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ELECTRICAL CIRCUITS AND THE SECOND LAW OF THERMODYNAMICS

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ABSTRACT

The present paper sets some analogies between the processes of consumption and exchange of energy upon the cyclic (steady-state) processes in electric circuits and the reversible processes in thermodynamic systems. One of the conditions of cyclic character of processes in electric circuits is the periodicity of voltage and current, or a periodic character of the switch functioning, but the most influential factor is the presence of the consumption by the circuit of the reactive power. The paper shows that it is precisely this factor that makes it possible to point out the presence in electric circuits, like in thermodynamic systems, of not only entropic but also negentropic processes. It is shown that being the source of negentropy, it is the reactive power that makes it possible to allow both to transform electrical energy to mechanical one, in analogy with heat energy in a thermodynamic cycle, as well as and the realization of a large variety of other important modes. Using as an example the basic RL circuit with power supplied by a sinusoidal source, and an RLC circuit supplied by a constant voltage source through a periodically commutated switch, as well as other examples, we have shown the formation of cycles in analogy to thermodynamic cycles, which in principle gives a possibility to obtain mechanical energy in accordance with the second law of thermodynamics as formulated by Max Planck. The paper analyzes the cyclical character of power transformations, shows an analogy with the Carnot cycle in the processes of power output, accumulation, and most importantly, the return of power. The assertion of the negentropy character of reactive power, which follows, in particular, from our analysis is accompanied by a proposition of a method of numerical estimation of the value of the negentropy also based on analogies with thermodynamic systems. The given analysis is accompanied by a detailed computer modeling.

KEYWORDS: Electrical circuit, Reactive Power, Carnot Cycle, Entropy, Negentropy, Second Law of Thermodynamics.

INTRODUCTION

As is well known, the first law of thermodynamics (Isayev, 2000, Waldram, 1985), being a law of energy conservation, is valid for all the natural phenomena, and naturally, for the electric systems. Although the thermal and electrical energies are based on completely different physics phenomena and laws – and the electrical energy is energy of a higher level, in science and technology a constant is widely used, which defines the equivalent quantities of the heat and electric energies. As concerns the second law of thermodynamics, we note that in it is common in it to discern the two logically independent patterns. One of them is called the second law of thermodynamics for equilibrium reversible processes – and this is the principle of the existence of entropy – and the second relates to irreversible process, as the principle of increasing entropy (Isayev, 2000, Waldram, 1985). The concept of entropy introduced by this law has acquired great importance, far surpassing the limits of thermodynamics, describing irreparable losses of energy, its degradation, and in general, the degree of chaoticity of processes (Brillouin, 1963, Prigogine, 1994). In this sense, the inevitable losses of thermal energy in electric circuits are a good illustration of the general principle of the increase of entropy. Of essence is also the fact the release of power on an active load resistor is accompanied by the production of entropy, which makes it possible to consider electric circuits as convenient models to illustrate the Minimum entropy production principles (MinEP) I. Prigogine or Maximum entropy production principle (MEPP) L. Onsager (Martyushev, Seleznev, 2006). These principles are confirmed in the case of electric circuits (Landauer, 1975, Bruers, et al., 2007, Županovi´c, et al., 2004, Axelrod, et al., 2005) due to their property to minimize the consumption of active power when the circuit is supplied by a voltage source, or to maximize it when the circuit is supplied by a current source (Dennis, 1959). On the other hand, the principle of entropy maximization is used as a criterion in solutions of purely electrical engineering problems. (Christen, 2009, Berkovich, 2006, Jablonsky, 1990).

The above described connection of the second law of thermodynamics with electric circuits related to the optimization principles of entropy production concerns the non-equilibrium processes in which the entropy increases. However, there arises a question about the existence of such a relation for equilibrium processes both in thermodynamics and electrical engineering. For it is precisely the equilibrium processes that lie in the basis of the functioning of devices that transform various kinds of energy making it possible to obtain mechanical work, or other useful results. It is known that in the cyclical equilibrium thermodynamic processes the changes of entropy in the course of each cycle equal zero due to the introduction of negative entropy from the environment, for example, from the cooling agent in thermal machines. Then the question arises: are similar processes observed in various electric machines, in particular in those that transform electric energy into mechanical work, producing entropy in the process of power consumption. Is there in such systems the negative entropy, negentropy, and if so, how it is being formed.

In this paper, we made an attempt at searching analogies between thermodynamic and electric systems, with taking into account, naturally, the fact that the processes in both are based on completely different physical phenomena. It is shown that in both cases the transformation of energy into mechanical work, or in other kinds of energy is possible only when cycles are formed, in thermodynamics into the pressure-volume plane, and in electrical engineering, the voltage-current plane. And in both cases in the process of each cycle along with energy consumption there necessarily exists a segment of return of a part of energy. Due to the different physical nature, the ways of utilizing the returned energy differ. If one assumes that the consumption of active power in electric circuits is related to the production of entropy, it is the circulation of reactive power that ensures a partial return of power back to the network, that is the reactive power plays the role of negentropy. In the absence of reactive power cycles do not form, and the whole of electric energy can transform only to heat.

In Sections I-III, the analogies mentioned are being followed up on the examples of various circuits of alternating and direct currents showing the role of the reactive power both in obtaining mechanical work and in current transform, and its regulation. Concluding, Sections IV and V describe the manifestations of the second law of thermodynamics in electrical systems, and formulate proposals for calculating entropy and negentropy values in them.

I. The processes of consumption and exchange of energy in a basic RL-circuit

Consider a basic RL-circuit (Fig. 1,a) connected to a sinusoidal supply voltage v_s with the amplitude $V_{s.m}$ and circular frequency ω, $v_s = V_{s.m} \sin \omega t$. The processes in such a circuit are well-known, so here we will dwell on some well-known formulas and curves in order to give some clarity and integrity to our narrative. We write down some evident formulas, which will be needed further:

$$Z=\sqrt{R^2+(\omega L)^2}; \qquad \phi=\tan^{-1}\left(\frac{\omega L}{R}\right); \qquad I_{s.m}=\frac{V_{s.m}}{Z}; \qquad i_s=I_{s.m}\sin(\omega t-\phi).$$

Here the instant value of the power consumed equals $p=V_{s.m}I_{s.m}\sin(\omega t)\cdot\sin(\omega t-\phi)$, and the instant value of reactive power $q=I_{s.m}^2\omega L\cdot\sin(\omega t-\phi+\pi/2)\cdot\sin(\omega t-\phi)$. Note that the instant value of active power $pR=I_{s.m}^2R\cdot\sin^2(\omega t-\phi)$. The input voltage of the circuit, the current consumed and the powers *p* and *q* are shown in Fig. 1,b.

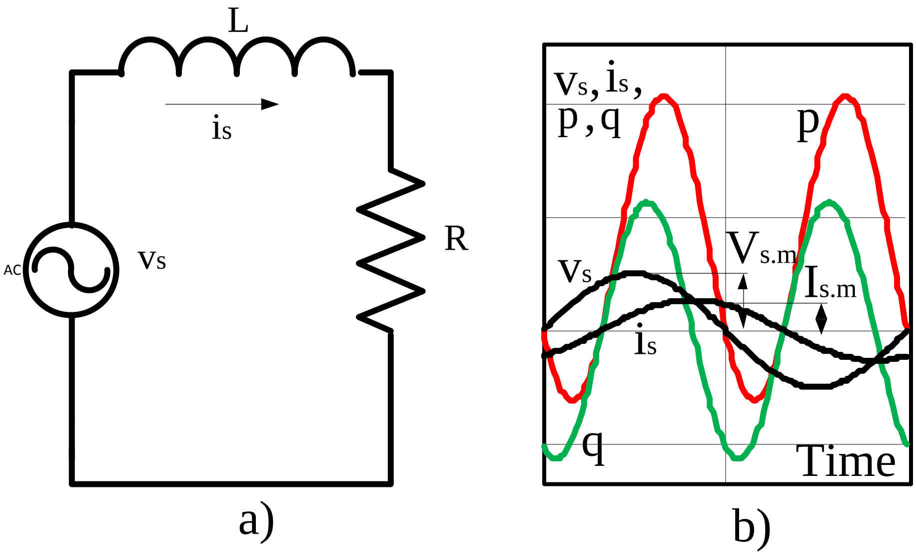

Fig. 1: a) R-L circuit, b) voltage, current and power curves.

The consumed active power is defined by the integral expression

$P=\frac{2}{T}\int_0^{T/2}pdt=\frac{2}{T}\int_0^{T/2}V_{s.m}I_{s.m}\sin(\omega t)\cdot\sin(\omega t-\phi)dt=V_sI_s\cos\phi$, where V_s, I_s - the effective values of voltage and current. The magnitude of reactive power is usually directly described by the relation $Q=V_sI_s\sin\phi$. At the same time, there is also known an integral method for determining the magnitude of reactive power (Emde, 1921, Mayevsky, 1978). The expression $I_S\sin\varphi$ is the effective value of the reactive component of the current, which we can write as the cosine component of the first harmonics

$$Q = V_S I_S \sin\varphi = \frac{1}{2} V_{S.m} I_{S.m} \sin\varphi = \frac{1}{2} V_{S.m} \left(-\frac{2}{T} \int_0^T i_s \cos\omega t dt \right) \quad (1)$$

Taking into account that $\omega V_{s.m} \cos\omega t = (V_{s.m} \sin\omega t)'$, we finally get

$$Q = -\frac{1}{2\pi} \int_0^T i_s \frac{dv_s}{dt} dt = -\frac{1}{2\pi} \int_0^T i_s dv_s \quad (2)$$

We put the minus sign before the integral in order that the positive values of Q correspond to the consumption of reactive power, while the negative, to its generation.

From (2), taking the integral of voltage along the whole of the contour of the curve of the current-voltage characteristic $i_s = f(v_s)$, we get that the reactive power equals the area encompassed by that curve divided by 2π. And when in the process of changing voltage and current the curve is traversed counterclockwise, $Q > 0$, and in the opposite case, vice versa, $Q < 0$. In the case under consideration, when the voltage and current are sinusoidal, the voltage-current characteristic is the ellipse in Fig. 2,a, and its area divided by 2π, is the reactive power of the active-inductive load.

In the same way, for the value of the active power P an expression similar to (2) can be obtained if we introduce a fictional current $ia_s = I_{s.m} \sin(\omega t - \phi - \pi/2) = -I_{s.m} \cos(\omega t - \phi)$ and take into account that $I_{S.m} \cos\phi = \left(-\frac{2}{T} \int_0^T ia_s \cos\omega t dt \right)$. Then we get

$$P = -\frac{1}{2\pi} \int_0^T ia_s dv_s \quad (3)$$

And, correspondingly, the voltage-current characteristic will also take on the form of an ellipse whose area divided by 2π, will equal the value of the active power (Fig. 2,b).

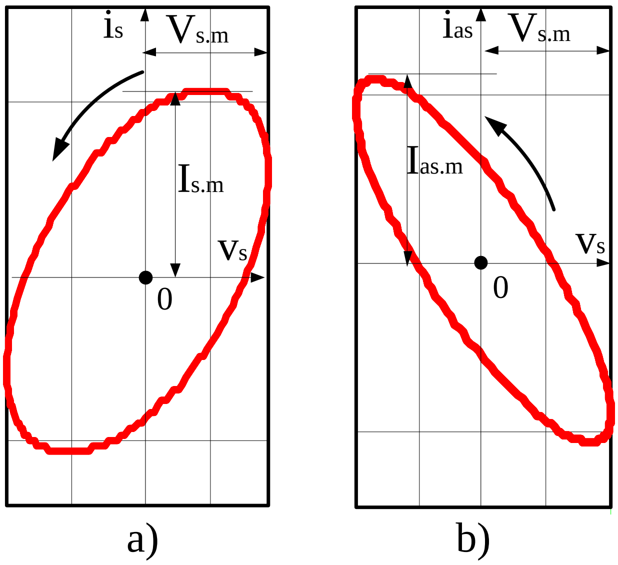

Fig. 2: Volt-ampere characteristics – a) reactive and b) active power ellipses.

We further establish a connection between the mean values of various segments of the curves of the instant powers *p*, *q* and *pR*. In order to do so, we split the semi period *T/2* into the following four intervals: the first and second intervals (a-b) and (b-c) with the durations $h_1 = h_2 = \phi$; the third and fourth intervals (c-d) and (d-e) with the durations $h_3 = h_4 = \pi / 2 - \phi$ (Fig. 3). The segments of the curves of the said powers on these intervals will be denoted in the order of succession: segments of the curve of the power *q: q1*, *q2*, *q3*, *q4;* segments of the curve of the power *p: p1*, *p2*, *p3*, *p4;* segments of the curve of the power *pR: pR1*, *pR2*, *pR3*, *pR4* respectively.

The first interval is characterized by the fact that on it the powers *p1* and *q1* are negative: a part of the reactive power *q1* is being returned back to the network, while the other part is transferred to the load. These parts of the reactive power *q1*are shown in Fig. 4, on the first interval a-b, the reactive power *q1a*, which is returned to the network, and the part of the reactive power, which is being transferred to the load in the form of the active power, *q1b*.

The second interval b-c in Fig. 4 is characterized by the fact that in the course of it in the reactive power a reserve of power is accumulated, which equals the power returned to the network, *q2a*, and

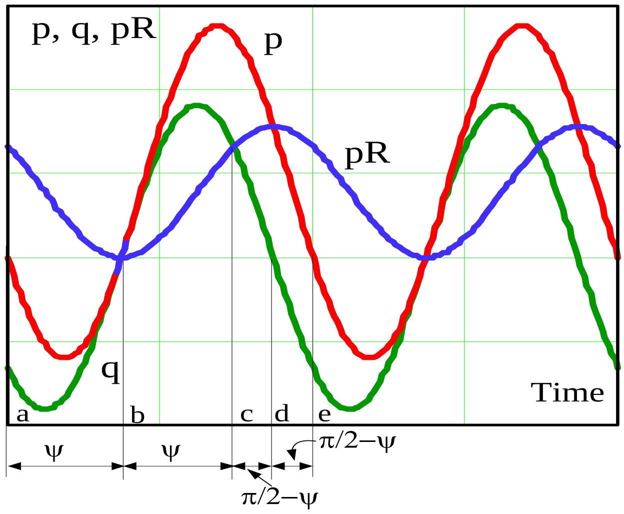

Fig. 3: Basic four intervals for the flow of instantaneous powers.

The power consumed to the transfer of the active power on the previous interval, *q2b*. On the next, third interval c-d the reactive power (*q3*, Fig. 4, c-d) is also accumulated, and which, in the whole is transferred to the load on the last, fourth, interval (*q4*, Fig. 4, d-e(a)).

The mean values of power over the semi period on these intervals were found, for instance, for the power *q*, by the formula $Q_i = \frac{1}{\pi}\int_r^s q_i d\omega t$, where Q_i is the mean power value over the semi period on the *i*-th interval, $i=1,...,4$; q_i is the segment of the power curve on that interval; *r*, *s* are the limits of these segments. Similarly, the same occurs in the case of other kinds of power. The mean values of the segments of the reactive power *q* are described by the expression $Q_i = (Q/\pi)\sin^2 h_i$, and its components, $|Q_{1a}| = Q_{2a} = Q/\pi - (P/\pi)h_1$ и $|Q_{1b}| = Q_{2b} = (P/\pi)\phi - (Q/\pi)\sin^2 h_3$.

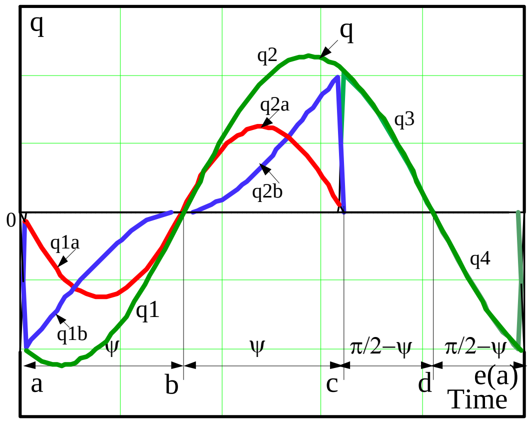

Fig. 4: Reactive power components at four base intervals.

II. A presentation of the process of consumption and exchange of energy in the basic RL circuit in the form of an electric cycle

Now we will perform an identification of the shares of power corresponding to the time intervals h_i, in the ellipses of the reactive and active powers. With this aim in mind, we introduce the unit functions *m1, m2, m3, m4,* which equal one on the respective intervals *a-b, b-c, c-d, d-e(a),* and zero outside of them. These function make it possible to select the voltages v_1-v_4 and currents i_1-i_4, as well as i_{a1}-i_{a4} on these intervals, for instance, $v_1= m_1v_s$, $i_1= m_1i_s$ etc. and to construct the plots of their voltage-current characteristics; for the intervals of the reactive power they are given in Fig. 5,a, and for the active, in Fig. 5,b (here the values of the currents i_{ai} are given with the opposite sign).

Note also that in Fig. 5,a,b, the voltage-current characteristics v_i-i_i (segments of the ellipse) are given for the semi period, that is, for the upper part of the ellipse The limits of variation of the current on the axes the ellipses of the reactive power (Fig. 5,a) and the active power (Fig. 5,b) differ, while the limits of variation of the voltage are identical. We also can equalize the limits of currents, if we take into account that $Q = P\tan\phi$ and multiply the values of the current i_{ai} by $\tan\phi$ in the plot of Fig. 5,b, and take them with the opposite sign.

Basing on (2) and (3), in order to calculate the total of the reactive power, that is, the total areas of the ellipses, we write the corresponding formulas for the calculation of the areas of all obtained parts $\bar{Q}_i$ of the ellipse of the reactive power and the parts P_i of the ellipse of active power. The results of the calculations give: $\bar{Q}_i = (Q/\pi)h_i$ and $P_i = (P/\pi)h_{i'}$, $i'=4,...,1$.

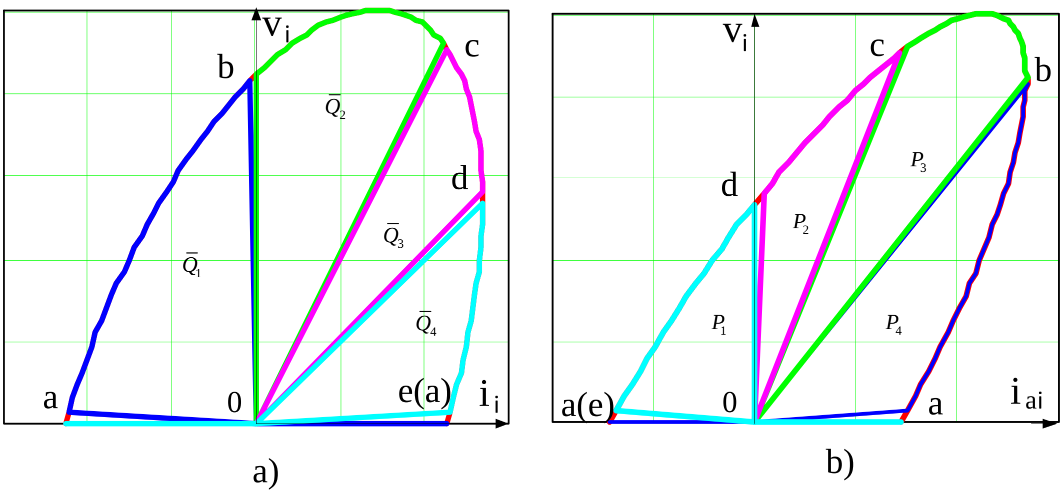

Fig. 5: Allocation of four intervals on half-ellipses of a) reactive and b) active powers.

Fig. 6 shows two overlapped power ellipses with the same limits of current variation, and with the intervals corresponding with those previously selected intervals.

Now we can see that to the two areas on the first time interval a-b in Fig. 4a, two areas on the left side of the voltage axis correspond. At the same time, the part ad'0 situated within the ellipse of reactive and active powers is the segment of the return of a part of the reactive power to the load, while the second part ad'b indicates the part of reactive power returned to the network. In the same way, the two consecutive segments in the clockwise direction correspond to the second interval, that is the accumulation of power equaling that previously given to the load (the lower part 0d'c, located within the limits of the ellipse of active power), and the accumulation of the power which equal that returned to the circuit (the upper part d'bc located within the ellipse of the returned power). Similarly, the parts of the next two segments of the ellipses – if only they lie within the limits of the ellipse of active power – describe its direct consumption from the network, and when they lie also within the limits of the ellipse of reactive power, they signify either the accumulation of power, or its return into the active load.

The curves in Fig. 6 form a cycle of the power transformation iin an active-inductive load during a semi period. In this cycle four characteristic sectors can be discerned, which correspond to the four intervals defined above. In the present case, we will count them clockwise from the point *b*. The curve *bc* runs over the first sector *0bc*, which is characteristic by the accumulation of the reactive power (d'bc) and the consumption of the active power (0d'c) from the network. Further, the curve *cb'* runs over the next sector *0cb'*, which means the consumption of the active power from the network and the accumulation of the reactive power (0cd). The sector with the curve *a'b'* reflects the continuation of the consumption of the active power, but this time partially directly from the network, (db'a'), and partially, on the account of the return to the load of the reactive power accumulated on the previous interval (0da').

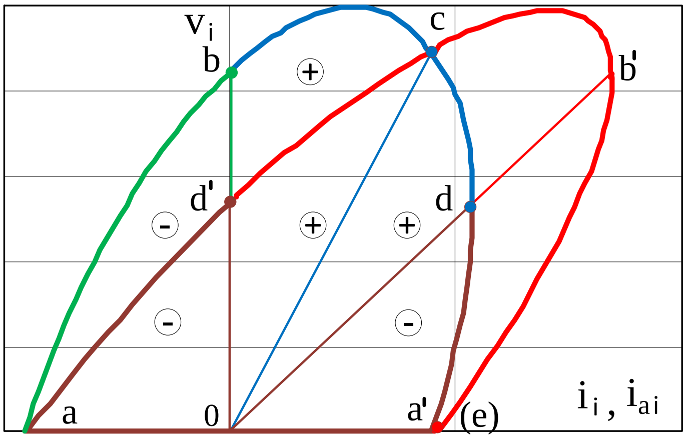

Fig. 6: United semi-ellipses of reactive and active powers and their basic sections.

And finally, on the last, fourth interval *ab* (sector 0ab) there occurs the transfer of the power accumulated on the first interval to the load, (ad'0), and the return of the reactive power back to the network, abd'. In Fig. 6 the segments of the ellipse of the reactive power, which correspond to the accumulation of power, are denoted by the sign "+", and those which correspond to its return, by the sign "-".

The curves in Fig. 6 describe the cycle of changes in the power in an active-inductive circuit in the course of a semi period in the plane voltage *v* – current *i*. Our task is to find analogies between this cycle and thermodynamics cycles; to do so, let us consider it in more detail on a simplified graph in Fig. 7,a.

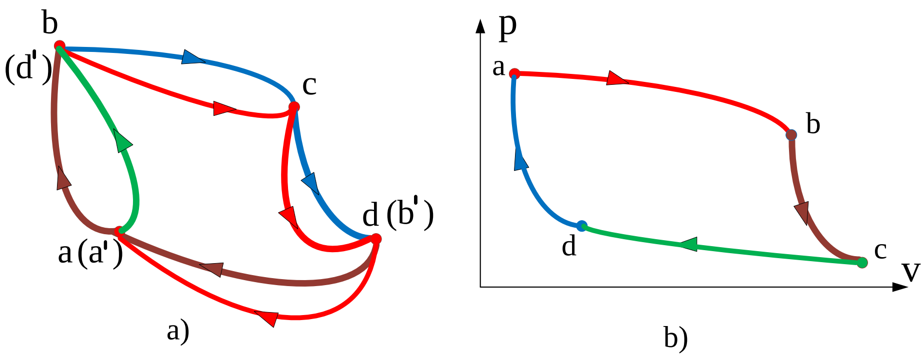

Fig. 7: Comparison of the power transfer cycle in the a) RL circuit and b) in the Carnot cycle.

For comparison, the same figure shows the thermodynamic Carnot cycle in the volume *v* – pressure *p* plane for the ideal gas (Fig. 7, b). The segment *a-b* describes the isothermal process of expansion of gas, and the performance of work by the gas, the segment *b-c* describes the adiabatic, without an exchange of heat with the environment, expansion of gas, as well as the production of work due to the accumulated internal energy. Next, the segment *c-d* is an isothermal process of gas compression with the release of heat into the environment. Finally, the last segment *d-a* describes the action of the energy accumulated in the outer system. In the ideal Carnot cycle under consideration the isothermal and adiabatic processes are clearly divided into two separate groups. As is well known, in the course of an isothermal process there is no increment of the inner energy of the substance being heated, and in an adiabatic process there is no delivery of heat to it.

Returning to the electrical cycle in Fig. 7,a, one can see a combination of analogous processes. So, in the first segment *b-c* an "adiabatic" process of accumulation of reactive power in the inductivity is going on, and, at the same time an "isothermal" process of performing work (the consumption of active power from the network). The same picture is observed on the segment *c-d*, differing only in that on the previous segment the accumulation was greater for the subsequent return of the reactive power to the network (i.e., into external environment). On the third segment *d-a* two processes are also being combined: the consumption of the active power and the "adiabatic" process of the return of inner energy to the load. The last segment *a-b* is partially "adiabatic": the transfer of the power of inner energy to the load, and an "isothermal" one, but with the return of a part of power into the network, that is, the external environment.

In thermodynamics the processes, which are characterized by simultaneous manifestations of both isothermal and adiabatic processes, as well as their generalizations are called polytropic processes. Therefore, we may say that the electric cycle of consumption of power in an active-inductive circuit is, in a sense, similar to a polytropic thermodynamic cycle. Both cycles are reversible, and characteristic for both of them is the return of a part of energy (power) into the outer environment (network). We emphasize that the return of part of energy into the network is possible only due to the inclusion of inductivity into the circuit.

III. Processes of consumption and exchange of energy in a RLC circuit powered by direct current through a periodically closed switch, and in an alternate voltage regulator

The circuit named in the headline is a step-down converter of direct-direct current, known by the name the buck converter (Fig. 8). Besides the constant power, it consumes a kind of reactive power accompanied by the circulation of the reactive component between the DC source and the converter.

The lowering and regulating of the output voltage level of direct current is achieved by the use of a switch (transistor) S (Fig. 8,a), which closes and opens periodically under the action of control pulses. The pulses that control the switch are being formed according to the principle of Pulse Width Modulation (PWM) explained in Fig. 8,b. When the switch is closed, the current i_o through the inductivity increases, and when it is open, decreases, and the direct component of the current passes through the load R_o, and the pulsation of the current, forming its reactive power, circulates

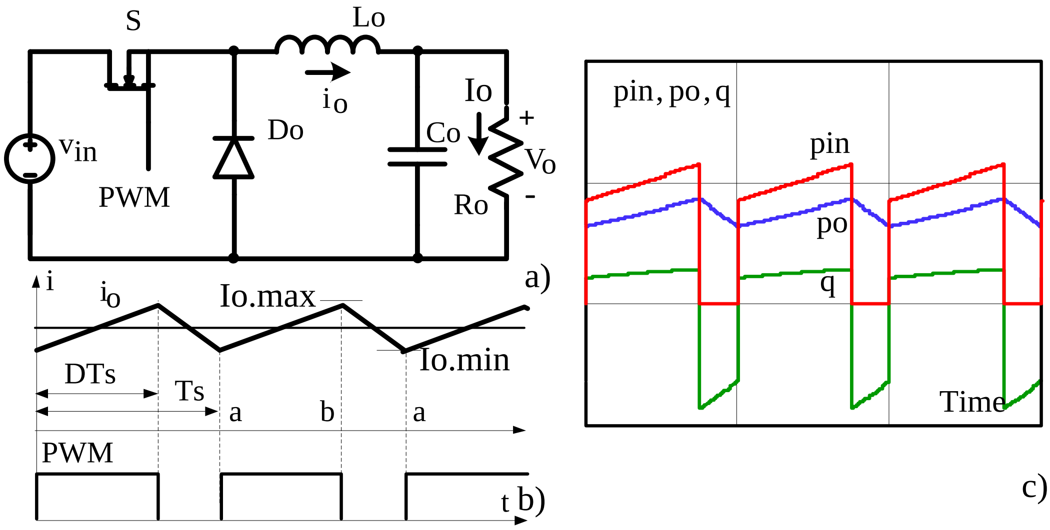

Fig. 8: a) buck converter diagram, b) operation diagrams and c) instantaneous power curves.

through the source and the capacitor C_o at the closed switch, or through that capacitor and the diode D_o , when the switch is open.

Such a working mode of the circuit makes it possible to get simultaneously the lowering and controlling of the output voltage in the process of change of the duty cycle *D*: $V_o = V_{in} \cdot D$. In order to make the duty cycle graphs more clear, we took *D=0.75*.

The curves of the power consumption of the buck converter are shown in Fig. 8,c , and they describe the consumption of the input power *pin*, which is constant with the pulsation, of the output power *po* and the reactive power *q*.

The voltage-current characteristic of the current pulsation in the voltage v_{Lo} – current i_o passing through the inductivity at $D=0.75$ is shown in Fig. 9,a. In the present case it forms practically a rectangle, and its area divided by 2π, according to (2), is equal to the reactive power Q, produced by the current pulsation through the inductivity. If, for finding Q, we make direct use of the non-sinusoidal voltage and current through the inductivity, in our case, the reactive power determined from (2), as is shown in (Emde, 1921, Mayevsky, 1978), will equal

$$Q = \sum_k k V_k I_k \sin \varphi_k \, , \qquad (4)$$

where k is the number of a harmonic. Note that due the integral, by (2), and graphic, by (Fig. 9,a) methods of finding the reactive power, there is no necessity to know the harmonic compositions of voltage and current.

The voltage-current characteristic of the current pulsation sets the cycle of the consumption of reactive power into inductivity and partially, into the capacitor (the internal cycle painted in blue). Where the part above zero describes the consumption of the reactive power from the power source when the pulsation current varies from $I_{o.\min}$ to $I_{o.\max}$, and the lower, negative part of the cycle describes the return of power into the load. In the form of a graph, the full cycle is shown in Fig. 9,b. The cycle starts at the point *a* with the consumption from the power source of the active, as well as reactive, power in the inductivity and partially in the capacitor (the switch is closed); this part ends at the point *b*, following which it continues by the return of the reactive power of inductivity (and partially of the capacitor) into the load, from the point *b* back to the point *a*.

Returning to the analogies with thermodynamic processes, we can note that in the present case, too, the electric cycle is similar to the thermodynamic one with isobaric (constancy of the voltage) and isochoric (constancy of the current) processes. It includes the surplus consumption of power at the start of consumption, and unlike a thermodynamic process, the return of that surplus power to the load, as well as a partial return into the source (capacitor), excluding the loss of power.

Concluding this section, we consider yet another cycle formed in the diagram in Fig. 10, which is a basic regulator of alternate voltage. This circuit is also known as Dimmer, if an electric bulb is used as the load.

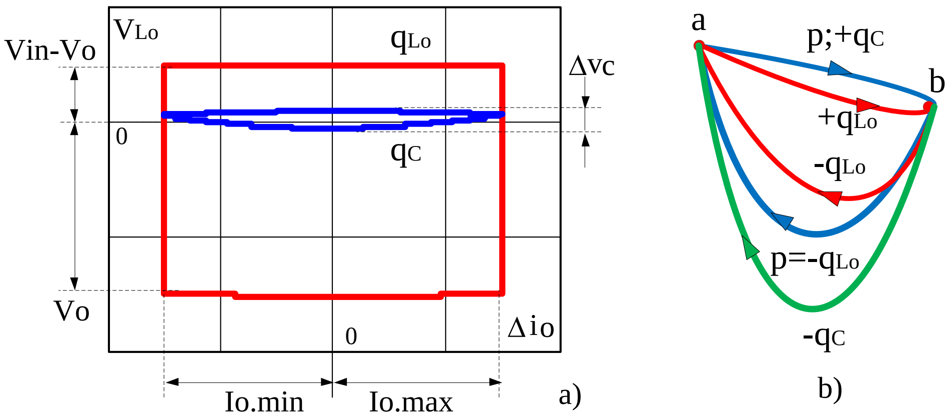

Fig. 9: a) current-voltage characteristics - reactive powers in the buck converter, b) power flow cycle.

Each of the thyristors T_1 and T_2 (Fig. 10,a) receives two respective sequences of control pulses shifted by the angle α with respect to the positive and negative semi waves of the voltage supply (Fig. 10, c) By changing the angle α, one can change the magnitude of the load current, as is shown in Fig. 10, b, the current i_s. On the same graph, the current i_{s1} of the first harmonic is shown. We see that in this case also the possibility to control the current is achieved at the cost of the

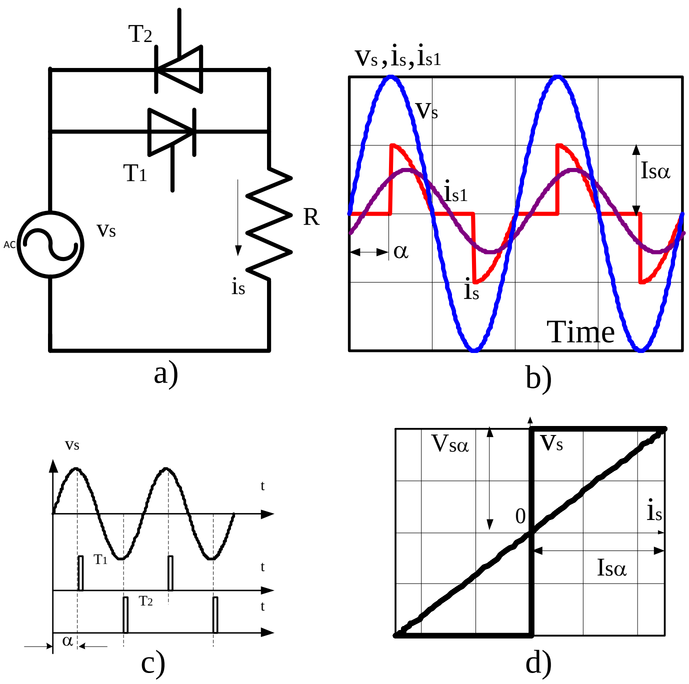

Fig. 10: a) AC regulator circuit, b) functioning diagrams, c) voltage and current curves, d) current-voltage characteristic i_s - v_s.

Occurrence of "reactive power": the first current harmonic lags behind the voltage, while the voltage-current characteristic i_s - v_s (Fig. 10, d) forms a cycle whose area is proportional to that "reactive power." This case is of special interest by the fact that the circuit lacks an inductivity, and the "reactive power" appears as a result of the phase control, a process, which introduces negentropy.

IV. Analogies in the courses of electric and thermodynamic cycles

Consider analogies, that are characteristic for both thermodynamic and electrical engineering processes, and which follow from the analysis conducted above. In a thermodynamic process greater consumption of energy is needed, since not all the heat energy can be transformed into work, so to ensure the reversibility of the process, it is necessary to remove part of non-transformed heat to the external environment. The process of heat consumption is characterized by positive entropy, while that of its return (cooling), by negative entropy (negentropy). In an electric cycle at the start, greater consumption of energy is needed than that spent on the work, but this energy, excessive at the beginning, accumulates in the magnetic field of the inductivity, or in the electric field of the capacitor, and, at subsequent stages is transferred to the load, that is, transforms itself to work, and its surplus is not lost, since it returns to the supply line, or a power source. Dwelling further upon the analogies, note that the magnitude of energy in thermodynamics corresponds to the magnitude of power in electrical engineering, the pressure of a substance subjected to heating - to the voltage in an electric circuit, the volume - to the current in it, the work on changing the volume - to the power on an active resistor, and finally, the accumulation of the inner energy - to the reactive power in an inductivity or capacity. (Berkovich, et al., 1998).

Consider a possibility of expanding qualitative analogies also with quantitative analogies and their generalizations. We will base on the concept of "de-Ohmization" (Entohmung), proposed by F. Emde as early as in 1930, instead of the concept of reactive power (Emde, 1930). The value of de-Ohmization was determined on the basis of instant values of voltage and current, therefore it was valid for the curves of any form:

$$M = \frac{1}{2}\left(v\frac{di}{dt} - i\frac{dv}{dt}\right) \qquad (5a)$$

In the case of sinusoidal voltage and current, $M = \omega VI \sin\phi$, and in the case of non-sinusoidal voltages and currents, it will be determined, according to (4), as $M = \omega_1 \sum_k kV_k I_k \sin\varphi_k$. The value of M is a constant, which equals zero, when $v/i = const$, that is in the case of an Ohmic load, and equals the product of a certain reactive power by the angular frequency of the basic harmonic, if $v/i \neq const$. The value of M as if characterizes the difference of the consumer from the Ohmic one, due to that, F. Emde called it de-Ohmization. For the time being, we will stress that this quantity – while describing de-Ohmization (the absence of the consumption of only the active power, and the consumption of the reactive, non-active power) – in other words, characterizes the negentropy of the circuit, which is given by the formula:

$$M = 2\pi \frac{Q}{T} \text{ (5a) or } S_E = \frac{Q(VAr)}{T(\sec)} \qquad (5b)$$

Where S_E is the electric negentropy, $S_E = M/2\pi$.

Of illustrative value is the process in a Dimmer, where it is de-Ohmization in the absence of reactive elements and the consumption of the reactive power that determines the presence of negentropy and implied by it possibility of controlling the output voltage. Thus, formula (5b) yields a quantitative estimate of the electric negentropy S_E.

This formula expands the analogies with thermodynamics, where the value of the entropy in an isothermal process in particular, is defined as $S = \frac{q(J)}{T(^oK)}$. From (5b), one sees what quantity in an electric process can be made to Correspond the most important quantity in a thermodynamic process, temperature $T(^oK)$. In an electric process, the temperature is not present at all, the more so, when the subject of discussion is the reactive power. It follows from formula (5b), that such a quantity is time T(sec).

When considering a thermodynamic cycle, we meant a reversible mode, while, when considering the electric cycle, a steady-state periodic mode with the period T. The previous analysis has shown that the transfer of the electric power to an active resistance of the circuit is analogous to the isothermal mode of a thermodynamic process. This makes it possible to suppose that that the electric process is taking place at the "temperature" T(sec). Note that the full ellipses of the reactive and active powers (Fig. 2) are being formed in the course of a period, and due to symmetry, their areas correspond to the double value of these powers. However, further, it is the value of the period T that we will take as an analogue of temperature in an electric circuit.

V. Manifestations of the second law of thermodynamics in electric circuits. Entropy and negentropy in electric processes

Previously, on the examples of completely different electric circuits, we have shown the existence of analogies between the reversible processes in thermodynamic systems and steady state modes in electric circuits. In both systems the processes of the exchange of energy (power) are cyclic, and – what is very essential – each of these systems has an interval of the return of a part of energy (power) to the external environment. In thermodynamics, it is precisely this fact, according to the second law as formulated by Max Planck that makes it possible to construct a cyclically working machine: *"It is impossible to construct a device which operates on a cycle and produces no other effect than the production of work and the transfer of heat from a single body"*. In the case of a thermal engine, it means that it could work in a cyclic mode when in it the difference of the temperatures of a hot and cold sources is cyclically maintained, that is, the body is periodically cooled by the external environment: the introduction of the negative entropy (negentropy).

Using a multitude of examples, one can see that in electric systems this law is manifested by the fact that in order to get an opportunity to transform electric energy into mechanical one, and in general, to get an opportunity to transform electric current into any other current or any other form of energy, a system must have reactive elements that ensure the circulation of reactive power, and its return back to the network.

Without the presence of reactive elements in a circuit, the electric energy can be transformed only into heat, that is, only to ensure the production of entropy. In particular, in the absence of reactive elements the cycles in Fig. 7 и Fig. 9 degenerate. On the example of Fig. 10, we have seen that the formation of a cycle is also possible upon the introduction into the circuit of a switch that periodically interrupts the consumption of energy and ensures the effect of the presence of a reactive element for the first harmonic of the current. The possibility of control is ensured, but still only the thermal energy is generated. Thus, further under a cyclically acting electric system we will understand a system that performs the transformation of electric energy into mechanical one, or into other forms of non-thermal energy, or, at least, it ensures the control of voltage and current and restricts the consumption of purely thermal energy.

So, one can formulate the manifestations of the second law of thermodynamics to the electric circuits in a following way: “It is impossible to realize a periodically (cyclically) acting electric system, which, along with the consumption of energy, performs no periodical partial returns of energy, and does not interrupt its consumption.

As concerns entropy, as we already mentioned in the introduction, this concept is widely applied in electric circuits, and they are used as convenient models to illustrate optimization entropy processes (Landauer, 1975, Bruers, et al., 2007, Županovi´c, et al., 2004, Axelrod, et al., 2005).

In these works the process of power consumption is assumed to be isothermal and taking place at a certain constant temperature, whose value is neglected. Therefore some conditional temperature was defined, which had to remain constant. That made it possible to write down the production of entropy as $\frac{dS}{dt} = \frac{P_W}{T^o K}$. But in energy processes in electric circuits the reactive power also takes part, and there is no sense in applying to it the value of temperature. For the negentropy of an electric circuit, we have obtained (5b). Since the temperature in an electric circuit is defined in an arbitrary way, it formally can be numerically equal to the value of the period. In that case, if we write in the numerator of (5b) the active power P_W instead of reactive power, we can speak, along with the electric negentropy, also of the production of electric entropy.

It was shown earlier that it was the circulation of the reactive power that in a cyclical process ensures the return of its part into the supply network, that is, ensures negentropy. The negentropy character of the reactive power is also confirmed by the fact that only due to its course an electric system, besides the most probable state of the transformation of electric energy to thermal energy, acquires far less probable opportunities: transforming it into many other forms and types, that is, one can also speak of the presence of information processes in electric systems. The calculations of negentropy in electric devices turns out to be of use, in particular, in determining the degree of chaos in the course of a process, and in the choice of the methods of its synchronization. However, such analysis is the subject of other papers.

VI. CONCLUSIONS

The present paper has shown some analogies between the course of cyclic processes in electric circuits and the reversible processes in thermodynamic systems, in particular, in the thermal engine. These analogies are analyzed in detail both on an example of a basic active-inductive circuit, as well as on the examples of some switch circuits, in comparison with the Carnot cycle for the ideal gas, and also with polytropic cycles.

We also have established analogies with various thermodynamic quantities (pressure, volume, energy, temperature) and electric quantities: voltage, current, power and period, respectively. It has also been shown that, since in order to realize a reversible thermodynamic process, the cyclic return of heat into the outer environment is needed, in electric circuits, the circulation and the return of the reactive power into the network corresponds to that. In the absence of these conditions, in both cases, the cycles degenerate. Concluding, it is noted that since on doing some work in a thermodynamic process, the entropy increases, which, in order to achieve the reversibility of the process on cooling is compensated by negative entropy, in electric circuits there are also analogs of these quantities based on the release of active power (entropy production), on the one hand, and on the circulation and return to the network of the reactive power (negentropy source), on the other hand. This made it possible to expand the second law of thermodynamics also to the cyclic processes in electric circuits. Some formulas for calculations of the production of entropy and negentropy in electric circuits have been proposed.

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