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# The Analysis of the Overvoltages Protection Development and their Characteristics Influence on the Overvoltages Level

***Abstract**. Different overvoltage protection devices installed in the electrical network have different voltage-current characteristics. Effectiveness of protection means depends not only on the voltage-current characteristic but also on the mounting place of the protection devices and their compatibility. Influence of protection devices with different characteristics on overvoltage level is analysed in this work.*

***Streszczenie.** Instalowane w sieciach elektrycznych różne środki ochrony przed przepięciami mają różne charakterystyki napięciowo-prądowe. Skuteczność środków ochrony zależy nie tylko od ich charakterystyki napięciowo-prądowej, lecz również od miejsca ich zainstalowania i ich kompatybilności. W niniejszej pracy analizowany jest wpływ środków ochrony, o różnych charakterystykach, na poziom przepięć **(Analiza wpływu rozwoju środków ochrony i ich charakterystyk na poziom przepięć)**.*

**Keywords:** overvoltages, arresters, metal-oxide surge arresters.
**Słowa kluczowe:** przepięcia, ograniczniki przepięć, beziskiernikowe ograniczniki przepięć.

## Introduction

Various factors may cause the increase of grid voltage above the maximum permissible value. The insulation of electrical equipment is designed to stand the short-term voltage pulses. Different means may be implemented to limit the overvoltages: changing of network parameters (e.g. installation of shunt reactors), using circuit breakers with shunt resistance for limiting of switching overvoltages, and using overvoltage dischargers and surge arresters that are the most efficient overvoltage protection devices.

Currently, the surge arresters are used instead of the dischargers. The surge arresters without spark gap start operate when the voltage in the electrical network exceeds the continuous operating voltage $U_c$. The surge arresters are suitable to limit switching and ferroresonance overvoltages as well. The surge arresters should be selected considering the following criteria: the insulation of the equipment must be effectively protected against lightning overvoltages, the surge arresters must be undamaged by internal overvoltages, and reliability of the insulation must not be decreased.

The objective of this work is to analyse overvoltage levels when overvoltage protection means with different voltage-current characteristics are used in the network. It is important to coordinate voltage-current and energy characteristics for the effective use of protection devices and effective protection of electrical equipment insulation.

## Characteristic of surge arresters

Effectiveness of electrical equipment insulation protection systems with surge arresters depends on the effectiveness of lines' lightning protection, electromagnetic characteristics of the network, network configuration, mounting place as well as quality and protection characteristics of the surge arresters [1].

Voltage-current characteristic of surge arrester depends on the long-term permissible voltage $U_c$, the rated voltage $U_r$ and the absorbed energy class.

The voltage-current characteristics of the class II surge arresters with different rated voltage values $U_r$ for the 110 kV network are presented in Fig. 1.
Analysis of the voltage-current characteristics shows that the surge arresters of the class II with $U_r$ higher than 132 kV are not suitable for the 110 kV electrical networks.

The voltage-current characteristics of the class III (7.8 kJ/kV) surge arresters are presented in Fig. 2. Analysis of these characteristics shows that the surge arresters of permissible long-term voltage of 78 kV up to 162 kV rated voltage may limit overvoltage level to the permissible test pulse voltage in the 110 kV electrical networks.

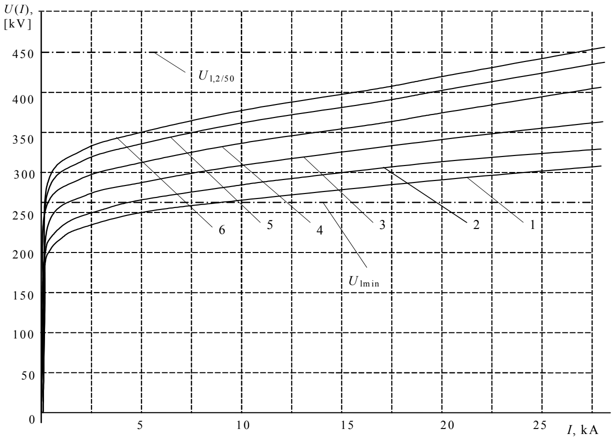


Fig. 1. Voltage-current characteristics of the class II surge arresters for 110 kV voltage: 1 – $U_r$ =102 kV; 2 – $U_r$ =108 kV; 3 – $U_r$ =120 kV; 4 – $U_r$ =132 kV; 5 – $U_r$ =138 kV; 6 – $U_r$ =144 kV ($U_c$=78 kV). $U_{1,2/50}$ and $U_{1\min}$ – test pulse voltage and 1 min 50 Hz voltage

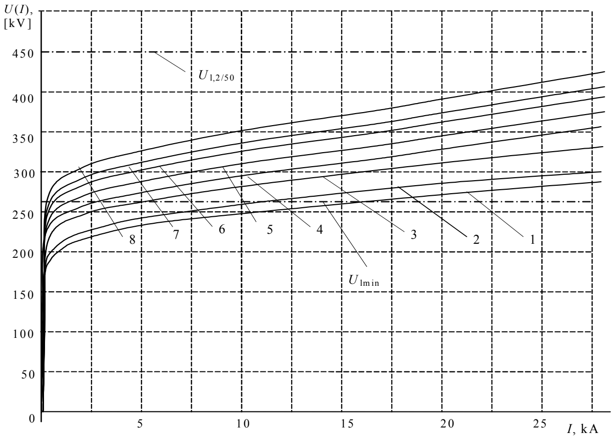


Fig. 2. Voltage-current characteristics of the class III surge arresters for 110 kV voltage: 1 – $U_r$ =102 kV; 2 – $U_r$ =108 kV; 3 – $U_r$ =120 kV; 4 – $U_r$ =132 kV; 5 – $U_r$ =138 kV; 6 – $U_r$ =144 kV; 7 – $U_r$ =150 kV; 8 – $U_r$ =162 kV ($U_c$=78 kV)

Comparison of voltage-current characteristics of the classes II, III and IV surge arresters at the same $U_c$ and $U_r$ is presented in Fig. 3.

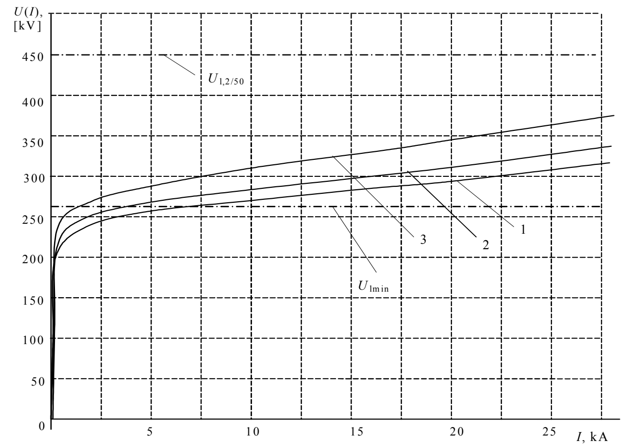


Fig. 3. Voltage-current characteristics of different classes surge arresters of 110 kV with $U_c$=78 kV and $U_r$ =120 kV: 1 – class IV; 2 – class III; 3 – class II

## Method for evaluation of surge arrester characteristics

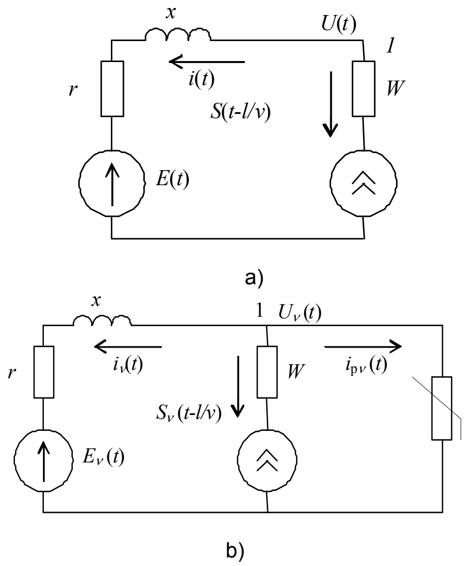
Overvoltage transient processes should be simulated for proper selection of surge arresters' place in the electrical network and analysis of operating conditions [2].

For composing of the digital model of electrical network, it is necessary to correctly simulate nonlinear elements. The property of differential equations integration step increment equivalence allows using the recurrence method for modelling of the elements with nonlinear voltage-current characteristic (e.g. surge arresters) in the buses of transformer stadion

The recurrence equation may be applied for the linear part of the circuit (Fig. 4, a):

$$\boldsymbol{Y}_1 = \boldsymbol{A}_0 \times \boldsymbol{Y}_0 + \boldsymbol{A}_1 \times \boldsymbol{S}_1 + \boldsymbol{A}_2 \times \boldsymbol{S}_0 \tag{1}$$

where: $\boldsymbol{Y}_1$, $\boldsymbol{Y}_0$ – matrix-columns of currents and voltages in Clarke coordinates for times $t_1 = (k+1)h$ and $t_0 = kh$; $\boldsymbol{A}_0$, $\boldsymbol{A}_1$, $\boldsymbol{A}_2$ – square matrix of equivalent coefficients of recurrence equation; $\boldsymbol{S}_1$, $\boldsymbol{S}_0$, – matrix-columns of the bus equivalent electromagnetic waves characteristics for times $t_1$ and $t_0$.



a)

b)

Fig. 4. Equivalent circuit of the network bus: a) circuit of linear part of bus; b) equivalent circuit

Equations of the nonlinear elements' part (Fig. 4, b) should be solved separately. Both parts are joined by iterative process. The voltage value in the point of junction of linear and nonlinear processes may be calculated according to:

$$\boldsymbol{U}_1 = \boldsymbol{W}_\mathrm{e} \times \left[ \boldsymbol{S}_0 - \sum_{j=1}^{n} \boldsymbol{I}_j - \boldsymbol{I}_{\mathrm{p}0} \right] \tag{2}$$

where: $\boldsymbol{U}_1$ – matrix-column of bus voltages; $\boldsymbol{I}_j$ – matrix-columns of elements of linear part of bus currents; $n$ – number of linear elements in the bus; $\boldsymbol{W}_\mathrm{e}$ – matrix of bus equivalent wave impedances; $\boldsymbol{I}_{\mathrm{p}0}$ – matrix-column of currents in nonlinear element.

The linear part of the equation is equivalented according to

$$\boldsymbol{V}_\mathrm{e} = \boldsymbol{W}_\mathrm{e} \times \left[ \boldsymbol{S}_0 - \sum_{j=1}^{n} \boldsymbol{I}_j \right] \tag{3}$$

where the currents in the elements are calculated according to (1). Then,

$$\boldsymbol{U}_1 = \boldsymbol{V}_\mathrm{e} - \boldsymbol{W}_\mathrm{e} \times \boldsymbol{I}_\mathrm{p} \tag{4}$$

where $\boldsymbol{I}_\mathrm{p}=f\{\boldsymbol{U}_1\}$ – current-voltage characteristic of the nonlinear element.

After transformation from Clarke coordinates $\nu$ to physical coordinates $\gamma$, the system of linear and nonlinear processes junction is obtained according to:

$$\begin{cases} \boldsymbol{U}_{1\gamma} + \boldsymbol{W}_\mathrm{e} \times \boldsymbol{I}_{\mathrm{p}\gamma} = \boldsymbol{V}_{\mathrm{e}\gamma} - (W_{\mathrm{e}0} - W_{\mathrm{e}1}) \cdot i_{\mathrm{p}0} \\ \boldsymbol{I}_{\mathrm{p}\gamma} = f\{\boldsymbol{U}_{1\gamma}\} \end{cases} \tag{5}$$

where $i_{\mathrm{p}0}(t)$ – zero sequence current in nonlinear element, $i_{\mathrm{p}0}(t) = [i_{\mathrm{pa}}(t)+i_{\mathrm{pb}}(t)+i_{\mathrm{pc}}(t)]/3$.

The iterative process should be composed for the general solution of the nonlinear equation system (5)

If in one integrating step not the equivalent characteristic of the bus wave $S_{e\nu}(t)$ varies linearly, but the $S_{e\nu}(t)$-$i_{p\nu}(t)$, the iterative process is composed by calculating currents of the linear bus part in elements according to (1) recurrence equation. After that, bus voltage is calculated (in the first iteration $i_{\mathrm{p}\nu}(t) = 0$). In the next iterations, the current in the nonlinear element is changed recurrently, and the correction for the solution is performed according to the current difference in neighbour iterating steps:

$$\Delta\boldsymbol{I}_{\nu[j+1]} = \boldsymbol{A}'_0 \times \Delta\boldsymbol{I}_{\nu[j]} \tag{6}$$

where: $\boldsymbol{A}'_0$ – square matrix formed from the three first columns of the matrix $A_0$; $j$ – number of the iteration; $\Delta\boldsymbol{I}_{\nu[j+1]}$ – matrix-column of current change in the iterating step.

The voltage is adjusted in iterations according to

$$\boldsymbol{U}_{1[j+1]} = \boldsymbol{U}_{1[j]} - \boldsymbol{W}_\mathrm{e} \times \Delta\boldsymbol{I}_{\nu\mathrm{p}[j+1]} \tag{7}$$

The iterative process is stopped when the current change in neighbour iterating steps is less than the determined error. For the error equal to 1 %, it is sufficient three to five iterations.

## Influence of surge arresters characteristics on overvoltage level

The surge arrester starts to limit overvoltages when the voltage exceeds long-term permissible value $U_\mathrm{c}$. The higher value of $U_\mathrm{c}$ means the greater limit of the overvoltage. The typical 110 kV switchgear of transformer substation connecting three lines is analysed in this work. The equivalent diagram used for digital simulation of transient processes of overvoltages is presented in Fig. 5.

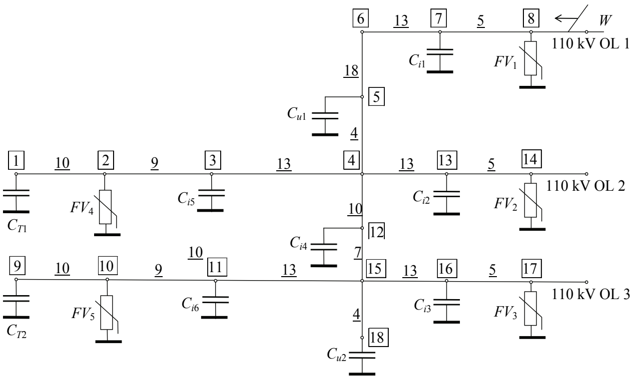


Fig. 5. Equivalent diagram of 110 kV switchgear of transformer substation: $\underline{10}$ – length of a branch between buses; $\boxed{10}$ – bus number; $C$ – equivalent capacity of substation equipment

It is assumed that the overvoltage wave induced by lightning discharge propagates to the switchgear along the first line. The front and the duration to half value on the tail of the overvoltage wave equals to 1.2 μs and 50 μs, respectively [3].

The maximum charge falls on the first surge arrester (bus 8) into which the overvoltages wave propagates. The current leaking through this arrester is stronger more that three times comparing to the currents leaking through other surge arresters in the substation. The lowest and the maximum values of voltage $U_c$ differs by 23 %. The maximum level of overvoltages affecting the insulation of substation equipment (bus 9) may vary in 34 % (Fig. 5). Surge arresters with the same energy characteristics where analysed. The comparison was performed for the surge arresters with equal energy characteristics [4].

Distribution of overvoltages in the substation with different sets of the surge arresters when the overvoltages wave propagates through the first line is presented in Fig. 6.

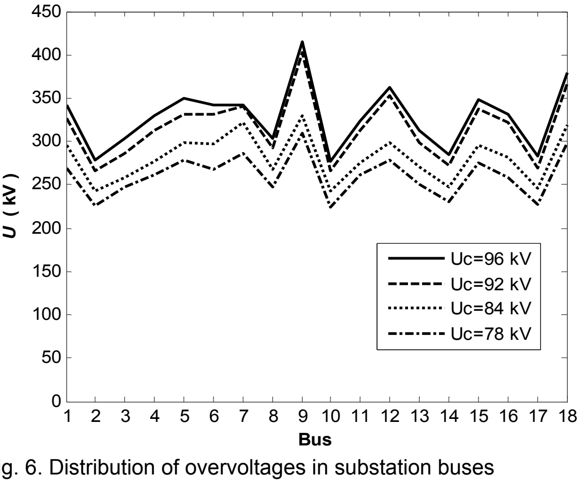


Fig. 6. Distribution of overvoltages in substation buses

If the surge arresters with different voltage-current characteristics are installed in the switchgear, it is advisable to estimate efficiency of surge arresters and to tune their parameters according to the voltage-current characteristics.

## Conclusions

1. Overvoltage level affecting all switchgear equipment must be estimated for the surge arresters with different voltage-current characteristics location selection in the electrical network.
2. For the protection of the switchgear electrical equipment insulation against lightning overvoltages induced in overhead lines, it is necessary to select the proper parameters and installation locations of the surge arresters as well as to coordinate their characteristics.
3. The maximum influence on the overvoltage level is made by the place of overvoltage protection devices and their voltage-current characteristic. The residual voltages may differ up to 17 % when the current of 20 kA flows.

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