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Electromagnetic compatibility of high voltage substation SMART devices

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The article presents the results of a study of the electromagnetic compatibility of SMART devices (SD) of automated technological control systems (ATCS) at a high voltage electrical substation. The interference immunity of relay protection and automation devices associated with the use of electrical control cables has been investigated. Possible sources of pulsed radiated noise at the electrical substation are listed. The levels of pulsed electromagnetic noise at the 220 kV Karatau substation of KEGOC JSC were determined by the calculation and experimental method, which in some cases exceeded the noise immunity of the installed ATCS devices. An experimental method for determining the actual shielding coefficients of control cables at an electrical substation is presented, as well as the measurement results. The influence of shielding of relay cables on the level of electromagnetic influences on SD is revealed. Possible levels of radiated interference were determined, taking into account the screening factor of existing control cables, and the need to replace control cables was argued.

Key words: electromagnetic interference, pulsed radiated interference, electromagnetic environment, electromagnetic compatibility, SMART device, automated process control systems.

1. Introduction

The relevance of studies of electromagnetic compatibility (EMC) of SMART devices (SD) of automated process control systems (ATCS) can be traced to their noise immunity associated with the use of unshielded cables in relay protection and automation (RPA) [1,2]. The analysis of failures carried out by us [3-5] testifies to the insufficiency of studies of the influence of the degree of shielding of cables on the accident rate of the automated control system. Failures and failures of the automated control system lead to the failure of the main high-voltage equipment at electrical substations (SS) or the appearance of hidden defects in its electrical insulation (6,7). In this regard, it is of interest to study the effect of shielding of relay cables on the noise immunity of the SD when exposed to radiated impulse noise (SMI) [8].

Devices of automated technological control systems (ATCS) must be tested for noise immunity in accordance with [9, 10]. An electromagnetic environment (EMO) must be provided at the facility so that, under any operating modes, electromagnetic interference (EMF) does not exceed the levels permissible for the equipment. The transition from the relay-contact element base of the ATCS high voltage substation (HV SS) to SMART devices (SD) revealed the problem of noise immunity of the latter.

All ATCS devices of SS that provide reliable, safe distribution and transmission of electrical energy are complex technical objects that have many geographically separated functional modules and have a very large number of various states. The interconnection of the relay protection and automation elements is provided by a variety of communication, signal and control cables (Figure 1) [11].

In general, the assessment of the noise immunity of the SD relay protection and automation system from the SMI is carried out in a single complex of works to ensure the EMC of the automated control system, including the examination of the EMO, the standardization of the parameters for the severity of the tests of the SD, the development of measures to ensure EMC [12].

Sources of SMI are switching and short circuits on equipment of outdoor switchgears (OSG). Electromagnetic communication occurs in the presence of simultaneous electrical and magnetic influences between two or more electric long lines: overhead lines, buses and cables ATCS HV SS (Figure 2).

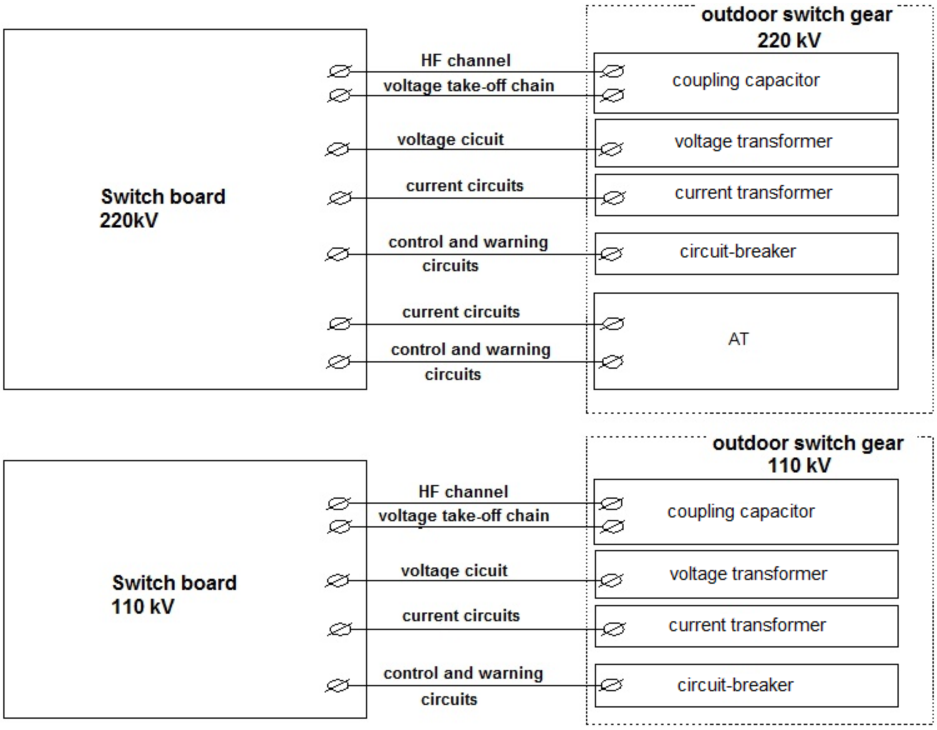


Figure 1 - Connection of relay protection and automation equipment with high-voltage equipment SS-220kV "Karatau"

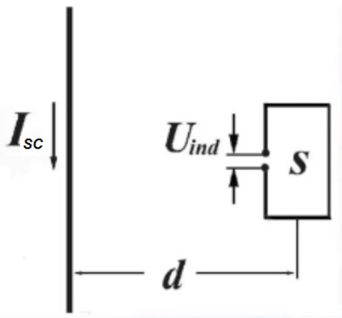


Figure 2 - I*sc* - short-circuit current, U*ind* - induced voltage, S-area of the circuit of relay protection and automation, d- distance from the overhead line (busbar) to the cable channel

Short-circuit currents (I_{SC}) flowing through the wires of the VLSh cause a magnetic flux. According to the law of electromagnetic induction, the magnetic flux excites the EMF of self-induction [13] in the circuits of the ATCS, the value of which determines the level of the influencing SMI.

$$E = U_{ind} = -\frac{d\Phi}{dt} \quad (1)$$

where *E* is EMF of self-induction, *dΦ* is magnetic flux, *dt* is time.

The value of the SMI is proportional to the amplitude and frequency of high-frequency oscillations Isc (2):

$$U_{ind} \approx A\frac{\mu_0 I_{sc} f}{2\pi d}S \quad (2)$$

where A is proportionality coefficient, Isc and f are amplitude and frequency of the high-frequency component of the short-circuit current correspondingly.

In accordance with [14], the transfer of the SMI from the source to the receiver is carried out through an electromagnetic field by radiation. The type of cables used, the presence of a shield, have a particular effect on the noise immunity of the SD. The shielding factor of a cable is the ability of its shield to one way or another to reduce the level of electromagnetic power supply and is defined as the ratio of the residual noise value (6) to the amount of external noise (5) penetrating the SMI from the external environment (Figure 3).

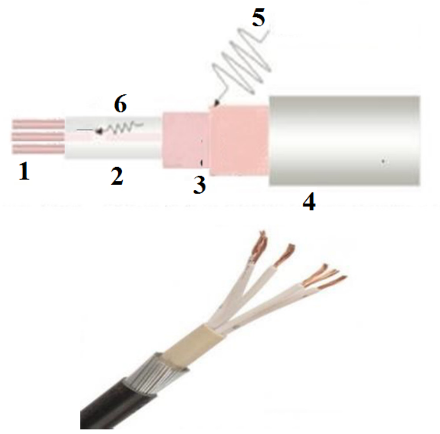


Figure 3 - ASTU cable: 1-cores, 2-insulation, 3-shield, 4-sheath, 5-external interference (SMI), 6-residual interference (RI).

In practice, the Ksc coefficient is a general shielding factor, it shows how many times, compared to a single wire, the radiated noise is attenuated by adjacent cores in the cable, adjacent cables in the cable duct or tray, metal structures of the cable duct, screens and cable sheaths (3).

$$K_{scr}=U_t/U_c \quad (3)$$

where U_t is the voltage on the test wire, U_c is the voltage in the circuit where the measurement is made.

The shielding factor depends on the material, thickness and density of the shield. The curves of the dependence of the screening factor on the interference frequency, shown in Figure 4, give an idea of the screening factor (Kscr) of cables with different types of screen. Figure 5 shows the frequency characteristics of screens of various designs.

The electromagnetic environment at the HV substation in terms of the SMI is determined by the characteristic sources of electromagnetic influences that can affect the relay protection and automation equipment, including:

- transient processes in high voltage circuits during commutation by power switches and disconnectors of HV lines;
- transient processes in high voltage circuits in case of short circuits, actuation of arresters or overvoltage limiters of HV overhead lines.

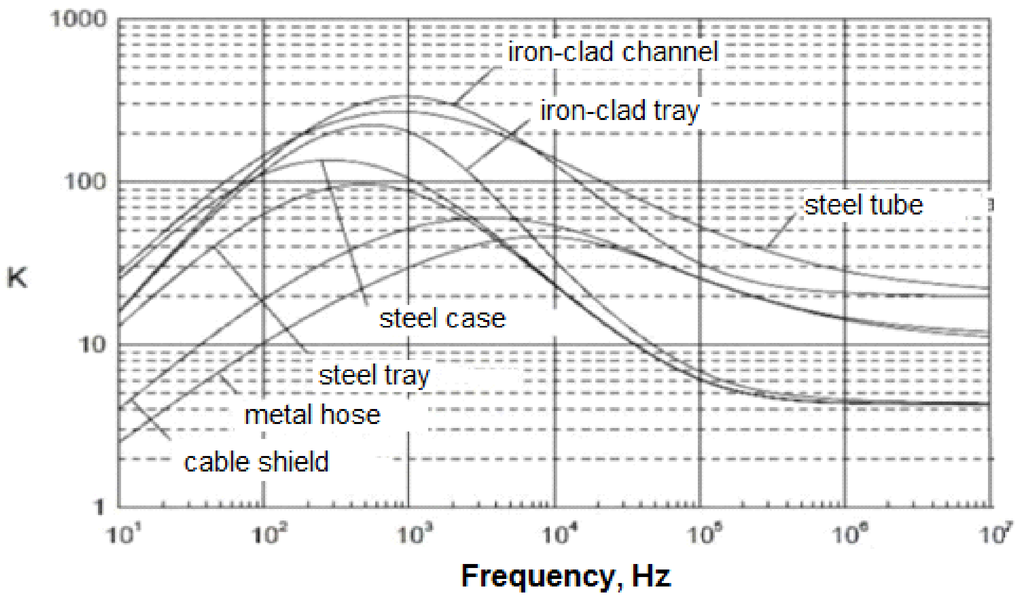


Figure 4 – Dependence of the shielding coefficient of various elements on the frequency of the SMI

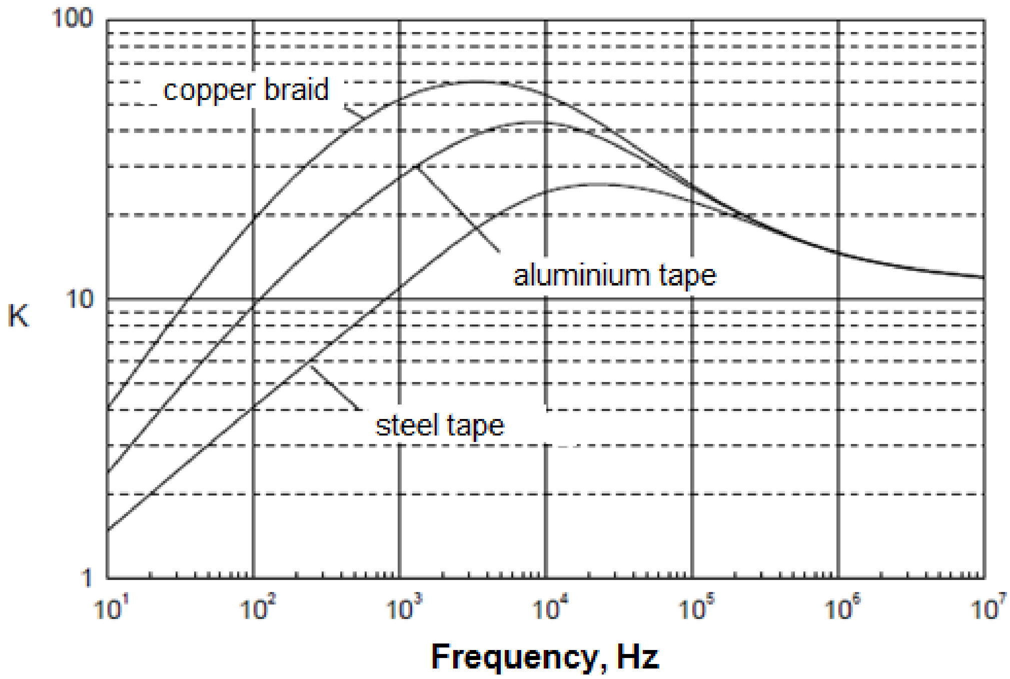


Figure 5 – Shielding factors for cable screens

In this case, as a result of the high-frequency transient process of the discharge of the equipment and busbars to the ground, the radiation of the SMI occurs. The amplitude-frequency characteristics of impulse noise arising in cables vary in a wide range and depend on the route and length of the cables, the load at the ends of the cables. The frequency spectrum varies from tens of kilohertz to several megahertz. The amplitude of impulse noise can range from tens of volts to tens of kilovolts.

The most important are: voltages and currents of transient processes arising during switching at the HV substation, the relative position of wires, buses and cables of the automated control system. The SMI levels at the SD of ATCS are normalized depending on the severity of tests [1,9] and depend on many parameters.

2. Methods

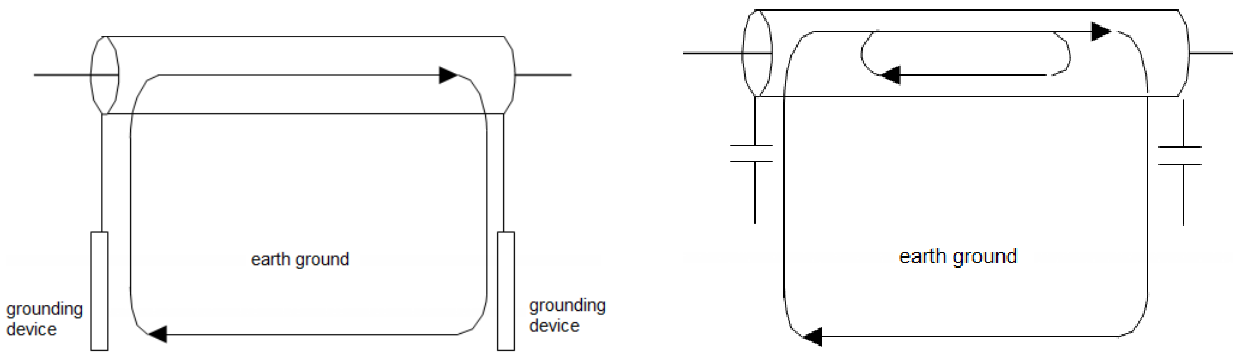
To determine the levels of SMI, computational and experimental methods are used with the use of computer programs. All models describing communication through an electromagnetic field are built on the basis of the well-known Maxwell equations. The most commonly used form for numerical solutions is the theory of long lines [14-16]. With the help of line theory, you can quickly and accurately solve problems related to the electromagnetic interaction of cables and lines. In electrically long lines, voltages and currents cannot be considered independently of each other. They are connected to each other through the characteristic impedance of the corresponding line. In the time domain, a line is considered electrically long if the rise time of pulses transmitted along it is of the same order of magnitude as the propagation time of a pulse along the line. In the frequency domain, a line is considered electrically long if the complex amplitudes of the voltage and current pulses depend on the location on the line. This effect occurs if the wavelength is of the same order of magnitude as the line length or less.

To calculate the induced overvoltage in cable lines, the computer program "Interference" was used. The physical and mathematical model is described in [17-19]. The mechanism of induction overvoltage generation is described in [20]. For sections of the cable line located underground, the attenuation coefficient of the electromagnetic field can be used [21].

To calculate SMI in cable lines, you need to know the shielding factors. In [21], a method is given for calculating the screening coefficients based on generalizations of the research results presented in [14]. The shielding property of cable screens, trays, channels and other elements (Figure 4) is explained by the fact that the noise source induces a current in the screen, the electromagnetic field of which compensates for the electromagnetic interference field. In order to obtain a high screening factor, the resistance of the loop through which the screening current flows should be kept as low as possible. At frequencies up to 10 MHz, the shielding current flows along the shield and closes in the ground through the shield grounding points (Figure 6, a). Only at frequencies above 10 MHz, the shielding current can close through the capacitance between the shield and ground, as well as in the shield itself (Figure 6, b).

The frequency of interference on the territory of the substation, as a rule, is below 10 MHz, therefore, to ensure their effective screening, it is necessary to ensure the minimum resistance of the loop through which the screening current flows. This is ensured by reliable galvanic connection of the screen on both sides to the grounding device (GD) with conductors with minimum inductance. The method for calculating the screening coefficients is described in [14]. The frequency of the SMI during switching, breakdown of electrical insulation, operation of arresters in the primary high-voltage circuits of the ORU-110.220 kV is 50-1000 kHz. The equivalent circuit for calculating the screening coefficient is given in [1].

The existing calculation methods give approximate estimates of the shielding coefficients, since it is difficult to take into account the set of various parameters inherent in cable lines: the cross-section of the conductors, the number of cores, the design of the screens, and the laying methods. Only the results of full-scale and simulation experiments in combination with numerical calculations of the shielding coefficient give a picture of the noise immunity of the SD RPA [12]. To calculate the induced overvoltage in cable lines, the "Interference" program was used. The program calculates induced overvoltages using field theory and the theory of long lines [17-21].



a) f<10MHz б) f>10MHz

Figure 6 – Shielding current paths depending on the frequency of the interference

3. Experiment results

To determine the values of the SMI on the ATCS devices, simulation tests were carried out at the HV “Karatau” substation of KEGOC JSC [11]. To simulate field impulse radiated noise, the routes for laying relay cables from the electrical equipment of 110 kV outdoor switchgear, 220 kV outdoor switchgear to the distribution center of the substation “Karatau” substation were determined. For measurements, 1-2 samples were selected from each group of cables: cables with a screen, cables without a screen, cables in a sheath.

On the selected section, parallel to the cable route, an insulated wire (1) is suspended at a height of 1.5 m relative to the ground level, simulating to the HV network (Figure 7). The control wire (3) was laid on the surface of the earth along the route of relay cables from the equipment of the outdoor switchgear-220kV, the outdoor switchgear-110kV, the AT-1 and AT-2 autotransformers to the building of the control room, where the switchgear 220 / 110kV, the main control board and the DC board are located. Control wires were laid along the surface of the ground next to the route of laying relay cables so that the length of the wire was approximately equal to the length of the cable (Figure 7). Oscilloscope "FLUKE 199" and pulse voltmeter VI-5M are alternately connected to the laid control wire and to the relay protection and automation circuits.

A high-frequency pulse generator GVCHI-4P is connected to wire 1. Background noise values were measured on the control wire and on the selected cables at the 220/110 kV distribution board, with the generator turned off using a VI-5M pulse voltmeter or a FLUKE 199 oscilloscope. Then, at a fixed amplitude and frequency of oscillations of the current pulse GVCHI-4P, measurements of the induced interference were carried out: on the control wire ($U_{\text{пров}}$) and on the selected ($U_{\text{цепи}}$).

Figure 8 shows the results of measuring the shielding coefficient for existing cables of the relay protection and automation circuits. The measured shielding coefficients of cables arriving at the switchgear-220/110 from the 110kV outdoor switchgear vary from 2.4 to 6.5, of the cables arriving from the 220kV outdoor switchgear - from 14 to 72.

Impulse radiated noise in the existing relay protection and automation circuits during short-circuit and switching on the outdoor switchgear-220 kV did not exceed the permissible levels. With a short circuit at the 110kV outdoor switchgear, the pulsed radiated interference in the existing relay protection and automation circuits can exceed the permissible levels. When switching on 110kV outdoor switchgear, pulsed radiated noise in existing relay protection and automation circuits will not exceed permissible levels. To ensure the required shielding factor and noise immunity of SMART ATCS, it is necessary to replace relay cables with shielded ones and use cables with higher Kscr.

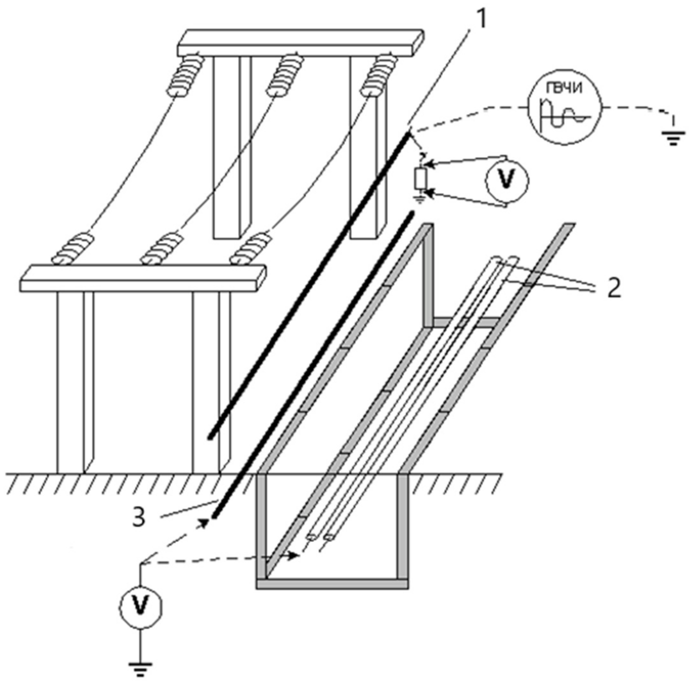
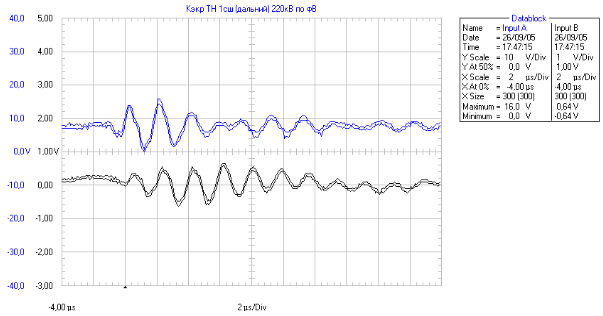


Figure 7 – Scheme for simulating radiated impulse noise.
1- wire simulating the HV bus, 2- relay protection and automation cables, 3-control wire

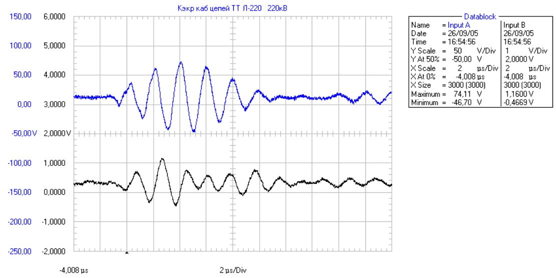
4. Discussions

The overall shielding caused by adjacent conductors in a cable, adjacent cables in a cable duct or tray, metal structures of the cable duct and cable sheaths has a low shielding coefficient [11]. Computer calculations of SMI in secondary circuits during switching in primary circuits were carried out in the INTERFERENCES program "Simulation of impulse pickups and overvoltages in branched cable lines". The results of calculations of the maximum SMI indicate that the Kscr is less than 14 does not allow to ensure the EMC of the SD RPA

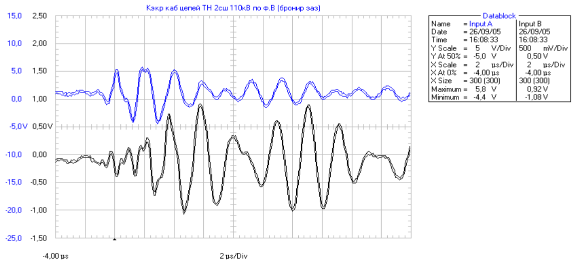
Investigations of electromagnetic influences in ATCS devices of SS "Karatau" have shown that impulse noise in existing relay cables during short-circuit and commutations exceeds permissible values. From the calculations carried out in the Interference program, it follows that the use of shielded cables allows reducing the levels of SMI in relay circuits to acceptable values and are necessary measures.



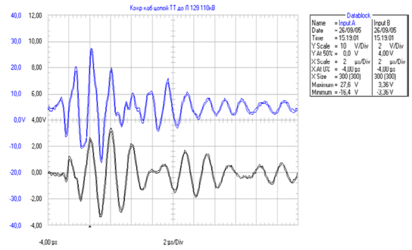
cable of TN 220kV circuits (Kscr = 14) of TT L



220 circuit (Kscr = 72)



110kV VT circuit (Kscr = 5.5) ShSV
control circuit (Kscr = 6.5)



110kV VT circuit (Kscr = 5.5) ShSV
control circuit (Kscr = 6.5)

Figure 8 – Results of measuring the screening coefficient

The screening factor is a characteristic of the ATCS cable and is used in calculations in the INTERFERENCES program. On real objects, the oscillation frequency of impulse noise can vary from tens of kilohertz to tens of megahertz. Measurements by the GVCHI-4P high-frequency pulse generator are performed at three frequencies. The results allow us to establish the dependence of the PI level on frequency. The measurement results when simulating the MT are reduced to the real value of the frequency of the high-frequency component of the short-circuit current. Researches allow to establish that for relay cables: at low frequencies in the range (50 ÷ 500) Hz, grounding of reserve wires of cables is more effective than grounding of screens; at high frequencies (0.5 ÷ 1) MHz and at aperiodic impulses (1.2 / 50; 8/20) µs - grounding of cable shields is more efficient; at frequencies (5 • 10-5 ÷ 10) MHz it is necessary to ground cable shields and backup conductors on both sides.

5. Conclusions

It has been established that SMI in relay circuits during short-circuit and switching on the switchgear of the HV substation can exceed the permissible values for SMART relay protection and automation devices, which indicates their low noise immunity.

It is shown that an increase in the shielding factor of cables can reduce the SMART levels of SMART devices to acceptable values, which will increase their noise immunity.

The use of shielded cables is a necessary measure to ensure the EMC of SMART devices of ATCS of HV SS.

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