DEVELOPMENT OF NEW METHODS FOR PROTECTING SUBSTATION AND OVERHEAD LINES FROM OVERVOLTAGES

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Abstract

This article explores various methods and devices used for protecting overhead lines and substations from surges, particularly those induced by lightning strikes. Traditional surge protection methods such as lightning rods, arresters, and grounding systems are discussed, highlighting their limitations and challenges, especially in long-distribution networks. The study examines the development and implementation of novel surge protection devices, including nonlinear surge arresters, frequency-dependent devices (FDD), and multi-chamber arresters. Special attention is given to FDD, which utilizes ferromagnetic materials to create frequency-dependent resistance, effectively suppressing high-frequency overvoltages. Experimental results demonstrate the efficacy of FDD in reducing the amplitude of lightning-induced overvoltage pulses and enhancing the lightning resistance of overhead lines and substations. However, challenges such as insufficient information on device effectiveness, limited ohmic resistance at high frequencies, and size constraints hinder widespread adoption. The article concludes by emphasizing the need for further research to optimize FDD designs, increase active resistance, and assess operational effectiveness to facilitate broader deployment across different voltage classes.

Keywords: overhead lines, substations, overvoltages, surge protection, surge arrester, skin effect, frequency-dependent device.

I. Introduction

Protecting substations and overhead lines from surges is critical to ensuring reliable electrical service and preventing equipment damage. First, let's look at the classic means (methods) of surge protection. To protect overhead lines and substations from damage due to lightning strikes, special lightning protection devices are used. These devices include lightning protection cables, lightning rods, tubular arresters, valve arresters, nonlinear surge arresters, grounding devices, etc.

The resistance values of the grounding of the supports play a significant role. Strictly speaking, grounding overhead line supports is not directly a measure for protection against lightning surges. However, despite this, it has a significant impact on lightning surge protection. It has a significant impact on the probability of reverse flashovers from the lightning protection support/cable to the phase wire. When reverse flashover occurs, high-frequency overvoltage pulses occur that cannot be suppressed by protective devices. Accordingly, they have a significant impact on substation equipment, such as transformers, and may have an impact on other equipment.

The lightning protection cable is suspended on lines with a voltage of 110 kV and above, built on metal and reinforced concrete supports. On 110 - 220 kV lines with wooden supports and 35 kV lines, the cable is usually suspended only at the approaches to substations. Despite the widespread use of cables as a means of protection, there are often cases of lightning strikes into phase wires bypassing the lightning protection cable, which reduces its reliability as a means of protection; in addition, without good grounding, there is a high probability of reverse flashover to the phase wire, which is also dangerous factor. At the same time, cable lightning rods also do not provide the declared reliability of protection against lightning damage [1-4].

To protect 110-500 kV overhead lines from lightning, the most common method of protection is the use of *linear protective devices*. The most common protective devices are pendant nonlinear surge arresters and linear arresters. It is worth noting that at present, there is no developed and approved universal method for using linear protective devices for overhead lines of various voltage classes. Therefore, operating organizations that own overhead lines experience certain difficulties in developing technical measures to protect problematic overhead lines.

Surge arresters are installed mainly in networks of 110 kV and above, but they can and can be used in networks of 35 kV. Surge arresters allow you to deeply limit the amplitudes of incoming pulses and provide protection against overvoltages. However, SS have a number of significant disadvantages. Figure 1 shows a scheme of the operating principle of the surge arrester.

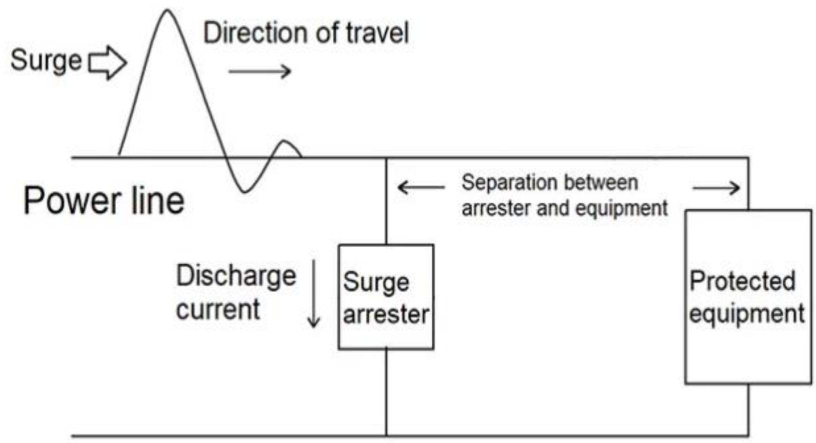


Figure 1: *Scheme of operation of the surge arrester*

First of all, the effective operation of surge arresters is ensured only when installed simultaneously in all phases of the protected circuit on each support of the protected section of the route. This is a very expensive undertaking and is only applicable for relatively short or critical overhead lines. The absence of spark gaps causes the currents of the operating voltage of the network to flow through the surge arrester with a frequency of 50 Hz. If these currents are large, the varistor may overheat and the arrester may fail. A significant disadvantage of surge arresters is the dependence of the design on the voltage class and network characteristics. The greatest difficulties arise when developing surge arresters for long-distribution networks. This leads to the fact that for trouble-free operation of the surge arrester, an accurate selection of its parameters is necessary. The main factors necessary when choosing an arrester are:
– maximum permissible voltage taking into account the duration of its impact;
– calculated pulse current;
– calculated switching current;
- energy intensity (throughput class).

In some cases, the last two parameters are replaced by the ability to absorb electrical energy, expressed in kJ per 1kV Um [5-8].

II. Materials and methods

In addition to common means of overvoltage protection, the development and implementation of new devices operating on various principles are actively underway: the combined use of an air gap and linear arresters, the use of surge arrester with a set of resistors and capacitors. However, often the devices retain the disadvantages of their prototypes, mainly: the need for a large number of devices, dependence on grounding, difficulty in installation and operation.

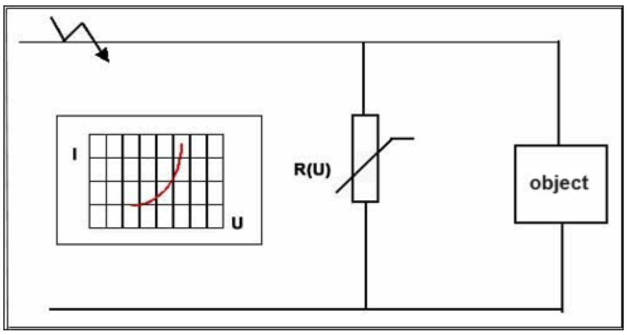
There is a solution that consists in the use of nonlinear surge arresters built into insulator housings. These solutions can significantly reduce labor costs for transportation, installation and installation, since instead of two devices, one will be used. However, this leads to a more complex design of the device itself, a decrease in its reliability, and an increase in size and weight. The typical problem of devices with varistors also remains relevant: the difficulty of monitoring its serviceability.

Also new is the concept of protective devices, the parameters of which vary depending on the frequency response of the incoming overvoltage. Thus, a combination of high-frequency magnetic material located on the main conductor with a parallel-connected resistance is proposed. According to the presented calculations and experiments, this combination is capable of suppressing and protecting against high-frequency overvoltages; this device is intended to suppress overvoltages with high dU/dt values, that is, with a high transconductance. However, the device requires tuning for a certain frequency range in which effective suppression will be achieved.

One of the latest developments is systems consisting of multi-chamber arresters. They show high efficiency, which is confirmed by a number of works, in particular, they effectively reduce the number of outages of overhead lines. However, despite the high declared efficiency, these devices also have a number of significant drawbacks: to ensure reliable protection against lightning surges, it is necessary to install arresters on each support on each insulator, precise adjustment of the spark gap is necessary (if the device is used with it), as well as the need for reliable grounding to ensure efficient operation [9-14].

Application of skin effect in protection against high-frequency overvoltages. The most promising from the point of view of ease of operation and application seems to be the use of protective devices based on the use of composite materials. There are other individual developments of protective devices based on the skin effect principle. These devices can effectively suppress high-frequency overvoltages, while being quite compact and their operation is not affected by the values of soil resistance or grounding of supports. The principle of their operation is to increase the resistance of the device as the frequency of the incoming signal increases. Figure 2 shows schematic diagrams for connecting protective devices: a nonlinear surge arrester and a frequency-dependent device.

a)



b)

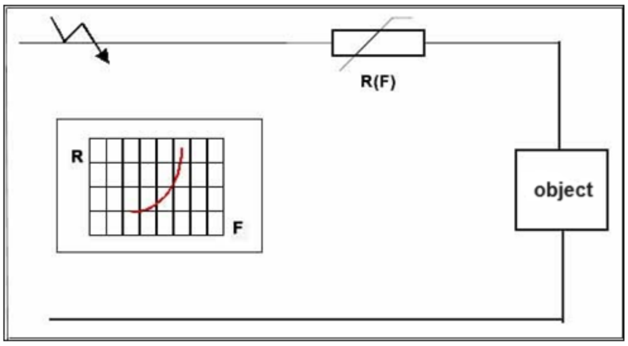


Figure 2: *Connection diagrams for protective devices: a) nonlinear surge arrester; b) frequency dependent device*

To use the skin effect, special devices have been developed, such as frequency-dependent devices (FDD). They are conductors covered with layers of ferromagnetic material with high magnetic permeability and high resistance. One of such materials is ferromagnetic tape 5BDSR. This material has high resistivity in the range of lightning (200-300 kHz) and switching frequencies (1-2 MHz). The use of this material has shown itself to be effective in early studies. On its basis, a frequency-dependent device (FDD) was created for a 110 kV overhead line. The developed frequency-dependent device is a phase aluminum wire wound into a coil with a ferromagnetic material deposited on it, which has high magnetic permeability and high resistivity. In this regard, the resistance of the wire becomes frequency-dependent, and when high-frequency signals pass through the wire, its resistance increases sharply [15-18].

In normal operation, at a frequency of 50 Hz, the frequency-dependent wire has a resistance equal to the resistance of the uncoated phase wire, since the current flows through an aluminum conductor having a low resistivity. When a high-frequency signal passes, the resistance of the wire, and accordingly the device, increases sharply by tens of thousands of times, due to the action of the skin effect and the pushing of current from the aluminum conductor into a high-resistance layer of ferromagnetic material.

Figure 3 shows the skin effect and, as a consequence, the uneven distribution of current in a round conductor.

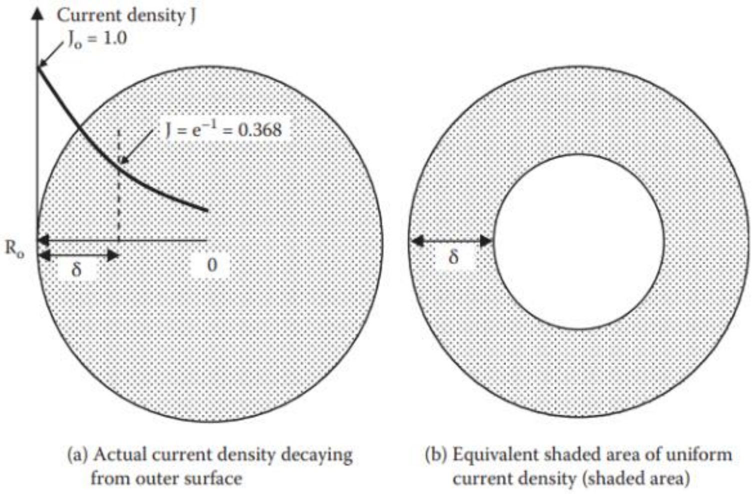


Figure 3: *Skin effect and resulting nonuniform current distribution in round conductor*

With a wire length of 120 meters used in the FDD, a resistance of 120 Ohms is provided at lightning frequencies (for comparison, the resistance of a wire without ferromagnetic tape for the same length is about 20 mOhm), which allows you to significantly reduce the amplitude of high-frequency overvoltage pulses. In turn, the shape of the device in the form of a spiral creates a high reactance, which significantly reduces the steepness of the oncoming pulse, thereby reducing the danger of interturn short circuits in the protected equipment, primarily in power transformers. As a result, the operation of this device can significantly increase the lightning resistance of overhead lines and substations. Despite the high efficiency of the device, a number of points should be noted that do not allow these devices to be put into widespread use quickly: insufficient information on the effectiveness of the device's suppression of high-frequency overvoltages, insufficiently high ohmic resistance at high frequencies, large dimensions, and the lack of devices for other classes voltages (for example, 35 kV).

In this regard, it is necessary to assess the effectiveness of trial operation of the FDD, consider the possibilities of increasing the active resistance of the FDD, and evaluate the possibilities of optimizing the designs of the FDD [19-22].

Advantages of skin effect devices:

- High efficiency of suppression of high-frequency overvoltages. Due to a sharp increase in resistance at high frequencies, the pulse energy is dissipated in the device, minimizing its impact on the protected equipment.
- Compact design. Skin effect devices can be quite compact compared to traditional protective equipment.
- Independence from ground resistance. Such devices are effective even under conditions of high soil resistance, which makes them ideal for use in complex geological conditions.
- Wide frequency range of operation. Due to the use of ferromagnetic materials with high permeability, the devices can be configured to operate in a wide frequency range, including lightning and switching pulses.

Limitations and areas for improvement. Despite their high efficiency, skin effect devices have a number of limitations, such as insufficient information on long-term reliability, relatively large dimensions and difficulty in setting up for certain voltage classes.

Important areas of research are:

1) Increasing active resistance at high frequencies;
2) Optimization of designs to reduce weight and dimensions;
3) Development of devices for lines with lower voltage classes, such as 35 kV;
4) Increased resistance to climatic and mechanical factors.

Thus, the use of the skin effect in protective devices provides enormous opportunities for increasing the resistance of power transmission lines and substations to lightning and switching overvoltages. Improvement of this technology may become one of the key areas of development of power grid protection systems in the future [23-25].

III. Conclusions

Traditional approaches such as lightning protection devices, surge arresters, and grounding systems are effective but come with limitations, especially in long-distribution networks. The development of new devices, including nonlinear surge arresters, frequency-dependent devices (FDD), and multi-chamber arresters, presents promising solutions to address these limitations. The introduction of FDD, utilizing ferromagnetic materials to create frequency-dependent resistance, demonstrates significant potential in reducing the amplitude of high-frequency overvoltage pulses and enhancing the lightning resistance of overhead lines and substations. Moving forward, it is crucial to conduct thorough assessments of the effectiveness of trial operations of FDD, explore methods to increase the active resistance, and optimize their designs.

Thus, the development and application of new methods and means of protection, taking into account both the amplitude and steepness of the pulses, becomes a necessity to provide more reliable and effective protection of substations and overhead lines from high-frequency overvoltages. Further research and innovation in this area could lead to the development of more effective and reliable protection measures, ultimately leading to increased stability and reliability of power supply.

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