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INFLUENCE OF ENERGY CHARACTERISTICS OF SURGE ARRESTERS ON THEIR SELECTION

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Виконані розрахунки теплових режимів обмежувача перенапруг нелінійного. Встановлено, що при виборі енергетичних характеристик обмежувача перенапруг нелінійного необхідно користуватися його вольт-амперною характеристикою. Використання емпіричних формул з нормативних документів не завжди виправдано. Встановлено, що для отримання коректних значень енергії, яку поглинає обмежувач перенапруг нелінійний, необхідно використовувати воль-амперну характеристику

Ключові слова: обмежувач перенапруг нелінійний, вольт-амперна характеристика, теплові режими обмежувача перенапруг, енергія перенапруги

Выполнены расчеты тепловых режимов ограничителя перенапряжений нелинейного. Установлено, что при выборе энергетических характеристик ограничителя перенапряжений нелинейного необходимо пользоваться его вольт-амперной характеристикой. Использование эмпирических формул из нормативных документов не всегда оправдано. Установлено, что для получения корректных расчетных значений энергии, которую поглощает ограничитель перенапряжений нелинейный, необходимо использовать вольт-амперную характеристику

Ключевые слова: ограничитель перенапряжений нелинейный, вольт-амперная характеристика, тепловые режимы ограничителя перенапряжений, энергия перенапряжений

1. Introduction

Protection of electrical plants of 6–750 kV from overvoltage has an important role in the operation of electric power facilities. Currently, the main way of protection of electrical equipment from overvoltage in electric networks of 6–750 kV is the application of nonlinear surge arresters (SA). That is why correct selection of SA in the course of designing is essential. Nowadays, majority of designing organizations select SA practically without taking into account the forms and duration of overvoltage action that can arise in the network, for which this selection is performed. This approach may lead to a damage of SA during operation due to the influence of overvoltage with large values of stored energy. Today, selection and application of SA are regulated by the following documents:

1. In Ukraine:

– SOU-N II 40.12-00100227-47 "Non-linear overvoltage limiters of 110–750 kV voltage. Guidance on selection and application";

– SOU-N MEV 40.100100227-67:2012 "Non-linear overvoltage limiters of 6–35 kV voltage. Guidance on selection and application in switchgear"

2. In Russia:

– "Guidelines on application of overvoltage limiters in electric networks of 110–750 kV";

– "Guidelines on application of non-linear overvoltage limiters in electric networks of 6–35 kV".

3. International standards:

– IEC 60099-5 Suppressors for overvoltage protection. Part 5. Recommendations on selection and application.

4. Developments of companies – manufacturers of SA:

– "Guidelines on selection of non-linear overvoltage limiters, manufactured by the enterprise "Tavrida Ecectric" for electric networks of 6–35 kV";

– Hinrichsen Volker. Siemens. Metal oxide overvoltage limiters. Fundamentals, selection and application of metal oxide overvoltage limiters in networks of medium voltage;

– Exlim. Technical information. Guidelines on selection of high voltage overvoltage limiters, manufactured by ABB company;

– Characteristics, selection and location of overvoltage limiters (110–220 kV).

All these documents include different approaches to the problem of selection of SA. However, they do not take into account the forms and duration of overvoltage, which affect SA in an actual network. This approach to selection of parameters of SA can lead to disturbance of thermal balance and damage to the device. Such accidents are usually accompanied by severe damages to switchgear at substations and costly repairs with removal of power equipment of service. Taking into account capability of SA to maintain thermal balance under overvoltage influence, which is possible in a particular network, will improve its operational reliability. That is why development of methods for determining energy that is released in varistors of SA is a relevant scientific and technical problem.

2. Literature review and problem statement

While considering the problem of selection of SA for reliable overvoltage protection of electric networks, all researchers apply the standard empiric formulae of such influences as a basis. This approach is recommended by manufacturers in numerous catalogues of energy evaluation and textbooks. This approach was implemented in papers [1–3], the authors of which use empirical expressions for determining the selection of throughput capacity class of SA. In article [4], researchers made an attempt at determining energy characteristics of SA with the help of their own expression, which does not take into account peculiarities of volt-ampere characteristics. The author of [5] assesses the impact of higher harmonics on thermal modes, however, it does not make it possible to evaluate their state under the influence of overvoltage. Paper [6] considers the impact of operating voltage only, while possible overvoltage is not taken into account. The method, described in article [7], requires a substantial improvement to be used during evaluation of overvoltage influence on SA. In research [8], energy that influences SA is estimated based on the known methods that do not consider the form and duration of overvoltage action. Work [9] is devoted to the assessment of risks, caused by SA damage. However, it does not practically take into account effects on thermal modes of devices. Paper [10, 11] does not consider electrical-physical properties of SA, which leads to errors while choosing it. Energy characteristics of SA are explored in detail in [12]. However, the used methods for determining the energy characteristics of SA do not take into consideration actual circuits, in which it is used, which can lead to errors in choosing its parameters.

At present, all regulations on the selection of SA recommend to estimate energy characteristics under influences of relatively high overvoltage of one particular form. Thus, they do not take into account influences of the form and rate of an increase in overvoltage surge. Similar influences can have rather high values and lead to disturbance of thermal balance of SA.

Researchers pay very little attention to the analysis of SA operation under the influence of overvoltage, pulse forms of which differ from the standard ones, and there are practically no publications that focus on this issue. At the same time, such analysis is necessary in order to determine capability of SA to withstand such impacts without disturbing thermal balance. However, papers [13–16] show that the form of overvoltage that can arise in the electrical network is substantially different from the standard one. However, the impact of such overvoltage on SA has not been studied enough.

All the foregoing reveals the need to study thermal modes of SA operation under the influence of overvoltage, the pulse forms of which are different from the standard modes of SA operation that actually are not determined. It is necessary to develop a procedure for the evaluation of thermal modes of SA provided there is an influence of overvoltage of electrical networks of any form.

3. The aim and objectives of the study

The goal of the conducted studies was to determine a method for the consideration of forms and duration of overvoltage when choosing SA for the assigned network. This will enable us to refine the choice of energy characteristics of SA and will result in enhancing their serviceability.

To accomplish the set goal, the following tasks were to be solved:

– to analyze thermal modes of SA;

– to perform calculations of energy that can be released in SA under the influence of different types of overvoltage;

– to substantiate the need for conduction of energy, dissipated by SA, to analyze the ability of SA to maintain thermal modes;

– to determine whether ability of SA to withstand all pulses without exception is influenced by their form and length.

4. Materials and methods for studying the influence of overvoltage of assigned form on thermal modes of non-linear overvoltage limiters

4. 1. Technique of determining thermal modes of non-linear overvoltage limiters

To analyze thermal processes that take place in SA under conditions of overvoltage of different nature in the electric network, it is necessary to conduct research using a volt-ampere characteristic. Thus, the energy, released in SA, is supposed to be determined. This approach is essential for the correct selection of SA parameters not only to protect an electrical network, where it is installed, but also to provide proper operation of a protective device itself. This will allow selection of SA parameters at a design stage, which will greatly reduce failure rate throughout the whole period of operation.

4. 2. Studied materials and equipment used in the experiment

To carry out research, we used volt-ampere characteristics of SA, given by manufacturers. Results of calculations are compared with values of energy that can be dissipated by SA, calculated according to information form companies-manufacturers. Based on this comparison, we made a decision whether SA has the ability to withstand the influence of overvoltage of the assigned form without compromising heat balance.

5. Results of influence of overvoltage of assigned form on thermal modes of nonlinear voltage limiters

The main objective when selecting SA is overvoltage limitation to the level that is safe for electrical equipment that is protected, and, at the same time, provision of limiters' resistance to overvoltage, which is unsafe for them. SA for electrical networks of 6–750 kV, presented in the Ukrainian market, are produced by different factories (both Ukrainian and foreign) based on their own technical solutions. That is why SA, produced by different factories and companies and designed for the same voltage class, can differ by characteristics that must be considered when choosing them.

Heat release and heat removal are main processes, which determine the temperature state, compliance with the parameters, specified in technical conditions, serviceability of varistors of SA, therefore, of SA as a whole.

While current, which is determined by applied voltage U, flows through varistors of SA, energy in the form of heat is released. This causes a rise in temperature of varistors according to thermophysical properties of their material, dimensions, and conditions of heat removal – heat transfer from resistors to the SA housing and to environment. If power of heat removal Q for varistors is presented in the form of linear dependence

$$Q = k(\theta - \theta_0), \qquad (1)$$

where k is the constant; θ is the temperature of the varistor; θ_0 is the ambient temperature, it is possible to estimate thermal conditions of varistors' operation.

It should be noted that, in fact, characteristic of heat removal has a more complex relationship with varistors' temperature and ambient temperature. Accepted simplification offers a possibility to perform a qualitative analysis of processes of thermal mode of SA and to determine major factors for defining temperature resistance of varistors, and therefore, of SA as a whole.

At ambient temperature of θ_{c1}, temperature of varistors rises to value of θ_{p11}, which is determined by thermal equilibrium (point 1, Fig. 1). When heat release (curve a_1) in varistors is balanced

Point 1 in Fig. 1 corresponds to condition of thermal balance $P_1(\theta_{p11})=Q_1(\theta_{p11})$. Characteristic of heat transfer Q_2 (line Q_2) and characteristic of heat release P_1 at the same voltage (curve a_1) correspond to the higher ambient temperature. Thermal balances $P_1(\theta_{p21})=Q_1(\theta_{p21})$ (point 2, Fig. 1) under these conditions reach a higher temperature of Q_{p21}. Permissible temperature of varistors of SA $\theta_{p.perm.length}$, if operational protective properties of continuous mode are retained at operational voltage, determines appropriate value of permissible ambient temperature $\theta_{c.perm.length}$ (point *3*, $P_1(\theta_{p.perm.length})=Q_1(\theta_{p.perm.length})$, Fig. 1). Under the modes of overvoltage influence, temperature of varistors of SA briefly increases according to duration and amplitudes of overvoltage and previous thermal condition of SA. It is possible to reach permissible (or critical) value of temperature $\theta_{p.critical}$ under short-term mode of heating varistors of SA, which determines boundary current load that meets parameters of permissible overvoltage.

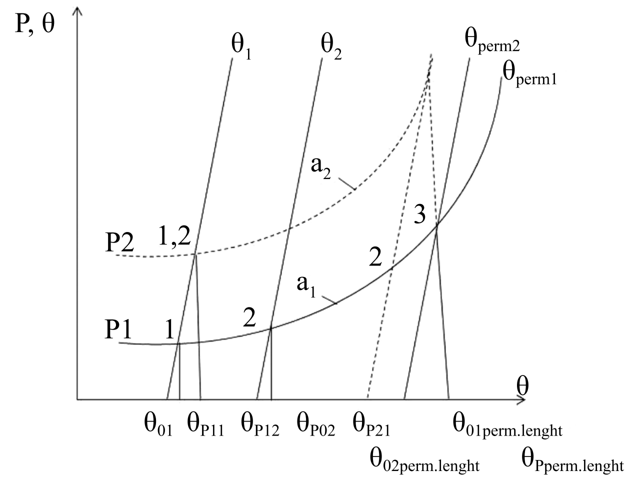


Fig. 1. Dependence of heat release and heat transfer for the state of thermal equilibrium of varistors

When overvoltage is limited, varistors (and SA as a whole) retain their operability and standard protective properties only at temperature, lower than permissible (critical) value, guaranteed by technical conditions of the manufacturer. However, this time is limited to reaching this temperature. Permissible (critical) temperature $\theta_{p.critical}$ of short-term mode of varistors of resistors, as a rule, determines thermal stability of SA, since sufficient capability of SA to heat transfer is foreseen for a mode of long operational voltage.

The rapid rise in the temperature of varistors happens under short-term overvoltage influence due to thermal inertia of heat removal. Temperature of varistors rises, and it takes time for them to cool down and for temperature to decrease to the initial value of θ_{p11}. If as a result of previous actions (for example, several large short-time pulses of current within a short interval of time), the temperature of varistors (one varistor from the entire set of SA is enough) reaches permissible (critical) value $\theta_{p.perm.length}(\theta_{p.critical})$ (point 3, Fig. 1), then any new overvoltage will cause additional energy and, consequently, heat release in resistors that were not cooled yet. As a rule, the varistor with the highest energy release is the first to lose thermal stability. This is caused by its volt-ampere characteristic. The varistor with the worst heat removal, caused by disrupted conditions of heat transfer from this varistor, can also be the first to get of service.

In this case, additional heat release will result in an additional rise in temperature over permissible (critical) value $\theta_{p.perm}$, in upsetting thermal stability and damage to varistor, leading to subsequent failure or destruction of SA. Temperature $\theta_{p.}$ of the varistor, elevated as a result of energy release immediately after overvoltage is over, corresponds to the mode of thermal equilibrium at a higher ambient temperature θ_0 [2].

Let us consider SA operation for voltage class of 110 kV under the influence of quasi-stationary overvoltage and lightning pulse of current. Volt-ampere characteristic of SA (VAC) is shown in Fig. 2.

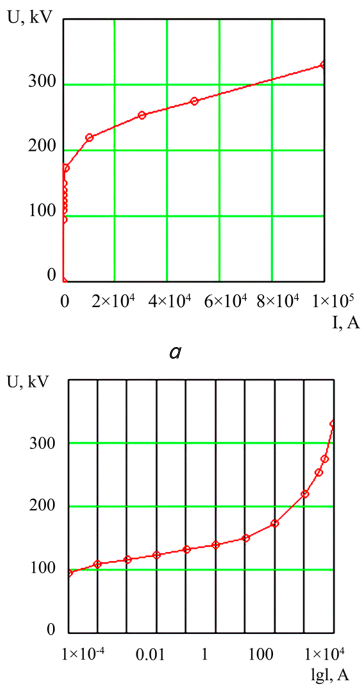


Fig. 2. Volt-ampere characteristic of overvoltage limiter: *a* — in coordinates *U. I....*; *b* — in coordinates *U.lg I*

In case of influence of sinusoidal voltage at operating voltage value of *U*=100 kV, current through SA is determined by VAC on assumption that the circuit of SA consists of a capacitor with capacitance C and a nonlinear resistor (varistor) with resistance, connected in parallel (Fig. 3).

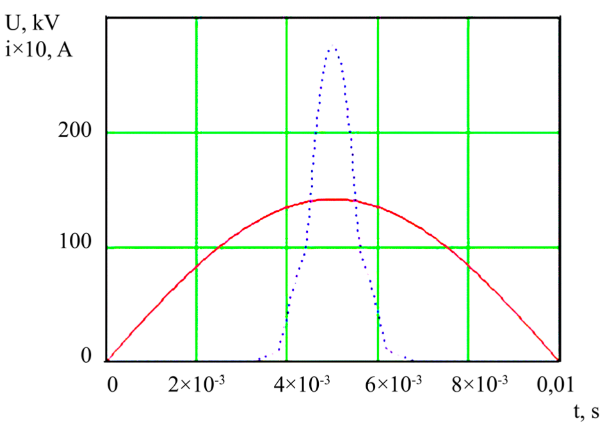


Fig. 3. Voltage on the overvoltage limiter and current through the overvoltage limiter

According to formula (2), we will determine active energy, released in SA for one pulse of current (time interval equal to half-period):

$$w = \int_0^{0,01} u(t)\cdot i(u)\mathrm{d}t, \qquad (2)$$

where $u(t)=U\cdot\sqrt{2}\cdot\sin(\omega\cdot t)$ is the instantaneous value of the sinusoidal voltage, kV; $i(t)=l\,\mathrm{int}\,erp(U,I,U\cdot\sqrt{2}\cdot\sin(\omega\cdot t))$ is the instantaneous value of current through SA, obtained by instantaneous values of voltage on SA and VAC.

Fig. 3 shows dependence of power that is released within one half-period in SA with operating voltage of *UHPO*= =80 kV and specific energy capacity w_{num}=4 kJ/kV. In Fig. 3, we can see that at overvoltage multiplicity of K=1.5, reserve of energy capacitance of SA is exhausted within one half-period.

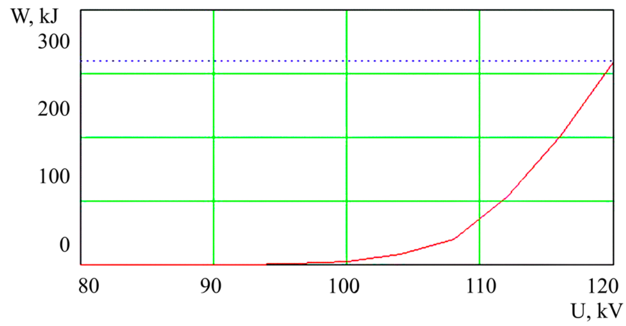


Fig. 4. Power, released in the overvoltage limiter within one half-period

Within *n* half-periods, power is released in SA:

$$W_n = w\cdot n. \qquad (3)$$

This result proves a position that SA do not protect a network from quasi-stationary overvoltage. If such overvoltage occurs, thermal balance of SA is disturbed and thermal breakdown of varistors occurs, which leads to their failure. Networks, in which they are mounted, must have protection from occurrence of overvoltage of such class, without considering the presence or absence of SA [17]. In addition, we can assume that if the network has higher harmonics of SA, thermal balance will also be disturbed due to an increase in capacitance component of current.

In the case of over-voltage influence within a short period of time (when the process can be considered adiabatic and when heat release to environment may not be taken into account), it is possible to determine serviceability zone of SA from inequality:

$$W = n\cdot\int_0^{0,01} U_{HPO}\cdot K\cdot\sin(\omega\cdot t)\times$$
$$\times l\,\mathrm{int}\,erp(U,I,U_{HPO}\cdot K\cdot\sqrt{2}\cdot\sin(\omega\cdot t)dt < W_{num}\cdot U_{HPO}. \qquad (4)$$

Fig. 5 shows the surface, formed by function $W=F(K,t)$, that intersects with plane $W_n = W_{num}\cdot U_{HPO} = 320$ kJ. The line of intersection is the characteristic "voltage – time" for adiabatic process of SA heating.

Fig. 6 shows a generalized form of lightning pulse of current in relative units.

Residual voltage on SA under the influence of lightning pulse parameters T_{front}/T_{pulse}=8/20 μs can be calculated by formula:

$$u(t) = l\,\mathrm{int}\,erp(I,U,I_r\cdot A(t)), \qquad (5)$$

where $I_{lightning}$ is the amplitude of lightning pulse, kA; A(*t*) is the dependence of relative current on time (Fig. 6).

As an example, Fig. 7 shows lightning pulse T_{front}/T_{pulse}= =8/20 μs with amplitude of 10 kA and residual stress on SA, which corresponds to such pulse of current.

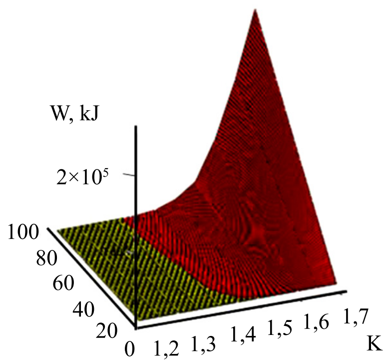


Fig. 5. Characteristic "voltage – time" for adiabatic process

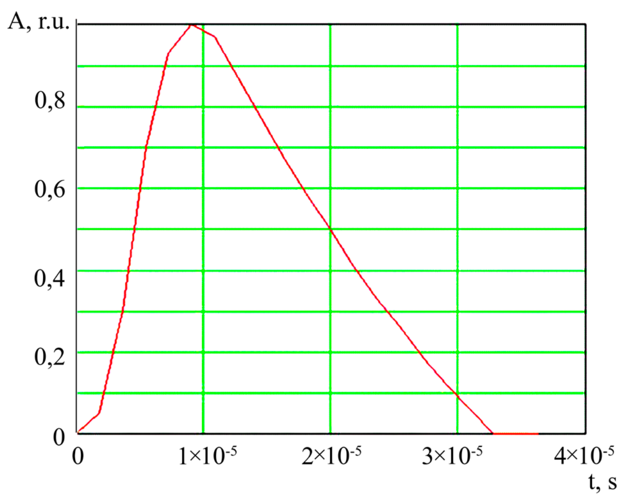


Fig. 6. Lightning pulse of current (DSTU IEC 62305-1)

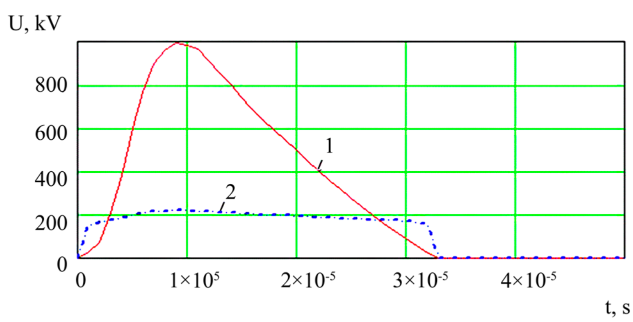


Fig. 7. Pulses of current and voltage of overvoltage limiters: 1 – lightning pulse of current with amplitude of 10 kA; 2 – residual voltage

Fig. 8 shows dependence of energy, released in SA at lightning pulse of current, on amplitude of pulse of current, boundary of this dependence in the form of energy capacity of SA and residual voltage of SA.

Energy, released in SA from pulse of current, was acquired from formula:

$$W_r = \int_0^{0,0001} I_r \cdot A(t) \cdot l\,\mathrm{interp}(I, U, I_r \cdot A(t))\,\mathrm{d}t. \qquad (6)$$

The maximum value of residual voltage on SA was determined based on VAC from formula (5).

Fig. 9 shows projections of specified dependence $W=F(I, U)$ on coordinate axis:

a) *I, U* is the dependence of residual voltage on amplitude of lightning pulse of current;

b) *I, W* is the dependence of energy, released in SA, on amplitude of lightning pulse of current;

c) *U, W* is the dependence of energy, released in SA, on amplitude of residual voltage during lightning pulse of current.

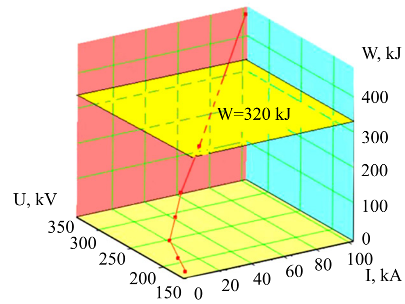
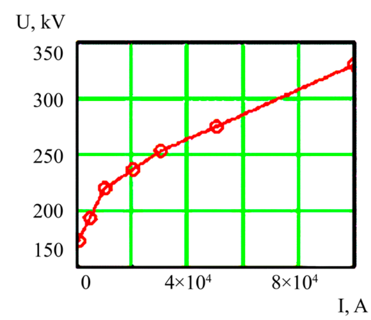
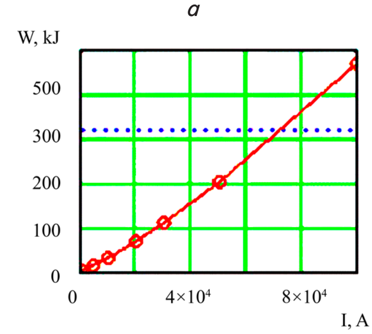


Fig. 8. Dependence of energy, released in overvoltage limiter of lightning pulse of current on amplitude of pulse of current, boundary of this dependence and residual voltage



a



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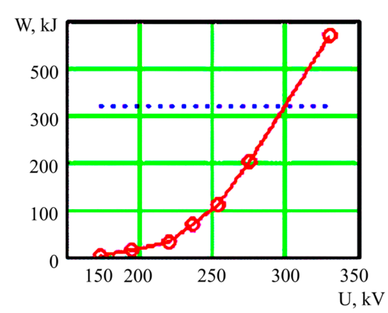

c

Fig. 9. Projections of dependence *W=F(I, U)* on coordinate axis: *a* – *I, U* – dependence of residual voltage on amplitude of lightning pulse of current; *b* – *I, W* – dependence of energy, released in voltage limiter, on amplitude of lightning pulse of current; *c* – *U, W* – dependence of energy, released in overvoltage limiter, on amplitude of residual voltage during lightning pulse of current

Presented results of calculations show that at standard pulse of atmospheric overvoltage, SA maintains heat balance at values of lightning current of up to 75 kA. Design lightning currents for electrical networks are of about 30 kA. However, it should be noted that this approach cannot be applied to the selection of SA in an assigned network because it may be different in values of amplitudes of the lightning currents, rates of increasing and number of lightning strikes in one channel (as we know, there can be 10 of them). All presented parameters will affect thermal balance of SA, and at some values they can lead to its disturbance, which will cause a failure of SA and damage to equipment of electric network. This conclusion emphasizes the need for detailed analysis of overvoltage that may occur within the network when choosing parameters and a place for SA mounting.

Fig. 10 shows switching pulse of current. Residual voltage on SA under the influence of switching pulse with parameters T_{front}/T_{pulse}=30/60 μs can be calculated by formula (5).

As an example, Fig. 10 shows switching pulse of current T_{front}/T_{pulse}=30/60 μs with amplitude of 100 A and residual voltage on SA, which corresponds to this pulse of current.

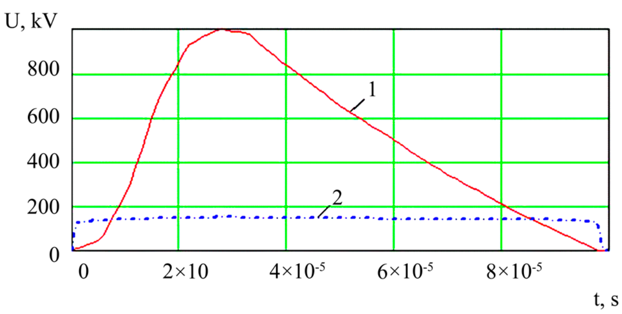

Fig. 10. Pulses of current and voltage of overvoltage limiter: 1 — switching pulse of current with amplitude of 100 A; 2 — residual voltage

Fig. 11 shows dependence of energy, released in SA at switching pulse of current, on amplitude of pulse current and residual voltage of SA. Energy, released in SA from switching current pulse, was derived from expression (6). The maximum value of residual voltage on SA is determined based on VAC from expression (5).

Fig. 12 shows projections of specified dependence $W=$ $=F(I, U)$ on the coordinate axis:

a) *I, U* is the dependence of residual voltage on amplitude of switching pulse of current;

b) *I, W* is the dependence of energy, released in SA, on amplitude of switching pulse of current;

c) *U, W* is the dependence of energy, released in SA, on amplitude of residual voltage during switching pulse of current.

Fig. 11, 12 show that energy of switching overvoltage at standard pulse is significantly lower than energy at lightning influences. It allows us to assume that the form and time of overvoltage action influence the energy, which affects SA. Obtained results prove the need to check whether SA is capable of dissipating energy of overvoltage at the stage of its selection. This approach will allow us to select energy characteristics of SA more reasonably.

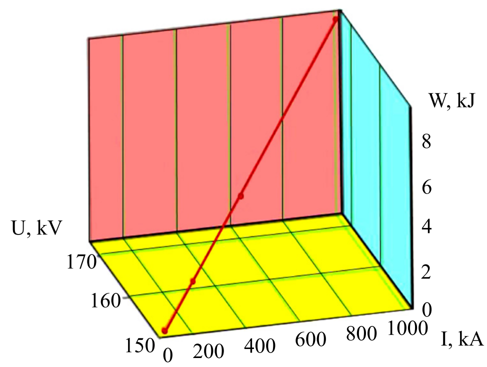

Fig. 11. Dependence of energy, released in overvoltage limiter at switching pulse of current, on amplitude of pulse of current and residual voltage

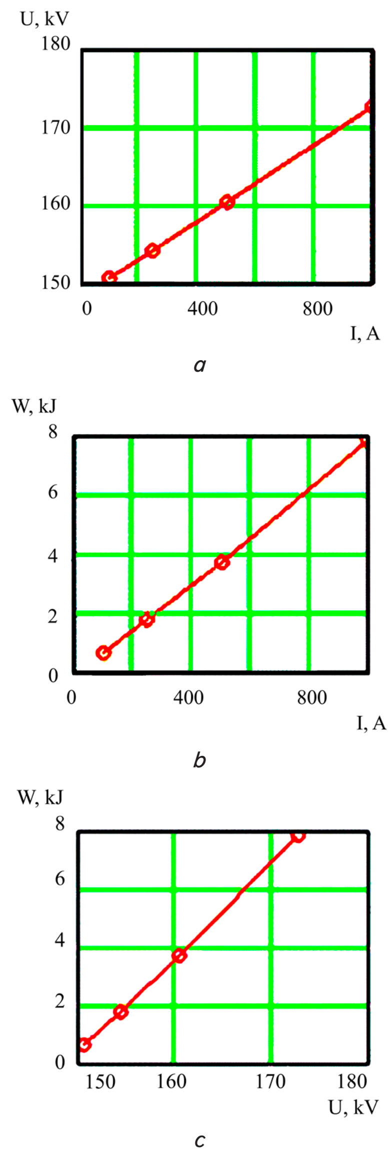

Fig. 12. Projections of dependence *W=F(I, U)* on coordinate axis: *a — I, U —* dependence of residual voltage on amplitude of switching pulse of current; *b — I, W —* dependence of energy, released in overvoltage limiter, on amplitude of switching pulse of current; *c — U, W —* dependence of energy, released in overvoltage limiter, on amplitude of residual voltage during switching pulse of current

6. Discussions of results of research into energies, released in the overvoltage limiter

Conducted research allowed us to calculate energies, released in SA under the influence of overvoltage. Increased accuracy of similar calculations is determined using the real volt-ampere characteristic (VAC) of SA. Most manufacturers do not indicate parameters of VAC in catalogues of products. Designers are forced to use the known expression, describing VAC of SA. It should be noted that VAC has three sections, which are completely different in terms of physical processes. It makes virtually impossible to describe VAC of SA by one equation. Among shortcomings of conducted studies, we should note the difficulty of obtaining real VAC of SA. This is due to complexity of acquiring them even under factory conditions.

From the above, it is possible to conclude that energies, that can be released in SA under influences of standard switching and lightning pulses, are much lower than energy that it can dissipate without disturbing thermal balance. However, it should be noted that actual impacts can have much larger amplitudes, in case of switching impulses, and the front length which are larger than the standard testing ones. This indicates the need to carry out calculations of possible magnitudes of switching overvoltage that can arise in the electrical network, connected with SA. Such calculations must be carried out in the electric networks, where switching overvoltage can affect electrical strength of insulation of equipment in the electric network. It should be noted that the standards of techSAogical design require special calculations when choosing SA. One of such calculations can be connected to determining the dimensions and form of switching overvoltage that may occur in the network, where SA will be installed at design stage. Subsequently, it is necessary to perform experimental work on determining of VAC of SA under laboratory conditions.

7. Conclusions

1. An analysis of thermal modes of SA was performed. It showed that when calculating the energy that affects SA, it is necessary to use actual volt-ampere characteristics. This will make it possible to significantly improve the accuracy of calculation of energy that is released in SA under the influence of overvoltage. Such refinement will allow us to select correctly the type and the model of SA in the process of designing.

2. We presented the technique of determining a thermal balance of SA, which should be used for the substantiation of selection of the design and type of SA to prevent emergencies in electric networks. This technique allows considering design features of SA due to employing actual volt–ampere characteristics for the calculation of the energy, released in it under the influence overvoltage of any form.

3. The obtained results proved that SA do not protect the network from quasi-stationary overvoltage. When such overvoltage occurs, thermal balance of SA is disturbed and thermal breakdown of varistors occurs, which leads to their failure. The networks, where they are mounted, must have protection from occurrence of overvoltage of such class despite the presence or absence of SA.

4. Calculations of energies, which are released in SA under the influence of lightning and switching pulses of overvoltage, were performed. They indicated that there are significant differences in magnitudes of released energies. For example, energy of support of thermal balance for SA of 110 kV was exceeded only under the influence of lightning overvoltage with amplitude of current of 78 kA. This is caused by small magnitudes of switching overvoltage in networks of such nominal voltage. However, when choosing SA, it is necessary to carry out overvoltage calculations in the assigned network. This will make it possible to accurately take into account the impact of any kind of overvoltage on energy characteristics of SA.

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