

REACTIVE POWER AS AN INFORMATION FACTOR IN ELECTRIC CIRCUITS

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ABSTRACT

This article examines information processes in electrical circuits using the introduced concept of electrical entropy, which is analogous to thermodynamic entropy. Electrical entropy is understood as the time density of circulating reactive power. Because electrical energy is higher than thermal energy, the magnitude of entropy, unlike thermodynamics, takes on a different direction. Indeed, active power supplied to the network is transmitted to the load with high efficiency, and reactive elements are not associated with active power consumption or heating temperatures. Electrical entropy characterizes neither the degradation of energy nor the tendency of processes toward the most probable state of the system. On the contrary, this entropy indicates the degree of its approach to a less probable state, thus being

a negative entropy—negentropy. This leads to the elimination of certain uncertainties, i.e., the generation of information processes in the electrical system. It has been shown that electrical entropy is a function of the system's state, characterizing the transformation of electrical energy from one form to another and the corresponding change in the parameters of the electric current. Zero electrical entropy means the absence of such transformations. This article examines various types of nonlinear electrical systems, using four basic power converters—rectifiers, standalone inverters, and buck and boost converters—as examples, where these phenomena are most evident. Circuits—models of transport networks, and general-purpose electrical networks—are also considered. It is shown that information

processes are driven by reactive power and nonlinear elements, primarily power valves, which constitute the mechanism for influencing electrical systems. This article expands our understanding of the processes in such systems, as well as our view of reactive power, current, and voltage pulsations as harmful and counteractable—and counteractable only by understanding their role. The analysis is supported by modeling various systems in Matlab.

KEYWORD: Entropy, Negentropy, Information, Electric System, Reactive Power.

1. INTRODUCTION

The natural process of developing the theory of various electrical devices, especially valve converters and other nonlinear systems, which occurred intensively in the middle of the last century, was based primarily on the study of their operating modes and the fundamental relationships between circuit parameters and voltage and current values. This was already the subject of extensive literature at that time, including (Rissik, H., 1935; Von Issendorf, J., 1935; Ostendorf, W., 1938; Demontvigner, H., 1952; Erickson, R., Maksimovic, D., 2004), and others. Problems of optimizing energy parameters—efficiency and power factor—were also considered. Based on these assumptions, factors with little influence on these quantities were neglected in such assessments, and reactive power circulation was considered only in terms of its impact on the power factor. As is generally the case, Kirchhoff's equations were used to determine operating modes (Hazen, A., 1998).

However, another approach to these purposes exists, which has become widespread in mechanics and, to a lesser extent, in electrical engineering. It is based on Hamilton's principle (White, D., Woodson, H., 1959, Sinitsky, L., 1978, Berkovich, Y., and Moshe, S., 2021), which states that if a force function is used in Hamilton's integral expression, then the actual dynamic trajectory of the system described by this force function is determined by finding the extremum (usually the minimum) of this integral function. The force function is considered to be the Lagrangian, which is the difference between the total kinetic energy of the system and its total potential energy. The former can be the total energy in the circuit's inductances, and the latter the total energy in its capacitances (or vice versa). It is proved that the conditions for the extremum of the Hamiltonian integral function for the Lagrangian are provided by the Euler-Lagrange equations, and their solution allows us to find the voltages and currents in the system, which, naturally, will coincide with those obtained from the Kirchhoff equations (Berkovich, Y., and Moshe, S., 2021; Berkovich, Y., 2024).

An important conclusion follows from the above: the reactive elements, their energy, or, in a more acceptable and familiar form, their power, are decisive in shaping the operating mode of an electrical system. Since electrical systems undergo a transformation of the type and parameters of electrical energy as a result of their operation, and reactive power plays a key role in this transformation, it seems useful to introduce a system state function characterizing this transformation. This function is defined as electrical entropy and represents, as already mentioned, the density of reactive power per unit time, assuming that steady-state conditions are being considered. The concepts introduced are analogous to thermodynamic ones—entropy, or state functions—describing the process of heat transfer from one body to another. In thermodynamics, this constitutes the content of the second law of thermodynamics—which, on the one hand, establishes the existence of entropy for equilibrium processes, and, on the other, asserts the increase in entropy in nonequilibrium processes (Isayev, S., 2000).

Let us emphasize again that electrical energy, compared to thermal energy, represents a higher level of energy, and this is reflected in the definition of electrical entropy. This quantity is not associated with energy loss, but rather with various forms of energy transformation, and therefore falls under the category of negentropy. That is, at the quantum level of microprocesses, it has the same probabilistic nature as thermal entropy. However, rather than dissipating energy, it generates a new form, and therefore constitutes negentropy—a quantity with a negative sign.

We will consider electrical entropy, like thermodynamic entropy, at the level of macroprocesses, i.e., its memorized level. On the other hand, this level represents the eliminated uncertainty of a certain probabilistic regime and, therefore, can be considered information. The term "entropy-information," introduced in (Hazen, A., 1998), has a similar meaning. When considering semantic information, the criterion for memorability is the achievement of the stated goal. In natural phenomena, the goal is the optimal nature of the quantities—their achievement of either a minimum or a maximum. It is important to emphasize that this condition is met for electrical entropy—in (Berkovich, Y., 2025), it is shown that reactive power, when correctly defined, always reaches its minimum value.

Until now, when discussing reactive power, we've been referring to the power produced by reactive elements—inductance and capacitance. However, an interesting feature is that switches elements—diodes, thyristors, and transistors—can exert an inductive or capacitive effect on processes during their periodic operation, leading to the circulation of reactive, or

more accurately, pseudo-reactive, power. The simplest example of such a circuit is a sinusoidal voltage source connected across a thyristor and a resistor in series. When a thyristor operates with a control angle, a shift in the first harmonic of the current appears in such a circuit, and the circuit functions as an active-inductive circuit, despite the absence of inductance (Mayevsky, O., 1978).

As is well known, a resistive circuit powered by voltage sources consumes a minimum amount of power, determined by Kirchhoff's equations. If current sources are used for power, the power will be maximized. An interesting example of optimization is a circuit whose branches consist of DC voltage sources and diodes. When such a circuit is powered by a current source, the sum of the voltages in the branches carrying the current will be the minimum of all possible. Such a circuit is said to simulate the shortest path (Dennis, J., 1959).

Similarly, a circuit whose branches consist of DC current sources and diodes, when powered by a voltage source, will have the maximum possible current flowing from one pole of the source to the other. Such a circuit simulates the maximum flow of a transport network. These examples demonstrate the role of switches in generating information in electrical circuits. If switches are controlled by pulse sequences, which can be considered elements of semantic information, then we see a combination of purely natural information (electrical phenomena) and purposeful information (pulses).

The value of reactive power underlies the magnitude of electrical entropy. Its definition itself has been the subject of debate and development throughout the history of electrical engineering. The primary motivation for this research was the desire to discover a deeper physical meaning in reactive (or inactive) power values beyond the exchange of power between source and load. As applied to purely sinusoidal current, these concepts emerged by the end of the 19th century based on orthogonal components (Steinmetz, Ch., 1898). However, the inappropriateness of this methodology for non-sinusoidal voltages and currents soon became apparent, and for practical purposes, the approach of Budeanu C., 1929 was adopted. Nevertheless, discussions on identifying the physical essence of inactive orthogonal components continued and generated new research. In (Fryse, S., 1932), it was proposed to retain the orthogonal components but not to resort to harmonic components. This approach was further generalized to polyphase circuits first by (Buchholz F., 1922) and then by (Depenbrock M., 1993) and was called the FBD method (based on the initials of the authors'

last names). The history of the development of the definition of reactive power is covered in detail in (Krogeris, A., 1993).

In this work and in all previous publications by the author, reactive power is defined according to (Emde, F., 1921, 1930). In (Berkovich, Y., 2024), the connection between this definition and Hamilton's principle is demonstrated, as well as the influence of reactive power on dynamic processes in DC-DC converters, including bifurcations and chaotic modes. In (Berkovich, Y., 2025), it is proven that it is in this form that reactive power takes optimal values. A comparison of the definitions of entropy in thermodynamics, mechanics, and electrical engineering is also provided. A more detailed explanation of the definition of reactive power according to Emde, F. is given below in the Preliminary Remarks section.

The concept of electrical entropy has already been considered in a number of the author's publications. The influence of reactive power on the occurrence of oscillations in a transistor Van der Pol oscillator is considered in (Berkovich, Y., and Moshe, S., 2021), and its effect on a Van der Pol oscillator loaded with a tunnel diode is investigated in (Berkovich, Y., 2024). Analogies between electrical and thermodynamic processes, as well as the action of the second law of thermodynamics in electrical devices, are analyzed in (Berkovich, Y., 2022).

In general, the article is structured as follows. In Section 3, using the example of a single-phase bridge rectifier with thyristors, an analysis of the information processes in it is performed based on tracing the reactive power flows in their correct definition for non-sinusoidal voltages and currents. In the following Section 4, a similar analysis is performed for a single-phase autonomous inverter, and in Section 5, for DC/DC converters. Section 6 discusses transport network models, followed by a brief overview of various information modes in utility-scale electrical systems in Section 7. The article concludes with conclusions.

2. Preliminary Remark

When considering the role of reactive power in electrical circuits, it is necessary, first of all, to clarify what we mean by this definition. It is well known that throughout almost the entire century-long history of the development of modern electrical engineering, this concept has been subject to refinements and modifications, accompanied by discussions and debates (Krogeris, A., 1993). The definition of reactive power, which forms the basis for all subsequent discussions and conclusions in this and other articles by the author, is given in most detail in (Berkovich, Y., 2024).

This definition is based on the quantity proposed by (Emde, 1930) for assessing reactive power, called *Entohmung* (German), which is defined as the following ratio of input voltage v_s and current i_s .

$$M = \frac{1}{2} \left(v_s \frac{di_s}{dt} - i_s \frac{dv_s}{dt} \right) \quad (1)$$

If we set $v_s = V_m \sin(\omega t + \phi_u)$, $i_s = I_m \sin(\omega t + \phi_i)$, and substitute these values into (1), we obtain:

$$M = \frac{1}{2} \left(v_s \frac{di_s}{dt} - i_s \frac{dv_s}{dt} \right) = \omega V I \sin \varphi = \omega Q \quad (2)$$

where $\varphi = \phi_u - \phi_i$. Thus, the quantity is equal to the reactive power multiplied by the angular frequency, or divided by the period T with a coefficient 2π . In the case of non-sinusoidal voltage and current waveforms, the expression for has two terms—one constant and the other a sum of sinusoidal functions of time, the average value of which over the period is zero (Krogeris, et al., 1993). The constant term will be equal to.

$$M = \omega \sum_k k V_k I_k \sin \varphi_k = \omega \sum_k k Q_k \quad (3)$$

where V_k, I_k are the effective values of the voltage and current of the k harmonic, φ_k is the phase shift angle between them, and k is the harmonic number of these quantities.

Thus, reactive power in the general case of non-sinusoidal voltage and current waveforms is defined as.

$$Q = \sum_k k Q_k \quad (4)$$

Note that for sinusoidal voltages and currents, it coincides with the generally accepted method. However, the integral method is also known for determining reactive power (Emde, 1921; Mayevsky, 1978; Berkovich, 2022)

$$Q = \frac{1}{2\pi} \int_0^T i dv \quad \text{or} \quad Q = \frac{1}{2\pi} \int_0^T v di \quad (5)$$

The quantity Entohmung M will be further considered as negentropy (information, electrical entropy) for electric circuits.

$$S_E = \frac{Q(VAr)}{T(s)} \quad (6)$$

In (Berkovich, 2024), several features of this quantity are noted. In electrical systems, only the generation and circulation of reactive power can transform electrical energy into other forms, transform its parameters and types; therefore, this quantity can be considered a state function, indicating the fact of electric current transformation. Without reactive power, only the transformation of electrical energy into thermal energy is possible, i.e., only the generation of entropy. Consequently, reactive power can be considered as negentropy, which allows the system to be brought to a different, ordered, low-probability state.

One of the reasons for this definition was also the analogy between thermodynamic and electrical cyclic processes identified in (Berkovich, 2022). The influence of reactive power on processes in a Van der Pol transistor oscillator is discussed in (Berkovich, Y., and Moshe, S., 2021) and in a similar oscillator with a tunnel diode in (Berkovich, 2024). The role of reactive power as an energy factor in synchronizing chaotic modes in converters is analyzed in (Berkovich, 2024).

In (Berkovich, 2024) the connection between the above definition of the quantities M and Q and the power functions is shown, and in (Berkovich, 2025) it is precisely with this definition that reactive power is minimized in an electrical circuit.

3. Analysis of information processes in a rectifier.

We will examine the operation of information processes in a rectifier using the example of a single-phase bridge rectifier on thyristors, containing a smoothing inductance and an ohmic load. The circuit diagram of such a rectifier is shown in Fig. 1, and its parameters, adopted in the illustrative modeling example, are as follows: $v_{in} = V_m \sin \omega t$, where $V_m = 20V$, $\omega = 314 \text{ rad/s}$, is the smoothing inductance $L_o = 0.02H$, the load $R_o = 1\Omega$, and the thyristor control angle $\alpha = 60^\circ$. The rectifier modeling was performed in Matlab using a small subroutine based on difference equations (7).

$$\begin{aligned} &\text{for } k=1:4*(10^4); \\ &x(1)=0; \\ &x(k+1)=((v_{in}(k)*a(k))/L_o-(R_o/L_o)*x(k))*dt+x(k); \end{aligned} \quad (7)$$

end

```
k1=1:4*(10^4)+1;
```

```
plot(k1,x(k1));
```

Here $a(k)$ is the commutation function in the form of a rectangular sine with unit amplitude, with a switching frequency equal to ω , and with a phase shift equal to the control angle α .

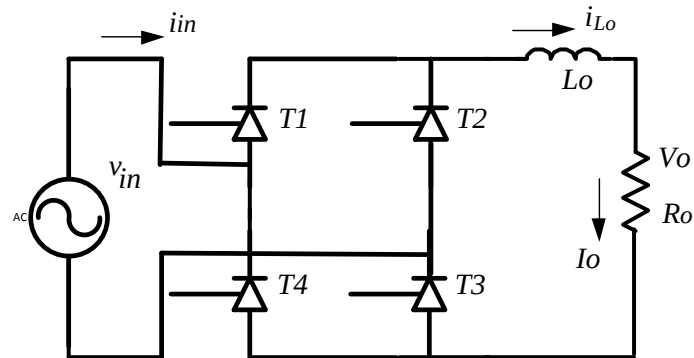


Fig. 1: Schematic diagram of a single-phase bridge controlled rectifier.

Here, $x(k)$ denotes the discrete value of the inductor current i_{Lo} . The calculation time step was adopted $dt = 10^{-5}$. The results of the current i_{Lo} and primary current i_{in} calculations are shown in Fig. 2.

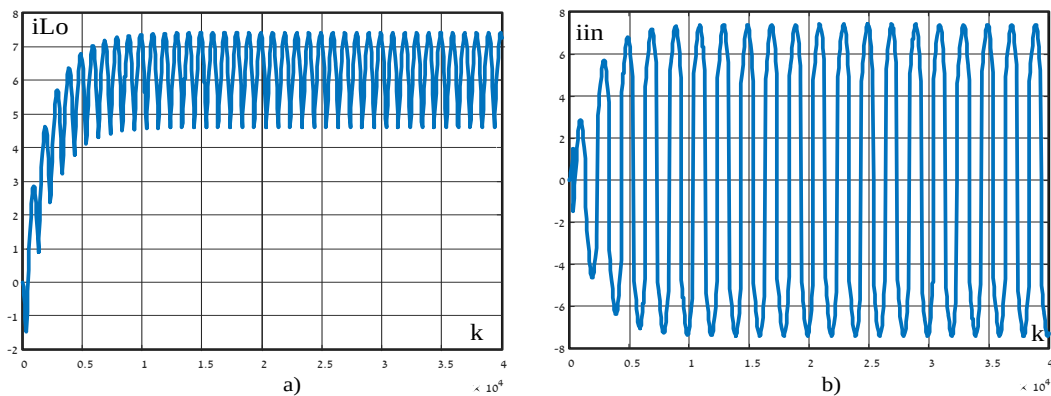


Fig. 2: Output and input current diagrams of the rectifier.

Let us present the results of calculations of some steady-state quantities: $I_o = \text{mean}(i_L) = 6.36\text{A}$, $V_o = \text{mean}(i_{Lo} \cdot R_o) = 6.36\text{V}$, $I_{in} = \text{rms}(i_{in}(n)) = 6.42\text{A}$, the first harmonic of the input current based on Fourier analysis $I_{1in} = 6.13\text{A}$. The apparent

power $S = V_{in} \cdot I_{in} = 91.24\text{VA}$, is then the active power $P_o = V_o \cdot I_o = 40.53\text{W}$. Reactive power at the input $Q_{in} = 75.80\text{VAR}$ and distortion $T = \sqrt{V_{in}^2 \cdot (I_{in}^2 - I_{1in}^2)} = 27.35\text{VA}$ power are.

Let us dwell in more detail on the definition of reactive power, which is, in fact, the carrier of negentropy (information). The calculation of reactive power here will be based on a definition different from other known ones. The key to this definition is that the value of reactive power is minimal, i.e., it reaches its optimum, and all harmonics, multiplied by their number, are taken into account in its calculation (see (3)). It is precisely this optimum value that is the main characteristic of negentropy (information). As shown in the works listed above and in Section 2, reactive power at the load rectifier input can be calculated as the area of the phase portrait in the plane of steady-state quantities $i_{in} - v_{in}$, divided by

$2\pi : Q_{in} = -\frac{1}{2\pi} \int_0^{T_s} i_{in} dv_{in} = -\frac{1}{2\pi} \int_0^{T_s} v_{in} di_{in}$. Accordingly, the reactive power on the load

$Q_L = -\frac{1}{2\pi} \int_0^{T_s} i_L dv_L = \frac{1}{2\pi} \int_0^{T_s} v_L di_L$. Taking into account the possible stepwise form of voltage

or current, the integral is replaced by the sum of the ordinates of these quantities, which in the Matlab program leads to the following expression.

$Q_{in} = \text{sum}(v_{in}(n1:(n2-1)) \cdot (i_{in}((n1:(n2-1))+1) - i_{in}(n1:(n2-1)))) / (2 \cdot \pi);$

$Q_L = \text{sum}(v_{Lo}(n1:(n2-1)) \cdot (i_{Lo}((n1:(n2-1))+1) - i_{Lo}(n1:(n2-1)))) / (2 \cdot \pi); \quad (8)$

where the values $n1$ and $n2$ distinguish in the total number of commutations k the beginning and the end of a certain period at a steady-state value, namely $n1 = 3.735 \cdot 10^4$; $n2 = 3.935 \cdot 10^4$; $n = n1:n2$; The specified phase portraits are given in Fig. 3a, b.

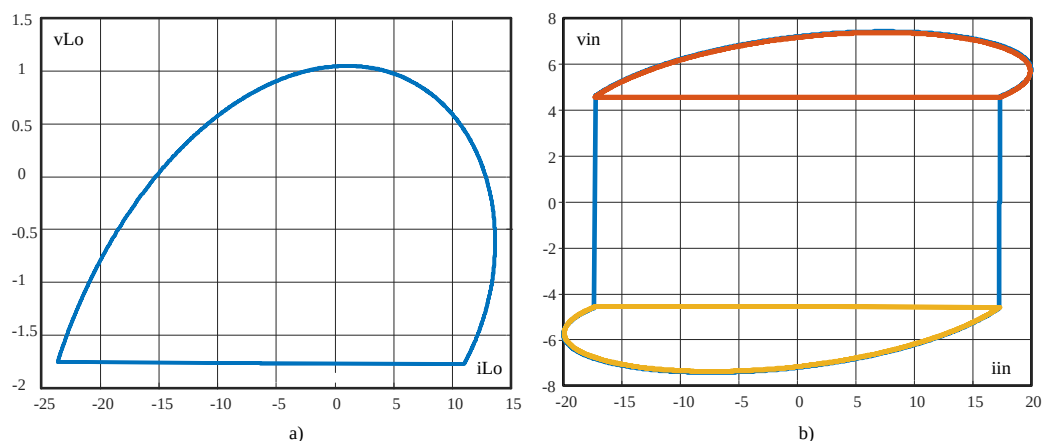


Fig. 3: Phase portrait of an inductor L_o - (a), and $v_{in} - i_{in}$ - diagram (b).

Fig. 3a shows the phase portrait of the inductance L_o , and accordingly, its reactive power, calculated according to (8), is equal to $Q_L = 25.14\text{VAr}$. The next Fig. 3b shows the phase portrait of the reactive power at the circuit input, $-Q_{in} = 75.81\text{VAr}$, and the outer contours of the figure correspond to it. Inside, at the top and bottom, phase portraits are shown on the inductance L_o - this is the same figure as Fig. 3a, but on a different scale for the positive and negative half-waves of the input current - Fig. 3b.

4. Analysis of information processes in the inverter

Next, we will analyze the information processes in a single-phase, stand-alone, full-bridge transistor inverter with an inductance and active resistance in the load. The schematic of such an inverter is shown in Fig. 4, and the following parameters of its components were chosen for the numerical example: $V_{in} = 20\text{V}$, switching frequency $\omega = 314\text{rad/s}$, load inductance $L_o = 0.03\text{H}$, and active resistance $R_o = 15\Omega$. A buffer capacitor $C_{in} = 1.5\text{mF}$ is connected at the inverter input, which absorbs the return energy of the inductance L_o . Typically, the inverter is powered by a rectifier, which, due to the valves it contains, cannot perform this function. The schematic of such an inverter is shown in Fig. 4, and the following parameters of its components were chosen for the numerical example: switching frequency, load inductance, and active resistance. A buffer capacitor is connected at the inverter input, which absorbs the return energy of the inductance. Typically, the inverter is powered by a rectifier, which, due to the valves it contains, cannot perform this function. To achieve energy return completely without the influence of the rectifier, a small resistance $R = 1\Omega$ is additionally included between the rectifier and the capacitor.

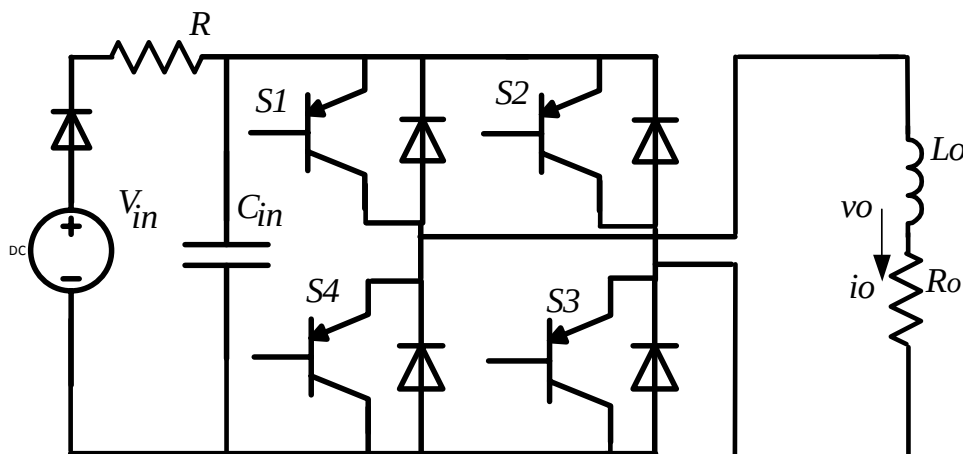


Fig. 4: Schematic diagram of a single-phase bridge inverter with freewheeling diodes.

The inverter simulation was performed in Matlab using a small subroutine based on difference equations (9). Here, denotes $x1(k)$ the discrete value of the inductor current i_o , and $x2(k)$ denotes the voltage across the capacitor C_{in} . The calculation time step is $dt = 10^{-5}$. As in the previous paragraph, $a(k)$ is the commutation function in the form of a rectangular sine wave with unit amplitude, with a commutation frequency equal to ω .

```
for k=1:4*(10^4);
x1(1)=0;
x2(1)=19.5;          (9)
x1(k+1)=((x2(k)/Lo).*a(k)-(Ro/Lo)*x1(k))*dt+x1(k);
x2(k+1)=-(x1(k).*a(k))*(1/Cin)*dt+x2(k)+((vin(k)-x2(k))/R)*(1/Cin)*dt;
end
k1=1:4*(10^4)+1;
plot(k1,x1(k1),k1,(vin(k)-x2(k1))/R);
```

The results of the calculations for the voltage v_o and current i_o in the load and the voltage v_c and current i_c in the capacitor are shown in Fig. 5.

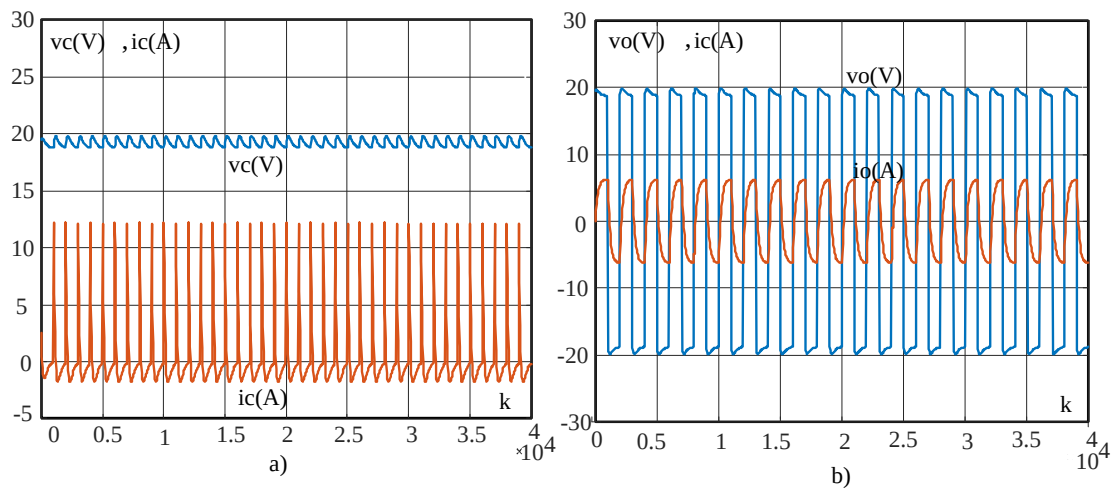


Fig. 5: Voltage and current curves on the input capacitor and at the inverter output.

Let us present the results of calculations of some steady-state quantities: the input quantities are $I_{in} = \text{mean}(i_{in}) = 0.784A$, $V_c = \text{mean}(v_c) = 19.21V$. The output quantities are - the effective values of the output voltage $V_o = \text{rms}(V_o(n)) = 19.20V$, the output current $I_o = \text{rms}(i_o(n)) = 0.999A$, and the effective value of the first harmonic of the output current based on Fourier analysis $I_{1o} = 0.97A$. The input active power is $P_{in} = V_{in} \cdot I_{in} = 15.68W$,

while the output active power is $P_o = I_o^2 R_o = 14.97W$. Power reduction due to the input resistor R: $P_o = I_{in,rms}^2 R = 0.739W$.

Reactive power at the input and output as the area of the phase characteristic of the reactive element.

$$Q_c = \sum (v_c(n1:(n2-1)) \cdot (i_c((n1:(n2-1))+1) - i_c(n1:(n2-1)))) / (2 \cdot \pi);$$

$$Q_o = \sum (v_o(n1:(n2-1)) \cdot (i_o((n1:(n2-1))+1) - i_o(n1:(n2-1)))) / (2 \cdot \pi); \quad (10)$$

and numerically, $Q_c = -0.548VA$, $Q_o = 15.335VA$.

The above mentioned phase characteristics on the input capacitor C_{in} and on the load inductance are shown in Fig. 6a,b, respectively.

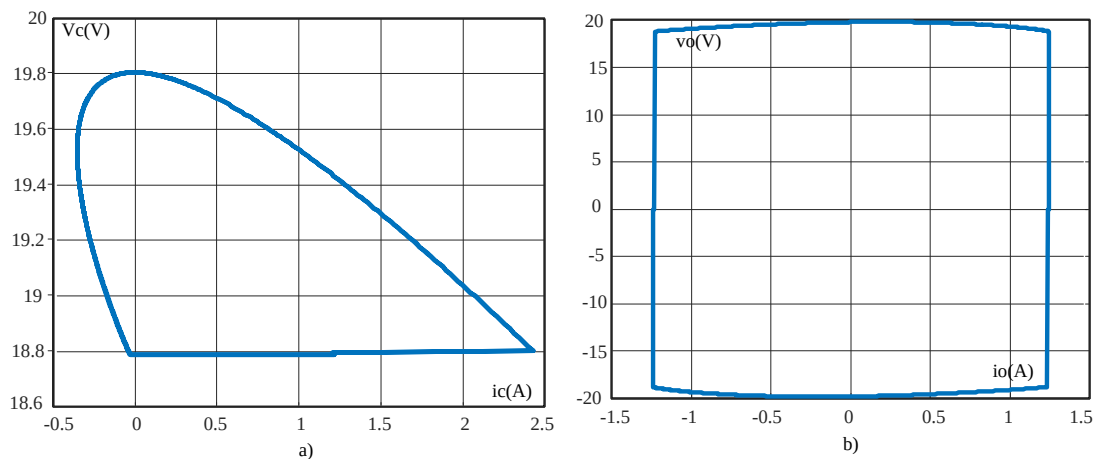


Fig. 6: Phase portrait on a capacitor C_{in} , a) and v_o-i_o diagram, b).

Now we can trace the role of reactive power during one period of inverter operation (Fig. 7). At the moment of transistor switching (point 0), the load current begins to close through the free-wheeling diodes of the other two bridge arms, i.e., the inductor power is transferred to the load resistor R_o and simultaneously to the capacitor C_{in} (up to point 1). After the inductor current reaches zero, the inductor begins to accumulate power, and the load resistance consumes power from the input source (interval 1-2). The average power value in the 0-1 section $P_{o,0-1} = 0.43W$, the apparent power in the 0-2 section $P_{o,0-2} = 14.97W$. In this case, the total reactive power $Q_s = Q_o + Q_c = 14.79W$, i.e., in this example, the entire reactive power coincides with the power on the load resistor.

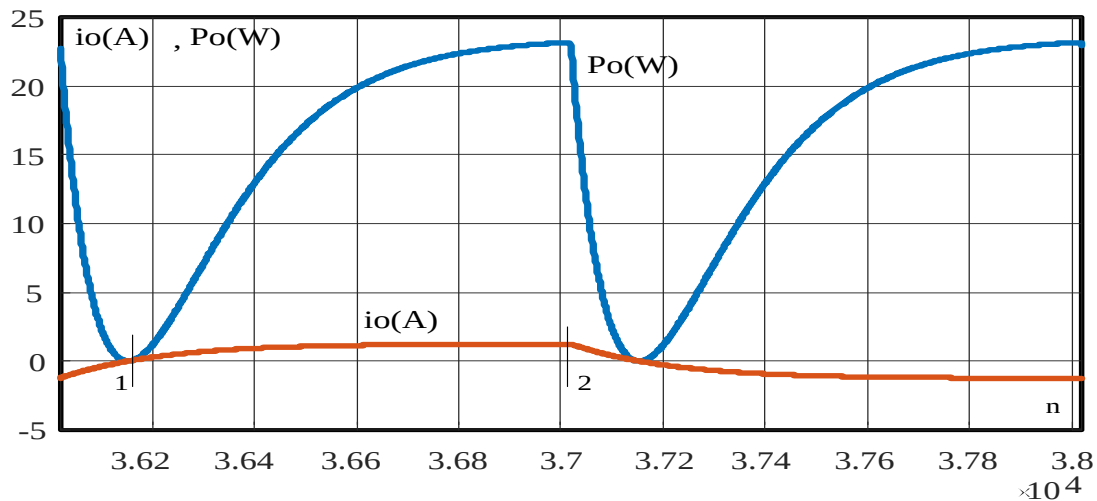


Fig. 7: Output current and output power diagrams.

In conclusion, based on the results of the last two paragraphs, we note the following. When designing these converters, the designer relies on their knowledge of electrical engineering and experience designing similar installations. Processes in an already designed and implemented installation occur at the quantum level, representing a set of random microstates. The set of most probable microstates is stored and expressed in the stored state as information, expressed by the observed final operating mode of the device. As can be seen, the information carrier is reactive power, generated by all harmonics of the process, taking into account their numbers. Its numerical indicator is negentropy, defined as the reactive power density over time.

5. Reactive Power and Information Processes in DC-DC Converters.

For completeness, let's briefly consider the functioning of reactive power in DC-DC converters – buck converters and boost converters. These issues are discussed in detail in (Berkovich, Y., 2024), (Berkovich, Y., 2025).

5.1 Buck converter. The converter circuit diagram is shown in Fig. 8, and its operating diagrams are shown in Fig. 9. The analysis of physical processes in the converter was carried out in Matlab using a mathematical model with the following parameters: $V_{in} = 20V$, $L = 100\mu H$, $C_o = 5\mu F$, $R_o = 1\Omega$, switch switching period $T_s = 20\mu s$, duty cycle $D = 0.6$. The calculation step is $dt = 10^{-8}$, and the current time is $tk = k \cdot dt$.

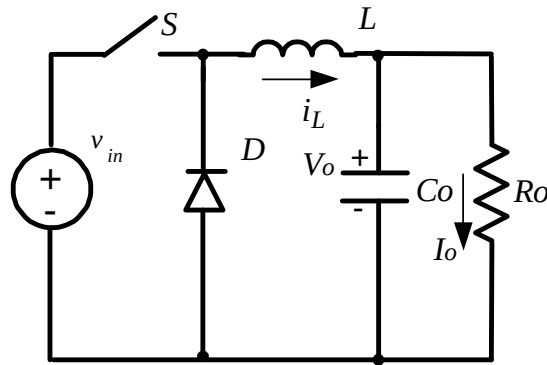


Fig. 8: Buck converter.

The calculations were performed using a simple difference equation calculation program.

for $k=1:(10^5)$;

$$x1(k+1)=(((V_{in}/L)*d(k)-(x2(k)/L)*(x1(k)>0))*dt+x1(k)); \quad (11)$$

$$x2(k+1)=((x1(k)/C_o)*(x1(k)>0)-x2(k)/(R_o*C_o))*dt+x2(k);$$

end

$k1=1:(10^5)+1$;

plot($k1,x1(:),k1,x2(:)$),

here the commutation function $d(k)$ is defined as $d = (ramp < V_{ref})$, with the sawtooth function $ramp = 10(t_k / T_s - floor(t_k / T_s))$ and the comparison voltage $V_{ref}=10V$. The inductor current i_L is denoted by $x1(k)$, and the voltage on the capacitor v_o is denoted by $x2(k)$.

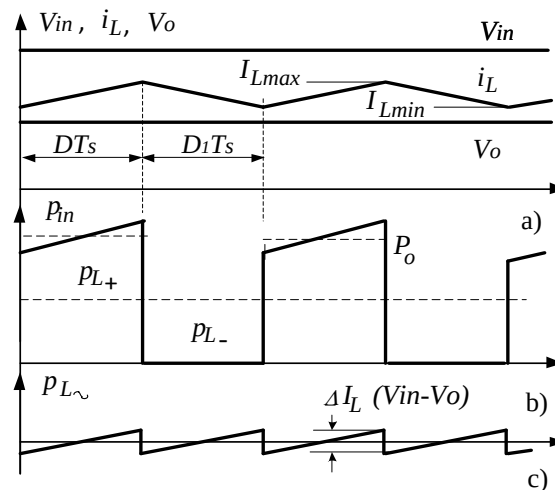


Fig. 9: Change of currents and powers in Buck converter – a)-c).

Fig. 10 shows the results of calculations of the current through the inductance i_L and the voltage v_o on the capacitor. According to these results, $V_o = \text{mean}(v_o) = 12V$, $I_{in} = I_o \cdot D = 7.2A$, which completely coincides with the results determined by well-known theoretical formulas.

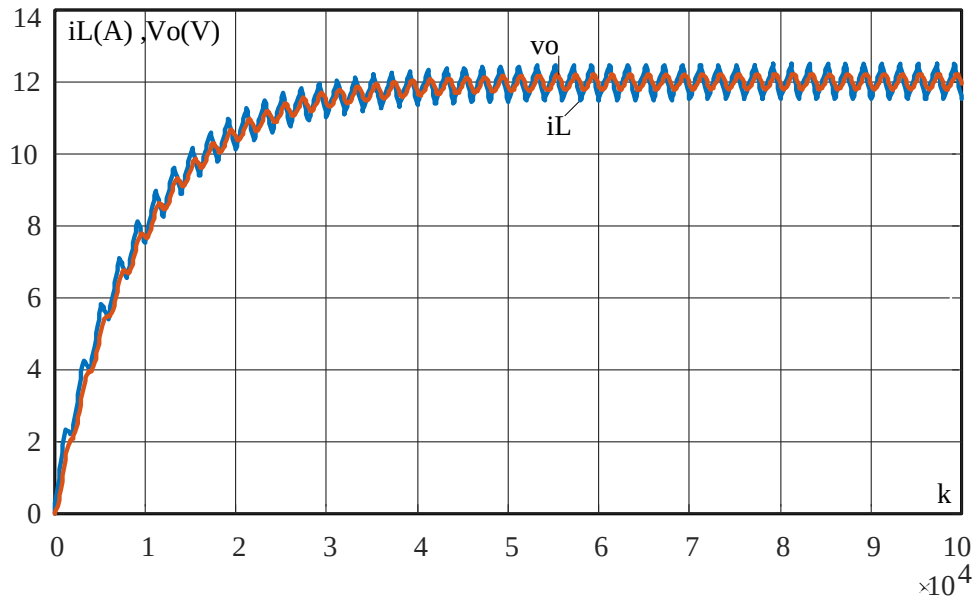


Fig. 10: Inductor current and output voltage change curves.

As in the previous examples, let's examine the circulation of reactive power in more detail. As can be seen in Fig. 9b, power consumption from the source occurs only when the switch is closed, and all power is consumed during the period. The lower portion, under the dotted line, shows the fraction of power consumed by the converter during the duty cycle interval D , while the upper portion shows the power stored in the inductor, which will be released to the load during the interval $1-D$ when the switch is open. If the current through the inductor were perfectly smoothed, no new energy accumulation would occur. However, due to current pulsation, i.e., the appearance of reactive power, such accumulation becomes possible.

Indeed, after the switch is turned on again, the inductor current changes from a certain minimum value I_{Lmin} to a maximum - I_{Lmax} and the current increment is $\Delta I_L = (V_{in} - V_o)DT_s / L$. This increment ensures the accumulation of energy $W = (1/2)L((I_{Lmax})^2 - (I_{Lmin})^2)$ in the inductor. Considering that $(1/2)(I_{Lmax} + I_{Lmin}) = I_L$, $(I_{Lmax} - I_{Lmin}) = \Delta I_L$, where I_L is the average value of the inductor current, $I_L = I_o$. As a result, after some simplifications, we obtain.

$$P_L = V_{in} D_1 D I_L \quad (12)$$

Clearly, the resulting power value is exactly equal to the power consumed by the converter during the $1-D$ interval when the switch is open. Thus, we see how a small amount of pulsation and the reactive power it generates drives the generation of significant power, which is then consumed by the load.

Fig. 11a shows the phase portrait of an inductor L , with the horizontal axis representing the ripple values iLp and the vertical axis representing the voltage across this inductor. Accordingly, its reactive power, calculated using (2b), is equal to $Q_L = 3.08 \text{ VAr}$. The following Fig. 11b shows the phase portrait of the reactive power across a capacitor, plotted along the axes: capacitor current – voltage ripple across it.

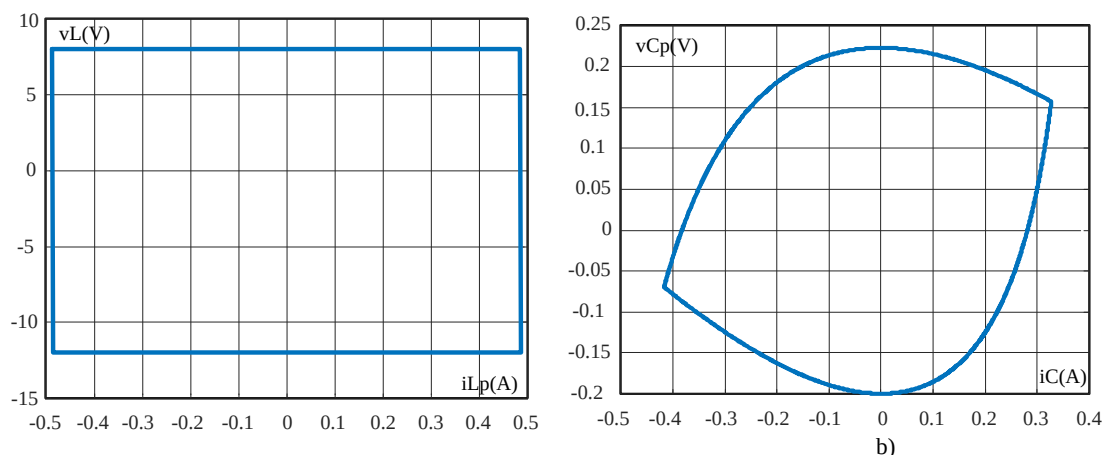


Fig. 11: Phase portraits on the inductance and on the capacitor of the Buck converter.

5.2. Boost converter. In the same vein as described in section 5.1, we will consider the operation of the Boost converter - its circuit is shown in Fig. 12, and the diagrams of its operation are given in Fig. 13. As before, the analysis of physical processes in the converter was carried out in Matlab using a mathematical model with the following parameters: $V_{in} = 20 \text{ V}$, $L_{in} = 200 \mu\text{H}$, $C_o = 5 \mu\text{F}$, $R = 10 \Omega$, the switching period of the switch S $T_s = 20 \mu\text{s}$, duty cycle $D = 0.6$. The calculation step is $dt = 10^{-8}$, and the current time is $t_k = k \cdot dt$. (Fig. 13).

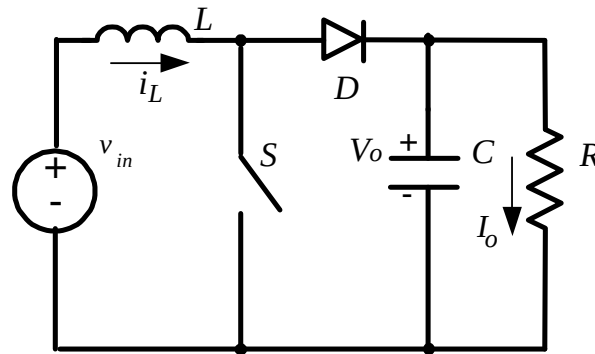


Fig. 12: Boost converter.

Below is a simple calculation program using difference equations.

```
for k=1:10^5;
```

```
x1(1)=0;x2(1)=0;
```

```
x1(k+1)=((Vin/Lin)-(x2(k)/Lin)*(1-d(k)))*dt+x1(k);
```

```
x2(k+1)=((x1(k)/Co)*(1-d(k))-x2(k)/(Ro*Co))*dt+x2(k);
```

(13)

```
end
```

```
k1=1:(10^5)+1;
```

```
plot(k1,x1(k1),k1,x2(k1));
```

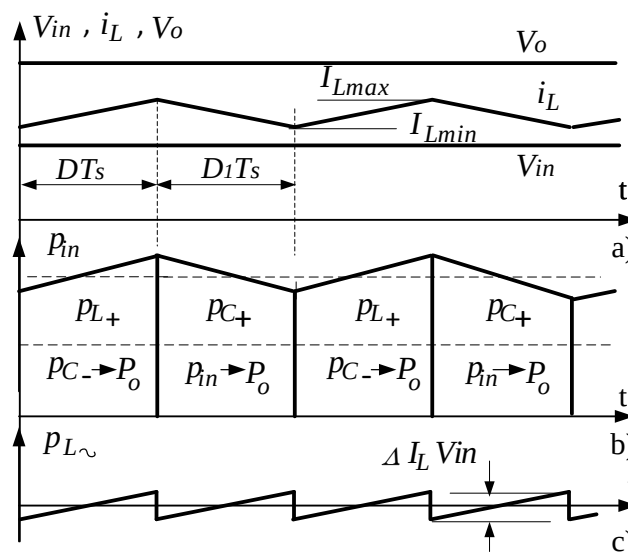


Fig. 13: Изменение токов и мощностей в Boost converter.

where the commutation function $d(k)$ is defined as $d = (\text{ramp} < V_{ref})$, while the sawtooth function $\text{ramp} = 10(t_k / T_s - \text{floor}(t_k / T_s))$ and the comparison voltage $V_{ref} = 6V$. As in the

previous case, $x1(k)$ denotes the inductor current i_L , and $x2(k)$ denotes the voltage on the capacitor v_o .

Fig. 14 shows the results of calculations of the current through the inductance i_L and the voltage on the capacitor v_o . According to these results for the steady-state mode $V_o = \text{mean}(v_o) = 49.7V$, $I_o = \text{mean}(i_o) = 4.96A$, $I_{in} = \text{mean}(i_L) = 12.49A$, which coincides with a minor error with the results determined using well-known theoretical formulas.

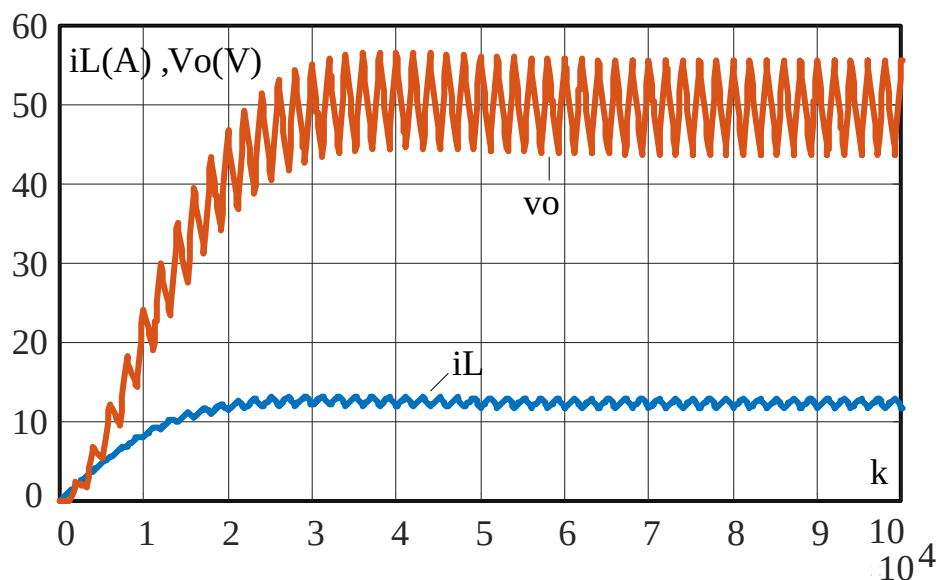


Fig. 14: Current curves on the inductor and at the output of the Boost converter.

As in the previous examples, let's examine the circulation of reactive power in more detail. As can be seen in Fig. 13b, power consumption from the source occurs both when the switch is closed and when it's open. At each operating point, the entire power consumed for the period is divided into two parts. The lower part, under the dotted line, shows the portion of power consumed by the converter during the duty cycle interval D due to the energy in the capacitor, while the upper part shows the power stored in the inductor, which will be released to the capacitor during the interval $1-D$ when the switch is open. If the current through the inductor were perfectly smoothed, no new energy accumulation would occur. However, due to current pulsation, i.e., the emergence of reactive power, such accumulation becomes possible.

Indeed, as with a buck converter, after each switch-on, the inductor current changes from a certain minimum value $I_{L\min}$ to a maximum $I_{L\max}$ —and the current increment is $\Delta I_L = V_{in}DT_s / L$.

This increment ensures the accumulation of inductive energy in the inductor $W = (1/2)L((I_{L\max})^2 - (I_{L\min})^2)$. Considering that I_L - average value of inductive current, where $(1/2)(I_{L\max} + I_{L\min}) = I_L$, $(I_{L\max} - I_{L\min}) = \Delta I_L$. As a result, after simplifications, we obtain:

$$P_L = V_{in}DI_L \quad (14)$$

Clearly, the resulting power value is exactly equal to the power consumed by the converter from the capacitor over the D interval when the switch is closed. This power, accumulated by the inductance, is transferred to the capacitor over the $1-D$ interval. Thus, we see how a small amount of ripple and the reactive power it generates drives the generation of significant power, which is then consumed by the load. Fig. 14a shows the phase portrait of the inductance L , with the ripple values iLp plotted on the horizontal axis and the voltage across this inductance plotted on the vertical axis (Fig. 15).

Accordingly, its reactive power, calculated using (2b), is equal to $Q_L = 9.4843\text{Var}$. The next Fig. 15b shows the phase portrait of the reactive power on the capacitor in the axes: capacitor current ripple – voltage ripple across it. The reactive power, also calculated using (2b), is equal to $Q_L = -0.1767\text{Var}$.

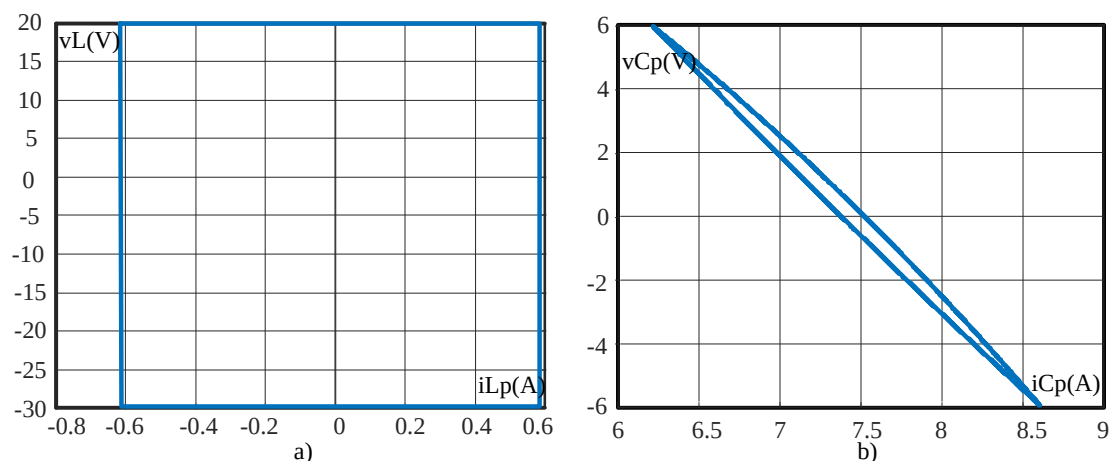


Fig. 15: Phase portraits on the inductance and on the capacitor of the Boost converter.

6. Diode electrical circuits as analog computing systems

Fig. 16a shows the graph of an electrical circuit with two characteristic input points s and output points t , connected to either a single voltage source E_s or a single current source I_s , depending on the problem. Depending on the problem and modeling goals, each branch has one of the following types: b), c), d), e).

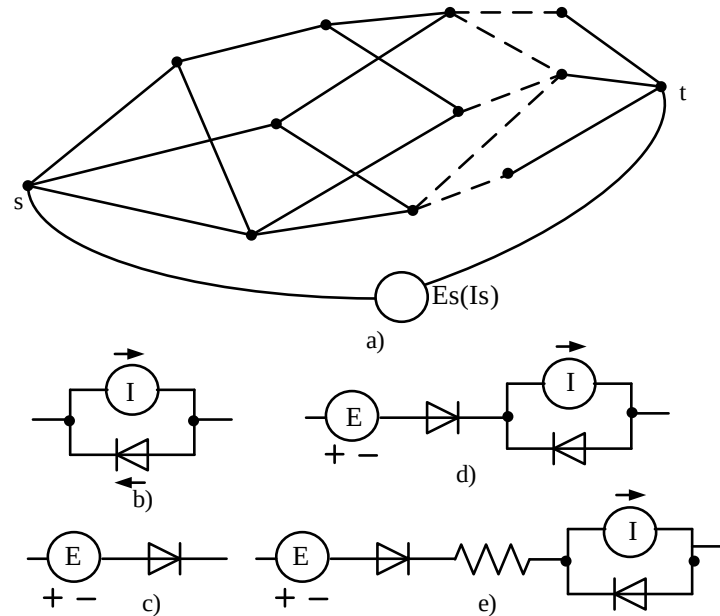


Fig. 16: Graph of the electrical model of the transport network and possible diagrams of its branches.

If all branches of the circuit are implemented as a link (Fig. 16b), then such a circuit is a model for solving the problem of maximum flow in a transport network, flowing between points s - t . To determine this, the circuit is exposed to a single voltage source E_s . The magnitudes of the currents I represent the maximum flow of a given link, and the resulting flow in such a circuit will be the maximum possible.

If all branches of the circuit are designed as a link (Fig. 16c), then such a circuit is a model for solving the shortest path problem in a transport network, existing between points s - t . In this problem, to determine the shortest path, the circuit is subjected to the action of a single current source I_s . The voltage values E reflect the path length of a given link, and the resulting path in such a circuit will be minimal.

If it is also necessary to determine the cost of carrying the maximum flow through the transport network, then a link (Fig. 16d) is used in all branches, representing the cost of carrying the flow through a given section of the path through the voltage E . If this cost is not constant, but depends quadratically on the flow value, then an additional resistor is included in this link (Fig. 16e).

Let's consider the basis for the above modeling results. In the shortest path problem, the voltage sources are connected to the diodes via the negative pole, meaning the diode connected to the source with the lower voltage will be the first to open, and so on for all sets of links. A unit current flowing through these sources will create power losses equal to the path length of a given link. Ultimately, due to the property of an electric circuit to minimize power losses, the total power losses will be the lowest of all possible for this circuit, and therefore, the identified path will be minimal.

Similarly, in the maximum flux problem, for the resulting circuit current, the diode that is biased in parallel by the large current source connected in parallel will most likely open. A unit voltage source applied to the resulting maximum flux will create power losses, which, according to the dual problem of optimizing power losses in the circuit, will be the maximum.

The problem of optimizing active power losses in an electrical circuit has been discussed in detail in the literature, for example, in (Dennis, 1959). If reactive power production generates electrical negentropy (information), then active power losses in each case generate electrical entropy. Since the period of change in power losses is infinite, the entropy itself is zero

$$S_{EP} = P/T_s = 0 \quad (15)$$

where S_{EP} is the electrical entropy caused by active power losses, T_s is the circuit switching period, $T_s \rightarrow \infty$. Zero electrical entropy means that no transformations occur in the system. Moreover, the magnitude of the power loss itself is a stored value and therefore also informative.

In (Berkovich, Y., Golan, G., 2005), it is shown that more complex DC circuits with diodes, voltage, or current sources can be convenient models for solving processes in economic systems using entropy, thanks to optimization of voltage, current, or power.

7. Reactive Power in Modern Electrical Systems.

In this section, we will examine information processes in electrical networks of any type, based on the concept of electrical entropy—negentropy. By simply "entropy," we will understand thermodynamic entropy, with the following meanings: a) entropy as a measure of energy degradation; b) entropy as a measure of system disorder; c) entropy as a quantity whose decrease indicates the acquisition of new information by the system due to a transition from a more probable state to a less probable one. A decrease in entropy is associated with the appearance of negative entropy.

With regard to electrical circuits, we will rely on the concept of electrical entropy, which is defined as a change in reactive power over a certain time interval (see Section 2). Specific and important processes and modes in electrical networks will be examined below in this context.

7.1. Reactive Power Compensation Mode. This section will examine two aspects related to reactive power: its appearance in the load and the need for its compensation. The presence of a load consuming reactive power in addition to active power indicates that, thanks to the introduction of certain new properties into the load, it gains the ability to utilize the supplied power in a more targeted and organized manner, not just by using active power (like a simple heater). In other words, its operation mode, compared to heating, becomes less likely. In this particular case, the most common load—an asynchronous motor—thanks to its rotating magnetic field and electromagnetic induction, which are accompanied by the consumption of inductive reactive power, gains new opportunities not only to waste power on heating the wires but also to convert it into mechanical power. It can be argued that reactive power generally leads to a decrease in entropy (energy is not converted solely into heat) and is also a factor in introducing negentropy (information) – the acquisition of new, less probable operational possibilities. However, every expenditure on entropy reduction in one place leads to a slight increase in it elsewhere.

Indeed, the load's need for reactive power is met by the power grid, which is a large "reservoir" of capacitive power. Clearly, its circulation along the transmission line leads to power losses in the wires, and these additional losses are a sign of increasing entropy.

Therefore, there is a need to compensate for inductive reactive power by connecting a reactive power source in close proximity to the load terminals—in the simplest case, a

capacitor bank. Obviously, this does not eliminate the consumption of inductive reactive power (the factor providing negentropy), but merely prevents its circulation through the transmission line wires (thereby reducing power losses and entropy).

7.2. Reactive power generation mode. Some loads, such as asynchronous generators and grid-followed inverters, require a capacitor bank to be connected to their input terminals to produce capacitive power. Let's consider this from the perspective of entropic processes.

The need for reactive power from these devices indicates that they acquire certain new energy conversion properties, i.e., an increase in negentropy. We can obtain this power from the grid, but this is accompanied by an increase in entropy elsewhere – line losses increase. Therefore, a capacitor bank is connected in close proximity to the load terminals, as in case 7.1, to provide the necessary reactive power and prevent it from circulating through the grid.

7.3. Harmonic Filtering. The most common nonlinear loads that generate higher harmonics in the grid are power electronics devices—rectifiers, AC regulators, fluorescent and gas-discharge lamp-based lighting systems, and other nonlinear loads.

Once again, we are faced with the need to pay a certain price for these devices to acquire new useful properties by introducing negentropy. In this case, its presence is accompanied by the generation (consumption) of higher harmonics, along with reactive power at the fundamental harmonic. Higher harmonics lead to additional losses in the grid and other equipment, i.e., we again see a sign of entropy growth. Passive or active filters are used to eliminate (reduce) this. Filters are installed in close proximity to the nonlinear load, so that the harmonics are confined within a limited loop without escaping into the grid.

7.4. Network Regulation Using Reactive Power. The electrical grid is primarily designed to transmit active power to various consumers. Therefore, to ensure stable operation, regulate power levels, and maintain frequency, the primary means is a sufficient reserve, i.e., a sufficient reserve of consumed entropy. However, in many modes, these tasks—increasing network stability, raising or lowering voltage—can be accomplished by injecting capacitive or inductive reactive power into the grid. Such operations are performed, for example, using Unified Power Condition Systems (UPCS) (Teodorescu R., et al., 2011). The reactive power supplied to the grid by these systems, according to specific algorithms, is precisely the additional negentropy that brings the grid to the required state.

7.5. Preventing Chaotic Modes. The occurrence of chaotic modes in electrical devices has been extensively studied, in particular (Tse, 2004). In electrical networks that are much more branched and complex, containing sources with varying power, nonlinear loads with extreme types of nonlinearity, and complex control circuits, the occurrence of such modes becomes highly probable. In (Beck, Y., Berkovich, Y., 2019, Berkovich, Y., 2024), methods for preventing chaotic modes by introducing additional reactive power into a buck converter and boost converter, respectively, are discussed in detail. The basic idea of obtaining additional reactive power is to add a rectangular voltage with the switching frequency of the converter to the supply voltage or to periodically shunt the input inductance. The influence of reactive power on the elimination of Hopf oscillations in the Van der Pol oscillator and other types of oscillators is considered in (Berkovich, Y., 2021, 2024).

8. CONCLUSIONS

1. The concept of entropy, introduced in thermodynamics, is generalized to processes in electrical engineering as electrical entropy, which in this case takes on a different meaning due to the fact that electrical energy has a higher level than thermal energy. Indeed, incoming active power is efficiently transferred to the load, and reactive elements are not associated with active power consumption or heating temperatures, so it is more appropriate to speak of negentropy and, accordingly, their informational role in circuits.
2. Electrical entropy characterizes not the degradation of energy or the tendency of processes to the most probable state of the system, but, on the contrary, the degree of its approach to a less probable state, and is therefore negative entropy – negentropy.
3. Since the electrical system tends to acquire a less probable state, this leads to the elimination of some uncertainties, i.e., the generation of information.
4. Electrical entropy is a function of the system's state, characterizing the transformation of electrical energy from one form to another and the corresponding change in the parameters of the electric current. Zero electrical entropy means the absence of such transformations.
5. Such transformations are most clearly visible in valve converters of the current or frequency type, where the circulation of even insignificant reactive power of pulsation currents plays a decisive role in their functioning.
6. Information processes in electrical circuits-models of transport networks-are quite revealing.

Composed of voltage sources or current sources and diodes, these circuits consume only active power, which is optimal for the circuit and thus indicates either the shortest path in the

circuit or the maximum flow. Active power consumption indicates the presence of electrical entropy (not negentropy), and due to the infinite period of the flow, this entropy is zero.

7. In general-type electrical circuits, reactive power is the only means of maintaining stability and regulation.

8. Further development of the negentropic concept of reactive power is seen in the direction of its statistical interpretation at the electron-quantum level.

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