Mathematical modeling of the asynchronous motors for underwater vehicle drives

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Abstract — **This paper approaches the mathematical modeling of the submersible asynchronous motor filled with MASUM dielectric liquid. These motors are used to drive submarine robots, which are guided through cables from the surface of the water. We described the necessity and the types of submersible motors. Later we presented the construction of the specialized asynchronous motor MASUM-10. The proposed mathematical model is designed considering the influence of the long supply cables, and hydraulic losses caused by the rotation in dielectric liquid, which fills the motor. The results of the computer simulation of mathematical model prove the functionality of the motor, and highlight the problems caused by the long supply cable.**

Keywords— underwater vehicle, electric drive, asynchronous motor, liquid dielectric, long power cable, modeling, hydraulic losses

I. Introduction

The research, development and use of underwater robots (vehicles) has known a massive evolution in latest year [1-3]. In this field, significant results were obtained in USA, Canada, Japan, France, Denmark, Russia, Australia and China.

Submarine robots proved to be useful in research of the world aquarium, service of technical objects and military submarines, rescue missions. They also proved to be extremely useful in gathering mineral deposits at big depths, installing and maintenance of gas/petrol pipes and underwater cables, servicing in ports and ships, ecologic monitoring, and other important fields. The vast majority (about 70%) of submersible robots are used at depths of up to 1000 m, and only a very small number are used at below 6000 m.

The parameter of propulsion and control method divides the underwater vehicles in two categories: we have Autonomous Underwater Vehicles (fig.1) and Remotely Operated Vehicles (fig.2), which are controlled and supplied from the surface through cables. The AUV are endowed with batteries for the means of propulsion with electric motors, and piloted or wirelessly controlled manual guidance system. ROV robots are supplied via cables from the ship's generator, at water surface. The ROV's electric motors are used for hydraulic system drive, which ensures the propulsion of the vehicle in plan (limited by cable's length) and the function of the robot's manipulator arms. The arms are used to perform specific technical procedures under water.

Direct current motors [6], as well as Alternative Current motors [7], can be used to operate underwater robots. The placement of the motor outside the vehicle's shell creates the necessity of using specialized electric motor, capable to function in sea water, at high pressure. For a number of years already, the Department of Electromechanics and Metrology from UTM is active in researching, designing and manufacturing electric motors and drives for AUV and ROV underwater robots.

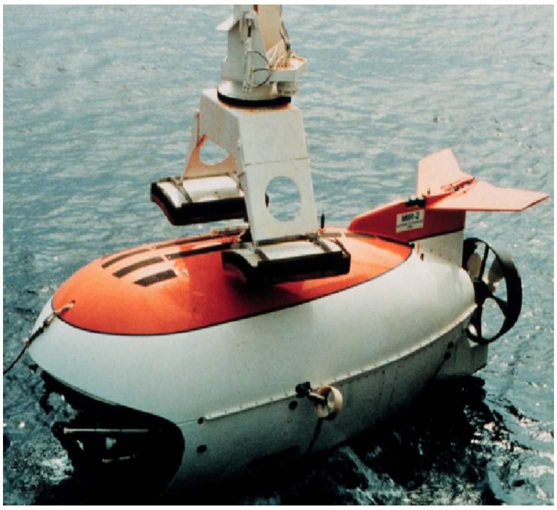

Fig.1. AUV underwater robot [4]

Fig.2. ROV underwater robot [5]

The aim of this paper is mathematical modeling and verifying of functionality and behavior of asynchronous motors filled with dielectric liquid, used in electric drives of ROV underwater vehicles, commanded with cable from water surface.

II. Design and Characteristics of the MASUM-10 Submersible Asynchronous Motor

At the request of foreign parties, the Department of Electromechanics and Metrology of UTM developed specialized submersible asynchronous motors MASUM-10 (fig.3), which has the rated work depth up to 1000 m and supplied through cables from water surface. The ferromagnetic core of stator and rotor is made of steel sheets. On the stator there is a three-phased winding in one layer. The rotor is made of welded copper bars and rings. The construction includes the filling of the motor with dielectric liquid (diesel fuel) through specialized holes. A flange of the case is destined for the motor's coupling with the pump's shell, and the second flange is meant to be connected to the hermetic terminals box, to which the high voltage supply cable is connected. Motor's case and flanges are made from specialized aluminum alloys. To seal the motor, the connection of the flanges and the shaft's cuffs are made with rubber rings. The cable is connected to the stator winding of the motor with a specialized hermetic connector that resists at pressures of up to 900 kg/cm^2.

The main parameters of the motor are presented in tab.1. The MASUM motors underwent lab tests according to the IEC 60034-1-83 standard, and tests in water and high pressures.

Fig.3. General view of the submersible asynchronous motor MASUM-10

TABLE I.
Parameters of the submersible motor MASUM-10

No	Name	m.u.	Valuie
1	Power rated	kW	10
2	Voltage rated	V	660
3	Frequency	Hz	50
4	Number of poles	-	2
5	Current rated	A	6.77
6	Efficiency	%	83
7	Power factor	-	0,89
8	Type of dielectric liquid	-	diesel oil

III. Hydraulic Losses of the Dielectric Filled Asynchronous Motor

The working environment of the submersible asynchronous motor in salt water and at great depth makes it a necessity to fill the cavity of the motor with dielectric liquid. This leads to a better heat transfer as well as compensating the high external pressure (for this motor in particular it is 30 MPa). On the other hand, the dielectric filling causes considerable hydraulic losses. The upper mentioned factor lead to choosing the type of liquid for MASUM not only by the dielectric properties, but also by taking in consideration its cinematic viscosity. Viscosity forms directly the hydraulic losses in the motor. For low speed motors, one can use transformer oil. Motors with synchronous speed above 1500 rpm it is recommended to use winter type diesel fuel.

The presence of dielectric liquid inside the motor leads to additional hydraulic losses. To determine these losses is a very complicated problem. Here are a number of factors that play a major role; such as the area of stator and rotor teeth, the area of front parts of windings, turbulent movement of the liquid caused by rotor movement, variation of liquid properties depending on pressure and temperature. To take into account all these factors, we needed to use mathematical models described by differential equations with partial derivatives and calculation methods such as MEF, MDF [6]. Other options, like those described in [7], are empirical calculation methods of hydraulic losses.

According to [7], the dynamic hydraulic losses of the MASUM motor can be calculated separately in the cylinder shaped airgap

$$\Delta P_{h\delta}(\rho,\nu,\omega) = 0{,}44\,\pi\rho\,\nu^{0,48} L\,R^{3,25}\delta^{-0,22}\,\omega^{2,52} \qquad (1)$$

and for the front areas of the winding

$$\Delta P_{hf}(\rho,\nu,\omega) = 0{,}0205\,\mathrm{Re}^{-0,2}\rho\,R^{5}\,\omega^{3}, \qquad (2)$$

where: ρ - specific density [kg/m^3] and ν - cinematic viscosity of the dielectric liquid[m^2/s], L, R, ω - length[m], radius [m] and angular velocity of the rotor [rad/s], Reynolds' number $\mathrm{Re} = \frac{V\,D}{\nu} = 2\frac{\omega R^2}{\nu}$.

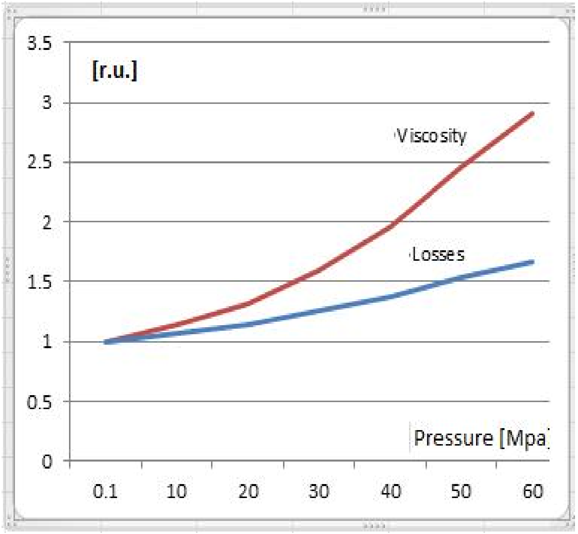

Fig.4.The influence of pressure on viscosity and hydraulic losses

According to (1, 2), hydraulic losses depend on the geometry of the airgap, angular velocity of the rotor and physical parameters of the dielectric liquid. Parameters of the dielectric liquid depend, in their turn, on the working depth of the underwater robot. Tests have concluded that the viscosity of the dielectric liquid at water surface is 1,1e-6 m^2/s (static pressure is 0.1 MPa). If the motor was to be submerged at 6000 m (static pressure would raise to 63 MPa), then the viscosity could raise by 300% (fig.4), while the hydraulic losses would raise by less than 170%.

The results of calculations (1, 2), demonstrate that the dependence of motor's hydraulic losses on angular velocity of the rotor, for different values of depth (which affects pressure, and viscosity), has a parabolic form (fig.5).

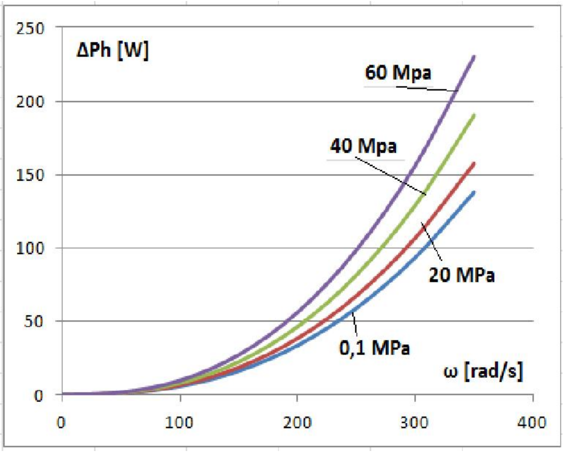

Fig.5. Dependence of hydraulic losses on the rotor's speed

IV. Mathematic Modelling of the Submersible Asynchronous Motor MASUM-10

For the modelling of the asynchronous motor filled with dielectric liquid, we used the equations of the usual three-phased asynchronous motor, but considering the particularities of the application – robots being commanded through cable from the water surface. The influence of the long supply cable (up to 3000 m) can be included in the mathematical model by the addition of the cable's resistance R_c to stator resistance Rs. The presence of dielectric liquid in the motor's cavity leads to additional hydraulic losses caused by the movement of the rotor. The hydraulic losses were included in the mathematical model by adding an equivalent friction torque to the motion equation.

According to (1), the dynamic friction torque caused by the hydraulic losses, which depends on density and viscosity of the dielectric liquid, and on the speed of the rotor; can be written in the following form:

$$m_h(t,\rho,\nu,\omega) = 0{,}44\,\pi\rho\,\nu^{0{,}48} L\,R^{3{,}25}\delta^{-0{,}22}\,\omega^{1{,}52} \qquad (3)$$

From the above said and according to notes in [8], the two-phased mathematical model of the three-phased asynchronous motor filled with dielectric liquid and supplied through cables, will be composed of voltage equations (4), flux equations (5), and motion equation (6).

The motion equation (6) on the right side has the electromagnetic torque of the asynchronous motor (4), the torque of the load $\boldsymbol{m_s = m_s(t)}$ and the torque of the hydraulic losses $\boldsymbol{m_h}$ (3) .

The general equations (4-7) describe the transient and stationary states of the submersible asynchronous motor filled with dielectric liquid. Basing on equations (4-7) we formed the Simulink model (fig.6).

$$\left.\begin{aligned} u_{sd} &= (R_s + R_c)\cdot i_{sd} + \frac{d\psi_{sd}}{dt} \\ u_{sq} &= (R_s + R_c)\cdot i_{sq} + \frac{d\psi_{sq}}{dt} \\ 0 &= R_r \cdot i_{rd} + \frac{d\psi_{rd}}{dt} + \omega\cdot\psi_{rq} \\ 0 &= R_r \cdot i_{rq} + \frac{d\psi_{rq}}{dt} - \omega\cdot\psi_{rd} \end{aligned}\right\} \quad (4)$$

$$\left.\begin{aligned} \psi_{sd} &= L_s \cdot i_{sd} + L_m \cdot i_{rd} \\ \psi_{sd} &= L_s \cdot i_{sd} + L_m \cdot i_{rd} \\ \psi_{rd} &= L_m \cdot i_{sd} + L_r \cdot i_{rd} \\ \psi_{rq} &= L_m \cdot i_{sq} + L_r \cdot i_{rq} \end{aligned}\right\} \quad (5)$$

$$\frac{J}{p}\cdot\frac{d\omega}{dt} = m_e - m_s - m_h \qquad (6)$$

$$m_e = \frac{3}{2}p(\psi_{sd}\cdot i_{sq} - \psi_{sq}\cdot i_{sd}) \qquad (7)$$

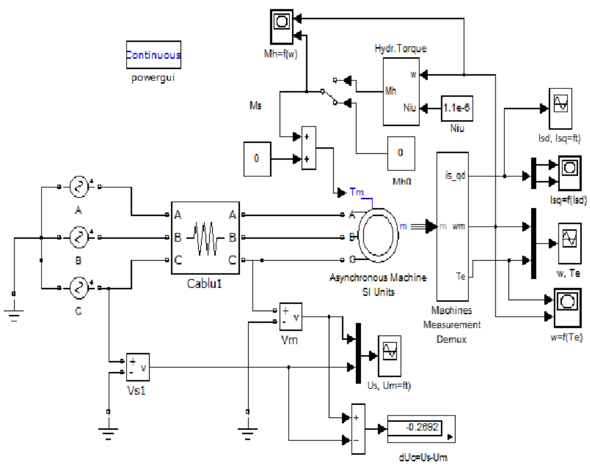

Fig. 6. Simulink model of the MASUM-10 motor, supplied via cable

V. Simulation of the Submersible Asynchronous Motor MASUM-10 in Dynamic Regimes

The simulation results for the submersible MASUM-10 motor at direct start without cable (***case a***) and at starting the motor from a long cable with resistance of R_C*=11.3 Ohm* (***case b***) are shown in fig.7 - fig.11.

To check the influence of long power cable and hydraulic losses were made more dynamic simulations of submersible asynchronous motor MASUM-10. Due to high starting currents, for power cable of 3000 m and 11.4 Ohm resistance, voltage drop (fig.7) overcomes 30%

of the supply voltage of 1140 V. As a result, the voltage at the motor terminals is reduced to 650 V at startup and to 950 V in steady regime (fig.8).

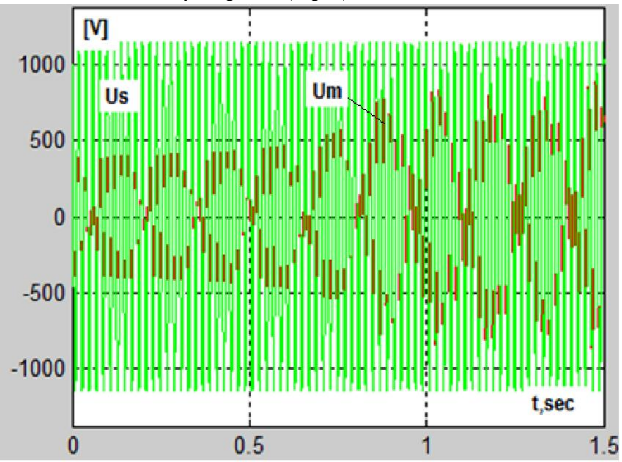

Fig. 7. The supply and motor voltages Us, Um=f(t) .

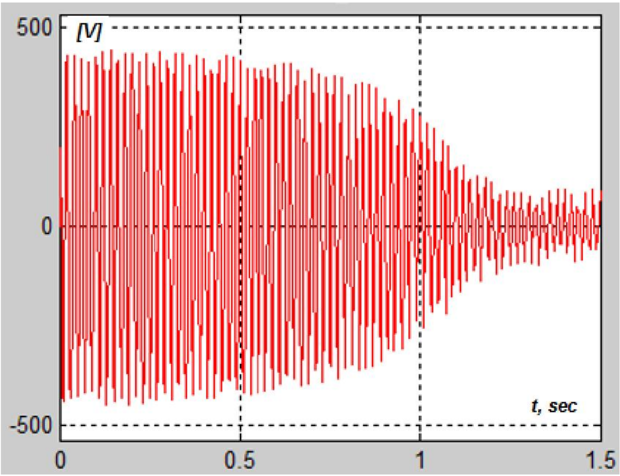

Fig. 8. The voltage drop in the power cable

In fig.9 one can observe that the supply of the motor with a long cable leads to a decrease of current's shock values to 42 A. In the case of direct start, the shock current reaches up to 63A. The effect of the long cable leads to decreasing shock values of the current by a factor of 1,5. At the same time, the duration of the motor's transient electromagnetic process; for starting the motor from the long cable grows from 0.45s to 1,55s; meaning an increase of 300%.

Comparing to direct start, according to fig.10, the duration of the mechanical transient process grows from 0,45s to 1,5s, when starting with cable supply. The effect of long cable starting on torque is a decrease from 245Nm to 100 Nm, which means a decrease by almost 2,45 times. Submersible motor MASUM-10 has a high starting torque (2.2 higher than the rated torque) and can provide start with rated load even for voltage drop on the considerated cable. But in other cases for greater cable length or resistance, the voltage drop could result unable startup of submersible asynchronous motor under higher load (such piston pumps). This requires need to compensate the voltage loss on the cable by increasing voltage supply using of the transformer either a static power converter

It was researched influence of hydraulic losses on transient processes of the asynchronous motor filled with liquid dielectric depending on the working depth (high

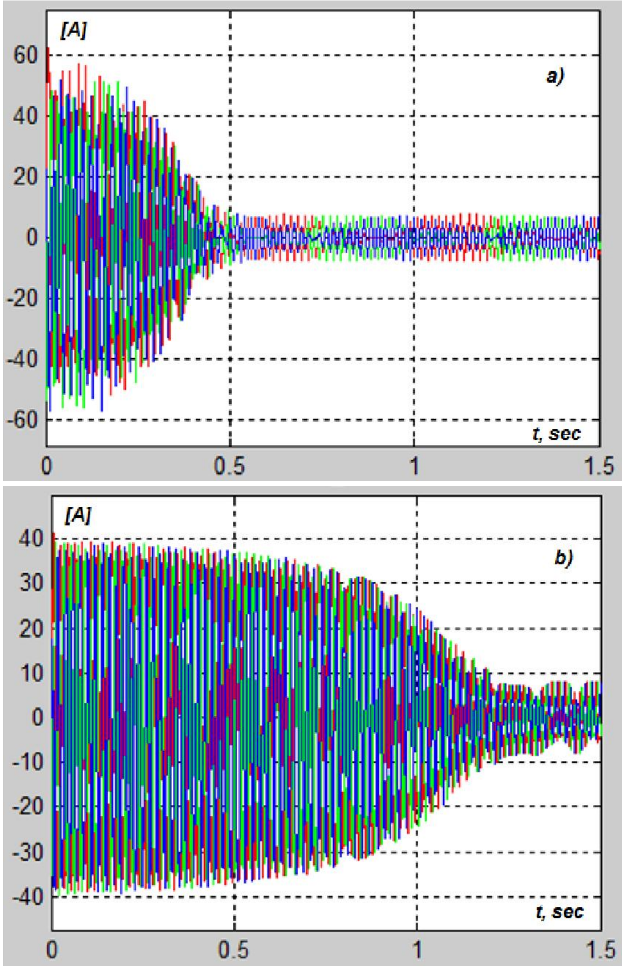

Fig.9. Stator phase currents $I_{ABC}=f(t)$

water pressure). For submersible motor MASUM-10 filled with diesel oil it is observed that hydraulic losses on the depth of 3000 m (static pressure 30sqm) reaches 118w (fig.11, a) compared with those of 82W (fig11,b) when motor operating for the atmospheric pressure on the surface.

Depending on the pressure increase the viscosity of the liquid what causes increase by about 50% of the hydraulic losses for working depth of 3000m.

Hydraulic friction torque has the same form as that losses. However, influence on the dynamics submersible hydraulic losses is insignificant, because hydraulic friction torque form less than 1% of the nominal torque of the motor.

VI. Conclusions

For underwater vehicle (robots) it is necessary to develop specialized electric motors, which would be capable to function submerged in sea water and at pressures of above 100MPa.

The mathematical modelling proved the functionality of asynchronous motor filled with dielectric liquid MASUM-10. On the other hand, we observed a significant voltage drop on the supply cable, compensation of which is vital.

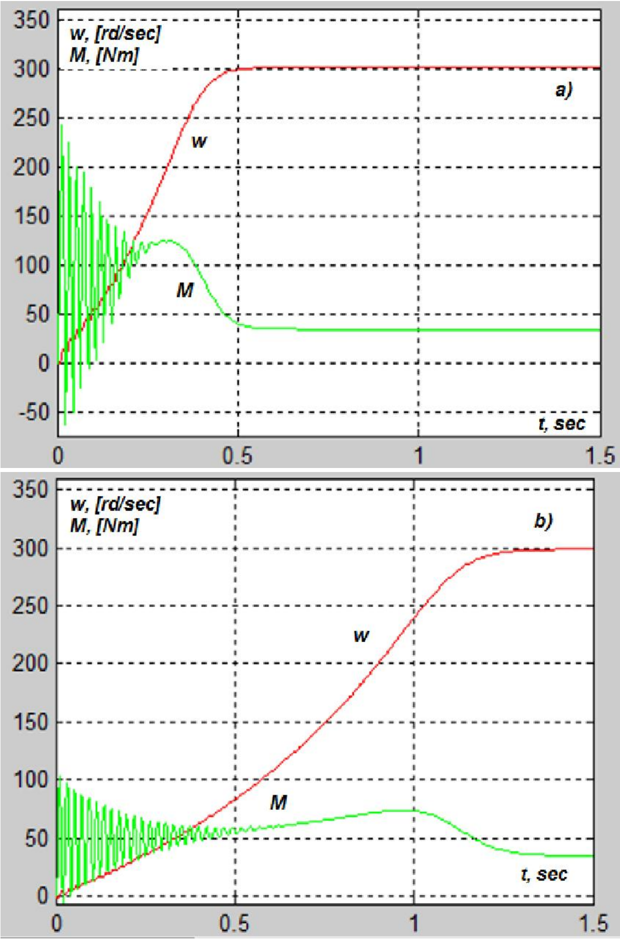

Fig.10. The motor angular velocity and torque *w, Me=f(t)*

It was found, that hydraulic losses insignificant influence on the dynamics of the submersible asynchronous motor filled with dielectric liquid (diesel oil).

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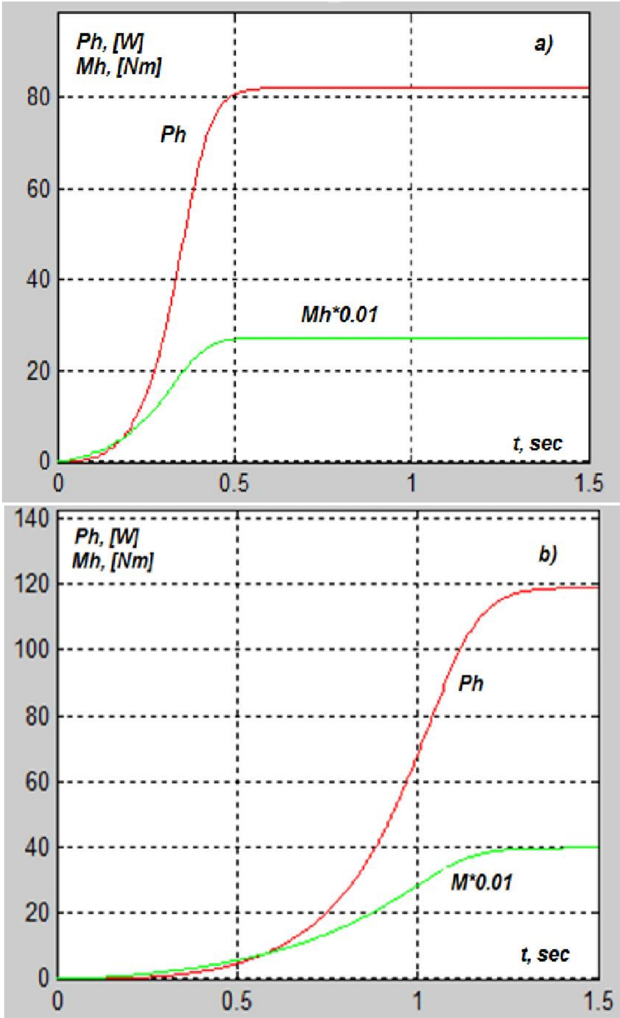

Fig.11. The dynamic hydraulic losses and torque *Ph, Mh=f(t)*