THE DIAGNOSIS OF ON BOARD GENERATORS

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Summary

In the paper select problems related to diagnosis of onboard generators and alternators with control systems are discussed. Problems refer to commutator generators and synchronous single and three phase alternators.

Special attention is paid to commutation effects. Results of incorrectness and possibility to detect them are discussed. There are also discussed effects concomitant with changes in a character of a pulsation during short-circuits or isolating clearance in a wiring of a rotor or a stator. Possibility of diagnosis of generator's or alternator's parts by means of analysis of pulsation component parameters is indicated.

In a case of alternators, there are discussed a number of diagnostic methods based on an observation of shape changes of voltage or frequency modulation. It provides to detect numerous mechanical or electrical faults of generators, alternators or their control systems.

Keywords: technical diagnostic, frequency modulation, turbine engine, rolling bearing.

DIAGNOZOWANIE POKŁADOWYCH PRĄDNIC LOTNICZYCH

Streszczenie

Starzejąca się technika lotnicza wymaga poważnego podejścia do problemu oceny trwałości statku powietrznego w tym, do niedawna nie zawsze doceniane, trwałości instalacji elektroenergetycznej. Szeroko pojęty system elektryczny statku powietrznego wpływa swą, często obniżoną, na skutek procesów starzeniowych, kondycją, na obniżenie trwałości wszystkich innych systemów.

W pracy omówiono wybrane problemy związane z diagnozowaniem pokładowych prądnic lotniczych wraz z układem regulacji. Problematyka poruszana w tym artykule dotyczy komutatorowych prądnic prądu stałego oraz przemiennego (synchronicznych prądnic jednofazowych i trójfazowych).

Podczas omawiania problemów diagnozowania prądnic prądu stałego szczególną uwagę zwrócono na zjawiska komutacji – omówiono objawy nieprawidłowości i możliwości ich wykrywania. Omówiono również pewne zjawiska towarzyszące zmianom w charakterze pulsacji podczas zwarć lub przerw w uzwojeniach w wirniku lub stojanie – wskazano na możliwość diagnozowania tych elementów prądnic za pomocą analizy parametrów składowych pulsacji. Zaproponowano zastosowanie metody obserwacji szczególnych korelacji pulsacji do wykrywania zwarć wirnika lub stojana. Analizując kształt i amplitudę składowej pulsacji prądnicy komutatorowej prądu stałego, można wykrywać zwarcia i przerwy w obwodzie wirnika. W przypadku przerw w obwodzie wirnika zmniejszeniu ulega amplituda składowej pulsacji a w przypadku zwarcia obraz charakterystyczny składowej pulsacji. Zwarte uzwojenie podczas przemieszczania się wirnika pod kolejnym biegunem stojana wywołuje wielokrotnie zwiększoną pulsację komutatorową. Dzięki pogłębieniu wiedzy doświadczalnej na ten temat możliwe było diagnozowanie szeregu uszkodzeń zarówno prądnic prądu stałego jak i całych węzłów elektroenergetycznych.

W przypadku prądnic prądu przemiennego omówiono szereg metod diagnostycznych opartych na obserwacji zmian kształtu przebiegu modulacji napięcia lub częstotliwości, umożliwiających wykrywanie wielu wad mechanicznych i elektrycznych prądnic oraz ich układów regulacji. Referat omawia aspekty diagnostyczne związane z obserwacją parametrów dynamicznych lotniczych pokładowych pierwotnych i wtórnych źródeł prądu przemiennego. Omówione zostały właściwości diagnostyczne takich parametrów jak: a) impulsy przepięciowe i zanikowe dla stanów przejściowych obciążenia sieci pokładowej, b) amplituda obwiedni, c) zniekształcenia kształtu przebiegu (całkowita zawartość harmonicznych, wartość poszczególnych harmonicznych, współczynnik amplitudy, odchylenie od kształtu sinusoidy), d) dewiacja częstotliwości, e) precesja częstotliwości, f) wartość harmonicznych cząstkowej transformaty Fouriera częstotliwości;

g) przebieg zmian wartości chwilowej częstotliwości.

Słowa kluczowe: diagnostyka techniczna, modulacja częstotliwości, silnik turbinowy, łożysko toczne, pulsacje żłobkowe, pulsacje komutatorowe, impulsy zanikowe, impulsy przepięciowe.

1. PULSATION CHARACTERISTIC OF A GENERAT

In a standard, school formulation, a commutate generator can be presented as it shown on Figure 1. Figure 2 shows an electromotive force. The commutate generator consists of:

- a motionless stator, which can be presented as a pair of permanent magnets (fig. 1), where: "N"- north pole, "S"- south pole generating permanent magnetic field with an intensity of B and a sense from "N" to "S";
- a rotor turned with a velocity of ω_2 by an outside mechanical force. On the rotor there is a rolled winding in which the electromotive force e is induced. The induced electromotive force (EMF) can be described by a formula:

$$e = \left| k \cdot B \cdot sin(\omega_2 t) \right| \quad (1)$$

where: k – design coefficient of the generator, B – magnetic induction, ω_2 – angular velocity of the generator's rotor;

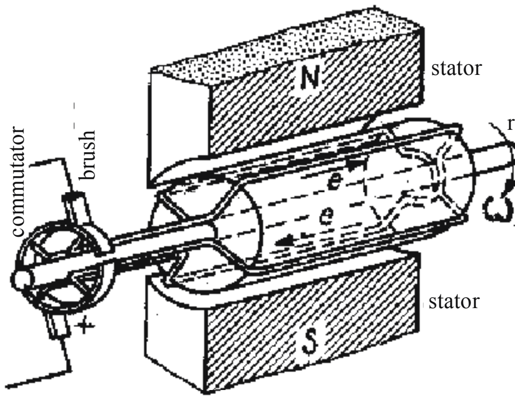

Fig. 1. The rotor with two coil elements and four-segment commutator

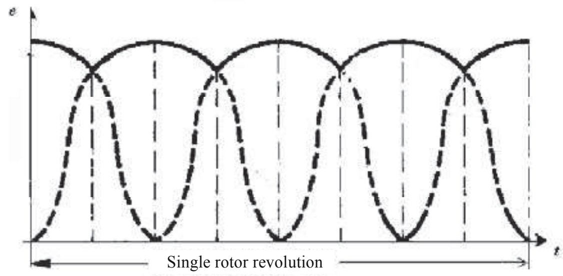

Fig. 2. The course of electromotive force between the brushes in the d.c. generator

- a commutator as a ring made of conducted material. This ring is cut and its segments are insulated. Segments create so-called sectors (staves) of the commutator. End of the winding is connected to each sector – the commutator is a mechanical current rectifier;
- electric brushes "+" and "-", which slide along commutator's sectors. Conductors conducting electric current to loads are conducted to brushes.

In order to increase induction B, rotor's windings are placed on a core made of silicon sheet pack. The value of electromotive force (EMF) is amplified about 10 000 times. For good mechanical connection windings on the rotor with the core, they are placed in special grooves called skewed slots. In a cross-section of the rotor's core these skewed slots have shape of teeth, therefore a term of "rotor's teeth" is used. A comparison of a function described by formula (1) – (Fig. 2) with the generator's pulsation component (Fig. 3) does not show their similarity.

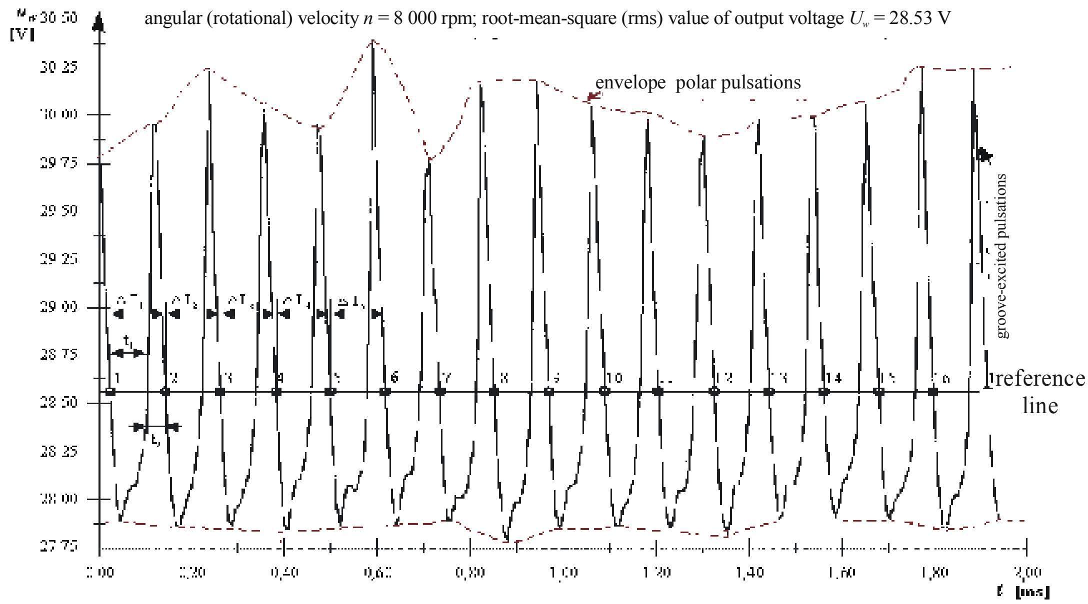

Fig. 3. Fluctuations in pulsation component for an aircraft d.c. generator under minimum load

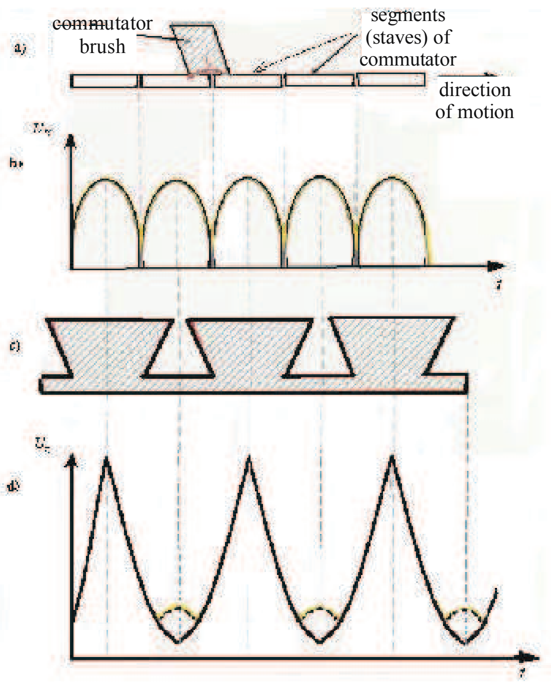

Fig. 4. The shape of pulsation curve plotted for the d.c. generator: a) developed view of mechanical components of the commutator node, b) commutator-excited pulsations – $U_K = f(t)$, c) developed view of rotor grooves, groove-excited pulsations (solid line) – $U_ż = f(t)$, with commutator-excited pulsations indicated (broken line)

Groove pulsation of generator output arises as a result of changes of reluctance, caused by rotation of a tooth rotor. The frequency of groove pulsation f_g according to [1 – 4] can be expressed by the formula:

$$f_g = Z\ n/60$$

where: Z – number of rotor's grooves, n – rotational speed.

In the references [1 – 3] pole pulsation of voltage is related to so-called rotational pulsation considering their similarity. A phenomena of pole and rotational pulsation is visible as amplitude modulation of commutate generator's output voltage. The envelope presented on Figure 3 testifies to it. The modulation frequency is directly proportional to product of number of stator's poles and rotor's angular velocity but amplitude's depth is proportional to changes of magnetic reluctance between the rotor and the stator. The frequency of pole pulsation f_p can be presented by formula:

$$f_p = 2pn/60$$

where: p – number of pairs of stator's magnetic poles.

The signal of pole modulation brings information about anisotropy of plates of generator's magnetic circuit. In special references pole modulation is usually related to rotational modulation, which is characterized by frequency of that type modulation equal to frequency of first or second harmonic (in some cases first sub harmonic) of generator rotor's rotational velocity.

This signal brings diagnostic information about errors:

– accomplishment of the generator, particularly about inaccuracy of geometric dimensions, appearing as asymmetry of an air-gap between the stator and the rotor;
– assembly of the generator, such as parallelism error, i.e. shift of the generator's rotor shaft axis in relation to the drive shaft, named sometimes as eccentricity error, as well as angular error of shift of the rotor' s shaft in relation to the drive shaft.

The voltage commutate pulsation is related to co-operation brushes and the commutator. During rotation of armature, brushes short-circuit different number of winding coils, what changes a number of coils in parallel branches and creates periodic pulsation of voltage on brushes. The frequency of that pulsation f_k depends on the number of commutator's sectors and can be expressed by the formula [1-2]:

$$F_k = K\ n/60$$

where: K – number of commutator's sectors.

2. GROOVE PULSATION

The phenomena of different groove pulsation is described in references related to induction alternators [1, 2]. Alternators do not have the winding rotors and useful signal is received from the winding winded on the stator. The rotor made of ferromagnetic (most often of silicon-steel sheet pack) has milled grooves (teeth) and the magnetic field strength of permanent magnets is modulated. In these alternators groove pulsation is the basic phenomena of the useful signal to be arisen. Because there is not the winding on the rotor, as in typical commutate alternator, only alternating component of pulsation occurs (commutate pulsation does not appear considering the lack of the commutator and the rotor's winding). On the base of information from reference [1-2], it is known that in order to obtain the output voltage signal in the highest degree approximate sine curve, skew teeth (fig. 4b) are most often used in induction alternators.

Rotors with grooves of "swallow's tail", presented on Figure 4c, are rarely used in induction alternators because they have asymmetrical shape of output voltage [1]. This shape of grooves is generally used in typical commutate generators. It ensures windings are good fastened on the rotor. Time between groove pulsation crossings the reference level for the alternator rotor's angular velocity ω_2 = const depends only on angle error of cuts of teeth. Because these errors appear periodically after each full rotation of the rotor, they can be easy filtered. Incontestable is the fact of rigid mutual angle position of grooves in relation to themselves. In this connection for ω_2 = var, time between succeeding crossings "zero" level (after filtering cut errors of rotor's grooves) is the measure of changes of rotor's angular velocity. Described

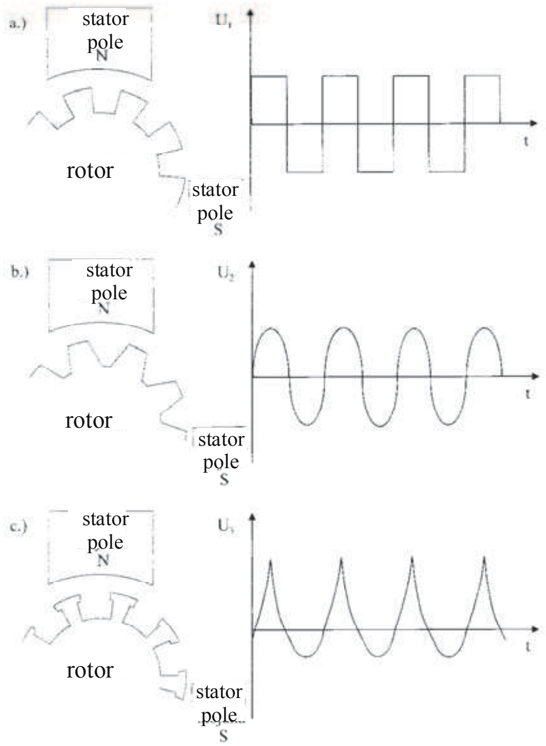

Fig. 5. Typical courses of output voltage of induction generators with a) trapezoid, b) rectangular, and c) 'swallow-tail' shaped rotor grooves

properties of groove pulsation have been used as a source of diagnostic information about technical condition of the alternator's power unit. It was the base to elaborate FDM-A diagnostic method, which is discussed in the another scientific description [5].

The measurement of amplitude of groove pulsation provides to locate brakes in rotor's winding. From data obtained during investigations [7] appears that after a failure of winding relative value (related to rms value of alternator's output voltage U_o) of groove pulsation $\delta_ż$ decreases. This value can be expressed by formula:

$$\delta_ż = \Sigma (U_{maxm} - U_{minm}) \cdot 100\% / \dot{Z} \cdot U_o$$

where: m – natural number as a number of succeeding period of groove pulsation, U_{maxm} – maximal value of voltage of pulsation component in given period m, U_{minm} – minimal value of voltage of pulsation component in given period m, $\dot{Z}$ – number of rotor's grooves.

Simultaneously after the failure of generator's winding, changes of rms value of output voltage ΔU_o occur practically imperceptible, especially for lower values ω_2). They are presented in Table 1 – on the base of data from [7]. Relative value of these changes for the failure of one winding of the rotor δU_o does not exceed 0,01%. In practice to notice the failure of alternator, i.e. the break in winding, by aircrew during operation is impossible. As it results from practice of staff managed by authors to notice the failure is possible by using special measure apparatus.

The failure of alternator's winding, e.g. its break, causes decreasing of value of groove pulsation given in Table 1 as coefficient $\Delta\delta_ż$ from 0,8% to 1,6%, what can be measured using measure apparatus of class 0,1%.

3. POLE PULSATION

The phenomena of pole pulsation can be observed on the curve of output voltage [5] of the generator as the amplitude modulation shown on Figure 3. The frequency of modulation is directly proportional to the product of the number of stator's poles and rotor's angular velocity, but the amplitude's depth is proportional to changes of magnetic reluctance between the rotor and the stator. This signal brings information about anisotropy of plates of the generator's magnetic circuit. The modulation can cause small errors of ΔT_i measurement. It is easy to filter, considering recurrence of it, characteristic for the given generator.

Relative pole pulsation δ_p can be expressed by the formula:

$$\delta_p = \{(U_{max0} - U_{min0})\ 100 / (U_{max0} + U_{min0})\}_{MAX} \quad (6)$$

where: 0 – natural number meaning number of succeeding period of pole pulsation; U_{max0} – maximum value of pulsation component voltage in period 0; U_{min0} – minimal value of pulsation voltage component in given period 0.

Pole pulsation brings some diagnostic information:

a) phase parameter informs about errors of geometrical distribution of stator's pole pieces,
b) pulsation amplitude (envelope shown on Figure 3) generally testifies to irregularity of magnetic field's distribution under stator's magnetic poles but in a few cases also to short-circuit or break of winding of rotor or stator:

- if amplitude of pole pulsation reaches, uniformly extended, in a whole period, values approximated amplitude of rotor's groove pulsation it means surcharge of one coil in consequence extended leakance of its insulation or partial short – circuit with ground or between rotor's coils in the given groove;
- if amplitude of pole pulsation reaches unequal values in the whole period, e.g. for one rotor's rotation peak value of that envelope decreases, it means surcharge of one coil in consequence extended leakance of its insulation or partial short – circuit with ground or between coils of one stator's pole;
- if amplitude of pole pulsation decreases uniformly in the whole period of rotor's rotation, as it is shown in table 2, it can indicate break of rotor's winding.

Considering diagnostic complexity of signal and its small amplitude in relation to carrier component (groove pulsation) to localize damaged

Table 1. Parameters of groove-excited pulsations prior to and after a failure to the generator

ω_2 →	rpm	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	Condition of winding
U_{ws}	V	28,6	28,5	28,5	28,5	28,6	28,7	28,7	28,6	28,6	28,6	28,6	28,9	Fit for use
$\delta_{\dot{z}}$	%	6,3	5,8	5,6	5,8	5,5	5,6	5,7	5,8	5,4	5,4	5,9	5,5	
U_{wz}	V	28,6	28,5	28,5	28,9	28,6	28,6	28,5	28,9	28,6	28,6	28,5	28,5	Damaged
$\delta_{\dot{z}}$	%	5,0	3,6	4,7	4,0	4,4	4,6	4,1	4,2	4,5	4,3	4,8	4,7	
ΔU_w	V	0	0	0	-0,4	0	0,1	0,2	-0,3	0	0	0,1	0,4	Indices effected by comparison between parameters
δU_w	%	0,00	0,00	0,00	-0,01	0,00	0,00	0,01	-0,01	0,00	0,00	0,00	0,01	
$\Delta\delta_{\dot{z}}$	%	1,3	2,2	0,9	1,8	1,1	1	1,6	1,6	0,9	1,1	1,1	0,8	

Table 2. Parameters of pole pulsations prior to and after a failure to the generator

ω_2 →	rpm	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	Condition of winding
U_{w1}	V	28,6	28,5	28,5	28,5	28,6	28,7	28,7	28,6	28,6	28,6	28,6	28,9	Fit for use
δ_{b1}	%	4,2	4,2	3,9	4,4	4,1	4,1	4,0	4,4	4,1	4,1	4,3	4,3	
U_{w2}	V	28,6	28,5	28,5	28,9	28,6	28,6	28,5	28,9	28,6	28,6	28,5	28,5	Broken
δ_{b2}	%	3,6	3,2	3,6	3,3	3,4	3,6	3,4	3,5	3,4	3,3	3,7	3,5	
$\Delta\delta_b$	%	0,6	1	0,3	1,1	0,7	0,5	0,6	0,9	0,7	0,8	0,6		Comparison

windings by means of the measurement of pole pulsation is not enough precise. Signal of pole pulsation grows significantly in the case of failure, e.g. short – circuit of any winding – its amplitude grows several times in comparison with amplitude of groove pulsation. Because during short – circuit of coil commutate pulsation amplitude considerably grows, phenomena of short – circuit is discussed below.

4. COMMUTATE PULSATION

The phenomena of commutate pulsation is not used in method FDM-A [5 i 6], because it has been admitted to be interference signal. Previous investigations carried out by authors [5, 8] have showed that value of amplitude of that pulsation is directly proportional to level of current load. Figure 4 presents interdependence between commutate and groove pulsation as well as localization of rotor's grooves and commutate staves. From experiments with using onboard generator it results that for generator's load current below 10% rated value - amplitude of commutate pulsation (fig. 4b) is almost imperceptible against a background of groove pulsation (fig. 4d). For load 10% pulsation is scarcely visible on output voltage. Angle displacements of each half – sinusoid of commutate pulsation (fig. 4d) change in relation to groove pulsation and are individually displaced during mechanical vibration of brushes in a brush – holder as well as generator's current load. In this connection commutate pulsation can not be used for diagnosis of failure value of power unit's kinematics pairs.

For rated load peak value of commutate pulsation reaches level about 50% of groove pulsation. It means that it can be used as a source of diagnostic information of failures e.g. generator's commutate – brush kinematics pair.

Interesting data were given by controlled short – circuit in the rotor. When midpoint of one winding was shorted, it appeared that pole pulsation, visible as slow changing component, was predominant (fig. 5) but commutate pulsation was fast changing (fig. 6).

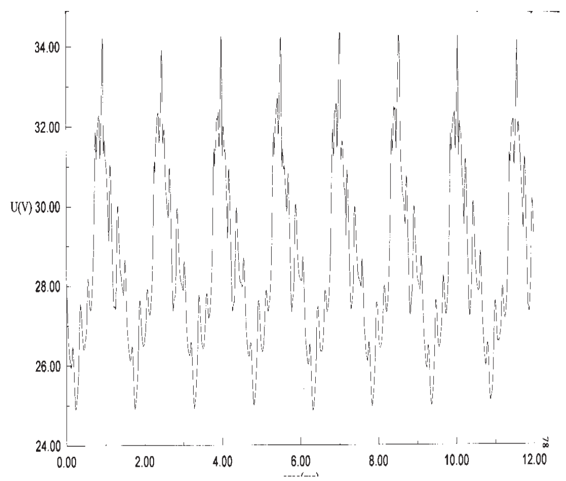

Fig. 6. Output voltage of the d.c. generator at the rotor winding fault (inter-turn short-circuit fault).

As far as component of pole pulsation was stable, in respect of frequency and amplitude, the component of commutate pulsation reached maximal value at the moment of passing under succeeding pole of the generator's stator. A univocal change of relation between amplitude of pulsation components provide to detect short – circuits in rotors of commutate generators.

5. SUMMARY

In the paper different kinds of pulsation of generator's output voltage have been discussed. However in practice they appear simultaneously, amplitude – phase relation between them are very different. Special references describe individually each of them. Authors, based on own developing, try to present practical relations between them. Pulsation component brings much diagnostic information about both technical condition of power unit as well as information source, i.e. generator. It is not mentioned in references. Diagnostic symptoms, contained in pulsation and precisely recognized, are used in professional practice of authors. Others having more than one meaning and not identified will be able to use after many arduous investigations that will provide to find precise relations between succeeding parameters of kinematics failures and parameters of output voltage component.

LITERATURE

1. Wróbel T.: *Studium teoretyczne i eksperymentalne zagadnienia pulsacji napięcia prądnic tachometrycznych prądu stałego.* Dodatek do Biuletynu WAT nr 3(259), Warszawa 1974.
2. Wróbel T.: *Studium zagadnienia pulsacji napięcia prądnic tachometrycznych o wyjściu stałoprądowym*. Dodatek do Biuletynu WAT nr 6(298), Warszawa 1977 (in Polish).
3. Liwschitz-Garik M.: *Direct-current machines* D. Van Nostand Company, New York 1962.
4. Plamitzer M.: *Maszyny elektryczne.* Wydawnictwo Naukowo-Techniczne, Warszawa 1962.
5. Biarda D., Falkowski P., Gębura A., Kowalczyk A.: Opis patentowy PL 175674B1: *Sposób diagnozowania technicznego elementów sprzęgających silnik, a zwłaszcza lotniczy silnik spalinowy, z prądnicą prądu stałego.* Zgłoszenie 08.07.1996, udzielenie patentu 29.01.1999.
6. Biarda D., Falkowski P., Gębura A., Kowalczyk A.: Opis patentowy PL 175645B1: *Sposób diagnozowania technicznego elementów sprzęgających silnik, a zwłaszcza lotniczy silnik spalinowy, z prądnicą prądu stałego.* Zgłoszenie 08.07.1996, udzielenie patentu 29.01.1999.
7. Gębura A., Prażmowski W., Kowalczyk A., Falkowski P., Głowacki T., Budzyński P., Pisarska K.: *Sprawozdanie z pracy – określenie związków pomiedzy parametrami jakości energii prądnic pokładowych a stanem zużycia skrzyń napędowych.* Warszawa, czerwiec 1997r, niepublikowane, nr BT ITWL 11818/I.
8. Gębura A., Prażmowski W., Kowalczyk A., Falkowski P., Głowacki T., Budzyński P., Gajewski T., Pisarska K.: *Sprawozdanie z pracy – określenie związków pomiędzy parametrami jakości energii prądnic pokładowych a stanem zużycia skrzyń napędowych. Część I.* Warszawa czerwiec 1997, niepublikowane, nr BT ITWL 12023/I.