DOI 10.1007/s10749-019-01065-1
Power Technology and Engineering *Vol. 53, No. 2, July, 2019*

INFORMATION BASES OF PROTECTION ALGORITHMS FOR SINGLE-PHASE GROUND FAULT OF A GENERATOR OPERATING IN PARALLEL ON BUSBARS.
PART I. UNIVERSAL MODEL OF A NETWORK

A. V. Soldatov,[1,2] V. A. Naumov,[1,2] V. I. Antonov,[1,2] M. I. Aleksandrova,[2,3] and A. V. Lifant'ev[4]

Translated from *Élektricheskie Stantsii*, No. 1, January 2019, pp. 45 – 51.

A new methodology is explained for the study of information bases of protection algorithms from single-phase ground faults in the stator winding of a generator operating in parallel on busbars. The basis of the methodology is a universal model of an electrical network, preserving generality in the analysis of information signals of the protection for any frequency. This fundamental property of the model is achieved by representing the parameters of the network elements and electrical values in relative units, selecting for base-line values the capacitive conductivity and the RMS value of the EMF of the protected generator at the frequency of the information signal. Analysis of the information value of the electrical variables and their components in various operating modes of the protected generator, and evaluation of the effectiveness of their use in protection, make it possible to study the chief properties of protection algorithms from unified positions.

Keywords: information bases of protection algorithms; information signals of protection; generator single-phase ground fault; universal model of an electrical network.

Ensuring the selectivity of single-phase ground fault (SPGF) protection of the stator winding of a generator operating in parallel on busbars is a complex task, since several generators operate on the station busbars, and there exists a galvanic connection with the end user electrical network. At the same time, the protection must be sensitive to SPGF at any point of the stator winding of the generator, including near neutral. It is true that high speed is not required here: cutoff of a damaged generator from the busbars is carried out over approximately 0.5 sec [1].

The majority of works [2 – 9] have been devoted to the study of the protection of the generator stator from SPGF, but a uniform approach to the analysis of protection algorithms has not been developed. This hinders the determination of a strategy for the development of protection from SPGF of the stator of a generator operating in parallel on busbars. In this regard, there exists an imperative need for analysis of algorithms for protection of generators from SPGF from unified positions.

The objective of this work is the study of the information bases of algorithms for protection of generators from SPGF, and detection of the most promising algorithms for application in new generations of adaptive protection from SPGF of the stator of a generator operating in parallel on busbars.

For the purposes of this article, adaptive protections are understood as functions of relay protection that are capable of modifying the characteristics and algorithms of their own functioning depending on the condition of the network, and are as a rule implemented in smart electronic devices. Information bases are understood as a set of information signals and the principles of their selection and use in protection. The concept of the information signal is used for determination of a component primary electric variable, transformed during the protection into a characteristic quantity in a specified manner. By monitoring the characteristic quantity, the protection will recognize the operating mode of the electrical network.

The study of information bases of protection algorithms includes analysis of the information signals from the point of view of recognizing the network modes, and analysis of the principles of their selection and use for assessment of the chief properties of protection (sensitivity, selectivity, and speed).

During the analysis of the sensitivity of generator protection from SPGFs, a limit width is estimated for the zone of detection for damage of the stator winding of the protected

---

[1] I. N. Ul'yanov Chuvash State University, Cheboksary, Russia
[2] JSC NPP Ekra, Cheboksary, Russia.
[3] e-mail: aleksandrova$mi@ckra.ru
[4] Kazan TÉTs-2 branch of JSC Tatenergo, Kazan, Russia.

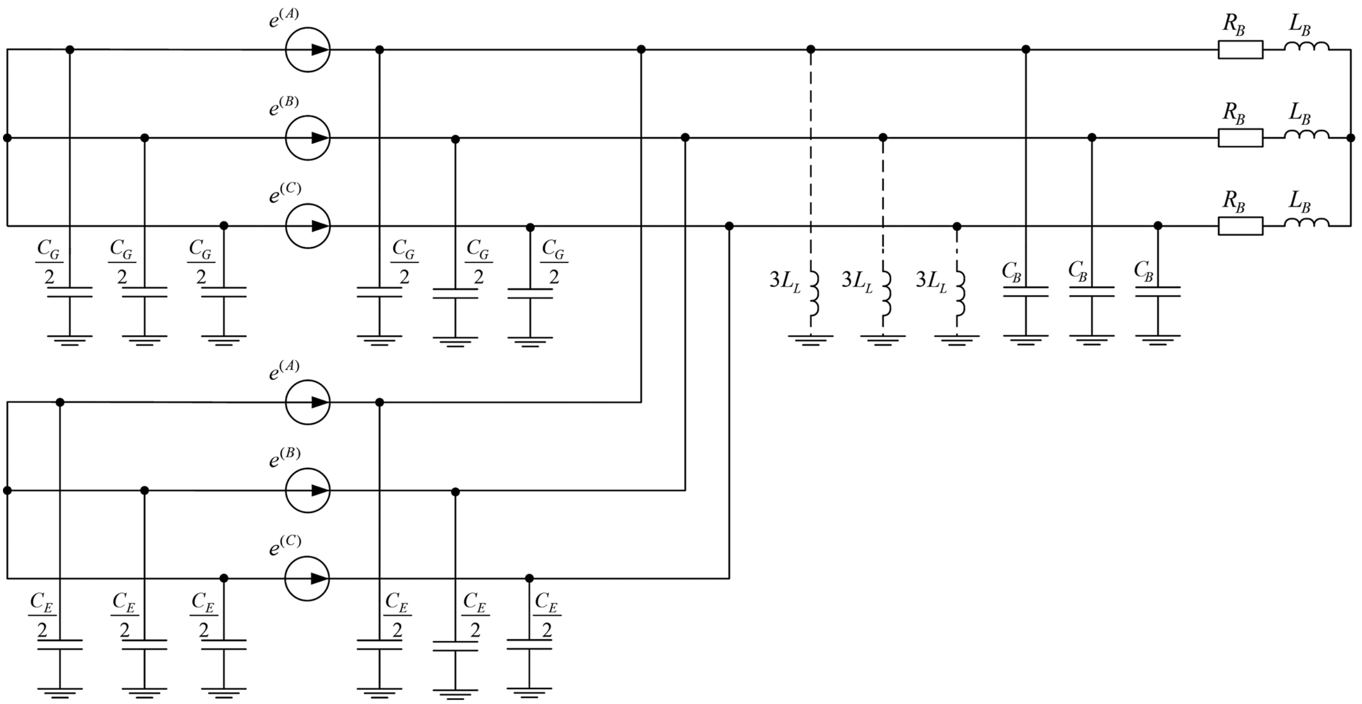

Fig. 1. An equivalent electrical circuit.

generator throughout the possible range of modification of network parameters. The coefficient of sensitivity K_S is taken as the measure of sensitivity of protection, and is defined as the minimum value of the ratio of the characteristic value ζ to the activation threshold of protection ζ_{th}:

$$K_S = \min\left|\frac{\zeta}{\zeta_{\text{th}}}\right|.$$

In the analysis of the selectivity of protection, its offset from excessive operation in normal mode is checked, and also for external SPGFs in the calculated range of the modification of parameters of network elements.

Since the requirements for time of activation of generator protection from SPGF are not shown, the speed of protection response is not estimated in this article.

Only metal SPGFs are considered in this work. Arc short circuits are not discussed, since the behavior of an electrical network with this type of damage differs radically from the behavior with a metal SPGF, and will require separate research.

This article consists of three parts. In the first part, a universal model of a network is examined; in the second part, the information bases of the algorithms using components of zero sequence are studied; and in the third part, algorithms using the higher harmonics of the current are investigated.

Equivalent circuit of an electrical network. In the formation of an equivalent circuit, a generator network with busbars is made equivalent relative to the terminals of the protected generator (Fig. 1). It is assumed that the system is completely symmetric.

Sources of the higher harmonics in a network with generators operating on busbars are the generators themselves and the load. The occurrence of harmonics from both types of sources is caused by the nonlinearity of their characteristics. An equivalent circuit of the network for each of the harmonics will consist only of linear elements, since a nonlinear network element generating this harmonic — whether the generator or the load — will be considered as the corresponding source of this harmonic, included instead of the nonlinear element by taking into account its linearized characteristics.

It is accepted that a high voltage network is not a source of the higher harmonics and generates only the primary harmonic.

In protection from SPGF of a generator operating on busbars, the voltages and currents are measured at the neutral and phase terminals of the protected generator. For external SPGFs, the information signals, such as the higher harmonics of a zero-sequence current, are chiefly caused by the EMF of the sources of harmonics of the protected generator itself, and are determined basically by the inherent capacitive currents of the protected generator and have practically no dependence on the location of the SPGF and the sources of harmonics in the network. For internal SPGFs, currents from the capacitive conductivities of the entire network flow into the protected generator, and the level of information signals at the measurement location are determined in practice by the values of the capacitive currents of the external grid. However, by the criterion of sensitivity of protection, there will be a mode calculated for when the level of capacitive currents of the external grid will be minimal, i.e., there are no external sources of harmonics. Therefore, in the analysis of the information bases of protection algorithms the sources of harmonics of the external grid are usually not considered.

All harmonics sources active in the network are represented in an equivalent circuit in the form of two generators: protected and equivalent.

The protected and equivalent generators are considered as a U-shaped equivalent circuit. Cross branches of the generators are represented in the equivalent circuit by the corresponding capacitances $C_G/2$ and $C_E/2$, and longitudinal branches by leakage inductances L_G and L_E. Since the energy of the sources of harmonics is basically concentrated in the low-frequency region, it is assumed that the inductive resistances of the longitudinal branches do not render any significant effect on the level of currents at the location of the SPGF. However, the relationship between the resistances of the longitudinal branches does render an effect on the distribution of currents between the generators, which is accounted for in calculations by the coefficient of distribution

$$k_D = L_G/L_E. \tag{1}$$

The EMF of the protected and equivalent generators are taken as identical and are represented by sources of a three-phase polyharmonic signal [10]

$$\begin{Bmatrix} e^{(A)}(t) \\ e^{(B)}(t) \\ e^{(C)}(t) \end{Bmatrix} = N \sum_{\nu=1,3,5,\ldots} E_\nu \begin{Bmatrix} \sin(\nu\omega_1 t) \\ \sin[\nu(\omega_1 t + 4\pi/3)] \\ \sin[\nu(\omega_1 t + 2\pi/3)] \end{Bmatrix}, \tag{2}$$

where ω_1 is the angular frequency of the primary harmonic, and E_ν is the amplitude of the EMF of the harmonic. Network elements (current-limiting reactors, inductance of power lines) — the values of the longitudinal resistance of which increase in circuits for higher harmonics — are accounted for in the equivalent load. Equivalent load is represented as an L-section circuit with active resistance R_B and inductance L_B of the longitudinal branch and capacitance C_B relative to the earth.

It is convenient to express all the capacitances of the circuit of the electrical network through the transverse capacitance of a phase of the protected generator. Then the capacitances of the equivalent generator

$$C_E = k_E C_G \tag{3}$$

and of the equivalent load are

$$C_B = k_B C_G \tag{4}$$

and the total phase power of the entire network can be expressed through the capacitance of the protected generator

$$C_\Sigma = C_G(1 + k_E + k_B), \tag{5}$$

where k_E and k_B are relative values of the capacitances of the equivalent generator and the cross branches of the equivalent load.

Neutral mode in a generator network with bus bars is determined by the arc suppression coils that are connected to buses through neutral-forming transformers. The arc suppression coils operate only in the equivalent circuits of the harmonics of zero sequence and are not considered in the operation of circuits of direct and inverse sequences. The leakage inductance of the neutral-forming transformers in calculations is taken account of in the inductance of the equivalent arc suppression coil.

In the three-phase equivalent circuit (Fig. 1), the arc suppression coil is switched on conditionally in each phase and is represented by a dashed line in the form of inductance. This depends on the total capacitance of the phase of the network (5) and the coefficient of compensation k_R of the capacitance currents at the frequency ω_1 of the primary harmonic, and is equal to

$$L_L = \frac{1}{3k_R\omega_1^2 C_\Sigma}, \tag{6}$$

In networks with isolated neutral, arc suppression coils are absent and $k_R = 0$. In networks with compensated neutral, the inductive conductivity of the arc suppression coil at the frequency of the primary harmonic must theoretically be equal to the total capacitive conductivity of the entire network, i.e., $k_R = 1$. However, in reality there is always compensation detuning, and $k_R \neq 1$. The magnitude of admissible detuning is defined by the PUÉ [1] and depends on the voltage class of the network.

It is convenient to represent the parameters of elements of equivalent circuits in relative units, taking for each νth harmonic a vector of the EMF of a special phase f as the base-line values:

$$\underline{E}_{\text{base},\,\nu} = \underline{E}_\nu^{(f)} \tag{7}$$

and the total conductivity of the cross branches of the phase of the protected generator

$$\underline{Y}_{\text{base},\,\nu} = j\nu\omega_1 C_G \tag{8}$$

on the corresponding harmonic. Therefore the base-line value of the current for the νth harmonic is

$$\underline{E}_{\text{base},\,\nu} = \underline{Y}_{\text{base},\,\nu}\underline{U}_{\text{base},\,\nu} = j\nu\omega_1 C_G \underline{E}_\nu^{(f)}. \tag{9}$$

Phase A is taken as the special phase in normal mode, and as the damaged phase in SPGF mode.

It follows from expressions (2) and (7) that the phase EMFs on the νth harmonic will be equal in relative units to

$$\begin{bmatrix} \underline{E}_\nu^{*(f)} \\ \underline{E}_\nu^{*(f-1)} \\ \underline{E}_\nu^{*(f+1)} \end{bmatrix} = \begin{bmatrix} 1 \\ \underline{a}^{2\nu} \\ \underline{a}^{\nu} \end{bmatrix}, \tag{10}$$

where $\underline{a} = e^{j120^\circ}$ is the complex operator of rotation; (f), ($f - 1$) and ($f + 1$) designate the special, lagging, and leading

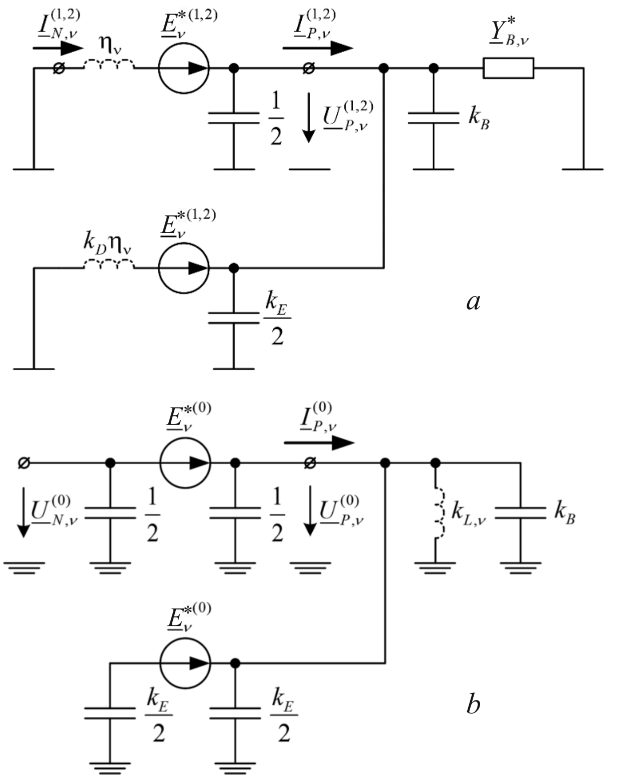

Fig. 2. An equivalent circuit of an electrical network, with parameters in relative units in normal mode for harmonics of direct and inverse sequences (*a*) and for zero-sequence harmonics (*b*).

phases, respectively, in three-phase order *A*, *B*, and *C*. Consequently, the complex values of the EMF of the harmonics for the direct, inverse, and zero sequences will be defined through the phase EMFs (10) as

$$\begin{bmatrix} \underline{E}^{*(1)}_{\nu} \\ \underline{E}^{*(2)}_{\nu} \\ \underline{E}^{*(0)}_{\nu} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \underline{a} & \underline{a}_2 \\ 1 & \underline{a}_2 & \underline{a} \\ 1 & 1 & 1 \end{bmatrix}.$$

The effect of the equivalent arc suppression coil on each of the phases of the network is characterized by the relative conductivity

$$k_{L,\nu} = \frac{\underline{E}_{L,\nu}}{\underline{E}_{\text{base},\nu}} = -\frac{1}{3(\nu\omega_1)^2 C_G L_L}, \tag{11}$$

which, taking into account expressions (5) and (6), can be calculated through the relative capacitive conductivities of the other elements of the network phase

$$k_{L,\nu} = -\frac{k_R C_\Sigma}{\nu^2 C_G} = -k_{R,\nu}(1 + k_E + k_B), \tag{12}$$

where

$$k_{R,\nu} = \frac{k_R}{\nu^2} \tag{13}$$

is the coefficient of compensation of the capacity current of the network on the νth harmonic.

The conductivity of the equivalent load also depends on the harmonic number

$$\underline{Y}^{*}_{B,\nu} = \frac{\underline{E}_{B,\nu}}{\underline{E}_{\text{base},\nu}}$$

Taking into account formula (8), it is possible to define the relative longitudinal conductivity of the protected generator as

$$\eta_\nu = -\frac{1}{(\nu\omega_1)^2 L_G C_G}$$

and, taking into account expression (1), that of the equivalent generator

$$\eta_{E,\nu} = -\frac{1}{(\nu\omega_1)^2 L_E C_G} = k_D\eta_\nu .$$

As mentioned earlier, these conductivities define the distribution of currents between generators.

Presenting the elements of the network on the basis of conductivity as in (8) and the calculated values of voltages and currents in relative units, taking into account the baseline values as in (7) and (9), we derive equivalent circuits for calculation of information signals of protection from SPGF in normal mode (Fig. 2) and with SPGF (Fig. 3). In the equivalent circuits, all parameters of capacitance elements no longer depend on frequency, i.e., these equivalent circuits become universal models of a network.

The arguments of the harmonics of the phase EMFs depend on their index number, in connection with which the harmonics of the EMF form direct ($\nu = 1, 7, 13, ...$), inverse ($\nu = 5, 11, 17, ...$) and zero ($\nu = 3, 9, 15, ...$) sequences. Therefore, monolinear equivalent circuits of the corresponding sequences are used for calculation of the currents and voltages of the individual harmonics of the normal mode (Fig. 2). For example, the EMF of the 3rd harmonic, being the source of a zero sequence, is operative only in zero-sequence mode, and the EMF of the 5th (7th) harmonic as the source of an inverse (direct) sequence, only in inverse (direct) sequence mode.

In SPGF mode the grid is non-symmetric, and the calculation of the harmonics of the currents and voltages for monolinear sequence circuits becomes complicated. Therefore it is convenient to perform calculations based on a three-phase equivalent circuit of the grid (Fig. 3). The posi-

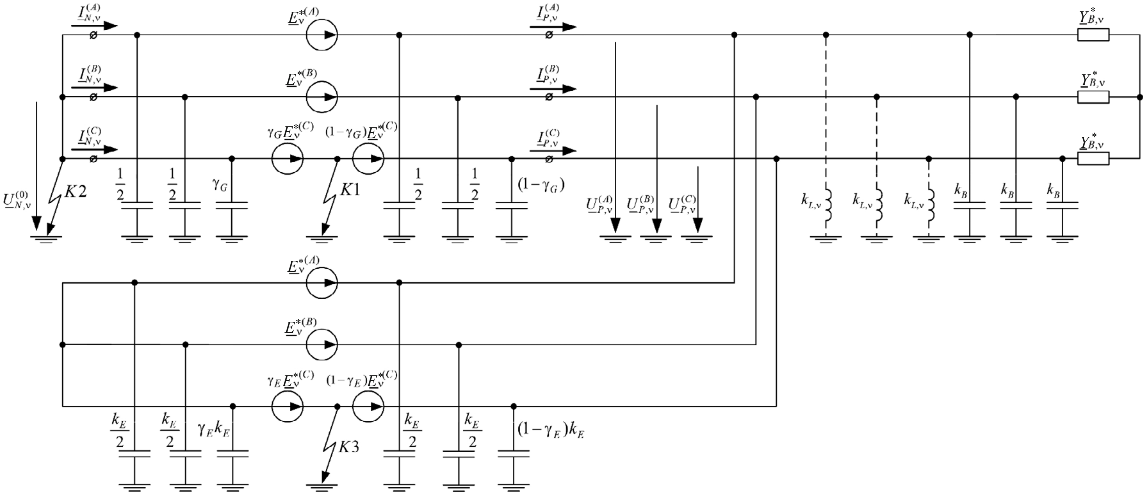

Fig. 3. An equivalent circuit of an electrical network, with parameters in relative units for various SPGF: interior (*K1*), at neutral of the protected generator (*K2*), and exterior (*K3*).

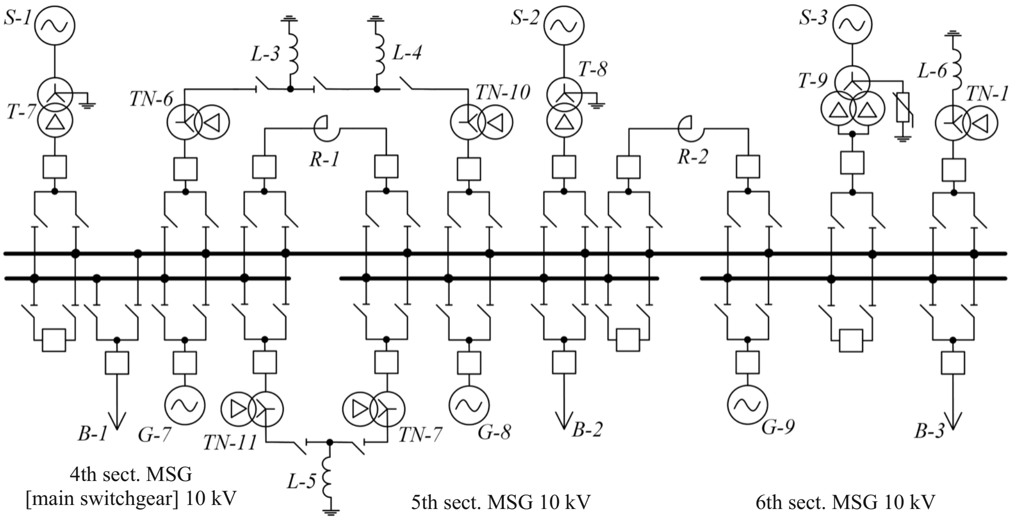

Fig. 4. Layout of parallel busbars of the 4th, 5th and 6th sections of the Kazan TÉTs-2: *G-7* to G-9: generators; T-7 to T-9: power transformers; TN-1, TN-6, TN-7, TN-10, TN-11: neutral-forming transformers; R-l, R-2: current-limiting reactors; L-3 to L-6: arc suppression coils; B-1, B-2, B-3: equivalent load of the 4th, 5th, and 6th section, respectively; S-l to S-3: power sources of external electrical grid.

tions of the SPGFs in the protected and equivalent generators are specified by the relative electrical distances γ_G and γ_E respectively, computed from the neutral of the generators. Faults in the user network are perceived by the protection as a variety of SPGF in a winding of the equivalent generator, and are not examined separately.

Example of the calculation of parameters of an equivalent circuit. We introduce an example of the creation of a universal model for Kazan TÉTs-2 (Fig. 4), and Tables 1 – 5 show the parameters of the equipment of the 4th, 5th, and 6th sections.

The equivalent inductance of all connected arc suppression coils in operating mode with one *G-7* generator is minimum when the capacitance of equivalent load of the grid is maximum. It follows from Table 3 that $L_{\Sigma\min} = 0.0608$ H. Then the capacitance of the grid is

$$C_{B\max} = C_{\Sigma} - C_G = \frac{1}{3\omega_1^2 L_{\Sigma\min}} - C_G = 55.3\ \mu\text{F}.$$

In accordance with (4), the maximum value of the relative conductivity k_B is equal to

$$k_{B\max} = \frac{C_{B\max}}{C_G} = 276.8.$$

The values of the coefficients k_D and k_E are calculated according to expressions (1) and (3), depending on the number of working generators.

TABLE 1. Parameters of Generators

Designation	Category	S_{nom}, MV · A	U_{nom}, kV	R, mΩ	X_d, rel. u.	L_d, mH	C, μF	q	α, deg.	β
G-7	TVF-63-2	78.75	10.5	2.19	2.2	9.804	0.2	12	27.45	0.833
G-8, *G-9*	TVF-60-2	75	10.5	4.34	1.7	7.955	0.21	12	27.45	0.833

Note. S_{nom}, rated full power; U_{nom}, nominal voltage; R: active resistance; X_d (L_d), synchronous inductive resistance (inductance) along longitudinal axis; C, power per phase; q: number of slots per pole and phase; α, half the angular length along which the excitation winding is placed; β, relative pitch of a winding in relation to pole pitch.

TABLE 2. Parameters of Power Transformers

Designation	Category	S_{nom}, MV · A	$U_{\text{nom.LV}}$, kV	$\Delta P_{\text{sñ}}$, kW	U_{sc}, %	R_{t}, mΩ	L_{t}, mH
T-7, *T-9*	TRDN-63000	63	10.5	245	10	6.806	0.557
T-8	TRDN-63000	63	10.5	275.38	10.87	7.649	0.605

Note. S_{nom}, rated full power; $U_{\text{nom.LV}}$, rated voltage on low voltage side; $\Delta P_{\text{sñ}}$: active power loss of a short circuit; U_{sc}, short-circuit voltage; R_{t}, active resistance; L_{t}, inductance.

TABLE 3. Parameters of Arc Suppression Coils

Designation	Category	S_{nom}, MV · A	U_{nom}, kV	I_{comp}, A	L, H
L-3	ZROM-300/10	300	10	25 – 50	0.3676 – 0.7351
L-4	ZROM-500/10	500	10	50 – 100	0.1838 – 0.3676
L-5, *L-6*	RDMR-485/10	485	10.5	10 – 80	0.2412 – 1.9297

Note. S_{nom}, rated full power; U_{nom}, rated voltage; I_{comp}, maximum compensation current; L, inductance.

TABLE 4. Parameters of Neutral-forming Transformers

Designation	Category	S_{nom}, MV · A	U_{nom}, kV	$\Delta P_{\text{sñ}}$, kW	U_{SC}, %	R_{t}, Îì	L_{t}, mH
TN-1	TMPS-250/10	0.25	10.5	2.84	4.5	5.010	63.169
TN-6	TM-5600/35	5.6	10.5	41	8	0.144	5.013
TN-7	TDNS-16000/20000	16	10.5	81	12	0.035	2.632
TN-10, *TN-11*	TD-10000/35	10	10.5	93.6	10	0.103	3.509

Note. S_{nom}: rated full power; $U_{\text{nom.LV}}$: rated voltage on low voltage side; $\Delta P_{\text{sñ}}$: active power loss of a short circuit; U_{sc}, short-circuit voltage; R_{t}, active resistance; L_{t}, inductance.

TABLE 5. Parameters of Current-limiting Reactors

Designation	Category	Q_{nom}, Mvar	U_{nom}, kV	L, mH
R-1	RTST-10	50	10	6.366
R-2	RTST-10	42	10	7.579

Note. Q_{nom}: nominal reactive power; U_{nom} : rated voltage; L, inductance.

TABLE 6. Equivalent Circuit Parameters for Various Number of Generators

Generators operating in parallel on busbars	k_D	k_E	k_B	k_R
G-7	0	0	0 – 276.8	1
G-7 and *G-8*	1.23		1.05	
G-7, *G-8*, and *G-9*	2.47		2.1	

Table 6 summarizes the values of the parameters of an equivalent circuit.

Calculation of the level of harmonics of the EMF is given in [11], and the results of calculation of the relative level of the harmonics of the EMF of the generators are presented thereafter:

ν	$E^{*}_{G,,\nu}$
1	1.0
3	0.116883
5	0.003181
7	0.000362
9	0.004116
11	0.001437
13	0.000057
15	0.000794

CONCLUSIONS

A new model of a grid with generators operating on busbars is proposed for analysis of the information bases of SPGF protection in a generator, using a representation of the parameters of the elements of the grid and electrical values in relative units. The model is universal and makes it possible to analyze the information signals of any frequency. This fundamental property of a universal model is achieved due to the selection for the base-line values of capacitive conductivity and the operating value of the EMF of the protected generator at the frequency of the information signal.

REFERENCES

1. *Regulations for Construction of Electrical Installations. 7th ed.* [in Russian], Izd. DEAN, St. Petersburg (2008)
2. V. A. Shuin and A. V. Gusenkov, "Ground fault protection in 6 – 10 kV electrical networks," *Bibl. Élektrotekh.*, No. 11(35) (2001).
3. I. M. Sirota, *Ground Fault Protection in Electrical Systems* [in Russian], Izd. AN UkrSSR, Kiev (1955).
4. V. M. Kiskachi, "Using the harmonics of EMF generators of power systems to provide protection against earth faults," *Élektrichestvo*, No. 2, 24 – 29 (1974).
5. V. M. Kiskachi, "New concepts in the performance of selective protection from single-phase ground faults for generators and 6 – 35 kV grids," *Élektr. Stantsii*, No. 10, 10 – 15 (1994).
6. V. G. Alekseev, "Current protection of ZGNP-4.2 from earth faults in the stator winding of a generator operating on bus rods," *Élektr. Stantsii*, No. 2, 51 – 56 (2006).
7. R. A. Vainshtein, et al., "Protection from ground faults in the stator winding of generators at power plants in the Siberian networks," *Élektr. Stantsii*, No. 12, 26 – 30 (2009).
8. F. R. Blánquez, et al., "On-line stator ground-fault location method for synchronous generators based on of 100% of stator low-frequency injection protection," *Elec. Power Sys. Res.*, No. 125, 34 – 44 (2015).
9. Yu. V. Romanov, "Digital ground fault protection in the stator winding of a synchronous generator operating in parallel on busbars," *Releishchik*, No. 4, 4 – 7 (2014).
10. A. V. Soldatov, et al., "Higher harmonics of the current of a synchronous generator as informational signals for relay protection," in: *Materials for the 11th All-Russia Scientific Coinference* '*Dynamics of nonlinear discrete electrotechnical and electronic systems*' [in Russian], Izd. Chuvash. Univ., Cheboksary (2015), pp. 380 – 385.
11. A. V. Soldatov, et al., "Information base of generator protection from single-phase stator ground faults with monitoring of the higher harmonics of the differential current," *Rel. Zashch. Avtomat.*, No. 3(24), 12 – 20 (2016).