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POWER SYSTEMS AND ELECTRIC NETWORKS

INFORMATION BASES OF ALGORITHMS FOR PROTECTING A GENERATOR OPERATING ON BUSBARS FROM SINGLE-PHASE-TO-GROUND FAULTS.[1]

PART III. INVESTIGATION OF THE INFORMATION BASES OF ALGORITHMS CONTROLLING HIGHER CURRENT HARMONICS

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The information bases of algorithms for protecting the stator of a generator operating on busbars from single-phase-to-ground faults (SPGFs) are investigated. The information bases of algorithms in which the effective values of the components of zero-sequence higher current harmonics and differential currents are studied. It is shown that higher harmonics in the current of the SPGFs of the generator stator are divided into three groups, the harmonics of each of which have the property of individuality, manifesting itself in the original character of dependence of their level on the location of the SPGFs. The information content of harmonics of one group enrich the information value of other harmonic groups, increasing protection sensitivity and selectivity. It follows from an analysis that the most promising direction of development of algorithms for protection against SPGFs is the use of components of higher current harmonics.

Keywords: Information bases of protection algorithms; information protection signals; property of individuality of harmonic groups; protection of generator from single-phase-to-ground faults.

The present article is a continuation of works [1] and [2]; it presents an investigation of the information bases of algorithms of generator protection from single-phase-to-ground faults (SPGFs), in which higher current harmonics are used as the information signals. The results of calculations of higher current harmonics given in [3] are used hereinafter.

Depending on the number, current harmonics of the SPGF can conditionally be divided into three groups-first ($\nu = 1, 7, 13, ...$), second ($\nu = 5, 11, 17, ...$), and zero ($\nu = 3, 9, 15, ...$) by analogy with the names of the emf sequences, being the sources for these harmonics. In other words, the current harmonic caused by the emf of the forward sequence belongs to the first group, the back sequence to the second group, and the zero sequence to the zero group. The need to divide the current harmonics into groups is because the harmonics of the groups have properties of individuality, consisting in that the amplitudes of harmonics of different groups have a different character of their dependence on the SPGF location. The amplitudes of the current harmonics of the first and second groups increase linearly from neutral to a maximum value with distance from the SPGF location. This is characteristic both for an internal and an external SPGF. The amplitudes of current harmonics vary depending on the SPGF location differently; transition of the curve of the dependence of the level through zero in case of the SPGF being inside the winding of the protected or equivalent generators is characteristic for them.

The names of the groups of the current harmonics should not be confused with the names of sequences of electrical quantities because in a circuit in which a three-phase generator emf with harmonics of one sequence acts, other sequences of the same current harmonics can rarely appear in an SPGF. This follows directly from the principles of the method of symmetric components, establishing that in an

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SPGF mode in schemes of sequences, sources caused by asymmetry appear along with corresponding sources of higher harmonics of the generator emf.

The property of individuality of harmonics of groups establishes that it is necessary to analyze information signals of protection from SPGF using higher harmonics separately for the zero and first (second) groups. Therefore, it is sufficient to analyze information signals of different groups only for the third and fifth harmonics as representatives of harmonics of these groups. Then the conclusions obtained can be applied also to other harmonics of the corresponding groups.

Protection controlling the effective value of higher harmonics of components of the zero sequence current. The ZGNP-4.2 unit [4] is a typical example of protection using as a characteristic quantity the effective value of higher harmonics of components of the zero sequence current. With consideration of the property of individuality of harmonics of the groups, we will analyze the information bases of the protection algorithm for the example of the third and fifth harmonics.

In a normal mode the relative value of the component of the third harmonic of the zero sequence current from the phase leads

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

with a considerable capacitive susceptance of the external network ($k_E + k_B \to \infty$) is determined only by the capacitive susceptance of the generator (Fig. 1):

$$(\underline{I}^{(0)}_{P,3})_{\text{norm}} \to \frac{1}{2}.$$

Although the emf of the fifth harmonic acts in the network, it does not cause the component of the zero sequence in the current, i.e.,

$$(\underline{I}^{(0)}_{P,5})_{\text{norm}} = 0.$$

In an internal SPGF mode, in the zero sequence current from the phase leads, in addition to the component of the third harmonic

$$(\underline{I}^{(0)}_{P,3})_{\text{int}} = (1-\gamma_G)[(1+k_E+k_B)(1-k_{R,3})-1] - \frac{k_E}{2} \tag{2}$$

the component of the fifth component appears

$$(\underline{I}^{(0)}_{P,5})_{\text{int}} = -\gamma_G[(1+k_E+k_B)(1-k_{R,5})-1]. \tag{3}$$

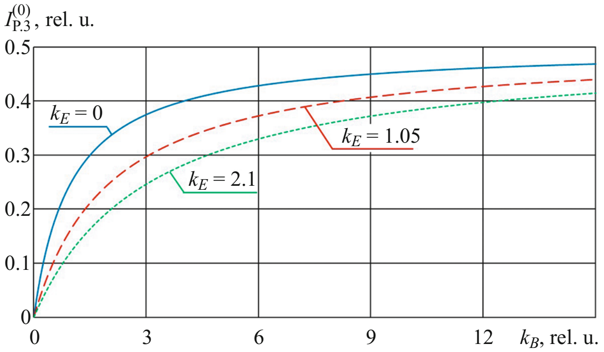

Fig. 1. Relative level of the component of the third harmonic of the zero sequence current on phase leads of the generator in a normal mode.

In an external SPGF, the same electrical quantities do not depend on the capacitive current of the external network:

$$\begin{cases} (\underline{I}^{(0)}_{P,3})_{\text{ext}} = \gamma_E - \frac{1}{2}; \\ (\underline{I}^{(0)}_{P,5})_{\text{ext}} = \gamma_E. \end{cases} \tag{4}$$

Here γ_G and γ_E are the relative electrical distances to the SPGF location in the protected and equivalent generators read from the neutral of the generator; k_E and k_B are the relative magnitudes of the capacitive susceptance of the equivalent generator and transverse branches of the equivalent load; kR is the degree of compensation of the capacitive currents at the frequency of the fundamental harmonic; the indices norm, int, ext are respectively the normal mode, internal or external SPGF.

To provide selectivity, protection should be tuned out from the maximum level of the currents of the load mode and external SPGF

$$\zeta_{th} = K_r \max[|(\underline{I}^{(0)}_{P,3})_{\text{norm}}|, |(\underline{I}^{(0)}_{P,3})_{\text{ext}}|], \tag{5}$$

where K_r is the tune-out coefficient.

With consideration of the smallness of the level of the currents of harmonics with numbers 5 and higher [5], the protection setting can be selected with respect to the third harmonic of the zero sequence current. As is seen from formulas (1) and (4) as well as from Fig. 1, the effective value of the current of the third harmonic does not exceed half of the self-capacitive current of the generator being protected:

$$\max_{k_E, k_B \to \infty} |(\underline{I}^{(0)}_{P,3})_{\text{norm}}$$

Then the setting according to expression (5) is equal to

$$\zeta_{th} = K_r/2.$$

The calculation mode for assessing protection sensitivity will be the internal SPGF with a minimum current, which occurs at a minimum capacitive susceptance of the external network or operation of an idling generator ($k_E = 0$, $k_B = 0$). In these modes, as seen from Eqs. (2) and (3), the components of higher harmonics of the zero sequence current

$$(\underline{I}^{(0)}_{P,3})_{\text{int}} = -(1-\gamma_G)k_{R,3} \text{ and } (\underline{I}^{(0)}_{P,5})_{\text{int}} = \gamma_G k_{R,5}$$

will be determined by the degree of compensation of the capacitive current of the network $k_{R,\nu}$ on the corresponding harmonic. Compensation is not fulfilled ($k_R = 0$) in a network with a small capacitance, then the current will be equal to zero.

Consequently, protection from SPGF of a generator using the effective value of higher harmonic components of the zero sequence current satisfies the requirements of sensitivity only in the case of considerable capacitance of the external network.

Protection controlling the greatest of the effective value of higher harmonic components of differential phase currents. Protection sensitivity in the case of a low capacitance of the external network can be increased by using as the characteristic quantity the greatest of the effective values of the higher harmonic components of the differential phase currents [6]:

$$\zeta = \max(I^A_{\Delta,RMS}, I^B_{\Delta,RMS}, I^C_{\Delta,RMS}). \tag{6}$$

The quantity $I^{\chi}_{\Delta,RMS}$ for each phase $\chi = \overline{A, B, C}$ is formed as the effective value of the residual signal obtained by excluding the fundamental harmonic from the differential phase current. To investigate the information bases of the protection algorithm, it is convenient to represent the effective value of the differential current in relative units:

$$I^{\chi}_{\Delta,RMS} = \sqrt{\sum_{\nu=3,5,7,\ldots}\left(\frac{I^{\chi}_{\Delta,\nu} I_{base,\nu}}{I_{base,RMS}}\right)^2}, \tag{7}$$

taking as the base the self-capacitive current of the protected generator on the third harmonic

$$\underline{I}_{base,RMS} = j3\omega_1 C_G \underline{E}^f_3. \tag{8}$$

The threshold of operation of protection is proportional to the median value of the effective values of the external harmonic components of the differential phase currents

$$\zeta_{th} = K_r \operatorname{mid}(I^A_{\Delta,RMS}, I^B_{\Delta,RMS}, I^C_{\Delta,RMS}) \tag{9}$$

and depends on the operating conditions of the network. It follows from expressions (6) and (9) that protection functions if the effective values of the current according to Eq. (7) of one of the phases exceed the effective value of the currents of the other two phases by more than K_r times. The tune-out coefficient K_r is selected from conditions of providing selectivity of the operation of protection in a normal operation mode of the generator and for an external SPGF.

The relative levels of individual harmonics of the differential current, as is seen from Figs. 2 and 3 [1], are practically independent of the number of the harmonic; they experience only the effect of the compensation coefficient of the capacitive current of the network $k_{R,\nu}$ (the component of the load current is absent in the differential current). But, as follows from Eq. (13) [1], the coefficient $k_{R,\nu}$ swiftly decreases with increasing number of the harmonic due to substantial weakening of the role of the Peterson coil in schemes for higher harmonics compared to a scheme on the fundamental harmonic. The Peterson coil compensates only about 11% of the capacitive currents of the third harmonic ($k_{R,3} = 0.111$) and only 4% of the capacitive currents of the fifth harmonic ($k_{R,5} = 0.040$), and at the limit as $\nu \geq \infty$, the compensation coefficient $k_R,\nu \to 0$.

In addition to this, the value of the current according to (7), expressed in the base according to formula (8) with consideration of Eq. (9) [1], is associated with the relative values of the higher harmonics of the differential phase currents $I^{\chi}_{\Delta,RMS}$ by the relation

$$I^{\chi}_{\Delta,RMS} = \sqrt{\sum_{\nu=3,5,7,\ldots}\left(\frac{\nu E_\nu I^{\chi}_{\Delta,\nu}}{3E_3}\right)^2}. \tag{10}$$

Therefore, the relative levels of the higher harmonics of the group will be close to one another. The contribution of each harmonic to the magnitude, expressed by Eq. (10), will be determined practically only by the coefficient

$$K_{s,\nu} = \left(\frac{\nu E_\nu}{3E_3}\right)^2.$$

Since the absolute level of the third harmonic of the emf considerably exceeds the levels of other harmonics [1] and the total contribution of all higher harmonics with numbers $\nu = 5$ is less than 2% (Fig. 2), then $I^{\chi}_{\Delta,RMS}$ is determined mainly by the level of the third harmonic of the differential phase current.

We will analyze the information bases of the protection algorithm by way of the example of the third and fifth harmonics with consideration of the property of individuality of harmonics of the groups.

In a normal mode the relative values of the third and fifth harmonics of the differential currents of a particular phase f of the generator are equal respectively to

$$(\underline{I}^f_{\Delta,3})_{\text{norm}} = \frac{1}{2} - \frac{1+k_E}{2(1+k_E+k_B)(1-k_{R,3})} \tag{11}$$

and

$$(\underline{I}^f_{\Delta,5})_{\text{norm}} = -\frac{1}{2}. \tag{12}$$

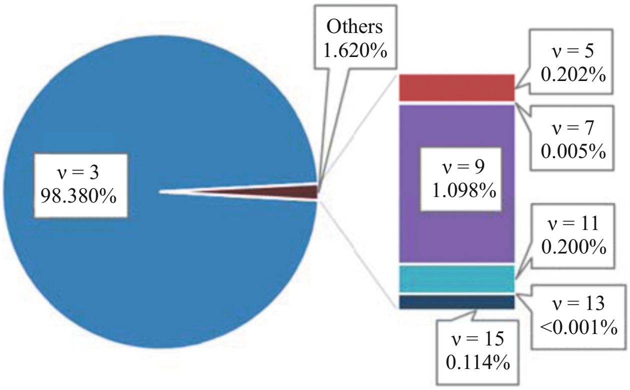

Fig. 2. Contribution of higher current harmonics to the level of the characteristic quantity for protection using the effective values of higher harmonic components of the current.

The differential currents of other phases are determined with consideration of the phase relations of the emf according to expressions (11) and (12). Therefore, when $K_r > 1$, the characteristic quantity ζ [formula (6)] will be less than the operating threshold ζ_{th} [expression (9)].

For an external SPGF the elative values of the third harmonic of the differential current of all phases will be equal to one another

$$(\underline{I}^{f}_{\Delta,3})_{\text{ext}} = (\underline{I}^{\sigma}_{\Delta,3})_{\text{ext}} = \gamma_E - \frac{1}{2}$$

and the levels of the fifth harmonic in undamaged phases

$$(\underline{I}^{\sigma}_{\Delta,5})_{\text{ext}} = \gamma_E - \frac{a^{5\lambda}}{2}$$

(where $a = e^{j120°}$ is a complex rotation operator) will theoretically be the same but greater than in the undamaged phase

$$(\underline{I}^{f}_{\Delta,5})_{\text{ext}} = \gamma_E - \frac{1}{2}.$$

Consequently, for external SPGFs protection is reliably blocked also when $K_r > 1$. Here and further $\lambda = 1$ for the leading phase ($\sigma = f + 1$) and $\lambda = 2$ for the lagging phase ($\sigma = f - 1$). In practice, for tuning protection out of imbalance currents and measurement errors, the value of the tune-out coefficient $K_r = 1.5$.

For an internal SPGF, the components of the third and fifth harmonic in the current of the damaged phase will be equal respectively to

$$(\underline{I}^{f}_{\Delta,3})_{\text{int}} = (1-\gamma_G)[3(1+k_E+k_B)\times$$

$$\times(1-k_{R,3})-1]-1-3\frac{k_E}{2} \qquad (13)$$

and

$$(\underline{I}^{f}_{\Delta,5})_{\text{int}} = -\gamma_G[3(1+k_E+k_B)(1-k_{R,5})-1]-\frac{1}{2} \qquad (14)$$

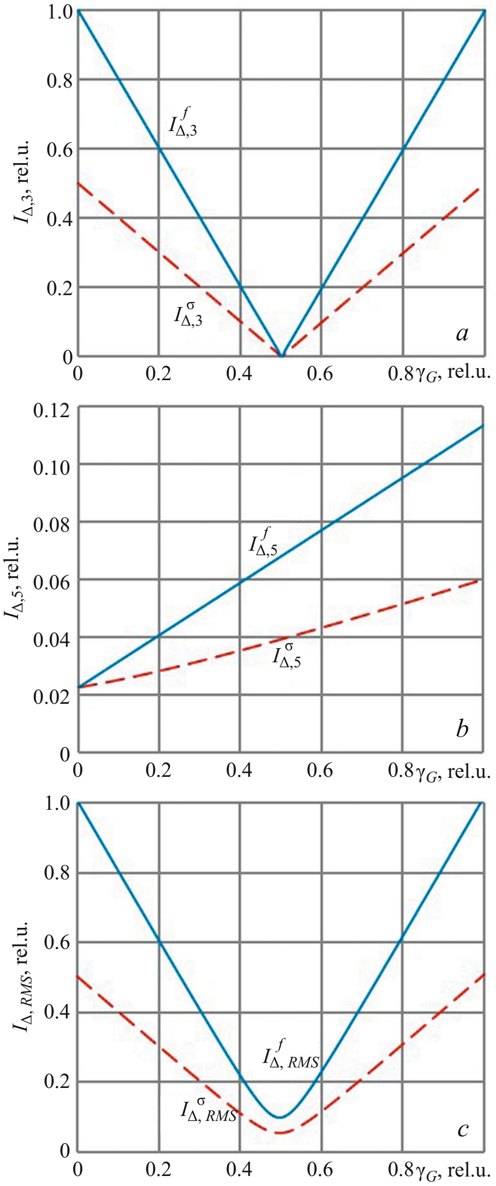

Fig. 3. Graphs of the dependence of the relative levels of the third (*a*), fifth (*b*) harmonics and effective value of higher harmonic components (*c*) of the differential current in damaged and undamaged phases on the location of the internal SPGF in the absence of compensation: the current determined by Eq. (8) is taken as the base value.

In the undamaged phases the same harmonics will be the following:

$$(\underline{I}^{\sigma}_{\Delta,3})_{\text{int}} = \gamma_G - \frac{1}{2} \qquad (15)$$

and

$$(\underline{I}^{\sigma}_{\Delta,5})_{\text{int}} = \gamma_G - \frac{a^{5\lambda}}{2}. \qquad (16)$$

In this case the capacitive currents of all network elements flow along the damaged phase toward the SPGF loca-

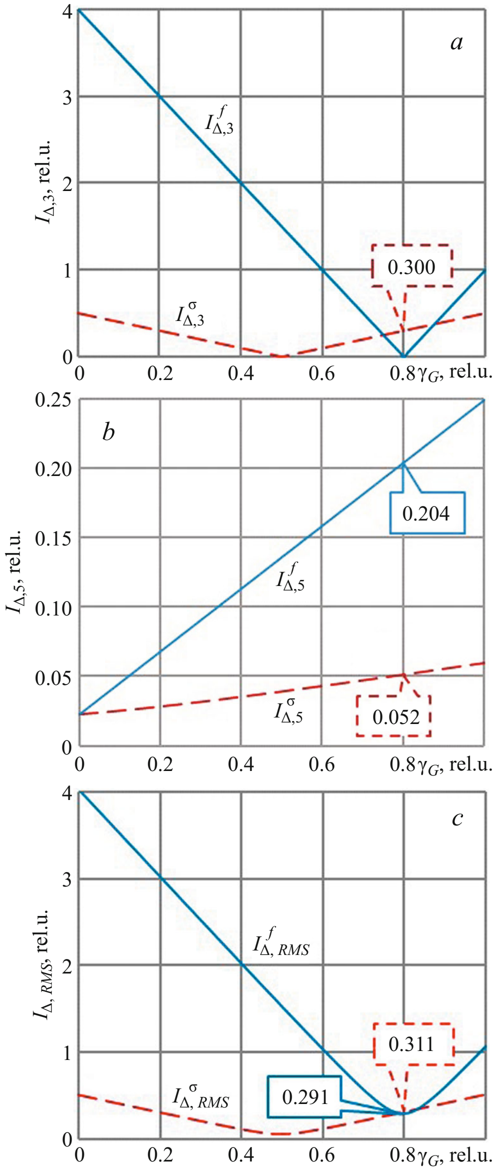

Fig. 4. Graphs of the dependence of the relative levels of the third (*a*) and fifth (*b*) harmonics and effective value of higher harmonic components (*c*) of the differential current in damaged and undamaged phases on the location of the internal SPGF with connection to the external network: the current determined by Eq. (8) is taken as the base value.

tion. Therefore, the amplitudes of the harmonic components of the differential current in the damaged phase of the generator for an internal SPGF increases substantially. This is valid also for the case of operation of an idling generator because the currents of the remaining undamaged phases of the generator flow toward the location of the SPGF.

At the same time, the differential current of the undamaged phase of the protected generator depends only on the capacitive current of this phase.

To check the correspondence of protection to the sensitivity requirements, we will estimate the levels of harmonics of the differential currents of damaged and undamaged phases for SPGF at different points of the stator winding of the protected generator and various parameters of the network elements. The operation of an idling generator ($k_E = 0$, $k_B = 0$) and with connection of the protected generator to the network with a small ($k_B = 1$) and considerable ($k_B \geq 3$) capacitance is examined for estimating protection sensitivity.

In an idling mode of the protected generator and in the absence of compensation ($k_{R,\text{v}} = 0$), the level of the third harmonic of the differential current of the damaged [formula (13)] and undamaged [expression (15)] phases decreases and reaches zero when the SPGF location moves toward the middle of the stator winding of the generator (Fig. 3*a*). The level of the fifth harmonic in the damaged and undamaged phases will increase linearly when the SPGF locationn moves from neutral to the phase leads (Fig. 3*b*). In this case, the effective value of higher harmonic components of the differential currents in the damaged phase is almost twice greater than in the undamaged phases (Fig 3*c*). Consequently, the characteristic quantity according to formula (6) is determined by harmonics of the differential current of only the damaged phase

$$\zeta = I^f_{\Delta,RMS}$$

and the operating threshold according to Eq. (9) is determined by harmonics of one of the undamaged phases

$$\zeta_{th} = K_r I^\sigma_{\Delta,RMS}.$$

Thus, in an idling generator mode, protection is sensitive to all internal SPGFs.

On connecting the generator to the external network, the total capacitance increases, consequently, the maximum levels of the harmonics [expressions (13) and (14)] of the differential current in the damaged phase for internal SPGFs increases. At the same time, the levels of the harmonics [expressions (15) and (16)] of the undamaged phases do not depend on the capacitance of the external network and therefore the character of their dependence on the SPGF location remains the same for any capacitance of the external network.

The minimum of the curve of the level of the third harmonic of the current [expression (13)] of the damaged phase with increase of the capacitance of the external network shifts to the right along the γ_G axis, and that of the undamaged phase still remains in the middle of the winding (Fig. 4*a*). In that case, according to Eq. (14) the character of the dependence of the level of the fifth harmonic of the current of the damaged phase on the SPGF location and its values for SPGF at the neutral do not change; however, the slope of the characteristic increases (Fig. 4*b*). Therefore, according to formula (7) the effective value of the current of the damaged phase for SPGF at a point where the level of the third harmonic [expression (13)] decreases to zero (Fig. 4*a*; $\gamma_G = 0.80$) will be determined mainly by harmonics of the

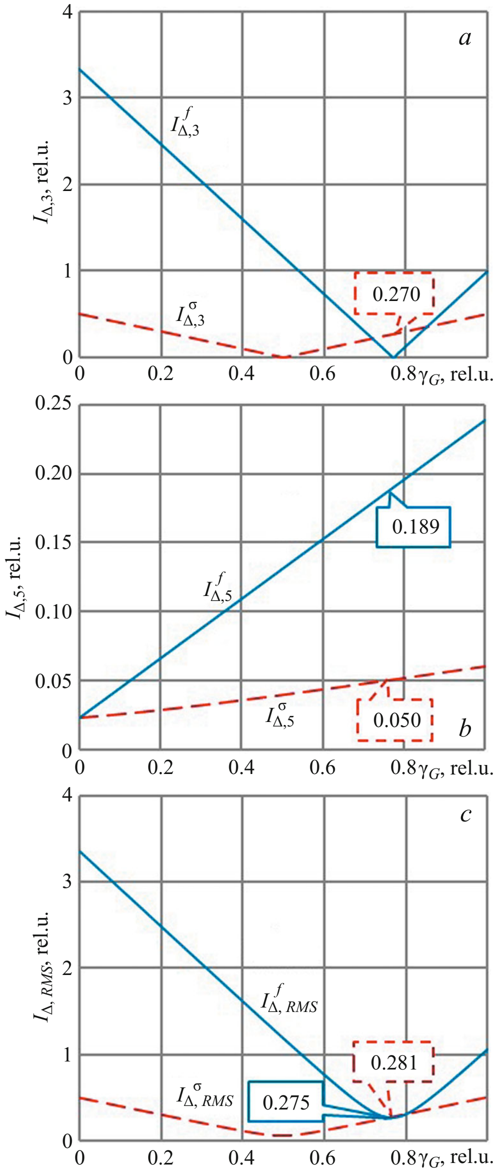

Fig. 5. Graphs of the dependence of the relative levels of the third (*a*) and fifth (*b*) harmonics and effective value of higher harmonic components (*c*) of the differential current in the damaged and undamaged phases on the place of the internal SPGF with introduction of compensation into the network: the current is determined by Eq. (8) is taken as the base value.

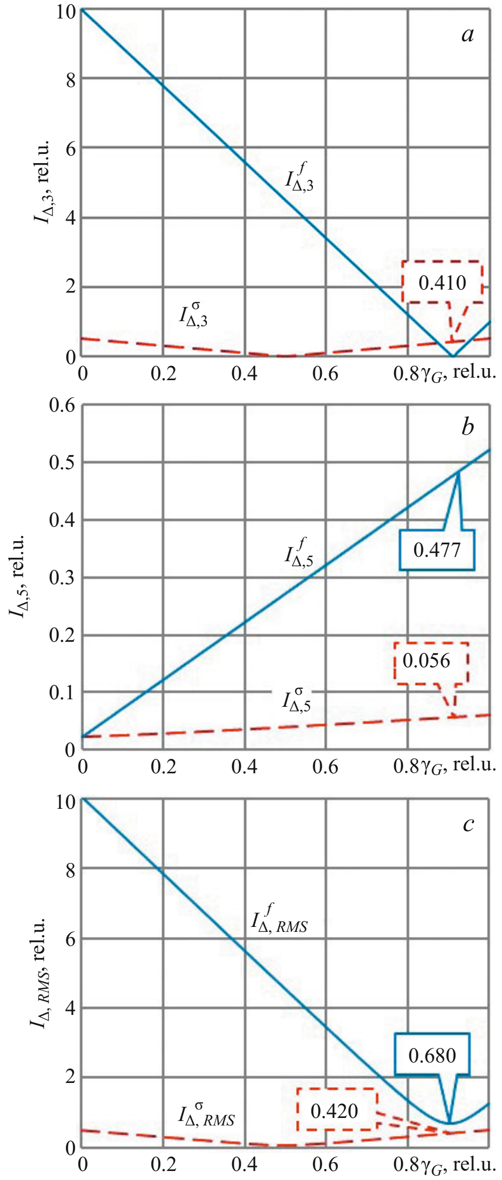

Fig. 6. Graphs of the dependence of the relative levels of the third (*a*) and fifth (*b*) harmonics and effective value of higher harmonic components (*c*) of the differential current in the damaged and undamaged phases on the location of the internal SPGF: the current determined by Eq. (8) is taken as the base value.

first (7th, 13th, etc.) and second (5th, 11th, etc.) groups, and the effective value of the current of the undamaged phases — by the level of harmonics of the zero group (3rd, 9th, etc.). It follows from Fig. 2 that the 5th and 11th harmonics make up the main share in the effective value of the current of the damaged phase at this point, and the 3rd harmonic at points of undamaged phases.

For certain relations of the capacitances of the network elements, a situation can develop (Fig. 4*c*; $\gamma_G = 0.80$) when the effective value of all higher harmonic components of the differential current in the undamaged phase ($I^{\sigma}_{\Delta,RMS} = 0.311$) will be greater than in the damaged ($I^{f}_{\Delta,RMS} = 0.291$). In other words, an insensitivity zone will occur when the SPGF is close to the phase leads or neutral of the generator because the characteristic quantity according to formula (6) will be less than the operating threshold according to expression (9).

Compensation of capacitance practically does not affect protection sensitivity (Fig 5) and leads only to movement of the minimum of the level of the third harmonic [according to formula (13)] of the damaged phase depending on the SPGF location ($\gamma_G = 0.77$) toward the neutral and, as a consequence, to movement of the minimum of the effective value of higher harmonic components depending on the SPGF location [expression (7)] ($I^{f}_{\Delta,RMS} = 0.275$; $I^{\sigma}_{\Delta,RMS} ==$ 0.281) due to the insignificant decrease of the total level of higher harmonics in the network ($I^{\sigma}_{\Delta,3} = 0.270$; $I^{f}_{\Delta,5} = 0.189$; $I^{\sigma}_{\Delta,5} = 0{,}050$).

Only in a network with a considerable external capacitance will the effective value according to formula (7) of the damaged phase for an internal SPGF at the point of the minimum of the third harmonic be higher than the effective value of higher harmonic components of the differential current of the undamaged phase (Fig. 6*c*; $\gamma_G = 0.91$; $I^{f}_{\Delta,RMS} = 0.680$; $I^{\sigma}_{\Delta,RMS} = 0.420$). Protection will not have an insensitivity zone in such networks.

Thus, protection controlling the greatest of the effective values of the higher harmonic component of the differential currents of phases loses sensitivity to SPGF on part of the stator winding of the generator in a network with a small capacitance, and in connection with this it did not find wide use.

CONCLUSIONS

1. An analysis of information signals shows that the use of higher harmonics is the most promising direction in the development of algorithms for protecting a generator operating on busbars from SPGFs.

2. Higher harmonics, the source of which are the generator emf, are divided into three groups, the harmonics of which have the property of individuality, manifesting itself in the original character of the dependence of their level on the SPGF location. The information content of harmonics of one group enriches the information value of harmonics of other groups, increasing protection sensitivity and selectivity.

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