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The Use of Resonance for Current Downloading of the Transistor Keys of the Inverter

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Abstract : The structure of the system of non-contact power transmission to the autonomous unmanned underwater vehicle to charge its batteries was determined. The advantages of such a system were identified, and the autonomous voltage inverter and the high frequency transformer with separated primary and secondary parts were defined as the object of study. The structural feature of the transformer in the form of a non-magnetic gap between its windings, determined by the thickness of the interfacing walls of the connecting sealed envelopes of the transformer parts resulting in the reduced coefficient of magnetic coupling between the windings, as well as in the increased magnetizing current of the transformer, was noted. The task to perform the current downloading of the transistors of the autonomous inverter due to a partial compensation of the inductive component of its output current by including of a resonance circuit into the diagram was set. The analysis of the design circuits for transformer substitution was performed and the use of the option, providing the magnetic decoupling of the magnetically coupled circuits, was justified. The operational linkages between the parameters of the allocated object of study were defined, and the numerical values of the autonomous inverter currents and transformer for the idling and short circuit modes were obtained based on the specific example. The reliability of the conclusions of the theoretical analysis and the results of the analytical calculations were confirmed by the circuit simulation. The requirements for the settings were defined and the compromise approach to the choice of the numerical values of the reactor inductance and capacity of the capacitor of the compensating resonant circuit, acceptable for both idle and short-circuit modes at the output of the high-frequency transformer were proposed. The results of the analysis of the object of study complete with the included resonant circuit prove the current downloading of the transistors of the autonomous inverter by reduction of its output current approximately three times both for the idle mode and for the short-circuit mode while maintaining the values of the power transmitted via the transformer.

Keywords : Non-contact power transmission; autonomous unmanned underwater vehicle; transformer with low coupling coefficient; autonomous inverter; compensating resonant circuit; downloading of the power switches; facilitation of the thermal mode.

1. INTRODUCTION

The storage batteries are used in the majority of applications as the source of energy required for the operation of the autonomous unmanned underwater vehicle (AUUV). They provide the performance of various electronic and sonar systems, underwater lighting equipment, cameras and camcorders; they also supply with power drives for all kinds of actuators and the electric motion and maneuver drives of vehicle. The electric energy of storage batteries, providing a given autonomy of the AUUV of the middle class, reaches thousands of watt-hours.

The continuation of the performance of the AUUV after the completion of its mission requires to charge the batteries, which can be done in various ways. The easiest by hardware implementation, but the most technologically laborious way is to lift the vehicle aboard the support craft and to perform the necessary mounting and switching procedures to charge the batteries using a charger.

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The increase in the efficiency of the process with a significant expansion of the functionality of the application of the AUUV is obtained in case of charging of the batteries by a non-contact electric power transmission method. This process involves a special transformer with separated primary and secondary parts that are durable sealed envelopes with the internal electrical windings of a certain configuration. The primary part of the transformer is placed on the base, and the secondary is installed on the AUUV. When docking the vehicle to the base and combining the contact surfaces of the primary and secondary parts of the transformer, the power transmission is carried out on board the underwater vehicle by the inductive coupling occurring between its windings [1].

The power supply of the primary winding of the transformer is performed using the autonomous voltage inverter (AVI) performing the conversion of the electric power of the base source into the high-frequency voltage, enabling the reduction of the weight and dimensions of the transformer, as well as the provision of the necessary regulation of the transmitted electric power.

Various mooring devices can be used as a base, for example, the charging station, submerged on a sling from the support craft with the help of the special launching and lifting devices. In this case, the power transmission to the AVIs located together with the primary part of the transformer in a charging station, is carried by SPC cable, which in addition to the electrical communication also provides a mechanical power communication between the craft and the charging station, as well as the operation of the information channel between the operator onboard the support craft and the AUUV.

The maximum benefits of the non-contact power transmission method are manifested in case of long-term underwater deployment of the AUUV [2-3]. This method of power transmission, despite a slight complication of the electricity transmission system in comparison with the contact one, has certain advantages, the main of which are the lack of physical and electrical contact and the invariance of the contacting surfaces of the transformer against the inaccurate connection and fouling. Moreover, in some cases, the determining factor in favor of the non-contact method may be such a useful property as the absence of the necessity for the regular maintenance of the system. The flow chart of the non-contact power transmission system to the AUUV is shown in the Figure 1, *a* [4-5].

The components of this system are: the storage battery (AB), the automatic battery charger (ABCh), which together with the secondary winding (T2) of the high-frequency transformer (HFT) are located on the AUUV as well as the autonomous voltage inverter (AVI), the direct voltage transducer (DVT) and the primary winding (T1) of the transformer, located on the demersal mooring device (DMD) [4]. The power source can be located on the shore and supply the power to the DMD via a special underwater cable. Another option is to use the isotope thermoelectric generator, installed on a demersal mooring device.

The AVI converts the input DC voltage into output AC high frequency voltage of rectangular shape which is connected to the primary winding T1. When combining the contact surfaces of the primary and secondary parts of the transformer, the magnetic coupling occurs between its windings and the voltage transformation to the secondary winding is performed.

The primary and the secondary parts of the HFT are separate sealed envelopes with the windings placed inside. Each of the envelopes contains a contact wall made of the insulating material, the thickness of which is up to several millimeters. In the power transmission mode, the winding axes must coincide, and their ends must be at a minimum distance relative to each other [6]. Thus, these windings form a transformer which, due to the presence of the said non-magnetic design gap between the ends of the windings, has the reduced value of the magnetic coupling coefficient k. This coefficient $k = \mathrm{M}/\sqrt{\mathrm{L_1 L_2}}$ is determined by a mutual inductance M between the windings of the transformer, and by the inductances L_1 and L_2 of its primary and secondary windings.

One way of embodiment of the HFT complete with the durable container with the autonomous voltage inverter is shown in the Figure 1, *b* and *c* for a visual representation of the size ratios of the elements included in the power supply system of the AUUV. In case of the diameter of the housings of the transformer equal to 100 mm and the dimensions of the AVI container equal to 500x150 mm, the transmitted active power shall be up to 0.5 kW. The increase in power is easily provided by the increase in the number of HFT, the windings of which are connected in series or in parallel depending on the set of electrical parameters of the transmitted power. In this case, the dimensions of AVI may remain unchanged or increase slightly.

The low value of the coefficient *k* of magnetic coupling between the windings of the transformer results in the increased magnetizing current of the latter and, consequently, the increased power loss in the transistor switches of the autonomous inverter, the output of which is connected to the primary winding T1 of the HFT. This requires the use of additional measures for heat removal from the transistors, which is complicated by the requirement to perform a dense arrangement of the inverter within a durable container limited in dimensions. For this reason, the definition of solutions allowing to reduce the current of the keys of the inverter, while maintaining the values of the transmitted power, seems to be urgent because the reduction of heat load on the electronic components increases the reliability of the device and increases the efficiency of the process of the non-contact charge of the batteries of the underwater vehicle as a whole.

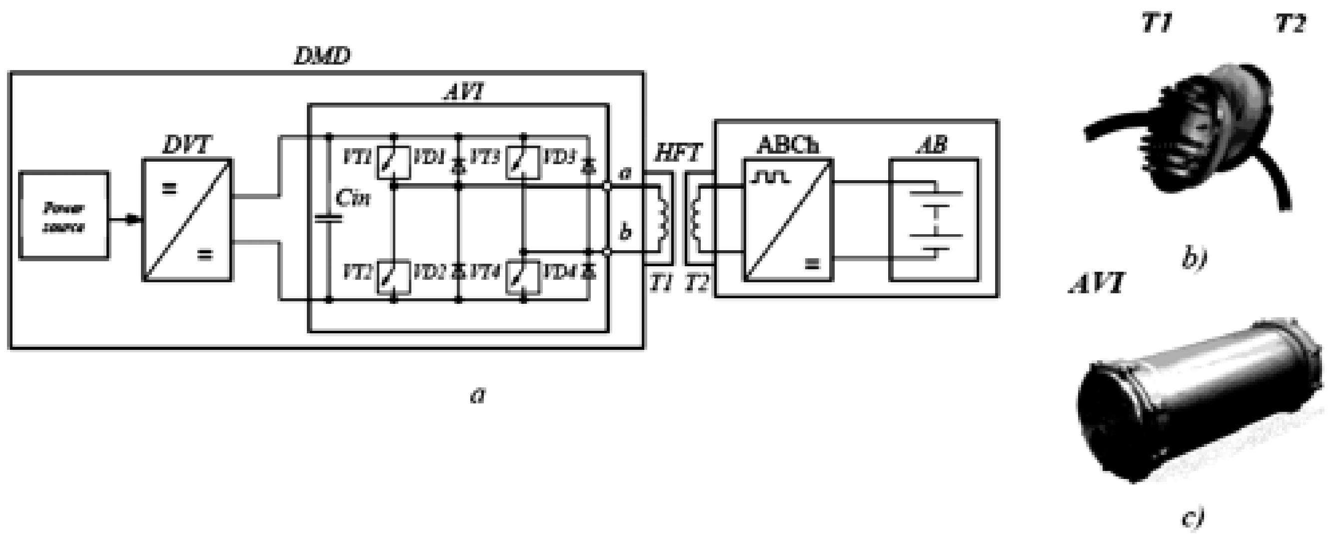

Fig. 1. The power supply system of the AUUV with the non-contact power transmission: (*a*) the flow chart; and the components: (*b*) – high frequency transformer; (*c*) – sealed container with the AVI.

The analysis of performance of the autonomous voltage inverter

The reliability of pulse transducers, including AVI, consisting of transistors and included anti-parallel diodes, is also dependent on the measures taken to protect the power keys from the surge, the level of which is determined by the parasitic inductances of the installation as well as by the values of the load current and frequency of switching. In the process of design of the inverter, it is necessary to adhere to certain recommendations, which are reduced to an appropriate choice of the inverter snubber circuits, as well as to the implementation of the installation with minimum parasitic inductance [7].

To ensure the operation of the AVI, the electronic key control drivers (transistors) are used in each pillar of the bridge. The driver forms a necessary interval, known as the “dead time”, in order to avoid short-circuit of one of the pillars of the bridge. The embodiments of the galvanic isolation of the driver and the inverter key can vary, for example, the bootstrap control circuit or the pulse transformer, or the optoelectronic separation of the isolated channels for the upper and lower arms of each pillar of the inverter may be used [7-8]. The common requirement for any of these methods is to provide a shift of the voltage level for the control of the upper keys of the pillars of the bridge. Since the performance of the autonomous inverter in the asymmetrical conditions with the variable coefficient of control pulse stuffing with its power keys is possible, then the application of the first two methods is limited and the optoelectronic galvanic separation of the control signals for the upper and lower keys of each pillar is preferable [4].

As already noted, the low value of the power coefficient of the AVI is a consequence of the low value of the coupling coefficient between the spaced windings of the transformer. The increased value of the magnetizing component of the input current of the transformer is equivalent to the increase of the inverter output current, and this current is increased several times compared to the minimum necessary value determined by the load of the transformer at its secondary side. This situation causes the following effects: the need to select the AVI transistors and diodes with oversized current ratings; the increase in power losses in these semiconductor devices, their mass and cost; the complication of the problem of heat removal corresponding to the additional power losses.

The negative nature of these effects is amplified in the power supply system of the underwater vehicle, as the electronic components should be placed in sealed containers with a tight layout and limited possibility to remove heat from the power devices.

The solution of the problem of current downloading of the keys can be found in the form of such AVI load structure at which a compensation of a certain percentage of the magnetizing component of the input current of the transformer is performed. Since this component is inductive, the compensation should be performed by a component having the load of capacitive nature. The application of a pure capacitor is limited here, because at the output of the inverter the voltage of rectangular shape is formed.

One method of current downloading of the power switches of the bridge inverter is the inclusion of the L-type filter for the low frequencies at the output [9]. This solution allows to download the AVI keys, however, due to the voltage drop across the reactor, external transformer characteristic is distorted, and as a result, the transmitted power is reduced.

The resonance serial LC-circuit, which is included at the inverter output in parallel to the transformer primary windings, is noteworthy [10]. This scheme also reduces the current of the inverter, but has virtually has no effect on the shape and the values of the currents of the transformer windings. When configuring the resonant circuit to the maximum compensation in the idle mode, the minimum inverter current value is achieved by the following conditions:

$$\left\{\begin{aligned} &\frac{1}{2\pi f\,C_{REZ}} - 2\pi f\,L_{REZ} = 2\pi f\,L_1 \\ &L_{REZ}\,C_{REZ} = \frac{1}{(2\pi m f)^2} \end{aligned}\right\}, \tag{1}$$

where m is the ratio of the own frequency of the resonant circuit to the operative switching frequency of the AVI: $m = f_0 / f > 1$.

The result of the system of equations (1) is the expressions, defining the reactor inductance L_{REZ} and capacity of the capacitor C_{REZ} of the serial resonant circuit:

$$L_{REZ} = \frac{L_1}{m^2 - 1}$$

$$C_{REZ} = \frac{m^2 - 1}{(2\pi m f)^2 L_1}. \tag{2}$$

The formulas (2) show that the closer the parameter m is to the unity, when the resonance frequency f_0 approaches the AVI switching frequency f, the lower is C_{REZ} capacity and the higher is L_{REZ} inductance. The last manifestation of reduction of the frequency f_0 results in the greater suppression of the higher harmonics of the resonant circuit current and the reduction of the active current of the inverter keys. However, at such circumstances the voltage, the size, the weight and the cost of the reactor L_{REZ} and the condenser S_{REZ} are increased. The parameter m should be selected taking into account all these circumstances. To determine the parameter m and the numerical values of the resonant circuit parameters, the computer simulation was carried out, the results of which are shown below.

The simulation of the power transmission system

A deeper analysis of the non-contact power transmission system can be performed by computer simulation via Simulink application of MATLAB software. The general scheme of the model and the schemes of the model of the individual units included in the power transmission structure are shown in Figure 2.

The scheme of the model (Figure 2, *a*) corresponds to the assumed design scheme of power transmission to the AUUV. This scheme includes a constant voltage source (Source), the autonomous voltage inverter (Inverter), a high-frequency transformer with the serial resonant LC-circuit, connected in parallel to its primary winding (LCT), a voltage rectifier (Rect) and a load (Load).

The Figure 2, *b* shows the scheme of the model of the DC voltage source. In the simulation of the voltage source, its inductive and active resistance, denoted as L0, were taken into account. The capacitor C_{IN} is the input filter capacitor of the autonomous inverter; the diode (Diode), included in the source, is necessary to prevent the discharge of the input capacitor C_{IN}

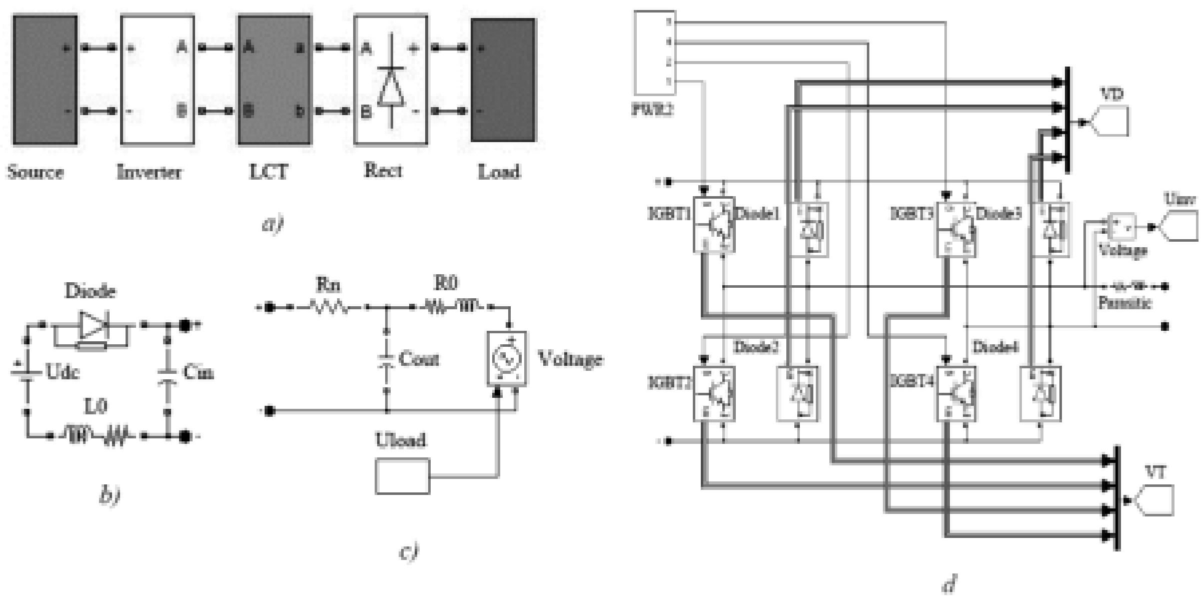

Fig. 2. The simulation of the electric power transmission via Simulink MATLAB software: (*a*) – assumed power transmission design model, (*b*) – constant voltage source model, (*c*) – load unit model, (*d*) – autonomous voltage inverter model.

The scheme of the load unit model is shown in the Figure 2, *c*. The components of this scheme are the resistor R*n*, taking into account the resistance of the wires, the rectifier output capacitor C_{OUT}, the voltage source (Voltage), as well as the active and inductive resistances designated as R0, taking into account the parasitic inductance of the wires. The voltage source (Voltage) is the back emf, controlled by the Uload unit. Such a structure of the model building is necessary in order to determine the external characteristics $U_H = f(I_H)$ of the power transmission channel for the source system, and for the case of application of the resonant circuit.

The AVI Model (Figure 2, *d*) is made up of discrete components of the MATLAB SPS library, collected according to a bridge circuit of inclusion. Each arm is represented by the transistors and diodes included in parallel, which allows to take into account more completely the properties of the components of the inverter bridge circuit.

The control over the transistor gates is performed by the unit (PWR2), generating the control pulses with a coefficient of charge close to unity minus the low value of the “dead time”. The inductive and the active resistance (Parasitic) simulate the parasitic inductance and the ohmic resistance of the input capacitor C_{IN} and the AVI transistors.

The dependences of the relative reactive powers of the components of the resonant circuit and the inverter output power on the relative frequency m (Figure 3) were obtained as the result of the simulation. The analysis of these dependences showed that the most balanced value of the relative frequency is $m = 1.5$. This value provides a compromise between the losses on the keys of the inverter and the power values of reactive components of the resonant circuit. According to the formulas (2) for $m = 1.5$, the following values of the resonant circuit parameters were obtained: L_{REZ} = 108 uH, C_{REZ} = 0.272 microfarads, given that they must be calculated for a current of about 20 A.

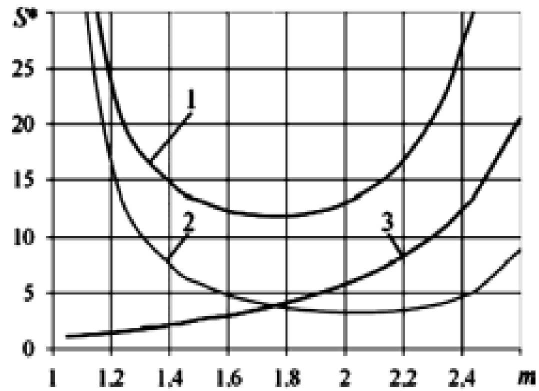

Fig. 3. The dependence of the relative power S* on the relative frequency *m*: 1 – of the resonant circuit capacitor; 2 – of the resonant circuit reactor; 3 – of the inverter

The simulation has also resulted in the assessment of the effectiveness of the proposed serial resonant circuit. The external characteristics of the non-contact power transmission channel, *i.e*. the dependence of the rectified voltage U_H on the load current I_H may serve as the sufficiently informative criterion for this assessment. Moreover, the quantitative result of the solution of the problem, measured by the degree of downloading of the inverter keys, is also important. The removed dependences $U_H = f(I_H)$, and the dependences on the inverter current I_{INV} on the load current I_H for the initial embodiment of a system and for the case of the introduction of the compensating resonant circuit are shown in the Figure 4, *a* and *b*. The results of computer simulation show that at the essentially constant transmitted power the introduction of the resonant circuit allowed to reduce the current of the inverter keys 2.5 ... 3 times.

2. CONCLUSIONS

The results of the analysis of the performance of the inverter when used to power the load via the transformer with the low coupling coefficient between its windings, in case of the inclusion of the proposed resonant circuit into the composition of the inverter, showed the achievement of this objective. Such a solution allowed to reduce the current of the inverter power keys, while maintaining the transmitted power, approximately three-fold.

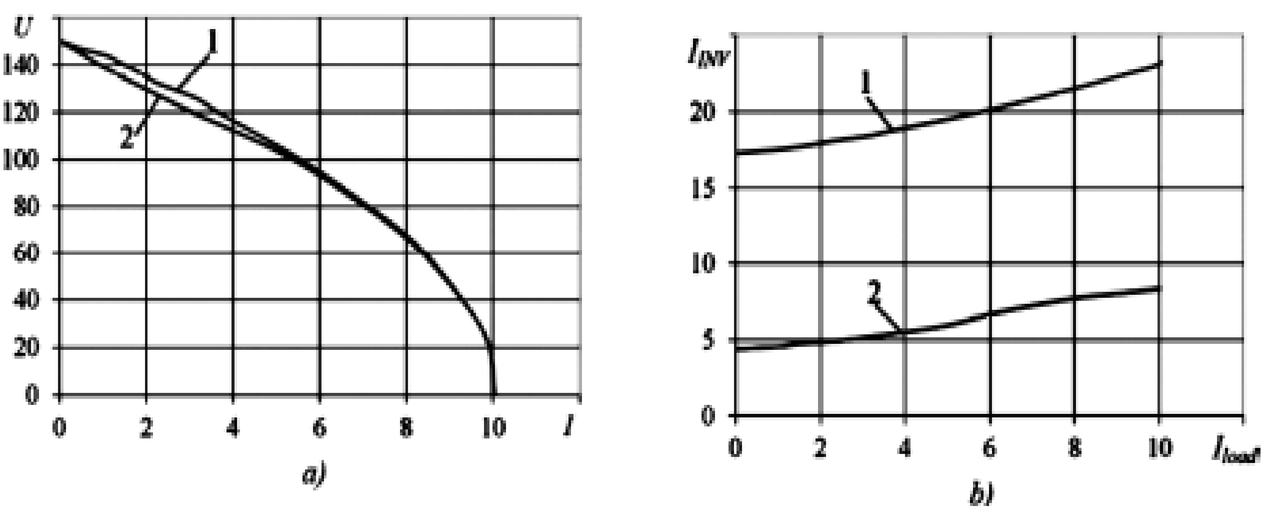

Fig. 4. The characteristics of non-contact power transmission system: *a* – external; *b* – the dependence of the inverter current I_{INV} on the load current I_H; (1 – without a resonant circuit, 2 – using a resonant circuit)

This advantage provides a variety of the inverter transistors and diodes with the reduced rated current; it allows to reduce the power loss in these semiconductor devices, their weight and cost, and facilitates the removal of heat corresponding to these losses.

The results obtained are of particular relevance when using the inverter as part of the non-contact system for power transmission to the autonomous unmanned underwater vehicle. The patent for the invention RU 2558681 has been obtained for this technical solution [10].

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