Suppression of Incoming High-Frequency Overvoltage in Transformer Coils

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***Abstract*-- High-frequency overvoltages are most dangerous for the insulation of transformer coils. It is because high-frequency pulse voltage creates an uneven distribution of voltage across the windings. The coil's first turns receive a disproportionately high voltage drop, leading to the inter-turn circuit. The paper analyzes the types of lightning pulses and proposes a new suppression method based on the anomalous skin effect in a multilayer material and the design in the form of a coil. The developed device is simulated, and the results of overvoltage monitoring at the substation with the installed high-frequency overvoltage suppression device are analyzed.**

***Index Terms*— transients, overvoltage, transformer protection, simulation, skin effect, lightning strike, monitoring.**

I. INTRODUCTION

One of the energy industry's main tasks is to ensure the reliable operation of the power system and protect its elements from the action of various harmful factors. Special attention is paid to the protection of substation equipment from the effects of various electrical phenomena. The different electrical phenomena like propagation of lightning and chopped impulse voltages can cause excitation of resonant frequencies in the windings leading to the magnification of the electric field in a specific area; studies on this topic are presented papers of some authors [1-3]. It can lead to physical, chemical wear, and insulation failure of transformers [4-6].

One of the most dangerous phenomena for transformer equipment is high-frequency overvoltage. Their sources may be switching equipment (e.g., vacuum circuit breakers [7]) or thunderstorm activity. Analysis of statistics on 110 kV aerial networks shows that in 80% of cases, the cause of faults is lightning flasher [8]. It should also be noted that, according to studies, the back flashover when a lightning strike (from a ground wire, overhead line support) is most dangerous due to the considerable steepness of the impulses that are formed [9]. The danger of such impulses is that the voltage unevenly distributed over the transformer windings, the first turns get overvoltage. It could lead to the inter-turn circuit. Various studies are being conducted to develop optimal, efficient, and cost-effective ways to protect against high-frequency overvoltage to solve this problem. This is how the principles of grounding are revised [10], several devices of the same type are used (series-connected chokes) [11], or the properties of several devices are combined in one device [12]. However, it should be noted that these methods have their limitations, which do not allow them to be applied everywhere. For example, a strong resistance dependence on soil characteristics and terrain does not effectively apply grounding in mountainous or high soil resistance areas. Improving lightning protection is very important for these areas with high soil electrical resistance, such as the Extreme North, desert steppes, and mountainous areas. In these areas, most of the year, including during thunderstorms, the soil (permafrost, sand, rocks) does not allow for proper resistance, which leads to weak lightning scattering by a ground wire or power line. When lightning strikes both a grounded air wire and a tower, an increase in voltage between the tower and the phase wire occurs due to the high grounding resistance. Under such conditions, a back flashover between the grounded part and the phase can occur, which leads to the formation of a short pulse, from which most of the protective devices used cannot protect. This pulse can lead to inter-turn short circuits of the transformer winding and its failure).

One way to reduce overvoltage is to install a device with a characteristic resistance less than that of an overhead line in front of the substation. Despite the possible significant reduction in the amplitude of the incident pulses, the use of these inserts is associated with specific difficulties. Real protection devices arranged according to this principle are not applied in the electric power industry.

Currently, the primary means of solving high-frequency overvoltage is applying arresters based on zinc oxide varistors [13]. These line surge arresters (LSA) can provide complete lightning protection of each tower's overhead line and each phase [14]. However, there are several essential details in the arrester's operation. The first one, arresters have a self-inductive connection, which leads to a delay in their operation. The second one - arresters that cut off the pulse when the specified amplitude is exceeded, but do not change the pulse steepness (dU / dt), which leads to an uneven distribution of voltage across the winding during the transient process, which, in turn, can lead to inter-turn fault if the pulse steepness is high.

The third one concerns the high cost of all electrical insulation equipment with arresters. For adequate protection, it needs to either fully equip the overhead line with surge arresters, or precisely determine the places where their use can be useful, namely, identify areas on the line with an increased risk of the lightning discharge. To obtain the necessary information about the intensity of thunderstorm activity and accurately determine the places of lightning strikes, the use of lightning monitoring and registration systems is required. The

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application of these measures can allow the use of protective equipment, such as surge arresters, with sufficient cost savings and, at the same time, maintain high-efficiency devices to reduce the number of shutdowns of substations. It will provide a reliable and uninterrupted power supply to consumers. After the triggering of protective devices, like surge arresters, one should mention that pulses are generated with small and safe amplitude but a considerable steepness. These pulses lead to premature rapid aging of the inter-turn winding and significantly reduce transformer equipment's service life.

And last but not least and dangerous. Usually, the strong influence of the grounding device's parameters on voltage limiting effectiveness when using a surge arrester is not taken into account. This effect is manifested in the formation of a high-frequency oscillatory process at the front of the cut-off arrester of a thunderstorm voltage pulse. The decisive influence on the parameters of this process is exerted by the reactive impedance of the grounding device, and the amplitude of the high-frequency component of the cut-off arrester of a voltage pulse can be several times higher than the limit of the arrester. Voltage amplitude above the expected level leads to insulation overload and reduced high-voltage equipment [15].

Less costly, one of the ways to solve the problem of accurately determining the towers of overhead lines with a large number of lightning strikes is to use the method for assessing the probability of the back flashover of strings used on the line. A technique was developed [16], and it allows us estimating the probability of a back flashover on any tower of the studied overhead line following the known values of the grounding resistance of the towers, inductance of towers, and types of strings, as well as data on the thunderstorm activity in the region. Accurate identification of the towers most prone to flashover will allow the LSA to be installed only in these places, significantly reducing costs compared to complete overhead line equipment.

However, this technique's disadvantages include the inability to use transient characteristics of grounding devices that describe the real resistance reaction under pulse action [17].

Another way to protect the transformer is to reduce high-frequency transients near the substation. The idea of a frequency-dependent method for reducing high-frequency overvoltage is proposed early [18-19]. A frequency-dependent device (FDD) is used, the active and reactive resistances of which depend on frequency. This device must be connected to the input of the substation in the series (Figure 1). At a frequency of 50-60 Hz, the resistance should not differ from the phase conductor's resistance, i.e., there is no current operating limit. However, at a frequency of hundreds of kilohertz, the resistance should increase sharply, so that the high-frequency passing current should decrease significantly. Therefore, this overvoltage component cannot reach the substation.

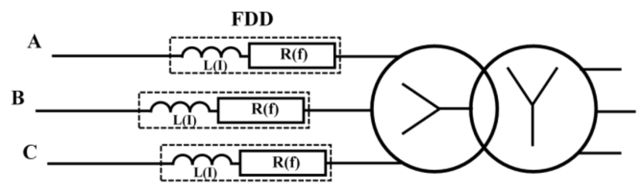

Fig.1. FDD connection diagram for transformer protection against incident waves.

The active resistance of a cylindrical homogeneous wire at high frequencies R (f) grows slightly with increasing frequency f: R (f) / R (50 Hz)) ~ $(f)^{0.5}$. This dependence is not very strong; the real values of resistance cannot be achieved when it is possible to limit overvoltages (> 100 Ohms).

Another situation is with heterogeneous conductors. For example, composite conductors with anisotropy along the radius of the conductive and magnetic properties can be used for this. It should be noted that in pulsed processes, when the level of magnetization changes following the current, the diffusion process into the ferromagnetic medium has a more complex character [18], and the reaction of the circuit element must be predicted by modeling the process taking into account the practical material magnetization curve.

The practical implementation of such wires and their structures was used in the method of high-frequency transients suppressing [19-21]. This method is not limited by matching the ground and effectively works on high-frequency pulses of any amplitude.

The FDD conductor consists of three parts in radius: the inner part is an aluminum conductor with a diameter of 15.8 mm (ordinary phase wire); the middle layer is a special ferromagnetic amorphous magnetic tape, a layer thickness of 300 microns; the outer layer is a dielectric heat-shrinkable high-voltage tube. The length of the frequency-dependent conductor in the device is more than 120 meters, to create the necessary active resistance. To provide the reactance necessary to "flatten" the pulse, the FDD is made in the form of a coil. The coil base is made of dielectric material, and the FDD itself has a height of 1350 mm and a diameter of 110 mm [19].

Low-voltage tests of experimental samples FDD were carried out at frequencies from 50 Hz to 1 MHz. The test results showed that the device's impedance at lightning frequencies increases more than 1000 times. It should be noted that the reactive component is more than the active one.

A high-current and high-frequency testing of the active resistance and the saturation currents were carried out [20]. An FDD model was used with the same conductor as in real FDD. The need for testing was caused by the fact that with the ferromagnetic layer's magnetic saturation, the FDD's high-frequency resistance should sharply decrease. A circuit in the form of an oscillatory circuit was used to conduct high-current tests of the sample. A capacitance charged to a voltage of several kilovolts was discharged using an uncontrolled spark gap through the ABB model. The capacitance value and PDD inductance determined the circuit's frequency, the voltage determined the maximum current value, and the attenuation determined the resistance. The experimental results showed that the frequency-dependent model retains its resistance level at frequencies of 50–250 kHz at currents up to 4 kA.

Three prototypes were made, which were subsequently installed for trial operation at the intake port of the 110 kV "Sugmutskaya" substation of JSC "Tyumenenergo" in the Tyumen region in front of the transformer [19] (Figure 2).

Fig. 2. On the left, the existing high-frequency line trap (stopper), in the center, and on the right is the mounted FDD. Substation Sugmutskaya, the Tyumen region, 110 kV.

The design described in the paper was developed over several years. Computer modeling of structural elements with the determination of device parameters, including magnetic fields in ferromagnetic elements, was carried out using the finite element method using a specially developed program. These results were published in several Russian-language papers [22-26].On the other hand, the parameters were selected by simulating a circuit in Simulink. The capacitors replaced the transformer and substation elements, and the FDD was replaced by a series connection of inductance and resistance. These results are also published in Russian-language articles. Here we decided to present only the final parameters of the device that was installed in trial operation. High-voltage insulation of the device, which protects the FDD from inter-turn short circuits and possible corona discharges, is provided by a shrink tubing layer. The layer is a heat-shrink tube TUT, 1.5 mm thick with a minimum electrical strength of 30 kV/mm. The minimum electrical resistivity of the tube is at least 10^{14} Ohm·cm. Amorphous tape 5BDSR is a nanocrystalline soft magnetic alloy (FeNbCuCoBSi) obtained by high-speed quenching of the melt on the surface of a rapidly rotating cooling drum. The alloy is made in the thinnest tape with a width of 33 microns, having an amorphous (glassy) structure. After the heat treatment of products from the tape, the alloy crystallizes with the release of small nanocrystals against the background of an amorphous matrix, which determines the highest magnetic characteristics.

This ferromagnetic tape chose due to the high magnetic permeability reaching a value of 50,000 (after some treatment) and high electrical resistivity. It performs to get high resistance at high frequencies.

The low voltage parameters of FDD are:

- resistance at f=50 Hz r_0<0.1 Ohm;
- resistance at f=200 kHz r_f ≅200 Ohm;
- inductance L≈ 1.5 mH;
- withstanding voltage for both full and chopped lightning impulse U_{full}> 600 kV.

This work aims to model the FDD and analyze the results of monitoring work at the substation.

The paper is organized as follows—section 2 dedicates to modeling a frequency protective device. Section 3 presents an analysis of the results of monitoring devices installed in trial operation. Section 4 deals with the discussion of the results and conclusion, respectively.

II. SIMULATION

The first attempt of FDD action simulation was performed in [19]. Modeling was done at MATLAB and Simulink. Two variants of the passage of several types of pulses at an unprotected and protected substation were simulated. The frequency-dependent device was modeled by a series connection of inductance (2 mH) and resistance (200 Ohm). A significant effect of the protective element on the slew rate and amplitude of the voltage pulse at the power transformer's voltage input in case of back flashover was revealed. Specified FDD parameters showed a decrease in pulse inclination almost an order of magnitude, and a reduction in the pulse amplitude is about two times.

However, gross simplifications were made during the simulation; in particular, the FDD resistance cannot be considered independent of the frequency.

The second FDD simulation was more realistic than the previous attempt. Using the COMSOL Multiphysics application package, computer simulation of the FDD operation was performed according to the scheme shown in Figure 3. The finite element modeling was performed based on the magnetic field FDD calculation for the magnetic vector potential in an axisymmetric formulation. The restoration of an equivalent circuit with the corresponding transient response is a solution to the inverse problem of circuit synthesis, which is not always unique. In our case, the presence of nonlinearity related to magnetization virtually eliminates the possibility of constructing an equivalent circuit [27-28].

A standard lightning voltage pulse (1.2 / 50 μs) is set as the source according to the following expression:

$$e(t) = U_m \cdot \left(\exp(-t/T_1) - \exp(-t/T_2)\right) \quad (1)$$

where U_m = 200 kV, T_1 = 0.5 μs, T_2 = 67 μs.

In series with the pulse voltage source, the line impedance is included as active resistance Z = 400 Ohms. Behind the line resistance, the finite element model FDD is connected; after the FDD, a ground capacitance of C = 7 nF is installed, simulating a transformer and substation capacitance.

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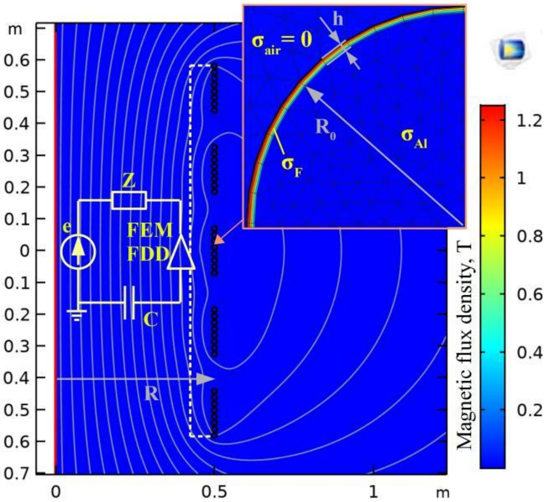

Fig. 3. The FDD simulation circuit with the distribution of the magnetic field induction at the time of the maximum current t = 3.5 μs. e is the source of the pulse voltage; Z is the wave impedance of the line; C is the transformer capacitance to earth; FEM FDD is a finite element model of FDD.

As seen in Figure 3, the FDD model is a solenoid consisting of 5 sections of 8 turns with a winding radius R = 0.5 m. Indeed, it can see all the FDD components in Figure 3: 5 sections with eight turns each. The figure also shows that the magnetic flux density is related to this real geometry. However, due to the large size, the increase in magnetic flux near the turns is not visible. Thus, a better understanding of the magnetic field distribution in the upper right part of Figure 3 shows an enlarged view of the magnetic flux density levels around one turn.

Each turn consists of aluminum wire with a radius of R_0 = 7.9 mm, over which a ferromagnetic layer 0.3 mm thick is applied. The electrical conductivity of aluminum and the ferromagnetic layer are accepted: $\sigma_{Al} = 38 \cdot 10^6$ 1/(Ohm·m) and $\sigma_F = 0.625 \cdot 10^6$ 1/(Ohm·m), respectively. For the ferromagnetic layer, the primary magnetization curve is set by the data given in table 1. Saturation must be taken into account, because when short pulses of strong current flow, it can only flow in the resistive part. In this case, the resistance is high. During the longer current pulses flow, the entire resistive zone reaches the full magnetic saturation level, and the current penetrates the central part with low resistance.

TABLE I
The points of the magnetization curve of the ferromagnetic layer FDD

B, T	H, A/m	B, T	H, A/m
0	0	1.2	5100
0.33	270	1.25	7000
0.5	600	1.28	10000
0.7	1200	1.3	17958
0.9	2000	1.302	19549
1.1	3350	1.303	20349
1.15	4000	1.304	21141

The simulation results allow us to obtain the time dependence of the current flowing through the circuit elements and the voltage on each of them. Due to the discrete nature of the data obtained, we use the Laplace transforms to analyze the behavior of the system impedance by implementing an algorithm in the MATLAB program that allows us to determine the behavior of the transition resistance of an element of a circuit under a given action [29].

It should be noted that the calculation results are of a qualitative integral character. It is difficult to obtain an exact, quantitative solution based on the numerical solution due to the large size of the model and the need for a detailed grid in the FDD region occupied by the skin layer, which increases the difficulty of the problem being solved. As a result of the calculation, the voltage dependences on the transformer are obtained, see Figure 4. It can be seen that the use of FDD reduces the slew rate of the voltage across the transformer.

We consider the most straightforward structural diagram containing a nonlinear inductance L and a transformer capacitance C. Representing a transformer in the form of capacitance is a simplification. It is a necessary measure since we do not have a more complex model. Besides, the relevant IEC document allows this to be done for the analysis of thunderstorm processes. The incident pulse voltage *U(t)* is determined by the sum of the voltage U_{FDD} drops across the inductance FDD and the capacitance of the transformer U_{tr} (2):

$$U(t) = U_{FDD} + U_{tr} = \frac{d(L \cdot i)}{dt} + \frac{1}{C}\int_0^t i dt \qquad (2)$$

And the rate of change, respectively, by the expression (3)

$$\frac{dU}{dt} = \frac{dU_{FDD}}{dt} + \frac{dU_{tr}}{dt} = \frac{d^2(L \cdot i)}{dt^2} + \frac{i}{C} \qquad (3)$$

During charging the capacitor, the current direction remains the same; a change in the sign of the derivative of the applied voltage can only be a consequence of a change in the magnetic flux in the inductive element. In this case, a reverse (opposite) polarity voltage is formed on the FDD with a voltage on the capacitance

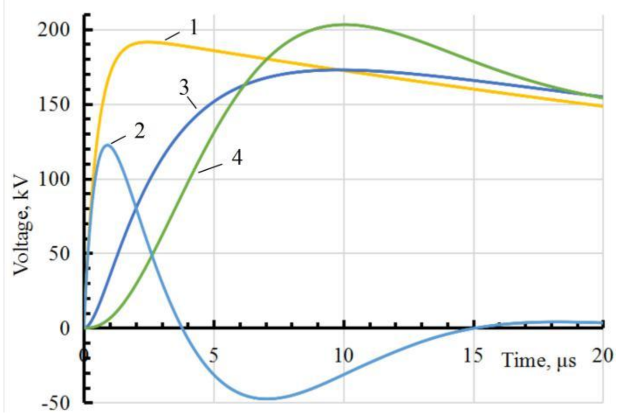

Fig.4. Dependences of voltage on time: lightning impulse (1); on FDD (2); on the transformer in the absence of FDD (3) and the presence of (4) FDD.

Based on the calculated dependencies of current and voltage using the Laplace transform, the FDD transient response is obtained, see Figure 5.

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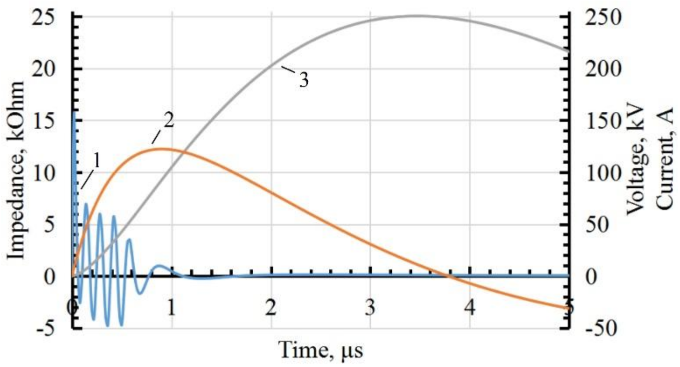

Fig. 5. Dependences of the transition characteristic (circuit response to voltage step input) (1), voltage (2), and current (3) on FDD versus time.

The FDD does not decrease the amplitude of the "full" lightning pulse, as it is shown in Figure 4. Nevertheless, the use of reduces the slew rate of the voltage across the transformer.

According to the obtained dependencies, Figure 3 and Figure 5 show that at the front of a lightning pulse, the FDD impedance can reach values of ~ kOhm, causing a significant voltage drop across the FDD and reduces the voltage across the transformer. In this case, the energy stored in the FDD inductance leads to an increase in the voltage at the transformer behind the lightning pulse front. Oscillations on the transition characteristic can be related to the nonlinearity of the magnetic field diffusion process into a two-layer wire. The transient response to 10-15 µs reaches an impedance of the order of 20 Ohms, which is significantly lower (~ 10^3 times) of the FDD resistance at the pulse front.

The most exciting transformer protection results were obtained by simulating a short pulse. As shown in Figure 6, the voltage on the transformer decreases by about five times compared with the FDD absence case.

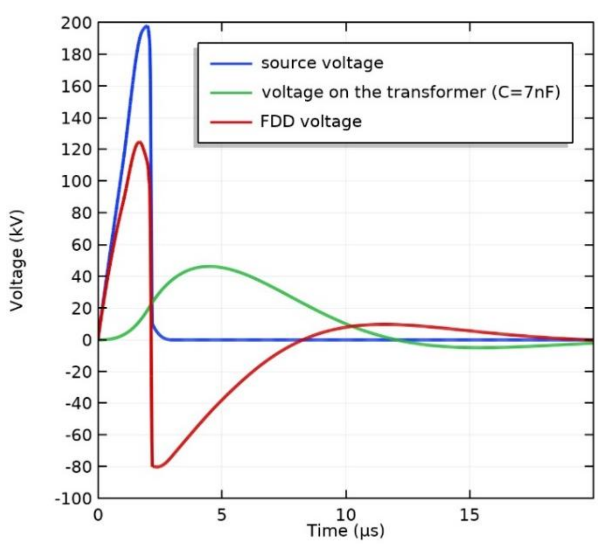

Fig. 6. Dependences of voltage on time: "short" pulse; on FDD; on the transformer in the presence of FDD.

Even more, dramatic results can be obtained by simulating the impact of the back flashover's impulse. However, the computational power of the supercomputer did not allow quantitative assessment. The only thing that can be said is that the overvoltage limitation in the winding should be much higher than in the case of a standard lightning impulse. Another case, which has not been simulated, but the FDD can work best, is the high-frequency overvoltage acting on the winding when the circuit breakers and disconnectors are operating.

III. MONITORING

The monitoring system was developed and installed to evaluate the effectiveness of a frequency-dependent device. This system registered the high voltage level at the input and output of a frequency-dependent device for several lightning periods. Several hundreds of overvoltage pulses of various nature, frequency, and amplitude were recorded at the FDD input during monitoring time. Two identical measurement systems consist of a capacitive divider, which is used as a string of insulators (a high-voltage part - 9 elements, a low-voltage part - two elements of a string connected in parallel), the voltage taken from the low-voltage parts was applied to the second divider and then to a recording oscilloscope (the electronic board L- card in a laptop).

Figure 7 shows the voltage control system. String insulators are represented by their capacitors C1..C10 with a value of 50 pF. Capacities Cf1..Cf10 and Cz1..Cz10 are stray capacitances per phase and ground, 1 pF and 5 pF, respectively. For generality, the circuit shows stray resistances R_i. An additional insulator connected in parallel to the last string element, which performs the lower arm's function, is represented by the C_{dop} capacity (50 pF).

A cable was used as a measuring track. Linear parameters of the cable: capacitance - 100 pF / m. The cable length was 75 m. The upper arm of the low-voltage divider is made of a high-voltage capacitor with an electric strength of 2 kV and a capacity of 50 pF. The capacity of the lower arm is 0.015 uF. Protective diodes at a voltage of 7 V were installed in parallel to the lower arm. The system was tested at the laboratory before installation on the substation.

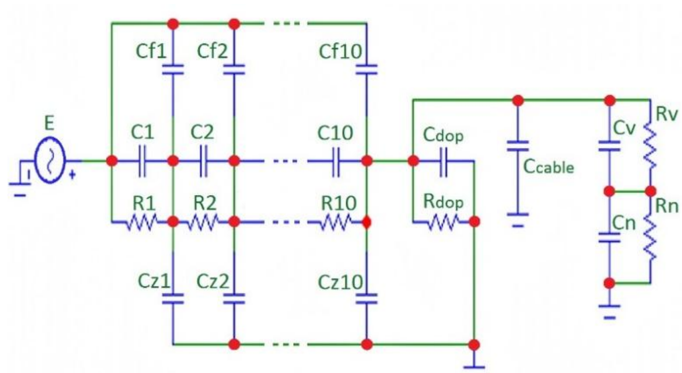

Fig. 7. System for voltage monitoring before FDD. (After FDD is the identical system.

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So, Figure 8 [19] shows the waveforms of a lightning overvoltage pulse. For clarity, these waveforms are shown in two different time intervals. As in the case of a 370 kV pulse, FDD completely suppressed its amplitude, and at the output of the device, it is seen that the overvoltage pulse corresponds to a measurement error that is, it did not exceed 10 ÷ 20 kV.

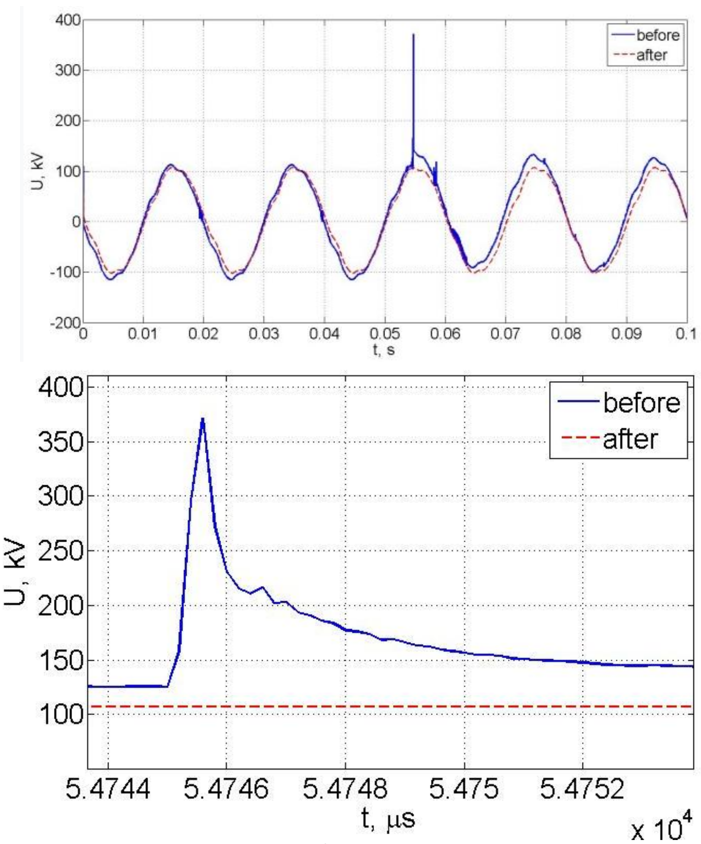
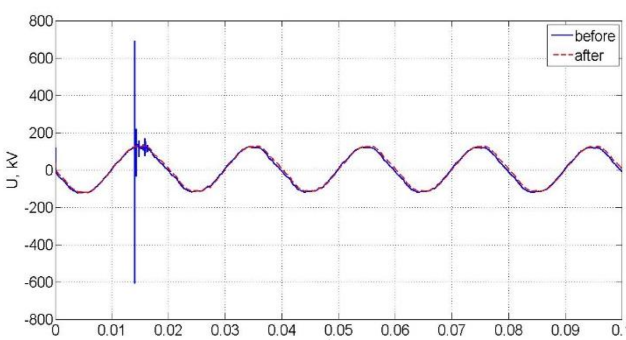


Fig.8. The registered voltage waveform 370 kV. [17]

The monitoring system showed that the FDD is also effective in protecting substation equipment from overvoltage pulses, which also have large amplitudes. Figure 9 shows the waveforms of an overvoltage pulse, presumably of a thunderstorm nature, whose amplitude was 700 kV.



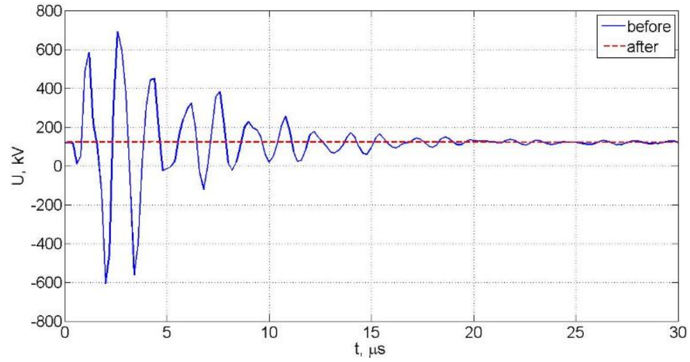


Fig. 9. The registered voltage waveform 700 kV.

The monitoring system showed that the frequency-dependent device effectively protects the network from lightning surges. Figure 10 shows the oscillograms of high-frequency overvoltage pulses, which occurred presumably during switching processes. Oscillograms for clarity are also given in two frequency ranges, which allows us to confirm high efficiency in protecting equipment from high-frequency overvoltages of various nature. These are real pulses recorded at the substation. Their nature remained unknown, in our opinion, judging by the quasiperiodic high-frequency structure of the signal, it has a switching origin.

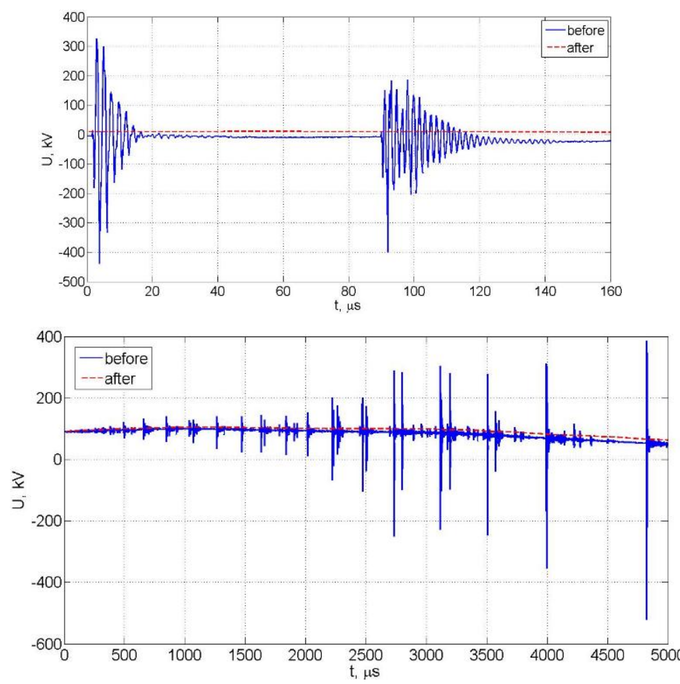


Fig. 10. Oscillograms of switching impulses of overvoltage.

IV. Discussion and Conclusion

The principle of operation of FDD is that its inductive part helps to reduce the steepness of the incident pulse, and the active part helps to dissipate the parasitic energy of a lightning or switching pulse. Therefore, FDD should protect well from short pulses and have little effect on long pulses. Existing protection in the form of arrester protects against long pulses.

In our opinion, the designed device should protect against pulses of both the microsecond and nanosecond ranges. For longer pulses, a device with other parameters must be developed or, possibly, a joint device based on the FDD and arrester principles.

Simulation of the FDD operation shows that in the case of a standard lightning pulse (1.2 / 50 μs), it does not reduce the amplitude of the voltage pulse acting on the transformer, but increases the duration of the leading edge by about a half to two times. This conclusion can be drawn from Figure 4., based on the pulses' steepness, or based on a formal definition of the front length, as the difference in times when 0.1 and 0.9 of the pulse amplitudes are reached. This is important to protect the coil insulation, since the arrester effectively reduces the amplitude, but does not affect the front's duration. In the case of a short pulse, the front duration should effectively increase, and the amplitude should decrease by about four-five times. However, monitoring showed that the incident pulses are significantly attenuated in amplitude, not less than ten times. What is the reason for such a significant difference? In our opinion, there may be several reasons. Firstly, the characteristics of the magnetic material are very approximate. Secondly, the capacitive divider at high frequencies can itself "fill up" the fronts. The divider consists of several stages: the first stage is a string of insulators, from one of the insulators of the string (closest to the tower), a signal is taken to the second stage, and after the second to the third stage. Laboratory tests showed that capacitive divider reproduces a standard lightning pulse without significant distortion, but a short pulse can reproduce much worse.

Despite the differences in simulation and monitoring results, the main conclusion about the effectiveness of suppressing high-frequency overvoltages can be made. Both monitoring and simulation have shown the high efficiency of using FDD as a measure of protection against high-frequency overvoltages. The installation of such devices on all intake portals of the substation will make it possible to successfully protect substation equipment from the effects of various high-frequency overvoltages. Moreover, this can significantly extend the period of trouble-free operation of the equipment. It is especially important in conditions where it is necessary to maintain uninterrupted power supply, or in places and conditions in which it is not easy to carry out the necessary repair measures. The simplicity of the device and its independence from soil resistance should also be noted, which also positively affects its reliability and allows it to use it even in high soil electrical resistance conditions.

As a result, simulations and experiments show that a frequency-dependent protective device (taking into account both inductance and resistance at high frequencies) effectively damps both the pulse rise rate and the voltage amplitude acting on the insulation of the substation equipment. The pilot operation of devices in real conditions fully confirms the operability and effectiveness of FDD.

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