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MODERN DEVELOPMENT PRINCIPLES OF PROTECTION AND DIAGNOSTICS IN MINING FACILITIES MAINS AND DISTRIBUTION GRIDS

Introduction. Electrical power systems grids and equipment of mines and quarries in Ukraine are operated in very specific circumstances, which to a large extent determine the level of power supply reliability and electrical safety. Improving of the electrical safety conditions and the reliability of mining facilities power supply depends on the successful resolution of the range of issues, the most important of them are problems of creation of methods and tools that provide prevention, search and restoration of the power supply damages. Analysis of operational crash data in mining facilities distribution grids shows that the share of ground faults is up to 65…90% of the total number of failures, most of which are related to the phase-to-ground insulation violation of the grid, i.e. to asymmetric faults emersion /1, 2/.

The main results of the research. Most of the damages in the distribution grids lead to a decrease in the level of electrical safety and reliability of electricity supply. Further, the reduction of power supply reliability leads to an increase in the share of losses from power supply outage. In general, this damage is determined by the duration of mining and transport machines idle-time and, thereafter, leads to product undersupply. Unwarranted downtime of mining and support mechanisms occurs as a result of wrong action of first and second protection level devices against ground faults due to the significant time searching for missing damages (with a false protection devices actuation). In addition, the ground-faults are often the cause of multi-phase damage, thereby increasing the amount of machinery idle.

The reliability of power supply is largely dependent on the quality of the ground fault protection functioning in the distribution grid. Furthermore, it was found that, ceteris paribus, the quality of named protections depends on the structure and construction of the neutral mode. The studies have shown that the main cause of false protection actuation against ground faults in networks with fully insulated or compensated neutral should be considered as the emergence in the network, after turning off the damaged connection (or damage self-destruct), an oscillatory process with a frequency close to the 50 Hz. In general, the time-changing process of the neutral shift voltage in system after disconnection or damage disengagement can be described by a differential equation

$$\frac{d^2U_0(t)}{d\ t^2}+\left(\frac{3R_{í}+R}{3\ \omega C\ R_{í}\,R}\cdot\frac{dU_0(t)}{dt}\right)-\frac{1}{3C\ L_p}U_0(t)=0\,, \tag{1}$$

whose solution and results analysis is made with a real parameters of distribution grids with different types of ground, led to the following conclusions:

1. In power networks with completely insulated neutral the transient process form (natural frequency and duration of the process) is mainly determined by the total grid capacity relative to the ground and the number of simultaneously switching voltage transformers. For real distribution grids parameters, the transient duration ranges from 2 to 10 commercial frequency cycles, and natural frequency value is typically less than commercial frequency, and the free oscillations frequency, directly in the damping process, changes due to nonlinear character of measuring voltage transformers reactance.

2. In compensated neutral networks the voltage damping is determined mainly by relative to the ground insulation parameters of the distribution grid and doesn’t depend on the compensation device params. Natural frequency and the time constant of decay in compensated networks significantly higher than similar characteristics in networks with a fully insulated neutral. The nature of the transient process, ceteris paribus, depends on the compensating device settings.

3. The transient process in networks with the neutral resistor to a large extent dependents on the value of the resistor. If resistor is installed with resistance, chosen from the condition that active component of the single-phase ground fault current value is 50% of the capacitive current, due to a sharp increase in the damping coefficient, the transient process is almost finished in a half-period of industrial frequency.

To study the characteristics of zero-sequence voltage and current in the steady ground fault state we used the equivalent circuit of the two connections that are connected to a single power transformer. In this case, the admittances of the applicable phases insulation of controlled connection ($Y_{A1}=Y_{B1}=Y_{C1}=Y_1$) and all the rest of the distribution grid $(Y'_A=Y'_B=Y'_C=Y')$ are related by the ratio $Y_1+Y'=Y$. For this scheme, in general, to the condition of single-phase ground fault in a controlled affixion or in the external network, could be written an expression:

- for the zero sequence voltage:

$$\dot{U}_0=-\dot{U}_A\frac{y_1}{3Y+Y_H+y_1};\ \text{or}\ \dot{U}_0=-\dot{U}_A\frac{y}{3Y+Y_H+y}, \tag{2}$$

- for the zero sequence current at the damage in controlled line

$$\dot{I}_0=-\dot{U}_0(3Y+Y_H{}') = -\dot{U}_A(3Y-3Y_1+Y_H)\frac{y_1}{3Y+Y_H+y_1} \tag{3}$$

- for the natural current in controlled line (zero sequence current at the external ground fault in controlled line).

$$\dot{I}_{OC}=3\dot{U}_0Y_1=-3\dot{U}_A\frac{y}{3Y+Y_H+y} \tag{4}$$

where $Y_{í}$ - neutral point admittance relative to the ground.

The studies of these relations on the impact on the zero-sequence voltage and current values of the insulation and the neutral operational mode and their analyze lead to the conclusion:

- zero-sequence voltage is determined by the parameters of network insulation relative to the ground, by network neutral point admittance relative to the ground (the degree of arc suppression coil resonant mode mismatch (for compensated grids) and the transient resistance value at the point of phase-to-ground.
- in a phase-to-ground short circuit (zero impedance) the compensating device mode does not affect on the value of zero-sequence voltage, which at such damages equals to a phase voltage of the power network;
- zero sequence current in the damaged line is defined by zero sequence voltage, by insulation parameters of an external network relative to the ground, that is, parameters of insulation of all network relative to the ground (including neutral point admittance) minus parameters of insulation of the damaged affixion;
- natural current of controlled affixion (zero sequence current at the external damage in controlled line) is determined by zero-sequence voltage and insulation parameters relative to the ground only in controlled affixion;
- current in the network neutral (in the compensating device or in the neutral resistor) at ground fault is defined by zero sequence voltage and by the compensating device or the resistor direct parameters.

For directional protection devices responsive to the zero-sequence power is also required to consider the phase or the mutual position of the compared values, i.e. the voltage and zero sequence currents vectors position. The characteristics of natural current of the protected line and current in a network neutral are of interest from the point of the creation of new methods and tools of directional protective devices or ground fault alarms

By phase characteristics research results taking into account real values of parameters of insulation relative to ground of the whole network and separate affixion, and also in view of a real mutual ratio of capacitor and active resistance of insulation, it is possible to draw the following conclusions:

1. The Grid with the full insulated neutral

- the angle between the zero sequence voltage vector and the damaged phase voltage vector changes ranging from 180 to 90 at change of transient resistance in a short circuit point from zero indefinitely;

- the angle between the zero sequence current vector and the zero sequence voltage vector doesn't depend on completeness of short circuit (transitional resistance in a short circuit point) and makes nearly 270 el. degrees, or minus 90 el. degrees.

- the angle between the own current vector of the controlled line (zero sequence current in the controlled line at external short circuit of one phase) and the zero sequence voltage vector is defined by relative to the ground insulation parameters of only controlled affixion and makes nearly 90 el. degrees.

2. The Grid with the compensated neutral

- the angle between the zero sequence voltage vector and the damaged phase voltage vector depends on parameters of network insulation, parameters of the compensating device and transient resistance value in a place of short circuit and can accept values in the range from 90 to 270 el. degrees, i.e. theoretically within 180 el. degrees. When the compensating device is tuned-up in a resonance with a network capacity relative to the ground the specified angle is almost equal 180 el. degrees and doesn't depend on parameters of a network and transient resistance value in a short circuit point;

- the angle between the zero sequence current vector and the zero sequence voltage vector doesn't depend on completeness of short circuit (transient resistance in a short circuit point) and is defined substantially by value of compensating device detuning from a resonant mode and for resonant tuning makes almost 180 el. degrees; in case of compensating device detuning from a resonant mode, both towards overcompensation, and towards undercompensation, the current vector deviates on an angle, accordingly, to plus and a minus 90 el. degrees, in such way the range of angle change theoretically makes 180 el. degrees;

- the angle between the natural current vector of the controlled line and the zero sequence voltage vector is defined by insulation parameters related to ground of only controlled affixion and makes 90 el. degrees;

- the angle between the current vector in the arc suppression coil and the zero sequence voltage vector is determined only by the arc suppression coil parameters and for their real value is 90 el. degrees.

3. The Grid with the resistor in a neutral

- the angle between the zero sequence current vector and the zero sequence voltage vector doesn't depend on completeness of short circuit and, unlike networks with full insulated neutral, is equal to value ranging from 180 to 270 el. degrees; for real parameters of network insulation related to the ground, and the recommended value of $R_H = (1...2)\,X_C$ this angle is about 225…240 el. degrees;

- the angle between the natural current vector of the controlled line (zero sequence current in the controlled line at external short one phase circuit) and the zero sequence voltage vector is determined by the parameters of the related to the ground insulation of only controlled affixion and is almost 90 el. degrees;

- the angle between a current vector in the resistor which has been switched on in a neutral of a grid and the zero sequence voltage vector doesn't depend on parameters of insulation of the network, the resistor and a short circuit mode and matches in the direction with the zero sequence voltage vector (the angle is equal 0 el. degrees).

It is important to note that the natural current phase of controlled affixion doesn't depend on a neutral operating mode, and is defined only by parameters of directly controlled affixion and is almost rigidly attached to zero sequence voltage.

The received results formed a basis for development of a way and creation of the protection device against leaks and short circuits on the ground for the mine distributive grids, using for definition the damaged affixion, except zero sequence voltage and current, the phase voltages of the grid /1/.

The principle of this protection method is based on the performance evaluation of the relative position of zero sequence current vectors and phase voltage vectors. Based on a sinusoidal signal phase voltage pulses are formed with a time interval which is equal to 120 °. The zero-sequence current signal also converted into pulses shifted in phase by 90 °, with an interval of 360 °. At coincidence pulses of voltage and current (corresponding to the damaged affixion), the signal to turn off the damaged circuit is formed. Thus on the unimpaired affixion impulses of zero sequence current are displaced on 180 ° and don't coincide with phase voltage impulses. This principle can significantly increase the sensitivity of the protection devices against ground faults and make it virtually independent of the total grid capacity, related to the ground.

Double ground short circuits in different points of a distributive grid are, as a rule, development of single-phase damages and are caused by influence of the internal overvoltages appearing thus. It is necessary to distinguish two main types of double short circuits on the ground: damage of related to the ground insulation of the same phase in two points of a distributive grid; damage of related to the ground insulation of different phases of a distributive grid.

Damage to the insulation of the two points of one phase of the distribution grid can be represented by the following failure modes: damages to two points of the controlled line; in two points of an external grid; in the controlled line and in an external grid. These emergency conditions correspond, in general, a single-phase ground short circuit via the contact resistance whose value is equivalent to two parallel resistances at different points in the network. The third case at which the zero sequence current value in the controlled line will depend on a ratio of transitional resistance value is of interest and with sufficient accuracy for practical calculations determined by the expression:

$$I_{01}^{(1)} \approx I_3^{(1)} r/(r_1+r), \tag{5}$$

Where $I_3^{(1)}$ - total current of single-phase short circuit on the ground.

The second type of double short circuit has several varieties, differing in the mutual arrangement of damaged areas concerning the controlled affixion. In this case it is necessary to observe the following emergency modes in a insulated neutral network:

- related to the ground insulation damage in two phases of the controlled line:

$$\dot{I}_{01}^{(1.1)} = -3\dot{U}_0^{(1.1)}\left(Y-Y_1\right), \quad \text{or} \quad \dot{I}_{01}^{(1.1)} = \frac{-3\dot{U}_A\left(Y-Y_1\right)\left(y_{1A}+a^2 y_{1B}\right)}{\left(3Y+y_{1A}+y_{1B}\right)}; \tag{6}$$

- insulation damage to two phases to an external network

$$\dot{I}_{0C}^{(1.1)} = 3\dot{U}_0^{(1.1)} Y_1 = \frac{-3\dot{U}_A Y_1\left(y'_A + a^2 y'_B\right)}{\left(3Y + y'_A + y'_B\right)} \tag{7}$$

- insulation damage in the two phases at different affixions (one - damaged in a controlled phase line, the other - on the external network)

$$\dot{I}_{02}^{(1.1)} = \dot{U}_A \frac{y_{1A}\left[3(Y-Y_1)+y'_B\right] - a^2 y'_B(3Y_1+y_{1A})}{3Y+y_{1A}+y'_B}. \tag{8}$$

The analysis of research results of zero sequence voltage and currents at double short circuits on the ground in distributive grids with the insulated neutral allowed to estimate influence of distributive grid insulation parameters, contact resistance in short circuit points on character of values change and the provision of zero sequence voltage and currents vectors. It is established that value of contact resistance in damage points has defining impact on operating value of zero sequence voltage. The influence of the distribution network insulation parameters to the value of zero sequence voltage is shown mainly at relatively high values of resistances. The phase of zero sequence voltage also substantially is influenced by a mutual ratio of values of contact resistance in points of damage and to a lesser extent by parameters of a distributive grid. The position of zero sequence voltage vector in relation to the phase voltage vectors in the double ground faults can theoretically vary between 210 °. In grids with compensated neutral the angle between zero sequence voltage and current in the double ground fault is not fixed, and is determined generally by the compensating device setup mode and the contact resistance values ratio in points of short circuit and can change within 300 el. deg.

So far the automatic reclosing devices almost didn't expand in distributive grids of opencast mining. Development and deployment of such devices restrains many factors, basic of which are:

- the design of power switching distributing devices, precluding the possibility of connecting the operational power supply;
- the existence of a sufficiently long run-out voltage at the powerful quarry electro receivers;
- rather high probability of non-actuating (in consequence of the mechanical system damage) of one or all phases by the switch after command for shutdown.

The main characteristics, reflecting conditions of electrical safety at operation of automatic reclosing devices in quarry power networks and demanding justification, are:

- setpointing of automatic reclosing device ban on level of active resistance of insulation related to the ground of the disconnected affixions;
- value of the operational power supply voltage for control of the disconnected affixions insulation.

From the insulation condition assessment point of view, operational voltage for insulation control of the disconnected affixion has to be close or equal to the working voltage of a grid. However, proceeding from electrical safety conditions, providing demands are made to a source and level of operational voltage in the following conditions:

1) the source is connected to the line which current carrying parts may be touched by people;
2) the person touches already disconnected line which own capacity is loaded up to the voltage of the operational power supply.

According to the requirements of the automatic reclosing devices for quarry power networks the algorithm of work of its logical part which realizes the following functional instructions is developed:

- AR start from the action of protection against ground fault or overcurrent protection (if necessary);
- counting the time delay required to reduce to a safe level of EMF motor runout;
- control of a voltage applied to affixion of the disconnected phase and the development of an appropriate command to continue or ban reclosure;
- connect to affixion of the disconnected phase source of DC;
- related to the ground insulation resistance measurement of disconnected affixion and compare it with the set point;
- selection by measuring results and supply to the actuator commands to "switch-on" the circuit breaker or the "switch-on inhibit";
- control of command execution and the transition of the scheme in an initial condition.

The main element of the automatic reclosing devise is program block, based on the Read-only memory (ROM) and implements a given algorithm. As indicated in the diagram: CPG - current pulse generator, produces a square wave with the frequency of 50 Hz and necessary to synchronize the device; FD - frequency divider, designed to convert CPG to communicate with the address inputs program block; HVMU- high voltage monitoring unit; CUSA - the control unit switches of BB-20 affixion device when performing monitoring presence on the power line voltage and insulation resistance to ground power line; AD - affixion device designed to communicate with the device disconnected line recloser; IMU - insulation monitoring unit that provides measurement and evaluation of the insulation level to ground disabled power line; CUCB - the control unit circuit breaker of served affixion /2/.

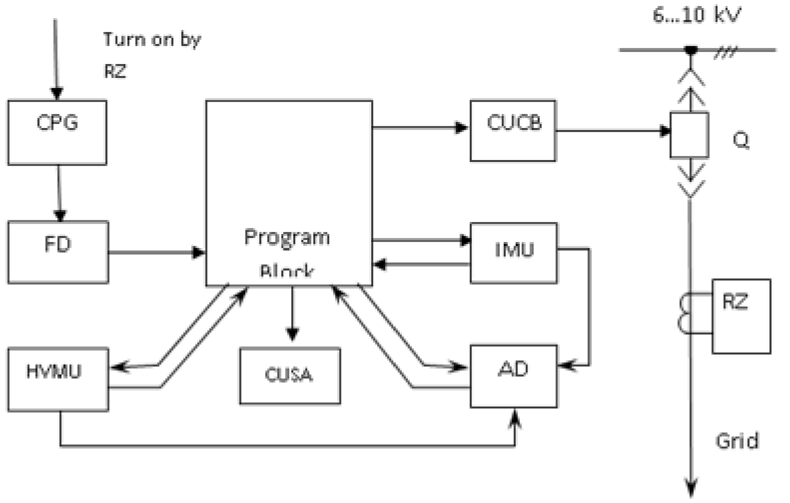

Fig. 1. The functional diagram of the AR for quarry power network

The developed automatic reclosing devise consists of three main components: insulation monitoring and control unit; connection device; the sensor of the high voltage existence, intended for installation in cells of mobile and stationary quarry distributive substations of power supply systems with the insulated and compensated neutral and with a working voltage of 6... 10 kV. The device can come into action from operation of protection against short circuits on the ground and, if necessary, the maximum current protection.

To predict the level of electrical safety and reliability of electrical grids and equipment in the operation of power systems (any enterprise and the more so quarres) for a number of reasons, primarily one should know the condition of their insulation. Continuous and automatic values control of insulation components of an electric grid (resistance and capacitance of the network phase insulation to the ground, the inductance of the compensating device) will allow predicting emergence of dangerous system conditions and, at available technical capability, to enter the advancing operating commands, allowing to minimize possible damage.

For the specified purposes essentially new way of continuous measurement of component values of insulation resistance related to the ground of an electric grid and its elements under the working voltage is offered. Which essence consists that on an electric network two operational sinusoidal signals are imposed at the same time whose frequencies are not equal and differs from commercial (figure 2).

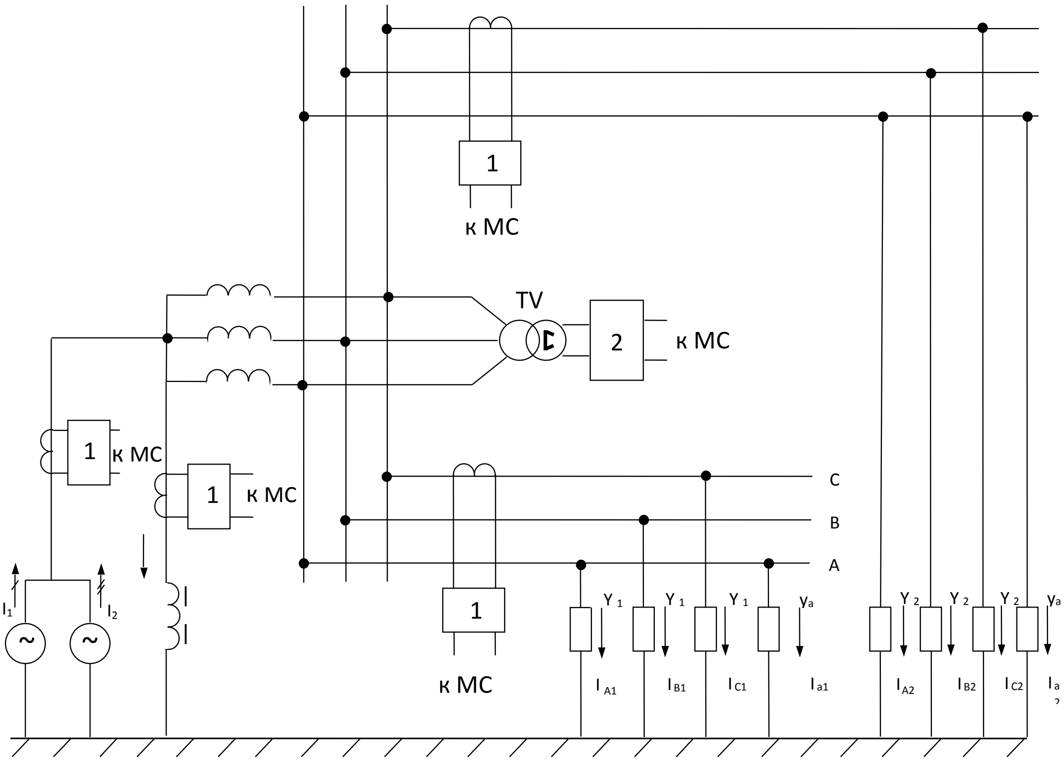

Fig. 2. The diagram illustrating the method of insulation continuous control of the distribution grid
1 - The device of operational currents selection and processing;
2 - The device of operational voltages selection and processing.

The values of insulation resistance R, inductance compensating device Lp and total capacitance C of the three phases to ground the entire grid or the relevant test section (affixion) are calculated based on the measured parameters of operational signals from the equation /3/

$$R = U_1 U_2 \sqrt{\frac{\omega_2^2 - \omega_1^2}{U_2^2 I_1^2 \omega_2^2 - U_1^2 I_2^2 \omega_1^2}}\,,\quad L_{\partial} = \frac{U_1 U_2}{\omega_1 \omega_2} \sqrt{\frac{\omega_1^2 - \omega_2^2}{U_1^2 I_2^2 - U_2^2 I_1^2}}\,,\quad C = \frac{1}{U_1 U_2} \sqrt{\frac{U_2^2 I_1^2 - U_1^2 I_2^2}{\left(\omega_1^2 - \omega_2^2\right)}}\,. \qquad (13)$$

Where U, I, ω - values of tension, current and angular frequency of imposed operational sinusoidal signals of frequency f_1 and f_2.

The functional diagram of continuous measurement system of related to the ground insulation parameters of all distributive grid or its elements without removal of working voltage is shown in Figure 3.

The system structure assumes a voltage channel and a few (controlled by the affixion number) of current channels. Voltage channel, on which entrance the signal arrives from the TV voltage (voltage measurement transformers), connected to the busbars of the switchgear, is designed for removing, handling and measuring the values of operating voltages $\boldsymbol{U_{f1}}$ and $\boldsymbol{U_{f2}}$ and transfer them to the computer module for future use. Current channels, on which input signals are received from the TA_i current sensors (current measurement transformers) for the outgoing feeders, are also designed to remove, process and measurement values and operating currents $\boldsymbol{I_{f1}}$ and $\boldsymbol{I_{f2}}$ of the distribution grid respective sections and transfer them to the computer module.

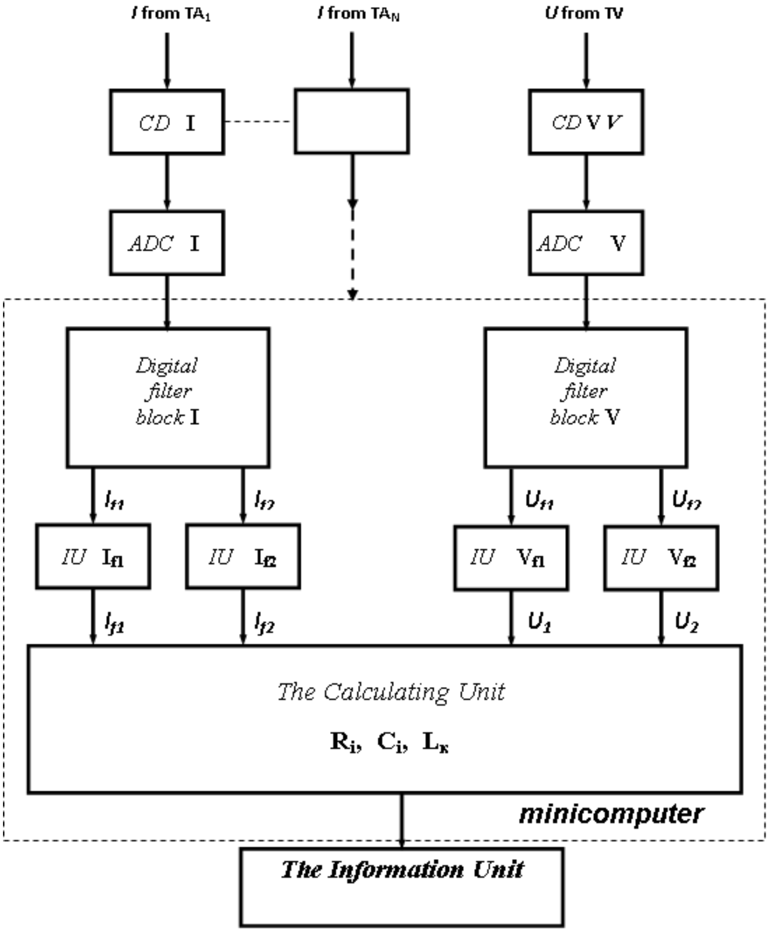

Fig. 3. The functional diagram of continuous measurement system
of related to the ground insulation parameters

These channels are differ by entrance blocks (coordinating devices) CD providing linking of analog-digital converters and the corresponding measuring sensors (transformers). When the signal processing system performs the following operations in sequence: the analog signals are converted to digital (ADC); the corresponding blocks of a digital filtration (are intended for selection by program methods from the general current signal of operational frequencies signals) allocated and separated of operating frequency components; signals are measured (IU - quantification of the signals corresponding frequencies) and their values are entered in the calculating unit of the system.

The calculating unit on the basis of both measured and recorded values of operating voltages and currents from the expressions (13) with the transformation coefficients voltage measuring transformers k_V and current transformers k_{Ai} at given points of the distribution grid of power supply system calculates:

- insulation resistance to ground of the three phases corresponding to the entire grid or controlled section (i-th affixion)

$$R_i = \frac{U_1 U_2}{k_V k_{Ai}} \sqrt{\frac{\omega_2^2 - \omega_1^2}{U_2^2 I_{1i}^2 \omega_2^2 - U_1^2 I_{2i}^2 \omega_1^2}}\ ; \qquad (14)$$

- the total capacity of all three phases of the grid or the corresponding controlled section (i-th affixion) related to the ground

$$C_i = \frac{k_V k_{Ai}}{U_1 U_2} \sqrt{\frac{U_2^2 I_{1i}^2 - U_1^2 I_{2i}^2}{\left(\omega_1^2 - \omega_2^2\right)}}\ ; \qquad (15)$$

- arc-suppression coil inductance

$$L_{\hat{e}} = \frac{U_1 U_2}{k_V k_{A\ddot{a}\eth} \omega_1 \omega_2} \sqrt{\frac{\omega_1^2 - \omega_2^2}{U_1^2 I_{2\ddot{a}\eth}^2 - U_2^2 I_{\ddot{a}\eth i}^2}}\ . \qquad (16)$$

The information unit of the system is intended to the calculation results representation in a form convenient for specific conditions or form message and sending it to the power dispatcher and other interested services. In general, the use of microcontrollers or the microcomputers allows the offered method to use:

- for an operational measurement of insulation resistance level of both all power network as a whole, and each of affixion of a distributive grid;
- for an operational measurement of related to the ground capacity level of both all power network as a whole, and each of affixion of a distributive grid;
- for an operational measurement of arc suppression coil inductance values (compensating device);
- for automatic compensating device adjust in a resonance with the distributive grid capacity;
- to carry out selective leakage protection, protection against earth fault or alarm in power systems (quarries and mines), regardless of the configuration and mode of neutral network.

Conclusions

1. The new principle of protection method work is given, which is based on the performance evaluation of zero sequence current vectors and phase voltage vectors relative position, which can significantly increase the sensitivity of protection devices against ground faults and make it virtually independent of the total network capacity relative to the ground.
2. The theoretical substantiation is given and the method of ground insulation parameters selective determination of an electric network under the operating voltage is developed, based on imposing on a distributive grid of bi-frequency operational sinusoidal signals of noncommercial frequency.
3. The function diagram of continuous and automatic control system or relative to the ground insulation resistance and capacity measurement for a three-phase electric network over 1000 V is presented.
4. Depending on a place of current measuring sensors turning on the system is able to provide selective measurement of the whole power grid ground insulation or the corresponding affixion, also the arc suppression coil inductance.

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