Closed-loop power supply for an autonomous object with a DC power transmission line and voltage drop compensation

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Abstract. The paper considers a closed-loop power supply for an autonomous object that is operated remotely. The power to the object is delivered via a direct current (DC) power transmission line representing a three-wire cable. The length of the cable is considered to be 8 km. The model in MATLAB Simulink has been created to investigate the essentials of the power supply operation and adjust the voltage controller. To compensate the voltage drop across the cable (over 500 V) the current signal correction was introduced. This correction proved to be a reliable method to provide a stable load voltage of 1200 V ± 2% in steady-state operating modes of electric equipment within the autonomous object structure. This will significantly enhance the overall performance of the equipment that is placed on the considerable distance from the power supply.

1. Introduction
Currently, stable power supplies for autonomous objects have significant impact on the performance of the electric equipment, manipulators and other tools arranged within the objects. Here we consider such autonomous objects as submersible pumps [1], remotely operated vehicles [2, 3], and other objects that perform useful functions far away from the power supply and linked to it via a long cable. For our purposes we consider a three-wire cable 8 km long.

One of the up-to-date problems during the design of the power supplies is power quality enhancement. This problem is well-investigated for the alternating current (AC) power supplies and there are a bunch of state-of-the-art solutions such as [4, 5]. Moreover, there is a broad class of devices referred to as power quality conditioners [6] that allow to mitigate voltage disturbances occurring in AC power systems and improve the electric power quality. In this paper we propose to modify a structure of a power supply [7] that combines AC and DC parts and employs a voltage feedback by implementing a voltage drop compensation. That would help improve the overall performance of the electric equipment that operates on a considerable distance from the power source. The structure under design may be referred to as an HVDC system with a DC transmission line with a three-level inverter as an AC link. Therefore, the major problem that we address here is to provide a constant level of the load voltage taking into account the voltage drop across the cable and possible load variation by 10% around its nominal value.

2. Block Diagram of the Power Supply
We adopted a block diagram from [7] and added to it a voltage drop compensation. The resulting block diagram is portrayed in Figure 1.
Accepted designations and parameters: $U_{ref}$ is the reference voltage in p.u.; $i(t)$ and is the current measured near the power supply on the filter output 1, $i'(t)$ is a disturbance signal, corresponding the current $i(t)$ and aimed at compensating the voltage drop across the cable; $U(t)$ is the voltage applied between the power terminals 1 and 2, $U'(t)$ is its signal taking into account the feedback coefficient $k_{fb} = 1/U_{max}$, where $U_{max} = 2730$ V is the maximum voltage of the power supply; $\xi$ is the error applied to the controller that form a control signal $m$ representing modulation index to drive the 4 power switches of the three-level inverter. The cable is considered as a lumped parameter system since it carries a DC current.

The crucial part of the power supply is a DC power transmission line (cable). Therefore, to improve the quality of power supply we need to provide the stable level of voltage not only in the vicinity of power supply but also at the load to ensure its rated voltage far away from the source of electric energy. Hence, we are aimed primarily on voltage drop compensation across the cable that delivers DC power to the autonomous object.

In the block diagram (Figure 1) the voltage drop compensation is realized through the positive current feedback that implies using a disturbance signal $i'(t)$ to provide a constant level of the load voltage [8]. We assume that this method will not affect the stability of the system since the signal correction used does not change its structure during the control process. A block representing the dependence of the disturbance signal $i'(t)$ on the current value $i(t)$ is embraced in a dashed rectangle. It represents a linear link with saturation to ensure the proper behavior of the power supply during its starting.

In Figure 2 we demonstrate the power circuit of the block diagram (Figure 1).
Accepted designations and their values: $E = 540$ V is the DC source voltage, $R_E = 20$ mΩ is its internal resistance; $C_1$, $C_2$ are the input capacitors (480 μF); $VT_1$…$VT_4$ are power MOSFETs of the three-level inverter, $VD_1$…$VD_6$ are its diodes; $TV$ is the transformer with two secondary windings; the diodes of the two bridge rectifiers connected to secondary windings of the transformer $TV$ are not marked; $L_f = 20$ mH, $C_f = 210$ μF are the filter inductances and capacitances, accordingly; $L_c = 17$ mH, $R_c = 12$ Ω are the cable inductances and resistances, accordingly; $R_{load} = 15.2$ Ω is the rated load equivalent resistance (the two resistors are considered to be the same and can be varied simultaneously by ±10% with respect to the rated value); 1, 2 are the power terminals where we acquire output voltage $U(t)$ and current $i(t)$ used to the control system.

3. Voltage Controller Adjustment
The method of voltage controller adjustment is represented in [7]. There we used the Real Interpolation Method [9] that implements a frequency response to obtain an open-loop transfer function of the system under study. We considered the signal $U_{ref}$ as an input and the voltage $U$, which is measured between the points 1 and 2 (Figures 1, 2), as an output of the system. We acquired the transfer function in the following form:

$$W_o(s) = \frac{b_3 s + b_2}{q_3 s^3 + q_2 s^2 + q_1 s + q_0},$$

(1)

where $q_0 = 1$, $q_1 = 4.4 \cdot 10^{-3}$, $q_2 = 7.26 \cdot 10^{-6}$, $q_3 = 1.33 \cdot 10^{-8}$, $b_0 = 1$, $b_1 = 3 \cdot 10^{-3}$ are a set of parameters. A complete procedure of parameter estimation, related to the power supply, is given in [7].

It should be emphasized that we cannot use the load voltage signal as an output since it is measured at the far end of the cable and this signal will come to the control system with a significant delay. Though, we are able to observe the load voltage via the optic channel embedded into the cable construction.

Within the scope of this paper we will use modular optimal adjustment [10] corresponding to the following desirable expression of the transfer function:

$$W_{MO}(s) = \frac{1}{k_{opt} \cdot T_o \cdot s \cdot (T_o \cdot s + 1)},$$

(2)

where $k_{opt} = 4$ is the coefficient of optimization, $T_o$ is the time constant that affects both the response time and overshooting of the voltage curve registered in the closed-loop system. For our experiment we accepted $T_o = q_1 = 4.4 \cdot 10^{-3}$ sec, since other higher order parameters in the denominator of expression (1) are negligibly small.

To find a transfer function of the voltage controller we divide expression (2) by (1):
\[ W_{\text{cont}}(s) = \frac{W_{\text{MO}}(s)}{W_{O}(s)} = \frac{q_{3}s^3 + q_{2}s^2 + q_{1}s + 1}{k_{\text{cap}}q_{1}s(q_{1}s + 1)(p_{1}s + 1)}. \]  

(3)

Although this controller gives a stable voltage \( U(t) \) at the filter output terminals, it cannot provide a stable voltage \( U_{\text{load}} \) across the load within the error band of 2% \([7]\). When the load is changed by 10% the load voltage deviation exceeds 5% around its rated value of 1200 V. So, we generate the disturbance signal \( i^*(t) \) and add it to the reference signal to compensate the voltage drop across the cable and will probably ensure the level of the load voltage within 2% around its nominal value. To check this issue we designed an experiment in MATLAB 2019b Simulink.

4. Experiment

In Figure 3 we demonstrate the modified control system assuming that the electric circuit of the power supply (Figure 2) looks very similar to its Simulink model and is easy to replicate.

![Control system of the power supply in MATLAB Simulink with voltage drop compensation.](image)

In this block diagram all the values correspond to that given in Figure 1. The frequency of the output voltage of the three-level inverter equals 1 kHz. The value of the carrier frequency used to perform PWM is 48 kHz. The voltage controller is represented by the fraction \( n/d \), where \( n = n(s) \) is the numerator of the transfer function (3), \( d = d(s) \) is its denominator. The function \( f(u) \) calculates the disturbance signal \( i^*(t) \). This function was found during the ground testing the following way. First, it was determined that at current \( I_1 = 37.2 \) A (corresponds to 10% decrease of the load resistance \( R_{\text{load}} \)) we need to add disturbance signal \( I_1^* = -0.018 \) to the reference signal \( U_{\text{ref}} \) to get the rated load voltage \( U_{\text{load}} = 1200 \) V. Similarly at \( I_2 = 41.6 \) A (corresponds to 10% increase of the load resistance \( R_{\text{load}} \)) we should apply \( I_2^* = 0.023 \). Therefore, we assumed a linear relation:

\[ \frac{i^*(t) - I_1^*}{I_2^* - I_1^*} = \frac{i(t) - I_1}{I_2 - I_1}, \]

and derived the following function:

\[ i^*(t) = a \cdot i(t) + b \]

(4)

where

\[ a = \frac{I_2^* - I_1^*}{I_2 - I_1} = \frac{0.023 - (-0.018)}{41.6 - 37.2} = 0.0093, \quad b = \frac{I_2^* - I_1^*}{I_2 - I_1} + I_1^* = \frac{0.023 - (-0.018)}{41.6 - 37.2} \cdot 37.2 - 0.018 = -0.3646. \]

Hence, expression (4) is used to calculate the disturbance signal \( i^*(t) \) that we need to add to the reference one \( U_{\text{ref}} \) to provide the rated load voltage of 1200 V when the equivalent load resistance \( R_{\text{load}} \) vary by 10% down and up at times 0.1 and 0.2 sec. In Figures 4 and 5 we illustrate the simulation results of the original and modified structures under specified load variation, correspondingly. The voltage drop across the cable and the disturbance signal \( i^*(t) \) for the modified structure are depicted in Figure 6.
Figure 4. Waveforms of the load voltage $U_{\text{load}}(t)$ and the current $i(t)$ measured at the terminal 1 in the original structure of the control system.

Figure 5. Waveforms of the load voltage $U_{\text{load}}(t)$ and the current $i(t)$ measured at the terminal 1 in the modified structure of the control system.

The load voltage waveform (Figure 5) demonstrates that using the proposed method we provide the desired voltage value of $1200 \, \text{V} \pm 2\%$, thus, compensating both the load voltage drop (Figure 4) and the voltage drop across the cable (Figure 6) in all acceptable operating modes (the equivalent load resistance is changed within 10% around its nominal value).
5. Discussion and Conclusion

Thus, consideration and comparison of Figures 4 and 5 confirm that the method we implemented to compensate the voltage drop across the cable is valid for the power supply design. At time $t_2 = 0.2$ sec we observe a voltage surge of 1470 V when the load resistance is increased by 10%. This is acceptable since the duration of the surge is short and relay protection devices within the autonomous object are properly tuned.

The disturbance signal $i^*(t)$ correlates with the voltage drop waveform $U_{\text{drop}}(t)$ (Figure 6) except for times $t_1$ and $t_2$, at which we see surges in the voltage drop curve. So, the signal $i^*(t)$ can serve a reliable indicator for the voltage drop across the cable. Though we limit the disturbance signal within the range $-0.05...0.05$ so as to mitigate its effect when the voltage is out of the operating range (at start).

The model of the closed-loop power supply created in MATLAB Simulink can be employed when designing power supplies containing DC transmission lines with significant voltage drops of up to several hundred of volts.

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Figure 6. Waveforms of the voltage drop across the cable $U_{\text{drop}}(t)$ and the disturbance signal $i^*(t)$.