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MOTOR CONDITIONS MODELING OF ASYNCHRONIZED SYNCHRONOUS SHAFT GENERATOR IN CONTROLLABLE PITCH PROPELLER SHIPS

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Abstract- The motor conditions of the Asynchronized Synchronous Shaft Generator (ASSG) mounted in controllable-pitch propeller ships are studied in the paper. ASSG, as a propulsion motor, can provide the ship's movement in the main motor (MM) emergency mode, and also work together with the MM to provide the increase of the speed of the ship. It was also noted that the synchronous shaft generator on noncontrollable-pitch propeller ships can be easily started as a squirrel-cage induction motor by means of a powerful semiconductor frequency converter installed at its output and a damping coil on its rotor. Currently, synchronous generators are used as shaft generators on controllable-pitch propeller ships, and due to the complexity of commissioning, the motor conditions are not provided for them. This is explained by the fact that to start a synchronous machine in the motor conditions, attentionally the starting induction motor, starting equipment connecting the shaft of the synchronous shaft generator with a gearbox and an electromagnetic coupling shall be provided. It is noted that, unlike the synchronous shaft generator on ships of this type, the ASSG is easily started as a phase-rotor induction motor by adding a three-phase starting resistor to the rotor circuit. Also, the phase-rotor induction motor (PRIM), considered as a sample, was modeled using "Simulink", being a "visual-block simulation modeling package" included in MATLAB and specified for the modeling of dynamic systems.

Keywords: Shift Generator, Asynchronized Synchronous Generators, Electromotor, Starting Resistance, Mode of Work, Screw of Regulated Ride.

1. INTRODUCTION

One of the main advantages of the shaft generator unit is that it can work under motor conditions. Usually, the power of shaft generators for ships of 8000÷12000 tons displacement is 500 kW. At that, the total power of the ship's power module is approximately 700÷800 kW. Considering that the starting current of the induction motor is 4÷6 times higher than the rated one, starting of shaft generator as an electric motor creates certain difficulties. It should be noted that this problem is solved differently in noncontrollable-pitch propeller ships and controllable-pitch propeller ships [5].

It is known that in order to stabilize the frequency of the energy produced in the shaft-generators on the noncontrollable-pitch propeller ships, a large powerful frequency converter is installed at its output. By means of this frequency converter, the starting of the synchronous generator as a squirrel-cage induction motor is easily performed [6]. After start-up, direct current is supplied to the excitation winding and the shaft generator operates as a synchronous motor. To perform such a start-up, synchronous generators in noncontrollable-pitch propeller ships must have a damper winding on the rotor and the frequency converter at the output must be able to operate in reverse mode.

The lack of a large-power frequency converter at the output of synchronous generator's shaft generator units, which are currently used in controllable-pitch propeller ships, makes it impossible to operate these generators in motor conditions. The start-up of the synchronous motor up to the specified speed can also be performed by means of an auxiliary asynchronous motor, which is connected to the shaft of the shaft generator unit by means of reducer or coupling during start-up. In this starting method, the large power asynchronous motor is rarely used in ships because of the availability of additional equipment such as reducer and splitter box [5].

2. MAIN PART

An asynchronized synchronous motor (ASM) is a phase-rotor induction motor with a symmetrical two- or three-phase excitation winding. It is known that during the application of the asynchronized synchronous shaft generator in controllable-pitch propeller ships, if the load of the MM decreases, by changing the angle of rotation of the controllable-pitch propellers, the efficiency of the power module can be slightly increased [2].

During operation of the ASSG in the generator mode, the voltage at the output of the generator is maintained constant at the expense of changing the excitation current in the rotor winding, and the frequency of the generated energy is kept constant due to adjusting the frequency of the rotor current. Unlike synchronous shaft generator units, ASSGs, which have recently been introduced in the controllable-pitch propeller ships, can be commissioned as easily as PRIMs. Additional equipment required for starting the motor is a three-phase starting resistor and starter controls.

It should be noted that due to certain difficulties in starting the synchronous machine as an electric motor, the 80-90% of motor conditions are not provided for the synchronous shaft generators of the controllable-pitch propeller ships. For example, in the Azerbaijan Republic, of controllable-pitch propeller ships with synchronous shaft generator only in one propeller liquid cargo carrier, the motor conditions are provided, with the synchronous shaft generator being started by means of the auxiliary asynchronous motor [5].

Taking into account that currently certain ship classification societies require for certain types of ships (liquid, gas, passenger and travel) to have an additional propulsion complex that ensures the emergency movement of the ship at the time of MM failure. A shaft generator unit (SGU) can be used as an emergency propulsion complex [2]. Knowing that during the application of ASSG as a synchronous shaft generator in the controllable-pitch propeller ships, an additional economic efficiency is obtained and the motor conditions of the SGU are provided, in ships with the controllable-pitch propeller synchronous SGU in operation, the rotor winding of the synchronous shaft generator can be replaced with a three-phase winding. The frequency converter for the three-phase rotor winding can be selected from catalog, provided that it varies within 15% of the output frequency of the asynchronized synchronous machine.

3. STARTING OF ASSG AS PRIM USING REMOVAL

The following simple graph-analytical method was used to calculate the starting of ASSG as PRIM and starting resistance. In order to determine the values of the resistances of the individual steps of the starter rheostat of the asynchronous motor, its mechanical characteristics should be established. During operation, electromagnetic power is transferred to the rotor of the asynchronous motor through the magnetic field [3, 4]:

$$P = M_e \times \omega_0 = m_1 I_2'^{\,2} \frac{C_1 r_2'}{S} \tag{1}$$

Motor slip at idle is S=0, C_1=1.03÷1.08, so, we take C_1=1. We get the expression for the electromagnetic moment from the Equation (1).

$$M_e = \frac{3 I_2'^{\,2} \frac{r_2'}{S}}{\omega_0} \tag{2}$$

Transposed expression of rotor phase current [1]:

$$I_2' = \frac{U_f}{\sqrt{\left(r_1 + \frac{r_2'}{S}\right)^2 + X_k^2}} \tag{3}$$

where, $X_k = X_1 + X_2'$ is an inductive reactance of the short-circuited phase of the induction motor.

If in Equation (3) we substitute the transposed current expression from Equation (2), we'll obtain the formula for the mechanical characteristic of the induction motor:

$$M = \frac{3 r_2' \times U_f^2}{S\omega_0 \left[(r_1 + \frac{r_2'}{S})^2 + X_k^2 \right]} \tag{4}$$

$$S_{kr} = \pm \frac{r_2'}{\sqrt{r_1^2 + X_k^2}} \tag{5}$$

It should be noted that only the upper part of the mechanical characteristic of the asynchronous motor (S=0÷S_{kr}) is used when determining the steps of the starter rheostat [1]. Asynchronized synchronous machines have been recently used in shaft generators of ships, and there is no enough information about their parameters in references. Therefore, for example, we used a phase rotor induction motor whose parameters are shown below:

Motor type:	MTH713-10
Rated power:	P_n=200 kVt
Rated rotation speed:	n_n=582 rpm
Phase voltage:	U_f=220 V

Maximum torque-rated torque relationship: $\frac{M_{\max}}{M_{nom}} = 2.3$

Active resistance of the stator winding: r_1=0.0135 Ω
Inductive resistance of stator winding: x_1=0.0438 Ω
Active resistance of the rotor winding: r_2=0.021 Ω
Inductive resistance of rotor winding: x_2=0.109 Ω
Transformation coefficient between rotor and stator windings: k_e=0.78

Let's determine the rated and maximum torques of the motor:

$$M_{nom} = \frac{975 \times P_n}{n_n} \times 9.81 = \frac{975 \times 200}{582} = 3287 \text{ Nm}$$

$$M_{mak} = \lambda \times M_n = 2.3 \times 3287 = 7560 \text{ Nm}$$

and the motor's rated slip:

$$S_{nom} = \frac{n_0 - n_n}{n_0} = \frac{600 - 582}{600} = 0.03$$

To establish the mechanical characteristics of the induction motor, the parameters of its rotor transferred to the stator are used [5].

That is: $I_2' = \frac{i_2}{k_e}$;

$$r_2' = k_e^2 \times r_2 = 0.78^2 \times 0.021 = 0.013 \text{ Ohm}$$

$$x_2' = k_e^2 \times x_2 = 0.78^2 \times 0.109 = 0.066 \text{ Ohm}$$

Let's find the motor's critical slip according to the Equation (6) based on the obtained values of r_2' and x_2' :

$$S_{kr} = \frac{r_2'}{\sqrt{r_1^2 + X_k^2}} = \frac{0.013}{\sqrt{0.0135^2 + 0.1098^2}} = 0.12$$

If we substitute the values r_2', U_f, ω_0, r_1 and X_k in Equation (4), we can establish the mechanical characteristic of the motor.

$$M = \frac{3r_2' \times U_f^2}{S\omega_0\left[\left(r_1 + \frac{r_2'}{S}\right)^2 + X_k^2\right]} = \tag{6}$$

$$= \frac{3 \times 0.013 \times 220^2}{S \cdot 62.8\left[\left(0.0135 + \frac{0.013}{S}\right)^2 + 0.1104^2\right]}$$

Changing the slip value from 0 to 1, we obtain the *M=f*(*S*) characteristic and use the below equation to obtain the $M=f(\omega)$ mechanical characteristic relationship.

$$\omega = \omega_0\left(1 - S\right) \tag{7}$$

$$\omega_0 = \frac{\pi \times n_0}{30} = \frac{3.14 \times 600}{30} = 62.8 \text{ r/s}$$

It is known that in the MATLAB/Simulink environment the modeling of the given control objects in the form of various models is possible [7]. Using the Equations (6) and (7) in the MATLAB/Simulink environment, the calculation model of the natural mechanical characteristic of the MTH713-10 type PRIM was constructed in Figure 1.

The results of calculations performed using Equations (6) and (7) are shown in Table 1.

Table 1. The results of calculations

S	0	0.03	0.05	0.1	0.12	0.15	0.2	0.4	0.6	0.8	1
M (Nm)	0	4731	6909	9168	9267	9014	8186	5249	3728	2871	2330
ω (r/s)	62.8	61	60	56	55	53	50	38	25	13	0

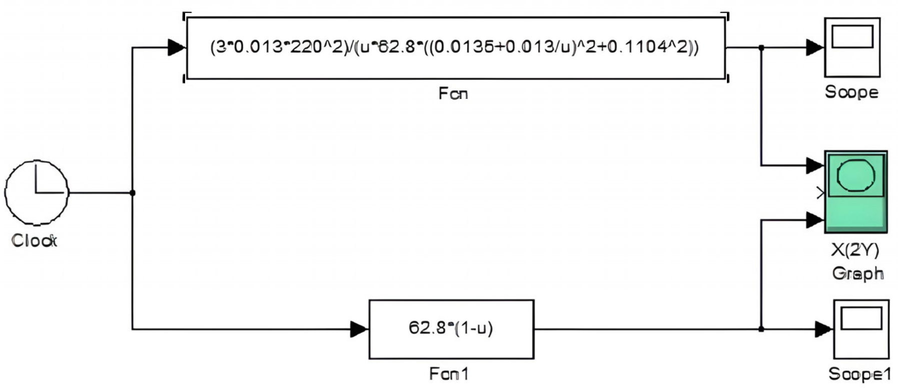


Figure 1. Calculation model of $M=f(\omega)$ natural mechanical characteristic of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment

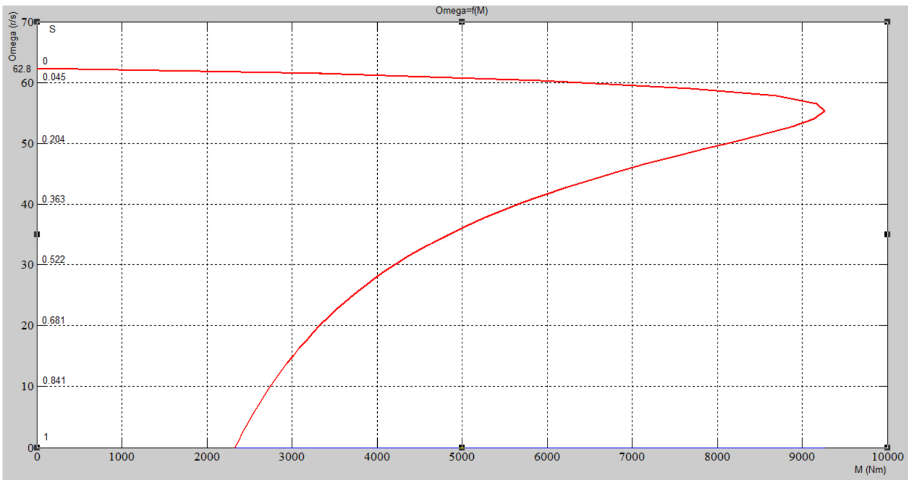


Figure 2. $M=f(\omega)$ natural mechanical characteristic of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment

Also, the curve representing the natural mechanical characteristic of MTH713-10 type PRIM is constructed in MATLAB/Simulink environment in Figure 2. As can be seen from Figure 2 and Table 1, the calculated starting torque ($M_{calc.start}$ = 2330 Nm) is less than the rated torque, which should be greater than the rated value for this type of motor. The resistance connected to the rotor circuit usually has 3 or 4 steps. The main purpose of connecting these resistances is to reduce the starting current of the motor and change the rotation speed when necessary.

The starting resistance can be calculated by the graph-analytical method as follows (Figure 3):

1. The starting torque value should not be more than $0.8 \times M_{mak}$. Usually, the starting torque value is taken $M_{calc.start} = (1.5 \div 2.2) \times M_n$.

$M_{calc.start} = 1.75 \times 3287 = 5750$ Nm

The value of the torque of removal of resistances from the circuit is taken $M_r = (1.1 \div 1.2) \times M_n$.

$$M_r = 1.11 \times 3287 = 3650 \text{ Nm}$$

2. We indicate $M_{calc.start}$ and M_r torque values and $S=f(M)$ characteristic on the torque axis (Figure 3);
3. We drop a perpendicular to the line S=0 and mark these points with "m" and "n", respectively.
4. We mark the points intersecting with the cm and en lines of natural characteristic with "b" and "a" respectively, and draw a straight line passing through these points. Let's mark the points of that straight line intersecting with the line S=0 with "t";
5. Dividing of the starting resistance into steps:

The point "t" is connected to the point "e" located on the S=1 line (the torque axis), and from the point where this line intersects with [cm], we drop a perpendicular from the point "q" [en], and mark that point with "z". Then point "z" is connected again with point "t" and the process is continued as shown below.

The calculation of the steps of resistance connected to the rotor circuit was performed in the following sequence. The motor slip is determined by the active resistance of the rotor circuit. At the same time, the slip depends on the mechanical characteristic curve, that is, the distance from the ω=0 line to the characteristic curve. The number of steps is determined based on the commissioning diagram, which is 4 in our case. The proportional dependence of the slip on the transposed resistance value in the rotor circuit determines the number of resistances, according to which the mechanical characteristic is constructed.

$$an \equiv r_2' \quad \text{and} \quad ad \equiv r_{b.4}' \qquad (8)$$

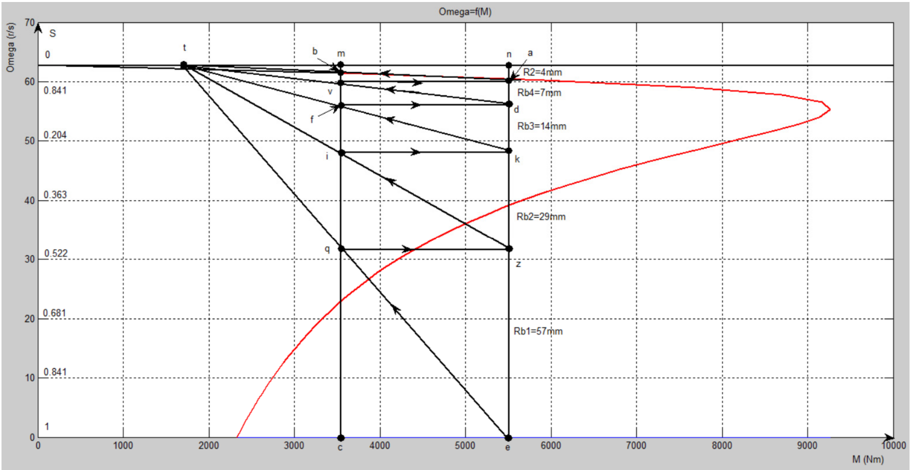


Figure 3. $M=f(\omega)$ artificial mechanical characteristic of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment

In this case, we can replace the slip by the same distance and write the transposed expressions for the steps of the starting resistance according to Equation (8):

$$\frac{r_{b.4}'}{r_2'} = \frac{ad}{an} \quad \text{from here} \quad r_{b.4}' = r_2' \frac{ad}{an}$$

$$\frac{r_{b.3}'}{r_2'} = \frac{dk}{an} \quad \text{from here} \quad r_{b.3}' = r_2' \frac{dk}{an}$$

$$\frac{r_{b.2}'}{r_2'} = \frac{kz}{an} \quad \text{from here} \quad r_{b.2}' = r_2' \frac{kz}{an}$$

$$\frac{r_{b.1}'}{r_2'} = \frac{ze}{an} \quad \text{from here} \quad r_{b.1}' = r_2' \frac{ze}{an}$$

Knowing the value of the active resistance of the rotor winding transposed to the stator, the (r_2') distances are measured and their values are written in the proportionality equation shown above, and the transposed expressions of the resistances of the individual steps are determined:

$$r_{b.4}' = r_2' \frac{ad}{an} = 0.013 \frac{7}{4} = 0.023 \ \text{Ohm}$$

$$r_{b.3}' = r_2' \frac{dk}{an} = 0.013 \frac{14}{4} = 0.045 \ \text{Ohm}$$

$$r_{b.2}' = r_2' \frac{kz}{an} = 0.013 \frac{29}{4} = 0.094 \ \text{Ohm}$$

$$r_{b.1}' = r_2' \frac{ze}{an} = 0.013 \frac{57}{4} = 0.185 \ \text{Ohm}$$

The total transposed value of the starting resistances connected to the rotor circuit:

$$r_{b.um}' = r_{b.1}' + r_{b.2}' + r_{b.3}' + r_{b.4}' = 0.347 \ \text{Ohm}$$

In order to construct the artificial mechanical characteristics of starting process of the MTH713-10 type PRIM in MATLAB/Simulink environment, the calculation models are put together in Figure 4.

The artificial mechanical characteristics of the starting process of the PRIM by means of calculation models compiled in the MATLAB/Simulink environment are constructed in Figure 5.

Also, in order to construct the velocity characteristics $\omega = f(I_2)$ of the MTH713-10 type PRIM in the MATLAB/Simulink environment, the calculation models are put together in Figure 6.

In Figure 7, the $\omega = f(I_2)$ velocity characteristics of the PRIM are constructed by means of calculation models compiled in the MATLAB/Simulink environment. From the characteristics, it is possible to analyze the currents generated by the rotor according to the resistances connected to the rotor circuit during starting. As it can be seen from the velocity characteristics, as the resistances in the rotor of the PRIM are removed during the start-up, the current strengths generated in rotor decreases accordingly.

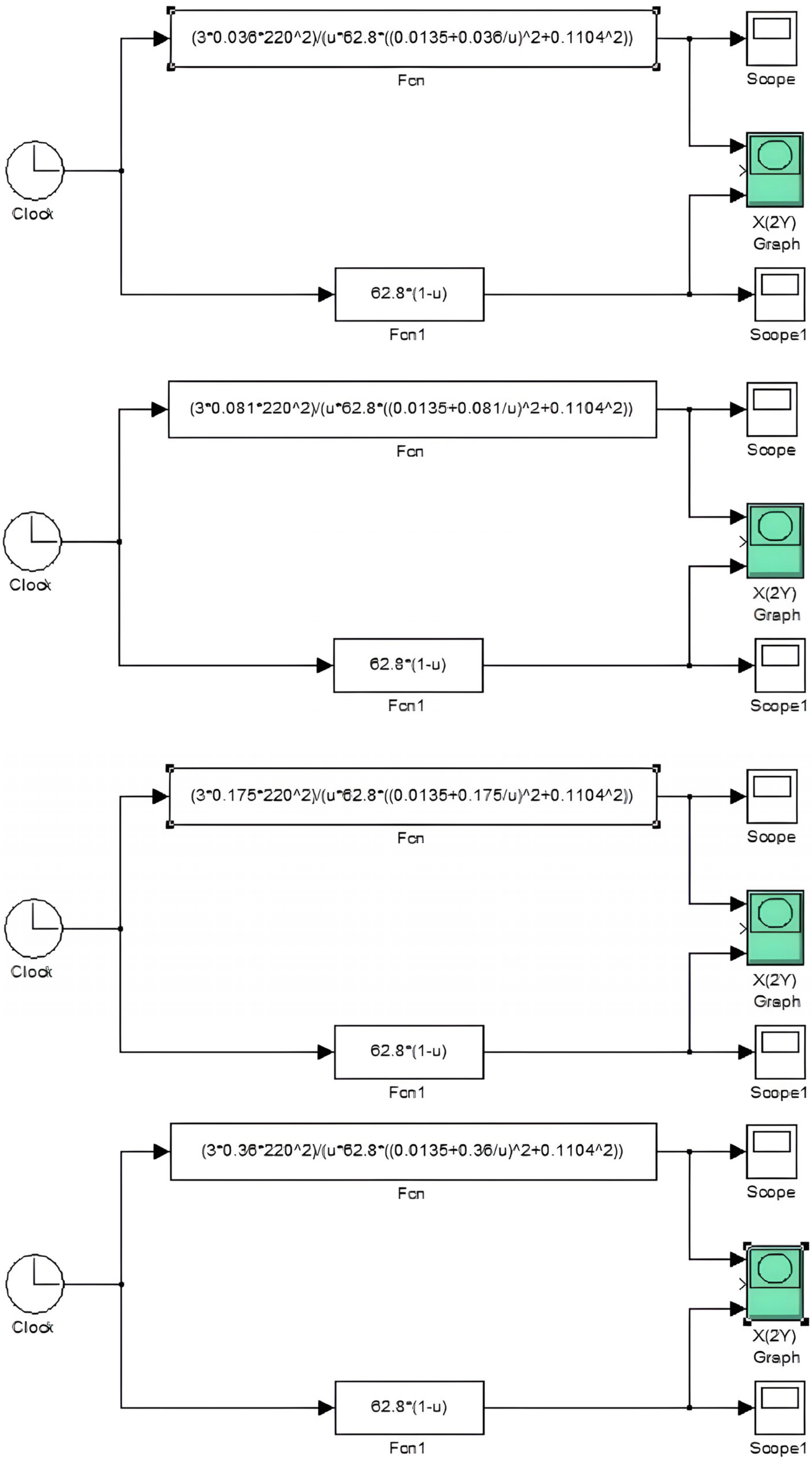


Figure 4. Calculation models of $M=f(\omega)$ artificial mechanical characteristic of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment

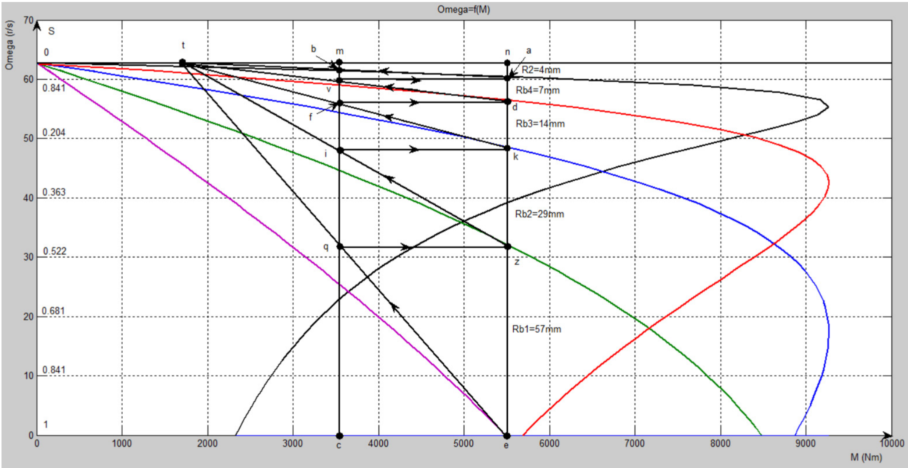
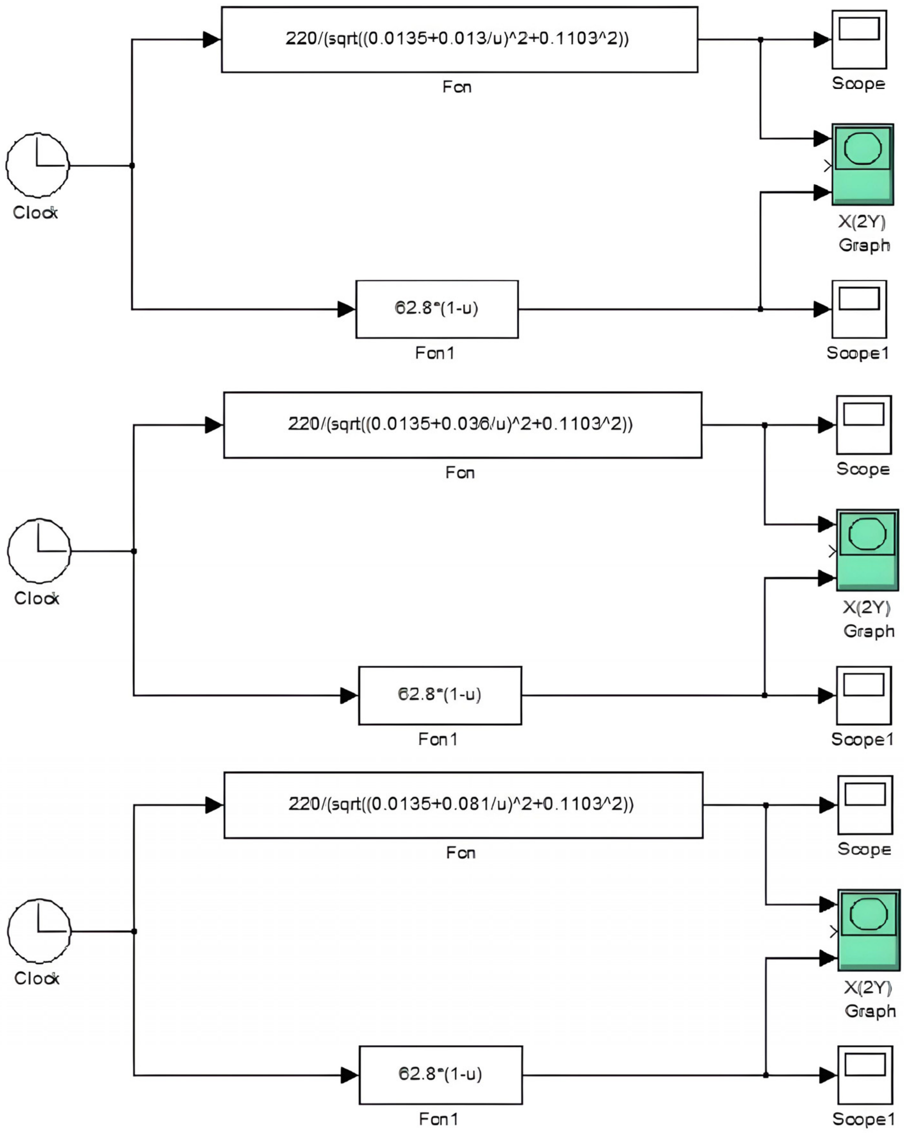


Figure 5. $M=f(\omega)$ artificial mechanical characteristics of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment



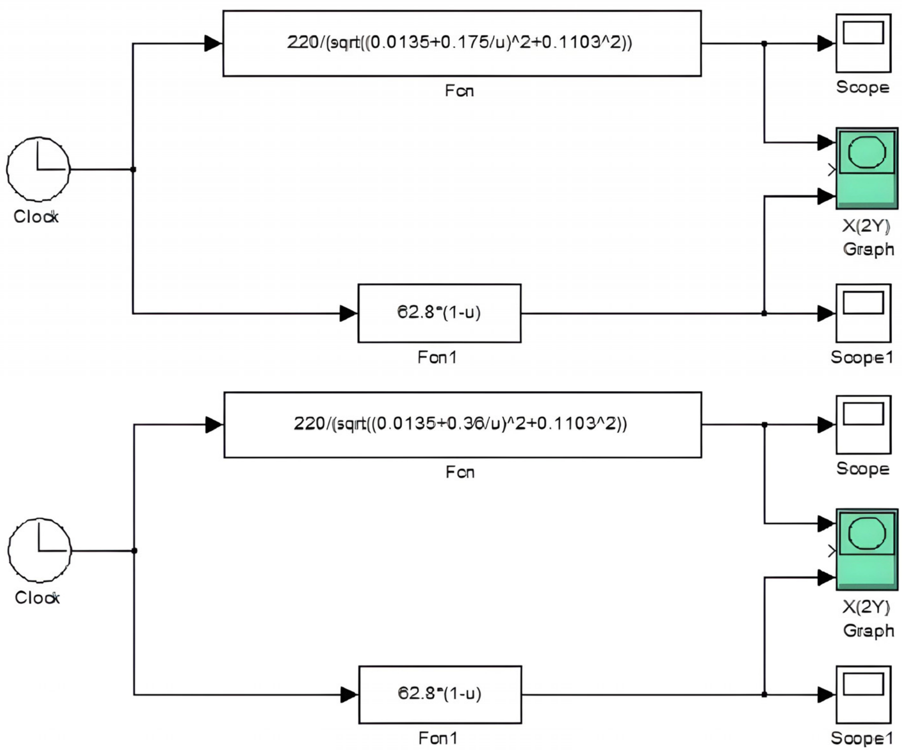


Figure 6. Calculation models of $\omega=f(I_2)$ velocity characteristics of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment

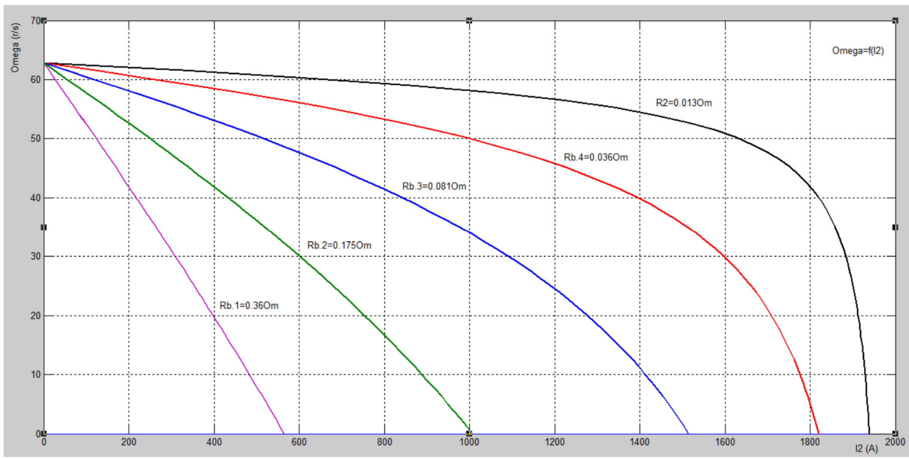


Figure 7. $\omega=f(I_2)$ velocity characteristics of the MTH713-10 type PRIM constructed in the MATLAB/Simulink environment

In the conducted study the motor conditions of ASSG mounted on the controllable-pitch propeller ships are considered. That is, the rotation speed of the ship propeller may not be executed by the MM. In this case, only starting mode can be implemented by connecting resistance to the rotor circuit of the PRIM, which in turn minimizes the energy loss that will occur in the rotor of the motor. It can also be noted that due to connection of the resistance to the rotor circuit, the starting system is cheaper than modern frequency converters. The main disadvantage of the starting system by connecting resistance to the rotor circuit is that when adjusting the motor rotation speed using the system, the energy loss in the rotor is high and the adjustment is fuzzy [3].

4. CONCLUSIONS

By installing a three-phase winding on the rotor of synchronous generators that operate as a cluster inside the SGU in the controllable-pitch propeller ships, and selecting a frequency converter for this winding, replacing synchronous shaft generators with asynchronized synchronous shaft generators, the economically advantageous power module can be obtained. In this case, it will be easier to realize the motor conditions of SGU.

It is considered more advisable to start the ASSG, mounted in controllable-pitch propeller ships (rotation speed is not controllable by MM) only in the motor conditions, using a cheap and simple method, i.e., by connecting resistance to the rotor circuit, as a PRIM.

Also, in the paper, the motor conditions of ASSG mounted in the controllable-pitch propeller ships are modeled using "Simulink", being "visual-block simulation modeling package" included in MATLAB and designed for modeling dynamic systems.

NOMENCLATURES

1. Acronyms

ASSG	Asynchronized Synchronous Shaft Generator
MM	Main Motor
ASM	Asynchronized Synchronous Motor
SGU	Shaft Generator Unit
PRIM	Phase Rotor İnduction Motor

2. Symbols/Parameters

M_e: Electromagnetic torque of the motor

$\omega_0 = \frac{2\pi f_1}{p}$: Angular velocity of rotating magnetic flux

f_1: The current frequency given to the stator

p: Number of motor pole pairs

I_2' , r_2' : Transposed expressions of phase rotor, current and active resistance

C_1: It reflects the relationship between the primary voltage U_1 and the electromotive force

S: Motor slip

m_1: The number of phases in the stator

M_{kr}: Maximum torque generated by the motor during the critical slip (S_{kr})

$r_{b.4}'$, $r_{b.3}'$, $r_{b.2}'$, $r_{b.1}'$: Transposed expressions of starter resistance steps.

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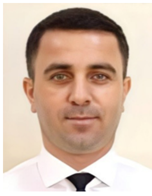

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