Fuzzy Systems and Data Mining IX
A.J. Tallón-Ballesteros and R. Beltrán-Barba (Eds.)

doi:10.3233/FAIA231081

Research on Speed Control Strategy of Asynchronous Motor in Marine Electric Propulsion System

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Abstract. With the widespread application of new technologies and new equipment, due to the differences between ship power systems and land power systems, it is necessary to model and digitally simulate the ship electric propulsion system. This paper establishes a mathematical model of the ship's electric propulsion system, and uses Matlab to initially implement digital simulation of the system. The simulation adopts a hierarchical structure and modular design. Based on the slip frequency speed regulation control strategy, the motor speed, electromagnetic torque, three-phase current and dq-axis current of the asynchronous motor starting process and loading process are simulated and analyzed. Under two common working conditions, the speed change curve was simulated and verified using the slip frequency speed regulation control strategy and without using the control strategy. The examples proved the correctness of the simulation model and method.

Keywords. Marine electric propulsion system, Asynchronous motor, Speed control strategy

1. Introduction

Since the 1980s, the application of AC electric drive technology in ship propulsion systems has become a new development direction. Compared with land power systems, ship power systems using electric propulsion have some significant characteristics [1]: The power supply capacity and propulsion load of ship power systems are comparable, and their propulsion power usually accounts for 60% to 70% of the total power supply. [2], the complexity of ship operating conditions will directly affect the operation of ship power supply, and the interaction between the two places more stringent requirements on the coordination between control systems.

In order to study, calculate, and analyze these issues, it is necessary to provide a digital simulation tool that can reflect the static and dynamic performance of the ship's power system. In response to this, a lot of research has been done at home and abroad. Literature [3] proposed the PFM concept for frequency conversion speed regulation devices in ship power systems; Literature [4] used the simulation software EMTP to

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simulate the ship's electric propulsion system. Simulation research has been carried out; Literature [5-6] focuses on the research of propulsion motors and generators in ship power systems; Literature [7] uses Matlab software to conduct simulation research on ship propulsion devices. These works focus on Separate study of the motor speed control in the electric propulsion device and the separate study of the control effect of the generator set adjustment device lacks digital simulation research on the overall ship power system; although literature [8-9] has established separate power generation systems for diesel engine ship electric propulsion systems, and mathematical model of the load system, and simulated the generator terminal frequency and voltage. However, the load model only considered the static model and did not simulate the dynamic performance of the propulsion system.

The main work of this paper includes simulating ship propulsion performance under different steady-state operating conditions based on ship speed, mainly the rotation speed and torque of the propulsion shaft motor. And it refers to the simulation of ship maneuverability, that is, it can realize the simulation of dynamic processes such as the speed and torque of the propulsion motor when the ship's operating conditions change. An example was simulated using this system, and the results proved the correctness of the simulation model and method.

This paper consists of five parts. The first part is the introduction, which mainly introduces the development status and existing problems in the field of asynchronous motor control. The second part gives the overall architecture of Marine electric propulsion system and the modeling of analytical problems. The third part mainly introduces vector control theory and method and design of asynchronous motor slip frequency closed-loop speed regulation the system. The fourth part is mainly simulation verification analysis. These include simulation and verification of slip frequency closed-loop speed regulation system and comparative simulation analysis of the system typical working conditions. The fifth part summarizes the full text.

2. Ship electric propulsion system

2.1. Structure of ship electric propulsion system

This article uses this simulation system to simulate an example of a ship's power system. The main electrical wiring of this example is shown in the figure 1. The central power station of the system consists of 5 diesel generator sets, 4 of which are main generators with a power of 4400kW, and 1 is an auxiliary generator with a power of 1600kW. The AC propulsion system adopts AC-DC-AC frequency conversion, and the rectifier part adopts 12-pulse rectification. The main propulsion motor uses two 3000kW asynchronous motors, and the side propulsion motor uses three 2200kW asynchronous motors.

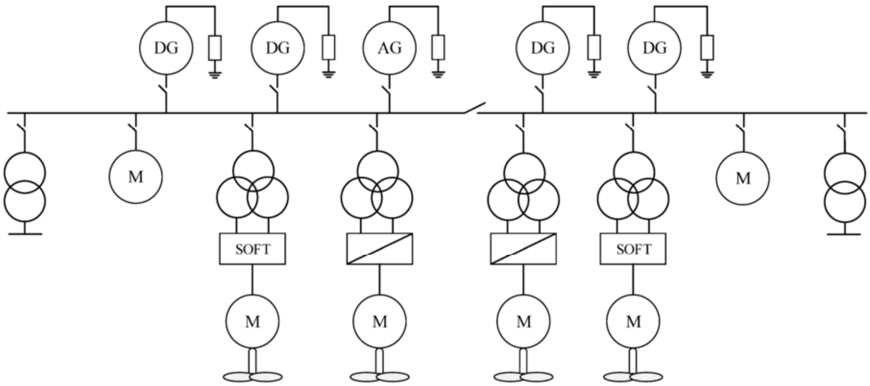

Figure 1. Electrical main wiring diagram of ship electric propulsion system.

2.2. Modeling of asynchronous propulsion motor and its speed control system

The propulsion motor in Marine integrated electric propulsion system is a high order, nonlinear and strongly coupled multivariable complex system. In order to simplify the analysis and calculation of the physical relationship inside the motor, some important simplifying assumptions are adopted in the establishment of the induction motor mathematical model. In this simplified model, we mainly consider the main physical characteristics of the motor, and introduce the following simplified assumptions: the core loss is ignored; The phenomenon of magnetic circuit saturation is ignored. The variation of winding resistance with temperature is ignored. Assume that the three-phase windings are symmetrically distributed. Based on these assumptions, we get a primitive asynchronous motor model, as shown in figure 2.

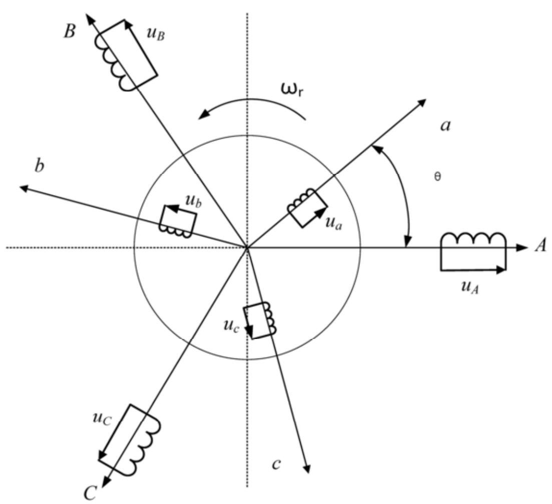

Figure 2. Original motor model of asynchronous motor.

The mutual coupling relationship matrix between the three-phase stator winding and the equivalent three-phase rotor winding of an asynchronous motor is:

$$\begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \\ \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} & L_{Aa} & L_{Ab} & L_{Ac} \\ L_{BA} & L_{BB} & L_{BC} & L_{Ba} & L_{Bb} & L_{Bc} \\ L_{CA} & L_{CB} & L_{CC} & L_{Ca} & L_{Cb} & L_{Cc} \\ L_{aA} & L_{aB} & L_{aC} & L_{aa} & L_{ab} & L_{ac} \\ L_{bA} & L_{bB} & L_{bC} & L_{ba} & L_{bb} & L_{bc} \\ L_{cA} & L_{cB} & L_{cC} & L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

where ψ_A, ψ_B and ψ_C are the stator three-phase winding flux, ψ_a, ψ_b and ψ_c are the rotor equivalent three-phase winding flux, i_A, i_B and i_C are the stator three-phase winding current, i_a, i_b and i_c are the rotor equivalent three-phase winding current, and L_{xy} is the three-phase inductance.

Convert the voltage equation of the propulsion motor to the $dq0$ rotation coordinate system:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ u_{rd} \\ u_{rq} \end{bmatrix} = \frac{d}{dt} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} + diag \begin{bmatrix} R_s \\ R_s \\ R_r \\ R_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} -\omega\psi_{sq} \\ \omega\psi_{sd} \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

where u is the voltage, i is the current; ψ is the magnetic linkage; r represents the rotor; s represents the stator. The flux linkage equation of an asynchronous motor is:

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \tag{3}$$

where L_r is the three-phase equivalent rotor winding self-inductance; L_s is the motor stator winding self-inductance; L_m is the motor stator and rotor winding mutual inductance. The electromagnetic torque and rotor motion equations are:

$$\begin{aligned} T_e &= n_p L_m (i_{sq} i_{rd} - i_{rq} i_{sd}) \\ \frac{d\omega}{dt} &= \frac{n_p}{J_1}(T_e - T_L - B\omega) \end{aligned} \tag{4}$$

where T_L is the load resistance torque; J_1 is the rotor inertia of the asynchronous motor; n_p is the number of pole pairs of the asynchronous motor; B is the friction coefficient.

3. Asynchronous motor control technology for ship electric propulsion system

3.1. Vector control theory and method

Vector control is currently a relatively advanced control method in the field of asynchronous motor control. Usually, AC motor control methods containing vector transformation are called vector control. The principle of vector transformation and the equivalent DC motor model are shown in the figure 3.

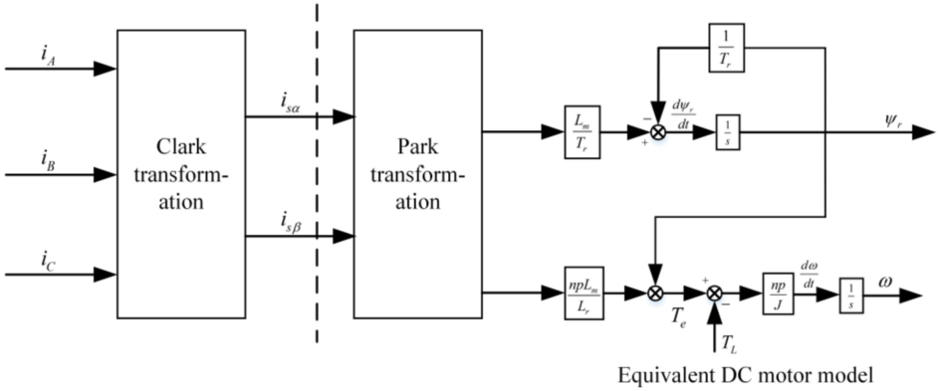

Figure 3. Principle of vector transformation and equivalent DC motor model.

3.2. Design of asynchronous motor slip frequency closed-loop speed regulation system

To solve the torque control problem of AC asynchronous motor, it can be achieved by controlling the slip frequency. The basic idea of the scheme is to realize the torque control problem of the asynchronous motor and improve the stability of the bus voltage by controlling the slip frequency. The figure 4 below is a schematic block diagram of an asynchronous motor vector control speed regulation system with speed closed-loop slip frequency control.

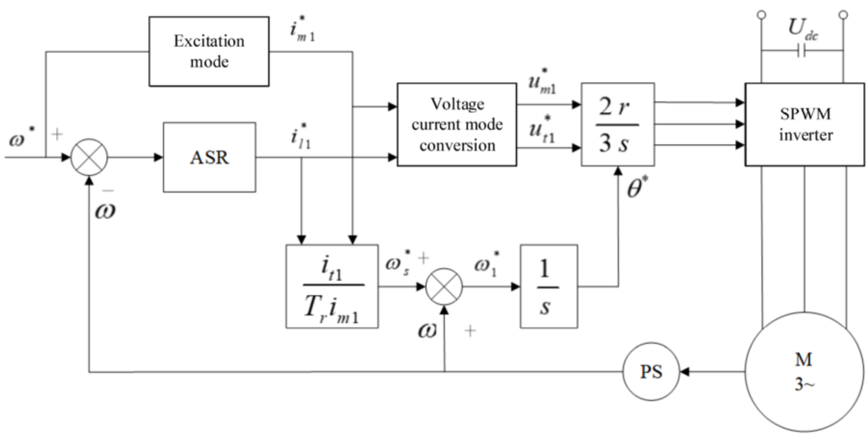

Figure 4. Principle block diagram of the vector control speed system of speed closed-loop slip frequency.

The main circuit of the speed control system is a SPWM voltage-type inverter, which is the circuit topology generally used in general-purpose frequency converters. For asynchronous motor speed control, the slip frequency control method is selected as follows:

$$\omega_1 = \omega + \omega_s \tag{5}$$

Among them: ω_s is the slip angular frequency; ω is the angular frequency of the rotor; ω_1 is the stator angular frequency of the asynchronous motor.

According to this formula, during the adjustment process of the motor speed, the stator current frequency of the AC asynchronous motor and the actual rotor speed can rise or fall synchronously from beginning to end, so that the speed can be adjusted smoothly.

The vector control equation of an asynchronous motor can be described as:

$$T_e = n_P \frac{L_m}{L_r} i_{st} \Psi_r \tag{6}$$

$$\omega_s = n_P \frac{L_m i_{st}}{T_r \Psi_r} \tag{7}$$

$$\Psi_r = n_P \frac{L_m}{T_r p + 1} i_{sm} \tag{8}$$

where n_P is the number of pole pairs; i_{st} is the torque component of the stator current; i_{sm} is the excitation component of the stator current; Ψ_r is the rotor flux linkage of the motor; T_r is the rotor electromagnetic time constant, $T_r = L_m / R_r$, L_m is the same in the two-phase coordinate system The mutual inductance between the stator and rotor windings, R_r is the resistance value of the rotor one-phase winding.

It can be concluded from the vector control equation of the asynchronous motor that if Ψ_r is kept unchanged, T_e will be directly controlled by i_{st}, and the slip angular frequency ω_s can also be directly obtained from i_{st}, and Ψ_r can be obtained from i_{sm}. In the vector control speed regulation system of AC asynchronous motor with speed closed-loop slip frequency control, the speed regulator (ASR) adopts PI (proportional integral) control mode, and the output signal of PI is the given value of the stator current torque component. From this, the given value of slip frequency ω_{s1}^* can be obtained. During the control and adjustment process, if the magnetic flux is kept at a constant value, then $p\Psi_r = 0$. It can be seen from Eq.8 that,

$$\Psi_r = L_m i_{sm} \tag{9}$$

According to Eq.7, it can be obtained:

$$\omega_s = \frac{i_{st}}{T_r i_{sm}} \tag{10}$$

4. Simulation verification and analysis

4.1. Simulation and verification of slip frequency closed-loop speed regulation system

In order to observe the dynamic adjustment process of the system more directly, the step signal n^* is used to set the given speed value in the simulation model of the slip frequency closed-loop speed regulation system, so that the dynamic operation of the speed regulation system at different given speed values can be observed.

First, verify the simulation analysis of the stability performance of the whole system of the closed-loop speed regulation system with slip frequency. The simulation time is set as 1s, the given speed of the propulsion motor is n=200r/min, the load torque of the motor when starting is TL=25000N·m, and the load torque is abruptly increased to the rated torque of the motor TL=48800N·m when it runs to 0.5s. The simulation results are shown in the figure 5-8 below.

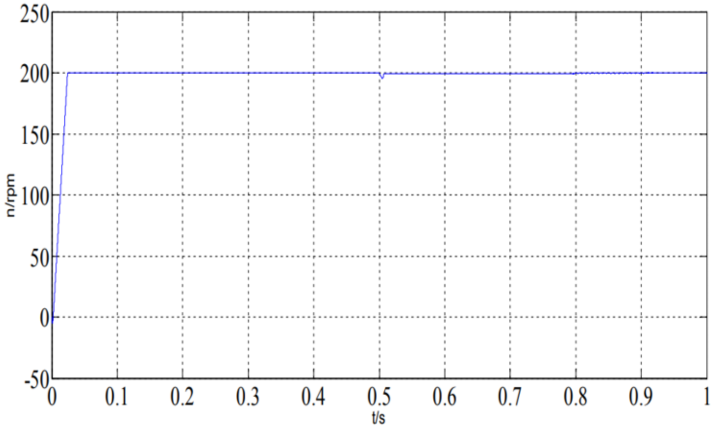

Figure 5. Motor speed simulation waveform.

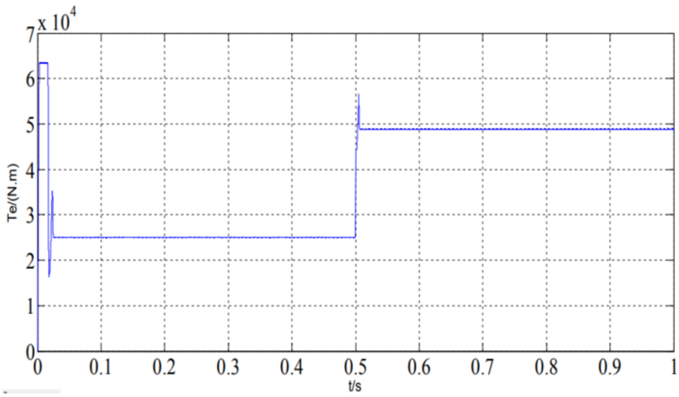

Figure 6. Motor electromagnetic torque simulation waveform.

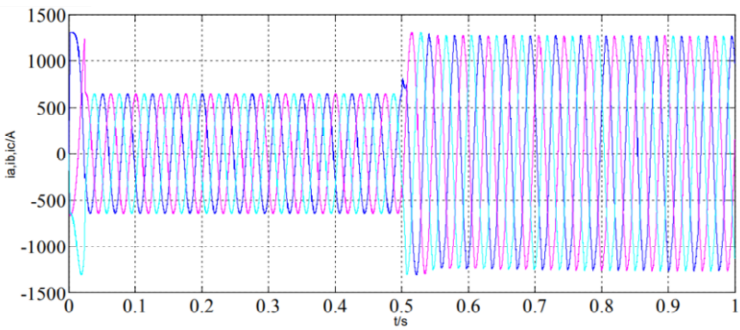

Figure 7. Motor stator three-phase current simulation waveform.

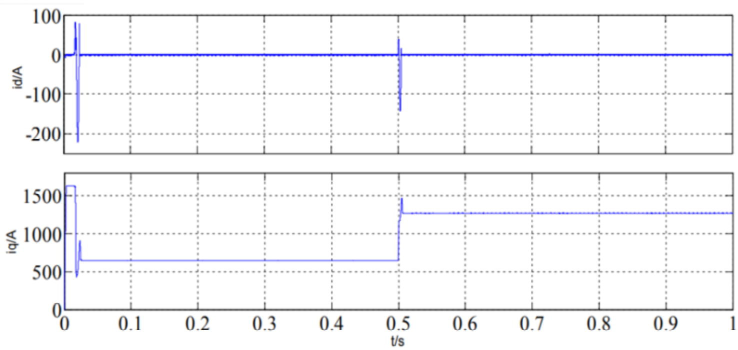

Figure 8. Motor dq axis current simulation waveforms.

Figure 5 shows the speed adjustment waveform. From the figure, we can see the starting, steady speed and loading process of the motor. The speed gradually rises from zero to 200r/min and remains stable. When running to 0.5s, the load torque is suddenly added to the motor. rated torque. Figures 6 to 8 show the motor electromagnetic torque simulation waveforms, three-phase stator current simulation waveforms, and d and q-axis current simulation waveforms respectively. It can be seen from the figure that the current and torque are relatively large during the starting stage. The motor starts with a given maximum current. After 0.5s of loading, the electromagnetic torque and armature current increase, and the torque and current also increase. corresponding fluctuations.

4.2. Comparative simulation analysis of typical working conditions

Compared with traditional control methods, the above-mentioned slip frequency closed-loop speed control system has a more superior speed control effect. The impact of high maneuverability indicators on the system response characteristics under cruising conditions and full-speed sailing conditions is analyzed, and the propulsion force and speed of the ship are controlled by adjusting the motor speed.

Calculate the dynamic adjustment accuracy and action response time of the main propulsion motor before and after using slip frequency control under the two working conditions, as shown in the following table 1.

Table 1. Comparison table of high mobility indicators before and after adopting slip frequency control strategy under different working conditions

Dynamic adjustment accuracy	Different working conditions	Before use	After use	Optimization and improvement
	Cruise condition	1.13%	1.04%	0.09%
	Full speed sailing condition	1.14%	1.11%	0.03%
Action response time	Different working conditions	Before use	After use	Optimization and improvement
	Cruise condition	18.3s	17.6s	0.7s
	Full speed sailing condition	18.8s	17.8s	1s

Based on the above calculation results, in order to further analyze the influence of slip frequency control strategy on asynchronous motor control, we drew three results through simulation: expected speed curve, asynchronous motor speed curve with slip frequency control strategy and asynchronous motor speed curve without slip frequency control strategy, as shown in the figure 9 and 10 below.

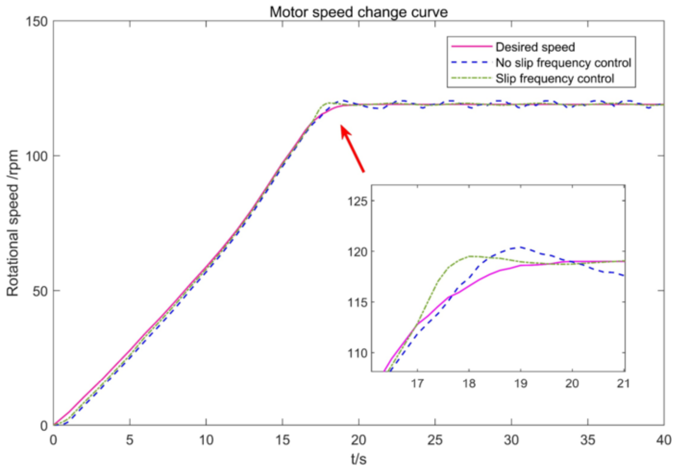

Figure 9. Motor speed variation curve during cruising condition.

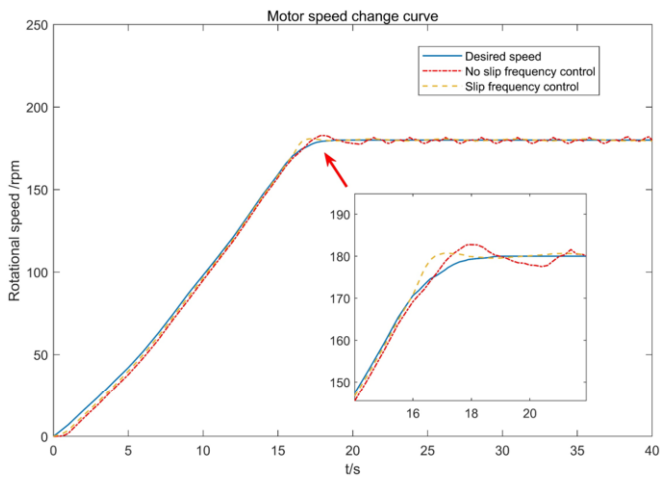

Figure 10. Motor speed change curve under full speed sailing condition.

Therefore, the use of slip frequency control strategy can help improve the flexibility and safety of ship operation, and at the same time, it can achieve smooth control of the main propulsion motor, avoid sudden changes and fluctuations in propulsion force, and reduce vibration and vibration of the hull.

5. Conclusion

In view of the differences between ship electric propulsion systems and land power systems and the rapid development of ship power systems, this article gives a mathematical model of the key parts of the ship electric propulsion system and uses Matlab to realize the digital simulation of the ship electric propulsion system. The simulation research of the example system shows that the mathematical model and digital simulation system established in this article can effectively simulate the steady-state and dynamic performance of the ship's power system.

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