

The diagnosis of onboard generators (alternators)

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Abstract

In the paper selected problems related to diagnostics of onboard generators and alternators fitted 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 associated with changes in a character of pulsation, which occur during shortings or insulation clearances in rotor or stator wiring. Possibility of diagnosis of generator's or alternator's parts by means of analysis of pulsation component parameters is indicated. In the case of alternators a number of diagnostic methods based on observation of changes in shape of voltage or frequency modulation, is discussed. This allows to detect many mechanical or electrical faults of generators, alternators or their control systems.

Keywords: technical diagnostics; frequency modulation

CHARACTERISTICS OF VOLTAGE PULSATION OF DIRECT CURRENT (DC) GENERATOR

In a classical educational approach the DC commutator generator is presented in the schematic form, as given in Fig. 1, and run of its electromotive force - in Fig. 2. The DC commutator generator is consisted of:

- the motionless stator which can be schematically presented in the form of pair of permanent magnets (Fig. 1, where: „N” – north pole, „S” – south pole), producing constant magnetic field of B intensity and the sense from „N” to „S”
- the rotor rotated with ω_2 velocity by an external mechanical force. On the rotor winding turns are wound in which the electromotive force e, (EMF), is induced. The force can be described as follows:

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

where:

- k – design coefficient of a given generator
- B – magnetic field intensity
- ω_2 – instantaneous angular velocity of generator rotor

- the commutator, i.e. the ring fastened on the rotor and made of a conductive material. The ring is cut into segments which are electrically insulated from each other and form the so called commutator sectors (bars). To each of the sector the end of winding turn is connected; the commutator serves this way as a mechanical electric current rectifier

- the electric brushes: „+” and „-”, which slide around commutator bars. To the brushes are connected wires conducting electric current to consumers.

In order to increase magnitude of the inductivity B, rotor's winding turns are placed on a core made of silicon steel sheets, that amplifies magnitude of EMF (e) about 10 thousand times. To correctly fasten the winding turns on the core they are placed in grooves. As cross-sections of the grooves have a toothlike form they are further called the „rotor teeth”.

Comparison of the theoretical run described by Eq. 1 (Fig. 2) with the real run of generator pulsation component (Fig. 3) does not show any similarity between them.

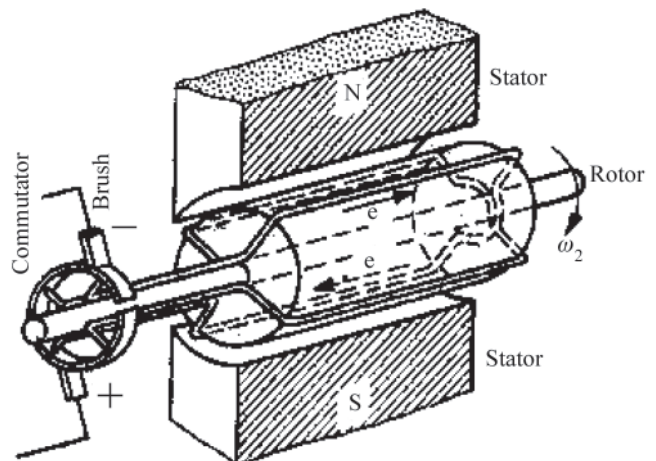


Fig. 1. Rotor with two winding turns and commutator of four segments

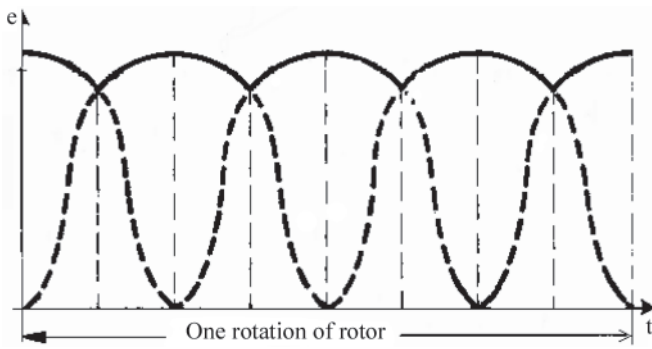


Fig. 2. Run of electromotive force between brushes in DC generator

Groove pulsations of generator's output voltage are produced as a result of change of reluctance due to whirling the grooved rotor. The groove pulsation frequency f_z can be expressed as [1÷4]:

$$f_z = \dot{Z} \cdot n/60 \quad (2)$$

where:

- \dot{Z} – number of rotor grooves
- n – rotational speed.

In the literature [1÷3] voltage pole pulsations are often associated with the so-called rotational pulsations because of their mutual similarity. The phenomenon of voltage pole and rotational pulsations is manifested in the run of output voltage of DC commutator generator, that can be observed in the form of changes of the run of the envelope shown in Fig. 3. Frequency of the modulation is directly proportional to the product of number of stator poles and angular velocity of rotor, whereas depth of its amplitude is proportional to changes of magnetic reluctance between rotor and stator. The pole pulsation frequency f_b can be presented by means of the formula:

$$f_b = 2p \cdot n/60 \quad (3)$$

where:

- p – number of pairs of stator magnetic poles.

Signal of pole modulations carries information on anisotropy of sheets of generator magnetic circuit. In the subject-matter literature the pole modulation is usually associated with

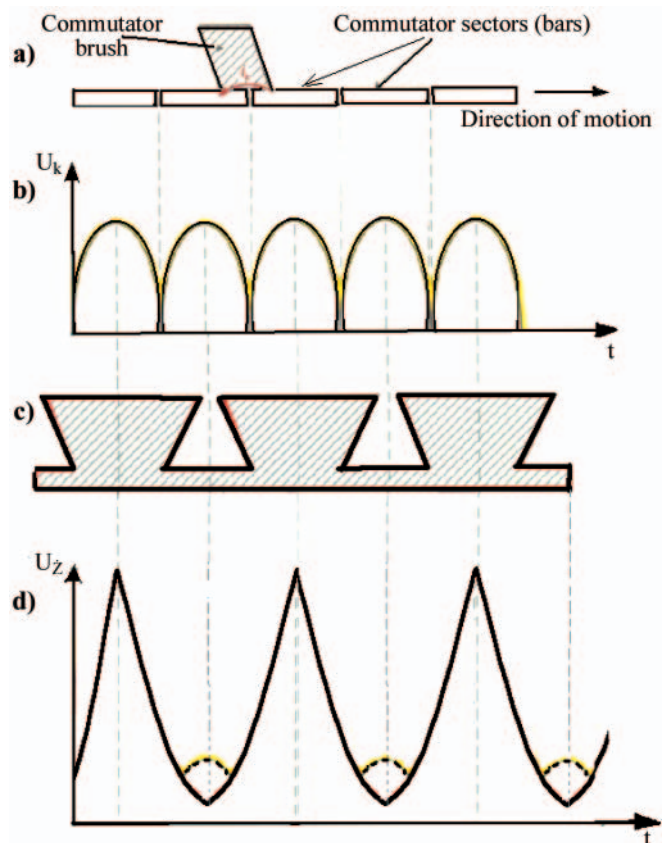


Fig. 4. Shape of pulsation curve for DC generator: a) developed view of mechanical elements of commutator unit, b) run of commutator pulsations - $U_k = f(t)$, developed view of rotor grooves, c) run of groove pulsations (continuous line) - $U_z = f(t)$ with added commutator pulsations (broken line), d) run of groove pulsation

rotational modulation which is characteristic of that such modulation frequency is equal to the first or second harmonic frequency (in certain cases - to the first subharmonic) of rotational speed of generator rotor. The signal carries diagnostic information on the errors:

- of workmanship of the generator, especially on inaccuracy of geometrical dimensions manifested as an asymmetry of air-gap between stator and rotor

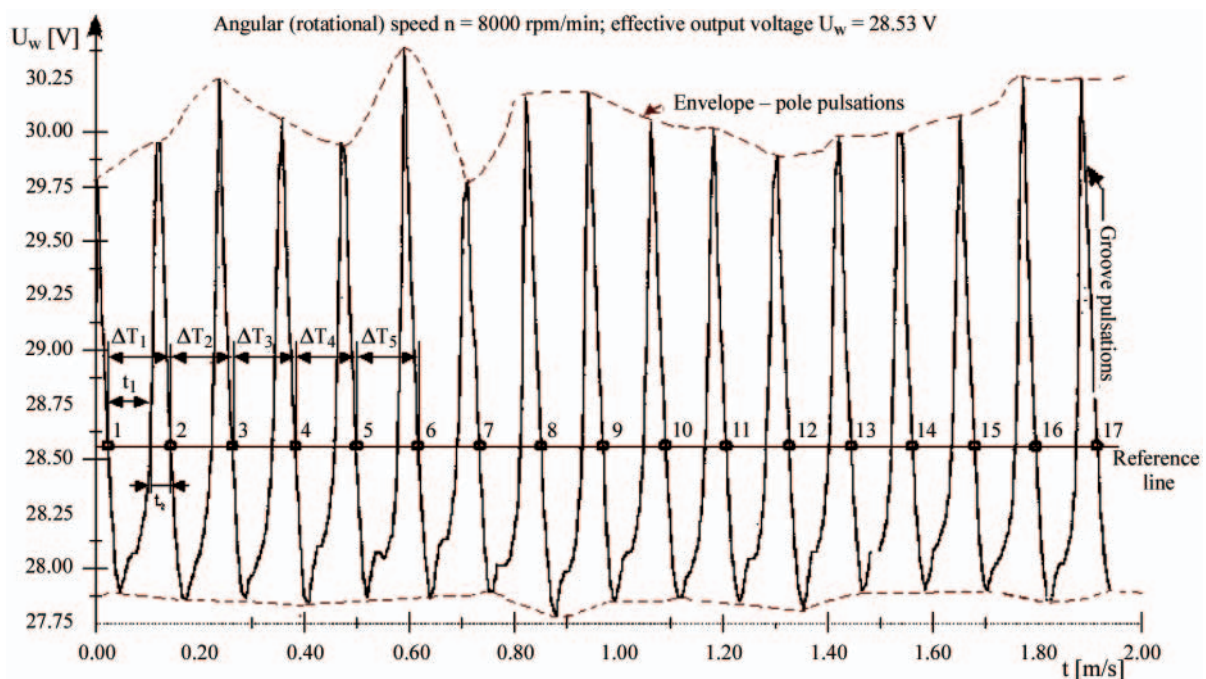


Fig. 3. Changes of pulsation component of an aircraft DC generator under minimum load

- of assembling the generator, such as parallelism error, i.e. shift of rotor shaft axis with respect to that of drive shaft, sometimes called also eccentricity error, as well as angular error of shift of rotor shaft axis against drive shaft axis.

Voltage commutator pulsations are associated with interaction of brushes and commutator. During armature rotation the brushes short-circuit alternately different number of winding turns, that introduces a change in number of turns in parallel branches and generates periodical pulsations of voltage at the brushes. The frequency f_k of the pulsations depends on number of commutator sectors and can be expressed by means of the formula [1, 2]:

$$f_k = K \cdot n/60 \quad (4)$$

where:

K – number of commutator sectors.

GROOVE PULSATIONS

The phenomenon of various groove pulsations is well described in the literature dealing with alternate-current (AC) induction generators [1, 2]. They do not possess any wound rotor and their useful signal is obtained from the stator winding. Their rotor is made of a ferromagnetic material (usually of a packet of silicon steel sheets) it has milled grooves (teeth) due to which modulation of magnetic field intensity of stator magnets is generated. In the generators groove pulsations are the crucial phenomena producing the useful signal. As there is no rotor winding - in contrast to the classical DC commutator generator - therefore only changeable component of pulsation is generated (commutator pulsations are not present because of lack of commutator and rotor winding).

As results from the literature information [1, 2], to induction generators, in order to achieve an output voltage signal close to sinusoidal one, skew form of teeth is usually applied (Fig. 5b).

Rotors having „dovetail” grooves (Fig. 5c) are rarely used in induction generators as then an unsymmetrical form of output voltage appears [1]. However such shape of grooves is commonly used in classical DC commutator generators. The shape makes firm fastening the winding onto rotor, possible. Time intervals between crossings of groove pulsations through the rotational speed reference level set for generator rotor, $\omega_2 = \text{const.}$, are dependent only on error in angle of milling the teeth. As the errors cyclically appear after every full rotation of the rotor they can be easily filtrated out. However the fact of stiff mutual angular position of grooves remains undeniable. Hence for $\omega_2 = \text{var}$ the time intervals between successive „zero”- level crossings (after filtrating any possible errors in milling the rotor grooves) will constitute a measure of instantaneous changes in angular velocity of rotor. The described features of groove pulsations have been used as a source of diagnostic information on technical state of generator drive system, on the basis of which the FDM-A diagnostic method (described in [5]) has been elaborated.

The measuring of amplitude of groove pulsations makes it possible to localize breaks in rotor winding. As results from the data collected by these authors [7] after a winding failure a decrease of the relative value (related to the effective value of the generator output voltage U_w) of the groove pulsation δ_z , is observed. The value can be expressed as follows:

$$\delta_z = \Sigma (U_{\max m} - U_{\min m}) \cdot 100\% / \dot{Z} \cdot U_w \quad (5)$$

where:

m – natural number being that of successive interval of groove pulsation

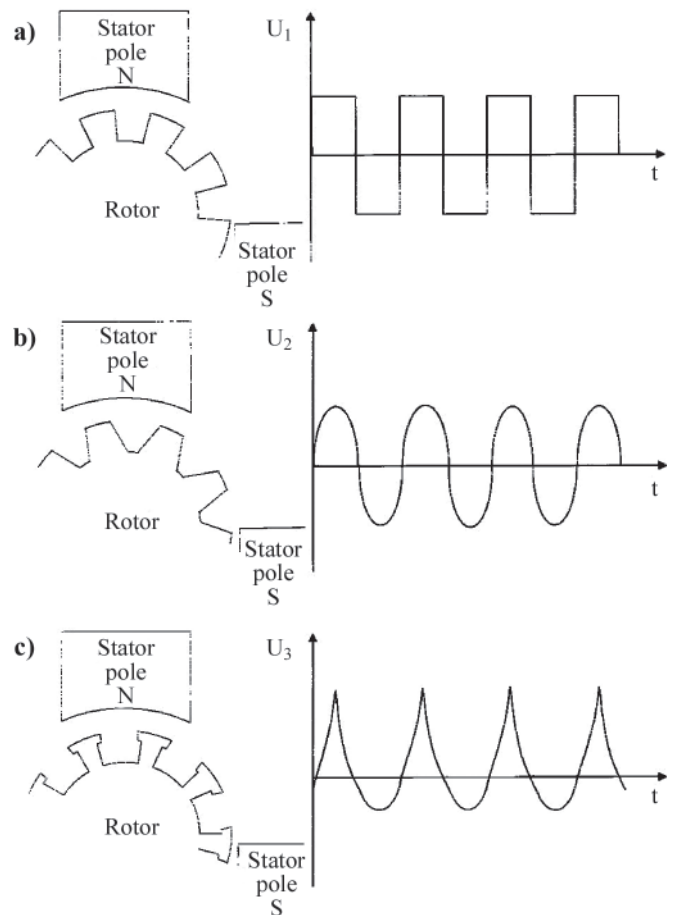


Fig. 5. Typical runs of output voltage of induction generators with rotor teeth of the form: a) trapezoidal, b) rectangular, c) „dovetail” – like

$U_{\max m}$ – maximum instantaneous value of pulsation component within a given interval m

$U_{\min m}$ – minimum instantaneous value of pulsation component within a given interval m

\dot{Z} – number of rotor grooves.

Simultaneously, after a failure of DC generator winding, the effective output voltage value changes, ΔU_w (practically imperceptible, especially at lower values of ω_2 shown in Tab. 1 based on the data of [7]), occur. The relative value of the changes, δU_w , due to failure of a single winding turn, does not exceed 0.01 %. In practice to detect a generator failure, i.e. occurrence of a break of its winding, by aircraft personnel under operation is entirely impossible. However this is fully possible, as results from experience gained by the team supervised by these authors, by making use of special measurement instruments.

A failure of generator winding, e.g. its break, results in the decrease of the values of groove pulsation, given as the index $\Delta \delta_z$ in Tab. 1, from 0.8 % to 1.6 %, that can be practically measured by using measurement instruments of 0.1% class.

POLE PULSATIONS

The phenomenon of pole pulsations can be clearly observed on the run curve of DC generator output voltage [5] in the form of amplitude modulation, shown in Fig. 3. The modulation frequency is directly proportional to the product of number of stator poles and angular velocity of rotor, and the amplitude depth - proportional to magnetic reluctance changes between rotor and stator. The signal carries information on anisotropy of sheets of magnetic circuit of generator. The modulation

Tab. 1. Parameters of groove pulsations before and after failure of generator winding

$\omega_2 \rightarrow$	[rpm]	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	State 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	Capable
δ_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	Failed
δ_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 used to compare parameters before and after failure
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	
$\Delta \delta_z$	[%]	1.3	2.2	0.9	1.8	1.1	1	1.6	1.6	0.9	1.1	1.1	0.8	

can introduce small errors in measuring ΔT_1 . It can be easily filtrated out because of its repeatability characteristic for a given generator. The relative value of pole pulsation, δ_b , can be expressed as follows:

$$\delta_b = \{(U_{\max o} - U_{\min o})100\% / (U_{\max o} + U_{\min o})\}_{\text{MAX}} \quad (6)$$

where:

- o – natural number standing for successive number of pole pulsation interval
- $U_{\max o}$ – maximum instantaneous value of voltage pulsation component in the o-th period
- $U_{\min o}$ – minimum instantaneous value of voltage pulsation component in the o-th period.

The pole pulsations carry a few kinds of diagnostic information:

- a) phase parameter informs on possible errors in geometrical distribution of stator pole shoes,
- b) pulsation amplitude (run of the envelope shown in Fig. 3) generally shows a non-uniformity of magnetic field distribution under stator magnetic poles and, in some cases, a shorting or break of rotor or stator winding:
 - if pole pulsation amplitude reaches, during the whole period, values uniformly increased and close to those of rotor groove pulsations, it means that one turn of winding is overloaded due to an increased leakance of its insulation or a partial fault to frame or between rotor winding turns in a given groove
 - if pole pulsation amplitude reaches non-uniform values during the whole period, e.g. during one rotation of rotor, the peak value of the envelope undergoes a decrease; it

means that one turn of winding is overloaded due to an increased leakance of its insulation or a partial fault to frame or between winding turns of one pole of stator

- if pole pulsation amplitude value uniformly decreases during the whole period of rotor's rotation, as shown in Tab. 2, it may constitute information on a break of rotor winding.

With a view of a diagnostic complexity of such signal and of its small amplitude with respect to the carrier component (groove pulsation), location of failed winding turns by measuring pole pulsations seems rather inaccurate.

However the pole pulsation signal becomes greatly increased in case of a failure, e.g. shorting of an arbitrary winding, consequently its amplitude increases many times with respect to that of groove pulsations. The shorting phenomenon is below described in detail as commutator pulsation amplitude greatly increases during shorting the winding turn.

COMMUTATOR PULSATIONS

The phenomenon of commutator pulsations has been not used in the FDM-A method [5, 6] as it has been regarded as a disturbing signal. The investigations performed under supervision of these authors [5, 8] have showed that amplitude value of the pulsations is directly proportional to current-load level. In Fig. 4 are presented mutual relations between commutator pulsations and groove ones, as well as location of rotor grooves and commutator bars. From the investigations performed with the use of an aircraft DC generator it results that at the generator's current load lower than 10% of its rated value the commutator pulsation amplitude (Fig. 4b) is rather

Tab. 2. Parameters of pole pulsations before and after failure of generator winding

$\omega_2 \rightarrow$	[rpm/min]	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	State 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	Capable
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	0.8	Compari-son

unperceptible against groove pulsation background (Fig. 4d). At the current load of the order of 10% the pulsations are barely visible on the output voltage run. Angular displacements of particular halves of sinusoids of commutator pulsations (Fig. 4d) change with respect to groove pulsations and undergo individual angular displacements due to mechanical vibrations of brushes in brush-holder and during current loading the generator. Therefore the commutator pulsations cannot be used to diagnosing magnitude of failures of drive system's kinematic pairs.

Under rated load, the peak value of commutator pulsations reaches the level of about 50% of groove pulsations. It means that they may serve as a source of diagnostic information on e.g. commutator-brush unit failures.

Trials of a controlled shorting in rotor have provided interesting data. In the case of shorting in the middle of one of the rotor winding turns it was revealed that the pole pulsation visible in Fig. 6 as the slow-varying component, became dominating, and the commutator pulsation visible in Fig. 6 as the fast-varying component, appeared to be that of the second order.

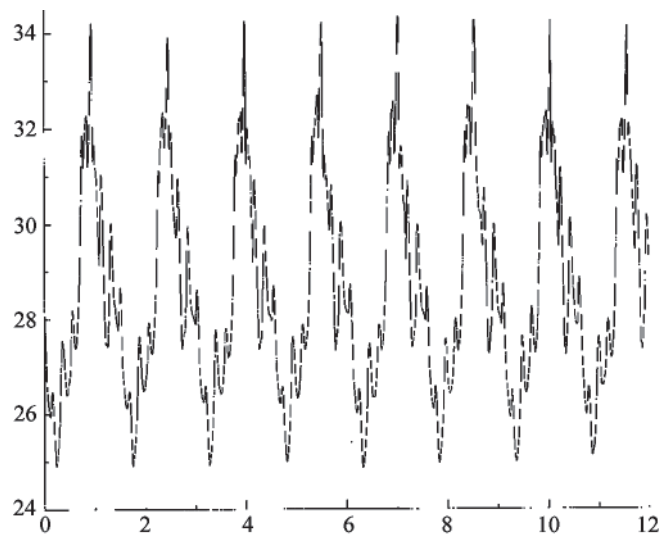


Fig. 6. Diagram of DC generator output voltage in the case of rotor winding's shorting (the shorting localized in the middle of one of winding turns)

However if the pole pulsation component was stable with respect to its frequency and amplitude, the commutator pulsation component reached its greatest value in the instant of passing under successive pole of generator stator. The unambiguous change of the relation between amplitudes of pulsation components makes it possible to detect shortings in rotors of commutator generators.

CONCLUSIONS

- In this paper different kinds of output voltage pulsations of DC generator were described. Although they simultaneously occur in practice their amplitude-phase relations are very different. The subject-matter literature fully describes each of them separately.

- These authors, basing on their personal experience, have made an attempt to highlight practical relations between the pulsations. The pulsation component carries several diagnostic signals both concerning technical state of drive system and DC generator itself, i.e. the very source of the information, which has been not mentioned at all in the literature.
- The diagnostic symptoms contained in the pulsations, precisely recognized by these authors, have been implemented by them to practice a few years ago. The other, ambiguous and not fully identified ones will be ready for application only after performing many arduous investigations aimed at finding accurate relations between successive parameters of kinematic faults and parameters of output voltage component.

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