Voltage stabilizer in power supply of underwater vehicle

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Abstract. The technique of the transfer function development is described. The results simulated by comparison of stabilizers are presented.

1. Introduction
Based on the modern theory for linear systems, the tested controller design techniques involve the approximation of nonlinear controlled objects by the linearized state-space models [1-4]. Moreover, the numerical description of the objects such as the power supply system (PSS) of a remotely operated underwater vehicle (ROV) is connected with some crucial difficulties related to the relevant analytic representation of the discrete continuous processes in an autonomous voltage source inverter and a strength-power communication cable.

To design controllers, the equivalent transfer functions can be used in the stabilizing systems for the power supply output variable in complex technical objects. The further rearrangement of algebraic operator equations which characterize the input-output relationship in a differential form is quite trivial. The obtained numerical models in the form of deterministic differential equations make it possible to consider the inside and outside nonlinear disturbance as well as random initial operation conditions of a controlled object.

2. Materials and methods
Using the transfer functions, let us consider the synthesis problem of the optimal stabilizer in the ROV power supply [5, 6] with the direct current supply via a strength-power communication cable. The operating diagram of the ROV power supply is presented in Figure 1. The onboard PSS consists of a three phase rectifier, the F1 input filter, an autonomous voltage source inverter, a TV1 step up transformer, a bridge circuit rectifier and its filter F2, the CSD current sensor and a VSD voltage sensor. The underwater part of the power supply includes deep diving devices DDD and ROV. ROV with the N3 and N4 loads is connected with DDD via buoyant cable BC. The deep diving device along with the load includes balancing system BS as well. The underwater PSS is connected with the onboard part through strength-power communication cable SPCC.
In this paper, a simplified electric circuit of the ROV power supply (Figure 2) without the three phase rectifier filter and the balancing system was studied. The operating principle involves the conversion of the three-phase voltage at the VD1...VD6 three phase rectifier input into the Ud1 rectified voltage. The Ud1 voltage is imposed to the VT1...VT4 autonomous voltage inverter. The converted AC voltage U1 with the frequency of 1000 Hz is increased with the TV1 transformer to balance the voltage drop at the resistance of the strength-power communication cable. Increased AC voltage U2 is converted via the VD7...VD10 bridge rectifier into the DC voltage Ud2. The rectifier filter, which includes the L1 inductance and the C1 capacitance, provides the required voltage ripple factor for Ud2. Then, the voltage is imposed to the DDD and ROV loads via the C2 capacitor filter.

One of the ways to record the total transfer function for the open loop system is the use of a prior data about the transfer functions of each element in the power supply. Another technique is based on the obtaining the output transient response of a certain system part. In that case, the transition to the power supply structure in terms of transfer functions is based on the numerical simulation of the processes in the controlled object. Principles of the numerical simulation of the similar PSS were studied in following papers [7, 8]. It should be noticed that the object simulation essentially simplifies the numerical operations on identifying the transfer function type. The identification of the transfer function finite order in the open loop power supply is a necessary stage in both techniques. The simplified diagram of the studied power supply in the operator form is presented in Figure 3. The diagram consists of the transfer functions of the controlled object WCO(p), which includes the transfer functions of autonomous voltage source inverter WAVI(p), the step-up transformer with magnetic bias circuit WTV(p), bridge rectifier WTV(p) and filter WF1(p), strength power communication cable WSPCC(p) and capacity filter WF2(p).

![Figure 1. The power supply operating diagram of a remotely operated underwater vehicle](image1)

![Figure 2. The simplified power supply operating diagram of a remotely operated underwater vehicle](image2)

![Figure 3. The simplified diagram of the power supply presented in a chart of transfer functions](image3)
The reduction in time for obtaining the object transfer function was due to the System Identification, an embedded MatLab tool. After setting the initial data in the Transfer Function Models, the calculation method (continuous or discrete) as well as the polynomial degree were defined. As a result, a non-canonical view of the transfer function, the approximation accuracy and the root mean square of approximation error were obtained.

The techniques of the optimal system design providing the technical (TO) or modulus optimum (MO) can be used to define the stabilizer parameters [1-4]. With the set of technical optimum, the transfer function of the closed object was recorded, as follows:

\[ W_{wo}(p) = \frac{1}{2T_{\mu} \cdot p \cdot (T_{\mu} \cdot p + 1)}, \]

where \( T_{\mu} \) is the equivalent non-compensated time constant.

The controller transfer function was obtained from the following equation:

\[ W_c(p) = \frac{W_o(p)}{W_{wo}(p)}, \]

where \( W_o(p) \) is the transfer function of the open loop controlled object.

The modulus optimum setting is based on the selection of the characteristic polynomial of the close loop system and the evaluation of the controller feasibility which is defined with following equations:

\[ n_G \leq n_M + n_N + 1; \]
\[ n_{R^+} + n_M \leq n_{P^{-}} + n_N + r; \]
\[ n_G = n_{R^+} + n_N + r; \]

where \( n_G \) is the normed polynomial degree of the required function; \( n_{R^+}, n_{P^{-}} \) are the polynomial degrees with negative zeros and poles; \( n_{R^+} \) is the polynomial degree with zero and positive zeros; \( n_M, n_N \) are the undetermined polynomial degrees; \( r \) is the disturbance related degree which defines the degree of the steady-state deviation.

The feasibility provided the obtaining \( M(p) \) and \( N(p) \), the unknown polynomials, from the equation:

\[ P^*(p) \cdot M(p) + R^*(p) \cdot N(p) \cdot p^r = G(p). \]

As a result, the authors obtained the controller transfer function:

\[ W_c(p) = \frac{R^*(p) \cdot M(p)}{P^*(p) \cdot N(p) \cdot p^r}. \]

Using the described setting techniques for the power supply controller with calculated parameters (Table 1), the relevant transfer functions were defined with the following equations:

\[ W_{c,0}(p) = 176.627 + \frac{3.087 \cdot 10^4}{p}; \]
\[ W_{c,mo}(p) = \frac{137.931 \cdot (1.497 \cdot 10^-7 \cdot p^2 + 8.749 \cdot 10^-3 \cdot p + 1)}{p \cdot (6.734 \cdot 10^-5 \cdot p^2 + 0.011 \cdot p + 1)}. \]

3. Results

To compare the efficiency of controllers, a model simulated in the MatLab Simulink (Figure 4) was used with the calculated parameters summarised in Table 1. The simulation was carried out with following assumptions: semiconductor elements were considered to be ideal; the strength-power communication cable parameters were represented as two wires with lumped elements, on- and off-load rates were simulated by counter electromotive force of 10.8 V/ms.
Figure 4. The MatLab Simulink designed model of the remotely operated underwater vehicle DC power supply via a strength-power communication cable

Table 1. Simulation parameters of the remotely operated underwater vehicle DC power supply system via a strength-power communication cable

| Parameter                                      | Name       | Value   |
|------------------------------------------------|------------|---------|
| Phase voltage, V                               | $U_A, U_B, U_C$ | 220     |
| Output voltage frequency, Hz                   | $F_{AIN}$  | 1000    |
| Transform factor TV1                           | $K_{fr}$   | 0.1217  |
| Filter inductance of the single-phase bridge rectifier, mH | $L_1$ | 500     |
| Filter capacitance of the single-phase bridge rectifier, µF | $C_1$   | 1.8     |
| Strength-power communication cable resistance, Ohm | $R_K$ | 11.667  |
| Strength-power communication cable inductance, mH | $L_K$   | 8.5     |
| Load filter capacitance, µF                    | $C_2$ | 60      |
| Load resistance, Ohm                           | $R_n$ | 30.638  |
| Load current, A                                | $I_n$ | 39.17   |

Figure 5. Waveforms of the output voltage in the onboard power supply system with controllers set on the technical (red) and modulus optimum (black)

The waveforms (Figure 5) display the smooth voltage increase at the start of power supply when controllers were set on the technical and modulus optimum. When the PI-controller was used, there was no delay, but the 20% overshoot occurred at the start point, the transit time was 54 ms, the voltage change rate at the on- and off-load was 8.3 V/ms. Using the modulus controller, there was no overshoot
at the start point, but there was a 3 ms delay, the transit time was 40 ms, the voltage change rate at the on- and off-load was 8.9 V/ms.

![Figure 6. Waveforms of the output voltage in the underwater power supply system with controllers set on the technical (red) and modulus optimum (black) (0.1)](image)

When the PI-controller was used, the load voltage compensation at the on- and off-load (Figure 6) was ±1% with the voltage ripple factor of 0.09%. The modulus controller provided the load voltage compensation within the range of ±10% with the voltage ripple factor of 0.17%.

4. Conclusion

The main summary and results of the research are as follows:

1. The use of a real integral transformation and the MatLab System Identification built-in tool simplifies the synthesis of the object transfer function with a high degree of approximation (over 95% under the correct selection of the transfer function order).
2. Tuning on the modulus optimum is more flexible than the technical optimum tuning.
3. The modulus optimum tuned controller takes a form of a non-standard controller which makes its implementation with a microcontroller more difficult.

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