FACULTY OF ELECTRICAL ENGINEERING
KTE
September 10 - 12, 2007
Pilsen, Czech Republic

SELECTED PROBLEMS OF AUTONOMIC OPERATION OF THREE-PHASE SYNCHRONOUS GENERATORS

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Abstract: *The paper presents selected problems related to autonomous operation of three-phase synchronous generators used in diesel-electric sets appropriated to emergency supply of various receivers of electric power located in stationary, communal, or industrial objects in case of failure of the basic electric power supply. A set of equations adapted to analysing the conditions of autonomous operation of three-phase synchronous generators is presented (in the conditions defined by means of computer simulations). The equations are presented in the form enabling analysis of the operation conditions of the generators driven by combustion engines of oscillating rotational speeds that, inducing variations of the frequencies of induced electromagnetic forces. The equations are so formulated as to allow for analysing operation of the generators under various operation conditions, particularly forced by asymmetric impedances of the receivers. The equations enable analysis of non-symmetric conditions of the generator operation states, among others, in the cases like single-phase asymmetric loads or internal asymmetry giving rise to electromotive forces of symmetric components of negative and zero sequence. The equations enable calculating the active and reactive power delivered by the generators under various frequency values and asymmetric conditions. The formulated equations were used for calculating characteristic parameters of generators under various operation conditions.*

Key words: electrical machines, synchronous generator, asymmetry of currents, asymmetric loads of generators

1 INTRODUCTION

Synchronous three-phase machines are used as generators or engines. As from the one hand, the engines must be always supplied from a source of electric energy, usually from the mains, from the other hand the generators are used for supplying various receivers directly connected to them or through the electric network. At present synchronous and asynchronous AC generators of small and medium power are used as emergency power sources for supplying various stationary, communal, or industrial objects in case of failure of basic supply from mains. Most of diesel-electric sets used for purposes of emergency supplying of various receivers are provided with synchronous generators offering much better operational features than the asynchronous ones. Synchronous generators are also readily used in vehicles as a basic source of electric power. For purposes of assessing operation of the generators used in power generation sets, particularly in case of asymmetric loads, the analysis of their non stationary condition operation is the most important, as it is decisive not only for the input parameters of the machine but, first of all, fir heating of the windings and the rotor core. Analysis of the set operations under the non-stationary condition, with regard to electromagnetic and electromechanical features, is of very complex character and appears feasible only provided that all the parameters of the generator, its controllers, and controllers of the combustion engine are known. The non-stationary conditions of the generators are of short duration and, therefore, for purposes of assessment of their operation conditions the stationary conditions, dealt in the present paper, are of fundamental significance. Within the standardization system binding for the diesel-electric set generators most of the resolutions regulate the stationary conditions.

In various binding legal documents the admissible voltage and frequency deviations from the rate levels are not uniformly defined. The resolution [3] related to the requirements related to the power mains defines the admissible deviation values but their determination manner is rather of complex and inexplicit character. The above mentioned disposition provides that average frequency measured within 10 seconds should be in the range 50Hz±1% during 95% of the week or 50Hz+4%/-

6% during 100% of the week. On the other hand, within every week 95% of 10-minutes average rms supply voltage values should not exceed ±10%. The standard pertaining to non-traction power sets [2] says that frequency characteristics under stationary conditions depend, first of all, on the properties of the controller of rotational velocity of the motor, while the characteristics under dynamical conditions depend on all elements of the system. At the same time, it was found that voltage characteristics of a power set depend chiefly on the generator design and properties of automatic voltage controller. Limiting operational values depend on the class of the power set requirements (G1, G2, G3, or G4). Frequency drop for a set of the G1 class should not exceed 8%, or 5% for G2, and 3% for G3. In case of a G4 set the frequency drop should be subject to negotiations between the manufacturer and the ordered. Voltage deviation under stationary conditions should not exceed, according to the class of the set, ±10% in case of small units (up to 10kVA) of G1 class, or ±1% in case of a G3 class. The voltage deviation of a G4 class should be subject to agreement to be made between the manufacturer and the ordered.

A specific feature of synchronous generators consists in the fact that, irrespective whether they operate in an electro-power system or autonomic (individual) mode, they show different exploitation properties. A synchronous generator operates in an autonomic mode, if supplies one or more receivers directly connected to its output terminals, without the mediation of a power network. In power generator sets driven by combustion engines, designed for emergency supply of stationary receivers, or used in traction vehicles or vessels, the synchronous generates in practice always operate autonomously. The following cases of cooperation of combustion engine driven power generator sets may occur:

- ensuring reliability of continuous supply of high power receivers – the set generators are permanently connected to the net;
- a rated load of the set is required, with a view to carry out a periodical technical survey, such a load is unfeasible without a permanent network connection.

The need of a different analyzing in cases of autonomous operation and electro power system operation results from different properties of these synchronous generators, in consequence of the operation mode. The differences in the generator properties result, first of all, from differing reaction of the generator to such parameters, like the excitation current and rotational speed. During autonomous operation, when the receivers are connected directly to the generator windings, the impedances of the receivers connected to particular phases significantly affect the output parameters (i.e. voltage and current) for a definite excitation current and rotational speed. The impedances connected to the system should be equal, as the generators are designed with the assumption of symmetry of the loading currents. Nevertheless, in case of autonomous operation the impedances of the receivers connected to the circuit are not equal, with regard both to their modules and angles. In consequence, such receivers operate in an asymmetric condition. In consequence of asymmetry of the receivers (loads) not only asymmetric currents occur in particular armature windings but also asymmetric output voltages. This, in turn, negatively affects operating conditions of all the receivers supplied by the generator. At present, the standardization system pertaining to the power set generators includes no requirements related to asymmetry of a three-phase output voltages of the generator. Since during operation of such generators the receivers are connected directly to their output terminals, the asymmetry of the three-phase system of the generator output voltages arising this way disturbs the quality standards of the power delivered to the receivers. The standards are characterized, first of all, by admissible values of the ratio of negative and zero sequence currents to the positive sequence current. In most cases the standard defines only the ratio of negative to positive sequence currents as the negative component gives rise to particular hazard to the generator. In order to prevent exceeding of the admissible degree of current asymmetry, no asymmetric receivers should be connected to the generator. The voltage asymmetry arising in such a situation must not exceed the admissible asymmetry level of the generator. The easiest way consists, in such situations, in observance of the standards determined for industrial plants that define three classes: the first, the second, and the third one. The requirements pertaining to the second class are similar to the ones binding for communal networks, defined by the Minister’s disposition [3].

Asymmetry of armature winding currents results in unequal heating of particular phase windings and excessive heating of the rotor core. Therefore, the standard system determines an admissible degree of the currents asymmetry, defined as the ratio of negative-sequence to the rated armature current or to the positive sequence current.

While analyzing operation of the generators under asymmetric conditions the degree of asymmetry of currents and voltages should be permanently checked, as admissible values of these factors differ each from other. The synchronous generators for power generating sets should be so designed as to withstand asymmetric loads but only to such extent in which the ratio of the component of negative phase sequence to rated current does not exceed the level 0.1. Moreover, during automatic operation of the generators the rotational speeds of the engines should be also checked, as their variations result in frequency oscillation unless the receivers are supplied by rectifiers, as is the case of automotive alternators. Asymmetric conditions should not be admitted, particularly in alternator armature winding, as this might result in excessive heating of the rotor core. Asymmetric condition of alternators may be due, in particular, to failure of bridge-rectifier diodes or their broken connections.

Taking into account harmful consequences of asymmetric loads of generators, the use of prevention measures replying to value of the ratio of the component of negative phase sequence to rated current. Assessment of the ratio based on the phase currents is difficult or even unavailable. Value of the ratio may be easily estimated only in case of a single-phase load of the generator (with regard to the neutral conductor), for which the component of negative phase sequence is equal to 1/3 of the phase current.

2 BASIC EQUATIONS FOR ANALYSIS OF GENERATOR OPERATION UNDER ASYMMETRIC CONDITIONS

Operation of a generator may be analyzed by means of current-voltage equations including the impedances connected to particular phase windings of a star-connected armature. Since the generators used in power generating sets are the machines of low voltage, the neutral point of the armature must be conducted to the terminal board and earthed. Such connection of the windings enables connecting the receivers in a three-phase four-conductor system, i.e. with the use of the phase and inter-phase voltages. In order to analyze a generator loaded like that the method of symmetric components appears the most convenient, using equivalent schemes (Fig. 1) for the components of positive, negative, and zero-phase sequences, in which electromagnetic forces of particular symmetric components are separated.

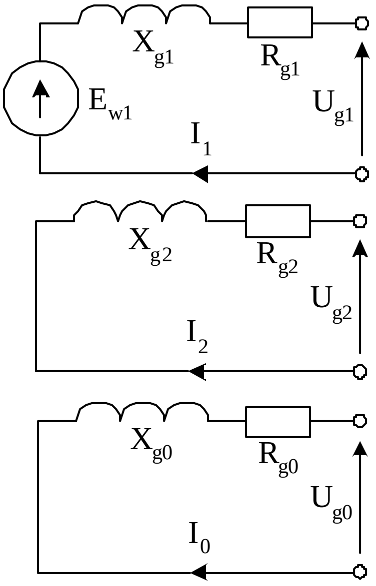

Fig. 1. Equivalent schemes of a synchronous machine for symmetric components

Therefore, parameters of the generator for all three (symmetric) components should be known. In order to enable analyzing operation of the generators under various frequencies a coefficient $k_f = f / f_n$ was introduced, where f is the frequency of the induced electromagnetic force, proportional to the engine rotational speed n, i.e. f=(n·p)/60, p being the number of pole pairs, while f_n is the rated frequency. The impedances of the machine $Z_g(k_f)$ occurring in the equivalent schemes include the real (resistance) and imaginary (induction reactance, that depends on the frequency f) parts. In the expression of the induction reactance the denotation k_fX_g is assumed, where X_g is the machine reactance at the rated frequency. According to these rules, the machine impedance for the positive phase sequence is formulated as follows $Z_{g1}(k_f) = R_{g1} + jk_f X_{g1}$, the impedance for the negative phase sequence as $Z_{g2}(k_f) = R_{g2} + jk_f X_{g2}$, while the impedance for the zero phase sequence as $Z_{g0}(k_f) = R_{g0} + jk_f X_{g0}$.
As the parameter exciting the voltage and current at asymmetric loads the exciting current I_w was assumed, converted to the values of electromagnetic force E_w related to the rated voltage $E_w = k_u U_n$. The electromotive force induced during the rated (symmetric) load was calculated according to the formula $E_{wn} = U_n + I_n Z_{g1}$, in which the phasor of the rated voltage $U_n$expj0 was assumed as a reference. The phasor of stator current Iexp -jφ is shifted by the angle φ with respect to the voltage phasor. The angle φ corresponds to the value of rated power coefficient.
Electromotive forces occurring in the equivalent scheme for particular symmetric components are described by the expressions: $E_1(k_f, k_{u1}) = k_f k_{u1} U_n$ for the positive phase sequence component; $E_2(k_f, k_{u2}) = k_f k_{u2} U_n$ for the negative component, and $E_0(k_f, k_{u0}) = k_f k_{u0} U_n$ for the zero component. The values k_{u1},k_{u2} and k_{u0} occurring in these expressions are the coefficients determining values of each of symmetric components of electromotive forces referred to the rated voltage.

Generator load is represented by the impedances of active-induction character, connected to the circuits of particular phases. Assuming that the induction reactances of the load also depend on the frequency, the impedances connected to particular phases are formulated as follows: (U) $Z_{zu}(k_f) = R_{zu} + jk_f X_{zu}$ for the first phase, (V) $Z_{zv}(k_f) = R_{zv} + jk_f X_{zv}$ for the second, and (W) $Z_{zw}(k_f) = R_{zw} + jk_f X_{zw}$ for the third one.

Rated power of the generator is provided by the relationship $S_n = 3U_n I_n$, where U_n is the rated phase voltage, and I_n is the rated armatur current $I_n \exp - j\varphi$. According to the requirements of the standard [1] the angle φ should correspond to the values of the power coefficient cosφ_n = 0.8, 0.9 or 1.0 (under excitation).

Symmetric components of positive, negative, and zero-phase sequences of receiver impedance are calculated from the formula (1):

$$\begin{pmatrix} Z_1(k_f) \\ Z_2(k_f) \\ Z_0(k_f) \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} Z_{zu}(k_f) \\ Z_{zv}(k_f) \\ Z_{zw}(k_f) \end{pmatrix} \qquad (1)$$

Phase voltage values of particular symmetric components are described by the expressions:

$$U_1 = E_1 - I_1 Z_{g1} = I_1 Z_1,$$

$$U_2 = E_2 - I_2 Z_{g2} = I_2 Z_2,$$

$$U_0 = E_0 - I_0 Z_{g0} = I_0 Z_0.$$

For particular circuits of the symmetric components the following system of voltage-current equations is obtained

$$\begin{pmatrix} E_1(k_f, k_{u1}) \\ E_2(k_f, k_{u2}) \\ E_0(k_f, k_{u0}) \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} I_1(k_f, k_{u1.2.0}) \\ I_2(k_f, k_{u1.2.0}) \\ I_0(k_f, k_{u1.2.0}) \end{pmatrix} \tag{2}$$

where $(a_{11}$ too $a_{33})$ is

$$\begin{pmatrix} Z_{g1}(k_f) + Z_0(k_f) & Z_2(k_f) & Z_1(k_f) \\ Z_1(k_f) & Z_{g2}(k_f) + Z_0(k_f) & Z_2(k_f) \\ Z_2(k_f) & Z_1(k_f) & Z_{g0}(k_f) + Z_0(k_f) \end{pmatrix}$$

Equations of symmetric current components are obtained by transformation of the equation
(2) to the form

$$\begin{pmatrix} I_1(k_f, k_{u1}, k_{u2}, k_{u0}) \\ I_2(k_f, k_{u1}, k_{u2}, k_{u0}) \\ I_0(k_f, k_{u1}, k_{u2}, k_{u0}) \end{pmatrix} x$$

$$\begin{pmatrix} M_{11}(k_f) & M_{12}(k_f) & M_{13}(k_f) \\ M_{21}(k_f) & M_{22}(k_f) & M_{23}(k_f) \\ M_{31}(k_f) & M_{32}(k_f) & M_{33}(k_f) \end{pmatrix} \cdot \begin{pmatrix} E_{wn}(k_f, k_{u1}) \\ E_{wn}(k_f, k_{u2}) \\ E_{wn}(k_f, k_{u0}) \end{pmatrix} \cdot \frac{1}{D(k_f)} \tag{3}$$

where

$$M_{11}(k_f) = (Z_{g2}(k_f) + Z_0(k_f))(Z_{g0}(k_f) + Z_0(k_f)) - Z_1(k_f)Z_2(k_f)$$

$$M_{12}(k_f) = Z_1(k_f)^2 - Z_2(k_f)(Z_{g0}(k_f) + Z_0(k_f))$$

$$M_{13}(k_f) = Z_2(k_f)^2 - Z_1(k_f)(Z_0(k_f) + Z_{g2}(k_f))$$

$$M_{21}(k_f) = Z_2(k_f)^2 - Z_1(k_f)(Z_0(k_f) + Z_{g0}(k_f))$$

$$M_{22}(k_f) = (Z_0(k_f) + Z_{g1}(k_f))(Z_0(k_f) + Z_{g0}(k_f)) - Z_1(k_f)Z_2(k_f)$$

$$M_{23}(k_f) = Z_1(k_f)^2 - Z_2(k_f)(Z_0(k_f) + Z_{g1}(k_f))$$

$$M_{31}(k_f) = Z_1(k_f)^2 - Z_2(k_f)(Z_0(k_f) + Z_{g2}(k_f))$$

$$M_{32}(k_f) = Z_2(k_f)^2 - Z_1(k_f)(Z_0(k_f) + Z_{g1}(k_f))$$

$$M_{33}(k_f) = (Z_0(k_f) + Z_{g1}(k_f))(Z_0(k_f) + Z_{g2}(k_f)) - Z_1(k_f)Z_2(k_f)$$

$$D_1(k_f) = (Z_0(k_f) + Z_{g1}(k_f))(Z_0(k_f) + Z_{g2}(k_f))(Z_0(k_f) + Z_{g0}(k_f))$$

$$D_2(k_f) = -Z_1(k_f)Z_2(k_f)[3Z_0(k_f) + (Z_{g1}(k_f) + Z_{g2}(k_f) + Z_{g0}(k_f))]$$

$$D_3(k_f) = Z_1(k_f)^3 + Z_2(k_f)^3$$

$$D(k_f) = D_1(k_f) + D_2(k_f) + D_3(k_f)$$

The phase currents are calculated from the formulae

$$\begin{pmatrix} I_u(k_f, k_{u1}, k_{u2}, k_{u0} \\ I_v(k_f, k_{u1}, k_{u2}, k_{u0}) \\ I_w(k_f, k_{u1}, k_{u2}, k_{u0}) \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{pmatrix} \begin{pmatrix} I_1(k_f, k_{u1}, k_{u2}, k_{u0} \\ I_2(k_f, k_{u1}, k_{u2}, k_{u0}) \\ I_0(k_f, k_{u1}, k_{u2}, k_{u0}) \end{pmatrix} \tag{4}$$

The current of the neutral conductor is expressed as:

$$I_{p0}(k_f, k_{u1}, k_{u2}, k_{u0}) = 3I_0(k_f, k_{u1}, k_{u2}, k_{u0})$$

The standards state that generators should not be overcharged with a current exceeding its rated value and the ratio of the negative sequence current to the rated value should not exceed 0.08 or 0.1. On the other hand, the ratio of negative or zero-sequence current to the positive sequence current should not exceed 0.05. Values of these factors are calculated from the expressions

$$\frac{|I_2(k_f, k_{u1}, k_{u2}, k_{u0})|}{I_n} \quad \text{and} \quad \frac{|I_2(k_f, k_{u1}, k_{u2}, k_{u0})|}{|I_1(k_f, k_{u1}, k_{u2}, k_{u0})|}$$

Consideration of operating conditions of the receivers supplied from synchronous generators, particularly in case of non-symmetric loads, leads to a conviction that the values of phase voltage and the ratio of negative or zero-sequence voltage to positive sequence voltage are of high importance. When the generator supplies three-phase motors, the ratio of negative to positive sequence voltage should not exceed 0.01. In case of a power network the ratio should not exceed 0.02 or 0.03. Making use of the expressions allowing to calculate the phase voltage values, the following relationships may be formulated:

$$U_u(k_f, k_{u1}, k_{u2}, k_{u0}) = I_u(k_f, k_{u1}, k_{u2}, k_{u0})Z_{zu}(k_f)$$

$$U_v(k_f, k_{u1}, k_{u2}, k_{u0}) = I_v(k_f, k_{u1}, k_{u2}, k_{u0})Z_{zv}(k_f)$$

$$U_w(k_f, k_{u1}, k_{u2}, k_{u0}) = I_w(k_f, k_{u1}, k_{u2}, k_{u0})Z_{zw}(k_f) \tag{5}$$

Voltages of the symmetric components may be calculated from the formulae

$$\begin{pmatrix} U_1(k_f, k_{u1}, k_{u2}, k_{u0} \\ U_2(k_f, k_{u1}, k_{u2}, k_{u0}) \\ U_0(k_f, k_{u1}, k_{u2}, k_{u0}) \end{pmatrix} = \begin{pmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{pmatrix} \frac{1}{3} \begin{pmatrix} U_u(k_f, k_{u1}, k_{u2}, k_{u0} \\ U_v(k_f, k_{u1}, k_{u2}, k_{u0}) \\ U_w(k_f, k_{u1}, k_{u2}, k_{u0}) \end{pmatrix} \tag{6}$$

The voltage asymmetry factor is given by the expression:

$$k_{nu} = \frac{|U_2(k_f, k_{u1}, k_{u2}, k_{u0})|}{|U_1(k_f, k_{u1}, k_{u2}, k_{u0})|}$$

The factor depends on the degree of receiver asymmetry and the degree of intrinsic asymmetry of the generator. If the generator is internally symmetric, the coefficients k_{u2} and k_{u0} are equal to zero.

If the inter-phase voltages U_{uv}, U_{vw}, and U_{wu} are known as measured or calculated, for example, from the formula:

$$U_{uv}(k_f, k_{u1}, k_{u2}, k_{u0}) = U_u(k_f, k_{u1}, k_{u2}, k_{u0}) - U_v(k_f, k_{u1}, k_{u2}, k_{u0})$$

The voltage asymmetry factor may be also calculated from the formula:

$$k_{nu} = \sqrt{6\frac{U_{uv}^2 + U_{vw}^2 + U_{wu}^2}{(U_{uv} + U_{vw} + U_{wu})^2} - 2}$$

The formulae for current and voltage values may be used for calculating the active, reactive, and apparent power as well as the power coefficient.

In case of asymmetric generator load the sum of active, reactive, and apparent power is equal to the sum of the power received by the receivers connected to particular phases U, V, and W.

The active power output has a form:

$P_{od} = \sum (P_u + P_v + P_w) = P(k_f, k_{u1}, k_{u2}, k_{u0})$.

The active power received by the receivers connected to the phase U is calculated from the formula:

$$P_u(k_f, k_{u1}, k_{u2}, k_{u0}) = P_u^{'}(k_f, k_{u1}, k_{u2}, k_{u0}) + P_u^{''}(k_f, k_{u1}, k_{u2}, k_{u0})$$

where

$$P_u'(k_f, k_{u1}, k_{u2}, k_{u0}) =$$

$$\mathrm{Re}(U_u(k_f, k_{u1}, k_{u2}, k_{u0})) \cdot \mathrm{Re}(I_u(k_f, k_{u1}, k_{u2}, k_{u0}))$$

$$P_u''(k_f, k_{u1}, k_{u2}, k_{u0}) =$$

$$\mathrm{Im}(U_u(k_f, k_{u1}, k_{u2}, k_{u0})) \cdot \mathrm{Im}(I_u(k_f, k_{u1}, k_{u2}, k_{u0}))$$

According to similar formulae are calculated the power values received by the receivers connected to the phases V and W. It is convenient to consider the total power $P(k_f, k_{u1}, k_{u2}, k_{u0})$ calculated this way with reference to the rated power of the generator (P_n). Relative value of the active power is given by the relationship:

$$p(k_f, k_{u1}, k_{u2}, k_{u0}) = \frac{P(k_f, k_{u1}, k_{u2}, k_{u0})}{|P_n|}$$

The reactive power output from the generators has a form:

$$Q_{od} = \sum (Q_u + Q_v + Q_w) = Q(k_f, k_{u1}, k_{u2}, k_{u0})$$

The reactive power received by the receivers connected to the phase U is calculated from the formula:

$Q_u = Q`_u + Q``_u$

where

$$Q_u'(k_f, k_{u1}, k_{u2}, k_{u0}) =$$

$$\mathrm{Im}(U_u(k_f, k_{u1.2.0}))\,\mathrm{Re}(I_u(k_f, k_{u1.2.0}))$$

$$Q_u''(k_f, k_{u1}, k_{u2}, k_{u0}) =$$

$$-\,\mathrm{Re}(U_u(k_f, k_{u1.2.0}))\,\mathrm{Im}(I_u(k_f, k_{u1.2.0}))$$

According to similar formulae are calculated the reactive power values received by the receivers connected to the phases V and W. It is convenient to consider the total power $Q(k_f, k_{u1}, k_{u2}, k_{u0})$ calculated this way with reference to the rated reactive power of the generator (Q_n). Relative value of the reactive power is given by the relationship:

$$q(k_f, k_{u1}, k_{u2}, k_{u0}) = \frac{Q(k_f, k_{u1}, k_{u2}, k_{u0})}{|Q_n|}$$

In order to calculate the apparent power the following relationship may be used:

$$S(k_f, k_{u1}, k_{u2}, k_{u0}) =$$

$$\sqrt{P(k_f, k_{u1.2.0})^2 + Q(k_f, k_{u1.2.0})^2}$$

The apparent power calculated this way with referred to the rated apparent power is given by the expression:

$$s(k_f, k_{u1}, k_{u2}, k_{u0}) = \frac{S(k_f, k_{u1}, k_{u2}, k_{u0})}{|S_n|}$$

Equivalent power factors cosφ and tanφ may be calculated from the formulae:

$$\cos\Theta(k_f, k_{u1}, k_{u2}, k_{u0}) = \frac{|P(k_f, k_{u1}, k_{u2}, k_{u0})|}{|S(k_f, k_{u1}, k_{u2}, k_{u0})|}$$

$$\mathrm{tg}\Theta(k_f, k_{u1}, k_{u2}, k_{u0}) = \frac{|Q(k_f, k_{u1}, k_{u2}, k_{u0})|}{|P(k_f, k_{u1}, k_{u2}, k_{u0})|}$$

Power losses in the machine windings, referred to the rated power losses, may be calculated from the formulae:

$$Dp_c(k_f, k_{u1}, k_{u2}, k_{u0}) = \frac{DP_c(k_f, k_{u1}, k_{u2}, k_{u0})}{DP_{cn}}$$

$DP_c = DP_{c1} + DP_{c2} + DP_{c0}$

$$DP_{c1}(k_f, k_{u1}, k_{u2}, k_{u0}) = 3R_{g1}[(|I_1(k_f, k_{u1}, k_{u2}, k_{u0})|)^2]$$

$$DP_{c2}(k_f, k_{u1}, k_{u2}, k_{u0}) = 3R_{g2}[(|I_2(k_f, k_{u1}, k_{u2}, k_{u0})|)^2]$$

$$DP_{c0}(k_f, k_{u1}, k_{u2}, k_{u0}) = 3R_{g0}[(|I_0(k_f, k_{u1}, k_{u2}, k_{u0})|)^2]$$

3 SELECTED CALCULATION RESULTS

The equations provided in Section 2 were used for analyzing operation of generators under asymmetric conditions. In order to display usefulness of the formulae for purposes of calculation and analysis of the generator operation, particularly under asymmetric condition and frequency deviation, the parameters of many synchronous generators were used. One of them of rated power 16kVA, rated delta voltage 400V, rated current 23.1A, rated power factor cosφ = 0.8. The impedances of the 16kVA generator for the symmetric components and rated frequency are shown in Table 1.

Impedance	Symbol	Value
for the positive-sequence component	$Z_{g1}(k_f) = R_{g1} + jk_fX_{g1}$	$1 + jk_f17$
for the negative-sequence component	$Z_{g2}(k_f) = R_{g2} + jk_fX_{g2}$	$0.5 + jk_f1.6$
for the zero-sequence component	$Z_{g0}(k_f) = R_{g0} + jk_fX_{g0}$	$0.5 + jk_f1.8$

Tab. 1: The impedances of symmetric components of the 16kVA generator

The reference impedance of the generator amounts to Z_{odn}=10.

The paper presents selected calculation results for two variants of the receiver impedance so chosen as to maintain the ratio of the negative sequence to rated current at the level of 0.1, i.e. admissible value defined by the regulations. The calculation was carried out for the rated frequency k_f=1.00, with the frequency decreased by 5%, i.e. for the coefficient k_f=0.95, and increased by 5%, i.e. for the coefficient k_f=1.05. Frequency reduction by 5% is admissible under stationary state for the assemblies of the G2 Class. Results of calculation for the 16kVA generator

The receiver impedance data assumed for the calculation (in relative values) are shown in Table 2.

Phase	Impedance	Value
The first	Z_{zu}	0,99expj36.8
The second	Z_{zv}	1.20expj39.6
The third	Z_{zw}	1.45expj34.8

Tab. 2: Receiver impedance values for the 16 kVA generator

Values of the armature winding current for the excitation current amounting to 0.91 of the rated excitation current I_{wN} are specified in Table 3.

The ratio of the symmetric component of negative sequence to rated current calculated in this case amounts to 0.1 i.e. complies with the requirements of the regulations. The calculated ratios of the symmetric component of negative to positive sequence current amount to 0.117 and 0.118, exceeding the required level of 0.05. The ratios of the symmetric component of zero to positive sequence current amount to 0.079, 0.080, and

0.081, thus exceeding the required value 0.05. The neutral conductor current amounts to 0.204 of the rated current. The phase armature voltage values are shown in Table 4.

k_f	The first phase		The second phase		The third phase		I_2/I_1
	A	I/I_n	A	I/I_n	A	I/I_n	
0.95	22.9	0.992	19.3	0.838	16.3	0.706	0.118
1.00	23.1	1.000	19.5	0.843	16.5	0.714	0.117
1.05	23.3	1.008	19.6	0.848	16.6	0.721	0.117

Tab. 3:Values of the current for the excitation equal to 0.91 I_{wN}

k_f	The first phase		The second phase		The third phase		U_2/U_1
	V	U/U_n	V	U/U_n	V	U/U_n	
0.95	222.9	0.965	227.5	0.985	232.8	1.008	0.016
1.00	228.8	0.990	233.7	1.012	239.2	1.036	0.017
1.05	234.6	1.016	239.9	1.039	245.6	1.063	0.017

Tab. 4: The phase armature voltage values

The ratios of the symmetric component of negative to positive sequence voltage amount to 0.016 and 0.017. These values comply with the regulation requirements related to supply systems of communal and industrial networks. Three-phase AC motors should be supplied with the voltage of the U_2/U_1 symmetric components ratio not exceeding the value of 0.01.

The calculated load of the generator for assumed receiver impedances are shown in Table 5.

k_f	P/P_n	Q/Q_n	S/S_n	$\Delta P_{cu}/\Delta P_{cun}$	$\cos\vartheta_{sr}$
0.95	0.843	0.811	0.831	0.721	0.810
1.00	0.857	0.868	0.861	0.733	0.797
1.05	0.870	0.925	0.890	0.744	0.782

Tab. 5. The calculated load of the 16kVA generator

Figures 2-4 show selected characteristics illustrating the effect of various parameters of the generator on its output values.

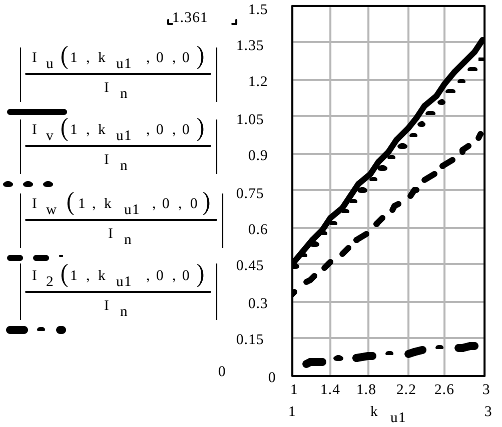

Fig. 2. Armature winding currents and the component of negative sequence current of the 16kVA generator at various excitation values

Influence of the excitation current on the armature current values and on the value of symmetric component of negative sequence current for the 16kVA generator is presented in Fig. 2. Figure 3 shows a characteristics illustrating the effect of the excitation current on the values of phase voltage of the 16kVA generator.

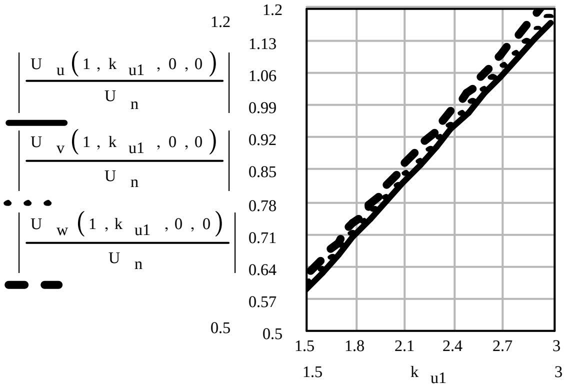

Fig. 3 Phase voltage values of the 16kVA generator at various excitation intensities

Figures 4 present the output voltage characteristics as the functions of the coefficient k_f. It may be easily noticed that for small frequency deviations the generator output changes only insignificantly.

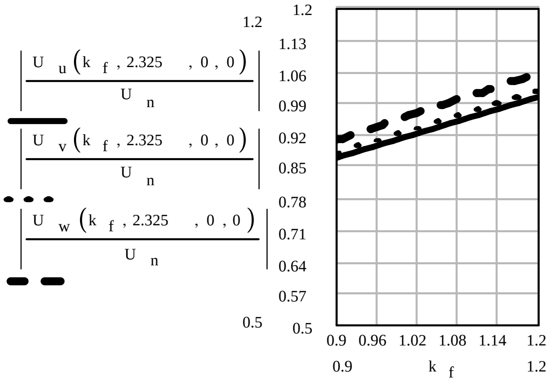

Fig. 4. Output voltage of the 16kVA generator as a function of frequency

4 CONCLUSIONS

Comparison of simulation results under various asymmetric conditions is uneasy, as the above mentioned standards define no admissible current load of particular windings, providing only the limits of the negative sequence component. Paragraph 3 of the paper specifies the most characteristic simulation results of asymmetric loads of the low 16kVA generators. The cases of these generators show that the requirements formulated by the regulations in force are so inaccurate that observation of the regulations on admissible ration of the component of negative phase sequence to rated current allows for various patterns of current propagation in the generator windings. Differences in the current propagation result in different power losses in the windings and, at the same time, various rates of their heating. According to the examples, in case of the 16kVA generator with a receiver connected and the ratio I_2/I_n=0.1 the power loss ratio of the windings amounts to 73.3%, while for the 630kVA generator the power loss ratio reaches up to 103.7%. Taking into account that for three-phase loads value of the I_2/I_n ratio depends on many variables, once a receiver is connected it is difficult to foresee what should be the currents in particular windings that ensure the required value of the ratio. It seems necessary to formulate a requirement saying that total power losses of the windings must not exceed the rated value of the losses. Only an asymmetric single-phase load-case may be considered as a simple instance, for which I_2/I_n=0.1 and the load current equal to 0.3 of the rated armature current. Nevertheless, in such a case in spite of observance of the regulations the generator is evidently under loaded.

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