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Investigation of Boosting DC-DC Converter by Numerical Experiment

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Abstract
The physical processes of the operation of a pulse boosting DC-DC converter of electrical energy are considered. A computer model of a step-by-step conversion of energy: a power source into magnetic field energy, magnetic field energy into electric field energy and its accumulation by a capacitor at increased voltage was created. The converter works in the mode of pulse-width regulation. Energy conversion processes are described by equations reduced to the Cauchy form. The computer model is built in the application package Simulink, MatLab. DC-DC modelling involves calculating each pulse, storing the results, and transmitting it to the beginning of the next pulse. The described modelling algorithm, at the operating frequencies of the DC-DC converter, imposes increased requirements on the speed of the computer and the amount of its memory. The modelling program was carried out for t = 10 s at a frequency of 100 kHz, more than six hours $t_m > 6$ hours. Using such a model for research is not effective. A method was found for modelling at lower frequencies and transferring their results to the frequencies of the converters. Modelling was carried out at frequencies of 1 kHz and the adequacy of the results of the converters at higher frequencies was confirmed. The duration of the experiment is reduced to 30 seconds, which provides convenient modelling conditions.

INTRODUCTION

Pulse technology and DC-DC converters are widely used in a great variety of electromechanical systems, including power supply and control systems for DC motors, land and air vehicles, power conversion and storage systems, control devices for non-conventional energy sources, solar, wind and tidal power plants, electric drive control systems, etc. Its advantages include a wide range of functionalities, controllability, low power losses, small size and the ability to provide the required operating parameters. A wide class of such equipment is represented by pulse regulators of constant voltage DC-DC converters. However, their use is associated with the need to predict operations as part of the control system, study the nature of operation during start-up, changes in the operating mode, input voltage and external load, and calculate the quality of operation in transient modes. One of the promising methods of studying the operation of these devices is a numerical experiment, which is implemented by mathematical modelling on a computer.

ANALYSIS OF KEY ACHIEVEMENTS

DC-DC converters are widely used in electrical power conversion and storage systems, solar and wind power plants, electric drive systems, and various types of control systems. The diversity of objects and requirements for them, the availability of different types of converters imposes increased requirements for a detailed study of the features of their operation.

References [1–3] enlight the operation of DC-DC converters, options for using such converters, and operating modes. The issues of modelling the operation of converters and their operation in technical systems are discussed in paper [4]. Papers [5–12] consider the use of DC-DC converters in the DC motor power supply circuit, where they are used to regulate the operation of motors. These converters are switched on the motor excitation winding power supply circuit, regulate the magnitude of the winding current and the induction of the motor magnetic field to regulate the output of the battery as it discharges, or the DC-DC converter directly supplies

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the motor and provides regulation of its operation by changing the trolleybus supply voltage [13]. Converters are also used in vehicles powered by renewable energy sources [14], where DC-DC converters are used in a complex conversion system that additionally includes an AC system with a voltage transformer. Photovoltaic renewable energy systems use systems that, in addition to DC-DC, contain controllers with PID regulators. This expands the range of applications for DC-DC controllers and provides opportunities to generate additional renewable energy and its practical use. Renewable sources are defined as environmentally friendly sources, such as photovoltaic panels or wind turbines. They are also popular in industrial, physical, military, medical, transport, aerospace, and many other applications, but require ultra-high input voltage boost [15]. Paper [16] discusses the issues of voltage boosting in more detail, considering various methods of voltage boosting using repetition and multiple leveling processes. The method of equations in the state space was used as the basis of the research.

BUILDING A MODEL OF A DC-DC CONVERTER

The Simulink and MatLab software packages were used to build a model of a DC-DC converter and study the operating modes in renewable energy sources, electric drive systems, etc. The modelling of pulse systems operation is mainly based on the consideration of equilibrium states and generalised characteristics, and the establishment of dynamic equilibrium of processes. Such methods allow obtaining generalised characteristics of converter operation, but do not allow tracing the process in detail. Another method of modelling is based on pulse systems, which include the calculation of each stage of switch operation, according to the control signal, and the transfer of the calculation results as the initial conditions for the next phase. For this purpose, integrating links are used and modelling is performed using analogue circuits and analogue computers. Nowadays, this is simulation modelling using mathematical packages such as SimPowerSystems and Scilab/Xcos [17, 18].

The electrical circuit of the boost DC-DC converter is shown in Fig. 1.

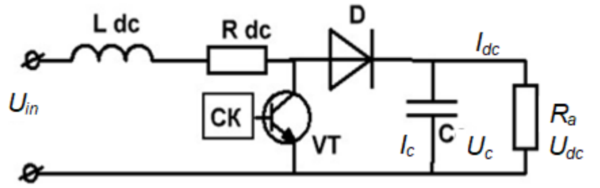

Figure 1. Electrical diagram of a boosting DC-DC converter

DC-DC converter in Fig. 1 contains: inductance – L_{dc}, resistor – R_{dc}, whose resistance is the sum of the active winding resistance and the regulator resistor; a switching key consisting of a transistor VT and diode D and capacitor C. The load resistor R_a is connected to the output of the converter. The operation of the converter is controlled by the control device CS, which uses a rectangular pulse generator operating in the pulse width modulation mode with an adjustable pulse filling factor – d. The converter increases the voltage by switching the inductor supply circuit and transferring the accumulated magnetic field energy to the capacitor at the required voltage. The switching is performed by a key that periodically switches the inductance to the power supply and then to the capacitor. The inductor L_{dc} is connected to the power supply in series with the resistor R_{dc}. Electric current is supplied to the capacitor C through the diode D and is spiked in its electric field. The value of the charge voltage of the capacitor C is regulated by selecting the pulse filling factor – d. Shorter pulses – t_i provide an increase in the voltage across the capacitor in accordance with the law of electromagnetic induction (1).The duration of the capacitor charging time increases with the increase in the pulse coefficient d

$$U_L = \frac{\Delta\Phi}{\Delta t} = \frac{1}{T} L_{dc} \int_0^{t_i} \frac{U_{in}}{R_{dc}} cos\omega t \, dt \quad (1)$$

where $\Delta\Phi$ is the magnetic field induction of the inductor L_{dc}, the time interval of the magnetic field change is $\Delta t = T \cdot d\%$, T is the pulse period.

The process of charging the capacitor takes place when the diode D is open, i.e. when the transistor VT is open (*OFF)*. When the switch is closed (*ON*), the current flows from the source through the inductance and forms a magnetic field.

The transistor is switched when the generator voltage changes during the period T. During the time t_i, the generator voltage is 1 V, and the rest of the time $(T - t_i)$ is zero. The time t_i is set by the pulse filling factor d

$$d = \frac{t_i}{T}. \quad (2)$$

The main characteristic of the converter is the control characteristic (CC). The theoretical CC, which corresponds to the steady-state DC-DC operation mode, calculated under the condition of dynamic equilibrium of the processes of charging and discharging the capacitance, corresponds to the equation [2]:

$$U_{dc} = \frac{U_{in}}{1-d}. \quad (3)$$

The equations describing the processes in the pulse and pause modes were used to model the converter and study its properties.

Pulse mode, key K is open, diode is open:

$$\begin{cases} U_{in} = L_{dc}\frac{di_{dc}}{dt} + i_{dc}R_{dc} + U_C; \\ U_C = \frac{1}{C}\int_0^t i_c dt\,; \\ i_{dc} = i_c + i_R; \\ i_R = \frac{U_c}{R_a}. \end{cases} \quad (4)$$

Pause mode, key K is closed, diode is closed:

$$\begin{cases} U_{in} = L_{dc}\frac{di_{dc}}{dt} + i_{dc}R_{dc}; \\ -\frac{1}{C}\int_0^t i_c dt = 0. \end{cases} \quad (5)$$

After reducing the equations to the Cauchy form, the system of equations (4) and (5) will look like this:

$$\begin{cases} \frac{di_{dc}}{dt} = \frac{1}{L_{dc}}(U_{in} - i_{dc}R_{dc} - U_C); \\ \frac{dU_{dc}}{dt} = \frac{1}{C}(i_{dc} - i_R). \end{cases} \quad (6)$$

Equations (6) describe the electrical processes of the converter only with the use of two integrating links that correspond to the magnitude of the magnetic field of the inductor and the electric field of the capacitor.

Using the notation adopted in the Simulink package for circuit elements, according to the system of equations (6), the model is shown in Fig. 2.

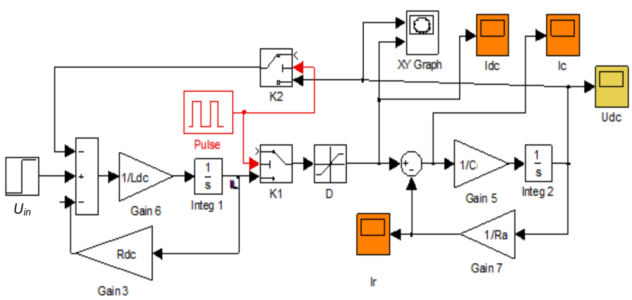

Figure 2. Computer model of a boosting DC-DC converter

In the computer model of Fig. 2, the control unit contains a rectangular pulse generator «Pulse» and two switches $K1$ and $K2$. The control electrode of the switches is supplied with the generator voltage, which changes to switch the DC-DC pulse modes. The switching moment is 0.5 V, the filling factor – d is set in the range from 1% to 99%, the frequency is set according to the selected pulse period T: $f = 1/T$. The model also includes an oscilloscope for recording current and voltage changes on the converter elements and a two-coordinate recorder. The model fully describes the electrical processes of the DC-DC converter according to equations (6).

ANALYSING THE OPERATION OF A DC-DC CONVERTER USING A MODEL

The proposed computer model of the DC-DC converter is shown in Fig. 2. It meets the requirements of numerical modelling. In research practice, the use of such models was widely used in the period of analogue computers, where the solution of research problems was reduced to sequential integration by a set of integrating devices. The term «integration» is also used in the sense of studying the course of processes. These methods are now used in simulation modelling [17]. When studying the operation of converters, transfer functions or state equations are usually used [18]. Therefore, it is necessary to analyse the operation of the proposed model and make sure that the modelling results are adequate to the processes in real converters.

As a rule, DC-DC converters operate at frequencies from 10 kHz to 100 kHz and higher. The proposed model of Fig. 2 includes a generator of rectangular pulses, which can operate at frequencies covering the entire possible range. The parameters of the model used have the following values: inductance – L_{dc} = 0.01 H; capacitance – C = 5 F; inductor winding resistance – R_{dc} = 0.1 Ohm; external load resistance – R_a = 20 kOhm. The voltage of the power supply is U_{in} = 10 V.

The operation of the model of Fig. 2 was studied at different values of the pulse frequency of the control generator. The pulse period was set in the range T = 0.1–0.00001 (frequency f = 10–100 000 Hz). Since the steady-state value of the output voltage of the converter U_{dc} is established after a certain time after its switching on, the operation was modelled during the time from the moment of switching on to the transition to the steady-state mode. We considered the operation time of the DC-DC converter of t = 10 s. The duration of the simulation time, at different frequencies, with a pulse filling factor of d = 50% is given in Table 1. The modelling time significantly exceeds the operating time of the DC-DC converter due to the increase in the number of calculations with increasing frequency. The modelling results are shown in Table 1.

Table 1. Results of modelling the operation of the DC-DC converter for a time t = 10 s, at different control pulse frequencies

Pulse frequency, Hz	$U_{dc}max$, V	$I_c max$, A	Calculate quantity	Duration of the modeling process
10	24.18	258.7	212	< 1 s
100	24.159	257.22	2 013	3 s
1000	24.156	257.110	20 015	0.5 min
10 000	24.156	257.102	200 011	17.5 min
100 000	24.156	257.1016	2 000 012	375 min

Table 1 shows the results of modelling at frequencies from 10 Hz to 100 kHz, the size of the data arrays (the number of calculations performed), and the duration of the modelling process. The final voltage values and maximum current pulse values are given.

With an increase in the pulse frequency, the modelling time increases significantly. The computer modelling process at different operating frequencies lasts from a fraction of a second to 6,25 hours. At the operating frequency of the DC-DC converter of 100 kHz, the modelling is not effective due to its long duration. To use the proposed model, it is necessary either to replace the equipment with a faster computer or to find a way to reduce the modelling time.

Table 1 also shows the values of the maximum output voltage $U_{dc}max$ and the magnitude of the current pulses $I_c max$ of the capacitor charge. The modelling results at different frequencies of the model's operation coincide up to the fifth significant figure (except for the frequency of 10 Hz). This coincidence opens up the possibility of reducing the modelling time.

A more detailed analysis of the electrical processes of the modelling at different frequencies is shown in Fig. 3.

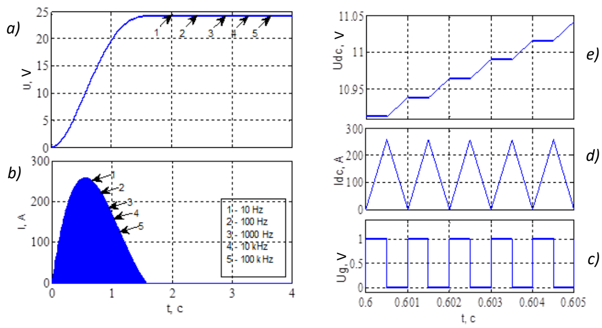

Figure 3. Analysis of processes in the DC-DC regulator obtained on the model at frequencies of 10 Hz – 100 kHz; d = 50%: (*a*) is the variation in the voltage of the regulator U_{dc}; (*b*) is the charging currents of the capacitor I_c; (*d*), (*e*) – detailing of electrical processes: (*c*) is the voltage of the control generator, (*d*) is the pulses of the charging current I_c, (*e*) is the voltage on the capacitor

Fig. 3, a shows the graphs of changes in the output voltage of the DC-DC converter at simulation frequencies from 10 Hz to 100 kHz. The duration of the modelling time corresponds to the data in Table 1. The modelling results reflect the operation of the DC-DC regulator for t = 10 s (the graphs in Fig. 3 are limited to t = 4 s). The voltage change at the output of the converter U_{dc} is the same at all modelling frequencies, and the graphs coincide. The steady-state voltage value is established after 1.5 s from the moment of switching on. At any modelling frequency, the duration of the control transient is the same and the voltage changes are identical (including the ultra-low frequency of 10 Hz).

Fig. 3, b shows the change in the capacitor charge current pulses I_c at different frequencies of the control pulses U_{in}. Their values, as well as the voltage value (see Fig. 3, a) at different frequencies, coincide. At frequencies of 1 kHz to 100 kHz, the converter output voltage and the capacitor current coincide to the fifth decimal place, i.e., by 0.002%.

The pulses of the capacitor charging current in Fig. 3, b last for a certain time and stop. The converter voltage is set at 24.5 V, which is greater than the control characteristic and does not change during the modelling. This situation can be explained by the fact that the load resistance in the model is assumed to be quite large, 20 kOhm. There are no pulses of the capacitor charging current (at the output of diode D). The magnitude of the pulses is typical for a transient process with a gradual increase to a maximum value that is the same for different frequency values, equal to $I_c max$ = 257.1 A. A direct current of about 1 mA flows through the load resistance R_a.

Diagrams Fig. 3, c, d, e show the details of electrical processes. Fig. 3, c shows a graph of the voltage pulses of the control device U_{in}, which correspond to operation at a frequency of 1000 Hz with a pulse filling factor d = 0.5 c). Fig. 3, d shows the current pulses of the capacitor I_c. The shape of the current pulses in Fig. 3, d is presented in the form of triangles, the same for all frequencies of the model. This is due to the integration method, since the integration step is selected automatically, depending on the specified pulse period. Fig. 3, e shows a graph of the voltage change $U_{dc}(t)$ starting from time t = 0.6 s. The voltage across the capacitor increases with each current pulse.

The magnitude of the voltage rise depends on the magnitude of the current pulses. At the moment the pulses stop, the voltage rise stops and it is set at a value higher than the regulatory characteristic, namely $U_{dc}max$ = 24.5 V. Similar graphs were obtained for other frequencies of the model, and they coincide on the scale of the entire model, although the duration of the pulses is shorter and their number is greater.

The theoretical analysis and estimation of the time constants of electrical circuits, which are characteristic of the operation of converters, shows that they are significantly longer than the duration of the pulses of the generator during the modelling. The formulas for describing the operation of the converters (3)–(6) do not explicitly include the pulse frequency. Therefore, the modelling results describe the electrical processes of the converters with sufficient accuracy.

The analysis shows that it is possible to use the proposed model to study the operation of a DC-DC converter at lower frequencies and transfer the results to converters operating at high operating frequencies. The increase in the operating frequency of DC-DC converters in their manufacture is associated with the energy parameters of the elements, their ability to accumulate energy, with the limitations of the amount of energy accumulated by them in one cycle of operation, and the weight and dimensions of the converter elements. The computer model works with numbers, and there are no significant limitations on the values it works with, such as the accumulated energy per pulse, voltage, current, dimensions and weight of the device, etc. Based on these considerations and modelling results, it is concluded that the proposed model allows us to study processes on a slower-acting model and transfer research results to real converters operating at higher frequencies. This possibility is ensured by an appropriate choice of modelling time intervals and time constants of the modelling object.

Taking into account the above considerations and the analysis of the equivalence of the model to the object of study, we conclude that it is legitimate to use the proposed mathematical and computer model to study the operation of DC-DC converters. We will use this model at control signal frequencies of the order of 1 kHz and transfer the research results to regulators operating at higher frequencies. This significantly reduces the time spent on modelling and allows us to use existing equipment. The duration of the modelling is reduced from 6.5 hours to 30 seconds, which allows for efficient detailed studies.

It should also be taken into account that when considering the operation of converters in electrical process control systems, it is necessary to take into account the change in the output voltage of the converter from the start of operation, which in the example under consideration is 1.5 s. Traditional power sources change the voltage value in a fraction of a second, and in the case of a DC-DC converter, the rate of change of electrical parameters at its output is much lower.

STUDY OF THE REGULATORY CHARACTERISTIC OF A BOOSTING DC-DC CONVERTER USING THE PROPOSED COMPUTER MODEL

The regulatory characteristic obtained by the model, namely the dependence of the steady-state value of the output voltage on the pulse filling factor, is shown in Fig. 4 as a solid line. The dotted line shows the modelling results.

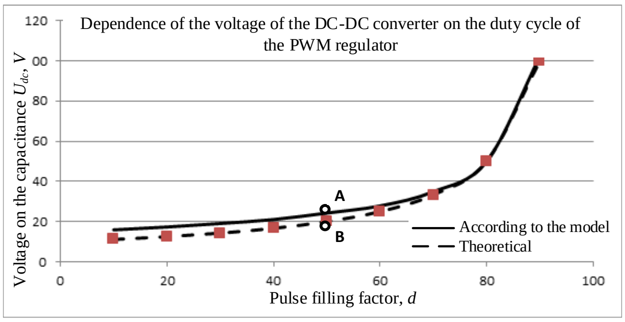

Figure 4. Regulatory characteristic of a boosting converter

The experiment gives approximately the same dependence as the theoretical formula. According to the model, most of the control characteristic passes above $\Delta U_{dc} \approx 4.5$ V (see Fig. 4, points A and B). The question arises: why the results of the experiment do not coincide with the calculation according to formula (3)? The measurement results were performed accurately, repeatedly, at different frequencies of the model. The model is based on equations that describe in detail the operation of the converter. Is this a measurement error or something else? Let's accept the result as a fact and continue our research.

In the practice of using DC-DC converters as a control element, the peculiarities of its operation with different load values and the processes when it changes are important. One of the important parameters is the dependence of the converter voltage on the load. The voltage at a given pulse ratio is determined by the control characteristic, but to some extent depends on the load. The theoretical formula for the control characteristic (3) does not take this into account. It does not describe the time characteristics of the regulator voltage stabilization process. If DC-DC is used in a control system, the time characteristics are important.

The dependence of the converter output voltage on the load was studied at different values of the load resistor resistance R_a in the range from 200 Ohm to 0.2 Ohm and operating currents from $I_r \approx 0.1$ A to $I_r \approx 70$ A. Fig. 5 shows the measurement results at a pulse filling factor d = 50%. In addition, we note that in the experiment of Fig. 5, the control characteristic was obtained at a load of R_a = 2 kOhm.

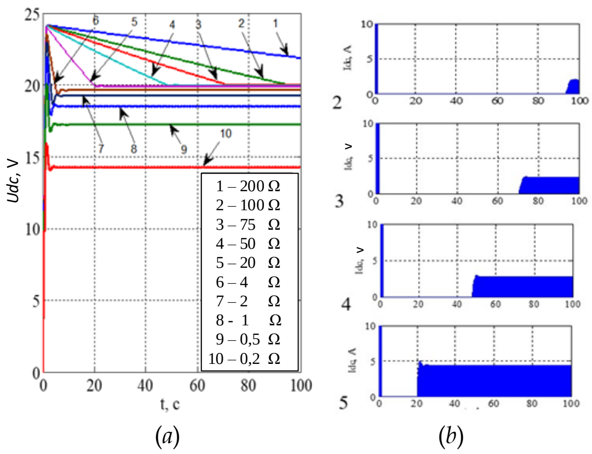

Figure 5. Regulator voltage and capacitor charging current at different loads: (*a*) is the voltage change graphs after switching on the regulator; (*b*) is the change in capacitor charging current (pulse delay periods)

The analysis of the data in Fig. 5 a) shows complex processes of voltage and current changes in the regulator. At different values of the resistance R_a = 200–

0.2 Ohm, the DC-DC voltage and the charging current of the capacitor U_c (the same as U_{dc}) change in different ways (see graphs No 1÷10 in Fig. 5, a). Common to most of the graphs is the presence of a voltage peak at the initial moment – $U_{dc}max$ ≈ 24.5 V, and a further decrease in voltage to a steady-state value of U_{dc} = 20 V. Moreover, the voltage changes almost linearly. If we compare the data (see Fig. 5, b), the voltage peak value corresponds to point A on the DC-DC model, and the steady-state voltage values approximately correspond to point B of the theoretical control characteristic. The voltage difference at points A and B ΔU_{dc} ≈ 4.5 V. This result partially explains the deviation from the theoretical values of the control characteristic. It can be assumed that the experimental curve corresponds to peak values, and the theoretical curve to steady-state values.

Fig. 5, a shows that the steady-state value of the regulator voltage U_{dc} is set at different intervals, depending on the load. After switching on the model, a transient process occurs, characterized by a peak voltage $U_{dc}max$ ≈ 24.5 V and a gradual change to the steady-state value U_{dc} = 20–19,5 V. The time to reach the peak voltage value is t ≈ 1. The steady-state time is longer, up to 90 s or more. It depends on the load value R_a. At lower values of resistance R_a (the current of the used converter is greater than 10 A), the voltage U_{dc} decreases more significantly, for example, at a current of I_{dc} = 35 A, the voltage value U_{dc} = 17.5 V (Fig. 5, a No. 9), and in the case of a current of I_{dc} = 70 A, it is equal to U_{dc} = 14 V (Fig. 5, a No. 10).

The results of the experiment showed that after switching on the DC-DC converter, three consecutive processes take place: transient – from the beginning of switching on to the peak voltage value, stabilisation – the output voltage decreases and stabilises at a value that corresponds to the regulatory characteristic, and steady-state – operation at a constant voltage. For the model under consideration (see Fig. 4), point A corresponds to the peak voltage value, and point B to the steady-state value. The model was obtained at d = 50% U_{dc} = 20 V.

As a result of the transient process, the voltage across the capacitor rises above the level of the control characteristic after switching on and is set at 24.5 V. In our example, the control characteristic corresponds to a voltage of 20 V. Gradually, the voltage across the capacitor decreases to a value that corresponds to the control characteristic. During this period of time (see Fig. 5, b), there are no pulses of charging the capacitor, the process of discharging the capacitor is underway, the current passes only through the resistor R_a. The diode D does not pass the charging current. Only after the voltage is reduced to the value of the regulating characteristic, the diode D passes the capacitor charge pulses. That is, the charging process does not take place until the voltage is reduced to U_{dc}.

The described process can be explained by the fact that as a result of the initial transient process, excess energy is accumulated in the capacitor and the dynamic equilibrium of the processes is disturbed. During the transient process, the excess energy stored in the capacitor is reduced by the load consumption, and the capacitor charge pulses stop. Based on this, it is possible to calculate the duration of the transient process during which the capacitor discharge stops.

The amount of excess capacitor charge:

$$Q = C \cdot \Delta U_{dc}, \quad (7)$$

where $\Delta U_{dc} = U_{dc}max - \Delta U_{dc}$, the voltage difference corresponding to the overcharge of the capacitor; Q is the excess charge of the capacitor, C.

The excess charge of the capacitor Q (compared to the equilibrium process) allows to calculate the time of stabilisation of the converter operation in the transient period. Average load current (capacitor discharge)

$$i_a = \frac{U_{dc}max}{R_a}. \quad (8)$$

Pulse absence time t_{pd} (transient duration):

$$t_{pd} = \frac{Q}{i_a}. \quad (9)$$

Calculation results at different values of load resistance R_a are given in Table 2.

Table 2. Transition period duration

No.	R_a, Ohm	C, F	$U_{dc}max$, V	I_{pd}, A	Q, C	t_{pd}
1	200	5	24.5	0.12	22.5	183.7
2	100	5	24.5	0.25	22.5	91.8
3	75	5	24.5	0.33	22.5	68.9
4	50	5	24.5	0.49	22.5	45.9
5	20	5	24.5	1.23	22.5	18.4
6	4	5	24.5	6.13	22.5	3.7
7	2	5	24.5	12.25	22.5	1.8
8	1	5	24.5	24.50	22.5	0.9
	2000	5	24.5	0.012	22.5	1837 s 31 min

According to the results given in Table 2, the duration of the delay time of the capacitor charging current pulses is obtained. The voltage of the converter varies almost linearly from a maximum value equal to the voltage pulse in the transient process to a voltage corresponding to dynamic equilibrium (voltage according to the control characteristic), Fig. 5, a. From Fig. 5, b it can be seen that the numerical values of the delay of the charging pulse of the capacitor correspond to the values given in the column t_{pd}. The obtained results fully coincide with the given results of calculations according to formulas (7)–(9) confirm the correctness of the proposed model and the expediency of its use for the study of processes in pulse power supply systems.

When using a DC-DC boost converter, especially in control systems, in addition to the adjustment characteristic, it is important to take into account the time characteristics of operation in different modes. The study of adjustment and time characteristics was performed using the proposed model. The output of the DC-DC converter of Fig. 6 represents a change in the voltage U_{dc}, with different values of the duty factor d.

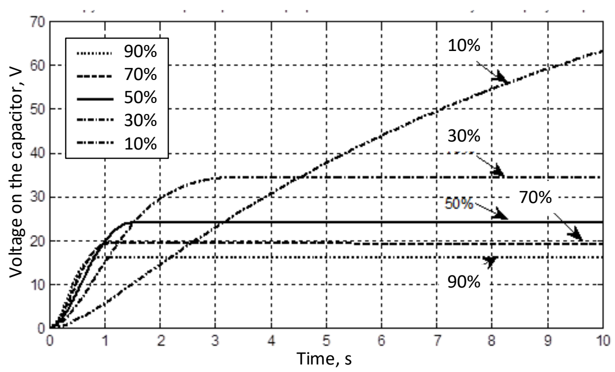

Figure 6. Variation of DC-DC converter output voltage at different filling factor (10 Ohm load resistance)

The output voltage of the converter U_{dc} varies depending on the duty cycle d, for different times. Decreasing the duty cycle d results in a higher voltage U_{dc} (3) and a longer time. With values of the duty cycle within 30 to 70 %, this time is from 1 to 3 s. When the duty cycle increases to 10 %, the voltage stabilization time increases to 40 s. The steady-state voltage value of the DC-DC converter does not depend on the frequency of the model. This confirms the possibility of transferring the results of studies performed at a lower frequency of the model to a higher frequency of the converter. In addition, this confirms the conclusion that the DC-DC output parameters are independent of its operating frequency.

Verification of the experiment results is done on a real converter. Fig. 7 shows an increase in the voltage of the converter above the control characteristic practically at a shallow value of the external load.

The value of the load resistance R_a = 820 kOhm and voltage 27 V, i.e. significantly higher than the steady-state voltage 20 V (see Fig. 7). As can be seen from Fig. 7, almost in the absence of a load, the voltage of the converter rises above the equilibrium value, which confirms the results obtained in the work. However, the transient is monotonic rather than aperiodic as in the model in question. This can be explained by the fact that the real converter has extraneous energy loss not taken into account in the model and the nature of the transition process at a high operating frequency (71 kHz) changes.

Figure 7. DC-DC converter output voltage change at load *20 kOhm (Input voltage 10 V, d = 50%)

Perhaps the reason for the lack of a sharp transition process is that the model used two switches K1 and K2 (see Fig. 2), as a result of which the inductance L_{dc} is not constantly connected to the diode D, and at the moment of switching the connection is broken and re-restored, which can contribute to increasing the pulse of the transient process.

Considering the results of the studies performed, it should be noted that the proposed model is promising and allows to identify the details of the operation of pulse power systems. If we consider examples of using DC-DC converters in control systems, we should take into account the peculiarities of the operation of pulse systems and processes that are often not taken into account when analyzing their operation. When analyzing a number of publications, the processes of DC-DC converters are not reflected, which raises doubts about the accuracy of the results obtained. The use of state equations and the methods of continuous systems used to analyze pulse systems do not take into account all the details of the work of the latter.

CONCLUSIONS

A mathematical model of the DC-DC converter has been created, which provides a detailed analysis of each cycle of converting the energy of the power source into the energy of the magnetic field of the throttle and the subsequent conversion into energy of the capacitor's electric field at increased voltage. A model of the equations of the dynamics of processes reduced to the Cauchy form and a computer model developed in the Matlab package, Simulink.

The use of the proposed model puts strict conditions on the speed of the computer and the amount of its memory, which complicates the study of the DC-DC converter at its operating frequencies. It has been experimentally proved that the use of the proposed model is possible with a significant decrease in the frequency at which the DC-DC converter operates, and the adequacy of the modelling results with the operation of the converter at its own frequencies has been proved. With the help of the model, a detailed analysis of physical processes in a typical DC-DC converter was carried out and it was shown that during DC-DC operation the following three periods are changed: transient, stabilization and steady operation.

The transient period of operation of the amplifying converter is characterized by a voltage rise at the output above the value of the dynamic processes of charging and discharging the capacitor, which exceeds the values of the adjustment characteristic of the converter, as a result of which an excess electric charge is created in the capacitor.

The DC-DC voltage stabilization period occurs by gradually reducing the accumulated excess energy of the electric field to a value corresponding to the control characteristic. During this period, the pulses of energy transfer of the magnetic field from the inductance stop. The reduction of excess energy in the capacitor occurs almost according to a linear law.

The period of steady work comes at the end of the stabilization process, the inductance current pulses are restored, the dynamic equilibrium of the processes of charging the capacitor and discharging it through the load resistance occurs. Depending on the parameters of the converter and its load, the equilibrium process can be of an oscillatory nature, in which groups of pulses are transmitted and their absence.

A mathematical description of the process of voltage stabilization is obtained on the basis of calculating the reduction of excessively accumulated energy by the capacitor during the transition process and the discharge rate through the load.

In the case of using the DC-DC converter in control schemes, it is necessary to take into account the alternation of periods of its operation and approach the theoretical analysis taking into account the marked periods of operation. In view of this, a number of research results in which the processes considered are not taken into account require additional analysis.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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Дослідження підвищувального DC-DC перетворювача шляхом чисельного експерименту

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Анотація. У статті розглянуто фізичні процеси роботи імпульсного підвищувального DC-DC перетворювача електричної енергії. Створено комп'ютерну модель покрокового перетворення енергії: від джерела живлення в енергію магнітного поля, від енергії магнітного поля в енергію електричного поля та її накопичення конденсатором при підвищеній напрузі. Перетворювач працює в режимі широтно-імпульсного регулювання. Процеси перетворення енергії описуються рівняннями, зведеними до форми Коші. Комп'ютерну модель побудовано у програмному пакеті Simulink, MatLab. Моделювання DC-DC перетворювача передбачає розрахунок кожного імпульсу, збереження результатів і їх передачу на початок наступного імпульсу. Описаний алгоритм моделювання, при робочих частотах DC-DC перетворювача, накладає підвищені вимоги до швидкодії комп'ютера та обсягу його пам'яті. Моделювання було проведено для t = 10 с при частоті 100 кГц, і тривало більше шести годин (t_m > 6 годин). Використання такої моделі для досліджень не є ефективним. Було знайдено метод моделювання на нижчих частотах з подальшою передачею їх результатів на частоти перетворювачів. Моделювання проводилося при частотах 1 кГц, і була підтверджена адекватність результатів для перетворювачів на вищих частотах. Тривалість експерименту скорочено до 30 секунд, що забезпечує зручні умови для моделювання. Дослідження, проведені за допомогою запропонованої моделі, дозволяють виділити три часові періоди роботи підвищувальних перетворювачів: перехідний, стабілізаційний і стаціонарний. Перехідний період характеризується зростанням вихідної напруги DC-DC вище значення динамічної рівноваги перетворювача, тобто значення, яке перевищує визначене регулювальною характеристикою. При цьому надлишкова енергія накопичується в накопичувальному елементі, а динамічна рівновага процесів заряджання і розряджання зміщується. Починається період стабілізації, під час якого відсутні імпульси струму, енергія не надходить до конденсатора, і він розряджається струмом навантаження. Надлишковий заряд зменшується до значення, яке відповідає стаціонарній роботі. Напруга в цей період зменшується майже за лінійним законом, обернено пропорційним до величини навантаження. Отримано формули для розрахунку часу стабілізації. Період стаціонарної роботи характеризується динамічною рівновагою процесів заряджання конденсатора імпульсами струму і розряджання навантаженням постійного струму. Він триває доти, доки не відбудеться зміна навантаження або напруги на вході перетворювача. Час стабілізаційного періоду може перевищувати кілька хвилин, супроводжуватись повторюваними оновленнями та зупинками імпульсів струму, а в деяких випадках взагалі не встановлюватись. Оскільки DC-DC перетворювачі широко застосовуються в системах керування та мають описані вище робочі періоди, при проєктуванні систем керування та аналізі їх роботи недостатньо враховувати лише рівноважні режими. Необхідно також враховувати зміну робочих періодів. У ряді цитованих робіт ці періоди не описані, що частково знижує надійність їхніх результатів. Динамічна рівновага процесів не може бути встановлена одразу після перемикання режимів DC-DC, і тривалість цього процесу залежить від величини навантаження. Використання DC-DC регуляторів, наприклад, у схемах живлення від акумуляторів, за зміни зовнішнього навантаження може призвести до небажаної зміни режиму роботи DC-DC, що знижує ефективність його використання.

Ключові слова: підвищувальний DC-DC перетворювач; комп'ютерна модель; широтно-імпульсна модуляція; Simulink, MatLab; моделювання; операційні періоди; ефективність використання.

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