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Automation of the Control of Electric Drive of Manned Submersibles




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ABSTRACT

Currently, there is an intensive development of manned and unmanned submersibles due to development of offshore oil and gas fields, development of underwater archaeology and exploration activities in transit zones regarding seabed mineral extraction. The depth of immersion and the nature of the underwater technical works performed determine not only the design of the underwater vehicle, its power-to-weight ratio and technical equipment, but also impose high requirements on reliability, survivability, and habitability, if the underwater vehicle implies that the operator is on board inside a pressure hull. The main objectives of the study carried out by the authors were to achieve high reliability and survivability of the main elements of the propulsion-steering complex, which ensure movement of a human-occupied vehicle in the water column, its positioning and retention at a given point in the water area.

For this purpose, it was proceeded to development of an automated control system for the electric drive of the propulsive device of manned immersible. The proposed developments include a flowchart of the movement control system, circuitry engineering solutions using power semiconductor devices to maintain operability of the electric drive in extreme and emergency operating conditions, and movement control algorithms. Electromagnetic calculations of the active part of the electric machine were performed by the finite element method, considering the geometric features of the dental zone of the rotor and stator. The proposed mathematical apparatus served to calculate optimal control actions of the electric drive and to quantitatively assess the reduction in electrical losses once optimal control was applied. The calculation of the optimal control parameters was carried out using the maximum principle. The initial conditions for auxiliary functions are determined by the Newton–Raphson method. A comparison of various modes of operation of the electric drive was made regarding their influence on duration of the campaign, and other parameters.

The calculations did not consider the parameters and geometry of the propulsive device (the propeller) since the developers of electric propulsion systems for manned and unmanned underwater vehicles of various classes often deliberately reduce the efficiency of the propeller to increase speed of the electric motor shaft, resulting in a decrease in the dimensions and weight of the latter.

Keywords: *automated control system, manned submersible, human occupied vehicles, reliability, energy efficiency, optimisation, fault tolerance.*

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INTRODUCTION

Smart information technologies providing automated control functions are a mandatory attribute of specialised transport equipment while working in an environment alien to human, including under water. High risk of underwater technical works imposes exceptional requirements on reliability of units, parts, and systems, and on survivability of the entire manned submersible.

Some success in design and production of domestic manned submersibles intended for various immersion depths with an objective dominant of electrical engineering components still leaves not definitively solved a set of issues to increase energy efficiency with extension of duration of the campaign, optimise the cost of production and maintain competitiveness in the world market.

Relevance and Analysis of the Problem

The desire to explore the oceans led to creation of two manned submersible vehicles which once descended into the Challenger Deep, the deepest place of the Mariana Trench: the bathyscaphe *Trieste* and the deep-submergence vehicle *Deepsea Challenger*, designed for a maximum depth of 11,000 m [1]. Underwater technical works of the survey of the condition, repair and restoration of various objects located on the seabed and near it involve the use of deep-sea equipment including habitable underwater vehicles[1].

The Russian manned project 03660 submersible with a transparent spherical solid hull, designed for performing underwater technical work on offshore gas pipelines, was presented to the public at the Gasprom science and innovation exhibition at 9th St. Petersburg International Gas Forum. The project is being implemented by Gazprom with involvement of the National Research Centre «Kurchatov Institute», the Malachite Marine Engineering Bureau of St. Petersburg, and the Underwater Research Centre of the Russian Geographical Society[2].

The motion of the unmanned submersible through the water column, its positioning and manoeuvring is provided by moving and steering complex consisting of two sustained, two vertical and one horizontal thruster columns. In modern practices, developers of underwater vehicles often reduce the efficiency of the propeller by increasing speed of the engine shaft to optimise its dimensions and weight to achieve the required flow parameters with a given traction effort. In this regard for various reasons propellers continue to be the main effective type of engines despite development of water-jet systems that can endow unmanned submersibles with greater manoeuvrability [2].

Depending on the operating requirements the propellers can be driven by: DC electric motors, asynchronous and synchronous electric machines, including those with the use of permanent magnets in the rotor of the traditional layout and of ring type, of dry or oil filled versions with an outboard pressure compensation system; less often by open-type electric motors and hydraulic motors. AC motors do not have manifolds, allow so to smoothly adjust the shaft speed but require a relatively more sophisticated control system. At the same time the operational features and efficiency of the unmanned submersibles depend directly on the parameters of the drive of the propulsive device[3].

Problem Statement and Research Methods

Pic. 1 shows the flowchart of the automated system controlling moving and steering complex of the manned submersible intended to improve its reliability, survivability, and dynamic characteristics. Interactive remote controls allow setting, controlling and quickly adjusting movement parameters through direct and feedback connections by influencing the microprocessor system with automatic visualisation of the response. The microprocessor system provides communication with all elements of the electric drive, realising automatic setting of the specified parameters of movement or positioning at a given point optimising control algorithms, and simultaneously performing diagnostic, protective and information functions.

Switched Reluctance Motor (SRM) is considered as an electric drive prototype. This electric machine, thanks to a number of positive

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[1] To the bottom of the ocean: top 5 Russian deep-sea submersibles [*Na dno okeana; top-5 rossiyskikh glubokovodnykh apparatov*]. [Electronic resource]: https://tvzvezda.ru/news/201707121549-v8fk.htm. Last accessed 22.08.2021.

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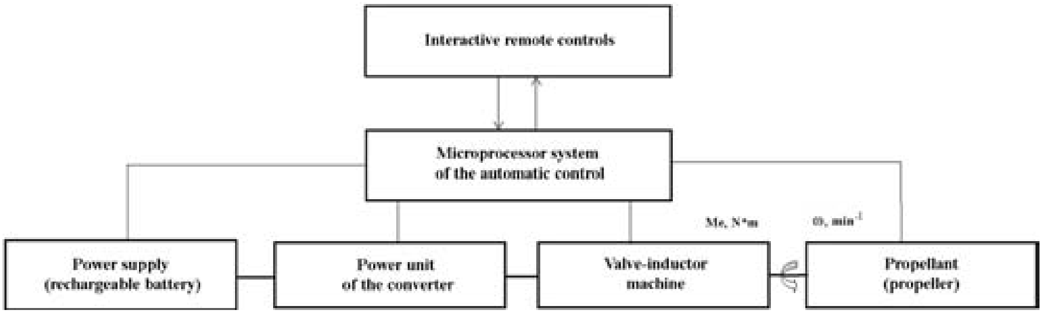
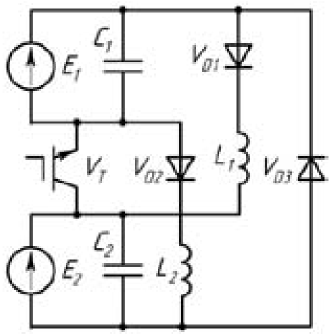


Pic. 1. Flowchart of the motion control system of an unmanned submersible [performed by the authors].



Pic. 2. Power circuit of a SRM single phase [performed by the authors].

features, is used in various vehicles [3–5]. With its simple design and reliability, SRM has a high efficiency value, which is important for analysing duration of the campaign, time of travel and the range of navigation at the target depth of immersion.

To ensure a high level of survivability of the moving and steering complex, the power circuits of the electric drive control system which connect the phases of the electric machine with the power source should be designed and manufactured using galvanic separation. The power supply is partitioned, the independent section feeds a separate SRM phase. With such a structure of the power part, the failure of any element such as the winding, the semiconductor component or the power supply section does not lead to interrelated failures and does not impact the performance of the remaining phases of the electric drive, and therefore the damaged unit of the moving and steering complex retains survivability with a partial loss of power. In this case, the power supply circuit of a phase of SRM (Pic. 2) will have one semiconductor switch V_T, which makes it possible to form two circuits of the voltage supplied to the winding: a positive one with energy entering the electromagnetic circuit and a negative one with energy returning to the source at the end of the switching cycle [6].

Pic. 3 shows the active part of the SRM designed by the authors of the paper and optimised using the Monte Carlo method according to the criterion of maximum electromagnetic torque in a given geometric volume with the placement of all elements of the electric motor and considering its external design. The SRM dental zone is formed using optimal design tools with a curved shape of the air gap between the stator and the rotor [7]. The dental zone is selected from the ratio of 10-teeth stator and 8-teeth rotor [8]. With this magnetic circuit design, the rotor teeth are divided into teeth fragments, and the angle between the axes of the rotor teeth in each fragment is equal to the angle between the axes of all evenly spread stator teeth. The stator teeth with the coils placed on them are evenly spread over the inner surface of the stator.

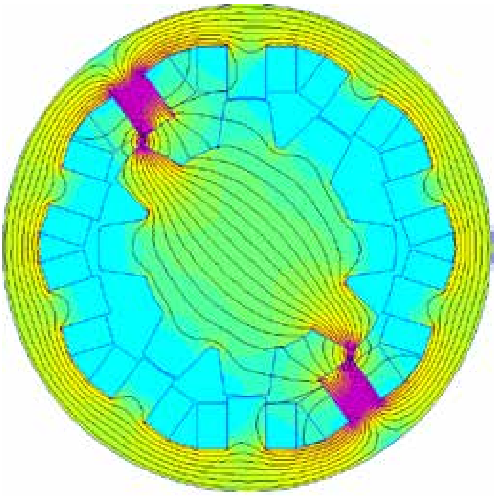
The task of the research was to ensure the energy efficiency of SRM operation by controlling the electric machine according to the optimal algorithm, which allows to significantly reduce the electrical losses in the winding during electromechanical energy conversion.

The calculations are carried out for an electric machine with a rated power of 5 kW and a rotation speed of 500 s^{-1}, the moment of inertia of the rotor and of the rotating parts attached to it of 0,25 kg•m^2, the supply voltage being 220 V for the rectangular voltage pulse supply option and 400 V for the winding supply with optimal control.

RESULTS

Theoretical Part

The mathematical model of SRM is based on the assumption that there is no magnetic connecting between the phases. The Kirchhoff



Pic. 3. The active part of the SRM with an excited phase [performed by the authors].

equations of the electric circuit for the first phase of the winding have the form [9]:

$$V = R_s i_1 + \frac{d\psi_1(\theta, i_1)}{dt}, \qquad (1)$$

where V is the supply voltage of a phase, V;

i_1 – current of the first phase, A;

R_s – active resistance of each phase, Ohm;

$\Psi_1(\theta,\ i)$ – interlinkage of the first phase, depending on the angle of rotation of the rotor θ, electric deg., and current i;

t – time, s.

Equation (1) expressed in terms of SRM parameters and reduced to the Cauchy form, is presented in the following form:

$$\frac{di_1}{d\theta} = \frac{1}{\omega \bullet Z_r \bullet L_1} \bullet (V - i_1 R_s - i_1 \bullet \omega \bullet Z_r \bullet \frac{dL_1}{d\theta}), \qquad (2)$$

where ω is angular speed of rotation, s^{-1};

Z_r – number of rotor teeth.

The equation of motion is represented as:

$$\frac{d\omega}{d\theta} = \frac{1}{J \bullet \omega \bullet Z_r}\left(T_m - T_r\right), \qquad (3)$$

where n – number of SRM phases;

J – moment of inertia, kg•m^2;

T_m – electromagnetic moment, N•m;

T_r – moment of resistance on the shaft, N•m.

To determine the optimal control actions for SRM control, the maximum principle was used. The square of the input voltage to the stator winding is chosen as the optimisation criterion [10]:

$$J_k = \int_{\theta 1}^{\theta 2} V^2 d\theta. \qquad (4)$$

For linear electrical circuits, criterion (4) allows to obtain the minimum electrical losses. However, SRM works with periodic saturation of a magnetic circuit having a nonlinear magnetisation curve, so criterion (4) will not correspond to the minimum of electrical losses, but, as calculations have shown, will significantly reduce them.

The dependence of the supply voltage on the angle of the rotor's rotation is selected as the control action [11]. At the optimisation stage, the following assumptions are made: the dependence of the inductance on the angle of rotation of the rotor is approximated by a harmonic function, the saturation of the magnetic circuit was not considered. Then, the intermediate function H according to the maximum principle has the following form:

$$H = \left[\frac{1}{\omega \bullet Z_r \bullet L_1} \bullet (V - i_1 R_s - i_1 \bullet \omega \bullet Z_r \bullet \frac{dL_1}{d\theta})\right]\psi_1 +$$
$$\left[\frac{1}{J \bullet \omega \bullet Z_r} \bullet \left(\sum_1^n \frac{Z_r \bullet i_i^2}{2} \bullet \frac{dL_i}{d\theta} - T_r\right)\right]\psi_2 + V^2.$$

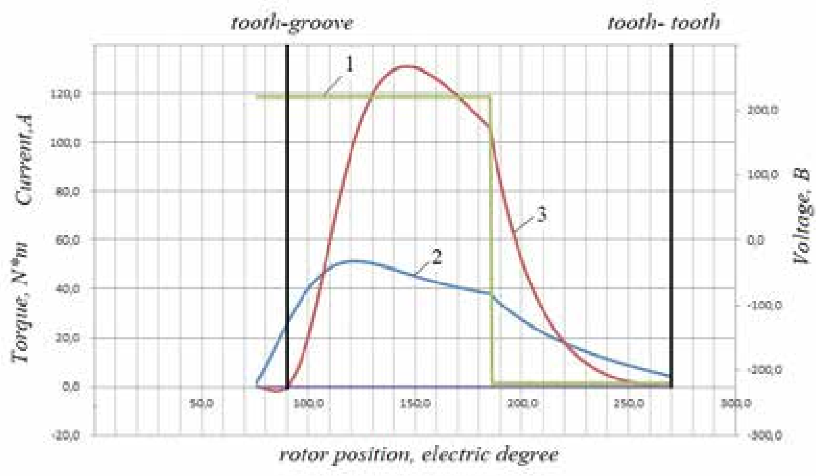
Let us define the optimal supply voltage V^* as a partial derivative of the intermediate function with respect to the control action V:

$$V^* = \frac{\psi_1}{2 \bullet L \bullet \omega \bullet Z_r}. \qquad (5)$$

Let us then define auxiliary functions Ψ_1 and Ψ_2:

$$\begin{cases} \dfrac{d\psi_1}{d\theta} = \psi_1\left(\dfrac{R_s}{L \bullet \omega \bullet Z_r} + \dfrac{1}{L} \bullet \dfrac{dL}{d\theta}\right) - \dfrac{i_1 \bullet \psi_2}{J \bullet \omega} \bullet \dfrac{dL}{d\theta} \\ \dfrac{d\psi_2}{d\theta} = \dfrac{\psi_1}{L \bullet \omega^2}\left(V - i_1 R_s\right) + \dfrac{\psi_2}{J \bullet \omega^2}\left(\dfrac{i_1^2}{2} \bullet \dfrac{dL}{d\theta} - T_R\right). \end{cases} \qquad (6)$$

When solving the optimisation problem, the initial conditions for auxiliary functions are determined using the Newton–Raphson method [12].



Pic. 4. SRM phase parameters when powered by DC pulses:
1 – supply voltage, 2 – current, 3 – electromagnetic torque [performed by the authors].

The calculation results for SRM control without using an optimisation algorithm for one phase of stator winding are shown in Pic. 4.

DC voltage pulses with an amplitude of 220 V were applied at the following control angles: the switching angle was of 15 electric degrees to the tooth-groove position and the turn-off angle was 85 electric degrees to the tooth-tooth position.

The results of the calculation for SRM control using the optimisation algorithm under the condition of equal performance with the non-optimisation option are shown in Pic. 5.

In the optimal mode, the current of the SRM stator winding, in contrast to the mode without optimisation, does not have an explicit maximum (Pic. 5) but has a flat characteristic in the range of 135–185 electric degrees. In the optimal mode, when performing the same work, the electrical losses in the winding are reduced. If the electrical losses for one switching cycle in the non-optimised mode are taken as 100 %, then in the optimal mode the electrical losses will be by 6–7 % less.

To implement the optimal mode, you should increase the supply voltage of the SRM while reducing the capacity of the batteries, so that the space for placing the batteries remains the same.

Practical Significance

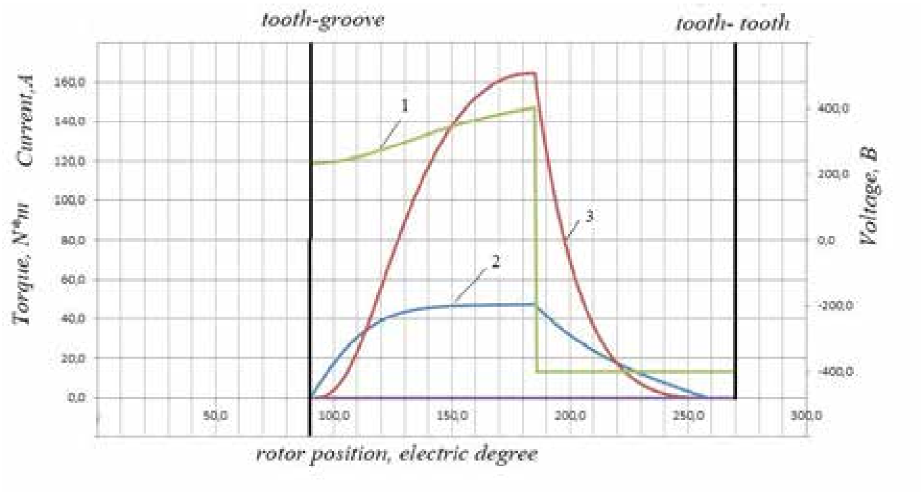
The practical implementation of the optimal SRM control algorithm is achieved using the microcontroller control program, which generates the parameters of the control pulses in real time according to the mathematical model of optimal SRM control. The current in the winding is generated using Pulse–Width Modulation (PWM). The quality of the supply current shape with optimal SRM control is ensured by a rational choice of PWM parameters.

The practical significance of the results obtained is associated with the increase in the reliability, survivability and energy efficiency of the SRM electric drive of the moving and steering complex, in better quality of functioning of the proposed automated motion control system of manned submersibles, which are decisive for the operational attractiveness and achieving competitiveness in the world market.

CONCLUSION

The proposed automated system intended for the control of the electric drive of the manned submersible's moving and steering complex makes it possible to increase the reliability and survivability of the entire vehicle. The use of galvanically separated power circuits connecting the phases of the electric machine to the power source additionally provides fault tolerance and emergency operation when the power on the shaft decreases.

The developed mathematical apparatus and the quantitative estimates of energy efficiency carried out with its use had a positive impact on the possibility of optimising the consumption of electricity from the onboard power source. Reducing electrical losses during electro-mechanical energy conversion directly affects the range of manned submersible and duration of the campaign.



Pic. 5. SRM phase parameters with optimal control algorithm:
1 – supply voltage, 2 – current, 3 – electromagnetic torque [performed by the authors].

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