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INFORMATION BASES OF PROTECTION ALGORITHMS AGAINST SINGLE-PHASE GROUND FAULTS OF A GENERATOR OPERATING ON BUSBARS
PART II. STUDY OF INFORMATION BASES OF ALGORITHMS IN WHICH NULL-SEQUENCE COMPONENTS ARE USED

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Information bases of algorithms against single-phase ground faults for stator protection of a generator operating on busbars are studied. The cornerstone of the analysis is the use of the universal network model examined in part I of this article (*Élektricheskie Stantsii*, 2019, No. 1). The information bases of algorithms are used in which the fundamental harmonic of a current, the basic and third harmonics of zero-sequence voltage, and low-frequency harmonic injection into a network are studied. The efficiency of the existing algorithm based on control of a harmonic injected into a network is found. However, application of these protections requires installation of additional equipment in the network and is associated with degradation of the electric power and the characteristics of other RPA devices.

Keywords: information bases of protection algorithms; protection information signal; generator protection against single-phase ground fault.

This article examines the information bases of protection algorithms for generators from single-phase ground faults (SPGF) in which the following informational signals are used:

a) the fundamental harmonic of a current;

b) the basic and third harmonics of zero-sequence voltage;

c) the low-frequency harmonic injection into a network.

The objective of these studies is the assessment of the limiting capabilities of algorithms for protection from SPGF from the point of view of sensitivity and selectivity. Hence, methods of extracting informational signals, as well as the effect of errors of measurement transducers are not examined, assuming that these studies are a separate problem originating in the concrete implementation of one or another algorithm in a device.

In practice, ensuring calculated sensitivity and selectivity of protection is interfered with by the shortcomings of the measurement channels and the errors of digital processing of informational signals [1]. The complexity of the problem lies first of all in the fact that among the electrical magnitudes is the fundamental harmonic, the level of which can exceed the level of the higher harmonics by several orders of magnitude. For example, in protection using the higher harmonics of a current or harmonic injection in a network, the signal-to-noise ratio may be less than some thousandths. As a consequence of this, the traditional digital devices for relay protection, which have a relatively small dynamic range of measurement of electrical values and are in addition shifted towards large frequency rates, are not capable of distinguishing weak informational signals against the predominating noise [2].

Special channels of an analog-digital converter (ADC) containing analog filters for blocking the high-order fundamental harmonic are usually applied in extracting the higher harmonics in the protection of generators from SPGF. Since the frequency in a generating network in various operating modes varies over a wide range (from 40 to 60 Hz) [3 – 5], likewise the ADC channels in these conditions lose efficiency, leading to loss of sensitivity and selectivity of protection.

In the opinion of the authors, one of the priority directions of development of protection from SPGF of the stator of a generator operating on busbars is the use of tools of

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adaptive structural analysis [6, 7] in the extraction of informational signals, particularly active-adaptive recognition of weak harmonic signal components [8, 9].

Protection using the fundamental harmonic of the current. The level of short circuit components of the fundamental harmonic of SPGF currents is determined generally by the value of the capacitive susceptance of elements of the network relative to earth, and this is less by several orders of magnitude than the load currents and is comparable to the level of noise caused by the shortcomings of the measurement channels for protection. Therefore, the use of the fundamental harmonic of the phase currents [10] for identification of an SPGF in networks with isolated and compensated neutral is technically complex. However, the phase currents can be used for blocking the protection from SPGF for interphase short circuits.

At the same time, the fundamental harmonic of the zero-sequence current has large informational value for protection from SPGF [11], and this is explained by the fact that in normal mode it is practically absent

$$(\underline{I}^{(0)}_{P,1})_{\text{norm}} \approx 0.$$

Generally, the level of the fundamental harmonic of a zero-sequence current depends on the location of the SPGF, and for an internal SPGF this is determined by the mode of the neutral and the capacitive susceptance of the network:

$$(\underline{I}^{(0)}_{P,1})_{\text{int}} = -\gamma_G[(1+k_E+k_B)(1-k_R)-1] \qquad (1)$$

and for an external SPGF, by the intrinsic capacitive current of the protected generator:

$$(\underline{I}^{(0)}_{P,1})_{\text{ext}} = \gamma_E. \qquad (2)$$

Here and thereafter, the indexes norm, int, and ext will signify the value in normal mode, and for internal and external SPGFs, respectively; γ_G and γ_E are the relative electrical distances to the location of the SPGF in protected and equivalent generators, respectively, as read off from the neutral of the generators; k_E and k_B are the relative magnitudes of the capacitances of the equivalent generator and the transverse branches of an equivalent load; k_R is the degree of compensation of capacitive currents at the frequency of the fundamental harmonic.

In a network with a compensated neutral ($k_R = 1$), the fundamental harmonic of a zero-sequence current with an internal SPGF is equal to the intrinsic capacitive current of the protected generator

$$(\underline{I}^{(0)}_{(P,1)})_{\text{int}} = \gamma_G,$$

as also for an external SPGF, by expression (2). Therefore, protection from SPGF of a generator operating on busbars, using the fundamental harmonic of a zero-sequence current in the capacity of the informational signals in a network with a compensated neutral, loses selectivity.

In the case of a network with isolated neutral ($k_R = 0$), the fundamental harmonic of the zero-sequence current will be determined by the total capacitive currents of the external network, and as follows from formula (1)

$$(\underline{I}^{(0)}_{P,1})_{\text{int}} = -\gamma_G(k_E+k_B). \qquad (3)$$

The set point ζ_{th} of the protection using the current value of the fundamental harmonic of the zero-sequence current in the capacity of the characteristic quantity

$$\zeta = |\underline{I}^{(0)}_{P,1}| \qquad (4)$$

is detuned from the maximum value of the current for an external SPGF, and will be equal to

$$\zeta_{th} = K_r \max[(\underline{I}^{(0)}_{P,1})_{\text{ext}}],$$

where K_r is the offset factor.

As follows from expression (2), the maximum value

$$\max_{\gamma_E=1}[(\underline{I}^{(0)}_{P,1})_{\text{ext}}] = 1$$

is reached by the current $\underline{I}^{(0)}_{P,1}$ for an SPGF at the terminals of the equivalent generator, and hence $\zeta_{\text{th}} = K_r$. Then the condition of triggering protection will be defined by the expression

$$\zeta > K_r. \qquad (5)$$

The width of the deadband from the side of the neutral is

$$\gamma_\zeta = \frac{K_r}{k_E+k_B},$$

as follows from formulas (3), (4), and (5), this will depend on the relationship of the capacitive susceptance of the protected generator and the total capacitive susceptance of the equivalent generator and load (Fig. 1). Hence for small capacitance of the external network ($k_E + k_B$) < 2 already at an offset factor of $K_r = 2$, the protection is insensitive to internal short circuits.

It follows from expressions (2) and (3) that the zone of operation of protection can be expanded, giving it directionality due to its use as the characteristic quantity of the real part of the vector of the fundamental harmonic of the zero-sequence current

$$\zeta = \text{Re}(\underline{I}^{(0)}_{P,1}).$$

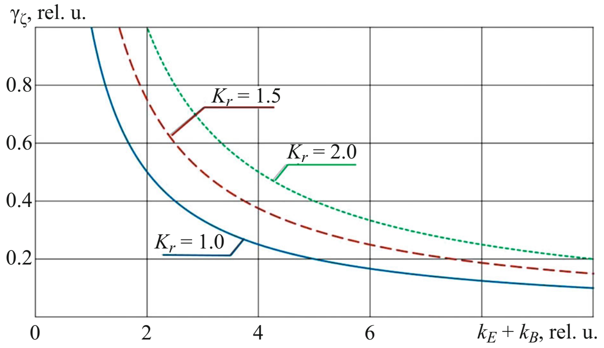

Fig. 1. Graphs of the dependence of the width of the deadband of the protection using the fundamental harmonic of a zero-sequence current, on the relative total conductivity of the external grid and the coefficient of offset.

The condition of triggering protection will be defined by the inequality

$$\zeta < 0,$$

and theoretically the protection will encompass the entire winding of the stator, but in practice the zone of operation will be restricted because of need for an offset from the unbalance currents.

Hence, protection from SPGF of a generator operating on busbars by using the fundamental harmonic of the zero-sequence current during operation in the network with an isolated neutral does not satisfy the sensitivity requirement; and in a network with the compensated neutral, the selectivity requirement also.

Protection using the fundamental and third harmonics of zero-sequence voltage. The basic and third harmonics of zero-sequence voltage are widely used in the capacity of informational signals of 100% protection from SPGF of the generator-transformer unit not having conductive coupling with the user and other sources [12]. However, these informational signals did not find application in protection from SPGF of a generator operating on busbars. We will clarify this circumstance.

The fundamental harmonic of zero-sequence voltage on the phase leads of the protected generator, $\underline{U}_{P,1}^{(0)}$, is practically absent in normal mode, and in emergency modes varies over a wide range depending on the location of the SPGF. Its complex value is

$$(\underline{U}_{P,1}^{(0)})_{\text{int(ext)}} = \gamma,$$

where $\gamma = \gamma_G$ or $\gamma = \gamma_E$ in the case of internal (int) or external (ext) SPGF, respectively.

The protection using, as the characteristic quantity, the fundamental harmonic of zero-sequence voltage detects an SPGF on the greater part of the generator stator winding, except for a zone near the neutral. The width of the deadband is defined by the level of unbalance and the precision of measurement of the fundamental harmonic of zero-sequence voltage, and in modern protection is less than 15% of the generator stator winding [13].

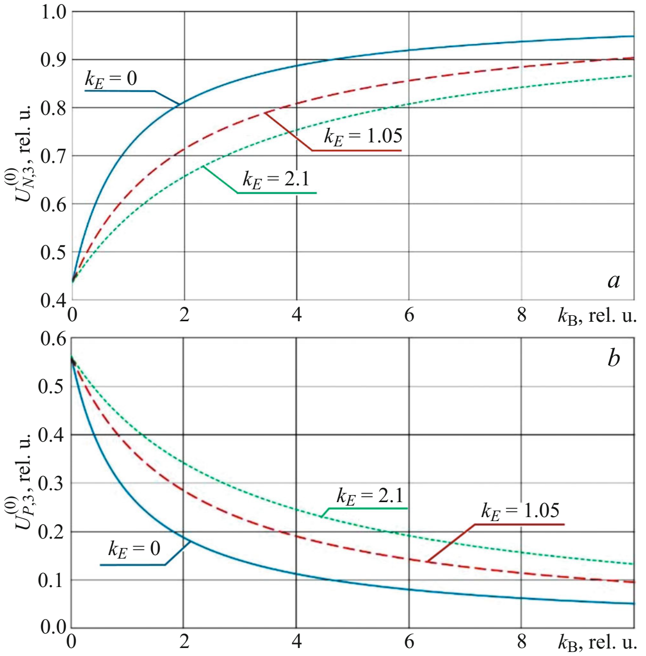

Fig. 2. Relative level of the third harmonic of the zero-sequence voltage at the neutral (*a*) and the phase leads (*b*) of the generator in normal mode, depending on capacitive susceptances.

For protection of the part of the generator stator winding located in the deadband of the protection on the fundamental harmonic, the third harmonic of the zero-sequence voltage is additionally used.

This is present in normal mode both on the phase leads of the generator

$$(\underline{U}_{P,3}^{(0)})_{\text{norm}} = \frac{1 + k_E}{2(1 + k_E + k_B)(1 - k_{R,3})}$$

and in its neutral

$$(\underline{U}_{N,3}^{(0)})_{\text{norm}} = (\underline{U}_{P,3}^{(0)})_{\text{norm}} - 1.$$

The voltage levels of the third harmonic on the phase leads and in the neutral depend on the relationship of the transverse conductivities of the generators and load and the neutral mode.

The most adverse operating conditions for the protection develop in a network with compensated neutral. In this case $k_R = 1$, and the degree of compensation of the capacitive currents at the frequency of the third harmonic $k_{R,3} =$ $= 0.111$, and for any relationship of parameters of network voltage $(U_{N,3}^{(0)})_{\text{norm}}$ is always greater than 0.4, and the voltage $(U_{P,3}^{(0)})_{\text{norm}}$ is less than 0.6 (Fig. 2).

To the extent that the location of the SPGF is close to the neutral ($\gamma \to 0$), the level of the third harmonic of the zero-sequence voltage on the phase leads

$$(\underline{U}^{(0)}_{P,3})_{\text{int(ext)}} = 1-\gamma \tag{7}$$

increases, and from the neutral side

$$(\underline{U}^{(0)}_{N,3})_{\text{int(ext)}} = -\gamma \tag{8}$$

decreases. The voltages in expressions (7) and (8) do not depend on the parameters of the network and are equal for an SPGF both in the protected (int: $\gamma = \gamma_G$) and in the equivalent generator (ext: $\gamma = \gamma_E$).

If in the compensated network $\gamma > 0.4$, then the voltages in formulas (7) and (8) are located in the range of values of the voltage of normal mode. This means that when the actual value of the third harmonic of the zero-sequence voltage is used in the capacity of the characteristic quantity, an SPGF can be indicated theoretically for only 40% of the generator stator winding in the neutral zone.

The electrical installation regulations [14] regulate that the coefficient of sensitivity of the protection reacting to the third harmonic of zero-sequence voltage must be no less than 2. This requirement shortens the operating protection zone to 20% of the winding near neutral. In practice, the sensitivity of protection decreases even more due to the asymmetry of the parameters of the equipment and errors of sections of ADC, and the use of the characteristic quantities in formulas (7) and (8) becomes inexpedient.

It is possible to enhance the sensitivity of protection to an SPGF near the neutral of the generator when using the characteristic quantity [12, 15]

$$\zeta = \left| \frac{\underline{U}^{(0)}_{N,3} + \underline{U}^{(0)}_{P,3}}{\underline{U}^{(0)}_{N,3}} \right|. \tag{9}$$

For an SPGF near the neutral, the characteristic quantity defined by expression (9) significantly increases (Fig. 3*b*).

In normal mode the maximum value of the characteristic quantity corresponding to expression (9) for the entire range of variation of parameters of the network does not exceed 1 (Fig. 3*a*). Since the sensitivity of protection, according to PUÉ, must be no less than 2, then, as seen from Fig. 3, the zone of protection will be no greater than 25% of a generator stator winding from the neutral side.

Hence the joint use of the basic and third harmonics of the zero-sequence voltage makes it possible to detect an SPGF at any point of the stator of the protected generator. However, as seen from formulas (6) – (8), the nature of the variation of voltages $U^{(0)}_{P,1}$ and $U^{(0)}_{P,3}$ is identical for an SPGF both in the protected and in equivalent generators. Consequently, it is impossible to delimit the modes of internal and external SPGF on the basis of the components of zero-sequence voltage. Hence, protection from SPGF of a generator operating on busbars, using as the informational signals the fundamental and third harmonic of the zero-sequence voltage, will not satisfy the selectivity requirements.

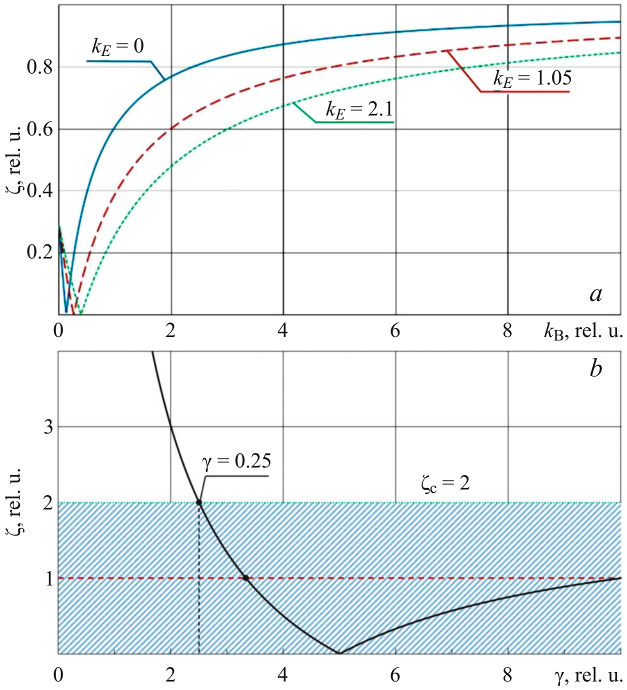

Fig. 3. Level of the characteristic quantity defined by expression (9), in normal mode (*a*) and with SPGF (*b*).

Protection with subharmonic voltage injection in a network. Because of the technical shortcomings of protection using the natural harmonics generated by the network, it was proposed to inject into the network artificially-created low-frequency harmonic signals (in Russia, as a rule, harmonics of frequency 25 Hz) [16, 17]. The source of the harmonic is switched on sequentially with the Peterson coil (Fig. 4), and in the capacity of a characteristic quantity

$$\zeta = I^{(0)}_{P,\nu} \quad (\nu = 0.5)$$

the actual value of the injection harmonic of frequency 25 Hz of the zero sequence current, measured at the phase leads of the protected generator, is used.

The EMF of the current source of frequency 25 Hz is taken as the base-line value voltage

$$\underline{U}_{\text{base},\nu} = \underline{E}_s \tag{10}$$

and the base-line value of conductivity is calculated by formula (8) [18] for $\nu = 0.5$

$$\underline{U}_{\text{base},\nu} = j0.5\omega_1 C_G.$$

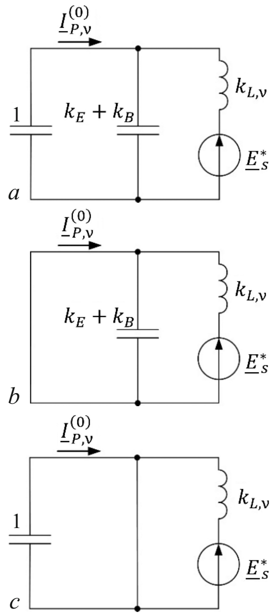

Fig. 4. The equivalent circuit of an electric network during action of just the source of an injection harmonic in normal mode (*a*), and during internal (*b*) and external (*c*) SPGF.

Then the base-line value of the current is

$$\underline{I}_{\text{base},\nu} = \underline{E}_{\text{base},\nu} \underline{U}_{\text{base},\nu} = j0.5\omega_1 C_{G_s}.$$

Taking into account expression (10), the EMF of the source in the circuits in Fig. 4 is

$$\underline{E}^*_s = 1.$$

The relative transverse conductivity of the equivalent generator k_E and of the external network k_B will be defined by expressions (2) and (3) in [18], and of the Peterson coil kL. v by expression (11) in [18], taking into account ν = 0.5.

The injection harmonic of the current at the phase leads, taking into account the connection of (12) in [18] between the conductivity of the Peterson coil $k_{L,\nu}$ and the total conductivity of the network $(1 + k_E + k_B)$ in normal mode (Fig. 4*a*), is equal to

$$(\underline{I}^{(0)}_{P,\nu})_{\text{norm}} = -\frac{k_{L,\nu}}{1 + k_E + k_B + k_{L,\nu}} = \frac{k_{R,\nu}}{1 - k_{R,\nu}}, \qquad (11)$$

for an internal SPGF (Fig. 4*b*):

$$(\underline{I}^{(0)}_{P,\nu})_{\text{int}} = -k_{L,\nu} = (1 + k_E + k_B)k_{R,\nu}, \qquad (12)$$

and for an external SPGF (Fig. 4*c*):

$$(\underline{I}^{(0)}_{P,\nu})_{\text{ext}} = 0.$$

Under the condition of full compensation of the capacitive current at the fundamental harmonic ($k_R = 1$), taking into account formula (13) in [18], we derive expressions for currents (11) and (12) in normal mode

$$(\underline{I}^{(0)}_{P,\nu})_{\text{norm}} = -\frac{4}{3}$$

and for an internal SPGF

$$(\underline{U}^{(0)}_{P,\nu})_{\text{int}} = 4(1 + k_E + k_B).$$

It is clear from this that the protection provides selectivity and sensitivity for the entire range of variation of parameters.

Hence, the protections using the harmonic of a current of non-commercial frequency [16, 17] provide the necessary sensitivity and selectivity, but require the installation of an additional expensive source of the harmonic, which affects the quality of electrical power and the precision characteristics of other RPA devices.

CONCLUSIONS

1. Studies of the information bases of algorithms for protection from SPGF of the stators of a generator operating on busbars show that an algorithm based on control of a harmonic injection into the network is the most effective. However, application of these protections requires installation of additional equipment in the network and results in deterioration of the quality of the electric power and the characteristics of other RPA devices.

2. The entire informational richness of the higher harmonics can be implemented fully by protections of the generator from SPGF that have the ability to estimate the level of harmonics on the background of the significantly predominant fundamental harmonic in network modes with a wide range of variation of frequency.

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