LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

FACULTY OF TECHNOLOGY
LUT ENERGY
ELECTRICAL ENGINEERING

MASTER'S THESIS

PROTECTION OF THE HIGH-VOLTAGE EQUIPMENT WITH REDUCED INSLATION STRENGHT

Examiners Professor, D.Sc Jarmo Partanen
Associate professor, Natella Gumerova

Author Natalia Grigorova

Abstract

Lappeenranta University of Technology
Faculty of Technology
Electrical Engineering

Author: Natalia Grigorova

Protection of the high-voltage equipment with reduced insulation strength

Master’s thesis
2009
59 pages, 30 pictures, 7 tables and 1 appendix

Examiners: Jarmo Partanen, Natella Gumerova

Keywords: surge arrester, transformer, reduced insulation strength, overvoltage

Power transformer is the most expensive equipment on a substation. It is always necessary to get needed benefit with the lowest expenses. Producing of power transformers with reduced insulation strength is one of the possible ways to reduce expenses. Exploitation of such transformers was begun in the end of 70-th in the last century. Protection from overvoltages was done with valve-type magnetic combined surge arresters with increased blanking voltage during switching overvoltages. Nowadays there is the necessity of replacement of those devices. That’s why modernized nonlinear surge arrester was invented.

This master’s thesis is focused on the use research of that modernized device in comparison with usual nonlinear surge arresters. The goal is to show the lightning overvoltages level using different types of nonlinear surge arresters and then calculations of the lightning protection reliability.

Table of contents

Abbreviations and symbols

HPP	Hydro power plant
HV	High voltage
MV	Medium voltage
NSA	Nonlinear surge arrester
RG	Rod gap

A	coefficient describing insulation behaviour
B	coefficient describing insulation behaviour
c	wave velocity
C	capacity
E	electromotance
I	current
k	coefficient
M	lightning-surge proofness index
t	time
z	impedance
α	refraction coefficient

Subindexes

b	blanking
c	cancel
d	discharge
e	equivalent
g	grounding

imp	impulse
j	number of the node
m	number of the line
n	nominal
s50Hz	sparkover, 50 Hz

Acknowledgment

I want to express my gratitude to Natella Gumerova, Jarmo Partanen for assistance during this thesis writing.

1 Introduction

External actions, technical conditions, aspiration to reduce expences often make people to create something new.

There was designed nonlinear surge arrester for protection of the equipment with reduced insulation strength. This device has more complex construction which allows to react selectively on different overvoltages types. Voltage-current characteristic falls down from some value of the current through NSA for limitation lightning overvoltages. At a time during switching overvoltages (energy of switching overvoltages is quite higher) voltage-current characteristic stays in the high level that doesn't allow to device to overheat. Presence of the "standard" voltage-current characteristic without any overvoltages doesn't lead to increasing of surface-leakage current which influents to choice and NSA sorting during exploitation.

Any construction complication results in reduction of its reliable work. In the beginning when technology isn't perfect only piecework is done, it causes producing appreciation. So it is always necessary to know: what efficiency will have new technical decision, if there is any use to create the new device.

Zchigulevskaya HPP is the first place of possible application of modernized NSA. There appeared the necessity to change old valve-type surge arresters with new protective devices. Specificity if this object is presence of lightning overvoltages because of long conductors between equipment one part of which was placed on the dam and another part – on the shore. Conductors are hanged over the water where they are the highest objects. Increased distances between poles lead to high probability of direct lightning stroke into phase conductor that is the most typical exposure for 500 kV voltage level. So such object should be very suitable place for modernized surge arresters application.

It should be noticed also that transformers which are placed on some HPP have reduced test voltages of the lightning impulse, so they need more careful protection.

The aim of this work is comparison of modernized NSA efficiency with widely used usual NSA. For such analysis there were done calculations of voltages which influence on transformer insulation at direct lightning stroke into phase conductor, and calculations of lightning-surge proofness index M for schemes with different protective devices were done.

2 Overvoltages classification

During the exploitation of electric energy systems voltage across insulation can exceed limits which have been accepted as permissible in normal operating conditions. This effect is named an overvoltage. Unfavourable atmospheric conditions, transient phenomena in the network, mechanical actions can cause overvoltages, therefore insulation breakdown or insulation flashover, insulation deprecation and premature outage can occur. Different types of overvoltages can last from the several microseconds till several hours. Therefore along with other measures which are directed on the increasing of the insulation lifetime, it is necessary to limit overvoltages occurring during different operation modes of the utilities equipment and power lines.

Depending on a place of occurrence it can be separated different types of overvoltages: phase, phase-to-phase, intraphase, between contacts overvoltages. Phase overvoltages concerning the earth have the most practical meaning. Overvoltages influence on the conducting part insulation from the earth or from the connected to the earth construction.

Depending on reasons of initiation overvoltages can be separated on internal and external. Internal overvoltages are after-effects of different processes in a network, incorrect shape of a network, commutations of power equipment or damages of insulation. External overvoltages result of energy sources which are external to the network under consideration, for example, lightning stroke. In the Table 2.1 characteristics of the various overvoltages types are shown.

Table 2.1 Characteristics of the various overvoltages types.

overvoltage type (cause)	MV-HV overvoltage coefficient	term	steepness of frequency front	damping
at power frequency (insulation fault)	≤ √3	long > 1 s	power frequency	low
switching (short-circuit disconnection)	2 to 4	short 1 ms	medium 1 to 200 kHz	medium
atmospheric (direct lightning stroke)	> 4	very short 1 to 10 μs	very high 1,000 kV/μs	high

2.1 Internal overvoltages

Internal overvoltages are divided into quasi-stationary and switching (it depends on exposure time on an insulation).

An overvoltage value depends on many parameters, inclusive of a way of neutral ground. In the Table 2.2 are shown different ways of a neutral ground depending on voltage level.

Table 2.2 Ways of a neutral ground depending on voltage level.

<table>
<tr><td>• 6-35 kV</td><td>• 110-220 kV</td><td>• 330-750 kV</td></tr>
<tr><td>• insulated neutral</td><td>• effectively earthed neutral</td><td rowspan="4">• dead-earthed neutral</td></tr>
<tr><td>• neutral earthed through arc-suppression coil</td><td rowspan="3">• dead-earthed neutral</td></tr>
<tr><td>• neutral earthed through resistor (high-ohmic or low-ohmic)</td></tr>
<tr><td>• neutral earthed through placed in parallel arc-suppression coil and resistor</td></tr>
</table>

2.1.1 Quasi-stationary overvoltages

During the planning of an electrical network it is necessary to avoid conditions whereby quasi-stationary overvoltages can increase levels which can lead to a insulation breakdown. Possible overvoltages magnitudes also increase with a rise in forced component of an overvoltage. In this case a work of electric surge arrester and nonlinear surge arrester become more difficult. Quasi-stationary overvoltages take place during temporary operating regimes, negative combination of network parameters from the exploitation point of view. A durability of such overvoltages is form a fractions of a second till tens of minutes. It is limited to an operation of a relay protection or operating employees. (Kuchinsky 98)

Quasi-stationary overvoltages conditionally are divided into operating, resonance and ferroresonance. The most dangerous for nonlinear surge arresters are ferroresonance processes taking place with open-phase supply of transformers. This situation can be a result of burning-out high voltage filament in one or two phases, open-phase commutation of a disconnector or a switchgear, open-wire breakage. (Dmitriev) Such regimes lead to operation of protective devices in the area of magnitude power frequency signal, that is every 0.02 s. Energy losses that evolve during current passage through a voltage-depended resistor have no time to disperse therefore a device breakdown.

2.1.2 Switching overvoltages

Switching overvoltages take place at the time of fast changes of a network regimes, that is develop because of transient phenomena. The maximal values of such overvoltages can occur during commutations of parts that have large amount of reactive energy. It can take place at the time of power transmission lines commutations (planned switching on/off of unloaded lines, automatic reclosing, switching off lines with short circuit); power transmission lines commutations in a block with transformer; during switching off of reactance coil, transformers and electrical machines; at the time of edging the current in an arc-suppression coil; during commutations of high voltage electric motor. It is necessary to notice that the ratio of switching overvoltages (an overvoltage magnitude to phase voltage in the nominal operation conditions ratio) can’t be more than 3.

2.2 External overvoltages

Lightning strokes are the main source of external overvoltages in high voltage networks. The most dangerous are direct lightning strokes in current-carrying parts of a network. Lightning strokes in an earthed constructions lead to appearing on it momentary overvoltages and possibility of an arc-over from earthed parts to current-carrying.

When a lightning stroke occurs near with line or substation induced overvoltages appear caused bilateral electro-magnetic (inductive and capacity) connection of lightning with current-carrying and earthed parts of a network. In most cases it has less value than overvoltages from a direct lightning stroke, but it constitutes a danger for insulation of network equipment to 110 kV level included. (Dmitriev)

Waves of overvoltages advance along power transmission line on large distances with a little damping, therefore lightning overvoltage also can influence on a electrical installations insulation, which are situated at considerable distances from the place of lightning stroke.

Ingoing waves can constitute a danger for electric equipment of stations and substations, that has less electric strength reservoir in comparison with a power transmission line insulation. Hence difficult tasks of insulation coordination and lightning protection appear, in other words tasks of equipment protection from waves which can come along a line (the more an overvoltage magnitude the more probability that it will overlap a line insulation and will not arrive on a substation in the case of direct lightning stroke in the wire, and conversely in the case of direct lightning stroke in a pole or ground wire).

Lightning overvoltages can be transmitted through transformer in its neutral and on an output side both magnetic and electrostatic ways. Hence lightning overvoltages constitute a danger for an effectively earthed neutral of a transformer, which is insulated at that moment, and for neutral of transformer secondary, also for attached equipment.

3 History of protective devices development

As it was said above some types of overvoltages constitute a serious danger for equipment, hence power transmission lines, electric equipment of stations and substations are in need of protection. Suppression of a power frequency signal overvoltages (quasi-stationary, periodic component of a short circuit, ferroresonance) is a result of so called system actions that is selection of a neutral grounding type, devices, schemes etc. Suppression of surge overvoltages (overvoltages which have time characteristics less than a period of a power frequency signal, such as lightning and switching overvoltages) is a result of operations of special protective devices.

Main protective devices, which are used at this time, are nonlinear surge arresters. A large number of valve-type arresters are also installed in networks. There is a necessity in the design of protection schemes to solve following tasks:

1) selection of a number, places of installation and parameters of protective devices, which provide reliable protection of insulation from lightning and switching overvoltages;
2) maintenance of protective devices fail-safe working at the time of nominal operation conditions, also during quasi-stationary overvoltages for which protection devices are not designed.

There is also a task of protection of equipment with decreased insulation strength (selection of a main insulation was done according to a permissible working voltage), in particular – transformers.

3.1 Rod gaps

The first protection devices for insulating constructions from breakdown or flashover were rod gaps (RG). Circuit schematic of protection with use of RG is shown in the Figure 3.1.

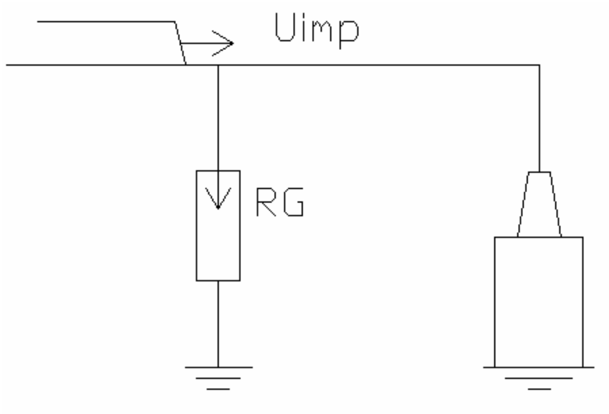


Fig.3.1. Protection with help of rod gap circuit scheme.

Voltage-time curve of a RG should be lower than voltage-time curve of protected insulation. When this condition is performed rod gap shuts down and voltage across RG and insulation shortly reduces. Besides pulse current along ionized way also follow current is directed (it is conditioned with power frequency signal). If the neutral of device is grounded or RG flashover occurred in 2 or 3 phases then arc can't stop and impulse breakdown will change to sustained short circuit, which will lead to switching off of electrical installation or to damage and displacement of electrodes.

A necessity to provide arc blowout of follow current gave a new impulse in development of protective devices. There were invented protective arresters with two radically different ways of arc blowout: valve-type and expulsion-type arresters.

3.2 Expulsion-type arresters

Construction of expulsion-type arrester is shown in the Figure 3.2.

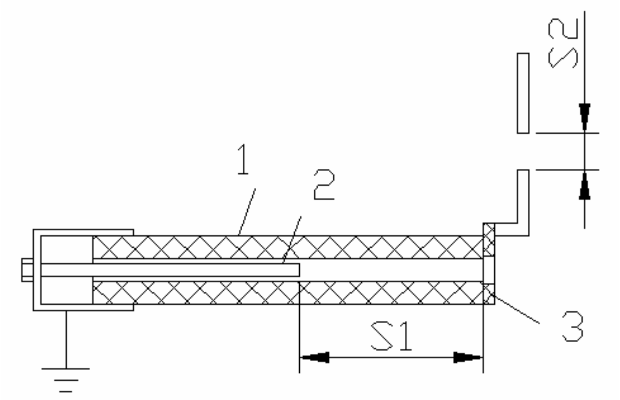


Fig.3.2. Expulsion-type arrester construction.

The arrester basis is a tube from gas-generating material – 1. One end of the tube is closed with metallic cover cap, on which internal stick electrode - 2 is fixed. On the open end of the tube hoop-type electrode - 3 is placed. A space S_1 between stick and hoop-type electrodes is called internal arc-suppressing space. The tube is separated from the phase wire with external rod gap S_2, in other case gas-generating material would break under an influence of surface-leakage current. (Kuchinsky 98)

Both of the gaps begin to pass current when lightning overvoltage appears and impulse current shunt off in the earth. When impulse ends the arrester continues to pass follow current and spark discharge changes into arc discharge. At this time under the effect of high temperature of an arc alternating current channel in the tube gas evolves intensively and pressure increases very much. When gases tear along the tube direct-axis blowing is created, then arc is blown out at the moment of the first current crossing of the zero value.

It is necessary sufficiently intensive gas generation in the tube which depends on the let-through current value for successful arc blowout. Therefore there is lower current limit which can be switched off by expulsion-type surge for one or two half-cycle. Upper current limit should be determined besides lower current limit because at the high current intensive gas generation takes place and it can cause the tube rupture.

Before the installation of such surge arresters it is necessary to check short circuit current, it should stay within the limits of the possible cutoff current.

Basic materials are fibrobakelite and viniplast.

Disadvantages of such surge arresters are unstable characteristics, presence of the possible cutoff current limits, abrupt voltage-time curve (there is no availability as a basic protective device of the substation equipment), as a result of repeated work internal surface of the tube is worked out and there appears a necessary to change surge arrester.

But the simplicity of the construction and low-price of production allowed to use expulsion-type surge arresters for a long time as secondary protective devices and also to use it for protection of low-power and low-duty substations.

3.3 Valve-type surge arresters

Main parts of the valve-type arrester are repetitive rod gap and series-connected resistor with nonlinear current-voltage curve.

Rod gap shuts down on exposure to lightning overvoltage and pulse current goes through surge arrester; it creates resistor voltage drop. In a strong change of the pulse current this voltage has a little change and a low difference from pulse breakdown voltage of the rod gap. One of the main surge arresters' characteristic is discharge voltage U_d (voltage at the defined current, called coordination current, 5-14 kA for different values of the nominal voltage). Pulse breakdown voltage of the rod gap and discharge voltage should be 20-25% lower than disruption voltage of the insulation. After the ending of the overvoltage suppression current through a surge arrester doesn't stop. This current is called follow current and it is defined by the power-frequency voltage. Resistance of the resistor rapidly increases with working voltage; follow current is limited drastically and an arc in the rod gap stops when current crosses over a zero value. The maximal power-frequency voltage across a surge arrester whereby follow current ends reliable is called blanking voltage U_b, corresponding current – cancel current I_c. Blanking voltage should be equal:

$$U_b = k_g \cdot U_n \tag{3.1}$$

Where k_g is coefficient depending on a way of neutral grounding, U_n is nominal line voltage.

There are two equations which characterize operations of a surge arrester:

$$k = U_{s50Hz} / U_b \tag{3.2}$$

$$k_{pr} = U_d \Big/ \left(\sqrt{2} \cdot U_b \right) \tag{3.3}$$

Where U_{s50Hz} is sparkover voltage of a surge arresters' rod gap at 50 Hz.

k_{pr} has a basic meaning for lightning protective surge arresters that can be attained by two ways. First way is obtainment more flat current-voltage curve, second way – increasing of the cancel current using a rod gap with better arc-suppression characteristics.

Valve-type surge arresters can pass definite limiting current without changing its electrical characteristics, this phenomenon is called discharge capacity. Heat stability of a nonlinear resistor influences on the discharge capacity. From the very beginning because of undercapacity valve-type surge arresters were based on internal overvoltages, in other words they had sparkover voltage higher than possible value of the internal overvoltages and were intended for limitation lightning overvoltages. Development of nonlinear resistors with higher discharge capacity and application of new principles of the follow current arc-suppression allowed to use surge arresters for limitation of internal overvoltages.

3.3.1 Nonlinear resistors of valve-type surge arresters

Nonlinear resistors of valve-type surge arresters are made from carborundum powder and bonding material in the form of disk. Basic material of the disks is vilite or thervite.

Carborundum grains are covered with thin coat of a silicone oxide, it is called barrier layer. Its resistance nonlinear depends on electric-field strength. At the low electric-field strength resistance is high, with increasing – resistance rapidly reduces. In this case resistance of the nonlinear resistor is defined by carborundum.

Material property - rapidly change its resistance depending on voltage is called valved property. Herefrom, name of this device is valve-type surge arrester.

Discharge capacity of the nonlinear part of the surge arrester is characterized by the limit energy that can be output without damage of the disk, it also depends on maximal current and on its duration.

The limit maximal value of the pulse current for vilite and thervite disks is 5-14 kA. As is known, lightning currents can be higher. Limiting currents passing through the surge arrester until the allowed value is vested on the scheme of the protective substation approach.

3.3.2 Rod gaps of valve-type surge arresters

The work of the valve-type surge arrester begins from the RG flashover and ends with blow-out of the follow current arc. There are different requirements to the RG on every stage of work.

Flat voltage-time curve is necessary for successful work on the first stage. It is possible to get it only with series-connected rod gaps.

The simplest rod gap consists of two brass electrodes divided with a mica disk (fig.3.3)

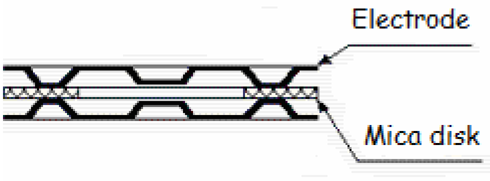


Fig.3.3 Rod gaps.

The blow-out of the current arc is based on natural recovery of electric strength between cold electrodes. The limit amplitude of the cancel current is 80-100 A.

Protective coefficient for surge arresters with simplest rod gaps is 2.6; for surge arresters with magnetic blow-out – 2.2. Reducing of the protective coefficient to 1.7 was reached by application so called current-limiting rod gaps.

Equal distribution of a recovery voltage between series-connected rod gaps plays an important role during the blow-out of the follow current arc. It can be reached by shunting of the rod gaps with high resistance resistors.

A typical form of the voltage-time curve of the surge arrester with repeated rod gaps is shown on the fig.3.4.

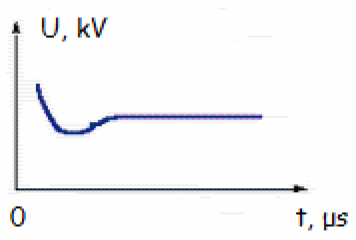


Fig.3.4 Voltage-time curves' typical form of the surge arrester with repeated rod gaps.

3.4 Valve-type magnetic combined surge arresters with increased blanking voltage during switching overvoltages

Operation principle and construction of such type of surge arresters and of the nonlinear surge arrester with shunting of a part of voltage-depended resistors are similar. In these valve-type arresters rod gaps with magnetic blow-out was used.

Nonlinear resistors are made from thervite disks. During designing of such surge arresters some difficulties emerged because thervite has nonlinearity factor worse than vilite. Thervite resistor provides a protection from internal overvoltages when current till 1.5 kA passes through a surge arrester, but during lightning overvoltages currents can reach 10 kA and because of high nonlinearity factor it isn't possible to provide insulation protection. This thing led to combined scheme of a surge arrester which is shown on the fig.3.5. (Razevig)

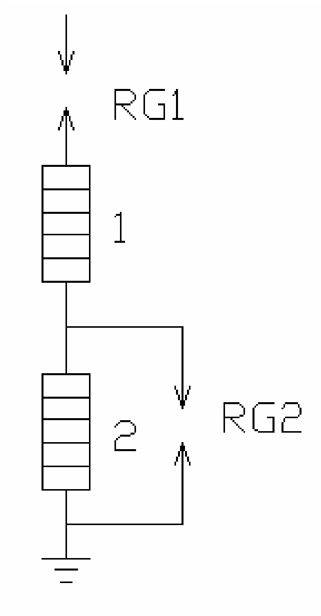


Fig.3.5 Circuit schematic of the valve-type magnetic combined surge arresters with increased blanking voltage during switching overvoltages.

In such surge arresters about 40% of thervite disks are shunted with additional rod gap, which don't flashover during internal overvoltages, in this case discharge voltage is according to characteristic 1 on the fig.3.6. After passing through the surge arrester current higher than normative current of internal overvoltages voltage across the shunting rod gap (the curve №3 on the fig.3.6) becomes more than its sparkover voltage and some disks are shunted. In this case voltage follows characteristics №2 and keeps within tolerable limits.

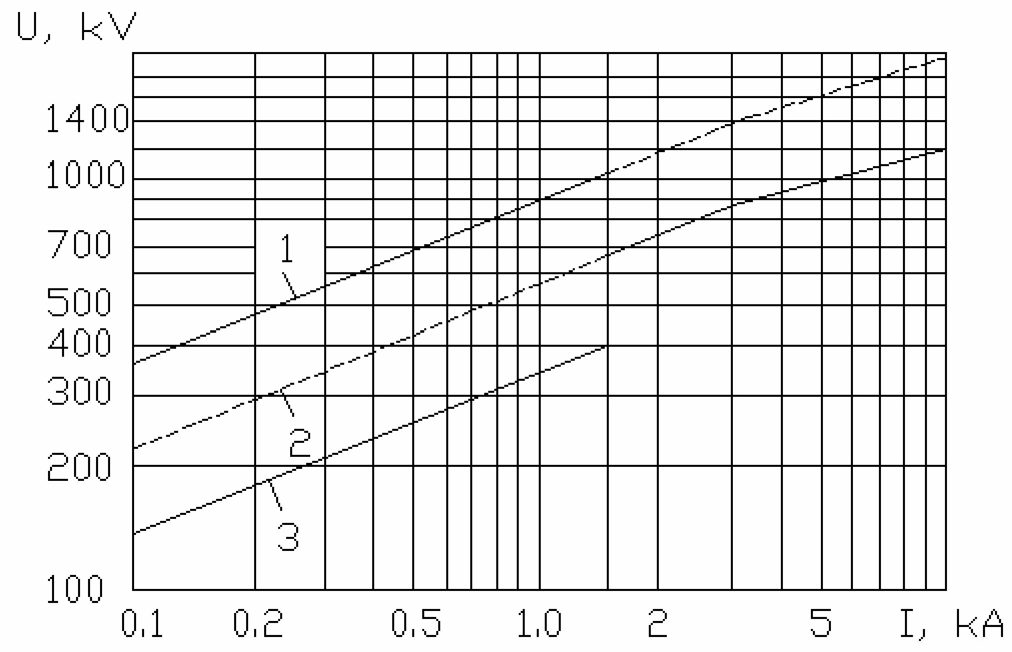


Fig.3.6 Volt-ampere characteristic of the 500 kV surge arrester. 1-surge arrester characteristic at internal overvoltages; 2- surge arrester characteristic at lightning overvoltages; 3-voltage across RG2.

The hookup of elements and sketch of the 500 kV valve-type magnetic combined surge arrester with increased blanking voltage during switching overvoltages is shown on the fig.3.7

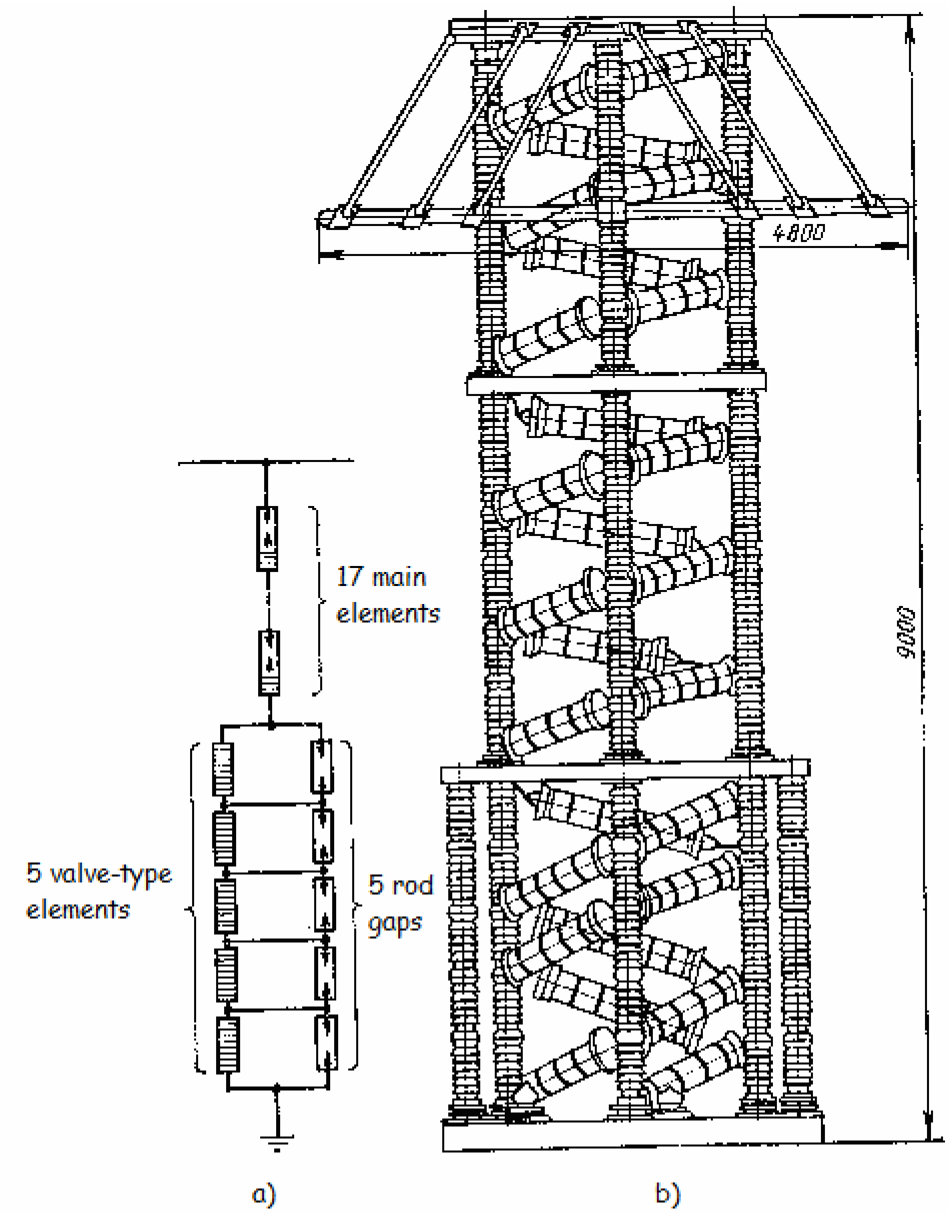


Fig.3.7 a-the h ookup of elements; b-the sketch of valve-type magnetic combined surge arresters with increased blanking voltage during switching overvoltages (Razevig)

3.5 Nonlinear surge arresters

For many years valve-type surge arresters were main protective devices from overvoltages. At present time nonlinear surge arresters (NSA) changed valve-type surge arresters. Nonlinear surge arresters consist of a column of high nonlinear resistors (voltage-depended resistors), bounded with hermetic housing providing defined mechanical strength and isolating characteristics.

3.5.1 NSA's benefits over valve-type surge arresters

Nonlinear surge arresters have some benefits over valve-type surge arresters:

1) Applied voltage-depended resistors have stable voltage-current characteristics. Its voltage-current characteristic does not change during operation. Hence, NSA are stable to ageing, service and parameters checkout are not necessary during all working time.
2) Simple design and reliability in exploitation. Considerably high nonlinearity of oxide-zinc voltage-depended resistors allowed to abandon from using rod gaps in NSA's constructions, therefore there is no contact wear while NSA operates.
3) High protective operations efficiency. Nonlinear elements of a NSA constantly are connected with a network during all working time. High nonlinearity of oxide-zinc voltage-depended resistors determines very small value of the current, which flows through the NSA at voltage capability, less than 1 mA. It allows for NSA all the time to stay under working voltage, because of it actuation time of the protective device during overvoltages decreased.
4) Absence of the follow current after attenuation of an overvoltage wave.
5) Recovering of the voltage-depended resistors properties after flowing through it current impulse at power frequency voltage.
6) Ability of high-energy dissipation.
7) Availability for exploitation in conditions of pollution.
8) Small size, weight and price.

3.5.2 Main characteristics of NSA

There are several characteristics of NSA from which its reliable work under working voltage and at the influence of quasi-stationary voltage:

1) maximal (admissible continuous) working voltage of the NSA, kV – phase voltage (when the voltage exceeds working voltage, current through a NSA begin to increase and it can lead to overheat and damage of the device).

2) nominal (working) voltage of the NSA, kV – system voltage, which NSA at certain conditions can survive during 10 seconds after influence of the current impulse with normalized parameters.
3) voltage-time characteristic of the NSA – it is defined as dependence of NSA's withstanding root-mean-square value of power frequency voltage on exposure time.

NSA characteristics from which equipment proofness is depended during lightning and switching overvoltages:

1) NSA's discharge voltage, kV – maximal voltage over NSA while impulse current with specified maximal value and form flows through it.

Discharge voltage is defined at impulse currents with standard forms:

1) lightning current impulse 8/20 μs – current impulse used for definition discharge voltage over NSA in the lightning overvoltage suppression mode;
2) switching current impulse 30/60 μs - current impulse used for definition discharge voltage over NSA in the switching overvoltage suppression mode;
3) sharp current impulse 1/10 μs - current impulse used for definition discharge voltage over NSA at high speed of current impulse increasing.

Below there are characteristics of the NSA from which its reliable work during switching and lightning overvoltages depends:

1) nominal breakdown current of the NSA, kA – maximum value of the lightning current impulse 8/20 μs used for nonlinear surge arresters classification and characterizing its properties during lightning overvoltages suppression;
2) high current impulse, kA – maximum value of the lightning current impulse 4/10 μs used for estimation of the NSA withstandability to direct lightning stroke;

3) current capacity (current impulse with big width), A – maximum value of the rectangular current impulse with width not less 2000 µs used for NSA classification and characterizing its ability to dissipate power of switching overvoltages;
4) dissipated (absorbed) power, kJ – NSA dissipated power gotten during imposition of one current capacity impulse during NSA test;
5) specific dissipated (absorbed) power (energy intensity), kJ/kV – dissipated by nonlinear surge arrester power of one current capacity impulse fallen into maximum NSA working voltage; it was gotten during NSA test; it is used for NSA classification and characterizing its ability to dissipate power of switching overvoltages. (Dmitriev)

4 Insulation co-ordination. Transformers with decreased insulation strength

Insulation co-ordination means to bring optimal correlation from the economical point of view between insulation strength and voltages effecting on it. Insulation strength is determined during designing and it is directly connected with test voltage. In turn, voltage which has an effect on insulation is determined by quality of the assumed measures about suppression overvoltages. This quality is determined by choice of the installation place and the type of the protective device, choice of the protective device characteristics with allowance for insulation strength of ingoing lines. Protective device has to limit overvoltages which don't cause insulation flashover of the ingoing lines, reducing it till allowable for equipment level.

At the present time in the whole world there is the tendency to reducing of the transformers insulation level. (Lohanin) For example, with increasing of maximal operating voltage from 252 till 1200 kV relation between withstanding voltage of the lightning impulse and maximal operating voltage to earth was reduced from 3,7 till 2,6.

This tendency is connected with reduction of weight and sizes of superhigh voltage transformers at reduction of the insulation strength. For 330-750 kV transformers for every 10% reduction of the insulation strength the full weight at the average reduces on 4-7%, mass of a steel and no-load losses – on 3.5-5%, power – on 6-8%.

Undoubtedly, reduction of the insulation gaps sizes at reduction of the insulation strength results in increasing of operating electric field intensity. Therefore reduction of test voltages is based not only on the improvement of the suppression overvoltages ways, but also it demands of improvement of the insulation construction, production methods, factory tests and measures to maintain necessary quality of the insulation during exploitation.

Field experience of the 330 kV transformers has shown that the insulation didn't damage during lightning and internal overvoltages. There were no any insulation faults which directly or indirectly could show that the test voltages level is insufficient.

The limit of the effective insulation strength reduction is determined by the strength during short-term exposures which was chosen with a glance of the long-term working voltage influence. The limiting allowable electric field intensity in the main insulation of transformers should be considered equal 50 kV/mm on basis of done tests.

During 20 years the group of 500 kV, 135 MVA transformers (15 units) with operating electric field intensity 46 kV/mm was exploited successfully. It confirms conclusions which were maid above. In the Table 4.1 characteristics of such transformers are shown.

During the last years 18 autotransformers (500/220 kV, 167 MVA) were designed and are exploited now, also 9 step-up transformers (500 kV, 210 MVA) with the test lightning overvoltage level 1050 kV and test switching overvoltage level – 900 kV, instead of standard 1550/1230.

Results of exploitation of such transformers didn't show any reducing of their reliability.

Though such tendency influences considerably on the requirements for lightning protection of a substation because power transformers are the least protected equipment through their big capacity. While lightning wave is coming big capacity charges to a bigger voltage. It is possible that invention of new insulating constructions will require soon of new types of protection devices.

Table 4.1 Transformer's characteristics.

Test voltage	Characteristics					
	Test voltage		Impedance voltage, %	Losses, kW		Weight, t
	impulse			no-load	short circuit	
	switching	lightning MVW/HVW				
		total				
Standard	1300	1550	13	160	450	200
Reduced	850	900	13	110	387	145
500/220 kV, 167 MVA transformers						
Standard	1230	1550/750	11	105	325	167
Reduced	900	1050/650	11	65	370	141

At the end of 70^{th} of the last century transformers with reduced insulation strength (500 kV, 135 MVA) were placed first on the Volzshskaya HPP (Russia), then on the Volgogradskaya HPP (Russia). Allowable lightning overvoltage level for it is 900 kV. Protection of such equipment was done with help of specially designed protective devices. Now these protective devices require replacement and modernization.

5 Nonlinear surge arrester for protection of the equipment with reduced insulation strength

In this nonlinear surge arrester reduction of lightning and switching overvoltages is reached with help of special commutating device which allows to reduce the suppression level till 10% in comparison with level of the usual protective device. The commutating device shunts the part of NSA after voltage over NSA exceeds allowable level.

Schematic circuit of the NSA is representated on the Fig.5.1. Nonlinear surge arrester is consist of the column serial connected high-nonlinear resistances – varistors (1). Switching elements (2) are connected in-parallel with the part of varistors. Amount of such elements is determined by necessary value of the additional reduction level of suppression overvoltages.

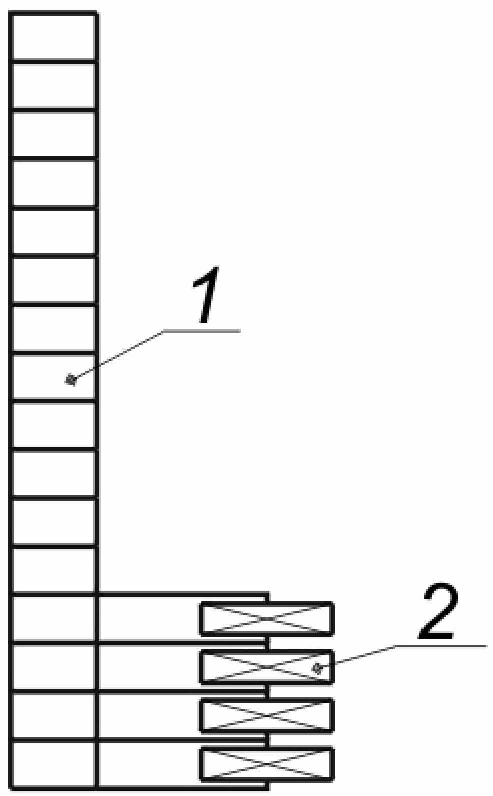


Fig.5.1 Schematic circuit of the modernized NSA. 1 – varistors: 2 – switching element.

On the Fig.5.2 we can see the appearance of such NSA.

Fig.5.2 Modernized NSA.

Under the working voltage and at quasi-stationary overvoltages the modernized NSA is operates like usual nonlinear surge arrester. At lightning and switching overvoltages when it reaches an established value switching device operates and shunts the part of varistors thereby suppression level reduces on the voltage drop value on the switching device.

Rod gaps are used as elements forming switching device. At designing as a basis was taken the construction of rod gaps with magnetic blowout (which was used in the some valve-type surge arresters). At the same time modern polymer materials were applied and construction of electrodes was changed. Designed rod gaps provide stability at functioning and blowout of the follow current arc. Stability of the firing characteristics of serial connected rod gaps is reached by shunting some of them with additional capacities (ceramic capacitors). Experimental oscillogram illustrating the moment of discharge firing in rod gaps blowout of the follow current arc is shown in the Fig.5.3.

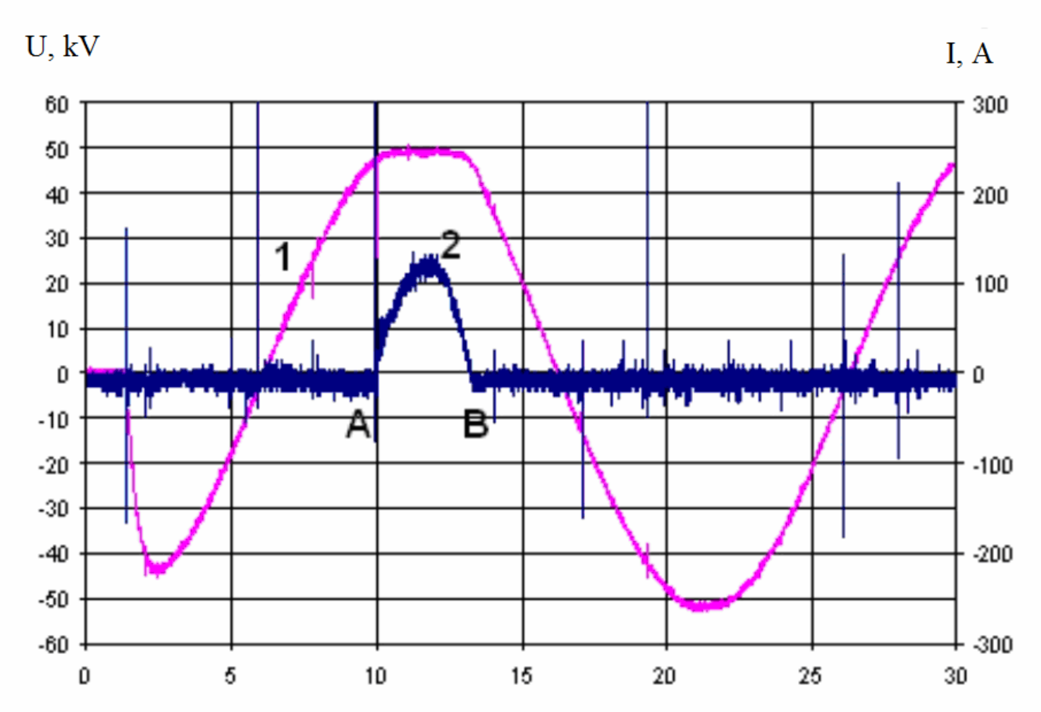


Fig.5.3 Oscillograms of the voltage – 1 and current – 2 during rod gaps operating. (SZP)

For group of rod gaps which are standing under working voltage (curve 1) at the time moment (A on the Fig.5.3) lightning impulse is delivered. After discharge firing through rod gaps the follow current flows. At the point B (Fig.5.3) blowout of the arc occurs, follow current through rod gaps is stopped. Voltage dispersion of the rod gaps operating doesn't exceeds 5% (it depends on the impulse type – lightning or switching impulse).

The process of the discharge firing in the rod gap is represented on the Fig.5.4. Curves of the current in the rod gap and the voltage on the elementary cell of the shunted varistor part are built there.

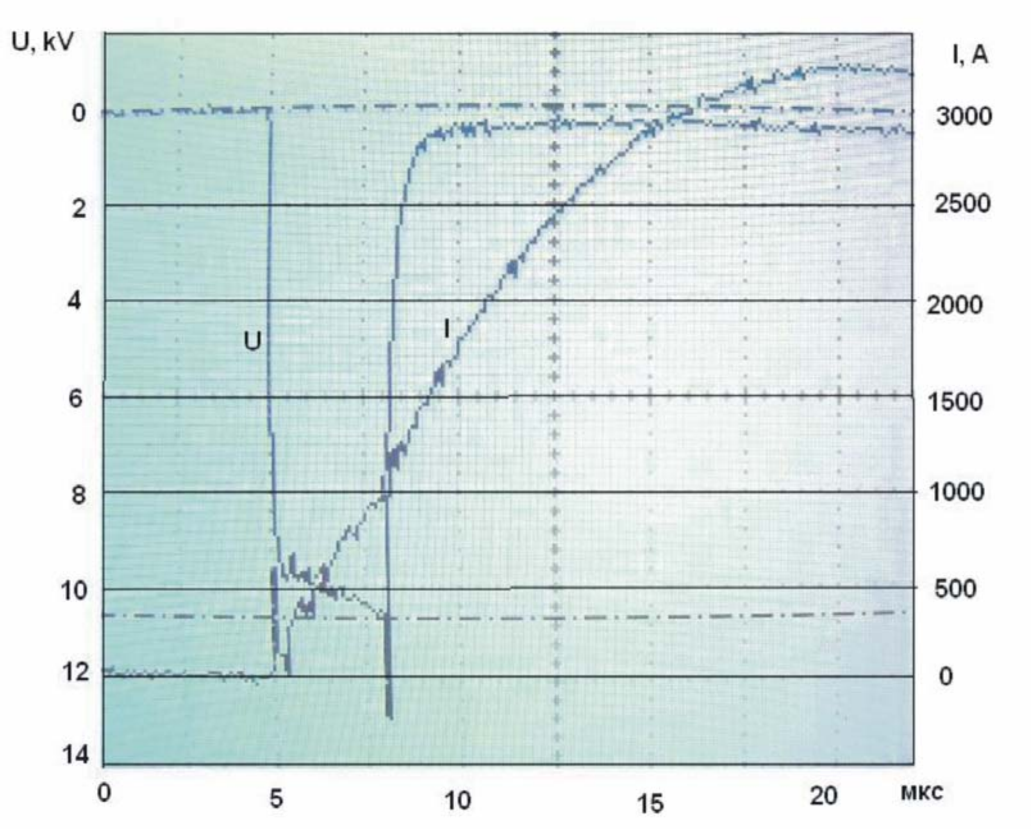


Fig.5.4 Discharge firing in the rod gap. (SZP)

From the Fig.5.4 it can be seen that rod gap functioning happens at the current through the resistor approximately 800 A. At the same time voltage over varistor falls down from 10 kV till parts of kV, current through the rod gap is over than 3000 A.

One section of this NSA with placed switching elements is shown on the Fig.5.5.

Fig.5.5 One section of the modernized NSA with resistor shunted with rod gaps. (SZP)

6 Program for calculating of overvoltages level

6.1 Calculating methods used in the program

6.1.1 Calculating method of the overvoltages in the nodes of a substation

Waves of overvoltages are represented as the group of square waves coming in the nodes in a special sequence with time interval Δt. Therefore it is possible to determine independently the voltage in the every node during every time interval. The problem reduces to calculating of voltages in the any node where several (n) single-lines with impedances z_{w1}, z_{w2}, …, z_{wn} are concentrating. Waves u_{1j}, u_{2j}, …, u_{nj} come in the node (Fig.6.1). The node j is connected with earth through resistance or impedance z_j with defined linear or non-linear characteristics (capacity, constant resistance, resistance related to the voltage). (Kostenko)

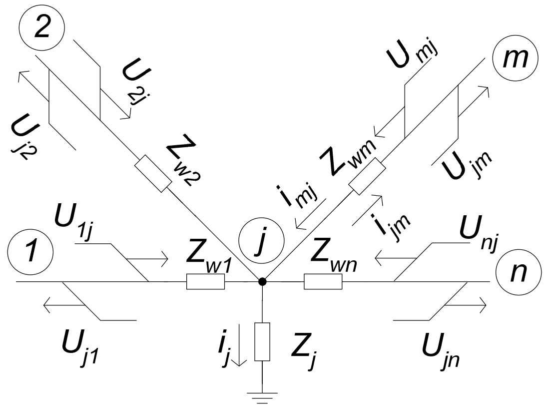


Fig.6.1 The rule of the equivalent wave – waves are coming in the node j in the several lines

If there is no intercoupling between lines and direction to the node is accepted as positive direction for the node j the following equations can be written.

$$u_{\mathrm{j}} = u_{\mathrm{1j}} + u_{\mathrm{j1}} = \ldots = u_{\mathrm{mj}} + u_{\mathrm{1m}} \tag{6.1}$$

$$\sum_{\mathrm{m=1}}^{\mathrm{n}} (i_{\mathrm{mj}} + i_{\mathrm{jm}}) = i_{\mathrm{j}} \tag{6.2}$$

$$u_{\mathrm{mj}} = z_{\mathrm{wm}} i_{\mathrm{mj}} \tag{6.3}$$

$$u_{jm} = -z_{wm} i_{jm} \tag{6.4}$$

Where u_j is voltage in the node *j*, u1m is direct wave of the overvoltage of the line *m*, u_{m1} is return wave of the overvoltage of the line *m*, *m=1,2,…,n* is number of line, i_{1m} is direct wave of the current of the line *m*, i_{m1} is return wave of the current of the line *m*, i_j is current in the node *j*, z_{wm} is impedance in the line *m*.

Equation for current we can see below.

$$i_j = \sum_{m=1}^{n} \frac{u_{mj}}{z_{wm}} - \sum_{m=1}^{n} \frac{u_{jm}}{z_{wv}} = 2\sum_{m=1}^{n} \frac{u_{mj}}{z_{wv}} - u_j \sum_{m=1}^{n} \frac{1}{z_{wv}} \tag{6.5}$$

The equation (6.5) can be transformed into (6.6).

$$2u_{ej} = u_j + i_j z_{ej} \tag{6.6}$$

Where u_{ej} is equivalent voltage in the node *j*, z_{ej} is self-surge impedance of the node *j*. Impedance z_{ej} is equivalent to all lines in parallel which are coming to the node *j* (Fig.6.2).

$$z_{ej} = \frac{1}{\sum_{m=1}^{n} \frac{1}{z_{wm}}} \tag{6.7}$$

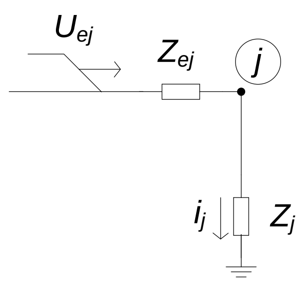


Fig.6.2 Coming of the equivalent wave u_{ej} in the node *j* on the equivalent line

Then for equivalent wave equation (6.8) can be written.

$$u_{\mathrm{ej}} = \sum_{\mathrm{m=1}}^{\mathrm{n}} \frac{z_{\mathrm{ej}}}{z_{\mathrm{wm}}} u_{\mathrm{mj}} \tag{6.8}$$

Relation (6.8) allows to establish the equivalent wave rule (the rule of simultaneous coming of waves in the node on several distributed-parameter lines) with help of inclusion of some electromotance in the lumped-parameter circuit (Fig.6.3).

$$E_{\mathrm{j}} = \sum_{\mathrm{m=1}}^{\mathrm{n}} \frac{2z_{\mathrm{ej}}}{z_{\mathrm{wm}}} u_{\mathrm{mj}} = \sum_{\mathrm{m=1}}^{\mathrm{n}} \alpha_{\mathrm{mj}} u_{\mathrm{mj}} = 2u_{\text{эj}} \tag{6.9}$$

Where E_{j} is electromotance, α_{mj} is refraction coefficient in the node j for the wave coming on the line with self-surge impedance z_{ej}.

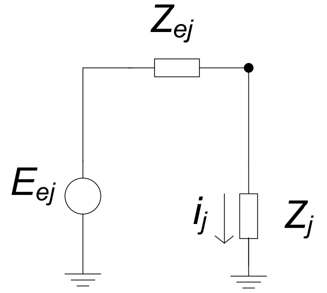


Fig.6.3 Equivalent lumped-parameter circuit

Because of the equivalent wave rule it is possible difficult problem of the voltage calculating in a node, where several distributed-parameter lines are concentrating, lead to simpler problem of process calculating in the lumped-parameter circuit.

At voltage calculating in nodes while there is no any resistance to earth on the basis of above described rule we can get (6.10).

$$u_{\mathrm{j}}(t+\Delta t) = \sum_{\mathrm{m=1}}^{\mathrm{n}} \alpha_{\mathrm{mj}} u_{\mathrm{mj}}(t+\Delta t) \tag{6.10}$$

Where $u_j(t+\Delta t)$ is voltage in the node j at the time $(t+\Delta t)$, $u_{jm}(t+\Delta t)$ is wave coming to the node j on the line m.

Amplitude of outgoing waves can be defined from the equation below.

$$u_{jm}(t+\Delta t) = u_m(t+\Delta t) - u_{mj}(t+\Delta t) \qquad (6.11)$$

The definition of the voltage in nodes is doing with the constant time step that makes calculating of nodes with capacity, because it is doing by analytical solution of the differential equation.

$$u_j(t+\Delta t) = (1 - e^{a_j \Delta t}) \sum_{m=1}^{n} \alpha_{mj} u_{mj}(t+\Delta t) + u_j(t) e^{a_j \Delta t} \qquad (6.12)$$

Where $u_j(t)$ is voltage in the node at the time t, a is the coefficient which is reversed to RC product of the circuit.

$$a = \frac{1}{C_j z_{ej}} \qquad (6.13)$$

6.1.2 Simulation of the direct lightning stroke in a phase conductor.

Let view lightning stroke in a separate phase conductor which is overhung to the pole.

To simulate moving of the voltage wave along the conductor it is necessary to use the conception of direct and return voltage waves, which are moving to the substation and out. Voltage over conductor is equal the sum of direct and return waves.

Direct voltage wave represents external action, it describes lightning current transmission. Its amplitude is equal to the half of the lightning current amplitude multiplied by line self-surge impedance. Coefficient ½ shows that self-surge impedances of conductors going to the substation and out are equal, so lightning current bisects. Let assumed that wave running back from the substation doesn't reflect from power transmission pole, that is outgoing line is half-infinite. Earthed resistor has to be put in the 1 node for its simulation. Resistance value is equal to line self-surge impedance.

Voltage over the power transmission pole allows us to estimate probability of the overhead line insulation flashover. Voltage-time curves are needed for flashover moment determination.

6.1.3 Voltage-time curve of the overhead line insulation

The method of the Stock Company High Voltage Direct Current Power Transmission Research Institute was used in the program for simulating the process of the overhead line insulation flashover. On the Fig.6.4 voltage-time curve of the insulation and different ways of flashover are shown.

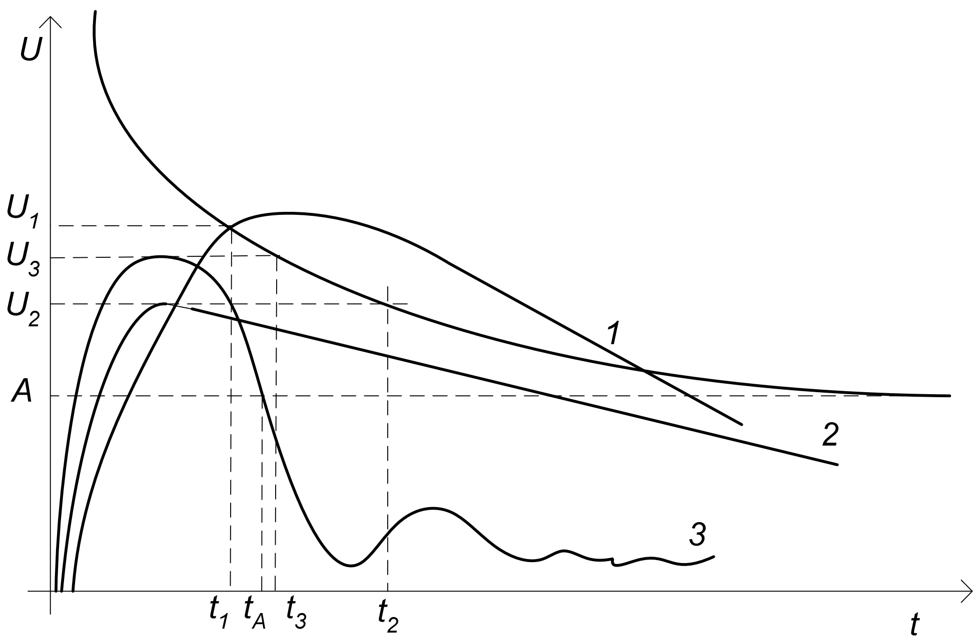


Fig.6.4 Voltage-time curve of the overhead line insulation. Different ways of line insulation flashover

Voltage-time curve of overhead line can be described with Mashkilleison-Gorev formula.

$$U(t) = A\sqrt{1+\frac{B}{t}} \tag{6.14}$$

Where $U(t)$ is voltage is function of wavefront time A and B are coefficients describing line insulation behavior, t is wavefront time.

There are shown on the Fig.6.4 three impulses for illustration of flashover ways. Impulse 1 has the maximal amplitude but lower-angle front. Intersection of the 1 curve with voltage-time curve happens on the impulse front at the voltage U_1 at the time t_1. The 2 curve has steeper leading edge and lower amplitude U_2, flashover takes place on the pulse wing at the time t_2. The 3 impulse is ranked among substandard impulses which can take place in the real circuits. In this case it was accepted if voltage falls lower than A then line insulation flashover doesn't take place. At the 3 curve flashover could be at the time t_3 but to that moment voltage falls lower than A and there is no flashover.

It is necessary to compose two combined equations (its own for every polarity) to get coefficients A and B for voltage-time curve. In the first equation impulse disruption voltage is substituted instead of $U(t)$ and the lowest time to breakdown – instead of t (usually $t=2$ μs). In the second equation – 50% discharge voltage at the time $t=20$ μs.

If there is no full voltage-time characteristics of a insulator string, which was got during special test of that string, it is possible to use the equation written below (method of the Stock Company High Voltage Direct Current Power Transmission Research Institute).

$$U_{\mathrm{i}}(t)=\frac{U_{\mathrm{i}}(t_2)}{\sqrt{1+\dfrac{a^2-1}{1-a^2\cdot\dfrac{t_1}{t_2}}\cdot\dfrac{t_1}{t_2}}}\cdot\sqrt{1+\dfrac{a^2-1}{1-a^2\cdot\dfrac{t_1}{t_2}}\cdot\dfrac{t_1}{t}} \tag{6.15}$$

Where $U_{\mathrm{i}}(t)$ is voltage as a function of wavefront time, t_1 is the lowest time to breakdown wherein $U_{\mathrm{i}}(t_1)$ is measured (usually 2-3 µs), t_2 is the time to breakdown wherein $U_{\mathrm{i}}(t_2)$ is close to 50% discharge voltage (usually 10-20 µs), a is coefficient determined as (6.16). For insulator strings with and without protection fitting at positive polarity it can be taken equal to 1.4, at negative polarity – 1.3-1.4 (at $t_1=2$ µs).

$$a=\frac{U_{\mathrm{i}}(t_1)}{U_{\mathrm{i}}(t_2)} \tag{6.16}$$

The number of insulators in string depends on nominal overhead line voltage. In the case under consideration the number of insulators was taken equal to 32.

Some calculations are represented below for 32 insulators in a string.

$$\begin{cases} U_1(t)=A\sqrt{1+\dfrac{B}{2}} \\ U_2(t)=A\sqrt{1+\dfrac{B}{20}} \end{cases} \tag{6.17}$$

$$A^{+2}=\frac{U_2^2\cdot 20-U_1^2\cdot 2}{20-2}=\frac{U_2^2\cdot 20-U_2^2\cdot 1{,}4^2\cdot 2}{18}=U_2^2\cdot 0{,}89333=U_2^2\cdot k^{+2}$$

$$A^{+}=U_2\cdot k^{+}$$

$$B^{+}=\left(\frac{U_2^2}{A^{+2}}-1\right)\cdot 20=\left(\frac{1}{k^{+2}}-1\right)\cdot 20=2{,}388$$

For negative polarity we get $k^{-}=0.9609;\quad B^{-}=1.66$. The number of insulators doesn't influence to these values.

There are shown on the Fig.6.5 dependences $U_{50}=U_2$ from string length. Values of the $U_{50}=U_2$ at the string length less than 2 m should be taken from the graph built for strings without protection fitting. In the case under consideration the length of the string exceeds 4 m therefore we have to take values from the graph built for strings with protection fitting.

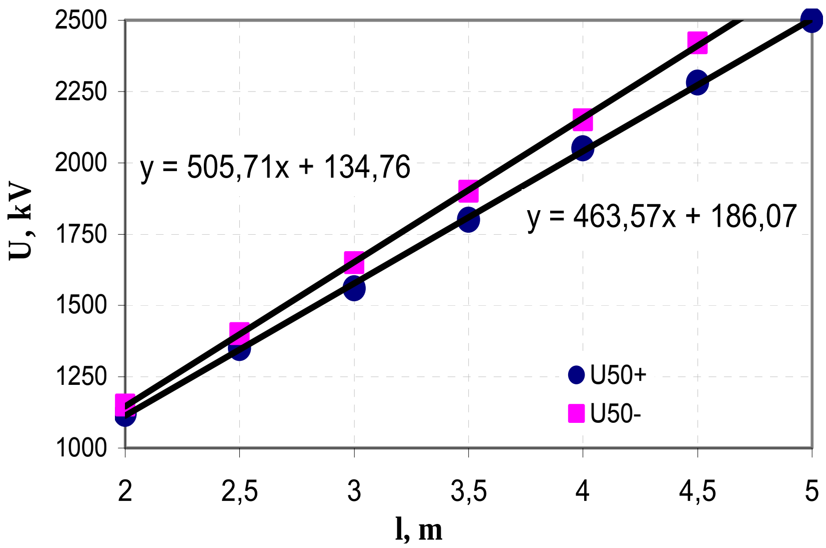


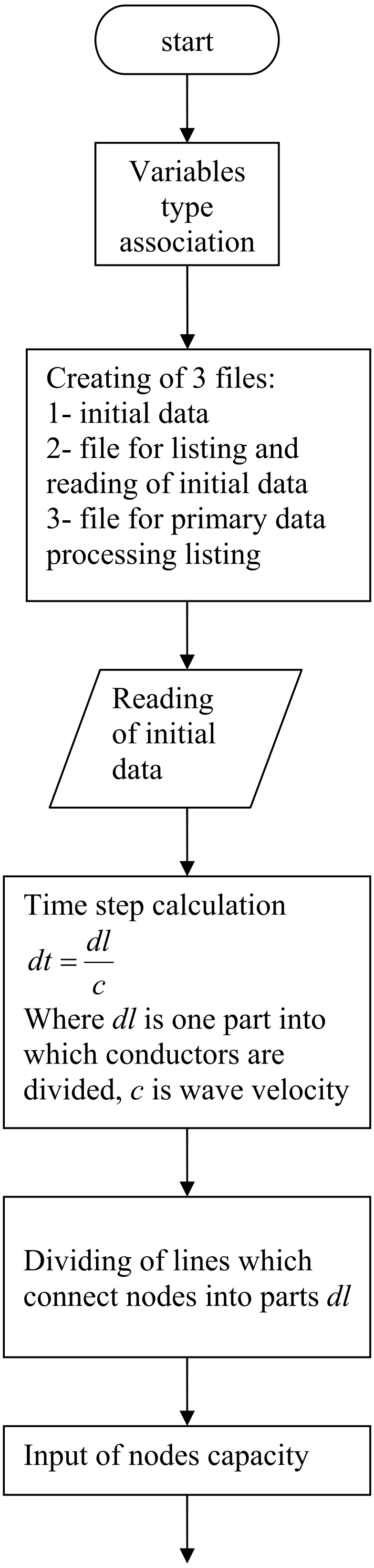
Fig.6.5 Dependence U_{50} from the length of insulator string with protection fitting for positive and negative polarity

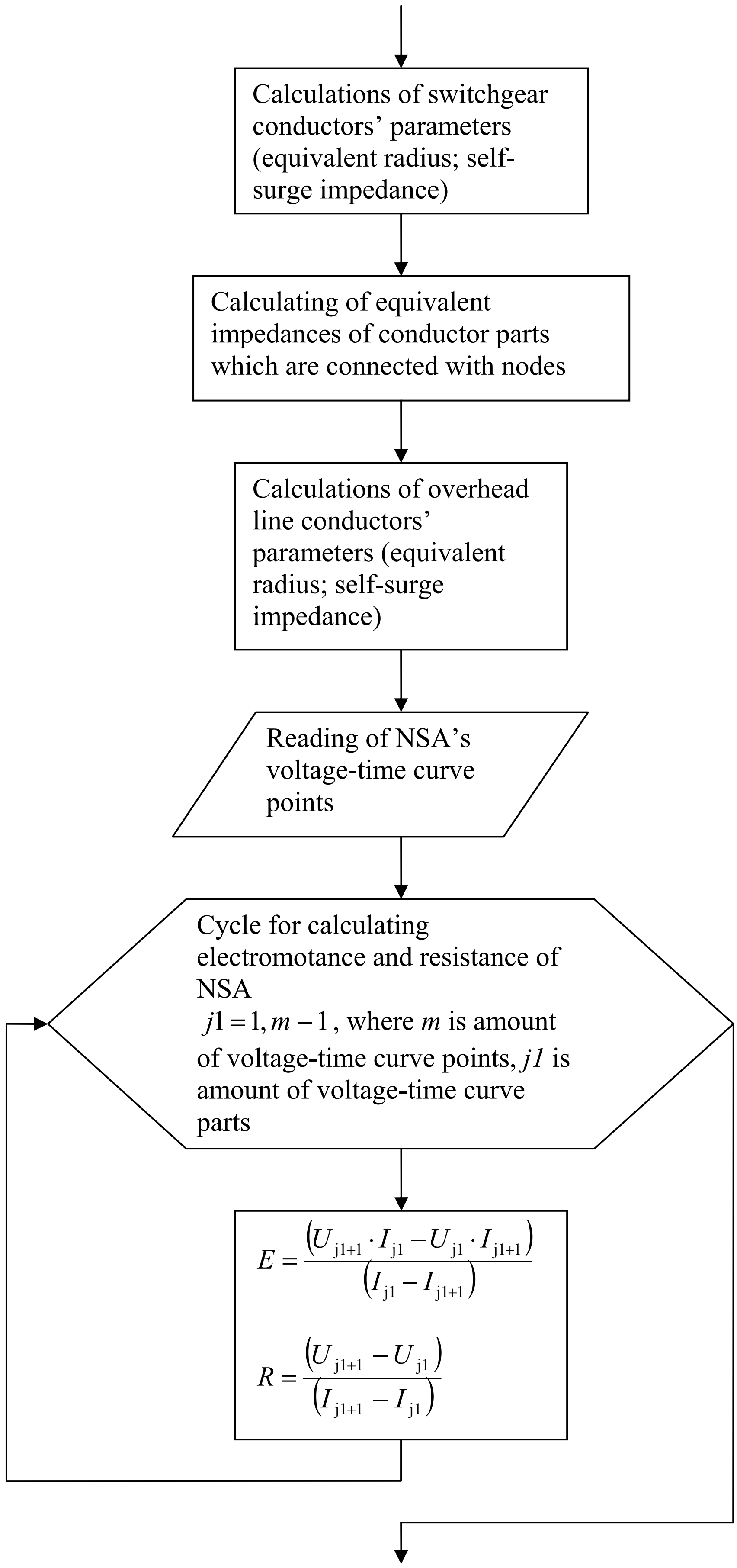
In the Table 6.1 values of the coefficient A for 32 insulators in the string are shown.

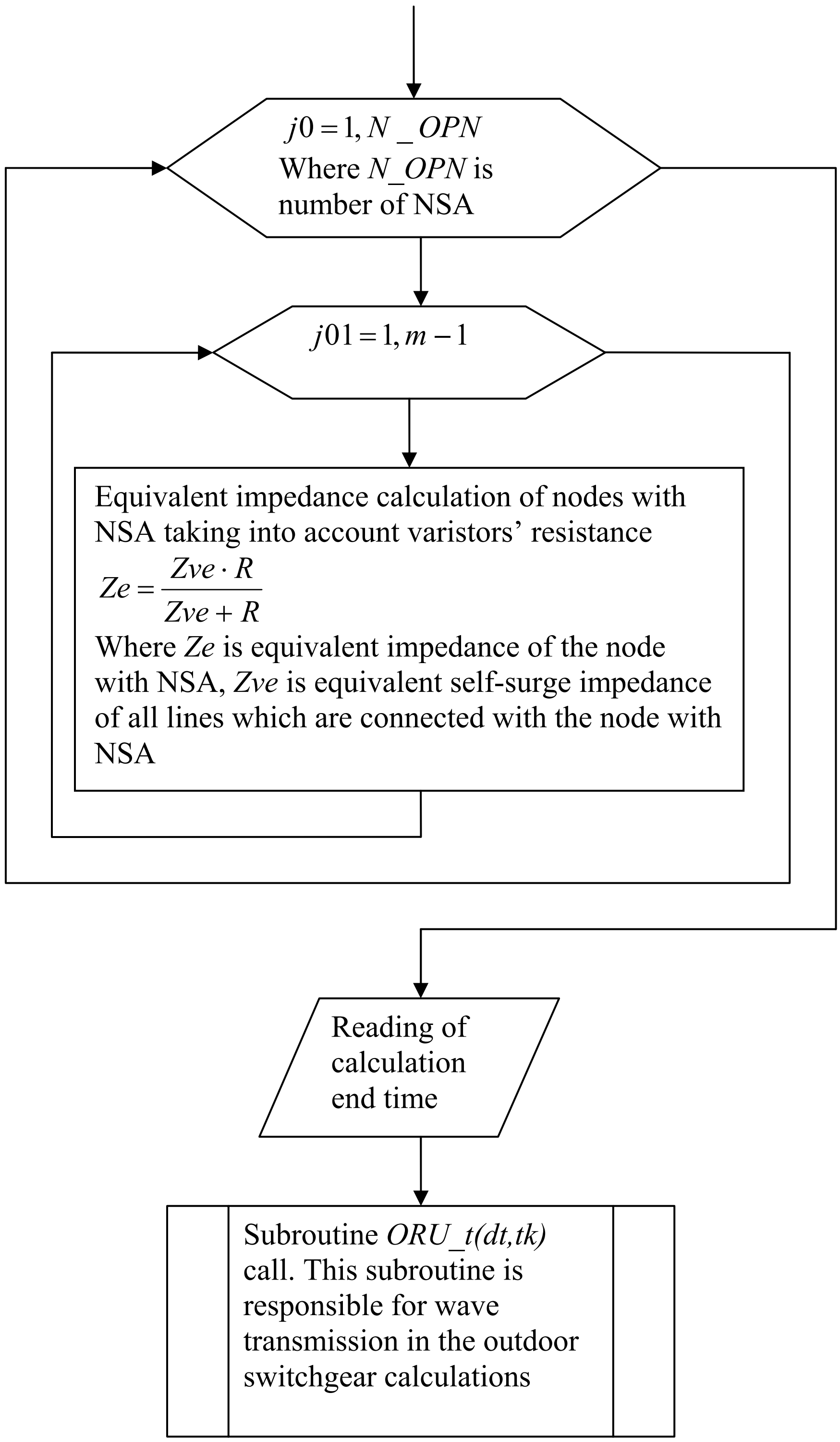
Table 6.1 Values of the coefficient A when the number of insulators is 32 for positive and negative polarity

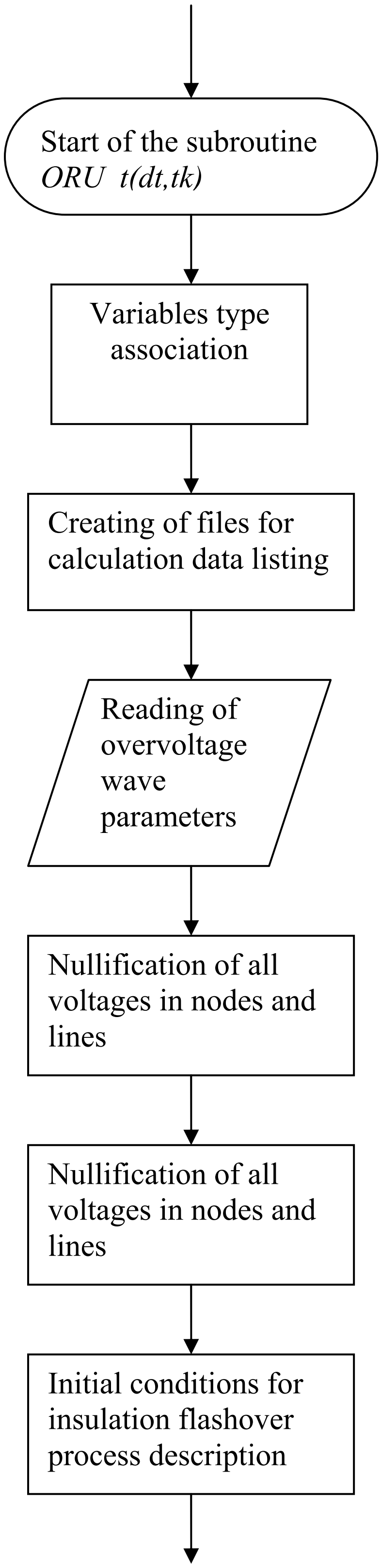
$n_{из}$, шт	$l_г$, m	$U_{50}=U_2$			
		U_2		A	
		"+"	"-"	"+"	"-"
32	4,1	2070,0	2190,0	1956,5	2087,5

6.2 Block diagram of the program

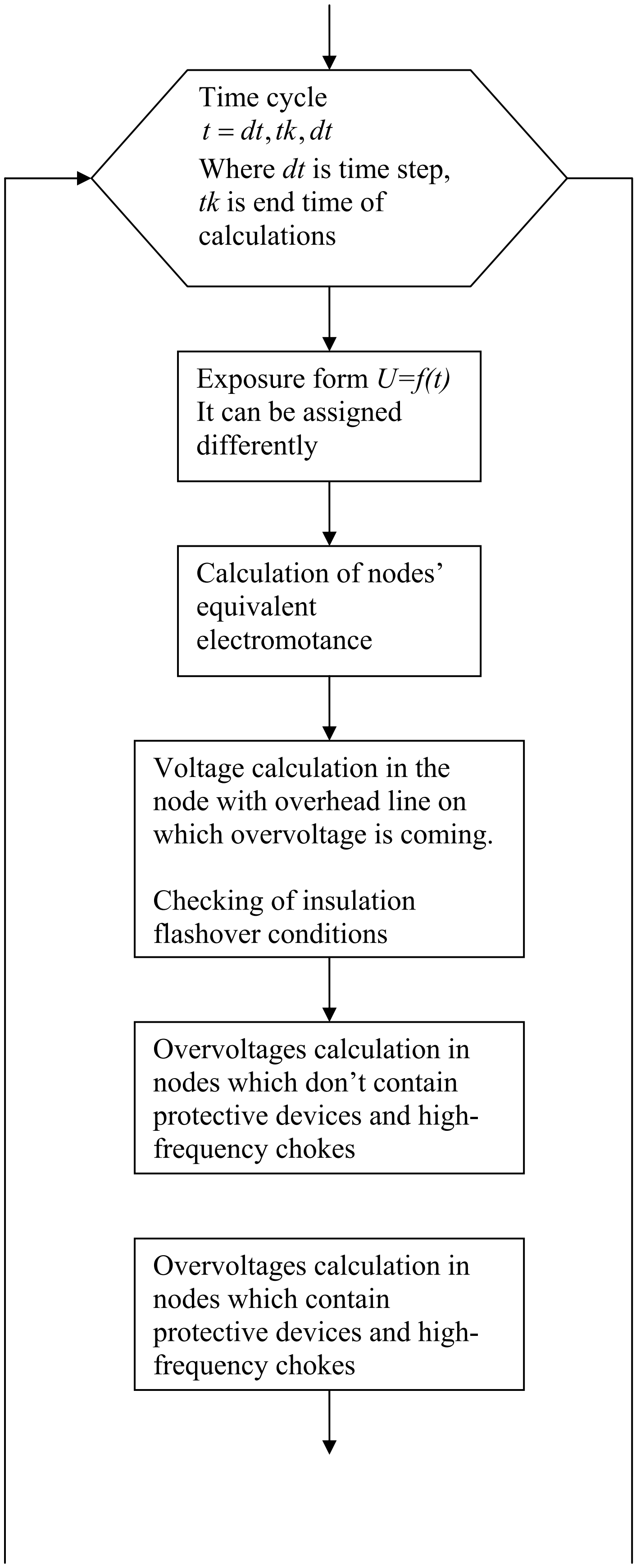


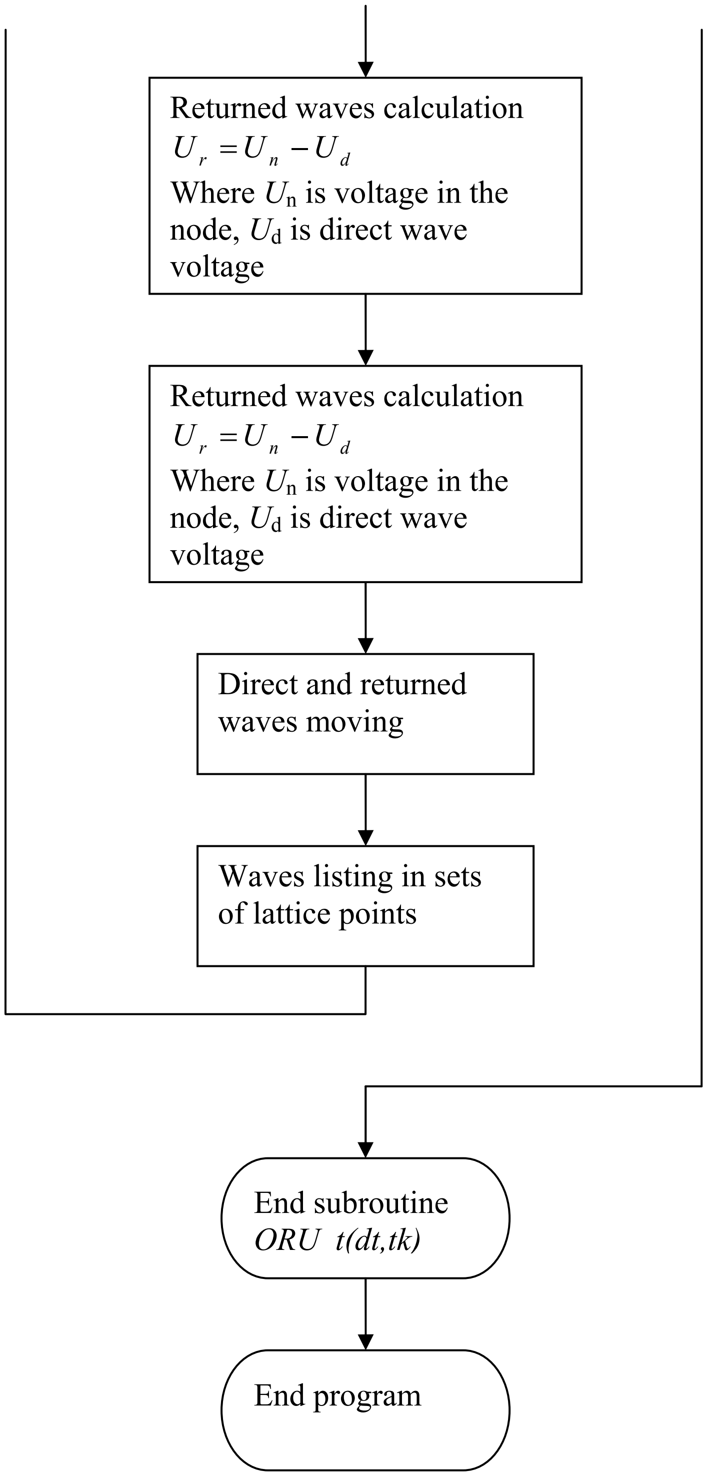

Calculations of switchgear conductors' parameters (equivalent radius; self-surge impedance)
Calculating of equivalent impedances of conductor parts which are connected with nodes
Calculations of overhead line conductors' parameters (equivalent radius; self-surge impedance)
Reading of NSA's voltage-time curve points
Cycle for calculating electromotance and resistance of NSA $j1 = 1, m-1$, where m is amount of voltage-time curve points, $j1$ is amount of voltage-time curve parts
$E = \frac{(U_{j1+1} \cdot I_{j1} - U_{j1} \cdot I_{j1+1})}{(I_{j1} - I_{j1+1})}$
$R = \frac{(U_{j1+1} - U_{j1})}{(I_{j1+1} - I_{j1})}$


$j0 = 1, N\_OPN$
Where *N_OPN* is number of NSA
$j01 = 1, m-1$
Equivalent impedance calculation of nodes with NSA taking into account varistors' resistance
$Ze = \frac{Zve \cdot R}{Zve + R}$
Where *Ze* is equivalent impedance of the node with NSA, *Zve* is equivalent self-surge impedance of all lines which are connected with the node with NSA
Reading of calculation end time
Subroutine *ORU_t(dt,tk)* call. This subroutine is responsible for wave transmission in the outdoor switchgear calculations



Start of the subroutine
ORU t(dt,tk)
Variables type association
Creating of files for calculation data listing
Reading of overvoltage wave parameters
Nullification of all voltages in nodes and lines
Nullification of all voltages in nodes and lines
Initial conditions for insulation flashover process description


Time cycle
$t = dt, tk, dt$
Where dt is time step,
tk is end time of
calculations
Exposure form $U=f(t)$
It can be assigned
differently
Calculation of nodes'
equivalent
electromotance
Voltage calculation in the
node with overhead line on
which overvoltage is coming.
Checking of insulation
flashover conditions
Overvoltages calculation in
nodes which don't contain
protective devices and high-
frequency chokes
Overvoltages calculation in
nodes which contain
protective devices and high-
frequency chokes



Programming language used for writing that program is FORTRAN.

6.3 Simulation of the NSA's operation

Nonlinear surge arrester during calculations usually is simulated with some capacity and nonlinear resistance. During overvoltages calculations presence of the capacity almost didn't influence on the overvoltage level, therefore for simplification of algorithm calculations were done only with NSA's resistance. During lightning proofness calculations NSA's capacity was taken into account.

Before response time current through the surge arrester is equal to 0. After response time voltage over surge arrester is determined by approximation of the voltage-current characteristics with straight lines (Fig.6.6).

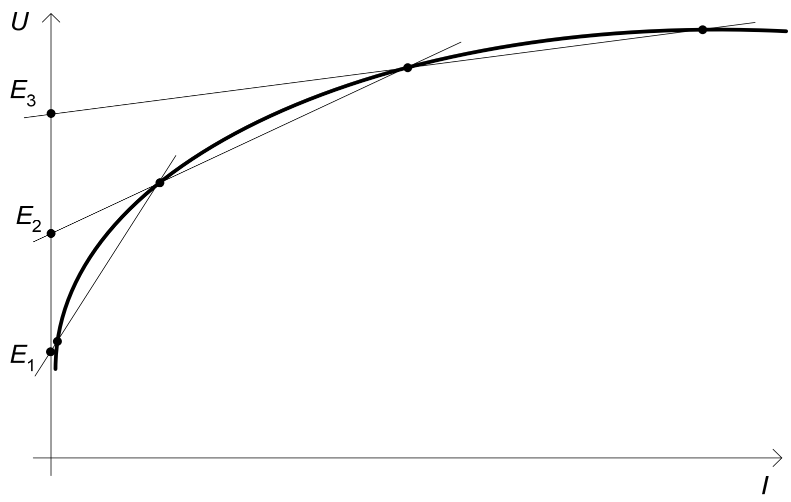


Fig.6.6 Approximation of the NSA's voltage-current characteristics

Scoping voltage calculation is done in the node with NSA at overvoltage wave coming. In case if it belongs to another part of voltage-time curve than in the beginning voltage in the node with protective device is recalculated with taking into account new value of the NSA's resistance.

On the Fig.6.7 voltage-current characteristics of nonlinear surge arresters under consideration are shown. $k=1$ corresponds to NSA with high voltage-current characteristic; hereafter it will be called NSA №1. $k=0.9$ (reducing relative to $k=1$) corresponds to NSA with low voltage-current characteristic; hereafter it will be called NSA №3. $k=0.833$ – such voltage-current characteristic modernized NSA has after exceeding current $I=800\ A$ through it (before $I=800\ A$

- modernized NSA has voltage-current characteristic of the NSA №1, after exceeding that limit 1/6 part of varistors is shunted), hereafter it will be called NSA №2.

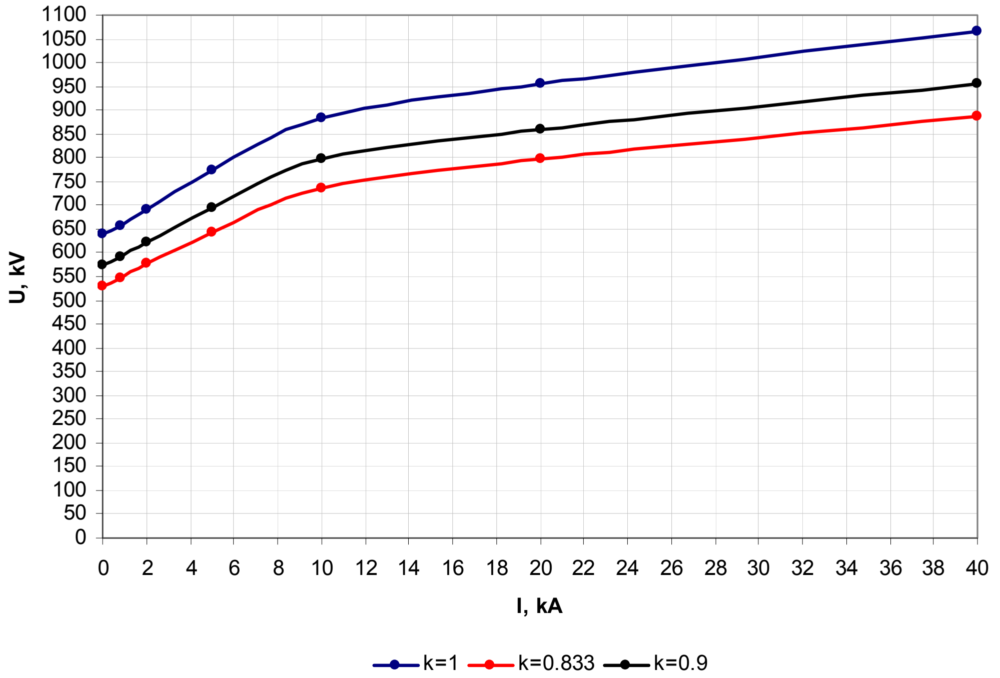


Fig.6.7 Voltage-current characteristics of nonlinear surge arresters

In the Table 6.2 there are numerical values of the NSA voltage-current characteristics

Table 6.2 Voltage-current characteristics

I, kA	U, kV (k=1)	U, kV (k=0,833)	U, kV (k=0,9)
0,001	638	531	574
0,8	658	548	592
2	692	576	623
5	772	643	695
10	885	735	796
20	956	797	860
40	1064	887	957

6.4 Initial data for calculations

The first step in such calculations is building of the equivalent circuit. On the Fig.6.8 scheme widely used on the electric stations with long busbar bridges to outdoor switchgear is shown. This scheme consists of transformer (node 3), protective device (node 4), coming line (node 1). Distances between nodes correspond to the real scheme of the Zshigulevskaya HPP transformer yard.

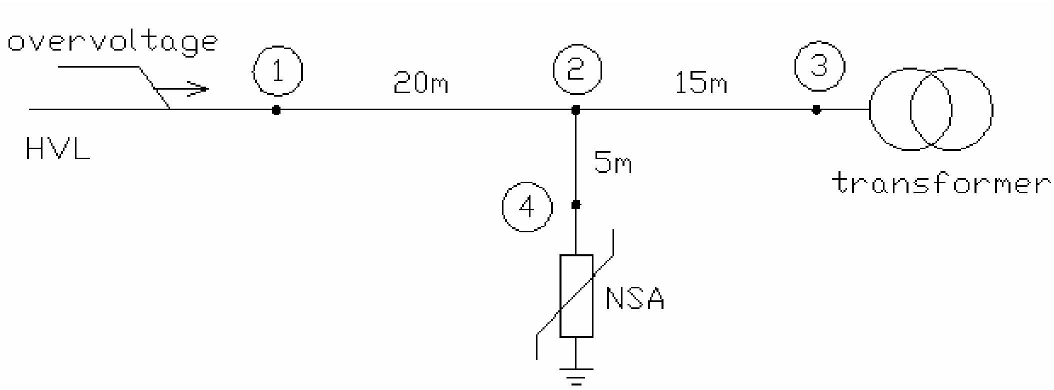


Fig.6.8 Equivalent circuit

That scheme is very simple, it doesn't contain big amount of devices and branches so it isn't necessary to simplify it. Absence of the simplifications leads to calculation error reduction.

In the Table 6.3 initial data are shown how they were input in the program file.

Table 6.3 Initial data

Parameter	Value
Number of nodes	4
Number of busbar parts	3
Number of overhead lines	1
Number of protective devices	1
Distances between nodes	1-2 20 m 2-3 15 m 2-4 5 m
Transformer capacity	4200 pF
Conductor radius	0,012 m

Conductor suspension height	33 m
Number of conductors in the phase	3
Unlumping radius	0,23 m
Number of the voltage-current characteristic points	7
Node number where NSA is placed	4
Coefficients for Mashkilleison - Gorev formula	□=2087.5 □=1.66
Earth resistance of the pole	10 Ohm

Voltage-current characteristics points are represented in the paragraph 6.3.

7 Calculating results and analysis

7.1 Calculating results and analysis for different NSA types

In the Tables 7.1-7.4 (Appendix 1) are represented calculation data (voltage over the NSA, current through the NSA, voltage over transformer) for three different types of nonlinear surge arrester, which characteristics were described in the Table 6.2.

From the Tables 7.1-7.4 (Appendix 1) we can see that at lightning current amplitude 5.89 kA at different lengths of the wave fronts NSA №2 and NSA №3 protect the transformer from overvoltages, that can’t be said about NSA №1. The example of curves: voltage over transformer and current through the NSA at lightning current amplitude 5.89 kA at the length of the wave front 1 µs are shown in the fig. 7.1 and 7.2.

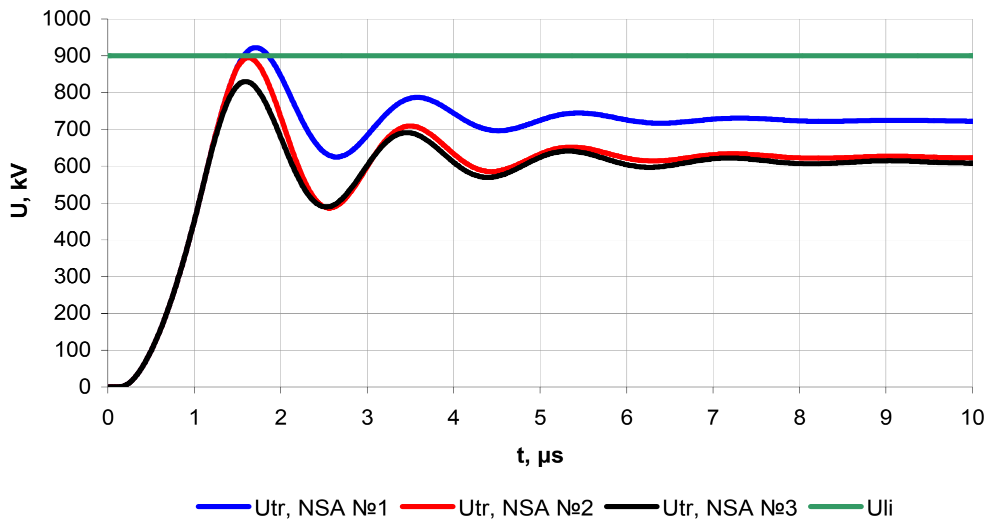


Fig.7.1 Voltage over transformer at lightning current amplitude 5.89 kA at the length of the wave front 1 µs

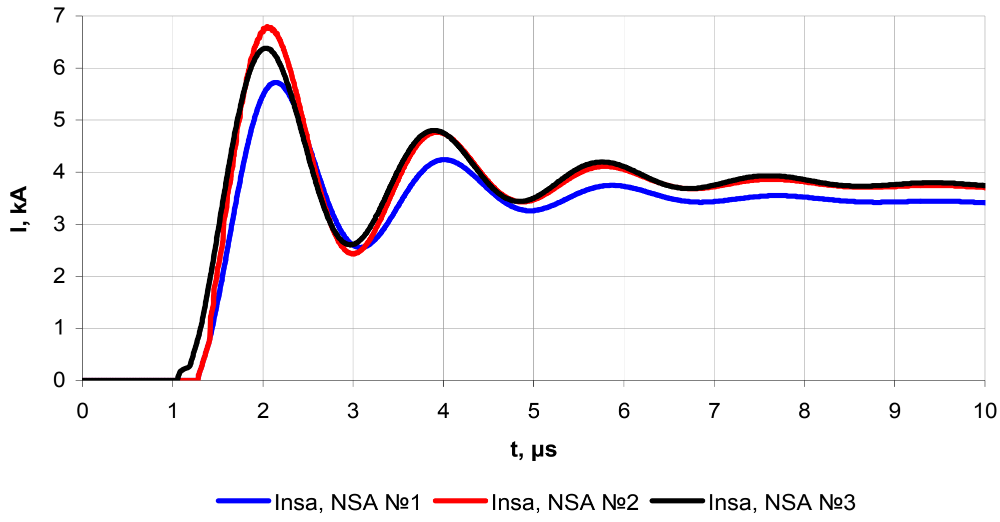


Fig.7.2 Current through the NSA at lightning current amplitude 5.89 kA at the length of the wave front 1 μs

There are shown on the Fig.7.3 differences between voltages over transformers with using NSA №1 and NSA №2 as a function of the length of the wave front.

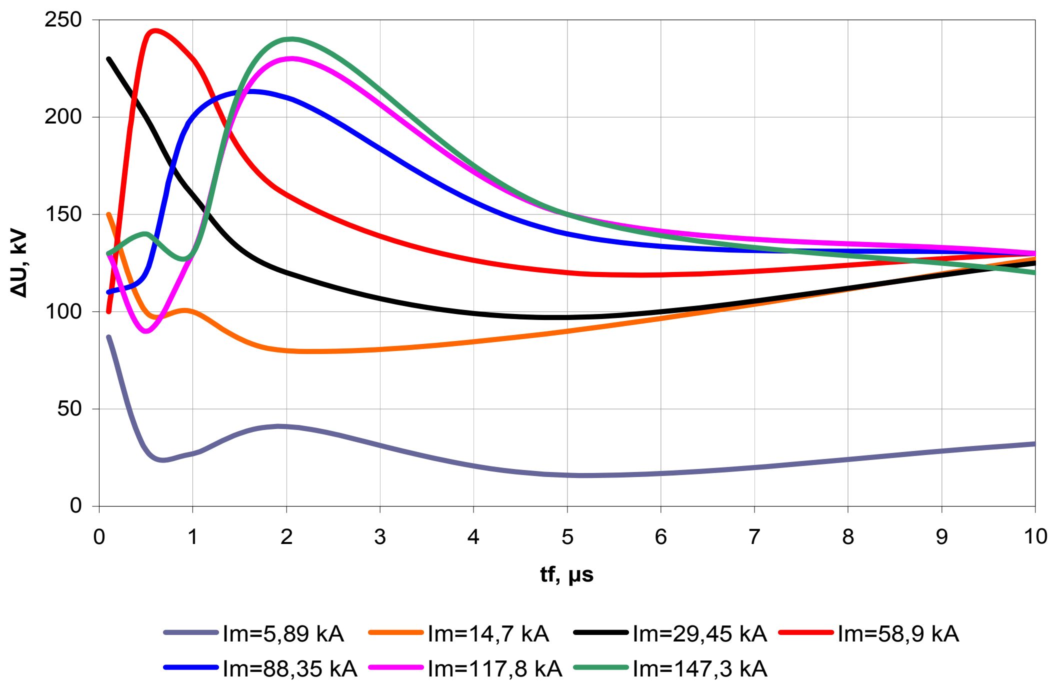


Fig.7.3 Difference between voltages over transformers with using NSA №1 and NSA №2 as a function of the length of the wave front

As it can be seen from the Fig.7.3, all curves lay in positive area that is in any case NSA №2 protects the transformer better than NSA №1. All curves have the maximum, with increasing of the lightning wave amplitude this maximum moves to the bigger wave fronts. Thereby it can be said that protective efficiency of the NSA №2 in comparison with NSA №1 increases with increasing of amplitude and wave front length of the overvoltage.

In the examined range of the amplitudes and wave front lengths maximal differences are reached at wave front lengths 0.5-2 μs, lightning wave amplitudes more than 29.5 kA. Reducing of the difference between voltages at lightning wave amplitudes less than 15 kA can be explained that these waves don't cause full opening of the protective device. Is should be noted also that lightning waves at the lightning wave amplitude less than 5.89 kA don't present any danger for transformer. In addition it is known that probability of the exposure (lightning break through the earth-wire) with high current amplitudes, with short wave lengths (about 0.1-0.5 μs) is extremely small.

At long wave lengths difference between voltages for all amplitudes with the exception of 1000 kV wave becomes almost equal and lies between 110 and 140 kV. It can be guessed that this difference will be kept at wave lengths more than 10 μs.

In whole it is shown that NSA №2 is more effective in comparison with NSA №1 at dangerous exposures with wave lengths 0.5-2 μs, at wave lengths more than 7 μs it provides less voltage over the transformer on the stable value 110-140 kV.

On the Fig.7.4 there are shown differences between voltages over transformers with using NSA №1 and NSA №2 as a function of the length of the wave front.

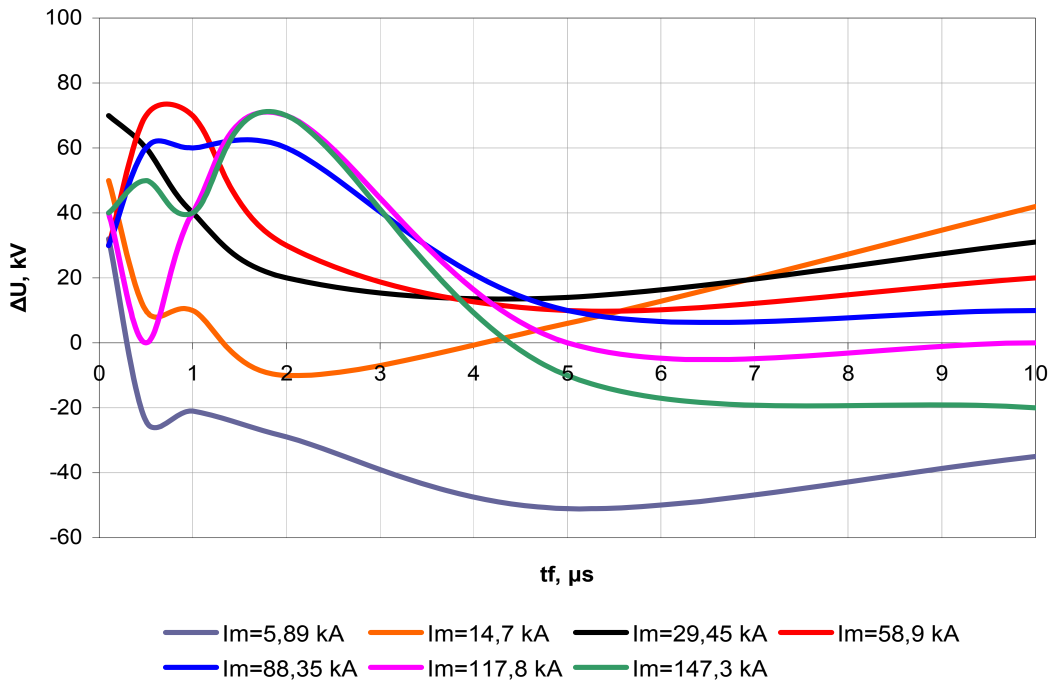


Fig.7.4 Difference between voltages over transformers with using NSA №2 and NSA №3 as a function of the length of the wave front

From the Fig.7.4 we can see that NSA №2 provides better protection of the transformer at lightning wave lengths less than 2 μs and lightning current amplitudes more than 25 kA. With increasing of the lightning wave length difference between voltages verges towards zero. With increasing of the lightning wave amplitude it becomes less zero. The NSA №3 shows better results at not dangerous waves or at waves with very long front length and very high amplitudes.

Difference between voltages in all cases isn't so big but it can be said that NSA №2 limits overvoltages better at the most frequent dangerous exposures (lightning currents till 100 kA). From the technical point of view its application proves its value but it is necessary to study this question from the economical point of view (its production needs more money). Complication of the construction any way results in reduction of the reliability, accidents connected with failures of additional elements can take place. Application of the NSA №3 have to be examined from the point its reliable work during internal overvoltages.

On the Fig.7.5-7.10 curves of the current through the NSA, voltages over NSA and transformer for different NSA are shown as an example (wave front length - 1 µs, lightning wave amplitudes – 29.45 and 117.8 kA).

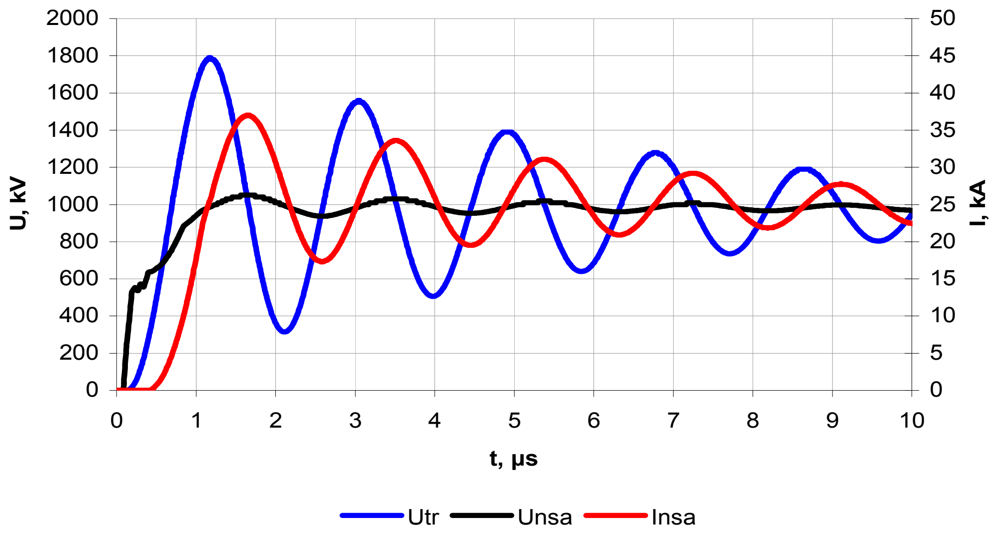


Fig.7.5 Curves of the current through the NSA №1, voltages over NSA №1 and transformer at the wave length 1 µs and lightning wave amplitude – 29.45 kA

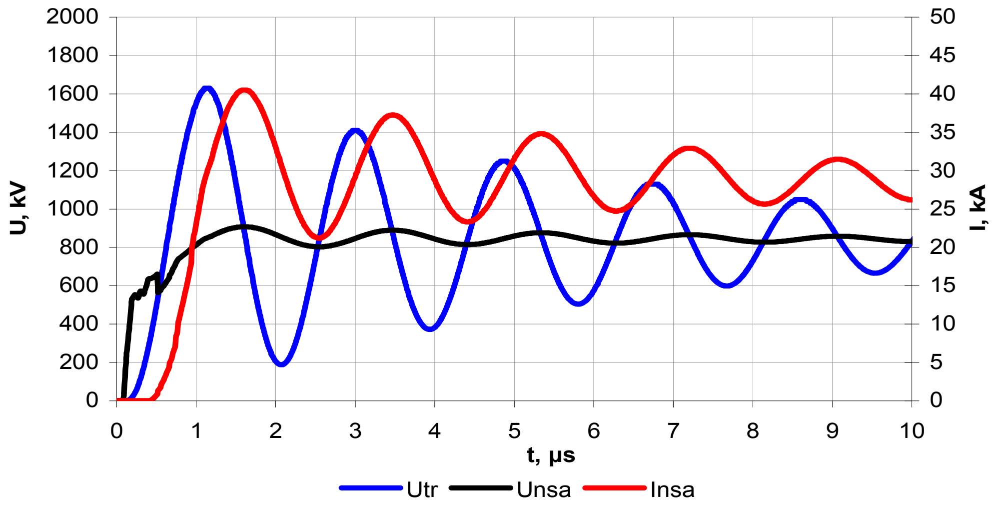


Fig.7.6 Curves of the current through the NSA №2, voltages over NSA №2 and transformer at the wave length 1 µs and lightning wave amplitude – 29.45 kA

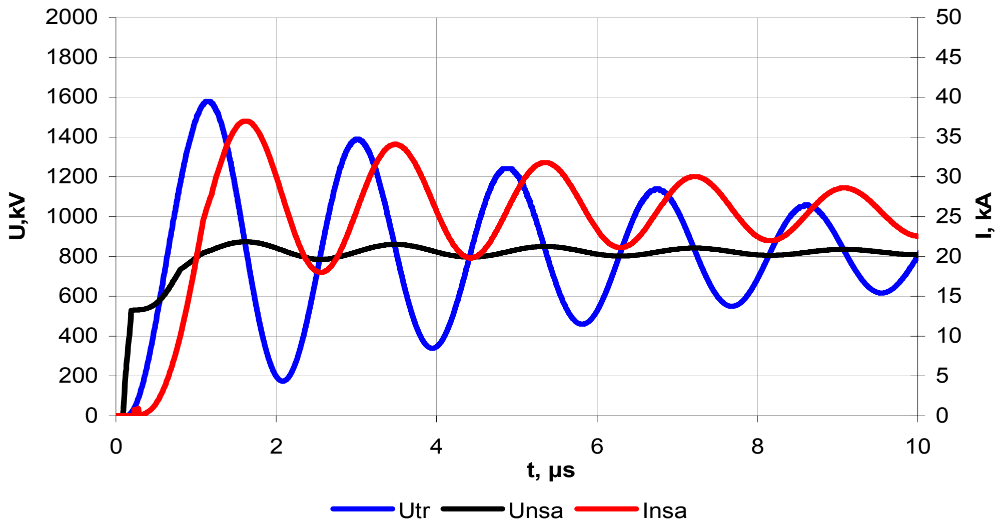


Fig.7.7 Curves of the current through the NSA №3, voltages over NSA №3 and transformer at the wave length 1 μs and lightning wave amplitude – 29.45 kA

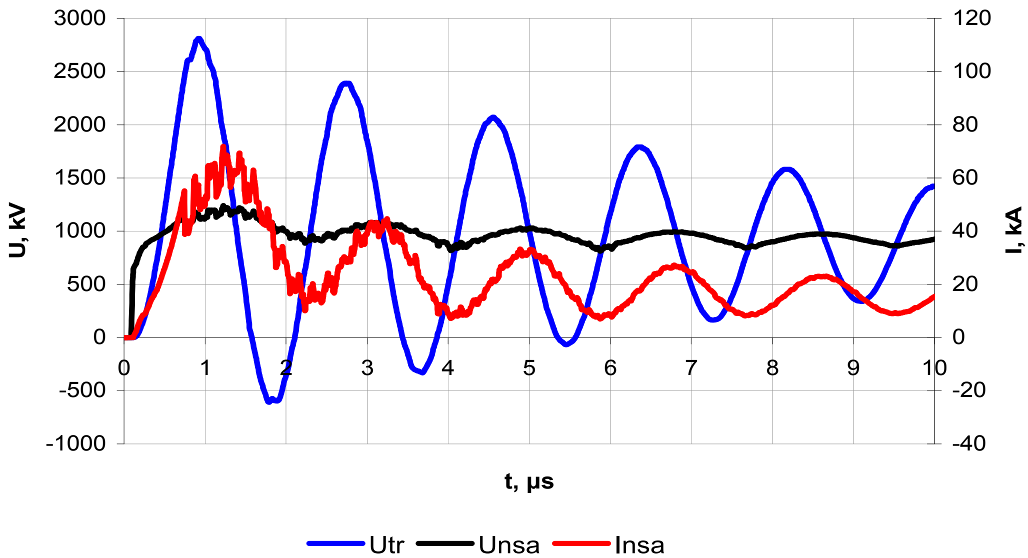


Fig.7.8 Curves of the current through the NSA №1, voltages over NSA №1 and transformer at the wave length 1 μs and lightning wave amplitude – 117.8 kA

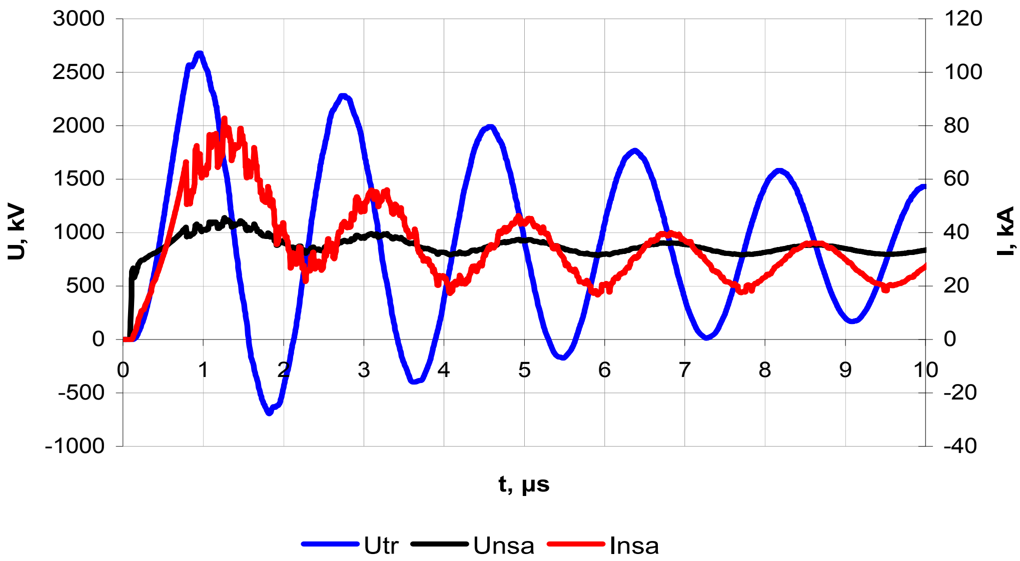


Fig.7.9 Curves of the current through the NSA №2, voltages over NSA №2 and transformer at the wave length 1 μs and lightning wave amplitude – 117.8 kA

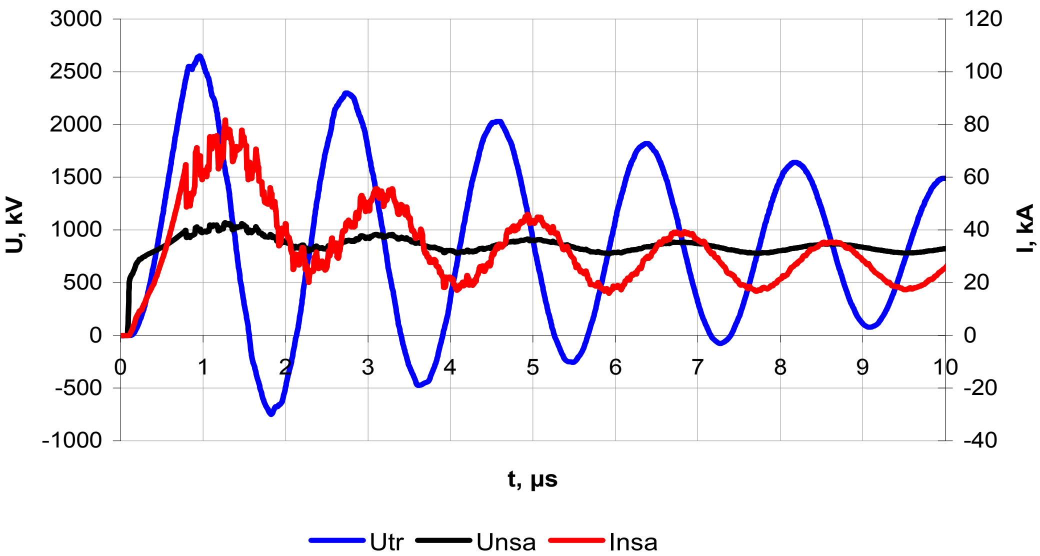


Fig.7.10 Curves of the current through the NSA №3, voltages over NSA №3 and transformer at the wave length 1 μs and lightning wave amplitude – 117.8 kA

7.2 Lightning protection reliability calculation data

Except estimations of the voltage over transformer there were done calculations of the transformer lightning protection reliability when using different types of protective devices. In other words the number of years was calculated when it is expected single insulation damage at lightning overvoltages.

It was done with help of special program called “Minsk” which was developed in Saint-Petersburg State Polytechnic University, Electromechanic faculty, High Voltage Department. In that program voltage over transformer can be calculated at lightning stroke in the phase conductor and at back flashover when there is direct lightning stroke in the pole near with substation. Obtained voltages are compared with allowable values. Then lightning-surge proofness index M is determined after that, taking into account probability of exposures occurrence with such parameters.

That program requires of the description of an overhead line near with substation. It is necessary to know distances between poles (at least of several spans); number, type and position of ground wires and phase conductors; poles footing resistances. When we know voltage-time curves of line insulation information mentioned above allows to separate the most dangerous combinations of amplitudes and front lengths, which can come from the overhead line. Lightning stroke in the phase conductor is an exposure which doesn’t cause line insulation flashover or it leads to its flashover in the pulse wing. In the case of back flashover there are lightning current impulses with high amplitude which leads to fast insulation flashover and to transfer of essential part of current into the phase conductor. Attenuation of wave due to corona discharge is also taken into account in that program. Consequently dangerous approach of the overhead line is limited. Lightning current amplitude have to be high to damage insulation of substation equipment. But with amplitude increasing wave attenuation becomes stronger. So from some distance to substation exposures stop to be dangerous because of such reasons: strong wave attenuation; small probability of high lightning currents; line insulation flashover attended by current flowing to the earth.

Dangerous exposures not limited with those reasons should be reduced to allowable level for protective device. That is the main aim of lightning protection co-ordination.

Special area which points describe dangerous for insulation exposures is calculated for every pole with approximated method on the two-dimensional subspace “lightning current - wavefront time”.

Researched transformers are 500 kV transformers with test voltage of the lightning impulse 1050 kV and switching impulse – 900 kV, instead of standard level 1550/1230. (Lohanin)

In the Table 7.1 calculation data of lightning-surge proofness index are shown depending on the place of lightning and protective device type. Also distances from which overvoltages waves dangerous for insulation can come are shown.

Calculations were done for two poles footing resistances values: 5 and 10 Ohm. I was done because of some reasons: it is very difficult to measure poles footing resistances in impulse mode and that result can contain high errors; increasing of poles footing resistances during exploitation because of corrosion. For HPP that parameter isn’t very different from poles footing resistances at power frequency mode, which is connected with big amount of steel constructions connected with poles footing. But we can see that poles footing resistances doesn’t influence very much on results.

Calculations were done for 4 types of protective devices: valve-type surge arrester described in the paragraph 3.4, NSA №1, NSA №2, NSA №3.

At allowable voltage of the lightning impulse $U_{li}=900\ kV$ lightning-surge proofness index at lightning stroke in the phase conductor approximately increases on 20% when NSA №2 changes NSA №1. At allowable voltage of the lightning impulse $U_{li}=1050\ kV$ lightning-surge proofness index at lightning stroke in the phase conductor increases approximately by an order, at lightning strokes to grounded wire or to pole with following back flashover into 2 times. This indicates that using of modernized NSA can increase lightning protection reliability of transformers at big voltage increasing.

Table 7.1 Lightning protection reliablity calculation data

Protective device	Poles footing resistance, Ohm	Lightning stroke place	Lightning-surge proofness index *M*, years	Approach distance, m
Valve-type surge arrester (paragraph 3.4)	10	Phase conductor	162,3	0, 600, 900
		Pole and ground wire	$2{,}99 \cdot 10^{6}$	0, 600, 900
	5	Phase conductor	162,3	0, 600, 900
		Pole and ground wire	$5{,}21 \cdot 10^{6}$	0, 600, 900
NSA №1	10	Phase conductor	481,2	0, 600, 900
		Pole and ground wire	228,3	0, 600
	5	Phase conductor	487,3	0, 600, 900
		Pole and ground wire	$1{,}86 \cdot 10^{6}$	0
NSA №3	10	Phase conductor	377,4	0,600
		Phase conductor	499,5	0,600,700,800
		Pole and ground wire	$3{,}69 \cdot 10^{6}$	0
	5	Phase conductor	479,1	0,600,700,800
		Pole and ground wire	$5{,}3 \cdot 10^{6}$	0
NSA №2	10	Phase conductor	766	0,600,700,800,900
		Pole and ground wire	$3{,}69 \cdot 10^{6}$	0,600
	5	Phase conductor	797,5	0,600,700,800,900
		Pole and ground wire	$3{,}01 \cdot 10^{6}$	0

Valve-type surge arrester as it was expected is the worst protective device for that scheme. NSA №3 showed results close to NSA №1. But it should be noticed that it is difficult to apply NSA №3 on power plants because there is always high nominal voltage. In such conditions at lower voltage-current characteristics surface-leakage current increases. Its limitation requires sophisticated design, that increases the price. Also there is probability of false protective device operation at power frequency overvoltages. Such false operations can lead to device damage because of high power consumption.

8 Conclusion

Obtained results allow to conclude that modernized NSA more effectively protects equipment of outdoor switchgears in comparison with usual NSA. The biggest difference was got at small wavefront lengths typical for lightning stroke in the phase conductor. Because for 500 kV voltage level that case takes place more frequently than back flashover (because of high line insulation strength and low footing pole resistance) application of modernized NSA become more actual.

But it should be noticed that this effect of overvoltages reduction at lightning stroke in the phase conductor disappears when there is scheme with high number of connections. It is connected with wave transmission possibility at big amount of branches in-parallel. So transformer yard connected with switchgear by long busbars is the best place for using modernized NSA. Probability of lightning stroke in such busbars is quite high. Lightning current in such scheme (at lightning stroke in the phase conductor) almost bisects that leads to overvoltages increasing influenced both on power transformers and auxiliary normal transformers.

Reliability of the modernized NSA corresponds to reliability of two usual NSA that is connected with appearance of new elements in the construction. This reason leads to necessity of its right setout and to reduction of protective devices number. Because it is too difficult to reduce the number of protective devices it is very optimal to place modernized NSA in compact schemes where all equipment is protected with one device. In this case reliability of the object still be quite high because of small equipment number in the whole.

Price is another important thing. Modernized NSA price exceeds price of usual NSA on 15-20%. When there are many protective devices it leads to project appreciation. But those prices can be compared with consequences of emergency switching.

So the modernized nonlinear surge arresters have advantages of other protective devices types in overvoltages protection but lose in price and reliability. Recommended application places for such devices are compact switchgear schemes, block schemes of power plants connected with long busbars with switchgear, substations placed in regions with high lightning activity or substations which have poor protected lines approaches (no grounded wires, high footing pole resistance, high distances between poles).

References

(Dmitriev) Dmitriev M.V. 2007. Применение ОПН в электрических сетях 6-750 кВ, Санкт-Петербург [NSA application in 6-750 kV networks, Saint-Petersburg]. (Available in Russian)

(Kostenko) Kostenko M.V., Efimov B.V., Zarhi I.M., Gumerova N.I 1981. Анализ надёжности грозозащиты подстанций, Ленинград. [Analysis of the substation lightning proofness reliability, Leningrad]. (Available in Russian)

(Kuchinsky 98) Bogatenkov I.M., Imanov G.M., Kizevetter V.E. etc. Edited by Kuchinsky G.S. 1998. Техника высоких напряжений, Санкт-Петербург. [High-voltage technology, Saint-Petersburg]. (Available in Russian)

(Lohanin) Lohanin A.K., Lizunov S.D. 2003. Проблемы современного трансформаторостроения в России. [Problems of the modern transformer industry in Russia]. Available from the World Wide Web:<http://www.transform.ru>. (Available in Russian)

(Razevig) Razevig D.V., 1976. Техника высоких напряжений, Москва. [High voltage technology, Moscow]. (Available in Russian)

(SZP) СевЗапПром 2008. ОПНГМ-Ф-500 для защиты оборудования с пониженным уровнем электрической прочности изоляции [SevZapProm 2008. Nonlinear surge arrester for protection of the equipment with reduced insulation strength] Available from the World Wide Web:<http://www.szp.ru>. (Available in Russian)

Appendix 1

Table 7.1 Calculation data for NSA №1.

I_m	U_{exp}	t_f	NSA №1		
			U_{nsa}	I_{nsa}	U_{tr}
kA	kV	µs	kV	kA	kV
5,89	1000	0,1	779	5,65	916
		0,5	780	5,67	918
		1	781	5,72	922
		2	769	5,24	875
		5	738	4	759
		10	732	3,75	735
14,7	2500	0,1	953	19,5	1480
		0,5	952	19,4	1470
		1	940	17,7	1340
		2	916	14,4	1100
		5	900	12,1	925
		10	900	12,1	904
29,45	5000	0,1	960	20,8	1760
		0,5	1060	39,6	1990
		1	1050	37	1790
		2	1010	29,9	1380
		5	997	27,5	1070
		10	993	26,8	1010
58,9	10000	0,1	1090	45,6	1250
		0,5	1150	55,5	2680
		1	1240	72,1	2410
		2	1170	59	1800
		5	1160	58,2	1370
		10	1150	55,6	1190

Table 7.1 Calculation data for NSA №1 (extension).

I_m	U_{exp}	t_f	NSA №1		
kA	kV	μs	U_{nsa} kV	I_{nsa} kA	U_{tr} kV
88,35	15000	0,1	1140	53,7	1460
		0,5	1090	45,1	2170
		1	1260	76,2	2870
		2	1330	88,6	2130
		5	1330	88,5	1620
		10	1300	84,4	1360
117,8	20000	0,1	1160	58,4	1650
		0,5	1080	42,2	1870
		1	1240	71,9	2810
		2	1430	108	2410
		5	1490	118	1860
		10	1460	114	1530
147,3	25000	0,1	1150	55,7	1800
		0,5	1110	48,7	1860
		1	1200	64,7	2550
		2	1310	86,2	2670
		5	1640	146	2080
		10	1620	143	1700

Table 7.2 Calculation data for NSA №2.

I_m	U_{exp}	t_f	NSA №1		
			U_{nsa}	I_{nsa}	U_{tr}
kA	kV	μs	kV	kA	kV
5,89	1000	0,1	684	6,08	829
		0,5	700	6,72	889
		1	702	6,8	895
		2	686	6,16	834
		5	658	4,58	743
		10	658	4,05	703
14,7	2500	0,1	813	23,1	1330
		0,5	816	23,6	1370
		1	807	21,9	1240
		2	787	17	1020
		5	769	14,5	835
		10	767	14,2	777
29,45	5000	0,1	823	25	1570
		0,5	918	42,5	1790
		1	907	40,5	1630
		2	866	32,9	1260
		5	860	31,8	973
		10	854	30,6	885
58,9	10000	0,1	957	49,8	1150
		0,5	1030	62,4	2440
		1	1090	74,7	2180
		2	1030	62,7	1640
		5	1020	62,2	1250
		10	1010	59,2	1060

Table 7.2 Calculation data for NSA №2 (extension).

I_m	U_{exp}	t_f	NSA №1		
kA	kV	μs	U_{nsa}	I_{nsa}	U_{tr}
			kV	kA	kV
88,35	15000	0,1	1000	57,8	1350
		0,5	978	53,7	2050
		1	1160	88	2670
		2	1180	91,9	1910
		5	1190	92,3	1480
		10	1170	88,3	1230
117,8	20000	0,1	986	55,1	1520
		0,5	967	51,5	1780
		1	1140	82,9	2680
		2	1310	115	2180
		5	1350	122	1710
		10	1320	118	1400
147,3	25000	0,1	1010	60	1670
		0,5	996	57	1720
		1	1090	74,2	2420
		2	1240	102	2430
		5	1510	152	1930
		10	1480	147	1580

Table 7.3 Calculation data for NSA №3.

I_m	U_{exp}	t_f	NSA №1		
			U_{nsa}	I_{nsa}	U_{tr}
kA	kV	µs	kV	kA	kV
5,89	1000	711	6,06	861	711
		711	6,1	865	711
		714	6,2	874	714
		697	5,46	805	697
		669	4,24	692	669
		663	3,97	668	663
14,7	2500	858	19,6	1380	858
		858	19,7	1380	858
		847	18	1250	847
		826	14,7	1010	826
		811	12,4	841	811
		811	12,4	819	811
29,45	5000	867	21,3	1630	867
		954	39,4	1850	954
		943	37	1670	943
		907	29,7	1280	907
		899	28	987	899
		894	27,1	916	894
58,9	10000	987	46,3	1180	987
		1050	58,8	2510	1050
		1110	72	2250	1110
		1050	59,3	1670	1050
		1050	58,7	1260	1050
		1030	55,9	1080	1030

Table 7.3 Calculation data for NSA №3 (extension).

I_m	U_{exp}	t_f	NSA №1		
kA	kV	µs	U_{nsa}	I_{nsa}	U_{tr}
			kV	kA	kV
88,35	15000	0,1	1030	54,3	1380
		0,5	1000	49,6	2110
		1	1170	83,1	2730
		2	1190	88,9	1980
		5	1190	89	1490
		10	1170	84,8	1240
117,8	20000	0,1	1050	59	1560
		0,5	983	45,4	1780
		1	1140	77,6	2720
		2	1310	112	2250
		5	1340	119	1710
		10	1320	114	1400
147,3	25000	0,1	1040	56,3	1710
		0,5	1020	53,9	1770
		1	1100	69,7	2460
		2	1230	96,6	2500
		5	1480	149	1920
		10	1460	144	1560

Table 7.4 Calculation data, differences between voltages.

I_m kA	U_{exp} kV	t_f µs	Difference between voltages over transformer (NSA №1 and NSA №2), kV	Difference between voltages over transformer (NSA №2 and NSA №3), kV
5,89	1000	711	87	32
		711	29	-24
		714	27	-21
		697	41	-29
		669	16	-51
		663	32	-35
14,7	2500	858	150	50
		858	100	10
		847	100	10
		826	80	-10
		811	90	6
		811	127	42
29,45	5000	867	190	60
		954	200	60
		943	160	40
		907	120	20
		899	97	14
		894	125	31
58,9	10000	987	100	30
		1050	240	70
		1110	230	70
		1050	160	30
		1050	120	10
		1030	130	20

Table 7.4 Calculation data, differences between voltages (extension).

I_m	U_{exp}	t_f	Difference between voltages over transformer (NSA №1 and NSA №2), kV	Difference between voltages over transformer (NSA №2 and NSA №3), kV
kA	kV	µs		
88,35	15000	0,1	110	30
		0,5	120	60
		1	200	60
		2	220	70
		5	140	10
		10	130	10
117,8	20000	0,1	130	40
		0,5	90	0
		1	130	40
		2	230	70
		5	150	0
		10	130	0
147,3	25000	0,1	130	40
		0,5	140	50
		1	130	40
		2	240	70
		5	150	-10
		10	120	-20