as a quotient of the maximum voltage $u_{2\mathrm{mx}}$ and the supply voltage $U_\mathrm{n}\sqrt{2}/\sqrt{3}$, and can be calculated from:

$$k_{\max} = \frac{u_{2mx}}{U_n\sqrt{\frac{2}{3}}} = \sqrt{1 + \frac{3}{2}\frac{i_a^2}{u_a^2}\beta\frac{L_2}{C_2}}$$

In a 3-phase system with a grounded neutral, the phenomenon can be interpreted in the same way as above for a single phase circuit.

Field measurements of the overvoltages in transformers of different types and voltages are shown in Figure 3.

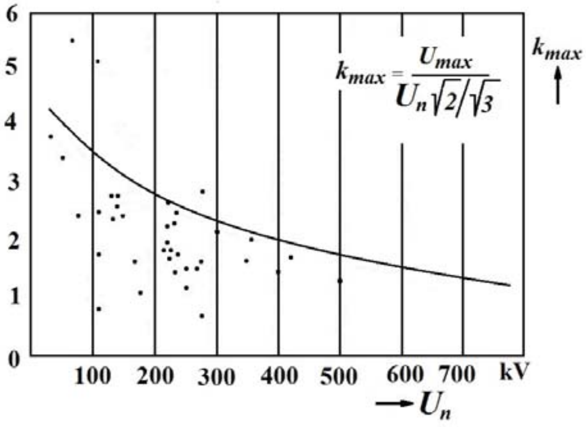


Fig. 3. Overvoltages due to switching inductive transformer currents [9]

As can be seen from Fig. 3 the overvoltages at 245 kV can reach about 2.7 U_n while at 420 kV they are smaller and are in the range of 1.8 U_n.

Switching the reactor currents from 100 A to 200 A at the surge impedance $\sqrt{L/C}$ from 35 kΩ to 50 kΩ can generate overvoltages of up to k_{max} = 2.5 U_n. To reduce their values arresters are used.

The overvoltages generated by the circuit breaker when switching the inductive currents of unloaded transformers are higher than the withstand test voltages which were applied to test the circuit breaker during the type tests. They amount to about 3 U_n at 123 kV, about 2.7 U_n at 245 kV, and 1.8 U_n at 420 kV – see Figure 3. When switching reactors the overvoltage level is about 2.5 U_n. For this reason properly selected arresters are mounted close to transformers for the protection of the transformers and other power station equipment.

3.2. Switching capacitive currents

High voltage circuit breakers must also meet the requirements for switching capacitor banks, cables and long HV lines.

The magnitude of the capacitive current depends on the capacitance of the capacitor bank the cable, and the line itself. The line’s own capacitance ranges from 200 nF/km to 700 nF/km depending on the cable type, and from 9 nF/km to 13.5 nF/km for an HV line. The recovery voltage waveforms can be analyzed using a single phase circuit diagram (see Fig. 4), as was done for the inductive current switching tests.

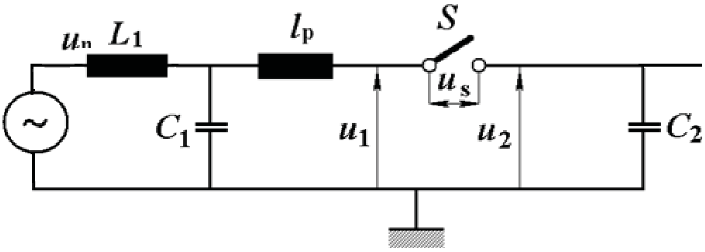


Fig. 4. Simplified circuit diagram for capacitive current switching

Before switching off the capacitive current at current zero, that is at the time when the voltages on the supply side and on the load side are equal $u_1 = u_2$ (see Fig. 5), the line voltage is higher than $U_1\sqrt{2/3}$ and depends on the inductance l_p on the supply line side.

After the current interruption by the circuit breaker the voltage of the load side on C_2 is equal to the maximum value of $U_2\sqrt{2/3}$ whereas voltage u_1 on the supply side oscillates around $u_1(t)$.

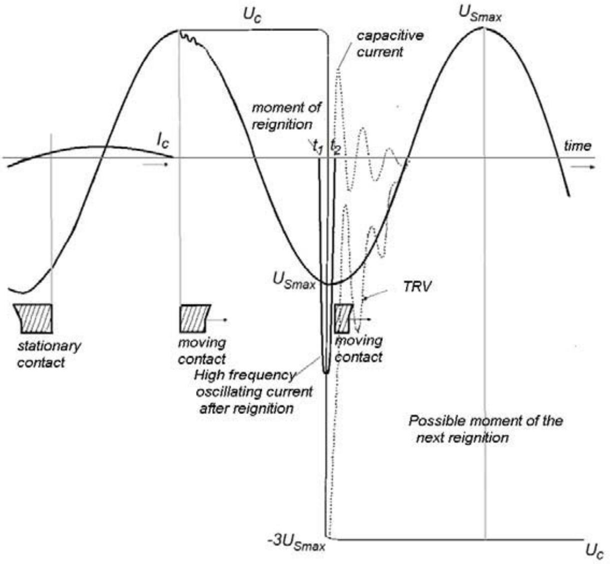


Fig. 5. Switching capacitive currents [4]

U_c – supply voltage, u_s – voltage on the load side, *Ic* – capacitive current, t_1 – moment of reignition, t_2 – interruption of the high frequency current, S_c – stationary contact, S_m – moving contact, *TRV* – transient recovery voltage after reignition

The voltage between the circuit breaker contacts is equal to $u_z = u_1 - u_2$ with an amplitude of $u_{z\max} = u_1\sqrt{2/3}\left(1+k_p\right)$, where:

u_1 – the nominal line voltage on the supply side;

k_p – the quotient of the instantaneous values of the power frequency voltage on the supply side and on the load side, at the moment of the current interruption.

Because $k_p > 1$, voltage $u_{z\max}$, between the contacts of the circuit breaker, can be more than double the magnitude of the nominal voltage $2U_1$ after 10ms. As Figure 5 shows, when an arc ignition takes place between the contacts at a time close to the maximum voltage value of the opposite polarity, the voltage between the contacts of the circuit breaker can achieve a value of 3 U_1 or even greater, up to 3.4 U_1, of the power frequency voltage (e.g. after some years of circuit breaker operation, due to a reduced withstand voltage of the gap between the contacts). This is because after arc ignition, the current flows for a certain time, e.g. from t_1 to t_2, as shown in Figure 5, and when the current is switched off, the line is still loaded to the maximum value of the voltage at which the current flowed, and the transitory voltage is superposed on the supply voltage.

Because the degree of overvoltage depends on the time of the arc reignition that takes place after the current interruption two types of case can be discerned:

- the first, when the reignition occurs after less than 5 ms;
- the second, when the arc reignition occurs after more than 5 ms.

In the first case the line voltage is of the same polarity as the supply voltage and consequently the probability of arc ignition is small; however in the second case the voltage difference is significant and there is a danger of arc reignition between the open contacts of the circuit breaker.

3.3. Switching unloaded lines on

A typical single phase circuit in which a circuit breaker S_1 switches the power station voltage on a high voltage line is shown in Figure 6. In this figure the power station voltage U_n before the switching, and the voltage U_{n2} after the switching at t_1, are shown, with the latter increasing from zero to $u_1 = U$. This increase is caused by a travelling wave of a maximum value U_{mx} superposed on voltage U_{n2} of an increased value. Due to the Ferranti effect the voltage at the line end is higher than the voltage at the beginning and the ratio of the former voltage to the latter is described by the expression:

$$U_k/U_p = 1/\cos(bl) \qquad \text{and} \qquad I_p = U_k/Z_f \cdot \sin(bl)$$

where:

l – the line length;

$b = \omega\sqrt{L_u C_u} = \frac{\omega}{c}$ – the propagation factor of a long line;

$Z = \sqrt{\frac{L_u}{C_u}}$ – the wave impedance of the long line;

c – the velocity of light, 300 m/μs;

L_u – long line inductance per unit length;

C_u – long line capacitance per unit length.

As b – the propagation factor of the long line and Z – the wave impedance of the line are constant, the voltage increase of the line depends mainly on its length. A well-pronounced voltage increase, amounting to 1.45, can be seen for a line length of 800 km. In Poland the length of 245 kV lines does not exceed 200 km so in these lines the Ferranti effect is insignificant. The transient component of the voltage depends on the moment the power station voltage on the line is switched. The maximum overvoltage values occur when switching (with a flashover between the CB contacts) at time t_1, when the transient voltage is superposed on the 50 Hz voltage close to its maximum.

In this example it is evident that for the highest overvoltage to occur a few circumstances need to coincide.

Assuming a single-phase short circuit to the ground in an HV line during test series of automatic reclosing cycle, circuit breakers S_1 and S_2 are opened at some time. The action of these circuit breakers is not simultaneous, consequently after one breaker switches off the short-circuit, the other switches the current in the other two phases of the unloaded line. These two phases may still have the maximum charge of 50 Hz, which is maintained during the test series, e.g. during the 0.3 s of the rated operating sequence. In Figure 6, circuit breaker S_1 is the first to open, followed by circuit breaker S_2 after 40 ms, with the HV line being charged.

After the dead-time current period of 0.3 s the circuit breaker must switch the two-phase negative polarity lines charged to the maximum voltage, which are open on the S_2 side.

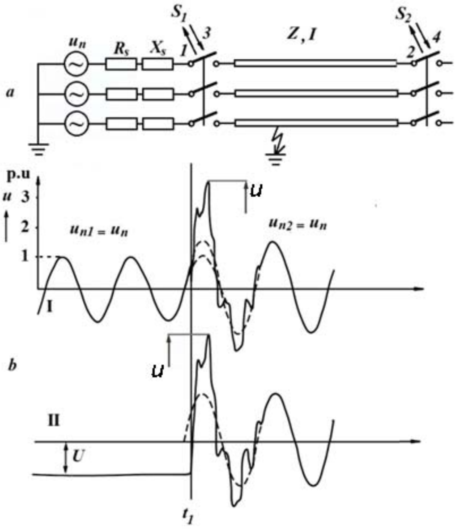


Fig. 6. Transient voltage waveform when switching a charged HV line with negative polarity
a – circuit diagram; *b* – voltage waveform; u_n – voltage supplied; R_s, X_s supply line resistance and inductance; S_1, S_2 – circuit breakers; *Z*, *I* – HV line wave impedance and current; I, II – waveforms at the first and the second circuit breaker; u_{n1} – voltage on the supply side, u_{n2} – voltage on the line side, *u* – peak overvoltage; *U* – charged line voltage

At the time t_1 the circuit breaker S_1 switches the negative polarity charged line. The highest overvoltage occurs when the polarity of the loaded line is opposite to the network voltage. If the line is loaded then the overvoltage level can be higher than $3.5\,U_f$.

It should be remembered that there is some non-simultaneity of the circuit breaker contacts closing because arc dispersion can last 3 ms for a new breaker but up to 5 ms for a breaker with many years of service and this can influence the overvoltage level at the circuit breaker. When the contacts close the line connection happens at the sparkover between the contacts. This moment defines the closing angle and is decisive for the overvoltage level.

The overvoltage level is influenced by the line inductivity L_2 and capacitance C_2, as well as the parameters of the supply circuit, the layout of the HV lines and the switching equipment in the power station.

Assuming that the station is equipped with inductive voltage transformers on the line side, the line is discharged after about 20 ms, and the overvoltage in the line cannot reach more than $2.8\,U_f$.

4. METHODS OF PREVENTING OVERVOLTAGES WHEN SWITCHING UNLOADED HV LINES

There are a few methods to prevent the formation of overvoltages that can be dangerous for contact breakers' insulation and other station equipment:

- the application of surge arresters;
- the application of circuit breakers that allow synchronous switching [13];
- the application of circuit breakers equipped with a parallel load switch and resistor.

The last method is used for the highest nominal voltages of 420 kV or more.

In summary, the expected levels of overvoltages when switching inductive and capacitive currents, and when switching unloaded lines on, can reach significant values.

TABLE 1
Maximum possible overvoltage levels across the open contacts of a 245 kV CB [kV]

Case	Multiple of the nominal voltage	Voltage $[kV_p]$
Switching on an unloaded line with a single restrike	2.8	970
Switching on an unloaded line with multiple restrikes	3.4	1178
Switching off an unloaded line with multiple restrikes	3.5	1213
Switching inductive currents	2.7	936
Switching capacitive currents	3.4	1178

As the levels of overvoltages, especially when switching HV lines, can be higher than the levels of the test voltages during the type tests of the circuit breakers there is a possibility of arc ignition between the open contacts of a circuit breaker. Such incidents have been noted in service [15].

This can be dangerous for the network and can be caused by many years of service without proper insulation diagnostics. The contact material's decomposition products are conductive, and any penetrating humidity lowers the insulation withstand even more.

5. DANGERS FROM ATMOSPHERIC OVERVOLTAGES

The insulation between the open contacts of a circuit-breaker is endangered when an atmospheric surge arrives at the breaker from the HV overhead transmission line. Conditions are critical when the U_f voltage on the power station side has the opposite polarity to the atmospheric surge in the line. Such a case is shown in Figure 7.

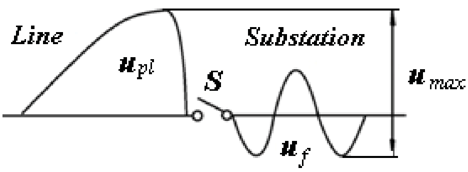


Fig. 7. Lighting overvoltage arriving at an open circuit breaker from an HV line
S – circuit breaker; u_{p1} – amplitude of the voltage surge coming from the line; u_f – phase to ground voltage at the station; u_{max} – overvoltage between the contacts

The minimum withstand voltage 1.2/50 between the open contacts is equal to the test voltage. According to Fig. 8 the admissible value of overvoltage u_{p1} and u_{f} is equal to:

$$u_{\mathrm{p1}} \leq u_{\mathrm{test}} - u_{\mathrm{f}}\sqrt{2}$$

Assuming the smallest value of the test voltage according to [3], i.e. $u_{\mathrm{test}} = 850\ \mathrm{kV_m}$, we have $u_{\mathrm{p1}} \leq 650\ \mathrm{kV_m}$ and assuming a safety factor of 1.15, we have the protection level of the arrester installed on the HV line:

$$u_0 = \frac{u_{p1}}{k_b} = 565\ \mathrm{kV}$$

Assuming the test voltage according to [15] $u_{\mathrm{test}} = 1050$ kV we have:

$$u_{\mathrm{p1}} \leq 850\ \mathrm{kV_m}$$

$$u_{\mathrm{o}} = 740\ \mathrm{kV_m}$$

245 kV transmission lines in Poland are suspended from steel towers and protected with ground wires. The impulse voltage withstand is 950 kV but the actual withstand can be much higher because a reinforced insulation is used in highly contaminated zones. It can be assumed that surge waves of 950 to 1500 kV can travel along an HV line.

Atmospheric surges coming over an HV line are generated by:

- a lightning strike to the tower or the ground wire;
- a lightning strike in the proximity of the HV line (induced overvoltage);
- a lightning strike to the phase conductor.

To determine the expected value of an atmospheric overvoltage coming from an HV line to a power station it is necessary to know the basic parameters of the lightning.

These parameters have been measured in transmission lines. Numerous measurements of the peak values of lightning have permitted a probability chart to be made for the occurrence of the lightning current value. Fig. 8 shows the probability curve for the occurrence of the lightning peak current values and Fig. 9 shows the cumulative frequency for the occurrence of the derivative of the lightning current, this data being taken from the relevant research [7, 8]. The polarity of the lightning current in 70% to 90% of cases is negative.

For calculating the number of lightning strikes to a line L km long, the following formula is used:

$$N = 0.001 \cdot 10 \cdot h \cdot L \cdot d \cdot 0.075$$

where:

h – the height of the line [m];
$10 \cdot h$ – the width of the area from which the line collects the lightning strikes;
L – the line's length [km];
d – the number of stormy days in a year;

0.001 – the calculation coefficient;
0.075 – the number of lightning strikes per 1 km^2 of the earth’s surface on a single stormy day.

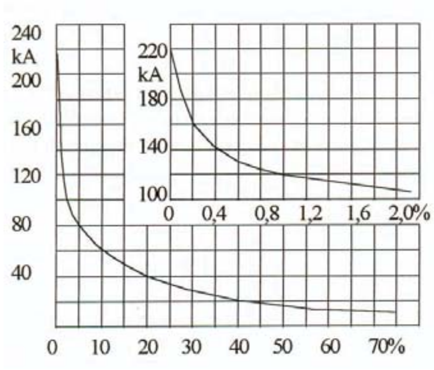


Fig. 8. Probability of the occurrence of the lightning peak current values. [8]

horizontal axis – values of probability in %, vertical axis – peak current values

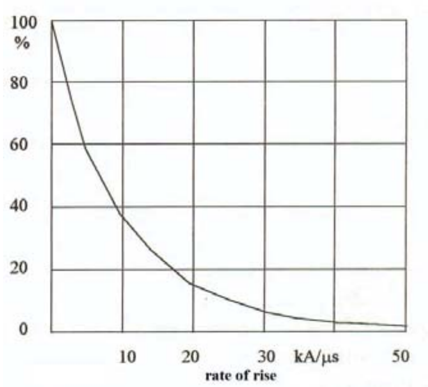


Fig. 9. Cumulative frequency of the occurrence of the derivative of the lightning current [7]

horizontal axis – derivative values, vertical axis – values of probability in %

Assuming an average 245 kV line height $h = 30$ m, one obtains 5.6 lightning strikes per 100 km of line per year.

5.1. Direct lightning strike to a line

A lightning strike to a line causes a discharge current flow over the tower construction and the tower grounding to the earth. The voltage across the line insulation results from the voltage drop over the tower inductance L_s and the tower footing resistance R_z. For a length of time smaller than the lightning current front time T_{cz} a simplified, linear increase in current with steepness s_p is assumed.

The current value after time t, smaller than the current front time is:

$$i_p = s_p t$$

The voltage across the tower footing resistance is:

$$U_{rz} = s_p R_z t$$

The voltage in the tower construction:

$$U_L = s_p L_{sł}$$

The voltage in the tower:

$$U_{sł} = U_L + U_{rz} = s_p L_{sł} \cdot + s_p R_z t$$

It follows from the above formula that the voltage over the line tower depends on the lightning current ($i_p = s_p \cdot t$) and its steepness s_p. The tower inductance is estimated to be about 30 µH and the footing resistance about 10 Ω. A back flashover of the line insulation can occur when the voltage across the tower exceeds 1000 to 1500 kV. Analyzing the above formulae and taking into account the frequency of the occurrence of the peak values of the lightning current (see Fig. 8), and of the steepness of the current front (see Fig. 9), it can be estimated that at least 10% of direct lightning strikes can cause a back flashover of the HV line insulation, which means that in the phase cables a travelling wave of 1000 – 1500kV can be generated.

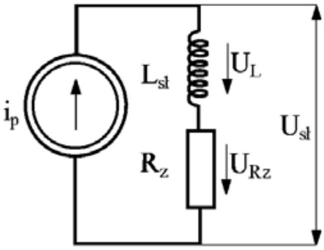


Fig. 10. Voltage drop over the tower inductance *L* and tower footing resistance *R*$_z$

5.2. Lightning strike close to an overhead HV transmission line

A lightning strike close to an overhead transmission line causes a travelling wave in the line's cables of a voltage value that can be approximately calculated from the following formula:

$$U_{ind} = 25 \frac{I_p h}{a}$$

where:

I_p – the peak value of the lightning current;
h – the average suspension height of the overhead line cables;
a – the distance between the line and the place of the lightning strike.

In the case of a lightning strike to the ground at the boundary of the protection zone ($a = 150$ m) with a lightning current $I_p = 100$ kA, and a cable suspended 30 m above the ground, this would cause a travelling wave of about 500 kV. The presence of the grounding wire reduces the induced wave in the current carrying cable by a factor of 1.5.

5.3. Lightning striking inside the protection zone of the ground wires

Lightning striking inside the protection zone of the ground wires results in the creation of a travelling wave in the conducting cables with the peak value:

$$U_\mathrm{p} = \frac{I_\mathrm{p}}{2\,Z}$$

where:

Z – the wave impedance of the cable;
I_p – the peak value of the lightning current.

The wave's peak value is not greater than the line voltage withstand because the amplitude of big lightning currents would be limited by a flashover of the line insulation.

5.4. Remarks concerning the danger due to lightning overvoltages

As can be deduced from the previous considerations, dangerous lightning overvoltages can come to the power station from the line only after a direct lightning strike to the line. Induced overvoltages are not dangerous in 245 kV lines. The number of overvoltages which could threaten the insulation between the circuit breaker contacts can be estimated at 5 cases per 100 km of line per year. The occurrence of a travelling wave in the line does not necessarily constitute a danger to the station, because when travelling over the line, the wave is strongly damped (mainly due to the corona effect). Its front is flattened and the peak value diminishes. For a 245 kV line and waves of 1000 to 1500 kV, it can be estimated that after a few kilometres the peak value of the wave would only be 50% of its initial value and its front time would exceed 10 μs. In practice, with such a waveform, the reflection at the open end of the line would not create any significant increase in the wave amplitude.

So the only dangerous lightning strikes to the line are those which strike less than 10 km from the station. This corresponds to about 0.5% of the dangerous overvoltages per HV overhead transmission line.

It should be noted however that incoming lines are provided with disconnectors. When the circuit breaker is switched off for longer periods, these disconnectors are opened and an overvoltage coming from the line can at most cause a flashover of the disconnector insulation to the ground without any danger to the circuit breaker. However, multiple lightning discharges are possible. During an automatic reclosing cycle a circuit breaker is not protected by a disconnector and the entire lightning voltage appears at the breaker terminals, causing the development of an arc and an increase in pressure in the circuit breaker pole, resulting in an explosion of the pole cover. Such cases have been noted in service [15].

In these circumstances the only rational way of preventing damage to an SF_6 isolated circuit breaker is its instantaneous closing, immediately followed by its opening. Only then can the arc current which has formed be switched off by the breaker.

6. OVERVOLTAGE PROTECTION

The length of an overhead HV line is usually considerable. When designing overhead HV lines it is assumed that the economically justified nominal line voltage depends on its length, usually assuming 1 kV per km of line. Consequently, although modeling such long lines as a lumped element circuit constitutes a simplification, it nevertheless allows the basic parameters of the overvoltages occurring in such electric power systems to be identified.

The voltage withstand of the open contact insulation of 245 kV SF_6 circuit breakers is verified in type tests, with an impulse test of 1.2/50 μs with both polarities and a peak value of at least 950 kV, and a power frequency voltage test of 460 kV for 60 s. The electric field distribution between the contacts of an SF_6 circuit breaker can be treated as quasi-uniform and subject to no changes in service thanks to its screening electrodes not being exposed to an arc. For 245 kV circuit breakers the insulation between the open contacts is not verified for switching overvoltages. According to data in topical literature [8] the withstand voltage for such insulation systems is lower for impulses of negative polarity and strongly dependent on the impulse front time. The minimum withstand voltage corresponds to front times of about 100 μs and can be estimated to be 75 to 80% of the withstand voltage for standard lightning impulse voltage. (The withstand voltage of SF_6 insulation systems is practically equal to the withstand voltage for the lightning impulse and is not a critical parameter in constructing the circuit breaker's insulation system). On this basis the withstand voltage for switching overvoltages can be estimated assuming eg. that the withstand voltage is equal to 77% of the withstand voltage for standard lightning impulse. So at a standard voltage level of 850 kV the open contact withstand for switching overvoltage can be estimated at around 654 kV, at a standard voltage level of 950 kV it is around 731 kV, and at a standard voltage level of 1050 kV it is around 808 kV.

As follows from chapter 2 and 3 of this paper, with open contact insulation of such limited withstand voltage, switching overvoltages as well as lightning overvoltages can initiate a flashover between the open contacts of the circuit breaker. International research (see chapter 1) has confirmed the reality of such a danger.

Therefore, it is advisable to use surge arresters at the line terminals connected to SF_6 circuit breakers [14].

The levels to which the overvoltages should be limited (because of the open contact withstand voltage) depending on the assumed test voltage, are given in Table 2. These values were calculated assuming that the overvoltage comes over the line at the maximum of the phase to ground voltage and with the opposite polarity (see Fig. 7). The safety factor was assumed, according to IEC standards [12], to be 1.15 for the lightning protection level (the arrester in the immediate neighbourhood of the protected CB), and 1.05 for the switching overvoltage protection.

Comparing the power frequency test voltages (col. 1 and 2) and the estimated switching overvoltages (col. 3) one can see that the overvoltages can be higher than the test voltages. Thanks to the application of lightning arresters the switching overvoltages can be reduced to safe levels.

According to IEC regulations [12] for 245 kV networks arresters of a nominal discharge current of 10 kA should be used.

TABLE 2
Standard requirements and the prospective overvoltages

Power frequency 1 min.		**Estimated switching overvoltages**	**Impulse test voltage acc. to [1]**	**Required arrester protection level**	
				lightning	**switching**
1	2	3	4	5	6
kV_{rms}	kV_{peak}	kV_{peak}	kV_{peak}	kV_{peak}	kV_{peak}
415	587	654	850	565	432
460	651	731	950	652	505
530	750	808	1050	739	579

The highest values of the discharge currents in the arresters can occur when switching unloaded overhead lines. In the critical case (an overvoltage of 2.8 times the nominal voltage, a line impedance of 450 Ω and a residual arrester voltage with switching impulses of 432 kV) the discharge current in the arrester is:

$$I_d = [2.8 \cdot 144.5 \text{ kV} \cdot \sqrt{2} - 432 \text{ kV}] / 450\ \Omega = 312 \text{ A}$$

and its duration does not exceed 1500 µs.

According to chapter 3.3 for a 245 kV line less than 200 km long, the voltage increase due to the Ferranti effect does not exceed 2%, so at the line end the peak value of the phase voltage does not exceed 144.5 kV. Hence the continuous operating voltage of the gapless arrester installed at the line end should be:

$$U_c \geq 1{,}05 \cdot 144.5 = 151.7 \text{ kV}$$

this corresponds to the rated voltage of the arrester:

$$U_r \geq 190 \text{ kV}$$

The selection of a proper arrester should be based on the data provided by the manufacturer.

Assuming for a 245 kV network that the coefficient of the earth fault is 1.3 times the value of the ground fault, overvoltage at the open line end does not exceed $1.3 \cdot 144.5 = 188$ kV, and its duration does not exceed 1s. The selected gapless arrester can withstand such dynamic overvoltages.

The majority of modern gapless arresters are characterized by similar protection features for all three variants of the normalized circuit breaker test voltages listed in Table 2.

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PRZEPIĘCIA ŁĄCZENIOWE I PIORUNOWE A WYMAGANY POZIOM WYTRZYMAŁOŚCI OTWARTYCH STYKÓW WYŁĄCZNIKÓW 245 KV

Janusz BANDEL, Artur HEJDUK,
Andrzej DZIERŻYŃSKI, Piotr KORYCKI, Henryk SIBILSKI

STRESZCZENIE *Przedstawiono sposób oceny wartości przepięć generowanych w sieci pomiędzy otwartymi stykami wyłącznika podczas operacji łączeniowych i wyładowań piorunowych. Wartości przepięć porównano z wartościami napięć probierczych wyłączników. Zaproponowano sposób doboru ograniczników napięcia. Wyłączanie prądów zwarciowych może powodować osłabienie izolacji komory wyłącznika zmniejszając jego wytrzymałość elektryczną i trwałość łączeniową. W energetyce zgłaszano przypadki zapłonów łuku na otwartych stykach wyłączników, tego rodzaju awarie mogą być bardzo groźne w skutkach. Problem ten dotyczy przede wszystkim wyłączników jednoprzerwowych, w których naprężenia elektryczne izolacji przerwy pomiędzy stykowej wyłącznika są bardzo duże. Z tego powodu pojawiają się postulaty zwiększenia liczby łączeń podczas badań typu wyłącznika, jakie należy wykonywać bez wymiany jakichkolwiek części komory wyłącznika, czy też napędu.*

Słowa kluczowe: *wyłączniki najwyższych napięć, łączenie prądów indukcyjnych i pojemnościowych, przepięcia łączeniowe i atmosferyczne, ograniczniki napięcia*