Study of the patterns of change in absorption current over time and its use for measuring insulation resistance

K Yu Solomentsev¹, V I Lachin¹, V B Dyachenko¹, D A Plotnikov¹, A A Khovpachev¹ and Ya K Solomentsev²

¹ Platov South-Russian State Polytechnic University (NPI), Novocherkassk, Russia
² Moscow Institute of Physics and Technology (MIPT), Dolgoprudny, Russia
³ E-mail: sol_kir@mail.ru

Abstract. The article presents a computer simulation of absorption currents in dielectrics. The results of the study of changes in the absorption currents in time, as well as accelerated measurement of the insulation resistance taking into account the absorption current, are considered. When measuring the insulation resistance of electric power facilities, the absorption current which flows through the insulation and drops to zero in a very long time may initially exceed the leakage current. The article analyzes various patterns of representing the absorption current and proposes a new formula containing exponential and power functions. An approach is proposed for accelerated measurement of insulation resistance using extrapolation of absorption currents, that is, the calculation of the value (forecast) of the steady-state current in the measuring circuit, without waiting for the end of the absorption current flow and transients.

1. Introduction

During the operation of various electric power facilities (EPFs), special attention is paid to their reliability, durability and safety [1, 2]. During operation, these objects are subjected to mechanical, thermal and atmospheric influences, as a result, their technical condition deteriorates [3, 4]. In this regard, continuous and reliable control of the EPF parameters is necessary [5, 6].

One of the most important parameters of an EPF is the insulation resistance [7, 8, 9]. Unlike powerlines with a grounded neutral, for electric networks with an isolated neutral and some other objects isolated from the ground, it is possible to control the equivalent insulation resistance of the entire network and galvanically connected objects [10, 11, 12]. In this case, we are talking about the equivalent insulation resistance of the entire network and galvanically connected objects [13, 14, 15]. Nowadays, DC and rectifier-type networks ground-isolated, which are called IT-circuits, are often used. Such networks, in particular, are used on marine vessels, in the metro, in mines.

Branched electrical networks have a large electrical capacity relative to the ground. A large capacitance is formed due to the large length of the cables, as well as due to the presence of noise suppressing capacitors which are placed between the powerlines and ground [16]. Often networks have capacities up to 100 microfarads, and some up to 500 microfarads. This leads to problems that arise when measuring insulation resistance: existing devices either give a large error or have a very long measurement time [17].

The process of measuring the insulation resistance is greatly influenced by the absorption current. When a constant measuring voltage is applied, an absorption current flows through the dielectric, which decreases for a long time and at first it can be commensurate with leakage currents flowing through the insulation resistance. Therefore, as a rule, existing instruments for obtaining the required accuracy in
the presence of an absorption current increase the measurement cycle time [18]. But for many objects, the absorption current has noticeable values for hours and even days, so we proposed methods for measuring insulation resistance taking into account the influence of absorption currents [19].

2. Approximation of absorption current curves

To study the absorption currents in various dielectrics, a setup was assembled with which a measuring voltage was applied to the test object. Different voltage values were used, but for most experiments, a value of 40 V was chosen, and a current-limiting resistor $R_{lim}$ with a resistance of 20 kOhm was connected in series with the voltage source $E_{meas}$. These values were selected commensurate with the corresponding values of existing devices for measuring insulation resistance.

As test objects, various electrical products containing insulation were used: various electrical cables, capacitors with various dielectrics. Below are described the results obtained when testing a block of capacitors of the MBGCh type with a paper dielectric with a total capacity of 500 μF. The obtained absorption current curves were approximated by various methods. There are several generally accepted analytical functions that can be used to approximate the decay curve of the absorption current, for example, they are approximated by an exponent or the sum of several exponentials with different time constants [20]. The most common is the approximation by a power function of the following form [21, 22, 23, 24]:

$$i_a(t) = A \cdot t^{-n},$$

where $i_a(t)$ is the absorption current;
$t$ is time;
$n$ is the exponent; as a rule, $n \in [0.2...1.5]$;
$A$ is a certain coefficient, depending on the geometric dimensions, the type of dielectric and the voltage applied to it.

During the experiments, the correctness of eq. (1) was checked. For this, curves were plotted and approximation was carried out. An important feature of the obtained curves is that the zero point in time on the graphs does not correspond to the zero point in time for the analytical expression (1). This is because after connecting the measuring voltage source for some time, the current meter cannot measure a large current that exceeds the measurement limit. In addition, due to the presence of a current-limiting resistor $R_{lim}$, the measuring voltage is not immediately established. In this regard, the analytical expression for the absorption current curve should be supplemented with the variable $t_0$, then the expression for the current in the measuring circuit will have the following:

$$i(t) = A_1 \cdot (t-t_0)^{-n} + A_0,$$

where $i(t)$ is current in the measurement circuit;
$A_1$ is a coefficient similar to coefficient $A$ in eq. (2);
$A_0$ is a settled current value or leakage current.

Consider the results of curve approximation for 500 μF capacitors. The approximation was performed using the Mathcad package. The source data was represented by an array that contained almost 25,000 values. These values were put into the $Fe$ array. Since the time step was 1 s, instead of the variable $t$, the variable $i$ was used, which denoted the number of the array element. For each $Fe$ value, the analytical value was calculated by the eq. (1); then, the standard deviation $\sigma$ of the experimental data from the analytical data was calculated. Then, by varying the values of $A_0$, $A_1$, $t_0$, $n$, we minimized the value of $\sigma$, i.e. the least squares method was implemented. The value of $\sigma$ was minimized by the function Minimize () (Fig. 1).

As a result, we obtain the vector $V_b$ containing the values $Vb_0$, $Vb_1$, $Vb_2$, $Vb_3$ corresponding to $A_0$, $A_1$, $t_0$, $n$, of eq. (2). Figure 2 shows the current plot and the approximation function plot with time in seconds along the abscissa axis and the current in microamperes along the ordinate axis.
Figure 1. Minimization of \( \sigma \) using formula (1).

\[
\sigma(b_0, b_1, b_2, b_3) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ (b_0 + b_1 f_i + b_2) e^{-b_3 f_i} - F_i \right]^2}
\]

\( b_0 \approx 0.04 \)
\( b_1 \approx 30 \)
\( b_2 \approx 0.3 \)
\( b_3 \approx 0 \)

With these parameters:
\( 100 > b_0 + 100 \)
\( 200 > b_1 > 100 \)
\( 100 > b_2 > 0 \)
\( 100 > b_3 > 100 \)

\( V_b = \text{Minimize} (\sigma, b_0, b_1, b_2, b_3) \)

\[
V_b = \begin{pmatrix}
0.024 \\
126.752 \\
0 \\
0.557
\end{pmatrix}
\]

Figure 2. Approximation by function (2).

Evidently, these curves clearly do not coincide. The reason for the mismatch is as follows. At the very beginning of the transition process, due to the presence of the resistor \( R_{\text{lim}} \), the current curve contains an exponential component. Therefore, the approximating function was supplemented by exponent:

\[
l(t) = A_0 + A_1 e^{-t / \tau} + A_2 (t - t_0)^{-n}.
\]

(2)

Using the Minimize () function, the following values were obtained: \( A_0 = 0.024 \); \( A_1 = 67.4 \); \( \tau = 10.7 \); \( A_2 = 30.2 \); \( t_0 = -0.16 \); \( n = 0.313 \). Figures 3 and 4 show the current plot and the approximation function plot at different scales with time in seconds along the abscissa axis and the current in microamperes along the ordinate axis.
The plots show that the approximating curve almost coincides with the current graph.

In the research process, mathematical processing of research results was carried out, including using the Fisher criterion [25]. The results of studies with various dielectrics showed that formula (3) gives the best results.

3. Accelerated insulation measurement

There are methods for measuring the insulation resistance, which make it possible to measure the insulation resistance without waiting for the end of the absorption current [19, 25]. All these methods are based on calculating the value (forecast) of the steady-state current value until the end of the absorption current. The same least-squares approximation mechanism is used for this.
We show in more detail how this works. Suppose a voltage is applied to an object and current is measured every second for 100 seconds. In this case, 100 values will be obtained, corresponding to the first 100 values in Fig. 3. Using these 100 values for approximation by eq. (3), the values $A_0, A_1, \tau, A_2, t_0, n$ will be obtained. We are only interested in the value of $A_0$, since it is an estimate (forecast) of the steady-state current value under the assumption that $t \rightarrow \infty$.

Obviously, if you use a very small time interval, that is, the initial section, then a large forecasting error occurs. Instead of 100 points, you can use a different number of them. Table 1 shows the number of points $N$ used, that is, the number of measurements with an interval of 1 s, the obtained predicted value $A_0$ and the absolute error $\Delta A_0$. In this case, the value of 0.021 $\mu$A is taken as the true value of $A_0$, which was obtained when measuring 2 days after applying voltage.

| $N$  | 10  | 20  | 50  | 100 | 500 | 2000 | 5000 | 10000 | 20000 | 25000 |
|------|-----|-----|-----|-----|-----|------|------|-------|-------|-------|
| $A_0 [\mu A]$ | 10.373 | 7.166 | 4.9 | 5.06 | 0.248 | 0.345 | 0.512 | 0.201 | 0.193 | 0.32  |
| $\Delta A_0 [\mu A]$ | 10.352 | 7.145 | 4.879 | 4.939 | 0.277 | 0.344 | 0.491 | 0.18  | 0.172 | 0.013 | 0.003 |

The table shows that after 10 s the prediction error (10.352 $\mu$A) is hundreds of times higher than the true steady state value of 0.021 $\mu$A.

4. Conclusions

Studies have shown that in the presence of a current-limiting resistor $R_{lim}$, approximation and extrapolation should be carried out using the proposed formula (3), which can be used for various dielectrics and at different measuring voltages.

The article presents the results of only one of the experiments. However, among the results there are both better and worse, for example, when the temperature changes on the current curve, there are noticeable fluctuations. Therefore, to accelerate the measurement of insulation resistance, it is possible to extrapolate, but the limits of applicability can vary greatly depending on the type of dielectric, the limit of measurement of insulation resistance, the required accuracy and very much depends on noise and spontaneous factors, for example, temperature changes.

Consider an example, even if the measuring voltage is 40 V, the limit of measuring the insulation resistance is 1 M$\Omega$, and the permissible error is 10%. The current corresponding to a resistance of 1 M$\Omega$ is $40/10^6 = 40 \cdot 10^{-6} = 40 \mu A$, and 10% of this current is 4 $\mu$A. In accordance with Table 1, one can use the initial section with a duration of 50 s, while the error in predicting the current will be 4.879 $\mu$A, which approximately corresponds to 10% of the current value created by the resistance of 1 M$\Omega$.

References

[1] Al-Gheiilani A, Rowe W, Li Y and Loon Wong K 2017 Stress control methods on a high voltage insulator: A review Energy Procedia 110 95–100
[2] Clark D, Dongsheng G, Lathi D, Harid N, Dongsheng G, Lathi D, Harid N, Griffiths H, Ainsley A and Haddad A 2014 Controlled largescale tests of practical grounding electrodes — Part II: comparison of analytical and numerical predictions with experimental results IEEE Transactions on Power Delivery 29 1240–48
[3] Hackam R 1999 Outdoor HV composite polymeric insulators IEEE Transactions on Dielectrics and Electrical Insulation 6 557–85
[4] Bretuj W, Fleszynski J, and Wiecz K 2010 Test method of composite insulators aged in high voltage rain chamber High Voltage Engineering and Application-ICHVE
[5] Shafieipour M, Chen Z, Menshov A, De Silva J and Okhmatovski V 2018 Efficiently computing the electrical parameters of cables with arbitrary cross-sections using the method-of-moments Electric Power Systems Research 162 37–49
[6] Liu Y and Wang X 2010 Study on online insulation monitoring system for working DC power of power plants and substations Int. Conf. on Electrical and Control Engineering (ICECE 2010) 4302–03
[7] Meng J, Wang W, Tang X and Xu X 2018 Zero-sequence voltage trajectory analysis for unbalanced distribution networks on single-line-to-ground fault condition Electric Power Systems Research 161 17–25
[8] Yea G, Nijhuis M, Cuka V and Cobbena J.F.G 2019 Incorporating network uncertainties in voltage dip state estimation Electrical Power and Energy Systems 113 888–96
[9] Wu Z. J and Wang L. F 2008 A novel insulation resistance monitoring device for hybrid electric vehicle IEEE Vehicle Power and Propulsion Conference (VPPC 2008) 1–4
[10] Liu Y.C, Chang E.C, Lee Y.L and Lin Y.Z 2019 Detection of ground insulation faults in ungrounded DC power supply systems by using a DC current injection method Energy Procedia 156 349–55
[11] Jiang J and Ji H 2009 Study of insulation monitoring device for DC system based on multi-switch combination Int. Symp. on Computational Intelligence and Design 429-33
[12] Jiang J and Ji H 2009 Study of insulation monitoring device for DC system based on four-switch combination Int. Conf. on Computational Intelligence and Software Engineering (CiSE) 1-4
[13] Marrero J. A 2000 Understand ground fault detection and isolation in DC systems IEEE Power Engineering Society Summer Meeting 3 1707-11
[14] Liwei L, Ping M and Yushun W 2008 A novel method for DC system grounding fault monitoring on-line and its realization IEEE Int. Conf. on Automation and Logistics (ICAL) 1813-16
[15] Liu Y. C and Lin C. Y 2012 Insulation fault detection circuit for ungrounded DC power supply IEEE Sensors 2012 1-4
[16] Jia X, Zhao C and Li B 1998 Affection of distributed capacitance on and a new method of detecting on detecting DC system earth fault Int. Conf. on Power System Technology, Proc. of the POWERCON’98 2 1168-72
[17] Liwei L, Shuzhe B and Jianfen Z 2010 Realization of the ground resistance detector based on different frequency signals in DC system World Congress on Intelligent Control and Automation (WCICA 2010) 5414-17
[18] Schepp K 1994 Verfahren und einrichtung zur isolationsüberwachung von ungeerdeten gleich- und wechselstromnetzen Europäische Patentschrift EP 0654673 B1 18.11.1994
[19] Lachin I and Solomentsev K. Y 2017 Increase in high-speed performance of electrical network parameters measurement Int. Conf. on Industrial Engineering, Applications and Manufacturing (ICEIAM 2017) 1-4
[20] Bogoroditskiy N.P, Pasynkov V.V, Tareev B.M 1985 Electrotechnical materials (Leningrad: Energoatomizdat. Leningradske otdelenie) p 304
[21] Schleif F.R 1956 Corrections for dielectric absorption in high voltage DC insulation tests AIEEE Transactions 75 513-17
[22] Curdts E. B 1958 Insulation testing by DC methods (James G. Biddle Company)
[23] Soma K, Aihara M and Kataoka Y 1986 Diagnostic method for power cable insulation IEEE Transactions on Electrical Insulation EI-21 1027-32
[24] Götz D, Schlapp H and Putter H 2011 Dielectric loss measurement of power cables using Hamon approximation 21st Int. Conf. on Electricity Distribution (CIRED 2011)
[25] Lachin V. I, Solomentcev K. Yu, Nguyen Q. U, Yufanova A. L and Balaban I. G 2015 High-speed device of measurement parameters of electrropower objects Int. Siberian Conf. on Control and Communications (SIBCON 2015) 1-5