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Universal protection against single-phase earth faults in compensated medium voltage cable networks

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***Abstract*— It is shown that overcurrent protections against single-phase earth faults based on higher harmonics in zero-sequence current does not allow to obtain a universal solution to the problem of effective protection providing of compensated medium voltage cable networks under the conditions of selectivity and sensitivity. Directional protection that reacts to the phase relationships of the higher harmonics in zero-sequence currents and voltage of steady-state and transient earth faults modes is provided universal solution. A method of execution of universal earth fault protection in compensated cable networks which increaseы operation stability and action possibility for all types of earth faults including short time self-clearing and arc intermittent, is developed.**

***Index Terms*— medium voltage cable networks, compensation of the capacitive currents, single-phase earth faults, higher harmonics, transient processes, directional protection against earth faults.**

I. INTRODUCTION

Resonant neutral grounding of medium voltage (MV) distributed cable networks through arc-suppression coil (with compensation of capacitive currents) is one of the most effective methods of combating of arc intermittent earth faults accompanied by dangerous overvoltages for whole electrically connected network, and it is widely used in Russia and other countries [1–7, etc.]. The main reason for reduction in resonant neutral grounding efficiency is a low technical perfection (selectivity and stability) of single-phase earth fault (SPEF) protection devices currently used in compensated medium voltage cable networks. In Russia, to protect and selective signaling of SPEF in cable 6–10 kV networks they use devices based on higher harmonics (HH) in zero-sequence current connections $3I_0$ [8, 9, etc.]. Current protections from SPEF based on HH are also used in some other countries [e.g., 10, etc.]. The method of relative harmonics measurement based on comparing the HH levels in the currents $3I_0$ of all connections of the protected object requires a centralized implementation of protection devices, which limits its application possibilities. Therefore, overcurrent protections (OCP) of absolute harmonic measurement based on the comparing of HH with operating value selected from condition of failure when external SPEF have become more widely used. This type of protection includes, for example, USZ-2/2 device, as well as its digital analogs in microprocessor terminals of relay protection and automation for MV transmission lines of some manufacturers [8, 9].

The analysis of operation experience of protection devices against SPEF of MV networks, conducted by ORGRES in 2000, revealed a low selectivity with external and not always sufficient sensitivity at internal faults of current protection based on absolute HH measurement [11]. The main reasons for a low efficiency, in our opinion, are as follows. The condition for selectivity of failures at external and sensitivity at the internal SPEF of the OCP set on the i-th connection of the protected object can be represented [12]

$$I_{c\,i*} = \frac{I_{c\,i}}{I_{c\Sigma\,min}} \le \frac{1}{1+(\alpha_{max}/\alpha_{min})K_a K_{s.min}} = \frac{1}{1+Z\,K_a K_{s.min}}, \quad (1)$$

where $I_{c\,i}$ – own capacitive current of i-th connection connected to buses of the protected object; $I_{c\Sigma\,min}$ – total capacitive current of network in minimum operation mode; α_{max}, α_{min} – maximum and minimum relative (in relation to the component of the capacitive current of the fundamental 50 Hz frequency) HH level in steady-state current in the protected network; K_a – offsetting ratio that takes into account the effect of operational errors on the stability of failures in external SPEF (errors of α_{max} estimation, calculation of capacitive current of i-th connection, primary zero-sequence current transformers, etc.); $K_{s\,min}$ – minimum allowed sensitivity factor for current protections based on HH.

The maximum value of parameter Z for compensated 6–10 kV cable networks is estimated at about 4–6 in [13, 14]. When Z = 4–6, K_a = 1.5, $K_{s\,min}$ = 1.5, from (1) we find that selectivity and sensitivity of OCP based on HH can be provided only on the connections with relative value of the capacitive current $I_{c\,i*} \le 0.07–0.1$. In [14] it was shown that the share of connections with $I_{c\,i*} \le 0.07–0.1$ from the total number of connections connected to buses of cable network power centers (6–10 kV buses of step-down substations and generator switchgear of heating power plant) does not exceed about 60–80%. An additional problem that significantly limits selectivity and sensitivity and, accordingly, possible application area of the considered protection type, is difficulty in determining of the significant values of the relative maximum HH level α_{max} for the specific conditions of the protected network, which is necessary for a reasoned choice of the settings for pickup current.

Thus, OCP based on HH does not allow to obtain a universal solution (in aspect of application area) for creation of protection against SPEF of compensated MV cable networks.

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Such protection can only be considered as a backup protection against this type of damage.

II. REQUIREMENTS FOR PROTECTION AGAINST SPEF OF COMPENSATED MEDIUM VOLTAGE CABLE NETWORKS

The known versions of OCP based on HH, for example, USZ-2/2 [8, 9], were developed for action only at stable SPEF, since offset from higher harmonic components of transient earth fault current would lead to an additional increase in the protection current and the limitation of possible application area. The basis for this approach to the construction of protection was the assumption, that the occurrence of dangerous arc interrupted SPEF in compensated networks with resonant or close to it tuning of arc-suppression coil is unlikely, and short time self-clearing insulation breakdowns are not dangerous either for the network or for the damaged element. In view of this, protection failure during transient current surges, as a rule, was provided by quick return of the protection current discriminating element after the arc blowout and the pickup time delay.

This method does not allow current protection based on HH to fix short time self-clearing SPEF in cables and other elements (for example, high-voltage electric motors), the share of which from total number of earth faults in the compensated cable networks can reach 70–90% [1, 2, 5, etc.]. At the same time, it is known that one of disadvantages of resonant grounded networks is their property to accumulate hidden defects of insulation after its short time breakdowns. This is due to the fact that the damages in the elements with solid or combined insulation (cables, motors), after their occurrence subsequently develops, passing into stable, double earth faults or phase-to-phase short-circuits. According to the data [16, 17], fixing short time self-clearing SPEF in 6-10 kV cable networks and using of information about them to conduct high-voltage tests of the damaged element will prevent up to 50% of sudden disconnections of cables and more than 30% of sudden outages of motors. Thus, selective signaling of short time self-clearing SPEF in compensated cable networks can improve their operational reliability.

The appearance of arc intermittent SPEFs, accompanied by dangerous over voltages, is possible with significant compensation differences, for example, in the absence of automatic tuning devices and the use of manual control of the arc-suppression coil current in compensated cable networks [4]. This kind of SPEF is much more dangerous for the network than stable SPEF; however, OCP based on HH can not fix them.

Thus, the main protection against SPEF of compensated MV cable networks should not only provide the possibility of its application without limitations on the relative value of the capacitive current I_{ci*}, but also be able to fix, in addition to the stable ones, also short time self-clearing and arc intermittent SPEF. Protection, which possesses all these properties, can be called universal.

The first of these properties is inherent directional protections, the selectivity of which does not depend on the I_{ci*} value of the protected connection. Only protections based on the use of transient electrical quantities can fix all types of SPEF, including short time self-clearing and arc intermittent. However, such protections do not have the property of operation continuity at stable SPEF, which is necessary when determining the damaged element or fault location in a complex network by the routine switching method. Thus, the greatest universality (in the aspect of application area and the possibility of fixing of all types of SPEF) in compensated MV cable networks can provide directional protection based on electrical quantities of both transient and steady-state earth fault. Phase relationships of zero sequence voltage and currents HH of the steady-state SPEF and phase relationships of the higher harmonic components of transient process of short time self-clearing and arc intermittent SPEF are advisable to use for the operation of such protection.

III. PHASE RELATIONSHIPS OF HIGHER HARMONIC COMPONENTS OF ZERO-SEQUENCE VOLTAGE AND CURRENTS IN STEADY-STATE AND TRANSIENT MODES

The limited spectrum, which includes, as a rule, harmonics of $\nu = 5, 7, 11, 13$ order is used in the protections based on HH of stable SPEF [8–10, etc.]. The HH main sources in 6–10 kV cable networks are nonlinear AC/DC converters (valve inverters), electric welding, electro thermal installations, power transformers, etc. generate mainly these harmonics [18]. It determines the operating frequency range of this protection type. In [15] it is noted that components with frequencies up to 1–1.5 kHz are expediently included in the operating range of protection devices based on HH to increase operation stability at internal SPEF (i.e. sensitivity). In the specified frequency range, the harmonic spectrum of SPEF current is determined by harmonic spectrum of voltage of the damaged phase at the moment preceding the occurrence of damage. And HH distribution in the zero-sequence currents of undamaged connections of the protected object at SPEF corresponds with sufficient accuracy to the distribution of the capacitive currents of fundamental 50 Hz frequency in network with isolated neutral [13].

With this in mind, the following relationships between instantaneous zero-sequence voltage $u_0(t)$ and zero-sequence currents in undamaged $i_{0\,und}(t)$ and in damaged $i_{0\,dam}(t)$ connections are valid in radial cable networks for harmonics of ν-th order in the steady-state SPEF mode

$$i_{0\nu\,und}(t) = C_{0und}\frac{du_{0\nu}(t)}{dt}; \tag{2}$$

$$i_{0\nu\,dam}(t) = -(C_{0\Sigma} - C_{0dam})\frac{du_{\nu 0}(t)}{dt}, \tag{3}$$

Where $C_{0\,und}$, $C_{0\,dam}$ – own phase capacitance to ground of k-th undamaged and damaged connections; $C_{0\Sigma}$ – total capacitance of network phase to ground.

It can be seen from (2) and (3) that the phases of all

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harmonic current components in damaged connection at stable SPEF are always opposite to phases of corresponding harmonics in undamaged connections. These relations are basis for method of performing directional protection against stable SPEF in compensated cable networks, which reacts to the sum of the voltage $u_0(t)$ and the current $i_0(t)$ harmonics of the protected connection [19]. Studies on mathematical and physical models (for example, [14, 17]) have shown that in the frequency spectrum up to 2 kHz, equations (2) and (3) are also satisfied for transient currents and voltages at SPEF with angular errors acceptable for directional protection.

Oscillograms of zero-sequence transient currents in damaged $i_{0\ dam}(t)$ and undamaged $i_{0\ und}(t)$ connections and voltage derivative $du_0(t)/dt$ obtained on the imitation model of 6 kV cable network in Matlab are shown in Fig. 1 as an example

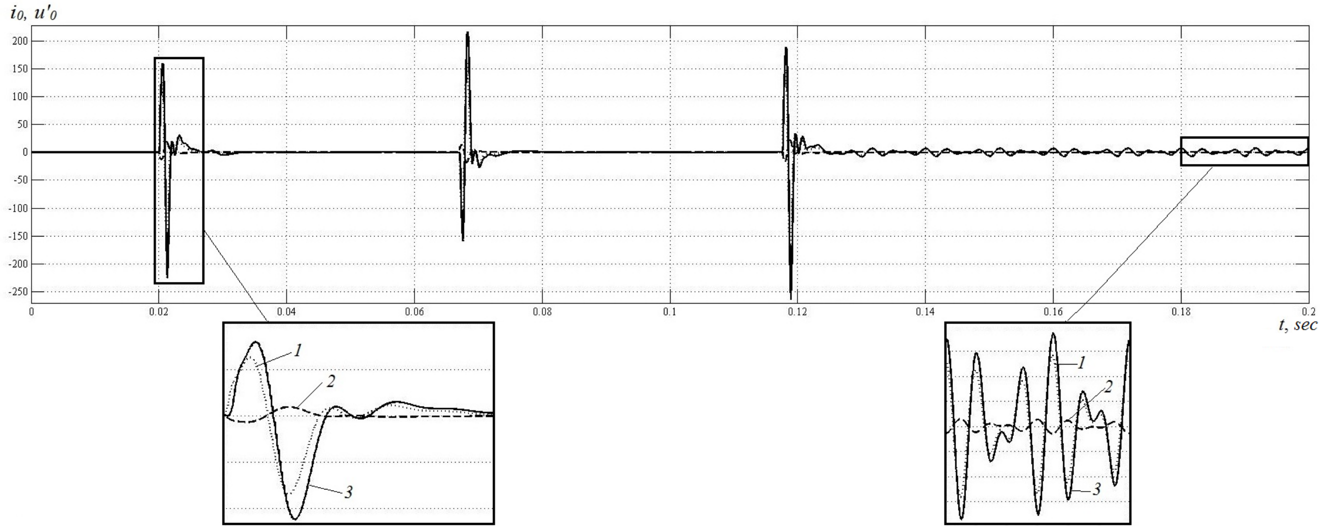

Fig. 1. Phase relationships of zero-sequence currents i_0 in damaged and undamaged connections (1 and 2) and zero-sequence voltage derivative u'0 (3) in SPEF transient and steady-state modes

Thus, the method of directional protection against SPEF based on the control of phase relationships of the higher harmonic components in the limited frequency range (with the upper frequency of 1.5–2 kHz) can be used to determine the damaged connection in compensated MV cable networks not only in steady-state, but also in transient SPEF modes.

It should be noted that practically all known developments of directed protection against SPEF based on transient electrical quantities are so-called impulse action protections. Such protections fix relationships of instantaneous signs of the transition zero sequence voltage $u_0(t)$ and current $i_0(t)$ or the instantaneous sign of zero sequence power at insulation breakdown moment [17, 20–23, etc.]. In contrast to impulse directional transient protections, the use of relations (2) and (3) in the transient SPEF modes allows us to perform a directional continuous protection. This protection monitors the phase relationships $du_0(t)/dt$ and $i_0(t)$ over entire time interval of the transient current existence (Fig. 1), which makes it possible to increase protection resistance to effect of impulse noises and interferences.

This approach is the basis for the microelectronic directional protection against SPEF «Spectr» for compensated MV cable networks [17]. The correlation integral is used in this protection for continuous monitoring of sign of zero sequence power mean value higher harmonic components in both transient and steady-state SPEF in accordance with

$$J_1 = \int_0^{T_{obs}} sign(i_{0\,HH}(t)) \cdot sign(u'_{0\,HH}(t))dt \qquad (4)$$

where T_{obs} – time of observation of transient or steady-state SPEF; $i_{0\,HH}(t)$ and $u'_{0\,HH}(t)$ – higher harmonic components of zero sequence current and voltage derivative.

The method of directional protection against SPEF based on the correlation integral J_1 calculating according to (3) of two amplitude-normalized signals actually realizes a comparison of their polarity time coincidence with non-coincidence time. The «Spectr» protection feature is also the use of a comparing circuit with the same pickup in transient and steady-state SPEF modes. This makes it difficult to ensure high operation stability in a large range of input HH currents (hundreds of milliamperes at stable SPEF and hundreds and thousands of amperes at transient SPEF modes). Operation experience and research on Matlab simulation models showed that distortions of compared quantities phase relationships caused by angular errors of the primary zero sequence current and voltage transformers and other elements of current and voltage channels can also have a significant effect on the stability of the «Spectr" protection device, especially in transient SPEF modes.

An effective solution of the above problems with ensuring a high operation stability due to a large dynamic range of input current variation and possible phase relationships distortions of compared values during both steady-state and transient SPEF modes, as well as the expansion of functional protection capabilities is possible only if this protection is performed on a modern microprocessor base.

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IV. MICROPROCESSOR DIRECTIONAL PROTECTION BASED ON HIGHER HARMONIC COMPONENTS OF ZERO-SEQUENCE CURRENT AND VOLTAGE IN TRANSIENT AND STEADY-STATE SPEF MODES

The structural diagram of the developed directional protection device against earth faults for compensated MV cable networks [24, 25] is shown in Fig. 2.

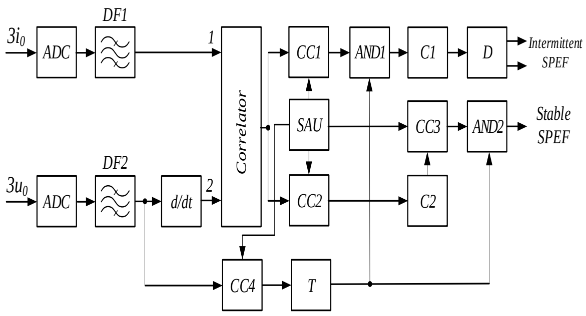

Fig. 2. Structural diagram of universal directional protection against SPEF based on HH for compensated MV cable networks

The device in Fig. 2 includes analog-to-digital converters (ADCs), digital filters for extracting higher harmonics from $3i_0$ current and voltage $3u_0$ (DF1 and DF2), differentiator (d/dt), correlator, comparing circuits (CC1–CC4), settings adjustment unit (SAU), counters (C1, C2), decoder D, an element of pickup time delay (T), logic elements (AND1, AND2).

Continuous monitoring of the direction of the higher harmonic components power in transient and steady-state SPEF modes is carried out using a correlator that calculates integral in accordance with

$$J_2 = \int_0^{T_{obs}} i_{0\,HH}(t) \cdot u'_{0\,HH}(t)dt. \qquad (5)$$

In contrast to the above-mentioned directional protection device «Spectr» input signals amplitude limiting in terms in this device is not applied, which provides operation stability increase in the presence of angular errors, impulse noises and interferences.

The devices operates as follows. At SPEF, current $3i_0$ and voltage $3u_0$ are applied to ADC inputs from the primary converters. Digital samples of the current $3i_0$ are fed to correlator input 1, digital samples proportional to $d(3u_0)/dt$ are fed to the correlator input 2. The correlator performs a digital convolution operation over the samples arriving at its inputs. As a result of the convolution, the mutual correlation function of sets of instantaneous zero sequence current $3i_0$ and the voltage derivative $d(3u_0)/dt$ is generated. The samples of the mutual correlation function from correlator output are fed to the first inputs of the comparison circuits CC1 and CC2, and to their second inputs from the SAU – the digital settings codes. Moreover, for CC1, a set point characterizing unstable arc intermittent SPEF mode is given, and for CC2 – set point characterizing the stable SPEF mode.

A voltage fault detector is used to exclude false protection tripping in transient processes that occur during switching operations in the network and in other modes (not SPEF). The fault detector includes comparison circuit CC4, the first input of which is supplied with voltage $3u_0$, and the second input – with a set voltage value from SAU (U_{pickup} = 15–20 V), and the pickup delay T (t_{pickup} = 10–15 ms). Information recording in the counter C1 and the issuance of command actions on alarm or trip at stable or arc intermittent SPEF on the protected connection are permitted only if the fault detector is triggered. Since the network neutral shift time and, accordingly, the time of voltage $3u_0$ existence after earthing arc suppressing, as a rule, is 100 ms or more, the fault detector does not limit the protection possibility of in the part of fixing short time self-clearing SPEFs. At stable SPEF, the set value exceeding number is counted by counter C2, whose output is connected to the first output of comparison circuit CC3. A digital code characterizing the time interval, from which the SPEF is classified as stable, from block 6 is fed to the second CC3 input. The CC3 output signal appears when this time interval is exceeded. If there is an enabling signal from T output of the fault detector and at CC3, then the stable SPEF signal appears at output of element AND2.

When an unstable arc SPEF, the set value excesses are fixed by comparison circuit CC1. The signal from the CC1 output through AND1 gate, when the voltage fault detector is triggering, is fed to the input of counter C1. A signal characterizing danger level of arc intermittent SPEF for the network appears depending on digital code (set value exceeding number) from the output of counter C1 on one of decoder D outputs. At the most arc intermittent SPEF, characterized by small time intervals (up to 50–60 ms) between repeated ground arc striking and extinction and accompanied by dangerous over voltages, the output signal appears on the first output of decoder D. The first decoder output can be used for a trip or a signal command. For arc interrupted SPEF characterized by longer than specified time intervals between repeated breakdowns, the output signal appears at the second output of the decoder D and is used only for protection action on signal.

Protection prototypes of are introduced into trial operation in compensated 10 kV cable networks. Operational experience confirmed that the device is capable of selectively fixing both stable and arc intermittent and short time earth faults in real operating conditions.

V. CONCLUSION

1. Maximum current protection based on higher harmonics of zero sequence current are widely used in compensated MV cable networks. Such protection have a limited application area due to HH spectrum instability and do not allow fixing short time self-clearing and network dangerous arc intermittent earth faults.

2. Directional protections based on control of phase relationships of zero sequence current and voltage higher harmonic components in steady-state and transient earth faults modes make it possible to obtain a much more universal solution to the problem of selective protection from

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single-phase earth faults in compensated cable networks.

3. The method of directed protection based on higher harmonic components providing the possibility of all earth faults types fixing in compensated MV cable networks is designed and tested in trial operation.

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