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Overview of selection methods for surge arresters 6-750 kV

Summary. *The article focuses on the correct choice of equipment overvoltage protection devices using a surge arrester. Regulatory documents on the selection of surge arresters in different countries and the methods recommended by leading manufacturers of surge arresters are considered. The main parameters for the selection of surge arresters are considered. The main parameter of the surge arrester is considered in detail - the maximum long-term permissible operating voltage. Special attention is paid to the selection of surge arresters for switching and lightning overvoltage. The choice of an overvoltage arrester based on the explosion hazard condition and mechanical characteristics is also considered.*

Keywords: *surge arrester, electrical networks, overvoltage, switching overvoltage, lightning overvoltage.*

Introduction. Overvoltage protection of 6-750 kV electrical installations has an important role in the operation of electric power facilities. Currently, the main method of protecting electrical equipment from overvoltage in electrical networks 6-750 kV is the use of nonlinear surge arresters (SA).

Currently, the use of OPN regulated by the following documents:

1. In Ukraine:

- SOU-N EE 40.12-00100227-47 "Non-linear surge arresters with voltage 110-750 kV. Guidelines for selection and application" [1];
- SOU-N MEV 40.1 "Non-linear overvoltage limiters with voltage of 6-35 kV. Guidelines for selection and use in distribution facilities" [2].

2. In Russia:

- "Guidelines for the use of limiters in 110-750 kV electrical networks" [3];
- "Guidelines for the use of non-linear overvoltage limiters in 6-35 kV electrical networks" [4]

3. The international standards:

- IEC 60099-5 Surge arresters. Part 5. Recommendations for selection and application [5].

4. The development of manufacturing companies:

- "Guidelines for the selection of non-linear surge arresters manufactured by the company" Tavrida Electric "for electrical networks 6-35 kV" [6];

"Hinrichsen Volker." Siemens. Metal oxide limiters. Fundamentals [7].

- Selection, testing and application of metal oxide surge arresters in medium voltage networks. - Kyiv: ABB Ukraine Representative Office [8].
- Exlim. Technical information. Guide to the selection of high-voltage surge arresters manufactured by ABB [9].
- Characteristics, selection and placement of surge arresters (110-220) kV: Textbook / G.M. Imanov, F.H. Khalilov, A.I. Tadzhibaev. - St. Petersburg: PEIPK Mintopenergo RF, 1997 [10].

The main task when choosing SA is to limit overvoltages to a safe level for the protected electrical equipment and at the same time ensure the resistance of the arresters to dangerous types of overvoltages. SA for electrical networks of 6-750 kV, presented on the Ukrainian market, are produced by various factories (both domestic and foreign) based on their own technical solutions, therefore, arresters of various manufacturers designed for one voltage class may differ in characteristics, which must be considered when choosing them.

Electric networks of Ukraine 6-35 kV operate mainly with an isolated or grounded through an arc-quenching reactor neutral, therefore the operating conditions of SA in these networks differ from the operating conditions in 110-750 kV networks by large values and durations of switching and quasi-stationary overvoltages. In this regard, a review of the methods for selecting the main characteristics of SA will be carried out for two types of networks: 6-35 kV and 110 - 750 kV.

Selection of the highest continuous operating voltage of the SA. The main characteristic of the SA is the highest long-term permissible operating voltage of the arrester U_{mov}. This is the highest value of the operating voltage of the power frequency, which can be applied continuously to the arrester during the entire period of its operation, and does not lead to damage or thermal instability of the SA [1]. The basis for choosing this voltage is the highest long-term permissible operating voltage of the electrical network U_{mv} (line voltage).

In the instructions [2, 4, 8], the choice of the highest long-term allowable voltage of 6-35 kV arresters is carried out based on the conditions for the duration of the existence of a single-phase earth fault:

- in networks that allow an unlimited long-term existence of a single-phase earth fault, $U_{mvo} \geq U_{mv}$;
- in networks where the duration of a single-phase earth fault is limited by the time t, $U_{mvo} \geq U_{mv} / K_t$, where K_t - coefficient equal to the ratio of the voltage increase allowed by the manufacturer during the time t to the maximum long-term allowable operating voltage of the SA. The method for determining K_t is indicated in [2, 4, 8].

Additionally, in [2], the specification of the highest long-term permissible operating voltage of the SA is carried out in case of single-phase arc earth faults and in the presence of quasi-stationary overvoltages in the network.

For voltage classes 6-35 kV, according to [5], a surge arrester with a voltage U_{mov} should be chosen not less than 5% higher than the highest voltage level of the network U_{mv} (line voltage).

According to [6], the long-term operating voltage of a 6-35 kV arrester is determined by the formula:

$$U_{mov} \geq \frac{K_0 \cdot U_{mv}}{T(t)}, \quad (1)$$

where K_0 is a coefficient that, depending on the characteristics of the electrical network and the conditions of its operation, can take values from 1 to 1.1; $T(t)$ is the multiplicity characterizing the arrester's ability to withstand voltage increases with a frequency of 50 Hz and a duration of t.

The exact values of the quantities K_0 and T(t) the methods for finding them are defined in [6].

For voltage classes 110-750 kV, according to [3], in all cases, to increase reliability, SA with a phase voltage U_{mov} is chosen at least 2-5% higher than the highest voltage level of the network U_{mv} (phase voltage).

If the stable existence of higher harmonics is possible, the methodological guidelines of RAO UES [3] and the standard [1] on the choice of 110-750 kV SA recommend proceeding as follows [1, 3]:

- if the amplitudes of the voltages of the fundamental frequency and harmonics are measured, then the highest level of the mains voltage at the place of the SA installation in normal mode is taken equal to their sum [3];

- if the amplitude of the harmonic is unknown, then the highest voltage level of the network at the place of installation of the SA in normal mode is taken equal to [1, 3]:

$$U_{mov} \geq \frac{1{,}1 \cdot U_{mv}}{\sqrt{3}}. \quad (2)$$

In [1], the coefficient of the level of the long-term allowable voltage of the SA was introduced, which depends on the limiting length of the connected line and is:

* 1.05 - at the maximum length of the line connected to the substation, less than half of the limit for voltage classes 110-330 kV;

* 1.1 - with the maximum length of the line connected to the substation, greater than or equal to half the limit for voltage classes 110-330 kV;

* 1.05 - for voltage classes 500-750 kV.

The lengths of the limiting lines for Ukraine are indicated in [1] based on the existing data of the NPC “Ukrenergo”.

$$U_{mov} \geq \frac{1{,}05 \cdot U_{mv}}{\sqrt{3}}. \quad (3)$$

In some other methods, the long-term permissible operating voltage of the SA is determined equal to or greater (it is not specified how much) the maximum operating voltage of the network, see, for example, [9].

It is important to increase the maximum long-term admissible operating voltage of the arrester in circuits with neutral grounding. Therefore, in [1] it is indicated that for voltage classes 110-220 kV in the mode when part of the transformers at the outdoor switchgear operates with an earthed neutral, the coefficient of the level of the long-term permissible operating voltage of the SA is 1.1.

If the U_{mov} level because of the choice of the SA was adopted insufficient, this will lead to the loss of its thermal stability and emergency damage.

Selection of SA for switching overvoltages. The next criterion for choosing an arrester is its reliable operation at switching overvoltages. When selecting, consideration must be given to the matching of the residual voltages during switching impulses with the rated test voltages.

Thus, in the methodological instructions of RAO UES [3], to determine the residual voltage of 110-750 kV SA, the ratio of the test and residual voltages of switching impulses is also used, which is characterized by a coefficient of 1.15-1.2, and for equipment with a service life of over 10 years - coefficient 1.3-1.4. If this condition is not met, it is necessary to choose an SA with the same U_{mov} value, but of a higher energy capacity class, since with an increase in energy intensity for the same nominal voltages, the level of the remaining voltage decreases.

The test voltage with a switching impulse is standardized by GOST 1516.3 [12] for electrical equipment of 330 kV and above. For voltage classes 110 – 220 kV according to [3], when calculating a certain effective test voltage of a switching pulse, one should be guided by the formula:

$$U_{SP} = \sqrt{2} \cdot 1{,}35 \cdot 0{,}9 \cdot U_{tv50}, \quad (4)$$

where U_{SP} - one-minute test voltage of industrial frequency 50 Hz; coefficients 1.35 and 0.9 are impulse coefficients, taking into account the strengthening of the insulation with a shorter than the test impulse, and the cumulative coefficient, taking into account the multiple effects of overvoltages and the possible aging of the insulation, respectively.

In the recommendations [1], the ratio of the test and remaining voltages of switching impulses is given only for classes 330-750 kV and is characterized by a factor of 1.15. It should be noted that the values of the test voltages by the switching impulse in [1] are taken for level *a* according to GOST 1516.3 [12].

The recommendations [4] indicate that the value of the residual voltage on the 6-35 kV arrester at the rated current of switching overvoltages should be no more than the withstand voltage of the insulation of the protected electrical equipment. Withstanding voltage by isolation of switching pulses is determined by the formula (4), in which for the isolation of power transformers the pulse factor and the cumulative factor are 1.35 and 0.9, respectively, and for the isolation of apparatus – 1.1 and 1.0, respectively. In [2], the protective level of the SA at switching overvoltages (according to [2, 4], this residual voltage on the arrester at the rated current of switching overvoltages) is also determined by the formula (4), only the impulse and cumulative factors are: for the insulation of power transformers – 1.3 and 0.85, respectively; for the isolation of apparatus – 1.1 and 0.9, respectively. For 35 kV networks, [2] additionally takes into account the coordination protective interval (the ratio of the protective insulation level and the residual voltage), which is characterized by a factor of 1.15 at switching overvoltages.

When considering switching overvoltages, it is also necessary to check the selected SA for energy absorption (dissipation). The IEC standard [5] recommends 2 types of checking the SA to absorb the energy of switching overvoltages. The first of them corresponds to checking the arrester by the discharge of the connected line, the charge of which has been preserved, for example, because of automatic reclosure (AR). The energy that is absorbed by the SA is calculated in this case by the formula:

$$W = 2U_{ps}\left(U_e - U_{ps}\right)\frac{T_w}{Z}, \qquad (5)$$

where U_{ps} – residual voltage at switching impulse;
U_e – overvoltage amplitude; Z – line impedance;
T_w – time the overvoltage wave travels along the line.

In [7, 9], a multiplier 3 is additionally introduced into formula (5) (to take into account, for example, an unlikely but possible threefold AR actuation), in [1], a multiplier 2 is additionally introduced into formula (5) (to take into account a possible double AR).

To unify the procedure for determining the absorbed energy from a line discharge, IEC introduces the concept of a line discharge class corresponding to the nominal line voltage.

If banks of capacitors with a capacity of C are used in networks, the IEC standard [5] recommends an additional check on the energy capacity W, which is found by the formula:

$$W = \frac{1}{2}C[\left(3U_0\right)^2 - (\sqrt{2}\,U_r)^2], \qquad (6)$$

Where U_0 – amplitude of the highest continuous operating voltage phase-to-ground; U_r – SA rated voltage.

Similar requirements for assessing the energy intensity of an SA are given in [6, 7, 9, 10,]. In the guidelines of RAO UES [3], formula (5) is not given, and formula (6) is given with a gross error.

In [2,4], the calculation of the energy intensity of 6–35 kV SA is recommended to be carried out at arc overvoltages of a single-phase earth fault. The choice of the maximum current carrying capacity of the arrester is determined depending on the magnitude of the capacitive earth fault current and the operating mode of the network.

Selection of SA for lightning overvoltage. The basis for determining lightning overvoltages is the selection of the rated lightning discharge current of 8/20 µs. According to the recommendations of IEC [5], the maximum current amplitude for the range of rated line voltages less than 142 kV is 5 kA; less than 360 kV – 10 kA; more than 360 kV - 20kA. In the methodological instructions of RAO UES [3], the levels of the rated discharge current of 5-10 kA previously adopted in the USSR have been preserved.

According to the recommendations [2,4,6], when installing a 6-35 kV SA to protect against lightning overvoltages, its rated discharge current is assumed to be 10 kA in cases of: lightning activity more than 50 lightning hours per year; in networks with overhead lines (OL) on wooden supports; in lightning protection schemes for motors and generators connected to OL; in areas with a degree of atmospheric pollution IV (according to GOST 9920), as well as when the surge arrester is installed at a distance of less than 1000 m from the sea. In other cases, a discharge current of 5 kA is assumed.

One of the parameters characterizing the operation of a SA during lightning overvoltage is its residual voltage during a lightning current impulse with a waveform of 8/20 µs and rated amplitudes of –5, 10, 20 kA, depending on the voltage class of the arrester.

Checking the residual voltage of the selected 6-35 kV SA in [6] is carried out based on the conditions of compliance, that is, it should be less than or equal to the residual voltage of the valve arrester. In [2, 4] it is indicated that the residual voltage of the SA during lightning overvoltages should not be higher than the residual voltage of the valve arrester of group III or group IV. For 35 kV networks, [2] additionally takes into account the coordination protective interval (the ratio of the protective insulation level and the residual voltage), which is characterized by a coefficient of 1.3 in case of lightning overvoltages.

In the methodological recommendations [7] for the selection of 110-750 kV SA for lightning overvoltages, the ratio of test and residual lightning impulse voltages is used, determined by a factor of 1.15.

In the standard [1], the residual voltage of an SA during lightning overvoltages was determined by two criteria:

1. The residual voltage on the SA during a lightning impulse should be less than 90% of the residual voltage of the replaced RV with the same impulse [11];

2. The ratio of test and residual voltages during lightning impulses is characterized by a factor of 1.4 - for voltage classes 110-500 kV; 1.3 - for a voltage class of 750 kV.

The lesser of the two calculated values is taken as the permissible residual voltage on the arrester during a lightning impulse.

The international IEC standard [5] proposes to estimate the energy absorbed by the SA during lightning overvoltages using the formula:

$$W = [2U_f - NU_{pl} \cdot \left(1 + \ln(2U_f / U_{pl})\right)] \frac{U_{pl} T_l}{Z}, \quad (7)$$

where

U_{pl} – residual voltage across the arrester during a lightning impulse; U_f – voltage of overlapping line insulation of negative polarity; Z – line impedance; N – the number of lines connected to the SA; T_l – the duration of the current during a lightning strike, taking into account the first and subsequent strikes.

In the standard [1], formula (7) is used for the case of connecting one line (the most difficult option is a dead-end substation).

The second aspect when choosing an arrester for lightning overvoltage is to determine the permissible distance of the SA installation to the protected equipment.

To protect electrical equipment from lightning overvoltages 35-750 kV [3] and [11], it is required to determine the permissible distance from the SA to the protected electrical equipment according to the formula:

$$L_{SA} = \frac{L_{VA} \cdot (U_{tv} - U_{SA})}{U_{tv} - U_{VA}}, \quad (8)$$

where L_{SA} – distance from the surge arrester to the protected electrical equipment; L_{RV} – distance from the arrester to the protected electrical equipment; U_{tv} – test voltage of the protected equipment at full lightning impulse; U_{SA}, U_{VA} – residual voltage across the SA (VA) at a lightning current of 5 kA - for voltage classes 110-220 kV; 10 kA - for voltage classes 330 kV and above.

The standard [1] also uses formula (8), but only for the case of determining the permissible distance from the SA to the protected equipment, if the equipment insulation corresponds to level b (protection using a valve arrester (VA)) according to GOST 1516.3 [12]. In the case of using electrical equipment (UEE) with insulation level *a* (protection using an SA) at 330-750 kV outdoor switchgear, it is recommended to calculate the permissible distance according to the formula:

$$L_{SA} = \frac{L_{VA} \cdot (U'_{tv} - U_{SA})}{U_{tv} - U_{VA}}, \quad (9)$$

Where U'_{tv} – the test voltage of the protected equipment with insulation level a according to GOST 1516.3 [12]; U_{VA} – test voltage of the protected equipment with insulation level b according to GOST 1516.3 [12].

Thus, in the standard [1], for the first time, the greatest protective distance from the surge arrester to electrical equipment of 330-750 kV voltage classes with *a* reduced insulation level is introduced.

In [2], when determining the permissible distance from a 6-35 kV SA to electrical equipment, 4 cases should be considered:

1) replacement of VA with SA during reconstruction;

2) replacement of a SA with an arrester with a different remaining voltage during reconstruction;

3) design of new substations according to standard designs;

4) design of a new substation, which, according to the scheme and arrangement of electrical equipment, does not correspond to standard projects.

In cases 1) and 3), it is necessary to be guided by the recommendations of the EIR [11].

In case 2), the permissible distance should be specified using the mean:

$$\Delta L \leq \frac{0,7 \times (U_{res.1} - U_{res.2}) \times V}{2 \times a}, \quad (10)$$

where ΔL – the difference between the distances to the protected electrical equipment from the SA1, which is being replaced, and the SA2, which is installed; $U_{res.1}$ – residual voltage on SA1; $U_{res.2}$ – residual voltage on SA2; V – the speed of propagation of the electromagnetic wave; a – the average steepness of thunderstorm waves.

In case 4), it is necessary to carry out special calculations of the substation lightning protection, which will make it possible to determine the installation locations of the SA.

Selection of SA according to explosion safety conditions. When choosing an SA according to the conditions of explosion safety, the magnitude of the actuation current of the anti-explosive device is normalized, at which there is no explosive destruction of the SA cover when it is internally damaged. So, according to [3], when choosing 110-750 kV limiters with anti-explosive device actuation currents up to 40 kA, its value should be 15-20% higher than the value of the current (single-phase or three-phase) short circuit. For SA with anti-explosive device triggering currents above 40 kA and the behavior of the tire as specified in the TC when burning along its arc surface, the introduction of a safety factor is not required.

In [5,7,9] it is said that the choice of an SA according to the conditions of explosion safety must ensure that there is no explosive destruction of the SA when short-circuit currents flow in the middle of its body.

In [1], in addition to the requirements of [3] for explosion safety, requirements for an SA, depending on its design, are given in accordance with IEC 60099-4 [13]. Therefore, for "design A" surge arresters, the values of the anti-explosive device actuation current are normalized, at which there is no explosive destruction of the arrester cover in the event of its internal damage. For "design B" SA, the maximum short-circuit withstand current determined by the manufacturer must be greater than the maximum short-circuit current at the outdoor switchgear for which the SA is selected.

The actuation current of the pressure relief device of 6-35 kV SA, according to [2, 4], is chosen at least 10% higher than the value of the two-phase or three-phase (the largest of them) short-circuit current at the place of the SA installation.

Selection of SA based on mechanical characteristics. According to [1,2], 110-750 kV SA of supporting design of location category 1 must withstand mechanical loads in case of ice with an ice wall thickness of up to 20 mm and wind at a speed of 15 m/s, and without ice - at a speed of 30 m/s (according to at the request of the customer with a wind speed of 40 m/s) and when tensioning the wires in the horizontal direction according to GOST 16357 [14]. In [1], the loads from the tension of wires are taken as for newly developed arresters according to [14], and in [2] - as for arresters of location category I, developed before 1983 according to [14].

The calculation of the bending moment of a 110-750 kV SA from wind force and wire tension is carried out according to the formula [1, 13]:

$$M = \frac{1,29}{2} \cdot V^2 \cdot H \cdot (d_m + 2 \cdot d_{ice}) \cdot \cdot 0,8 \cdot \frac{H}{2} + H \cdot P_{ten}, \qquad (11)$$

where V – the wind speed; H – the height of the SA; P_{ten} – tension force of wires; d_m – the outer diameter of the insulating part of the arrester; d_{ice} – ice wall thickness.

According to [6], 6-35 kV SA must withstand mechanical loads in accordance with GOST 16357 [14]. Similar requirements are in [2], however, in the absence of ice, the wind speed is increased to 40 m/s.

According to [1], the seismic resistance of a 110-750 kV SA is determined on the MSK-64 scale depending on the regions of Ukraine and varies from 6 (for example, the Kiev region) to 9 (for example, the Autonomous Republic of Crimea) points.

According to [2], when installing a 110-750 kV SA in areas with increased seismic hazard (more than 7 points according to MSK-64); it is necessary to contact the SA manufacturer to select the most suitable SA design.

Conclusions. In Ukraine and in other countries, methods for the selection and application of 6-750 kV SA have been developed, thanks to which it is possible to select arresters for replacing arresters at substations, as well as for newly built substations, directly by design organizations, without resorting to the help of manufacturers.

The choice is made according to the following main parameters:

- rated continuous operating voltage of the SA;
- rated discharge current;
- the level of the remaining voltage at the rated current of the switching overvoltage;
- the level of the remaining voltage at the rated current of lightning overvoltage;
- determination of the permissible protective distance from the SA to the protected equipment;
- compliance with explosion safety conditions;
- characteristics of mechanical resistance.

For the further development of methods for selecting SA, it is necessary to switch to statistical methods for calculating overvoltages.

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