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Permanent magnet synchronous generators in a ship's shaft generator systems

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Abstract

Among the various methods for generating electricity on a ship, a shaft generator system is characterized by the highest energy and economic efficiency. The use of a Permanent Magnet Synchronous Generator (PMSG) in these systems, in comparison to classic synchronous generators, improves the ship's propulsion efficiency and the system's reliability. The problem of adjusting the PMSG's excitation and changing the speed of the generator's shaft can be solved by the use of modern power and electronic systems. This article presents a method for controlling the mechatronic system of a shaft generator with a PMSG, which enables stable operation to be achieved when changing the rotational speed of the shaft. Analytical and simulation studies were carried out and have enabled the boundaries of the area in which the PMSG can operate to be determined, while maintaining the required electrical power. The results have shown that the use of a PMSG instead of an EESG can increase the energy efficiency of the shaft generator system and increases the system's reliability.

Introduction

The dynamics of changing fuel costs and changing freight prices are why engineers are searching for technical solutions to increase ships' economy. One of the methods that can be used to reduce the costs of generating electricity on ships is to employ shaft generators; they were first installed on ships in the 1970s.

The main reason for the use of shaft generators in marine power plants is the lower specific fuel consumption of the low speed main propulsion engine in comparison to the medium-speed auxiliary engines. The shaft generator makes up approximately 5–10% of the main engine's power – depending on the type of ship. Load tests carried out on the generating sets of different types of ships have shown that their average load in the "sea travel" mode is approximately 50% (Tarnapowicz, 2020). Figure 1 presents a comparison of the specific fuel consumption factor for two engines: the main engine (ME) and the auxiliary engine – Diesel Generator (DG) and their operation points during "sea travel", based on data from the literature (Giernalczyk, 2014; Kristensen, 2015).

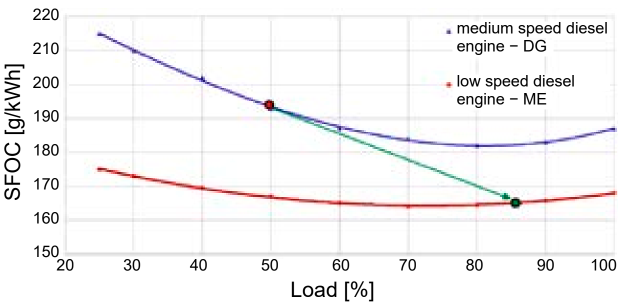

Figure 1. Comparison of specific fuel consumption for ME and DG and their operating points (based on Giernalczyk, 2014; Kristensen, 2015)

An analysis of the fuel consumption in the power plants of ships has shown that the cost of producing electricity using the DG units is approximately twice as high as the cost of a shaft generator 4 (Nicewicz & Tarnapowicz, 2011). These costs will change with both the type and price of the fuel used.

Other benefits of using shaft generators should be noted, which are:

- Lower consumption of lubricating oil for an ME compared to a DG;
- The interval of the periodic inspections and repairs of DG sets can be extended;
- Limited noise levels in the engine room (noise level of DG sets can exceed 100 dB);
- The possibility of conducting repairs and inspections of DG sets during the ship's explantation;
- In the case of underloading of the main engine, an additional load can be added by the shaft generator, and, in the case of bad weather conditions, it reduces the speed of the shaft;
- It is possible to use the generator in engine operation in both PTI mode (Power Take Input – hybrid propulsion of the ship) and in PTH mode (Power Take Home – emergency propulsion of the ship);
- Environmental reasons – the „Wet Stacking" phenomenon often occurs in the case of underloaded DG sets; this phenomenon results in increased air pollution (Tarnapowicz, 2010).

Despite their many advantages, shaft generators were not widely used when they were first introduced. Maintaining the high-quality of the electricity generated from the shaft generators was a big problem. This particularly involved maintaining a constant voltage frequency along with changes in the shaft's speed. This applied to ships with both a controllable pitch propeller and a fixed pitch propeller.

The rapid development of power and electronic technologies at the beginning of the 21st century resulted in the return of the concept of using shaft generators in shipbuilding.

Marine shaft generator with a PMSG

It is common in shipbuilding that an Electrically Excited Synchronous Generator (EESG) plays the role of a generator in autonomous generating sets.

The first shaft generator systems, with a power energy electronic converter to ensure a constant voltage frequency on the MSB, were based on thyristor converters (SCR), where the thyristor inverter is controlled by the grid voltage (external commutation); such solutions are still offered by some manufacturers. The thyristor inverter requires an additional electrical machine – a synchronous compensator, which is a source of reactive power. Additionally, the thyristor converter causes a large voltage distortion in the ship's network – therefore, the use of filters is required. The use of transistor converters has eliminated the disadvantages of the SCR converters (Tarnapowicz, 2010).

The increase in the efficiency of a ship's propulsion is connected with, among other things, the use of new technologies such as electric machines in the ship's power plants. One solution is to replace the EESG with a PMSG generator.

Compared to an EESG, a PMSG has the following advantages:

- Higher efficiency (especially when the generator is underloaded) primarily caused by the elimination of excitation losses (from 3 to 6% – depending on the load) (Jamieson, 2011);
- Thanks to the possibility of obtaining a large number of pole pairs, the PMSG's installation is carried out directly on the shaft of a low-speed motor. This eliminates the need to use a gear (losses from the gear –approximately. 2%, depending on the number of gear stages used) (Jamieson, 2011);
- High operational reliability and simple construction due to the lack of windings on the rotor and the lack of an exciter;
- Higher power density;
- Smaller lateral flow for the armature's impact causes reduced distortion of the magnetic field in the air gap of the machine;
- Lower weight and size;
- Low vibration level.

A PMSG has disadvantages that are not as significant or limited due to the development of the technology:

- The lack of a voltage regulator (AVR) – when using an energy electronic converter, this problem is not significant;
- Higher cost of a PMSG compared to an EESG – the main cost factors are permanent magnets that contain rare earths, the price of which has dropped significantly in recent years (The Switch, 2019);
- PMSGs are not produced on a large scale – due to the above-mentioned advantages, more and more manufacturers offer PMSGs with capacities up to several MW (e.g. ABB, The Switch).

Analytical tests of a marine shaft generator system with a PMSG

The mechatronic system of a marine shaft generator system with a PMSG is presented in Figure 2.

The basic element of the energy electronic converter system, which enables the accumulated electricity to be regulated and thus provides the ability

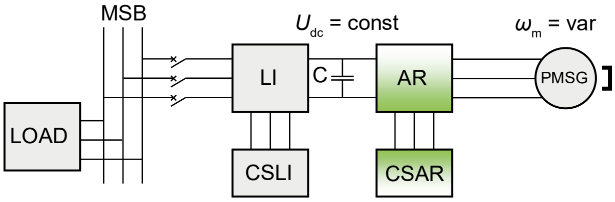

Figure 2. The functional diagram of a mechatronic PMSG-AR-LI system

to maintain constant voltage parameters in the network, is an active rectifier, AR, along with the SCAR control system. Assuming that the DC link voltage is constant then the CSLI control of the LI network inverter that is necessary to maintain constant voltage parameters in the MSBs can be known. Determination of the SG's working area is connected with the analysis of the circuit that is presented in Figure 3.

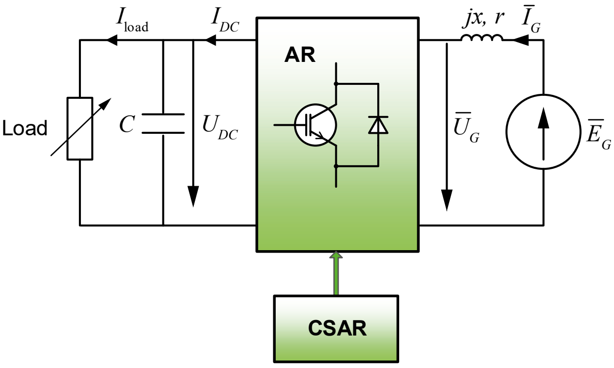

Figure 3. Equivalent circuit of the PMSG-AR- Load system

The mathematical description of the PMSG (Figure 3) implemented in a synchronously rotating coordinate system (x, y) with the use of the vector method can be presented in the following formula (Park, 1933):

$$\bar{E}_G(t) = \bar{U}_G(t) + L_G \frac{d\bar{I}_G(t)}{dt} + r_G \bar{I}_G(t) + jx_G \bar{I}_G(t) \quad (1)$$

where:
$\bar{E}_G(t) = j\bar{\psi}_0 \omega(t)$ – vector of the EMF induced in the stator windings,
$\bar{U}_G(t)$ – voltage vector on the PMSG's terminals,
$\bar{I}_G(t)$ – current vector of the stator windings,
r_G, L_G – resistance and inductance of the PMSG's windings,
$x_G = \omega L_G$ – reactance of the PMSG's windings.

In a quasi-steady state, equation (1) can be presented in the following way:

$$\bar{E}_G = \bar{U}_G + r_G \bar{I}_G + jx_G \bar{I}_G \quad (2)$$

For the purpose of energy analysis of the PMSG-AR-Load system (Figure 3) in a quasi-steady state, the vector quantities of the variables (2) are presented in a vector graph (Figure 4). The electromagnetic processes that occur in the PMSG are taken into account in the synchronously rotating coordinate system d, q, that is associated with the machine's construction (the d axis coincides with the flux vector), and the electromagnetic processes in the AR are connected with the voltage and current of the load that is taken into account in the synchronously rotating system of coordinates x, y.

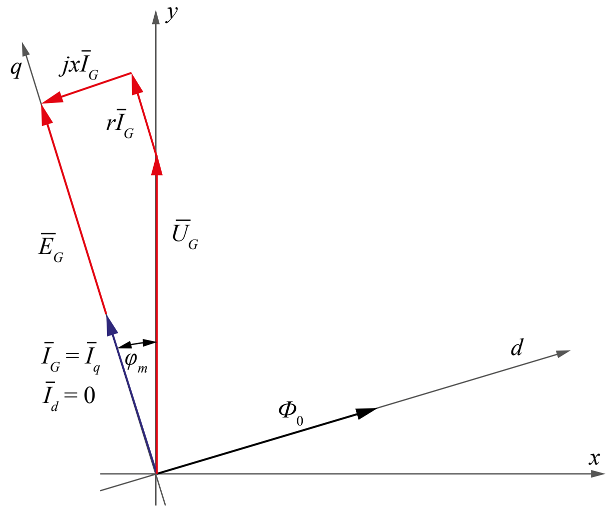

Figure 4. Vector diagram of the PMSG-AR-Load system

Set currents are implemented in the d, q axes and the reactive current component is $I_d = 0$. In this case, only active power is received from the PMSG ($I_q \neq 0$).

For energy analysis of the PMSG-AR-Load mechatronic system (Figure 3) in a steady state, the Kirchhoff equations and the energy balance equations in the d, q axes can be presented by the following equations (3) (Tarnapowicz, German Galkin & Jarlaczyński, 2019):

$$\begin{aligned} \frac{3}{2} E_q I_q &= U_{dc} I_{dc} + \frac{3}{2} r \left(I_d^2 + I_q^2\right) \\ I_L &= \frac{U_{dc}}{R} \\ \bar{E}_G &= p \omega_m \bar{\psi}_0 \end{aligned} \quad (3)$$

where:
m – modulation factor,
p – number of pole pairs,
j_m – phase shift angle between $\bar{U}_G$ and $\bar{E}_G$.

The equations (3) enable the electromagnetic and energy characteristics of the PMSG-AR-Load system in a steady state to be determined; this was taken into account when the determination of the stable working area of the PMSG-AR system was conducted (Tarnapowicz, German Galkin & Jarlaczyński, 2019):

$$
\begin{aligned}
&P = I_L^2 R = P_{dc} = \frac{U_{dc}^2}{R} \\
&P_G = \frac{3}{2} E_q I_q \\
&U_{dc} = \sqrt{R \cdot 1.5\left(E_q I_q - r I_q^2\right)} \\
&T_e = \frac{P_G}{\omega_m}
\end{aligned}
\tag{4}
$$

where T_e – electromagnetic moment.

The analysis was carried out for the PMSG; selected parameters are summarized in Table 1.

Table 1. The parameters of the PMSG used in the simulation

Parameters of the PMSG	Symbol	Unit	Size
Nominal electromagnetic torque	T_e	kNm	848
Nominal apparent power	S_n	MVA	2.24
Nominal phase voltage	U	V(rms)	398.4
Resistance of the armature winding	r_S	mΩ	0.821
Longitudinal armature induction	L_d	mH	1.573
Longitudinal armature induction	L_q	mH	1.573
Inductance of the armature winding	L_S	mH	1.6
Number of pole pairs	p	–	24

Figure 5 presents the results of the system operation tests with the permissible changes in the PMSG's shaft speed and load that are required in order to obtain stable operation of the PMSG-AR-Load system.

For an exemplary electrical receiving network (3 × 400 V), the DC link voltage should be maintained at a level of U_{dc} = 600 V. The test results presented in Figure 5 show that a PMSG-AR system with an active power load of approximately 1.8 MW will achieve stable operation; maintaining a constant voltage value (U_{dc} = 600 V) at a minimum speed of approximately 3 l/s – resulting in an electromagnetic moment at a level of about 2 × 10^5 Nm, and an active power load of 0.9 MW – at a minimum speed of approx. 1.5 1/s; resulting in an electromagnetic moment at a level of approximately 1 × 10^5 Nm.

Simulation tests of the marine shaft generator system with a PMSG

Simulation tests for the control system of a PMSG-AR system in a closed loop were carried out in the MATLAB – Simulink program. Figure 6 presents a diagram of the PMSG-AR-Load system implemented in the simulation tests.

According to the phasor (Figure 4), axis q coincides with vector E_G, and the active power is determined by the current I_q (I_d = 0). Stabilization of the U_{dc} DC link voltage at changes in the load takes place in the control system using the PID controller.

Figure 7 presents the U_{dc} voltage waveforms with reducing rotational speed ω until destabilization of the PMSG-AR-Load system's operation occurred. The active power load is P = 1.8 MW.

Figure 8 presents the U_{dc} voltage waveforms with reducing rotational speed ω until destabilization of the PMSG-AR-Load system's operation occurred. The active power load is P = 0.9 MW.

The results of the simulation tests (Figures 7 and 8), that determine the area of stability of the PMSG-AR-Load system operation, have confirmed the results of the analytical tests presented in the first part of this article (Figure 5). The holding time for the constant voltage (U_{dc}) when reducing the shaft speed for a load of 0.9 P_n (1.9 MW) is approximately 1 second shorter than that for a load of 0.45 P_n (0.9 MW). The results of the simulation tests confirmed that

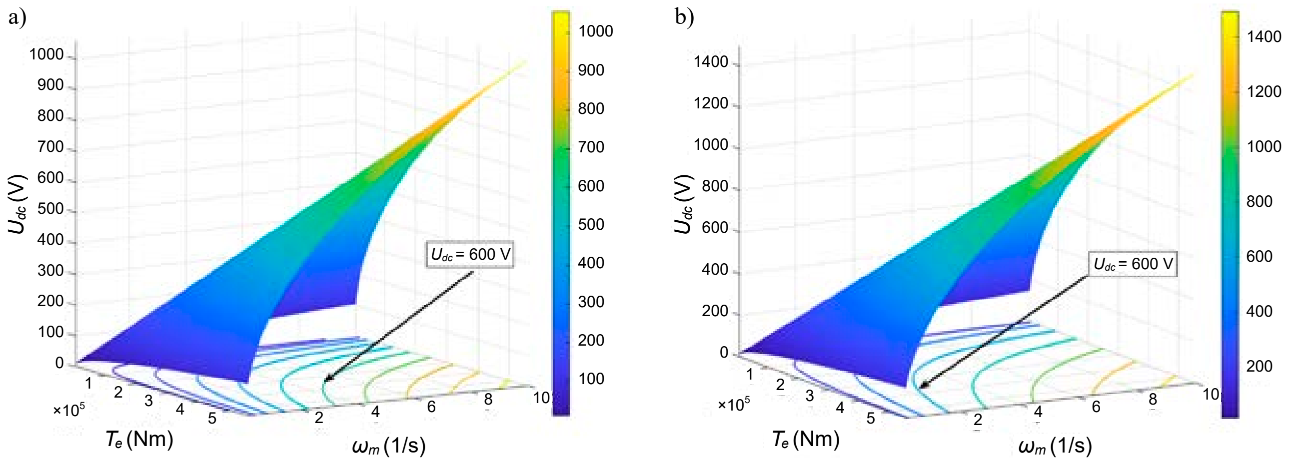

Figure 5. PMSG-AR-Load system stability diagram at 1.8 MW (a) and 0.9 MW (b) load

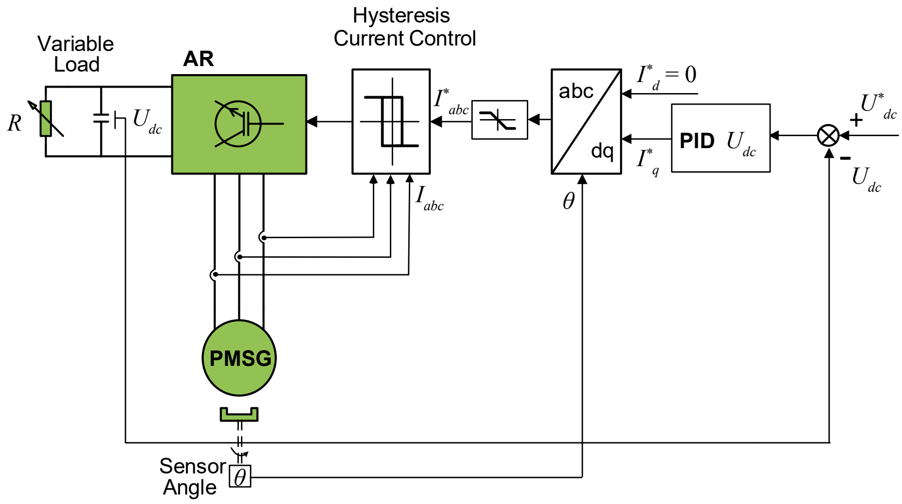

Figure 6. The PMSG-AR-Load system implemented in a simulation program

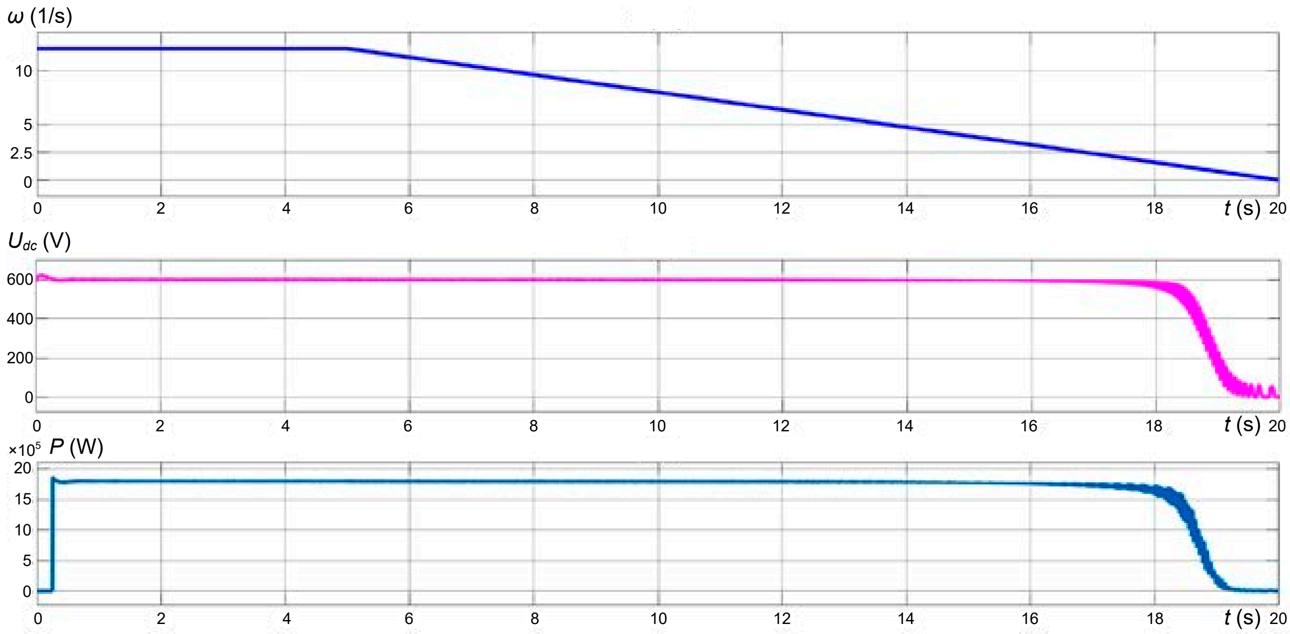

Figure 7. The DC link voltage (U_{dc}) and the active power *P* with reducing shaft speed *ω* in the case where load *P* = 1.8 MW

there is a wide area of stable operation of the system even with significant changes in the shaft's rotational speed. In real conditions, the time taken for the shaft speed to drop is much longer. For example, at the time of the occurrence of the main engine's "Shut Down", the revolutions per minute fall to zero after several minutes.

Conclusions

This article has shown that the use of shaft generators can increase the efficiency of a ship's propulsion, while reducing the overall operating costs. The results of this study have shown that the commonly used synchronous generators, with electromagnetic excitation (due to the technological development of electrical machines), can be successfully replaced by PMSGs. The use of a PMSG instead of an EESG can increase the energy efficiency of the shaft generator system and increases the system's reliability.

The results of the simulation tests of the PMSG-AR system show convergence with the results of the analytical calculations. In the simulation tests, the AR control method was confirmed in the analysis. Therefore, the selection of the last element of the energy and electronic mechatronic system (network inverter – LI) remains simple.

The presented analytical and simulation tests of the PMSG-AR-Load system, in a steady state, enabled the determination of the area of stability in which the generator can operate while maintaining the required electrical power.

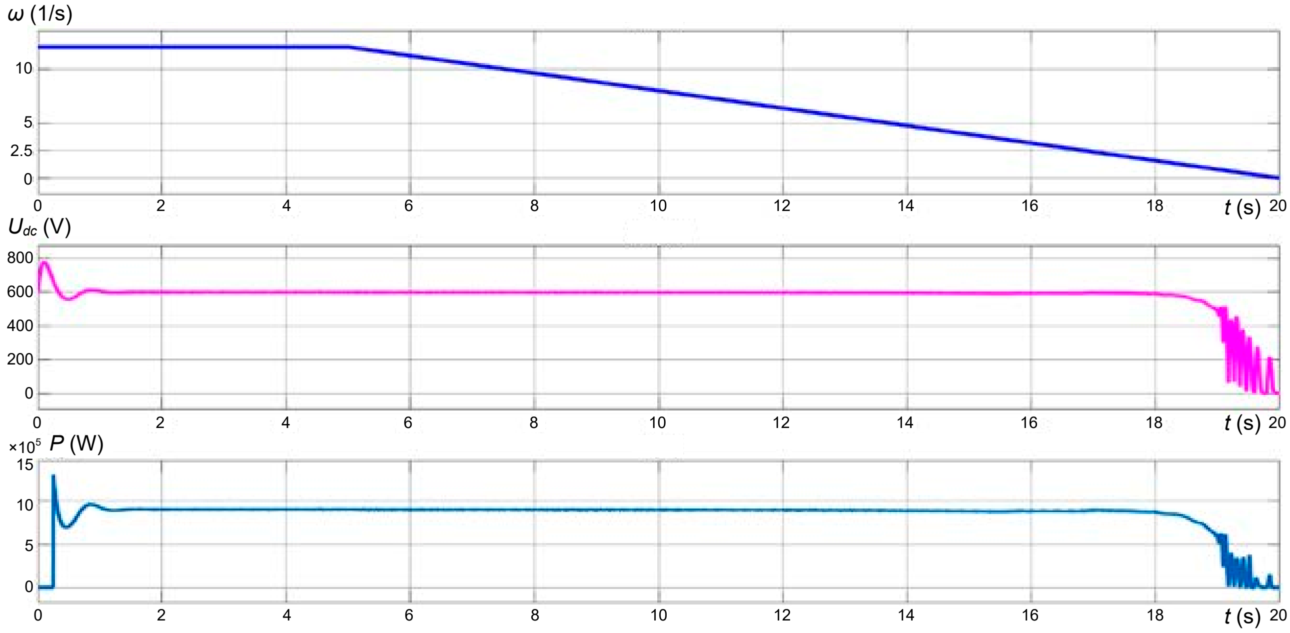

Figure 8. The DC link voltage (*U_{dc}*) and the active power *P* with reducing shaft speed *ω* in the case where load *P* = 0.9 MW

The results of tests show that the wide area of stable operation of the shaft generator system with a PMSG, enables the load to be taken over (uninterrupted) by Diesel-Generator generating sets in the event of a decrease in the shaft speed resulting from (for example) failure of the main engine.

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