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Information and Computer Complex for Identification of Single-Phase Earth Faults in Electric Networks of 6-10 kV

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Abstract: The original structure of Information and Computer Complex (ICC) for identification of Earth fault modes in phases of 6-10 kV electric networks of agricultural consumers is given in the study. The principle of operation of the complex is based on the analysis of two stages of the transient mode of the Single Phase Earth Faults (SPEF): the discharge of the phase capacity in which an electrical short occurred and recharge of the phases capacities that remained without damage. The ICC contains controlling, measuring, computing and software components that allow to identify the place where the SPEF occurs and determine the distance to it without disturbing the power supply to consumers, that is without switching off the voltage. The sources of the information are the parameters of the transient process of the SPEF: the shock current at the moment of electrical short, the voltage at the neutral, the amplitude values of the currents on the line after the electrical short and the natural frequencies of the discharge and recharge processes. Measuring transformers of current and voltage, voltage and current filters, comparators, phase-sensitive rectifier and a single-vibrator are used as control and measuring devices. The software and computing components of the ICC are original. The results of experimental verification of the functioning of the ICC for air and cable power line confirming its ability promptly to identify the birth of the SPEF and accurately to determine the distance to it.

Key words: Information and computer complex, electric network, single-phase earth fault mode, controlled parameters, identification algorithm, ICC

INTRODUCTION

The emergency regimes arising in the electrical networks of agricultural consumers with a voltage of 6-10 kV amount 65, 80% of all types of damage. This type of electrical short is due to congestion of rural networks and the deterioration of electrical equipment. The search for determination of the fault location is usually carried out when the damaged line is disconnected from the voltage which leads to a breakdown in the uninterrupted power supply of consumers and the infliction of technological and economic damage to enterprises (Abdullazyanov, 2014).

The known devices do not allow to reliably identify, monitor and diagnose the emergency modes of the 6-10 kV transmission lines when there is SPEF, since, only the estimated distance or the possible zone with a large measurement error in which the short-circuit occurred is determined (Borkovsky *et al.*, 2014). In the study of Shuin and Filatova note the need to improve the

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accuracy of measuring instruments. "The higher the accuracy of determining the distance to the SPEF, the shorter the length of the proposed damage zone is and the less time it will take to find the fault location".

In electrical networks of 6-10 kV, both stable and unstable short circuit can arise and search for unstable one is more difficult compared to stable one. In his research Abdullin notes: "Sometimes when there is unstable damage, there are no signs of damage at all and after disconnecting the line, it is not possible to find damage and to determine the distance to the place of such damage, the means of Determining the Fault Location (DFL) must operate before the line is disconnected from the network or before they are eliminated".

The development and improvement of DFL facilities in the 6-10 kV electric networks with SPEF under working voltage is promoted by the developments of many domestic and foreign scientists as well as specialists in the field of electrical engineering and electric power industry over the past decades.

So, in the research of Abdullazyanov (2014) for efficiency and accuracy increase, DFL is determined by the frequency characteristics of the networks. Abdullin in his research considered the approach to determine the emergency mode using a diagnostic sensor based on the fuzzy logic apparatus. In his research Baiburin, describes the original ways of solving the SPEF problem and proposes algorithms, programs, measuring and computing devices for finding the damage location with an experienced test of the operation. Kulikov and Lukichev (2016) in his research presented the technique of DFL in transmission line due to instantaneous values of oscillograms of emergency events and a software and hardware complex for its implementation. The research of Krasnykh *et al.* (2017) is devoted to the investigation of the current spreading zone in the SPEF. In the research of Shalin, the peculiarities of the earth fault in the 6-35 kV transmission lines are reflected and protection devices are proposed. The research of Shuin is devoted to the study of dynamic modes of functioning of an electrical network with current protection from the earth faults. The research of J.L. Blackburn is devoted to the principles of construction and application of relay protection from SPEF. Brahma (2005, 2006) proposed a new scheme for replacing the network to investigate ground fault processes and conduct synchronized voltage measurements. In the research of Izykowski *et al.* (2010) and others an algorithm of spacing the ground-fault location in a two-way power line was investigated. Kezunovic and Perunicic (1995) in his research provides operational and non-operational data for identification of fault detection signals and the elimination of accidents. Thompson (2011) examines the features of fault location in networks built on the basis of the concept of "Smart Grid".

Despite numerous studies in this field, the existing methods and devices for identifying and spacing the SPEF, currently used in regional distribution electric grids, do not take into account the technical features and operating conditions of the networks and are focused mainly on relay protection for analog substations (Abdullazyanov, 2014). The introduction of digital substations in the concept of smart grid (Thompson, 2011; Abdullazyanov, 2014) provides the combination of relay protection with the functions of information and measuring systems that ensure the established requirements for the quality of electrical energy, since, changes in the quality of electrical energy are significantly influenced by emergency regimes caused by the emergence of the SPEF in electrical networks of 6-10 kV (Thompson, 2011; Abdullazyanov, 2014).

The problem of studying the modes of 6-10 kV electric networks with SPEF and the development of devices for on-line diagnostics and determination of the distance to the fault site remains urgent. For example, in the study of Borkovsky *et al.* (2014) problems of diagnostics in networks with an isolated and compensated neutral are noted and difficulties in implementing algorithms of relay protection devices from the SPEF.

To solve this problem, the researchers suggest to introduce universal software and hardware complexes at substations to identify the parameters of the transient modes of the SPEF without disconnecting the voltage from consumers.

The purpose of the study is the algorithms of functioning of the original ICC, containing standard control and measuring components and software for identifying the modes of the emergence of SPEF in networks of middle voltage class with isolated neutral.

MATERIALS AND METHODS

During the research, methods of electromagnetic processes in the electric power industry, methods for calculating and analyzing the parameters of transient processes in the SPEF mode were used, methods of constructing information and computing systems for analyzing emergency modes and determining its location, software products of design center design lab release 8. The bases of the method of identifying the emergency mode are the stages of the transient process in the SPEF: the discharge of the capacity of the phase closed to the earth and the recharging the capacity of phases remaining in the research.

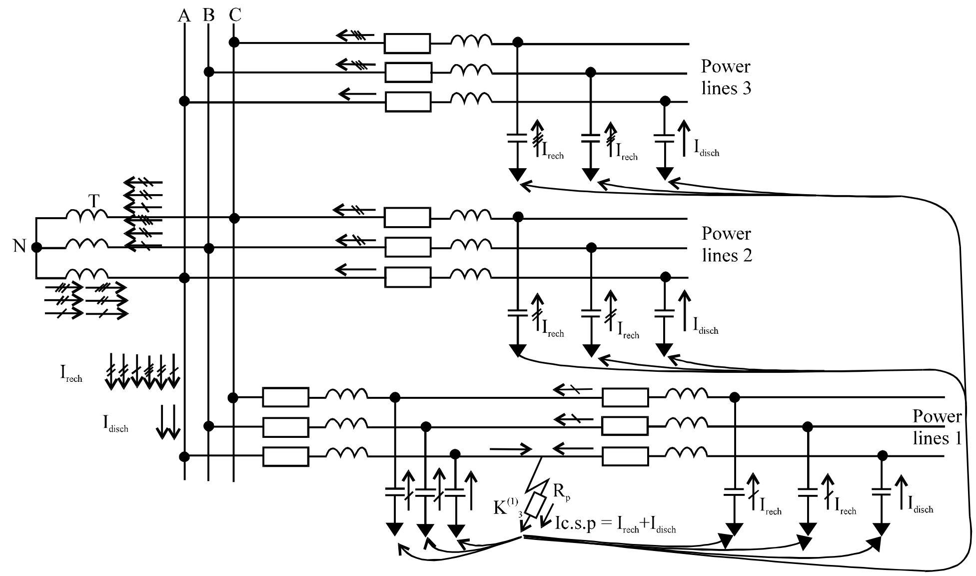

Fig. 1: Diagram for the analysis of SPEF: N) The isolated neutral; T) The secondary winding of the power transformer, TL1, TL2, TL3-power lines; $K_3^{(1)}$) The current at the point of fault; $I_{pa3p.}$) The discharge current of the capacity of phase A which has closed to the earth; I_{3ap}) The recharge current of undamaged phases capacity; R_n) The transient resistance at the point of fault and I_{033}) The current of single-phase earth fault

RESULTS AND DISCUSSION

The derivation of mathematical relationships for determining the location of the damage in the SPEF is carried out on the basis of a scheme substituting the electrical network with the earth fault of one of the phases of the transmission line proposed by Baiburin (Fig. 1).

The identification of the SPEF regime consists of three cycles: in the first cycle, the earth-closed phase is determined in the second-the parameters of the transient process are measured in the third after the completion of the transient process, the parameters are analyzed and the distance to the fault is calculated.

Let us consider in turn a transient process in the SPEF mode of phase. A with a capacity discharged and closed to the earth and the recharging of capacities of phases B and C that have not been damaged.

The calculation of the distance to the fault location from the analysis of the transient process of the capacity discharge of the closed phase is carried out according to Eq. 1:

$$l_K = \frac{1}{L_0} \cdot \frac{u - i\frac{U}{I_{m1}}\ln\frac{I_{m1}}{I_{m2}}}{\frac{di}{dt}} \quad (1)$$

Where:

L_0 = The specific value of the inductance of the closed line, per unit length (H/km)

u, U = The instantaneous and effective values of the voltage on the isolated neutral (N, B)

i = The instantaneous value of the current at the moment of SPEF (A)

I_{m1}, I_{m2} = The amplitude values of the currents that follow each other on the line after fault (A)

The derivation of the algorithm for identification of the SPEF taking into account the additional charging of the capacities B and C remaining in the research is illustrated by the diagram shown in Fig. 2.

The phase A which is closed to the earth is determined from the value of the shock current I_{yz} (Fig. 2b). The substitution scheme for the damaged phase and undamaged phases are shown in Fig. 3. The formula of calculating the distance to the fault taking into account an additional charging of phase capacities without damage has the form (Eq. 2):

$$l_K = \frac{1}{L_0}\left(\frac{2I_{m1}^2 - U^2 \ln\left(\frac{I_{m1}}{I_{m2}}\right)^2 C}{2\omega_{dH}^2 C I_{m1}^2} - \frac{4I_{m1}^2 - U^2 \ln\left(\frac{I_{m1}}{I_{m2}}\right)^2 C}{4\omega_{d\Pi}^2 C I_{m1}^2} \right) \quad (2)$$

Where:

L_0 = The linear inductance of the line (H/km)

C = The capacity of the entire line (mkF)

ω_{dn} = The frequency of the transient process with the capacity discharge of the phase closed to earth (c^{-1})

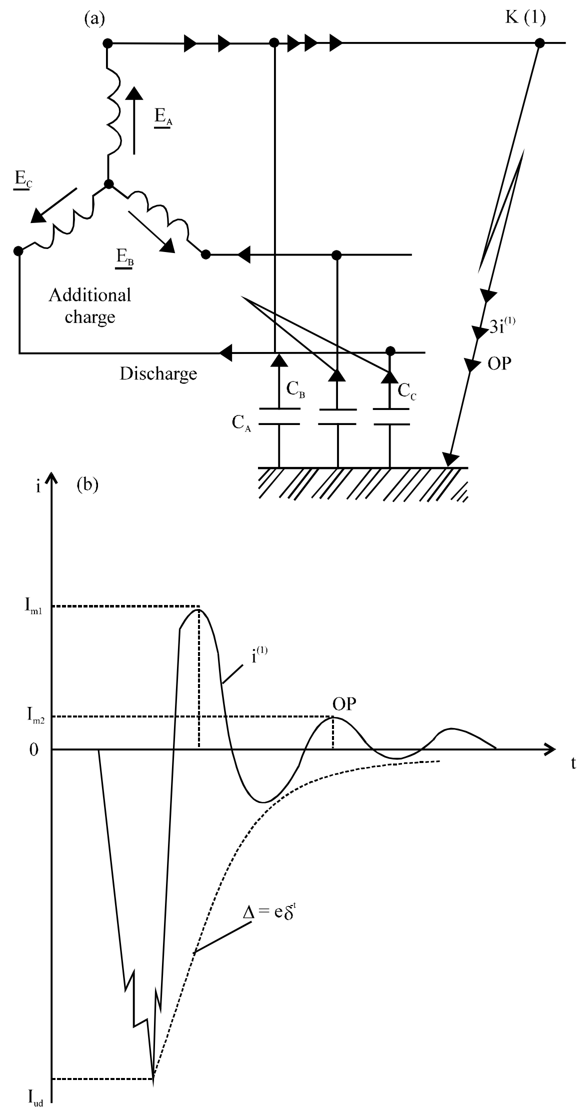

Fig. 2: Diagram of derivation of the algorithm for identification of the SPEF taking into account the recharging of the phases capacities remaining in the research: $K^{(1)}$) The earth fault point of the phase; A, E_A, E_B, E_C) The EMF of the secondary winding of the transformer; C_A) The capacity of the damaged phase A, C_B and C_C) The capacities of undamaged phases, B and C, $i^{(1)}$) Zero sequence current; $3i^{(1)}_{on}$) The total current of the transient process and $I_{уд}$) The shock current

$$\omega_{d\Pi} = \sqrt{\frac{1}{(L_{НЛ}+L_K)C} - \frac{R^2}{4(L_{НЛ}+L_K)}} \tag{3}$$

ω_{di} the frequency of the transient process with additional recharge of the capacities of the remaining phases (c^{-1}):

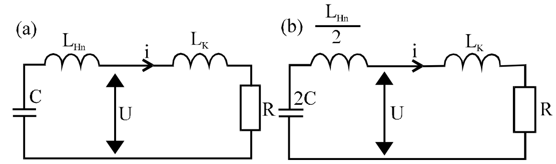

Fig. 3: Network substitution schemes in SPEF: a) In the damaged phase and b) In undamaged phases

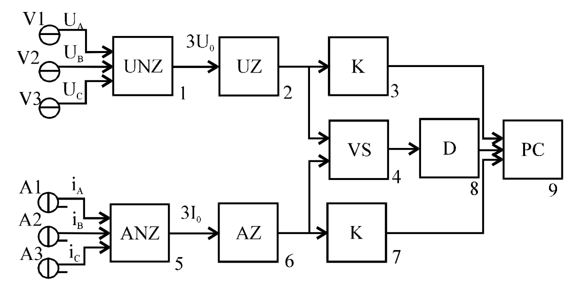

Fig. 4: The scheme of information and computer complex for identification of the SPEF

$$\omega_{dH} = \sqrt{\frac{1}{\left(\frac{L_{НЛ}}{2}+L_K\right)2C} - \frac{R^2}{4\left(\frac{L_{НЛ}}{2}+L_K\right)}} \tag{4}$$

Where:

- U = The voltage in the isolated neutral (B)
- I_{m1}, I_{m2} = the current amplitudes of the damaged line, following one another (A) (Patynowski *et al*., 2015)
- $L_{hл}$ = The inductance of undamaged line (H)
- L_k = The inductance of the closed line to the earth (H)
- R = The active resistance of the closure loop (Ω)

The implementation of Eq. 1 and 2 is carried out with the help of an information computer complex Fig. 4. The Information computer complex consists of two subsystems: information-measuring and information-computing.

The composition of the information and measuring subsystem includes: primary measuring current transducers (A_1-A_3), primary measuring voltage transducers (V_1-V_3), zero sequence voltage (UNZ) 1 and current (ANZ) 5 filters, voltage (UZ) 2 and current filters (AZ) 6, comparators (K) 3 and 7, a phase-sensitive rectifier (VS) 4 and a single-oscillator (D) 8.

The information and computing subsystem includes a Personal Computer (PC) 9 and an information display device.

The primary measuring current transducers (A_1-A_3) are scaled and designed to convert primary values of load currents to secondary values I_A-I_C, perceived by zero-sequence current filter ANZ. As primary measuring current transducers (A_1-A), 3 current measuring transformers are used, the type and brand of which is selected according to the calculated values of load currents and accuracy class in accordance with the requirements of GOST 7746-2015 current transformers. General technical specifications.

The secondary windings of the current measurement transformers connected in parallel form zero-sequence current filter ANZ which extracts the earth fault current from the load currents I_A-I_C, equal to triple zero sequence current ($3I_0$).

The Primary Measuring Transducers (PMT) of voltage (V_1-V_3) are also scaled and designed to convert primary values of phase voltages to secondary values U_A-U_C, perceived by the zero-sequence voltage filter UNZ. As a PMT of voltage it is recommended to use three-phase voltage measuring transformers, the type and brand of which should be selected according to the rated voltage of the electrical network and the accuracy class in accordance with the requirements of GOST 1983-2015 "Voltage transformers. General technical requirements.

The secondary winding of the voltage measuring transformer connected in the open triangle circuit is used as zero-sequence voltage filter which extracts the neutral voltage equal to the tripled value of zero-sequence voltage filter $3U_0$ from the phase voltages U_A-U_C.

The voltage circuit filter UZ provides the highest harmonic voltage, suppressing the first harmonic of the voltage of the industrial frequency. To measure the natural frequency of the transient process voltage on the neutral, a comparator (K) 3, performed on an operational amplifier is designed. The filter of the current circuit AZ suppresses the first harmonic of the current of the industrial frequency, producing harmonics of current higher frequencies and let them pass without damping. The filters of voltage circuits UZ and current AZ are T-shaped RC filters. To measure the natural frequency of the transient voltage on the neutral, the comparator (K) 3 is designed. The comparator (K) 7 is used to measure the natural frequency of the earth fault transient current. The comparators (K) 3 and (K) 7 are performed on operational amplifiers. The phase-sensitive rectifier VS determines the sign of the earth fault and damage zone by the signs of the voltage and current pulses. The single-oscillator D determines the polarity of the pulse at the output of the rectifier VS, separating the positive half-waves of voltage and current.

The PC 9 performs the role of analyzer and processing results in accordance with the algorithms for determining the natural frequencies ω_{dp} and ω_{dn} and identifying the location of the damage. The results of the processing are displayed on the computer display. The ICC is installed at the beginning of the monitored transmission line.

Information processing is carried out in accordance with the built-in software, containing:

- A module for specifying the parameters of the electrical network
- A module for collecting measurements results of the transient process parameters in the case of SPEF
- A module for analyzing the electrical network
- A module for choosing the method of calculating the transient process
- A module for calculating the fault location by the algorithm 1 or 2
- A module of output results

The module for setting the parameters of the electrical network records the data before the earth fault: the rated voltage, frequency, load currents, the number of power lines and their length, the type of wires, the type of suspension, the number of branches and the distance to them, the nature of the load, the parameters of the power transformer, the number bus sections operating in parallel, neutral type, types of current and voltage measuring transformers. The entered parameters of the electrical network are stored and used in the operation of all software modules during the operation of the ICC.

When a SPEF occurs, the measurement results collection module starts to record the oscillograms of currents and voltages of the transient process registered with a digital oscilloscope of PCS-64i type. From these oscillograms own frequencies of the transient process ω_{dp} and ω_{dn} are distinguished, the amplitude values of the currents I_{m1}, I_{m2}, voltages and their phases.

The network parameters before the earth fault and the results of the damage parameters measurements are used in the network analysis module to determine the network configuration and the nature of the fault. The network configuration is determined based on the control results on the conditions "Network 1", "etwork 2", "Network 3". The condition "Network 1" assumes the configuration of a dead-end substation with consumers of the third category, from which several air lines of small length and the nature of the damage through a large transient resistance flow. The condition "Network 2" assumes the configuration of the substation with consumers of the first and second categories having a branched network with a large number of outgoing transmission lines of different lengths with branching and the damage nature through an intermittent arc. The condition "Network 3" assumes the configuration of the

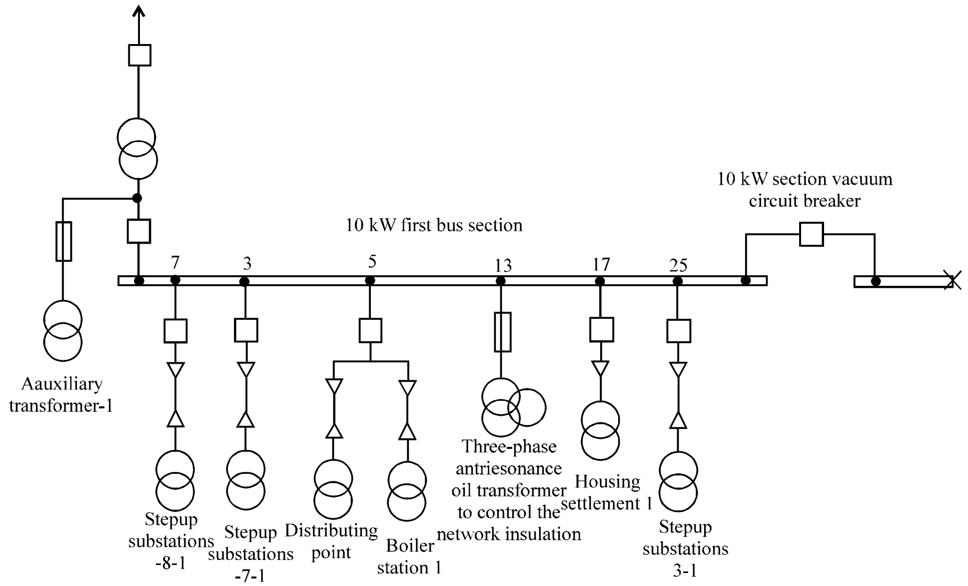

Fig. 5: Fragment of an electrical network section with a fault on the line with a feeder 3

substation with consumers of the first and second categories having a branched network with outgoing parallel lines, a different type of suspension of wires and the nature of the damage through an intermittent arc.

After determining the network configuration and the nature of the damage, a transition is made to the module for selecting the method for calculating the transient process. If the transient process is aperiodic, the identification of the fault location is based on the discharge of the damaged phase capacity. If the transient process is periodic, the identification of the fault location is based on the discharge of the capacity of the phase closed to Earth and the additional charge of the capacity of the remaining phases without damage.

After choosing the method for calculating the transient process, a transition is made to the module for calculating the distance to the fault location according to Eq. 1 or 2. With the help of the output module, the monitor shows the faulty phase, the feeder, the distance to the fault location in meters and the inaccuracies of the DFL.

The operation test of the ICC with the preliminary identification of the SPEF mode is carried out in a 10 kV cable network with an isolated neutral Fig. 5 using the example of a damaged line with a feeder 3. The network model in the case of earth fault of phase A is shown in Fig. 6.

In earth-fault mode of phase A Fig. 6, the undamaged phases B and C of all the lines are represented as two T-shaped substitution circuits. The equivalent elements of the substitution circuit (Resistance R_E inductance L_E, Capacitance C_E) are according to the rules of parallel connection of the elements of the corresponding phases of all lines of the electric network.

The damaged phase A of all undamaged lines is also represented in the form of two equivaged T-shaped substitution circuits with active Resistance $R_{Нл}$ inductance $L_{Нл}$ and Capacitance $C_{Нл}$. The damaged phase of the damaged line is represented by two T-shaped substitution circuits: from the substation to the fault location with the active Resistance R_K inductance L_K and Capacitance C_K;

From the fault location to the end of the line with the active Resistance $R_B = R_л - R_K$ inductance $L_B = L - L_K$ and capacitance $C_B = C_л - C_k$ where $R_л$, $L_л$, $C_л$ are the resistance inductance and capacity of the damaged line.

The power transformer is represented by a three-phase equivalent circuit, taking into account the magnetization of the core. Power from the high side of the transformer is simulated using the EMF system:

$$\begin{cases} e_A = E_m \sin(\omega t + 0°); \\ e_B = E_m \sin(\omega t - 120°); \\ e_C = E_m \sin(\omega t + 120°) \end{cases} \quad (5)$$

as well as active Resistances R_T and inductances L_T, reduced to the voltage of the secondary winding. Key Q-simulates an earth fault at point K through the transient Resistance $R_П$.

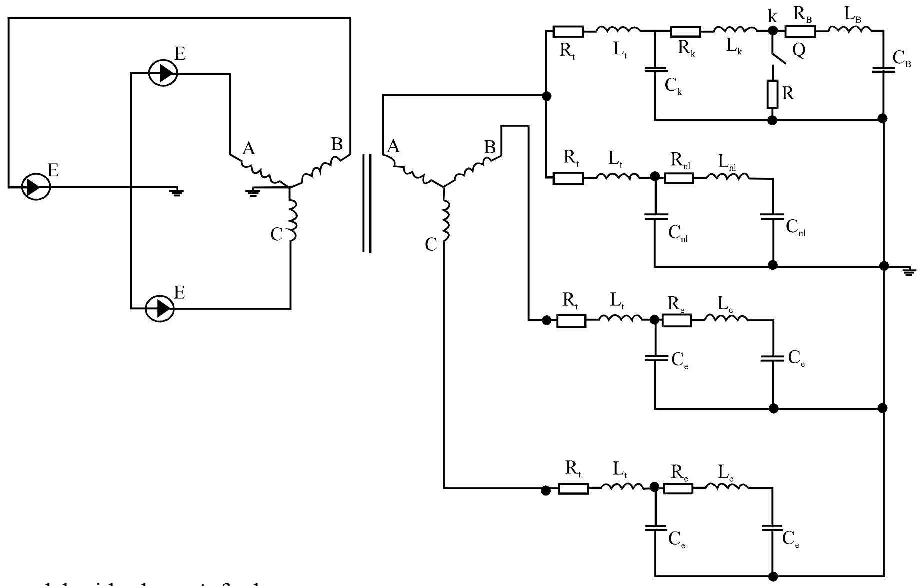

Fig. 6: Network model with phase A fault

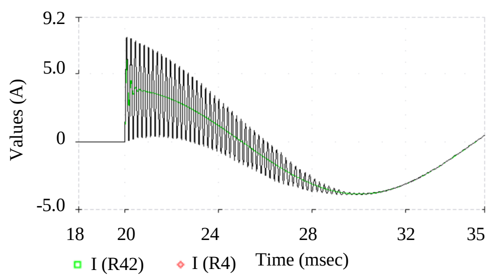

Fig. 7: Calculated values of the transient process parameters

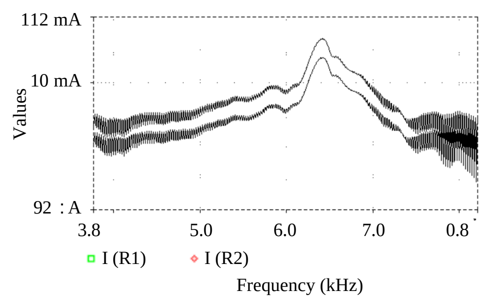

Fig. 8: Spectrum of the current frequencies of the transient process

The calculated values of the natural frequencies of the transient process of currents in the discharge and recharge of capacities are recorded to the computer data base (Fig. 7).

In the case of a damage in the substation, the damaged line and the actual natural frequency of the transient process are recorded using a digital recorder of the PCS type which is compared with the calculated frequencies recorded in the database and the distance to the fault location is determined with an accuracy determined by the step of setting the distance to the fault location (Fig. 8).

The calculation of the transient process was performed using the software product design center designlab release 8. As the initial data accepted: 10 kV network is made of AABlU cable 3×150 mm^2, the total network length is 4 km, the length of the damaged line is 2 km, the step of changing the distance is 10 m, the change step of the transient resistance at the fault location is 10 Ω.

RESULTS AND DISCUSSION

The described ICC is universal, since, its operation algorithm realizes two parts of the transient process in the SPEF mode: the charge of the phase capacity closed to the earth and the recharging of the capacities of the remaining phases. The ICC allows early recognition of the emergency mode by measuring the natural frequency of the current transient process and its decay time, further comparison with the calculated frequencies of the SPEF modes in the computer database and determining the distance to the fault location with accuracy depending on the specified distance step and the transient resistance. Errors in measuring the distance to the fault location on the basis of the natural frequencies of the transient process ω_{dp} in discharge and ω_{dr} in recharging are determined by the metrological characteristics of the current and voltage measuring transformers used which is confirmed by the results of the studies described in (Lebedev *et al*., 2014).

The speed of identification of an emergency mode is determined only by the duration of the transient processes of currents and voltages in electrical networks and amounts to a few milliseconds which is also confirmed by studies carried out by the researchers (Abe *et al*., 1995).

The proposed ICC meets the modern requirements of the electric power industry (GEM., 2015). Installation of the ICC at the substation allows to determine with high speed and accuracy with Eq. 1 and 2 the distance to the fault in electrical networks of 10 (6) kV without disconnecting the voltage from consumers. The choice of the corresponding algorithm is carried out by the type of the transient process in the network in the SPEF established by the results of measurements of the transient process parameters.

If the transient process in the network during the SPEF is aperiodic, then an algorithm should be chosen to identify the distance to the fault location 1 based on the capacity of the damaged phase. However, the use of the identification Eq. 1 phase shifts between current and voltage in the first half-cycle of transient processes (Krasnykh *et al*., 2017). Distortions of the phase relationships between current and voltage are due to the presence of angular errors in both the current and the voltage measuring transformers but they can be taken into account in processing the measurement results by including corrections, since, these errors are systematic.

If the transient process in the network is periodic, then it is recommended to use the identification Eq. 5 based on the discharge of the damaged phase capacity and additional recharging of undamaged phases capacities.

During the measurements current transformers of the TOL-10 series with accuracy class 0.2%, a three-phase voltage measuring transformer of the NAMI-10-U2 series with accuracy class 0.2%, a digital oscilloscope of PCs-64i type performing the functions of the blocks 2, 3, 4, 6, 7, 8 and a Pentium IV type computer were used.

Equation 2, carrying the information of the natural frequency of the transient process, used to calculate the distance to the fault location is advisable to use for 10 (6) kV electric networks with a high probability of arc faults and faults through a significant transient resistance.

In order to increase the reliability of the received information of location and nature of the damage, it is recommended to use current-voltage measuring transformers of the TOL-10 series with accuracy class 0.2% and anti-resonant voltage transformers of the NAMI-10-U2 series with accuracy class 0.2% as an analyzer a digital oscilloscope type PCS-64i and a computer type Pentium IV.

During the experimental verification of identification Eq. 2, it is established that the time to determine the distance to the fault location at a distance from the bus substation of 3 and 6 km is 5 and 8 msec. The instrumental error in determining the distance to the point of fault location caused by the error of the measuring instruments used above was respectively in absolute units of 4.8 and 10.2 m or 0.16 and 0.17%.

CONCLUSION

The described method of preliminary identification of the beginning of earth faults in 6-10 kV electric networks by means of an information and computing complex is expedient for introducing in rural substations, from which air or cable-air power lines of different lengths or parallel lines of other substations take beginning. The preliminary identification allows you to quickly identify an emergency situation on the line, determine the location of the damage, clarify the distance to it, display information on the computer monitor and quickly eliminate errors without disconnecting consumers.

The information and computer complex allows you to quickly determine the presence of a damage in the network due to phase fault, analyze transient processes, based on which you choose the method of determining the distance, taking into account the network configuration such as line, wire mark, branches and transient resistance at the fault location, change of lines input resistance in case of change of the fault location, calculate the distance from the substation to the fault location of the transmission line with an error not exceeding 0.2% and display the information on a computer monitor.

The information and computer complex for identification of single-phase earth faults of 6-10 kV electric networks contains standard control and measurement algorithms, built-in software modules for analysis of transient processes in the SPEF mode and choose the method of defining the fault location and is designed for installation in 6-10 kV electrical networks with isolated or compensated neutral.

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