Ship Diesel Engine-Generators Voltage Spectral Power Structure as a Parameter of Systems Technical Diagnostics

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Abstract – A method of technical diagnostics of ship diesel engine - generator installations is proposed. Spectral-power diagnostic parameters of the synchronous generator voltage and currents are used. The electric machine in this case is the multipurpose sensor of diagnostic parameters. A judgment on the quality of the operational processes in diesel engine cylinders and its technical condition is possible on the basis of these parameters. This method is applicable to piston compressor installations with the electric drive. On the basis of such parameters like rotating torque, angular speed and angular acceleration it is possible to estimate the quality of the operating process in cylinders of a diesel engine, a condition of its cylinder-piston group and crank gear mechanism. The investigation was realized on the basis of diesel-generator with a linear load. The generator operation was considered for the case of constant RL load. Together with the above mentioned a condition of bearings of synchronous machines, uniformity of its air gap, windings of the electric machine were estimated during the experiments as well. The frequency spectrum of the stator current of the generator was researched and analysed. In this case the synchronous machine is becoming a rather exact multipurpose diagnostic sensor. The signal of the non-uniformity in the operation process of the diesel engine cylinders and its technical condition is the increasing of the amplitudes of typical frequencies.

Keywords – Diesel engines; Generators; Torque measurement; Vibration measurement.

I. INTRODUCTION

Nowadays in approximately 80 % of cases diesel-generators are applied in ship installations as the main and emergency sources of the electric power. The questions of the diesels technical diagnostics are in details considered in [1, 2, 3, 4, 13]. In the present paper the authors propose a complex approach to the technical diagnostics of electro-mechanical system “diesel - generator”. Together with its basic purpose – electric energy generation - the synchronous electric generator is used as a multifunctional sensor of the diagnostic information. The shaft of the generator is rigidly fixed with the crankshaft of the diesel. All the operational processes influence the electromagnetic processes of the generator. On the contrary, the changing of the parameters of the electromagnetic processes makes an impact on those of the diesel operational process. In the paper the method of technical diagnostics of diesel-power installations is considered where the output voltage and current are used as diagnostic parameters for spectral-power characteristics of the higher harmonics and sub-harmonics. With the rapid development of means of measurement the storage and processing of the information is becoming possible including microprocessor techniques. Before more often the harmonics of voltage and current of 5-7 orders were applied for such analysis. Harmonics of higher orders usually were not considered because of their insignificant size and difficulty of measurement. Occurrence of modern high-speed analog-digital converters allows to measure spectral-power characteristics of higher harmonic components - up to 11... 15-th with the amplitude of 2 %... 0.2 % from that of the basic harmonic. Application of mathematical methods allows revealing a place and reason of their occurrence. Thus, spectral-power characteristics of higher harmonics can be accepted as diagnostic parameters as well as the sub-harmonics can be used with these purposes. Comparison of parameters of the harmonics of different order with reference values allows expanding opportunities of technical diagnostics systems. The harmonic components are a product of electromagnetic interaction of electric machine rotor and stator. Character of this interaction depends not only on the parameters of the electric machine, but also on the mechanical characteristics of drive engine - its instantaneous angular frequency and angular acceleration. These parameters characterize a technical condition of drive engine.

Non-uniformity of the rotating torque, instantaneous fluctuations of angular speed and angular frequency result in parameters variation of electromagnetic processes in generator. Thus the spectral structure of the output currents and voltages is changing. In the given paper the method of technical diagnostics based on the continuous control of non-uniformity of the diesel engine rotating torque, fluctuations of instantaneous angular speed and angular acceleration for one-two turn of a diesel engine crankshaft is suggested. The obtained data are compared either with reference values, or with the values received as a result of mathematical modeling. Deviations of these non-uniformity parameters from reference characterize a condition of diesel engine cylinder-piston group and quality of the operation process in its cylinders. The second feature of this method is used as the multipurpose sensor of the regular generator in a diesel engine-electric installation.
III. SHIP DIESEL ENGINE-GENERATORS PARAMETERS FOR TECHNICAL DIAGNOSTICS

Force of pressure of burning gases $P$ (Fig. 1) is directed along the axis of the cylinder downwards to a crankshaft [5, 6]. This force $P$ by rules of a parallelogram can be spread out on two aspects - force $P_a$ operating along an axis of a rod and cross-section force $P_c$, directed perpendicularly to an axis of the cylinder.

Force $P_a$ causes single action pressing the piston to the cylinder, increase in forces of friction and deterioration of rubbing details. At a stage of compression this force is directed to the opposite part. This force (perpendicular axes of the cylinder), being the top dead point (TDP), shifts the piston from one wall of the cylinder. Force $P_a$ can be defined as

$$ P_a = P \tan \beta. \quad (1) $$

Force $P_a$, directed along the axis of the rod, is presented as

$$ P_a = P / \cos \beta. \quad (2) $$

Force $P_a$ can be transferred along a connecting rod in a direction of its action from point A (the center of a piston pin) to point B - a point of connection of a connecting rod and a crank. Force $P_a$ can be divided into two components: the radial force $Z$ directed to the center of an axis of rotation of crankshaft and tangent force $T$, operating perpendicularly to radius of the crank. The angle between forces $P_a$ and $Z$ will be equal to both $\alpha + \beta$. The tangent force $T$ is equal to

$$ T = P \sin (\alpha + \beta). \quad (3) $$

Having replaced force $P_a$ expression (2), we obtain

$$ T = P \sin(\alpha + \beta) / \cos \beta. \quad (4) $$

Force $T$ creates rotating torque $M$ with arm of force, equal to radius of crank $R$

$$ M = TR. \quad (5) $$

Radial force $Z$ acts on bearings of crankshaft is detrimental. Its value can be defined as

$$ Z = P \cos (\alpha + \beta), \quad (6) $$

or

$$ Z = P \cos(\alpha + \beta) / \cos \beta. \quad (7) $$

Tangent force $T$ is a variable. Its size is equal to zero at top dead point (TDP) and bottom dead point (BDP) of piston. At these points force $P_a$ is directed precisely to the radius of the crank and along the axis of the cylinder. The arm of the force is also equal to zero. Hence the rotating torque at these points is zero. Crank gear, like to the converter of back and forth motion in rotary, is distinctive of the non-uniform rotating torque. It is necessary to consider, that the value of force $P$ in the process of direction of the piston downwards also does not remain constant. Fig. 2 demonstrates the diagram of the rotating torque according to the angle of turn of crankshaft $\alpha$.

During the stage of inject and exhaust the rotating torque of $M$ has sign-variable character and defines the torque of inertia forces. At this time pressure of gases in the cylinder can be neglected. During the step of compression tangent force $T$ is negative and force from pressure of gas increases, remaining positive. In the multicylinder engine the rotating torques from different cylinders sum up and total rotating torque $\Sigma M$ is becoming more uniform. While rotation the total rotating torque $\Sigma M$ overcomes the torque of resistance $M_r$ of the forces of friction, inertia, magnetic field of the generator. During the operation the total torque $\Sigma M$ can be either higher or lower than the torque of resistance $M_r$ (Fig. 3). Hence, the angular speed of crankshaft rotation will not be a constant. At $\Sigma M > M_r$, angular speed $\omega$ will increase, at $\Sigma M < M_r$ - will decrease. With the changing of angular speed, angular acceleration of a crankshaft will be also changed.
Ming torque repeated will not have time to end completely and will be periodically non-
by a diesel engine with the non-
the rotating torque of the diesel e-
also increase of angle and of diesel engine cran-
parts of the electric machine and diesel engine. I-
crankshaft of diesel engine will increase with a
constant electric loading of the generator and change of rota-
gular characteristic of synchronous machine.

Fig. 3. Angular speed (b) and the torque (a) of the generator diagrams.

A degree of non-uniformity of angular speed is character-
ized with the factor:

\[ \sigma = (\omega_{\text{max}} - \omega_{\text{min}}) / \omega_{\text{average}}. \]  

(8)

Working on the rowing screw the degree of non-uniformity \( \sigma \) is supposed \( \sigma = 1/20 \ldots 1/40 \); working on the generator of a direct current and \( \sigma = 1/100 \ldots 1/150 \); on the alternating current generator \( \sigma = 1/150 \ldots 1/200 \) [3, 4]. These changes of the rotating torque, angular speed and the angular torque lead to fluctuations of a magnetic flow vector in the generator. As diagnostic parameters change of the total rotating torque, angular speed and angular acceleration for one or several turns of a crankshaft of the engine are chosen.

In the setting process of the synchronous machine (the voltage of network \( U \) and excitation current \( I_e \) do not change) to each external torque \( M_{\text{ext}} \) quite certain position of a magnetic axis of a rotor is in relation to a vector of a total magnetic field [7, 8, 9, 10]. This position is characterized with angle \( \theta \), which is corresponded to external torque \( M_{\text{ext}} = M_{\theta} \) on the angular characteristic of the synchronous machine (point 1, in Fig. 4, for diesel engine \( M_{\text{out}} \) is the torque of loading \( M_{\theta} \)). At constant electric loading of the generator and change of rotating torque \( M_{\text{out}} \) on both \( \Delta M \) leads to the changing of angle \( \theta \) to \( \alpha \), which is reached not at once, but after transient (point 2 in Fig. 4). Angular speed of synchronous machine rotor and a crankshaft of diesel engine will increase with acceleration

\[ \frac{d\omega}{dt} = \frac{\Delta M_{\text{emag}}}{J}, \]

where \( J \) is the moment of inertia of rotating parts of the electric machine and diesel engine. Increase in angular speed of rotor and of diesel engine crankshaft, and also increase of angle \( \theta \) both \( \theta = \theta + \alpha \) will take place before the new moment of balancing (point 2 in Fig. 4) [11, 12, 14, 15]. At this point the electromagnetic torque \( M \) will be equal to the rotating torque of the diesel engine \( M_{\text{out}} \).

However in the case of rotation of the synchronous machine by a diesel engine with the non-uniform rotating torque and non-uniform angular frequency (Fig. 2) this transitive process will not have time to end completely and will be periodically repeated with each turn of the crankshaft. In this case the rotating torque of the diesel engine contains constant component \( M_{\text{out}} \theta \) and harmonic components \( M_{\text{out} v} \):

\[ M_{\text{out}} = M_{\text{out} 0} + \sum_v M_{\text{out} v} \cos(v \omega t + \varphi_v). \]  

(9)

At rotating torque \( M_{\text{out}} \) the angle \( \theta \) also will change in size for value \( \Delta \theta \) (Fig. 4), which can be presented in the form of Fourier series [7]:

\[ \Delta \theta = \sum_v \Delta \theta v = \sum_v \Delta \theta v \cos(v \omega t + \zeta_v). \]  

(10)

Similarly by means of Fourier series it is possible to express flux linkage values both \( \Delta \phi_d \) and \( \Delta \psi_q \) along \( d \) and \( q \) axes of the synchronous machine and corresponding currents \( \Delta i_d \), \( \Delta i_q \) :

\[ \Delta i_d = \Delta i_d 0 + \sum_v \Delta i_d v, \quad \Delta i_q = \Delta i_q 0 + \sum_v \Delta i_q v, \]  

(11)

where

\[ \Delta i_d 0 = \text{Re}(\Delta \phi_d) = \text{Re} \frac{\Delta \phi_d}{x_d(j\omega)} = -U \sin \Theta_0 \text{Re} \frac{\Delta \Theta_v}{x_d(j\omega)}, \]  

\[ \Delta i_q 0 = \text{Re}(\Delta \psi_q) = \text{Re} \frac{\Delta \psi_q}{x_q(j\omega)} = U \cos \Theta_0 \text{Re} \frac{\Delta \Theta_v}{x_q(j\omega)}, \]  

\( \nu \) - number of harmonic, \( \omega \) - angular speed of the machine.

The specified harmonic components of the rotating torque can not only sum up, but also be subtracted. The increment of the electromagnetic torque will be equal to

\[ \Delta M_{\text{emag}} = \sum_v \Delta M_{\text{emag} v}. \]  

(14)

Equation of synchronous machine rotor movement for small angle \( \theta \) fluctuations at sudden change of the external rotating torque \( \Delta M_{\text{out}} \) looks like the following:

\[ M_{\text{out}} - M_{\text{emag}} = J \frac{d\omega}{dt}. \]  

(15)

Fig.4. Angular characteristic of the synchronous machine.
In (15) $M_{out}$ is the external rotating torque.

In turn, $M_{emag}$ is the synchronous electromagnetic torque at angle $\theta = \theta_0 + \alpha$ equal to $M_0 + \Delta M = M_0 + M_{syn} \alpha$.

$M_0 = f (\theta)$ is the torque at $\theta = \theta_0$ under the angular characteristic (Fig. 4).

The specific synchronizing torque at both $\theta = \theta_0$ is found as

$$M_{syn} = \left( \frac{\partial M}{\partial \theta} \right)_{\theta = \theta_0}.$$

$M_{as}$ - asynchronous electromagnetic torque from interaction of currents induced in damper winding and a winding of excitation with a resulting magnetic field (with low slip) at sudden change of external rotating torque with both $\Delta M_{out}$, it will be equal to

$$M_{as} = M_{as} \cdot s = -D \frac{da}{dt}, \quad (16)$$

and

$$M_{as} = \frac{mU^2}{\omega_{syn} R_2}, \quad (17)$$

where:

- $m$ - the number of phases,

- $D = \frac{M_{as}}{\omega_{syn}}$ - damper factor.

The specified changes of angle $\Delta \theta$ depending on number of harmonics can achieve 6…12 degrees. The spectral structure of voltage and currents of the synchronous generator strongly depends on operating modes of ship network. In this case a combination of specified factors worsening electromagnetic conditions on a vessel probably takes place.

Movement of rotor at its fluctuations can be described, having expressed all necessary sizes through an initial position of rotor angle $\theta_0$ and its small angle deviation $\Delta \theta = \alpha$. The angle $\theta$ (between vector $E_f$ and vector voltage $U$) rotating with angular speed $\omega_{syn} = 2\pi f$ is shown in Fig. 5.

Electric angular speed of the rotor will be equal to angular synchronous speed $\omega_{syn}$ and the additional angular speed connected with additional change of angle $\theta$

$$\omega = \omega_{syn} + \frac{d \theta}{dt} = \omega_{syn} + \frac{da}{dt}. \quad (19)$$

Angular speed of rotor will be equal to

$$\omega = \omega_{syn} + \frac{da}{p dt}, \quad (20)$$

where $p$ - the number of pole pairs, but acceleration of rotor can be defined as

$$\frac{d \omega}{dt} = \frac{d^2 \alpha}{dt}. \quad (21)$$

Rotor slip

$$s = \frac{\omega_{syn} - \omega}{\omega_{syn}} = -\frac{da}{\omega_{syn} dt}. \quad (22)$$

Equation of movement of the rotor (15), expressed through angle $\alpha$ and its derivatives. It will be described by the linear non-uniform differential equation of the second order with constant factors:

$$\frac{d^2 \alpha}{dt^2} + \frac{Dp}{J} \frac{da}{dt} + \frac{M_{syn} P}{J} \alpha = \frac{P}{J} M_{out} \cdot \cos \omega t. \quad (23)$$

Fluctuations of angle $\theta$ is accompanied by fluctuations of the electromagnetic torque $M_{emag}$ (Fig. 5), angular acceleration $\alpha$ and angular rotation frequency $\omega$.

Fluctuations of the electromagnetic torque $M_{emag}$ cause the fluctuations of active capacity $P = \omega \Delta M$ and also fluctuations of rms value and phase of current. rms value of the current is possible to be found from the vector diagram of synchronous machine (Fig. 5).

$$J = \frac{E_f^2 + U^2 - 2UE_f \cos \Theta}{X_f}. \quad (24)$$

The specified changes of rotating torque, angular frequency and angular acceleration can be defined, analyze instantaneous voltage of the generator or to define actual position of the main magnetic flow vector of the generator by means of the Hall sensors placed in the air gap of magnetic circuit. In this case the synchronous machine is becoming a rather exact multipurpose diagnostic sensor.

IV. EXPERIMENTAL RESULTS

For the purposes of technical diagnostics a diesel engine-electric unit represents the greatest interest for the analysis of the specified fluctuations of the rotating torque, angular speed and angular acceleration.

On the basis of these parameters it is possible to estimate the quality of the operating process in cylinders of a diesel engine, a condition of its cylinder-piston group and crank gear mechanism. In this case it is necessary to supply diagnostic system with signals from the sensor of the top dead point (TDP) of the first cylinder and the sensor of angular position of a crankshaft of a diesel engine (a rotor of the synchronous machine). Comparing the obtained data with the reference, a condition of bearings of synchronous machines, uniformity of its air gap, windings of the electric machine are also estimated. Now the level of development of microprocessor techniques and the software allows measurements of the specified parameters with high accuracy and for a short time interval.

The block diagram of measurement spectral-power characteristics of output voltage and current is given in Fig. 6. Diesel engine 2 results in rotation synchronous generator 1. The voltage of the synchronous generator acts in a ship three-phase network 440/254 V. Current and its instantaneous value in phases of the generator are supervised by means of current sensors 3, 4, using Hall magneto-electric effect. The voltage from current sensors acts on correction device 5 and on the alarm processor 7.
Fig. 5. The vector diagrams of the synchronous machine.

Fig. 6. The block-diagram of measurement diagnostic parameters for the diesel engine installation.

Fig. 7. The frequency spectrum of the stator current of the generator. A - spectrum of the diesel-generator with disturbances of the cylinder-piston group parameters; B - spectrum is a standard of the diesel-generator voltage.

Fig. 6 illustrates block-diagram of the diagnostic diesel-generator installation. The sensors of the top dead point (TDP) of the first piston (sensor 3) and angular rotation frequency (sensor 4) are placed on its flywheel. Sensors 3 and 4 are of same type having frequency output. Sensor 4 is placed above the tooth row of the crankshaft flywheel. Flywheel is provided with a magnet sign for sensor. The sensors of the phase voltage and currents 5 and 6 have a uniform amplitude-frequency characteristic. They are also applied for the galvanic isolation of the powerful circuits and those of measurements. They are realised on the IC ACS712 ( Allegro Microsystems, frequency -80 kHz, voltage - to 2 kV, input current - to 30 A). Analogue signals of the instantaneous values of the current and voltage of each phase of the stator are supplied to micro controllers 7. Micro controllers (MC) have two analogue-digital converters (ADC) at its each input. The input of one ADC is connected to sensor of current 6, the other - to sensor of voltage 5. The phase instantaneous power and angle of phase shift can be calculated by means of the micro controller. The information comes to micro processor (MP) 8. The same way the signals from sensors 3 and 4 come. Signals are stored in the micro processor memory. From micro processor 8 the information goes to micro controller 9 of PIC16F2458 type. It converts the obtained information in accordance with USB standard. This channel is used for the connection with personal computer. By means of computer the synchronization of all processes is carried out. Under the set program the obtained information is analysed and the diesel engine installation is diagnosed. The obtained results of the measurements are analysed and compared. Fig. 7 presents a frequency spectrum of the stator current of the ship’s three-phase synchronous generator. Voltage of the generator is 440 V, Frequency: 60 Hz, power 16 kW, \( \cos \phi = 0.8 \), angular rotation frequency 94.19 rad/sek (900 rev/min). The number of poles is 8. The diesel engine is 4-cycle. The engine is 4-cylinder; the cylinders are placed in series.

The highest interest in this spectrum is raised by so called typical frequencies. These frequencies are caused when the generator main magnetic flux is modulated by changes of the instantaneous values of the angular frequency and acceleration of the diesel crankshaft, misalignment and rupture of the axes of the crankshaft and the shaft of generator, defects of the bearings, etc. With the help of this spectrogram the condition of the piston-cylinder group of the diesel can be determined in accordance with the amplitude of the typical frequencies in the range of 7.5 Hz, 15 Hz, 30 Hz. The increasing of the amplitudes of these frequencies (Fig.7.A) (in comparison with reference frequencies- Fig.7.B) states the non-uniformity of the operation process in the pistons of the diesel (disturbance of the cyclic supply of fuel in time and volume), ageing of the pistons and cylinders, false operation of the piston-valve arrangement.
V. CONCLUSION

The use of the synchronous machine in a diesel engine-generating and compressor installations as a multipurpose diagnostic sensor is represented. Analyzing the received electric parameters of non-uniformity of the rotating torque, angular speed, angular acceleration and spectral-power structure of output currents and pressure and comparing them with reference values an actual condition of systems and units both the piston machine, and the synchronous machine can be estimated.

The increasing of the amplitudes of typical frequencies is signalling about the non-uniformity in the operation process of the diesel engine cylinders and its technical condition. The condition of the piston-cylinder group of the diesel can be determined in accordance with the amplitude of the sub-harmonics in the range of 7.5 Hz, 15 Hz, 30 Hz.

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