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Centralized System of Selective Signaling of Earth Fault and Insulation Diagnostics of Medium Voltage Distribution Networks

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1 INTRODUCTION

Technical perfection of protection devices and devices of selective signaling of single phase earth fault (SPEF) in medium voltage networks determines greatly the reliability of electricity supply to consumers. It is known that fixation of short self-clearing insulation failure, constituting 70-90% of the total number of SPEF in 6-10 kV cable networks, and using information about them to diagnose the state of network elements isolation can prevent about 30-50% of sudden (from the protection relay) outages of electric motors and cable lines [1 - 3]. Devices of protection and selective signaling based on the use of transients allows to carry out fixing of short self-clearing SPEF, but these devices do not act continuously in case of sustainable SPEF needed in branched networks to identify the damaged element.

Research and implementation in Ivanovo State Power University showed that combo devices allow obtaining the most technically advanced solution in terms of protection devices and selective signaling of SPEF. Combo devices are based on the use of phase condition of transient electrical values and earth fault steady-state regime. Combination of two ways of directional protection in a single device provides the possibility to identify selectively the damaged feeder with all varieties of SPEF (stable, short-term self-extinguishing, arcing intermittent) and ensures the continuity of action in the process of stable earth fault [3]. Implementation of microprocessor components and modern digital signal processing methods can significantly improve technical excellence of protection devices and selective signaling, in particular, to increase the stability of operation of small values under noise and interference, and phase (angular) errors of cable zero-sequence current transformer (ZSCT). These principles are implemented in to a central microprocessor unit of selective signaling of SPEF and insulation diagnostics of electrical medium-voltage networks, performed by the method [4] and developed in cooperation with JSC FGC UES affiliate – Backbone Electric Grids of Center (Nizhny Novgorod) and ISPU.

2 MAIN PART

Phase relations of electrical values of the transient and methods to control in case of directional protection against SPEF. For the steady-state regime of SPEF in the networks of the radial configuration the following relations between the zero-sequence voltage $u_0(t)$ and zero sequence currents in undamaged $i_{0\text{ und}}(t)$ and the damaged $i_{0\text{ dam}}(t)$ feeders are true:

$$3i_{0und} = 3C_{0und} \frac{du_0}{dt}; \quad (1)$$

$$3i_{0dam} = -\sum_k 3C_{0kund} \frac{du_0}{dt} = -\sum_k 3(C_{0\Sigma} - C_{0dam}) \frac{du_0}{dt}, \quad (2)$$

where C_{0und} and C_{0dam} - respectively, capacity of phase to earth undamaged k-th and the damaged feeders; $C_{0\Sigma}$ - total capacity of the network phase to earth.

Theoretical and experimental studies performed in ISPU (eg, [2]) show that frequency spectrum to a few kilohertz relations (1) and (2) also are approximately performed for transient currents and voltages and higher harmonics of the steady state regime of SPEF even taking into account distributed nature of power lines parameters. [1, 2], taking into account relations (1) and (2) it shows that in the directional protection against OZZ, based on the use of initial phase relations of transient electrical values, as the polarizing quantity it is advisable to use a derivative du_0/dt , but not voltage $u_0(t)$; it provides noncriticality of protection devices for possible distortions of the initial relations of signs between the voltage $u_0(t)$ and current $i_0(t)$ due to displacement of the network neutral.

To determine the direction (sign) of transient zero-sequence power in pulsed protection devices against SPEF there are two basic approaches:

1) sign fixing of instantaneous zero-sequence power at the time of insulation failure of network to earth by the ratio of initial signs of the transient current $i_0(t)$ or the amount of free components $i_{0fr}(t) = i_{0dch}(t) + i_{0ch}(t)$ and the polarizing quantity: $u_0(t)$, du_0/dt or du_{0fr}/dt (practically in the known versions of impulse directional protection devices against SPEF signs fixation of compared values occurs in 20-40 microseconds after insulation failure for the detuning of transient in voltage transformer, which distort the initial sign of the transient voltage $u_0(t)$) [1, 2, 5, etc.],

2) sign determination of mean value of zero sequence power to the entire range of the lifetime of transient current $i_0(t)$.

The first approach to direction control of transient zero sequence power in case of SPEF is used in most known performances of impulse directional protection devices against SPEF: "Impulse", Y3C-01, etc. [1, 2, 5 and others]. The disadvantage of this method is the possibility of distortion of results of instantaneous fixation of power sign and failure of protection devices to operate due to the influence of impulse noise in the secondary circuits of current and voltage and the angular errors due primarily ZSCT.

The second approach, in general, provides greater stability of protection functioning or both internal and external SPEF under the influence of impulse noise, angular errors of ZSCT.

Continuous monitoring of sign of mean zero sequence power in the transitional regime of SPEF can be implemented based on algorithms described by the following expressions (when derivative du_0/dt used as a polarizing quantity):

$$J_1 = \int_0^{t_{obs}} i_0(t) \cdot \frac{du_0(t)}{dt} dt; \quad (3)$$

$$J_2 = \int_0^{t_{obs}} \text{sign}(i_0(t)) \cdot \text{sign}\left(\frac{du_0(t)}{dt}\right) dt; \quad (4)$$

$$J_3 = \max_{0 < \tau < t_{\tau}} \int_0^{t_{obs}} i_0(t + \tau) \cdot \frac{du_0(t)}{dt} dt, \quad (5)$$

where t_{obs} - observation time of the transition process of SPEF (response time of directional measuring part of protection).

Equations (1) and (2) show that the integral values $J_1 - J_3$ in (3) - (5) for a damaged feeder are always negative, and for all undamaged feeders are positive.

The method based on calculating the integral value J_2 by (4) is used, particularly in directional protection device against SPEF like "Spectrum", developed in ISPU [2, 3], and actually implements a known method of comparing concurrency time and non-concurrency time.

The value of the integral values J_3 by (5) corresponds to the temporal cross-correlation function combined instantaneous zero sequence current and slew rate (derivative) zero sequence voltage for selected t_{obs} .

The effectiveness of each of the above mentioned ways to run directional protection against SPEF is largely determined by its sensitivity to the influence of the phase (angle) errors due to ZSCT,

voltage transformers and other forming circuit elements of compared values. To assess the sensitivity of influence of phase errors in mathematical models «Power network - protection device against SPEF by method 1 (2, 3)», made in the modeling system Matlab, we calculated the ratio «signal / noise». For method 1 based on an assessment of integral J_1 the ratio «signal / noise» is defined by the expression

$$K_{1S/N}(t_c) = \frac{J_{1S}}{J_{1N}} = \frac{\int_0^{t_u} \left[i_0^{(+)}(t+t_d) \cdot \frac{du_0^{(+)}(t)}{dt} + i_0^{(-)}(t+t_d) \cdot \frac{du_0^{(-)}(t)}{dt} \right] dt}{-\int_0^{t_u} \left[i_0^{(+)}(t+t_d) \cdot \frac{du_0^{(-)}(t)}{dt} + i_0^{(-)}(t+t_d) \cdot \frac{du_0^{(+)}(t)}{dt} \right] dt}, \quad (6)$$

where J_{1S} - integral corresponding moments of the signs concurrency of current half-wave $i_0(t)$ and derivative du_0/dt , J_{1N} integral corresponding moments of the signs non-concurrency of current half-wave $i_0(t)$ and derivative du_0/dt ; t_d - time delay of current signal $i_0(t)$, taking into account influence of angular errors ZSCT and other forming circuit elements of compared quantities.

For methods 2 and 3, based on an estimate of the integral values J_2 and J_3 by (4) and (5) the ratio of «signal / noise» is defined similarly.

Fig. 1 shows the dependence of ratio «signal / noise» $K_{S/N}$ of the value of t_d .

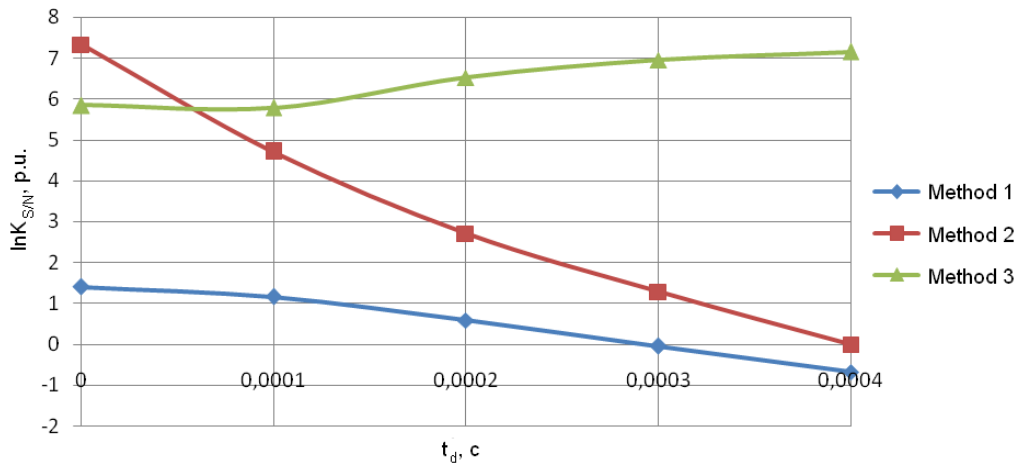


Fig. 1: Dependence of ratio «signal / noise» $K_{S/N}$ of the value of t_d for methods 1, 2, 3

The data presented in Fig. 1, shows that unlike methods 1 and 2, the method based on the calculation of cross correlation function to the utmost provides noncriticality of directional protection to the influence of the phase shift between the compared values, due to angular errors ZSCT and other elements of the protection device. Investigation of complex mathematical models «Power network - protection device against SPEF» also showed that implementation of protection against SPEF by method 3 provides increasing of functioning stability under the influence of noise and impulse noise.

Functional-block diagram of a centralized system of selective signaling of SPEF and diagnostics of network isolation. Simplified functionally-logic circuit of device that implements the method [4], is shown on Figure 2.

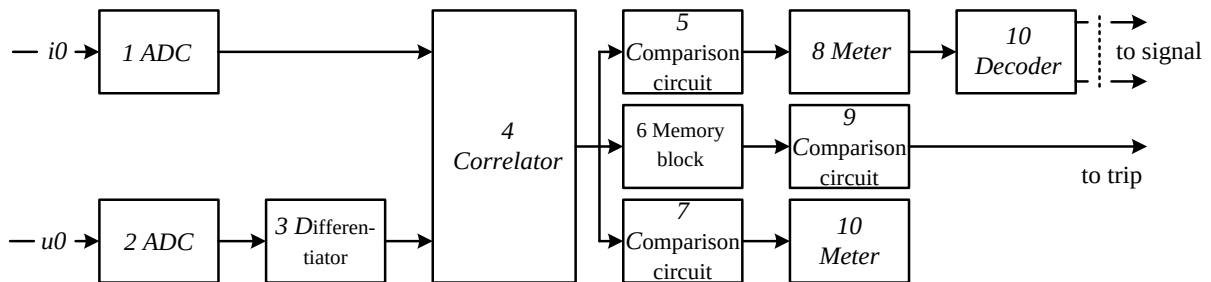


Fig. 2: Functional-logic circuit of signaling device of SPEF by the method [4]

The device includes: first 1 and second 2 analog-digital converter (ADC), a differentiator 3 (derivative calculator), the correlator 4, first 5, second 7 and third 9 comparison circuit, the memory block 6, the first 8 and second 10 meters and the decoder 11. The method is realized in the following way.

In case of earth fault from measuring transformers zero-sequence current i_0 and voltage U_0 come respectively to the inputs of analog-digital conversion (ADC) 1 and 2. After the analog-digital conversion block 1 digital readout of the zero-sequence current fed to the first input of the correlator. Digital readout proportional to the rate of rise of zero-sequence voltage occur after the analog-digital conversion in block 2 and the differentiation of zero-sequence voltage in block 3 fed to the second input of correlator. Correlator 4 executes the operation of the digital convolution of the readings, coming to its input. Digital codes, which are discrete analogues of (5), are generated at its output. Digital filter can be used instead the correlator for convolution. In this case, one of the discrete signals (e.g., digital readout of the zero-sequence current) acts as the impulse characteristic of digital filter. From the output of the correlator 4 digital readouts come to the first inputs comparison circuits 5 and 7, and on their second inputs from the memory block 6 digital codes of the settings enter. Along this process setting, which characterizes the unsteady intermittent regime of SPEF, is coming to the comparison circuit 5 and setting, which characterizes the steady-state regime of SPEF, is coming to the comparison circuit 7. The difference in the settings is due to the need for different signal / noise ratio in the unsteady and steady-state regimes of faults. In case of steady-state SPEF counter 10 calculates number of exceedances of settings, which output is connected to the first input of the tripping circuit 9. From memory block 6 digital code is given to the second input of tripping circuit 9. This digital code characterizes a time interval from which SPEF is classified as steady-state. If you exceed this time interval at the output of comparison circuit a commanding signal, which influences executive parts of the device, occur.

In case of single-phase earth fault number of exceedances of settings is calculated by counter 8, the output of which is connected to the decoder 11. Depending on the digital code (the number of exceedances of set value) a signal appears on one of the outputs of decoders 11 from output of counter 8. In this case the state of insulation of a test phase of the network is associated with the number of occurred breakdowns of insulation, and we can characterize it by the number of output decoder 11, where signal appeared. This information (the number of decoder output) can act as a diagnostic (or signal) or to provide command influence on the executive parts of the protection device influencing tripping.

Test of functioning algorithms of selective signaling SPEF device by the method [4]. Testing of SPEF detection algorithms by the method [4] was carried out on test complex (Fig. 3), which includes two personal computers, and debug prototype of protection device against SPEF by the method 4], performed on the basis of micro-processor set-type TMDXOSKL137BET (Fig. 4).

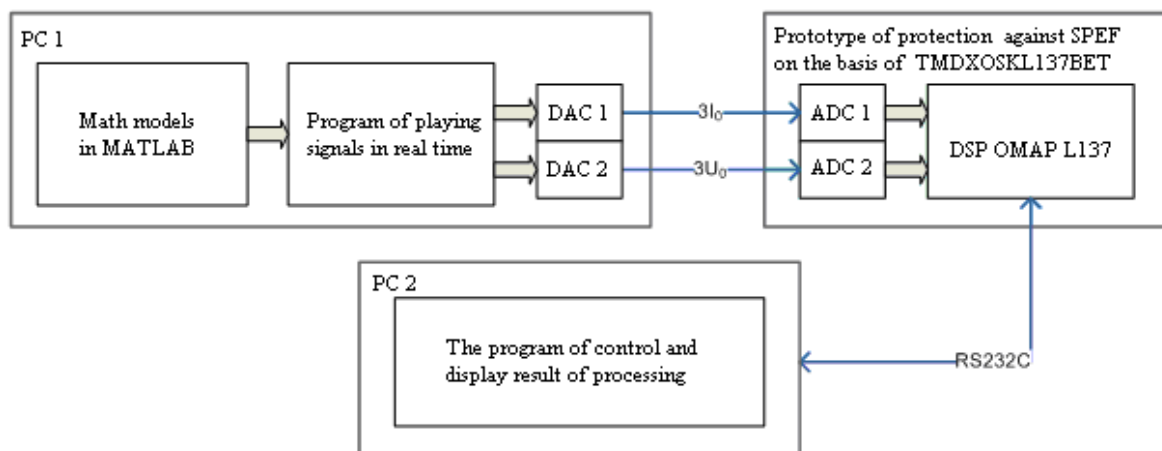


Fig. 3: The structure of complex for testing the functioning algorithms of debug prototype of SPEF signaling device by the method [4]



Fig. 4: Photo plate TMDXOSKL137BET, realizing the microprocessor part of SPEF signaling device by the method [4]

Signals $i_0(t)$ and $u_0(t)$ were simulated by using the first computer at different varieties of SPEF (single insulation fault on the theory of Petersen and Peters and Slepian, arc intermittent and steady-state SPEF). Test signals current $i_0(t)$ and $u_0(t)$ were obtained by mathematical models of electrical 6-10 kV networks, performed in a modeling program Matlab.

Creating a database of test signals parameters of controlled 6-10 kV network, parameters of the damaged lines (in particular, the remoteness of the place of the fault of isolation from buses), the character arc of intermittent SPEF were varied.

Obtained by this method signals $i_0(t)$ and $u_0(t)$ were reproduced by playing program, and after digital-analog conversion of digital sampling frequency of 44.1 kHz were applied to the analog inputs of the prototype of SPEF detector.

Debug prototype of SPEF signaling device by the method [4] consists of two analog-to-digital conversions (ADCs) with digital sampling frequency of 48 kHz and dual-core digital signal processor OMAP-L137 of Texas Instruments Company, which allows implementing the above algorithms for convolution and detection of unsteady SPEF in real time.

Software (SW) debug prototype of SPEF signaling device consists of three software components (Fig. 5):

- program that run CPU DSP/OMAPL137, which performs reading of information from the ADC and calculation of the cross-correlation between channels;
- program that run CPU ARM/OMAPL137, the main objective is to receive and process commands from the client application;
- client application Qt OZZ, running a personal computer PC 2.

Software of debug prototype of SPEF signaling device implements the following modes:

1. Measurement mode and display cross-correlation function. This mode of measurement is used to set the threshold for determining the pulse SPEF.
2. Mode of measuring the number of faults in the insulation in case of SPEF. This mode of measurement is used to calculate the number of fault isolations OZZ per unit time.

The algorithm working in software mode 1, is the following:

1. The client application passes in an ARM command at the start of measurements.
2. ARM processor translates the command to start the DSP and transferred to the state of expectations of data availability.
3. DSP runs the codec on the measurement, reads data from the two ADC channels (left channel - $3i_0(t)$, right - $3u_0(t)$) and writes them in a circular buffer.
4. Once the data is sufficient, DSP calculates the correlation point and continue reading data from the ADC.
5. When the number of correlation points reaches a preset value (8192 points), DSP ready flag is set and becomes the expectation of the next command.
6. After receiving the flag of readiness, ARM passes the entire array of correlation points to client application.

7. The client application processes the received array data correlation: it counts the number of correlation pulses by point-wise comparison of data from the threshold, pulse number is displayed.
8. The whole measurement process is repeated, starting with No. 1.

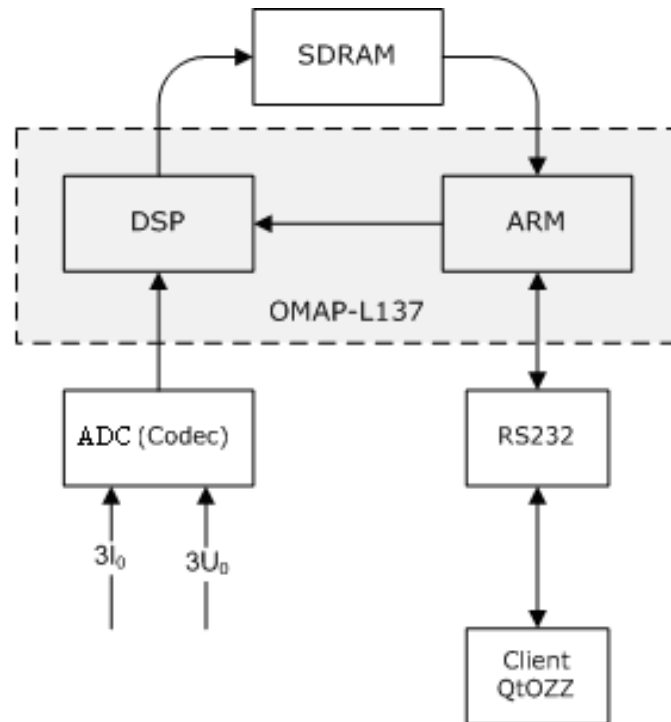


Fig. 5: The structure of software of debug prototype of protection device against SPEF

In mode 2 software implements the following algorithm:

1. The client application passes ARM command at the start of measurements and activates the timer.
2. ARM processor translates the command to start the DSP and transferred to the state of expectations of the command of data readiness.
3. DSP runs ADC measurements, reads the transformed data from two channels (Channel 1 - $3i_0(t)$, 2-Channel - $3u_0(t)$) and writes them in a circular buffer.
4. Once the data is sufficient DSP calculates the correlation point, and compares its value with the threshold. If the correlation value greater than the threshold value of the pulse counter is incremented by one and DSP continues reading of data from the ADC.
5. After receiving the command from the client application to read the counter, ARM transmits its value to the client application and resets the counter to zero state.
6. The client application displays the number of pulses.
7. The whole measurement process is repeated, starting with No. 4.

Thus, the testing facility provides the following main functions:

- continuous calculation of cross-correlation function of a given length between channels $3i_0(t)$ and $d3u_0(t) / dt$;
- comparison of the values of cross-correlation function with the set value;
- continuous count of the number of single or repeated SPEF for set time interval;
- comparison of the obtained magnitude of the pulses and the set value;
- display of the results on the screen PC 2.

The tests using the test signals corresponding to different varieties of internal and external SPEF confirmed the efficiency of protection devices against SPEF performed by the method [4].

Prototype testing protection devices against SPEF performed by the method [4] on the physical model of the 6 kV electrical cable. Block diagram of prototype testing protection devices against SPEF on a physical model of 6 kV cable network is shown in Fig. 6.

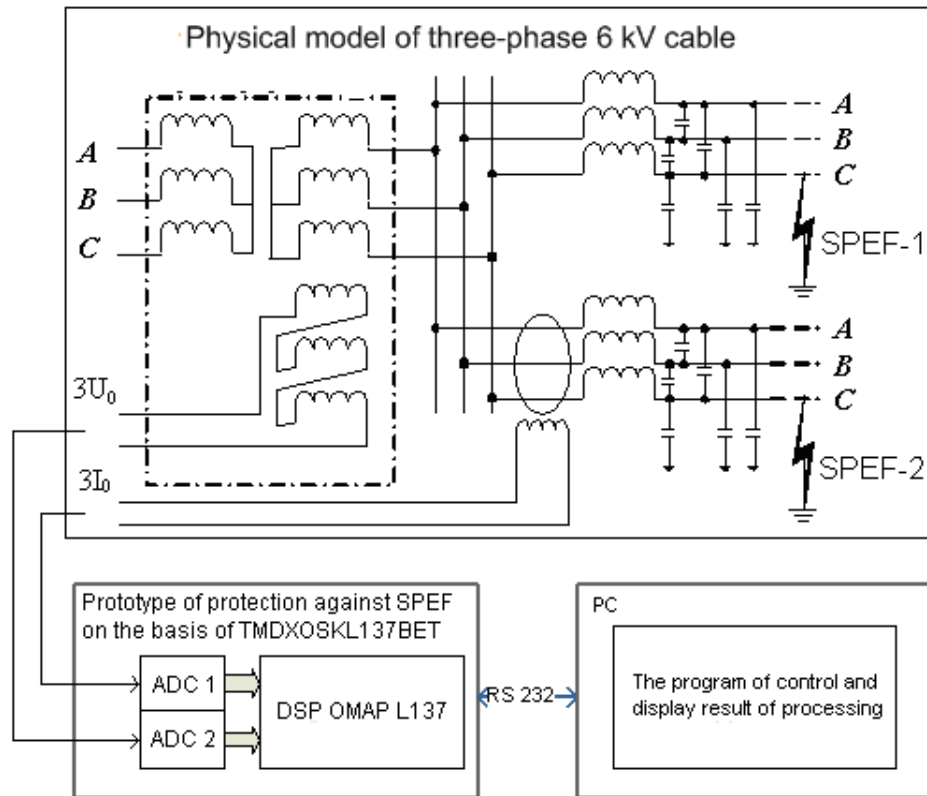


Fig. 6: Block diagram of testing prototype protection devices against SPEF by the method [4] on physical model of three-phase 6 kV cable

Physical model of the radial three-phase network is performed on voltage of 220 V and has several three-phase cable lines, executed in a chain of three-phase circuits of blocks to accommodate the distributed nature of their parameters. On the cable lines are installed ZSCT. To obtain the transient in-rush current close to the amplitude of the in-rush currents in case of SPEF in real networks, we used a larger number of primary turns of ZSCT. During testing a physical model of 6 kV cable network internal and external single, intermittent and steady-state SPEF (SPEF-1 and SPEF-2 on Fig. 6) were simulated.

The Tests on a physical model of the cable network, i.e. in functioning close to conditions of real networks, have confirmed high performance and high efficiency operation in case of internal and external faults of developed algorithms of functioning of protection against SPEF by the method [4], and implements these algorithms to the software.

3 CONCLUSION

1. Directed combined device based on the use of phase relationships of electrical quantities of the transition process and steady ground fault allow obtaining most technically advanced solution in terms of protection devices and selective signaling SPEF in electrical medium voltage networks, primarily working with resonant neutral grounding through the ASC.
2. Method based on the calculation of the time cross-correlation function combined instantaneous zero-sequence current and rate of rise (derivative) zero-sequence voltage is the most effective “signal / noise” ratio method of executing the directional protection against SPEF, responsive to the transient process.
3. Tests developed a prototype microprocessor protection against SPEF by the method of Section 2. performed using the test signal zero-sequence current and voltage with different varieties of SPEF (single fault, unsteady arc damages and steady-state damages) received in the system simulation of Matlab, as well as the physical model of a three-phase cable network confirmed the working ability and high efficiency of its operation.

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