Investigation of the operation of a ship's synchronous generator based on a numerical model

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Abstract. The article presents the results of modeling a ship's synchronous generator. Based on preliminary design calculations, a geometric model of the generator was built. The static and overclocking processes of the generator are investigated. For static modes, the frequency response of the process is obtained. A numerical model was used to identify a mechanical defect. On the example of a simulated defect of an electrical machine - the eccentricity of the generator rotor, the signature of the defect signal is obtained. The study revealed that the presence of rotor eccentricity leads to the appearance of a harmonic component in the spectrum of the force of large amplitude with a maximum value at a low frequency. Transient analysis was carried out using wavelet transformations. The results of the study of dynamics show how the rotor speed increases. The simulation revealed three frequency regions of the signal under study: the region of the increase in speed, the achievement of the critical speed (between the second and third seconds), and the exit to the steady-state. A diagram of a system for diagnosing defects in an electrical machine using a digital twin - a numerical model is proposed. Generator defects (mechanical and electromechanical) can be identified based on model data. Databases of defect signatures in a static mode and a diagnostic model, which contains algorithms for deciding on the presence of a defect, can serve as the basis of information for an operator to decide.

1. Introduction

The process of identifying defects in electrical machines in diagnostic systems is greatly simplified with the introduction of the so-called "digital twins" [1,2]. There are quite a few specific defects of condition that arise only in electric motors and generators of various types. The cause of the distortion of the parameters of electrical machines can be various internal electromagnetic defects, some specific features of the manifestation of electromagnetic processes in windings and cores, mechanical defects [3]. The eccentricity of the rotor can be the reason for the appearance in the spectrum of the current of harmonic oscillations, as well as the appearance of pulsating forces of electrical origin, creating vibrations and noise [4]. The eccentricity of the rotor has a serious impact on the quality of electrical energy. It leads to a distortion of the output parameters of the electric machine - current and voltage. And also has a negative impact on the performance of the electrical machine itself [5]. The paper shows the experience of modeling generator defects caused by eccentricity.
2. Generatorsimulation
A marine generator with a stator inner diameter $D_s=1.616$ m was selected as a generator model. The parameters were simulated using a finite element model presented in [6].

2.1. Staticmode
The study simulated the static mode for a rotor speed of 625 rpm. The result of the simulation are the time oscillograms of flux linkage, phase currents, and voltages, forces, and moments. Fig. 1 shows the magnetic field and direction vectors of the induced currents, and Fig. 2 shows a picture of changes in the magnetic field lines.

![Figure 1. The results of finite element modeling: a - the magnetic field of the generator; b - induced currents](image)

![Figure 2. Changing the magnetic force field](image)

Based on the simulation data, the frequency characteristics of a given generator in static operating modes can be obtained [6].

2.2. Analysis of dynamic modes.
To improve the quality of diagnostics of a time series, it is important to correctly determine the structure of the analyzed series. For this, the following are used: singular value decomposition, spectral analysis, wavelet transform, Hurst's method, fractal analysis and other methods [7,8]. It is known that the classical Fourier transform has several disadvantages in the study of signals, the periods, amplitudes, and phases of the harmonic components of which change with time.

An alternative to Fourier analysis is the windowed Fourier transform. Windowed Fourier Transform allows you to analyze either the high-frequency component or the low-frequency component, but not both. Therefore, an analysis method was chosen in which the width of the window function increased for low frequencies and decreased for high frequencies. The new window transformation was obtained because of stretching (shrinking) and shifting in time of one generating (so-called scaling function, scale) function. This generating function is called a wavelet.
Fourier analysis of a non-stationary process gives only information about whether the signal spectrum is broadband. In fig. 3 shows the results of studying the frequency-time characteristics of the voltage signal when starting the generator and reaching the stationary mode.

The light areas of the wavelet transform coefficients $C_a, b$ (Fig. 3, 4) show how the rotor speed increases. The analysis shows three frequency regions: the region of increasing speed, reaching the critical speed (between the second and third seconds, Fig. 4 a-c, 5), and the steady-state. The higher the wavelet transform coefficients (light areas on the scalogram), the more energy the frequency component of the series contains (Fig. 4 d).

In fig. 5 shows the decomposition of signal components. During the third second, there is a significant change in the signal, which cannot be determined by the original voltage signal.
Figure 4. Scalogram: (a) - phase A, (b) - phase B, (c) - phase C; and the surface of the generator voltage signal coefficients (d).

Figure 5. Decomposition at level 5: $s=a_5+d_5+d_4+d_3+d_2+d_1$
2.3. Simulation of generator defects.

Electric and magnetic loads in electrical machines depend on the size of the air gap between the rotor and stator. The influence on the quality of the network of a model defect - the eccentricity of the rotor - was investigated. The study produced the following types of rotor eccentricity (Fig. 6): a) mixed when the axis of rotation of the rotor RA does not coincide either with the axis of symmetry of the stator or with its axis of symmetry; b) dynamic, when the axis of rotation of the rotor RA coincides with the axis of symmetry of the stator and does not coincide with its axis of symmetry; c) static, when the axis of rotation of the rotor RA coincides with its axis of symmetry and does not coincide with the axis of symmetry of the stator.

![Figure 6. Generator eccentricity: (a) - mixed; (b) - dynamic; (c) - static](image)

The simulation results are shown in Fig. 7.

![Figure 7. (a) is the volumetric force acting on the rotor without eccentricity; (b) - force taking into account the action of static eccentricity, (c) - vibrations around an unbiased axis; (d) - vibrations around a displaced axis (mixed eccentricity)](image)

Fig. 7 shows the volumetric force without considering the effect of the defect. In the case of static eccentricity (Fig. 7, b), oscillations around an unbiased axis (Fig. 7, c) and oscillations around a...
displaced axis (Fig. 7, d), the oscillations have approximately the same amplitude. The imbalance of these forces acts on the bearings and supports of the electrical machine. The static eccentricity, in this case, shows mainly the shift of the static force, which is approximately equal to the shift of the dynamic part of the same amplitude [9].

The influence of the eccentricity of the generator can be estimated from the graph of the components of the force (Fig. 7d). This characteristic contains all the internal forces acting on the rotating parts. The radial portion of this internal force is compensated for when the rotor is balanced. The tangential part of this internal force creates torque. In general, this is the volumetric force acting on the rotor. But in the balanced configuration, this force is usually ignored. Instead, the study uses the magnitude of the rotor torque [7].

2.4. Identification of a defect in the spectrum of the generator signal using Fourier analysis.

The current and voltage spectrum is influenced by the nature and variation of the load. The results of the analysis of the signal spectrum can be used to construct a diagnostic system for generator defects to identify the signature of the defect (Fig. 8).

![Diagram of the generator defect diagnostics system](image_url)
The system controls and diagnostics of measurement data. Generator defects (mechanical and electromechanical) can be identified based on model data. Based on the database of defect signatures in the static mode and the diagnostic model, which contains algorithms for deciding on the presence of a defect, the information for the operator can be adjusted. The eccentricity of the rotor generates a series of harmonic components shifted by the same frequency step. Comparison of the spectra of voltages and currents is shown in Fig. 9, 10. Fig. 11 shows a frequency analysis of the components of the force vector $F_X$ without eccentricity (a) and with eccentricity (b). In fig. 12 – the same for the force component $F_Y$.

![Figure 9](image9.png)  
**Figure 9.** Comparative analysis of voltage spectra (X-axis - frequency, Y-axis - dB): a) without eccentricity; b) with eccentricity

![Figure 10](image10.png)  
**Figure 10.** Comparative analysis of current spectra (X-axis - frequency, Y-axis - dB): a) without eccentricity; b) with eccentricity

![Figure 11](image11.png)  
**Figure 11.** Frequency analysis of the components of the force vector $F_X$ (X-axis - frequency, Y-axis - dB): a) without eccentricity; b) with eccentricity
Comparative analysis of the spectra of currents and voltages (Fig. 9, 10) shows a change in the form of the spectrum at high frequencies, as well as a change in amplitude in magnitude.

Analysis of the graphs of the spectra of the force components (Fig. 11, 12) shows that the presence of the eccentricity of the rotor leads to the appearance of a harmonic component in the spectrum of the force of large amplitude with a maximum value at a low frequency. When eccentricity appears, the amplitude at low frequencies increases from 30 to 80 dB for FX strength and from 35 to 77 dB for FY strength. In the case of operation without a defect, the regular component is not visible in the force-frequency spectrum.

3. Conclusion

Using finite element modeling of a synchronous generator, time oscillograms of voltages and currents were obtained in the static mode and the generator start mode. Spectral analysis of the voltage signal at the output of the generator to the operating mode made it possible to identify the frequency regions corresponding to the phases of the signal change.

Simulation of generator defects three types of rotor eccentricity made it possible to identify the spectrum of defects in the design generator. Based on the proposed generator model, a diagnostic base of defects can be obtained for the proposed scheme of the diagnostic system.

The finite element model of the generator is scalable and allows you to change the design and physical parameters of the calculation, as well as identify other model defects of the electrical machine. These are, for example, inhomogeneity of the material of the elements, short circuit, phase failure. A computational experiment for these cases will adequately provide the functionality of the solution.

It should be noted that the results of such digital experiments should be compared with the passport data of the machine.

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