Information Parameters of Electrical Quantities of the Transient for Determining the Single-Phase Earth Fault Location in Cable Medium-Voltage Systems

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***Abstract* — Rapid fault determination of single-phase earth fault (SPEF) and SPEF location on the line are extremely important for the speedy elimination of damage and restoring normal operation of the power supply. Effective methods of SPEF determination on the cable lines under voltage do not still exist in medium voltage networks. The electrical values of the transition process that occurs during the breakdown of the insulation can be used for solving the problem of determining the place of single-phase including self-eliminating faults. The best method to study the electromagnetic transients at SPEF in medium-voltage networks and to identify the information parameters, which can be used for distant SPEF determination, is a combination of analytical methods on the basis of simplified models of the electrical networks and the method of computer simulation.**

Keywords— ***power distribution networks of medium voltage, determination of the single-phase earth fault place, computer simulation.***

I. Introduction

SPEFs are the predominant type of breaks in cable insulation in medium voltage networks (up to 85-90% of all electrical damage in cable lines, generator and electromotor stator coils) and are often the principal cause of accidents involving significant economic damage [1, 2, etc.]. Rapid determination of the damaged item and SPEF location in the cable line is extremely important for the speedy elimination of damage and restore normal operation of the power supply. According to the requirements of [3] the search and identifying the damaged element with SPEF in generator voltage electrical networks must not exceed 2 hours and in a networks powered by step-down substation buses – 6 hours.

However, for the above specified time of searching a damaged item significant part of SPEF enters phase short-circuit (SC), switched off by short-circuit relay protection. The latter is connected to the fact that much of the SPEF in medium-voltage cable networks, especially in the initial stage of the damage, has intermittent character, accompanied by a significant overvoltage on the healthy phases and the increase in the rms value of the current at the fault location even in resonant earthed neutral networks. Overvoltage covering all electrically communicated network increases the effective current in SPEF location and causes transitions in double and shared ground fault or short circuit in the breakdown of the insulation.

The suddenness of a power failure of consumers in most industries is the main cause of damage arising as a result of SPEG. Therefore, improving the reliability of electricity supply and the reduction of losses due to the SPEF is possible when the time required to SPEF location determination is dramatically reduced.

Solving this problem is actual for cable medium-voltage networks of urban power supply and for complex configuration cabling of power supply enterprises of certain industries (e.g., ferrous and nonferrous metallurgy, pulp and paper, automotive, and others.).

II. Statement of the Problem

Because of the small values of the steady-state fault current in electrical medium-voltage networks, working with isolated neutral, or with high resistance earthed or compensated capacitive currents, and the lack of dependence of this current on the distance between the place of SPEF and the installation place of fault locator for cable networks so far there is no actual use of effective methods of determining the SPEF place (location) on lines under operating voltage. In addition, the use of steady-state components of SPEF electrical quantities does not allow to determine the place of the most dangerous arc alternating SPEF, as well as short-term self-extinguishing faults.

At short-term self-extinguishing faults the free part of the transition process dominates in the phase currents and voltages and zero sequence components, the values of which, in contrast to the steady-state components of SPEF, depend strongly on the distance from the SPEF place to the supply buses. Therefore, to determine the place of short-term self-extinguishing faults it is preferable to use transient current and voltage (the so-called parametric methods of determining the place of the earth faults). It should be noted that the problem of determining the place of short-term self-extinguishing fault using the components of the transition process automatically solves the problem of determining the place of stable and more dangerous for the network arc alternating SPEG.

The aim of this work is to identify the most effective, in our opinion, information parameters of electrical quantities of the transition process, containing the dependence on the distance to the place of SPEF, and study the effect of various factors confounding measurement of electrical quantities.

III. PARAMETRICAL METHODS OF SPEF LOCATION DETERMIMATION

The advantage of parametrical SPEF determination compared to other distant methods is that there is no need to use generators probe pulses and there is no problem of the generator connection to the cable line under voltage. Parametrical methods of distant SPEF determination are, in our view, the only possible solution for the problems of searching short-term self-extinguishing breakdowns location. Therefore, the use of parametric methods based on the use of electrical quantities of the transition process is the most promising way to solve the problem of determining the place of SPEF, including short-term self- extinguishing insulation breakdown in cable networks.

The most common methods of distant SPEF determination and their main shortcomings are described in this paper.

The method discussed in [4 – 6] is based on the determination of the maximum derivative of the faulted phase voltage at the initial time of the SPEF.

This method, in our opinion, has a number of disadvantages connected with equivalent circuit used, which does not give a fairly accurate description of the transition process at SPEF, as it does not consider the difference loop resistance "phase – phase" and "phase – earth", the influence the active resistance of cable lines, the transient fault resistance and frequency dependent lines inductance. In practice the real fault location devices for calculated dependences to determine the location of the fault more complete and accurate models of the system being monitored are used. In addition, the studies did not investigate the influence of transition resistance at the fault location on the accuracy of measuring the distance to the fault.

It is also known that the transient current and faulted phase voltage at SPEF contains two main frequency components: the discharging related to the discharge of the faulted phase capacity, and charging related to unfaulted capacitance recharge of SPEF mainly The frequency of the discharge component depends on the distance to the SPEF place. The frequency of the charging component is mainly determined by the inductance of the power supply. Therefore, a significant impact on the accuracy of measuring the distance to the fault has a working frequency range of the fault location devices not reflected in [4 - 6].

The method based on the use of ratios of current and voltage transient for the faulted phase line at SPEF is proposed in [7]

In [7] the influence of transition resistance at the fault place on the accuracy of measuring the distance to SPEF is not investigated. The difference between circuit inductance "phase - phase" and "phase - earth," the impact of active resistance lines of the network are not taken into account. There are no recommendations for the dependence of calculated values of lines inductances on the frequency of the transition process, and others. Therefore estimates of the errors of the method presented in [7] (the order of a few percent) are questionable.

The method proposed in [8] is substantiated results of field experiments conducted in real networks. Artificial SPEFs on the power line at different distances from the buses were organized by connections to the "ground" of one phase under voltage through a special spark gap. Parameters of the transition process, which contain information about the distance to the fault place (L_{SPEF}) were identified by the oscillograms at SPEF. T_F – time proportional to the rise time of the transition curve of current through the high-resistance grounding resistor determined from the beginning of the transition process until the first maximum value – was accepted as the most informative feature that characterizes SPEF location. After processing waveforms showing the dependence of $T_F = f(L_{SPEF})$, the operating personnel can determine the distance to the SPEF place in the service of overhead lines.

The considered method is focused on the use of air networks grounded through a high resistor. In [8] the effect of various factors on the measurement accuracy of the SPEF place, incl. transition resistance, is not considered.

IV. METHODS OF TRANSIENTS ANALYSIS IN THE CABLE MEDIUM VOLTAGE NETWORKS

Considering the limits of the experiments in the existing electrical and physical modeling, as well as in connection with the development of effective systems of universal mathematical modeling (for example, MATLAB with the extension package SIMULINK [11]), the most powerful tool for the quantitative analysis of transients at SPEF in electrical medium voltage networks is a computer simulation. the use of which, however, is limited by the infinite number of settlement options, connected to the specific combinations of influencing factors.

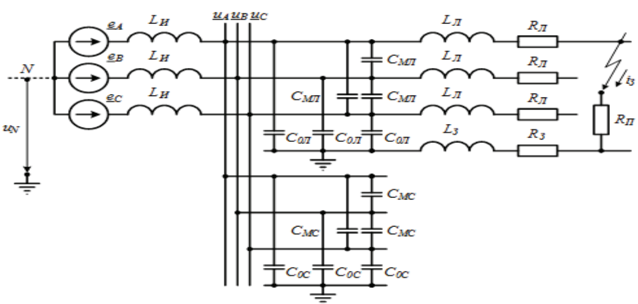

Figure 1. Dual-frequency equivalent circuit of the cable medium voltage networks [9] for the study of transients at SPEF

The difficulty of obtaining an analytic solution is primarily determined by the complexity of the design adopted by the equivalent circuit of the network for the study of transients at SPEF. The complexity of the calculation of the equivalent circuit electrical network depends on the purpose of research transients at SPEF and the related necessity of accounting the various stages of SPEF development.

In this paper the dual-frequency equivalent circuit (Fig 1) and the equivalent complex circuit process at SPEF, contained in [9, 10] are used to identify information parameters suitable in fault location devices in cable networks and to study the influencing factors.

To solve the problem of distant SPEF location determination any quantities, which parameters depend on the distance to the fault, can be used. For electric quantities of the transition process at SPEF the following quantities are:

– transient zero-sequence current and its free components;

– transient zero-sequence voltage and its free components.

The faulted phase current at SPEF, and the faulted phase voltage also depend on the distance to the fault place. Thus, except the zero sequence components of transient process at SPEF for SPEF location determination the current and voltage of the faulty phase faulted line may be used. The calculated transition zero sequence current and its free discharge component waveforms dependent on the distance to the SPEF place received by using the analytical expressions are obtained in Fig. 2 and 3.`

V. Normalization of electrical quantities in transitions

The amplitudes of the components of the free and full currents and voltages of the transition process and the parameters that can be used to determine the location of SPEF depend not only on the distance from fault location, but also on the initial phase of the insulation breakdown φ.

The above dependence for currents is illustrated by the calculated waveforms obtained by the equivalent models (Fig. 4).

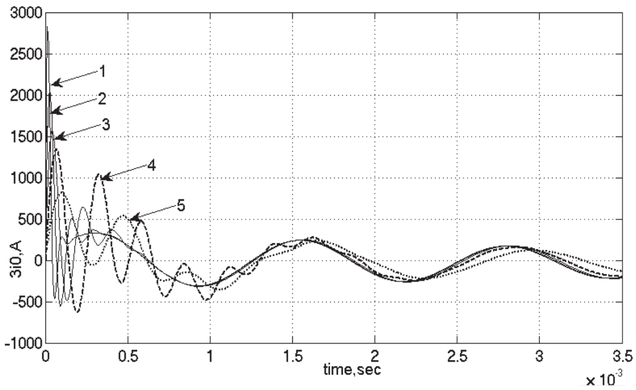

Figure 2. Calculated dependence of the transient current on the distance to the SPEF place for network U_{nom} = 6 kV and $I_{c\Sigma}$ = 30A:
1 – L = 0,2 km; 2 – L = 0,5 km; 3 – L = 1 km; 4 – L = 2 km; 5 – L = 5 km

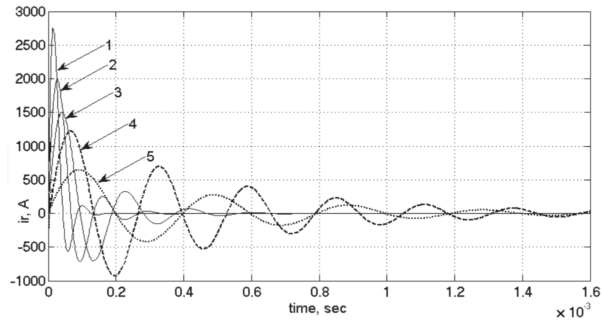

Figure 3. Calculated dependence of the discharge transient current on the distance to the SPEF place for network U_{nom} = 6 kV and $I_{c\Sigma}$ = 30A:
1 – φ = 90°; 2 – φ = 45°; 3 – φ = 30°; 4 – φ = 5°

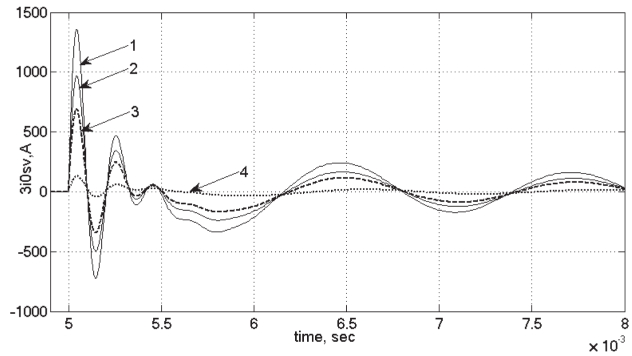

Figure 4. Calculated dependence of the transient current on the distance to the SPEF place for network U_{nom} = 6 kV and $I_{c\Sigma}$ = 30A:
1 – φ = 90°; 2 – φ = 45°; 3 – φ = 30°; 4 – φ = 5°

To eliminate the dependence of the electrical quantities parameters during the transition process from the initial phase of the insulation breakdown the usage of normalized values of the free current and voltage is necessary.

Free transient current and voltage amplitudes at the time of the SPEF presence on the faulted phase voltages close to the maximum is proportional to the value of *sinφ*. *Sinφ* value can be calculated according to the value of U_{max} at mode previous to SPEF and the voltage on the faulted phase at the time of the insulation breakdown

$$\sin\varphi = \frac{u(0)}{U_m} = \frac{U_m \sin\varphi}{U_m} \quad (1)$$

Fig. 5 shows the calculated dependence of the normalized values of the free components of the transient current $3i_0$ during SPEF.

Fig. 5 shows that the proposed approach to the valuation of the measured values of electrical quantities of the transition process virtually eliminates the dependence of the parameter information from the initial phase of an insulation fault φ, but gives significant errors at small angles of the breakdown in the order of 5-10°. Considering that vast majority of insulation breakdown occurs when the values of the angle φ close to $\pi/2$ these errors can be considered insignificant.

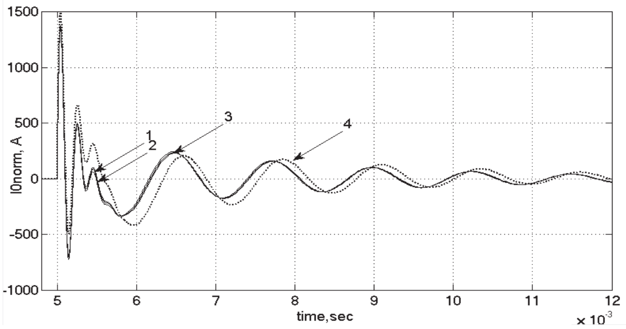

Figure 5. Calculated dependence of the normalized transient current on the distance to the SPEF place for network c U_{nom} = 6 kV and $I_{c\Sigma}$ = 30A: 1 – φ = 90°; 2 – φ = 45°; 3 – φ = 30°; 4 – φ = 5°

VI. Key factors that distort measurement of information parameter of transient electrical quantities at SPEF

The main factors affecting the accuracy of measurement of electrical quantities information parameters of the transition process at SPEF, include:

– transient resistance at the fault place R_t;

– value of the total capacitive current of the network $I_{C\Sigma}$;

– inductance of the power supply;

– grounding mode of the network.

Computer analysis of medium-voltage cable networks showed that the amplitude and duration of the first half-wave transition of the residual current and the transient current in the faulty phase faulted line essentially depend on the transition resistance in place of SPEF and the value of the total capacitive current of the network. That is why the use of such information parameters can lead to significant errors in the evaluation of the distance to the SPEF place. The initial values of the second derivative of the faulted phase voltage and the second derivative of the zero-sequence voltage also depend significantly on the total capacitive current.

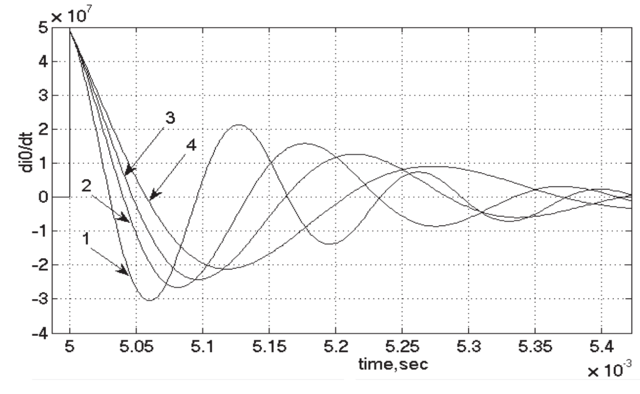

Figure 6. Calculated dependence of the normalized derivative of free transient zero-sequence current $3i_0$ on capacitive current for network U_{nom} = 6 kV и $I_{c\Sigma}$ = 30A, L = 0,8 km φ=90°: 1 – $I_{c\Sigma}$ = 10 A; 2 – $I_{c\Sigma}$ ==20 A; 3 – $I_{c\Sigma}$ = 30 A; 4 – $I_{c\Sigma}$ = 50 A

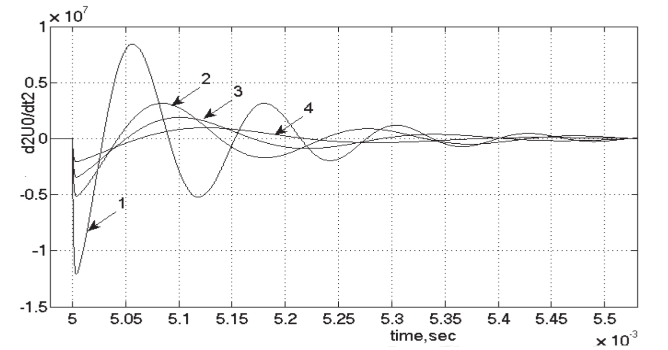

Figure 7. Calculated dependence of the normalized second derivative of free transient zero-sequence voltage $3u_0$ on capacitive current for network U_{nom} = 6 kV and $I_{c\Sigma}$ = 30A, L = 0,8 km φ=90°: 1 – $I_{c\Sigma}$ = 10 A; 2 – $I_{c\Sigma}$ ==20 A; 3 – $I_{c\Sigma}$ = 30 A; 4 – $I_{c\Sigma}$ = 50 A

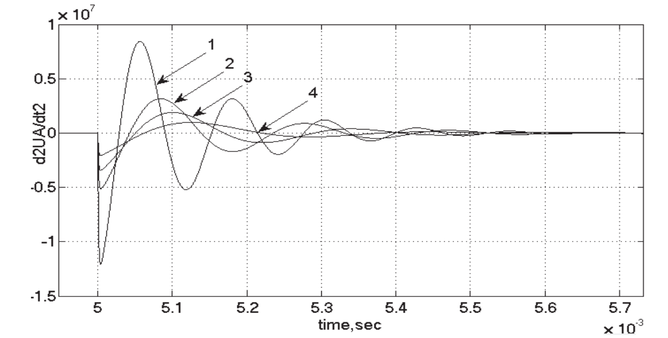

Figure 8. Calculated dependence of the normalized second derivative of free transient phase voltage U_A on capacitive current for network U_{nom} = 6 kV и $I_{c\Sigma}$ = 30A, L = 0,8 km and φ=90°: 1 – $I_{c\Sigma}$ = 10 A; 2 – $I_{c\Sigma}$ ==20 A; 3 – $I_{c\Sigma}$ = 30 A; 4 – $I_{c\Sigma}$ = 50 A

These factors do not allow to provide high accuracy measurement using the maximum value of information derived zero sequence voltage and the voltage of the faulty phase at the leading edge of the first half-wave of the specified values as information parameters. Fig. 6 — 8 show the dependence of various electrical quantities of the total capacitive current network.

The computer analysis shows that the most informative value for problem of distant SPEF determination is the initial value of derivative of the current $3i_0{}'$, which depends only on the distance to the SPEF place, and varies in direct proportion to the distance. This is confirmed by the results of mathematical modeling and simulation of simplified models of medium voltage cable networks (Fig.9).

VII. About obtained results

The above assessment of the effectiveness of using different information parameters of transition electrical quantities for SPEF location determination in medium-voltage cable networks obtained on the basis of the simplified analytical solutions and computer simulations using a fairly simple model of medium-voltage networks. The actual configuration of cable networks systems, urban and industrial power supply, as well as the distributed nature of the line parameters, can make significant adjustments in the results and evaluation. Investigation of influence of the network configuration, the distributed nature of the line parameters and other features of the real medium-voltage cable networks should make, in our opinion, the subject of further research.

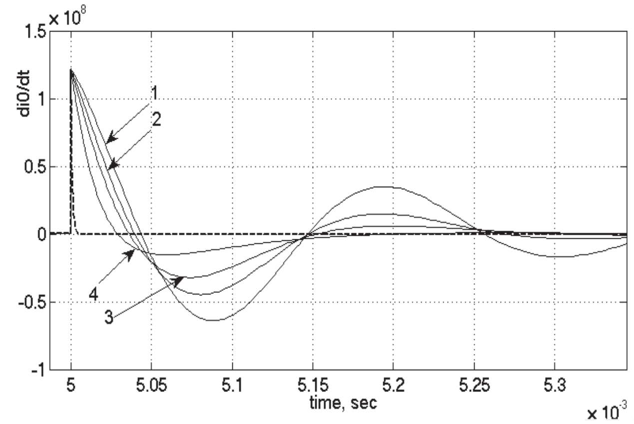

Figure 9. Calculated dependence of the normalized derivative of free transient zero-sequence current $3i_0$ on transient resistance for network U_{nom} = 6 kV And $I_{c\Sigma}$ = 30A, L = 0,8 km φ=90°: 1 – R_t = 0,1 Ohm; 2 – R_t = 1 Ohm; 3 – R_t = 2 Ohm; 4 – R_t = 5 Ohm

VIII. Conclusions

1. The most effective method for the study of electromagnetic transients at SPEF in medium-voltage networks in order to identify the information parameters that can be used to solve the problem of distant SPEF place determination, is a combination of analytical methods on the basis of simplified models of electrical networks and computer simulation.

2. From these analytical relations [9] for electric quantities of the transition process at SPEF the following quantities are:

–transient zero-sequence current and its free components;

– transient zero-sequence voltage and its free components.

– faulted phase current at SPEF, and the faulted phase voltage which parameters also depend on the distance to the fault place.

3. To eliminate the dependence of the information parameters of electrical quantities of the transition process from the initial phase of the insulation breakdown for distant SPEF determination normalized values of the free component of transient currents and voltages must be used. Normalized values are obtained by multiplying the measured values by the ratio of the amplitude of the phase voltage to the initial value of the faulted phase voltage at the time of the insulation breakdown.

4. The main factors affecting the accuracy of measurement of electrical quantities information parameters of the transition process at SPEF, include:

– transient resistance at the fault place R_t;

– value of the total capacitive current of the network $I_{C\Sigma}$;

– inductance of the power supply;

– grounding mode of the network.

5. The analytical solutions show that the most informative value for problem of distant SPEF determination is the initial value of derivative of the current $3i_0'$, which depends only on the distance to the SPEF place, and varies in direct proportion to the distance.

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