Improving the Quality of the Underwater Robot's Contactless Battery Charging System

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Abstract. A special feature of the contactless battery charging system of an autonomous underwater robot is the use of a transformer with separating primary and secondary windings. As a result, a non-magnetic gap arises, which leads to the need to increase the primary current and the output current of the autonomous inverter. One of the ways to improve the quality of the system is the use of a resonant circuit at the inverter output in combination with the "soft switching" mode of its power switches. The use of resonance on the transformer secondary side also allows you to equalize the current loads of the primary and secondary windings. In this way, a minimum of losses in the inverter is achieved and the power transformer of the system is optimized. This allows you to reduce the size of the system while maintaining the transmitted power, or increase the transmitted power while maintaining the dimensions. The problem solved by using mathematical modelling with verification of the solution adequacy in a full-scale experiment.

1. Introduction
The use of contactless power transmission for batteries charging of an autonomous underwater robot significantly expands the functionality of its application. This is especially important when it is necessary to increase the autonomy of such robot, for example, when servicing underwater mining complexes in the conditions of ice coverage of the water area, or when organizing long-term underwater work of the robot [1-3].

The main functionally necessary elements of the contactless charge system are an autonomous voltage inverter (AVI), a special power transformer and a rectifier. The transformer is made with separating primary and secondary windings. The primary winding is connected to the inverter output, and the secondary winding is connected to the rectifier input. In this case, the inverter with the primary winding is placed on the base, which is, for example, an underwater station. The secondary winding with a rectifier is placed on board the robot. When the robot is moored to the base, the transformer windings are overlapped. Due to the inductive coupling, electricity is transmitted to charge the batteries [4].
The transformer windings are placed in sealed shells, the thickness of the contact surfaces of which is several millimeters. Such a non-magnetic gap in the transformer of the contactless charge system (CCS) leads to a decrease in the magnetic coupling coefficient between the windings. This causes an increased value of the magnetizing component of the transformer input current, which corresponds to an increased output current of the AVI. In general, these factors cause such consequences as the need to choose AVI power elements with high rated currents; an increase in power losses in these semiconductor devices, an increase in their mass and cost; and also create problems of maintaining their thermal modes in the tolerance [5, 6].

The negative nature of these consequences is amplified in the underwater robot energy supply system, since the electronic components of the system must be placed in sealed containers with a dense layout and with limited heat removal capabilities from power devices.

These conditions determine the relevance of the search for solutions that will improve the CCS quality, such as: load current reducing on the AVI power switches and optimizing the transformer weight and dimensions. Ultimately, this should lead to an increase in the device reliability and an increase in the battery contactless charging system efficiency as a whole.

2. **Current unloading of the inverter power switches**

The problem of improving the quality of CCS can be divided into two separate tasks, without mutual influence:
- the first is the current unloading of the inverter power switches by increasing the AVI power factor when compensating for the magnetizing component of the transformer primary current;
- the second is the transformer mass-dimensional optimization.

The result of solving the second problem can be two options, the choice of which is determined by the set requirements for the battery charge parameters (the main ones are the current and charge time), as well as the conditions for placing the receiving part of the CCS on board an autonomous underwater robot. The first option of transformer optimizing allows for the transmission of the required active power value while reducing the transformer mass and dimensions relative to the initial values. The second optimization option is to significantly (several times) increase the transmitted active power while maintaining the original mass and dimensions. The initial mass and dimensions are understood here as the parameters obtained as a result of calculation using a special method for transformers with separable windings without the use of resonant elements [7]. In general, the specified optimization procedure can be considered as a development of this calculation method.

The first problem solution of improving the CCS quality is possible through the use of corrective resonant circuits in combination with the soft switching mode of the inverter power switches [8 ... 10].

It is known that the total power losses on the inverter switches consist of dynamic losses of turning on and off, as well as static losses in the open state of the switch. At the same time, it is considered [11] that the losses from leakage currents in the closed state are small, and they can be ignored. The main attention is paid to minimizing dynamic losses when switching on, which is achieved by creating conditions for the "soft switching" mode when switching on (zero voltage switching – ZVS). At the same time, calculations and experiments show that both dynamic losses during shutdown and power losses on switches in the open state also make a significant contribution to the total amount of losses [12]. This is noticeable when using IGBT transistors as switches. However, for MOSFET-based transistors, the switching losses and conduction losses can be significant. Thus, it is necessary to recognize the actual problem formulation of providing "soft switching" conditions when switching off, which is achieved, obviously, by switching off at zero current-the ZCS (zero current switching) mode. At the same time, the task of reducing the conductivity losses in the open state interval of the switches also deserves attention. Evaluation of the effectiveness of corrective actions on the system here should be performed together with the transmission of an unchanged set value of active power.

As noted above, the presence of a non-magnetic gap in the transformer leads to a decrease in the resistance of the magnetization circuit of the transformer and, accordingly, to an increase in the inductive component of the primary current. Therefore, the compensation of this component can be
performed by a resonant circuit having a capacitive character. The use of a capacitor in its pure form is limited here, since the inverter output signal is formed as rectangular voltage. It is shown in [9] that the best results are obtained by using a series resonant LC-circuit connected at the inverter output in parallel to the primary winding of the transformer. A positive property of this solution is that the inductive component compensation of the inverter output current is carried out without any influence on the shape and values of the transformer windings currents [6]. This reduces the effective value of the inverter output current while maintaining the transmitted active power.

For the first harmonic of the output voltage, the current load on the inverter transistor switches is minimized when the operating frequency \( f \) of the inverter switching and the resonance frequency of the currents \( f_{1I} \) in its load, consisting of the specified LC-circuit and the transformer primary winding with its own inductance \( L_1 \), are equal.

In [5], the concepts of the relative frequency of the current resonance \( n_{1I} = f / f_{1I} \) and the parameter \( m = f_{1I} / f_{1U} \) are introduced, where \( f \) – inverter switching frequency, \( f_{1I} \) – current resonance frequency of the inverter load circuit, \( f_{1U} \) – voltage resonance frequency of the LC-circuit. Also, in [5] the relations that link the specified parameters with the corresponding inductance and capacity values of the LC-circuit are given.

Note that for the first harmonic, the values of the inverter switching frequency \( f \) and the resonance frequency \( f_{1I} \) of the inverter load currents coincide, i.e. the relative frequency \( n_{1I} = f / f_{1I} = 1 \) and this value correspond to the minimum effective value of the inverter output current. For the real inverter output signal in the form of a meander, the value \( n_{1I} \) differs from 1, while the conditions of "soft switching" ZCS and ZVS will correspond to a certain range of relative frequency values \( n_{1I} \).

The study of mathematical models of the system [9, 12], performed in the MatLab, allowed us to establish requirements for the specified range, as well as for the numerical value of the parameter \( m = f_{1U} / f_{1I} \). The obtained values \( n_{1I} \) provide the maximum possible current unload of the inverter transistor switches. The recommendations for choosing the parameter \( m \) correspond to the compromise between the minimum dimensions of the LC-circuit elements with minimal power losses on the inverter switches. The results of the study are shown in figures 1 and 2, where the variables are presented in relative units, and the value of these variables is taken as the base value in the absence of a resonant LC-circuit. Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.
The area on the figure 1, located to the right of the frequency $n_{1l}^{(a)}$, corresponds to the ZCS area (switching at zero current). To the left of the frequency $n_{1l}^{(b)}$ is the ZVS area (switching at zero voltage), which corresponds to the inverter inductive load and is characterized by zero switching losses. Thus, the range of relative frequency values from $n_{1l}^{(a)} \geq 1.09$ to $n_{1l}^{(b)} \leq 1.19$, obtained by mathematical modeling, provides small power losses, both when switching on and off the inverter transistors. In this case, it is advisable to take the relative frequency value closer to the left border of the specified range, for example, $n_{1l} = 1.1$. So, the total losses on the transistors will be minimal. At the same time, it follows from figure 2 that an acceptable combination of inductance and capacitance dimensions with small losses in the inverter corresponds to the range $2 < m < 2.2$. Thus, if we take, for example, $m = 2$, and use this value to determine the optimal value of $n_{1l}$ (figure 1), it is possible to ensure maximum current unload of the inverter switches with minimal dimensions of the resonant LC-circuit elements. In this case, the capacitance $C_{1p}$ and inductance $L_{1p}$ values of this circuit are determined by the functional dependencies $C_{1p} = f(m)$, $L_{1p} = f(m)$, given in [5]. The obtained value $n_{1l}$ allows us to find the inverter frequency $f$, which determines the "soft switching".

3. Contactless charge system transformer optimization

As shown in [7], in the contactless battery charging system of an autonomous underwater robot, it is advisable to use special transformers with cup ferrite cores or with flat ferrite screens. The primary and secondary windings in such transformer should be placed in separate solid shells. In [7], a special method for calculating such transformers is also given, taking into account the non-magnetic gap and the axial displacement between its windings. Each type of transformer design has application features. So, for example, for transformers on cup cores, for a number of reasons, the sizes of the primary and secondary cores are forced to be the same [13]. As a result, the secondary winding is unloaded due to the use of the magnetic circuit window, or due to the current load of the winding wire.

In the accepted formulation of the problem, the mass and size transformer optimization is reduced to ensuring full loading of the secondary winding. The implementation of such optimization on cup cores can be performed by one of two solutions, depending on the set requirements for the charging system. The first solution gives an increase in the power transmitted to charge the batteries while maintaining the dimensions. The second solution makes it possible to reduce the power-to-size ratio of the transformer, while maintaining the set value of the transmitted power.

The initial variant is the characteristics of the charge system obtained using the transformer calculation method [7]. This optimization is based on the use of resonance on the transformer secondary side. One of the options is to connect a resonant capacitor in series with the secondary winding or in parallel with it. This option combines the simplicity of implementation and the efficiency. The choice of the connection method is determined by the conditions for matching the output voltage levels of the secondary winding and the battery voltage. A serial connection allows increasing the charge current, and a parallel connection allows raising the voltage. In the practice of developing underwater robots performed by the Institute of Marine Technology Problems of the Far Eastern Branch of the Russian Academy of Sciences, a variant with a sequential resonant capacitor is more often used.

It is possible to determine the specific capacitance value of a series resonant capacitor based on the analysis of the secondary circuit frequency characteristics of the system. These characteristics are shown in figure 3, where they are shown in relative units of the dependence of the transmitted active power $P_1^*$, the capacitor power-to-size ratio $S_C^*$, as well as the total capacities values of the primary $S_1^*$ and secondary $S_2^*$ circuits as a function of the relative resonant frequency $n_{2l} = f_2 / f_{1l}$. These variables are shown in relative units, where the values of these variables are taken as the base without a resonant capacitor. The choice of the value here is not unambiguous and depends on the desired relationship between the dimensions of the capacitor and the multiplicity of the increase in the transmitted power. For example, if the operating conditions allow a three-fold increase in the transmitted power relative to
the initial value, then the graphs in figure 3 can determine the relative frequency \( n_{2f} = 0.96 \), which, at a given frequency of the inverter \( f \), allows you to determine the frequency \( f_{2i} \) of the currents resonance for the secondary circuit of the system and, accordingly, the capacity of the series resonant capacitor \( C_{P2} \) [8]:

\[
C_{P2} = \frac{1}{4\pi^2 f_{2i}^2 L_2},
\]

where \( L_2 \) – secondary winding inductance of the transformer.

In this case, the system external characteristic takes the form of curve 2 in figure 4, which clearly illustrates the effect of using resonance on the transformer secondary side.

4. Conclusion
Using the proposed options for implementing resonance and providing a "soft switching" mode can significantly reduce losses in the inverter power switches and increase the active power transmitted for the batteries charge of the underwater robot. At the same time, a multiple increase in the quality of the contactless charge system is provided. The power loss in the inverter is reduced by about ten times, and the transmitted power (for the example considered) is increased by three times. The advantages of the proposed solution also include the almost absence of mutual influence of resonant elements on the primary and secondary side of the system. This allows you to independently determine the acceptable costs for current unloading and for increasing the transmitted power.

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