Automatic control systems with a synthesis of the transmitting function of single-cycle DC/DC converters

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Abstract. The article describes the effect of reducing general operating speed of the automatic control system which deteriorates the performance. Synthesis of the response function of the pulse converter was analyzed. The function takes into account the time of an electromagnetic transient process of the single-cycle converter. A mathematical model of the DC/DC converter as part of the element base of an adjustable electric drive was built.

1. Introduction
Currently, it is assumed that the impulse response function of the converter is lag-free, or the time of an electromagnetic transient single-cycle converter is lower than the time required for establishing a steady state signal of the automatic control system which reduces the overall performance of the automatic control system and deteriorates operational characteristics of a device.

Time required for the converter change the current of an engine from a minimum to a maximum value depends on the engine inductance and is not a constant value. It is necessary to build a mathematical model of the DC/DC converter as part of the controlled electric drive.

2. Mathematical modeling of the converter
In order for the simulation results to be used when debugging a real circuit, the model should demonstrate principles of operation and reflect basic processes. Another important function of the model is its use for when synthesizing and debugging the automatic control system.

Before building a mathematical model of the DC/DC converter, it is useful to analyze its operating modes. The DC converter can be considered in the following states: the semiconductor transistor is open, energy is accumulated; the semiconductor is closed, accumulated energy is transferred to the load. Let us describe single-cycle converters: a buck converter and a boost converter. For accuracy of the experiment, let us take the value of the converter so that its control characteristic will be the dependence of the load current on the fill factor.

All simplified states of the converters can be represented by equivalent substitution circuits in Fig. 1.
The following notation is used:
L - inductor inductance,
R - active resistance of the throttle,
RT - active internal resistance of the transistor and conductors,
E - EMF of the power source, voltage at power terminals of the converter considered stabilized,
UN - counter-EMF load.

3. Buck converter
The simplified electrical circuit of the single-cycle converter is shown in Fig. 1a.

During pulse ti, when the transistor is open (Fig.2,c), the current flowing through inductance L increases:

$$I_1 = \frac{E - U_n}{R + R_T} \cdot \left(1 - e^{-\frac{R_T + R}{L} t_i}\right) + I_0 \cdot e^{-\frac{R_T + R}{L} t_i},$$  \hspace{1cm} (1)

where $I_1, I_0$ - current inductance after time ti and before it, respectively.

During pause $t_p$, when the transistor is closed (Fig. 2d), the current flowing through inductance L decreases:

$$I_2 = -\frac{U_n}{R} \cdot \left(1 - e^{-\frac{R}{L} t_p}\right) + I_1 \cdot e^{-\frac{R}{L} t_p}.$$ \hspace{1cm} (2)

Substituting (1) into (2), we can obtain the recurrent expression for calculating the current flowing through the inductance

$$I_2 = -\frac{U_n}{R} \cdot \left(1 - e^{-\frac{R}{L} t_p}\right) + \left(\frac{E - U_n}{R_T + R} \cdot \left(1 - e^{-\frac{R_T + R}{L} t_i}\right) + I_0 \cdot e^{-\frac{R_T + R}{L} t_i}\right) \cdot e^{-\frac{R}{L} (1-D)},$$ \hspace{1cm} (3)

where $D = t_i/(t_i + t_p) = t_i/T$ is the fill factor equal to the ratio of the pulse duration to the period
Setting $R = R_T = 0.01\text{Ohm}$, $L = 1\text{mH}$, $E = 10V$, $U_N = 11V$, $T = 20\mu s$, we can obtain a family of curves establishing the load current of the converter at different fill factors (Fig. 2).

![Figure 2. The family of transfer function curves for the buck converter](image)

As can be seen from Fig. 3, the time required for setting the current in load $I$ depends on the fill factor $D$.

4. **Boost converter**

A simplified circuit of the single-cycle converter is shown in Figure 1b.

When the transistor is open (Fig. 2a), the current flowing through inductance $L$ increases:

$$I_1 = \frac{E}{R + R_T} \left(1 - e^{-\frac{R_T + R}{L}t_1}\right) + I_0 \cdot e^{-\frac{R_T + R}{L}t_1}.$$  \hspace{1cm} (4)

During pause $t_p$ when the transistor is closed (Fig. 2b), the current flowing through inductance $L$ decreases:

$$I_2 = \frac{E - U_N}{R} \cdot \left(1 - e^{-\frac{R}{L}t_p}\right) + I_1 \cdot e^{-\frac{R}{L}t_p}.$$ \hspace{1cm} (5)

Substituting (4) into (5), we can obtain the recurrent expression for calculating the current flowing through the inductance:

$$I_2 = \frac{E - U_N}{R} \cdot \left(1 - e^{-\frac{R}{L}T(1-D)}\right) + \left(\frac{E}{R_T + R} \cdot \left(1 - e^{-\frac{R_T + R}{L}T (1-D)}\right) + I_0 \cdot e^{-\frac{R_T + R}{L}T (1-D)}\right) \cdot e^{-\frac{R}{L}T(1-D)},$$ \hspace{1cm} (6)

Setting $R = R_T = 0.01\text{Ohm}$, $L = 1\text{mH}$, $E = 10V$, $U_N = 11V$, $T = 20\mu s$, we can have a family of curves for establishing the converter load current converter at different fill factors (Fig. 3).
Taking the data from Fig. 3 as a basis, the time required for setting the current in the load depends on fill coefficient D. Despite the violation of the proportionality of the load current to the fill coefficient, the minimum value of the current corresponds to the maximum fill coefficient.

5. Buck-boost converter.

During pulse \( t_l \), when the transistor is open (Fig. 1, a), the current flowing through inductance \( L \) increases according to (4).

During pause \( t_p \), when the transistor is closed (Fig. 1d), the current flowing through inductance \( L \) decreases according to (2).

Substituting (4) into (2), we can obtain the recurrent expression for calculating the current flowing through the inductance:

\[
I_2 = -\frac{U_N}{R} \left( 1 - e^{-\frac{R}{L}T(1-D)} \right) + \frac{E}{R_T + R} \left( 1 - e^{-\frac{R_T}{L}T_D} \right) + I_0 \cdot e^{-\frac{R_T}{L}T_D} \cdot e^{-\frac{R}{L}T(1-D)}, \tag{7}
\]

Setting \( R = R_T = 0.01 \text{Ohm} \), \( L = 1 \text{mH} \), \( E = 10V \), \( U_N = 1V \), \( T = 20 \mu s \), we can obtain a family of converter load current curves for different fill coefficients which is similar to that for the boost converter in Figure 3.

This is determined by similar charge schemes (Fig. 1a) and similar charge schemes (Fig. 1d and 1b) if \( E - U_N = 10V - 11V = -1V \) for the boost-boost converter and \( U_N = 1V \) for the boost converter.

6. Results

Time constant \( \tau \) is not static, it changes its value depending on the mode of operation of the converter whose value depends on fill coefficient D during the work as part of the pulse width converter (PWC).
If during impulse $t_i$, the charge circuit has a constant time value $\tau_i$, and during pause $t_p$, the time constant is $\tau_p$, the total $\tau$ of the converter will be determined as:

$$\tau = \tau_i \cdot \frac{t_i}{t_i + t_p} + \tau_p \cdot \frac{t_i}{t_i + t_p} = \tau_i \cdot D + \tau_p \cdot (1 - D).$$

For the buck converter whose time constant of the pulse is determined by the inductor inductance and the sum of active resistances of the inductor and the transistor, and the time constant of the pause is determined by the inductor inductance and its active resistance, the total time constant is:

$$\tau = \frac{L}{R_L + R} \cdot D + \frac{L}{R} \cdot (1 - D).$$

The time constant of the boost converter is similar to that of the buck converter (9). The difference in the values in Fig. 2 and 3 is determined by the action of currents of the inductor on the load in the booster circuit during pause $t_p$. Thus, there is a relationship between the inductor currents and load currents through the coefficient $(1 - D)$: $I_N = I \cdot (1 - D)$.

The time constant of the buck-boost converter is calculated by formula (9).

Based on the experiment results, we can conclude that single-cycle converters are a first-order aperiodic link having a time constant calculated by (9).

![Figure 4. Transfer function of the single-cycle converter](image)

7. Conclusions

According to the data described in [7], it is possible to find a method for calculating coefficient $K$ which takes into account the relationship between the control signal and the load current for a stationary mode. The method for calculating the transfer function makes it possible to achieve a greater speed of the automatic control system by accounting for the transfer function of the power module of the converter and increasing performance of the system.

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