wjert, 2024, Vol. 10 Issue 9, 133-157. *Review Article* ISSN 2454-695X

World Journal of Engineering Research and Technology

WJERT

www.wjert.org SJIF Impact Factor: 7.029

ENERGY FACTORS IN THE SYNCHRONIZATION PROCESS OF CHAOTIC MODES ON AN EXAMPLE OF DC-DC CONVERTERS

Yefim Berkovich*

Department of Electrical Engineering, Holon Institute of Technology, 52 Golomb st., Holon, 58102, Israel.

Article Received on 11/06/2024 **Article Revised on 01/07/2024** **Article Accepted on 21/07/2024**

***Corresponding Author**
Dr. Yefim Berkovich
Department of Electrical Engineering, Holon Institute of Technology, 52 Golomb st., Holon, 58102, Israel.

ABSTRACT

The paper is devoted to an estimation of the role of the reactive power in electrical systems considered as the determining factor in the course of all electromagnetic processes. To find its value, we use the area of the phase portrait of the voltages and current forming it. We have shown its connection with force functions, which, in accordance with Hamilton's principle, determine the character of the changes in the mode of an electrical system. Since the force functions are based on the formulas containing the values of the energies of reactive elements, the above said holds also in the case of reactive power. We establish a relation between the magnitude of reactive power and a new concept, negentropy of the system defined as the density of the reactive power in time. The magnitude of negentropy is considered as a factor that in the general case reduces the entropy character of modes both from the point of view of the dissipation of active power and of its ordering. In this sense, the processes in electrical systems are considered to be similar to thermodynamic processes, where in order to ensure reversible (periodic) processes, negentropy processes should be present along with entropy ones. This paper, in order to support this affirmation, on an example of the processes in the Current Mode Control (CMC) Boost Converters, analyzes, on the one hand, relations between various bifurcation modes and subsequent chaotic modes, and , on the other hand, changes of the reactive power of the pulsations of the input current. Two different CMC modes have been considered – with the input current bounded from above, and from below (bottom). The converters have been run through all the bifurcations stages with passing into chaotic modes, and in each of these modes the values of negentropy have been calculated. After that, the same evaluations have been conducted for various methods of mode synchronization. In all these cases, as well as some others, the magnitude of the reactive power, and the system's negentropy have been evaluated and it was shown that synchronized modes occur due to an essential increase of negentropy. Our analysis has been accompanied by computer modeling of the said modes and illustrated by the necessary diagrams and plots. Our final conclusion is that it is negentropy that is the determining energy factor that brings order in the processes in converters.

KEYWORDS: Reactive Power, Negentropy, Boost converter, Bifurcations, Chaos, Synchronization.

1. INTRODUCTION

In the recent decades, the phenomenon of determined chaos manifesting itself in non-linear dynamic systems is attracting special attention of the researchers in various areas of science and technology. This phenomenon is instrumental in better understanding of the course of complex transformation processes of very different nature (Hagen, 1983; Prigozhin, 1994). The determined chaotic modes are also observed in the power electronics machines which, as a rule, are nonlinear dynamic systems, and a vast literature is devoted to their research. Firstly, note the three important reviews devoted to the basics of nonlinear dynamics, the research methods and the laws of determined chaos (Tse, et. al., 2002, Nagy, 2001, Aroudi, et. al., 2005).

The CMC boost converters have attracted the greatest attention of the researchers of determined chaos and bifurcation modes in the oscillations of the input power preceding it. The first detailed research of that phenomenon was given in (Deane, Hamill, 1990, 1992) which caused an increased interest, and was followed by a multitude of research publications. First of all, one should note the paper (Tse, 2003) and his monograph (Tse, 2004). Two basic aims were pursued in these works: preventing this phenomenon (or putting it in use) in the functioning of boost converters (or other converters) as pieces of machinery, or scientific research of this phenomenon of nonlinear dynamics.

Of significant interest are the works of a group of authors (Baranovski, et. al., 1999, 2000, 2003, Woywode, et. al., 2003], which – on the basis of the whole set of instruments of nonlinear dynamics – gives a qualitative analysis of the functioning of the CMC boost converters, The authors put a special emphasis on the possibility to practically use the work of boost converters in chaotic mode in order to obtain a wide frequency spectrum more convenient for Electromagnetic Interference (EMI). Along with manifestations of nonlinear effects in a boost converter, the bifurcations and chaos in buck converters have also been researched (Aroudi, et. al., 2001). The work (Benadero, et. al., 2003) considered simultaneously manifestations of nonlinearity in three classic converters and emphasized similarities in their courses.

The main methods of evaluation of the courses of chaotic modes are related to infinitesimally small variations in a system and the differentiation operations, like the formation of the Jacobi matrix. Along with that, another approach to the research of the dynamics of systems of various origins is known. It consists in optimizing (most often, minimizing) a force function connected with the system's energy. In that case, the dynamic trajectory of the system is determined by the obtaining the extrema of some integral functions by variational calculus, that is the principles related to large movements of the system (White, Woodson, 1959, Hasen, 1998, Berkovich, Moshe, 2021). On the other hand, a change of the force function and energy in a system will result in a change of the trajectory of motion. In our case, it means either exiting from the chaotic mode, or, vice versa, entering it. Therefore, it seems to be interesting to find a force, energy variable, whose changes would result in such changes in a strictly defined direction. The present paper proposes to take the time density of the reactive power circulating in the system as such a variable. It should be noted that this concept is based on (Emde, 1930, Mayevsky, 1978, Krogeris, et. al., 1993), where the authors proposed the term *Entohmung* (German) или *de-Ohmization*. In more detail, the influence of the time density of reactive power has been considered in (Berkovich, 2022) and earlier in (Berkovich, et. al., 1998), where, basing on similarities between cyclic processes in thermodynamic systems and electric circuits, this variable is represented as negentropy. The influence of the reactive (non-active) power circulating through supply source has been considered in an analysis of oscillatory modes in the Van der Pol oscillator based on not a tube amplifier, but on a transistor one, whose nonlinear character differs significantly from that based on tubes (Berkovich, et. al., 2021, 2024).

In order to analyze the influence of the time density of the reactive power circulating in a system (negentropy) we have considered its action in a number of different occurrences of chaotic mode in CMC boost converters and shown a possibility of exiting (synchronization) from a chaotic mode upon its increase. In all of the cases considered, we introduced into the system an additional sequence of pulses carrying certain information, but it is the negentropy character of the action of the reactive (non-active) power leads eventually to the stabilizing the processes in the system.

The paper has the following structure. Section 2 considers some theoretical aspects related to the reactive power. Section 3 analyzes the processes in a CMC boost converter along the entire range of change of the kind of bifurcations and the subsequent chaotic mode. Further, Section 4 determines the magnitude of the time density of the reactive power – negentropy – in all of the modes considered. In Section 5 this magnitude has been determined after the elimination of anomalous modes by one of the types of synchronization: by periodic short-duration shunting of the input inductivity. In Section 6 the synchronization has been achieved with the help of a stepwise form of the input voltage, and the character of the changes in negentropy is determined anew. Section 7 analyzes the changes of negentropy for current-mode control with ramp compensation. And finally, Section 8 performs an analysis similar to that in Sections 2-4 for CMC boost converter bound from below.

2. Estimating the magnitude of negentropy in electric circuits

2.1. An approach to calculating the reactive power

The variable called *Entohmung* (de-Ohmization) introduced in (Emde, 1930) is given by a following relation between the voltage v_s and current i_s :

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

Assuming $v_s = V_m \sin(\omega t + \phi_u)$, $i_s = I_m \sin(\omega t + \phi_i)$ and substituting these expressions into (1), we get:

$$M = \frac{1}{2}\left(v_s \frac{di_s}{dt} - i_s \frac{dv_s}{dt} \right) = \frac{1}{2}\begin{pmatrix} V_m \sin(\omega t + \phi_u)\omega I_m \cos(\omega t + \phi_i) - \\ -I_m \sin(\omega t + \phi_i)\omega V_m \cos(\omega t + \phi_u) \end{pmatrix} = \omega VI \sin\varphi = \omega Q \tag{2}$$

where $\varphi = \phi_u - \phi_i$.

Thus, the quantity M equals the reactive power multiplied by the circular frequency, or divided by the period T with the coefficient 2π. In the case of non-sinusoidal forms of voltage and current the formula of M has two members, one a constant, and the second is a sum of sinusoidal time functions, whose average value over the period equals zero (Krogeris, et. al., 1993). The constant member will be equal

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

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

Along with this, an integral method to determine the magnitude of the reactive power is also known
(Emde, 1921, Mayevsky, 1978, Berkovich, 2022)

$$Q = -\frac{1}{2\pi} \int_0^T i dv \text{ or } Q = -\frac{1}{2\pi} \int_0^T v di \qquad (4)$$

The minus sign before the integral is inserted in order that a positive value of Q corresponded to the consumption of the reactive power, and a negative, to its generation. On the basis of (4), integrating with respect to the voltage over the entire contour of the volt-ampere characteristic curve $i_s = f(v_s)$, we get the reactive power to be equal to the area circumvented by the curve divided by 2π. The definition of the reactive power by (4) makes it possible to avoid finding the harmonic composition of the voltage and current. Note that the values of the reactive power found by (3) or (4) are equal.

2.2. The reactive power and force functions

The generation and circulation of the reactive power are closely connected with the so-called force functions. To consider that, let us dwell upon the optimization principle of Hamilton analysis.(Hasen, 1998). If in the integral formula (5)

$$S = \int_{t_1}^{t_2} \mathscr{L}(q_i, \dot{q}_i, t) dt \qquad (5)$$

a certain force function $\mathscr{L}$ is implemented, then the actual dynamic trajectory described by the function $\mathscr{L}$ is determined by finding an extremum (usually, minimum) of the function *S*. This means that the independent of time variation δ of the function *S* must be equal zero (6)

$$\delta S = \delta \int_{t_1}^{t_2} \mathscr{L}(q_i, \dot{q}_i, t) dt = 0 \qquad (6)$$

and satisfy the boundary conditions

$$\delta q_i(t_1) = 0 \text{ and } \delta q_i(t_2) = 0 \text{ for } i = 1, 2, 3, ..., N.$$

In other words, Hamilton's principle determines the character of changes of processes in electric circuits, the changes in voltages and currents. As the force function $\mathfrak{L}$, we will consider the Lagrangian whose great value is that it can be used both for conservative and non-conservative systems. Moreover, it is very important that in the case of a non-conservative system the Lagrange function can be applied only to its conservative part, while the influence of non-conservative elements can be taken into account separately. The independent coordinates of the system, $q_i(t)$ and the same number of coordinates $\dot{q}_i(t)$ are introduced; in a mechanical system they are respectively a space coordinate and its momentum; in an electric circuit they are the electric charge and flux linkage. Note in advance that depending of the goal, these two quantities may change roles.

For a conservative system, the Lagrange function is the difference of the kinetic $W_{\dot{q}}$ and potential W_q energies of the entire system:

$$\mathfrak{L} = W_{\dot{q}} - W_q \tag{7}$$

Consider a basic conservative circuit consisting of a capacitor C and a parallel connected inductivity L. In a most general form the Lagrangian assumes the form:

$$\mathfrak{L} = \frac{Li_L{}^2}{2} - \frac{Cv_C{}^2}{2} \tag{8}$$

In such a circuit, implied by the initial conditions, the following values of the voltage or current are established:

$$v_C = V_m \cos \omega t \,,\; i_L = I_m \sin \omega t \tag{9}$$

The derivative of the Lagrangian multiplied by $\frac{1}{2}\omega$ yields:

$$\frac{1}{2}\omega\mathfrak{L}' = \frac{1}{2}\omega L i_L \frac{di_L}{dt} - \frac{1}{2}\omega C v_C \frac{dv_C}{dt} = \frac{1}{2}\left(v_L \frac{di_L}{dt} - i_C \frac{dv_C}{dt} \right) \tag{10}$$

The general structure of this formula is similar to M. Substituting (9) into (10) gives a sinusoidal function with double frequency whose amplitude equals the reactive power.

$$M^* = \frac{1}{2}\omega V_m I_m 2\sin\omega t\cos\omega t = \omega Q\sin 2\omega t \qquad (11)$$

Along with this, on the basis of the integral formula (4), we get

$$-\frac{1}{2\pi}\int_0^{2\pi} v_L di_L = \frac{1}{2}V_{Lm}I_{Lm},\ -\frac{1}{2\pi}\int_0^{2\pi} i_C dv_C = -\frac{1}{2}V_{Cm}I_{Cm} \qquad (11a)$$

i.e., we obtain the values of reactive power Q on inductance and capacitance.

A similar formula we get by considering only the derivative $\mathcal{L}'$:

$$\frac{1}{2}\mathcal{L}' = \frac{1}{2}Li_L\frac{di_L}{dt} - \frac{1}{2}Cv_C\frac{dv_C}{dt} = \frac{1}{2}\left(i_L L\frac{di_L}{dt} - v_C C\frac{dv_C}{dt}\right) \qquad (12)$$

or after substituting the values of the voltage and current according to (9) we get

$$M^* = \frac{1}{2}V_m I_m 2\sin\omega t\cos\omega t = Q\sin 2\omega t \qquad (13)$$

By making use of the integral method (4), we again directly obtain Q.

In a more complex case, when the input voltage of the *LCR* circuit (*C* and *R* are connected in parallel) equals $v_s = V_m\sin\omega t$, the input current of the inductivity $i_s = i_L = I_m\sin(\omega t - \varphi)$, and the voltage on the capacitor equals v_C, substituting these values into $\frac{1}{2}\mathcal{L}'$ and applying the integral method makes it also possible to find Q.

Obviously, it equals the consumed reactive power and, in accordance to (2), we get

$$M = \frac{1}{2}\left(v_s\frac{di_s}{dt} - i_s\frac{dv_s}{dt}\right) = \omega VI\sin\varphi = \omega Q \qquad (14)$$

Note yet another connection between the Lagrangian (7) and the value of the reactive power,

$$Q = 4\pi f\left(W_{L.av} - W_{C.av}\right) \qquad (15)$$

where $W_{L.av}$, $W_{C.av}$ are the average values of the energy. Indeed, $W_{L.av} = \frac{1}{\pi}\int_0^{\pi}\frac{1}{2}L(I_{L.m}\sin\omega t)^2 d\omega t$, or $W_{L.av} = \frac{1}{4}LI_{L.m}^2$ and, similarly, $W_{C.av} = \frac{1}{4}CV_{C.m}^2$. After multiplying the difference of the average values of the energy by 2ω, we get $Q = VI\sin\varphi = \frac{1}{2}\left(V_{L.\mathrm{m}} I_{L.\mathrm{m}} - V_{C.\mathrm{m}} I_{C.\mathrm{m}}\right)$, since the resulting reactive power is defined by the sum of the powers of the reactive elements of the circuit.

The expression of the optimization Hamilton's principle (5), not accidentally denoted by *S*, in (Hazen, 1998) is considered as the value of the entropy-information in mechanics. The dimension of this quantity (in mechanics also known as action) is $J \cdot s$. We see that the dimension of the mechanical entropy-information differs from the dimension of entropy in thermodynamics in that the inverse value of time plays the role of temperature.

2.3.The magnitude of negentropy of an electric circuit

As we have shown, the magnitude of *Entohmung* is related to the Lagrangian force function, which in accordance with Hamilton's principle determines the changes in the trajectory of motion. As noted before, in the case of electric circuits, this function determines the values of voltages and currents. *Entohmung* will further be considered as negentropy (information) for electric circuits

$$S_E = \frac{Q(VAr)}{T(s)} \tag{16}$$

Note several specific features of that concept.

1. In electric circuits only when there occurs the production and circulation of reactive power, electric energy could be transformed into other forms with transformations of its parameters and types; without the reactive power only the transformation of electric energy into the thermal one is possible, that is the production of entropy only. So, the reactive power may be considered as negentropy, which makes it possible to transform the system into another ordered low-probable state. A basis for such a definition was also provided by an analogy between thermodynamic and electric cyclical processes discovered in (Berkovich, 2022).

2. The reactive power is produced by the reactive elements of a system which set the components of the energies in the force function and which, in accordance with Hamilton's principle, determine changes in the modes of an electric circuit. That is, the magnitudes of these energies and theirs derivatives, the reactive powers, determine the magnitudes of voltages and currents in a system.

3. The reactive power may have the same value in the systems functioning at different frequencies. Therefore, in order to make it possible to compare different modes, negentropy is defined as the time density of the reactive power over a period, which is given by the *Entohmung* value divided by 2π : $Q\ (VAr)/T(s)$.

4. The form of the negentropy formula is similar to that of the thermodynamic entropy, in which, the role of the thermal energy $Q\ (J)$ is played by the magnitude of the reactive power, and the temperature $T\ (^{0}K)$, a time interval is taken.

5. In order to check the given theory, in the subsequent sections of this paper we give the results of the action of increasing negentropy on the ordering (synchronization) of various modes in CMC boost converters.

3. The CMC mode in Boost Converters upon bounding from above without synchronization

This mode of the functioning of boost converters has been considered in detail in (Beck, et. al., 2020), and here we give only a brief summary. Fig. 1a gives a simplified diagram of the well-known CMC principle when the current is bounded from above, Fig. 1b when the current is bounded from below, and Fig. 1c and Fig. 1d, the pulse diagrams when the current is bounded from above and below respectively.

Fig. 2 shows in relative units bifurcations with transition to a chaotic mode for a specific example of a converter with the parameters V_{in}=20V; L_{in}=200□H; C=5□F; R_o=40□; f=50kHz and the range of the bounding current I_{ref} from 1.5A to 6.5A. In order to calculate relative units V_B=V_{in}, I_B= V_{in}/R_o. were taken as the base units. From now on the numerical values of the variables will be given in relative units, that is divided by the base values of V_B or I_B denoted by a capital letter with an asterisk (X^*). In Fig. 2 $I^*_{in.\min}$ denotes the values of the input current at the moments of arrival of pulse on the switch *S* (Fig. 1c). We see that the normal functioning of the converter remain preserved until the value I^*_{ref} =4.5, followed by a bifurcation mode which transforms into a chaotic one I^*_{ref} =7.3A.

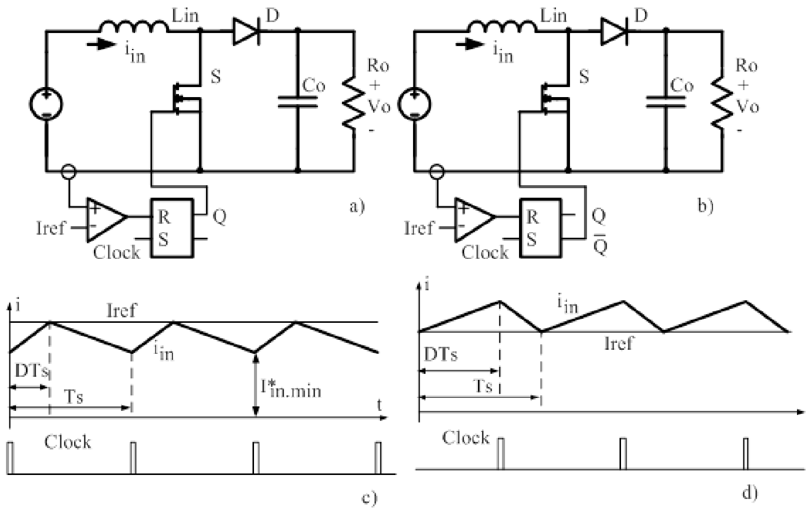


Fig. 1: Boost converter with CMC (a) CMC-above, (b) CMC-bottom, and currents diagrams for CMC- (c) CMC-above, (d) CMC-bottom.

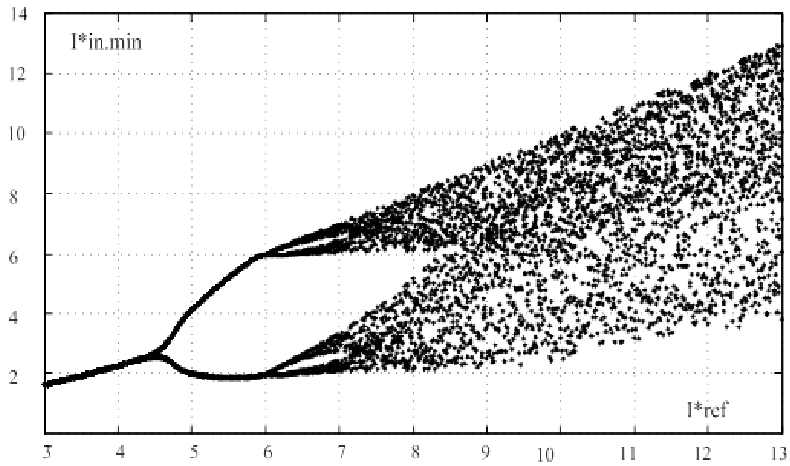


Fig. 2: Plot bifurcation diagrams for different values of I^{*}_{ref} (CMC-above).

4. Changes in the reactive power of the pulsations of the input current and negentropy in the processes of bifurcations (CMC-above).

The characteristic feature of a pulsation of the input current is the consumption and circulation of the reactive power, which plays an important role in the converter's functioning. These current pulsations and the voltage on the inductivity related to them determine the magnitude of the reactive (non-active) power circulating between the input source and the converter. To determine the magnitude of this power we will use the integral approach.[4]

Based on,[4] performing voltage integration along the entire contour of the volt-ampere characteristic curve of the input voltage and current values $v_s = f(i_s)$, we obtain that the reactive power is equal to the area described by this curve divided by 2π . In a classic case of sinusoidal voltage and current, the volt-ampere characteristic would be an ellipse (Fig. 3a), whose area divided by 2π , the reactive power of the active-inductive load.

Going back to the modes of the boost converter working, we will denote the pulsation current $\tilde{i}_{in}^*$ and, respectively, the pulsation voltage $v_L^* = L_{in}\dot{\tilde{i}}_{in}^*$. Obviously, the pulsation of the input current of the converter coincides with the pulsation of the inductivity current, but in the present case, the situation with the input voltage is more complicated. On the interval where the switch is closed the input voltage equals the source voltage. On the next interval – although formally the same voltage remains on the input, it is irrelevant for the determination the reactive power, therefore we will consider the voltage $v_o - v_{in}$, as the input voltage, the more so that it coincides with the voltage on the inductivity, which in this case is the main consumer of the reactive power. Since further we will deal with non-sinusoidal magnitudes of the voltages and currents, with breaks of continuity and jump-wise changes, the integration in (4) must be replaced by summation, which results in

$$Q = -\frac{1}{2\pi}\sum_{n=1}^{N} i_n \Delta v_n \quad \text{or} \quad Q = -\frac{1}{2\pi}\sum_{n=1}^{N} v_n \Delta i_n \qquad (17)$$

As noted above, and shown in (Beck, et. al., 2020), one could make correspond to the magnitude of pulsations on the inductivity and voltage a limiting cycle in the plane $\tilde{i}_{in}^* - v_L^*$, whose area divided by 2□□ gives the value of that power calculated by the formula (3).

Fig. 3b-3f shows a number of limiting cycles built up for various values of the current I_{ref}^* . In particular, the limiting cycle in Fig. 3b is constructed for the normal mode of the converter at I_{ref}^* =4.2. The subsequent cycles in Fig. 3c,d,e,f were obtained respectively: for I_{ref}^* *=5.4*, the mode of the doubling of the period, for I_{ref}^* *=6.3*, its quadrupling, further, for I_{ref}^* *=6.7*, its octupling, and finally, for I_{ref}^* *=12.2*, working in a chaotic mode.

Further in this paper we will be interested in how this power and the magnitude of negentropy (16) related to it changes with varying I_{ref}^* . Eventually our aim is to pursue the mutual influence of the quantity S_E of the bifurcation processes and the appearance of the chaotic mode, as well as the related possibilities of synchronization of the processes and the prevention of anomalous modes.

Table 1 shows the changes of the electric negentropy S_E with varying I^*_{ref}. Its upper row gives the values of the current I^*_{ref}, while the second, the relative values of the pulsations periods of the input current with bifurcations taken into account. For the chaotic mode we have taken thirty two periods of switching frequency which conditionally define its own period. The numerical values of the reactive powers found by the areas of limiting cycles in Fig. 3 are given in the third row, $Q^*_{1,a}$. The same powers calculated by (3) through the harmonic composition are given in the next row of that table, $Q^*_{1,b}$, from which we see a good coincidence of their values.

Table 1

Regime	I^*_{ref}	4.2	5.4	6.3	6.7	10	12.0
Bifurcations and Chaos	T^*	1	2	4	8	32	32
	$Q^*_{1,a}$	0.5242	1.2388	2.7709	5.947	-	-
	$Q^*_{1,b}$	0.5207	1.2209	2.7150	5.6879	27.1801	33.5764
	S^*_E	0.5207	0.6104	0.6787	0.7109	0.8493	1.0492

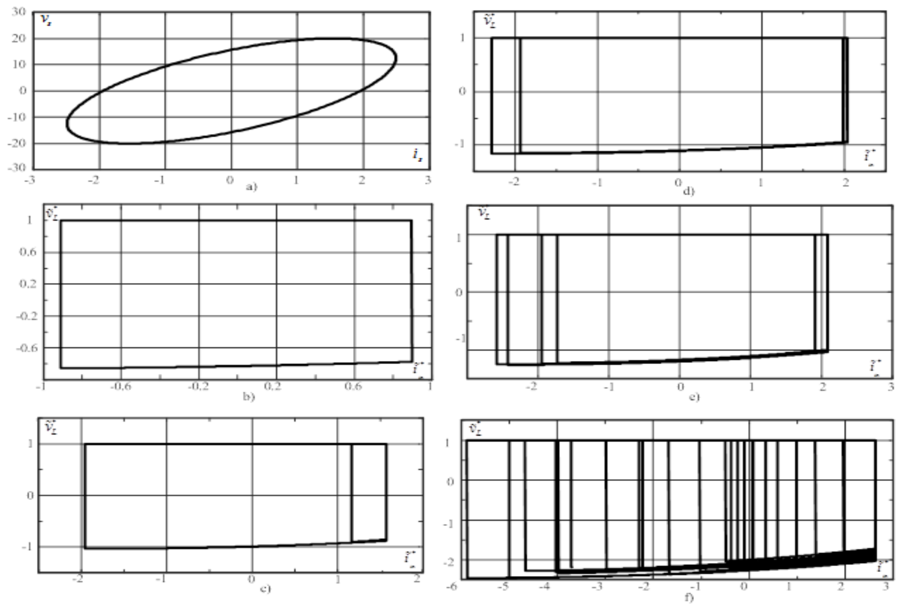


Fig. 3: (*a*) - limit cycle in the plane $i_s - v_s$ for sinusoidal voltage and current, (*b*), (*c*), (*d*), (*e*) and (*f*) - limit cycle in the plane $\tilde{i}^*_{in} - \tilde{v}^*_L$ for respectively I^*_{ref} =4.2, I^*_{ref} =5.4, I^*_{ref} =6.3, I^*_{ref} =6.7, I^*_{ref} =12.2.

Correspondingly, the lower row gives the values of electric negentropy which in accordance with the definition $S_E^* = Q^* / T^*$ have been calculated using the values of the reactive power in the fourth roe. As is seen from the table, in the process of deviation from the normal mode, a decrease in the bifurcation frequency and transition into the chaotic mode the reactive power increases. However, the magnitude of the electric negentropy S_E^* increases considerably less.

To compare the possible influence of this quantity when it assumes increased values on the functioning modes of the converter, in the next section we consider the work of a boost CMC converter with prevented bifurcation modes and the transition into the chaotic mode due to the synchronization by periodic shunting of the input inductivity for a short period of time $\approx 0.05T_s$ (Beck, et. al., 2020).

5. Changes in the reactive power and electric negentropy when oscillations are synchronized by periodic shunting of the input inductivity

Consider named in heading of the section method of preventing the chaotic mode independently of the changes in the bounding current I_{ref} and, correspondingly, of the value of the duty cycle D. The diagram for its realization is given in Fig. 4a.

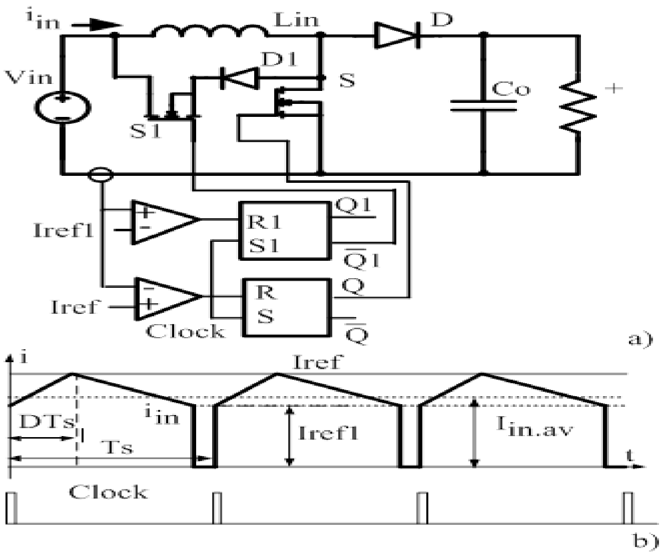


Fig. 4: Boost converter with synchronization of chaotic process, (a) circuit for CMC-above, (b) current and pulse diagram.

The diagram shows that a switch is connected in parallel to the input inductivity which is switched on for brief periods of time (approx. $\approx 0.05T_s$) when the inductivity current reaches the lower bound value of some current I_{ref1}, which approximately equals its value when functioning in a usual VMC mode. The current I_{ref1} changes with the variations in the current I_{ref} , that is increases or decreases simultaneously with it. The system of control of the boost converter is supplemented by yet another RS trigger (Fig. 4a, RS1), which forms a pulse on the output Q1 when the inductivity current reaches I_{ref1} and changes its state when a clock pulse reaches another input, as a result the additional switch opens.

Fig. 4b shows the diagram of the input current of the converter. As in previous Section 3, we take the voltage v_L as the input voltage, with a difference that during the shunting of the inductivity and the equality of the input current to zero, it also equals zero.

Fig. 5 gives, in relative units, a diagram of the variations of the minimal values of the inductivity current in the process of variation of the current I_{ref} and, correspondingly, the current I_{ref1}, in a sufficiently wide range, which do not result in the occurrence of bifurcations and transition into the chaotic mode due to the functioning of the switch *S1*.

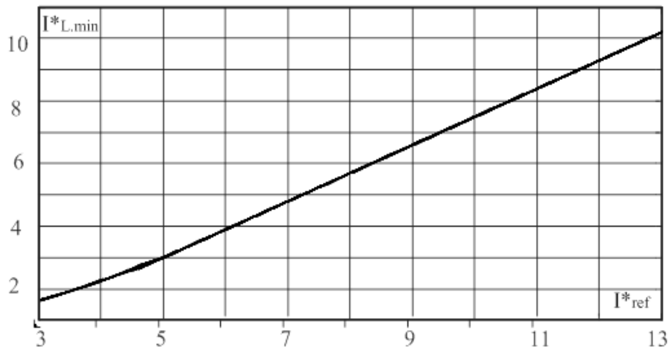


Fig. 5: Plot of variations of the lower limit values of the current $I^*_{L.min}$ with synchronization of the CMC-above.

Let us see how the input reactive power and negentropy, which were determined on the basis of limiting cycles and harmonic analysis vary in these conditions. The final results of our calculations are given in Table 2 for the CMC mode with the periodic shunting of the input inductivity.

Table 2

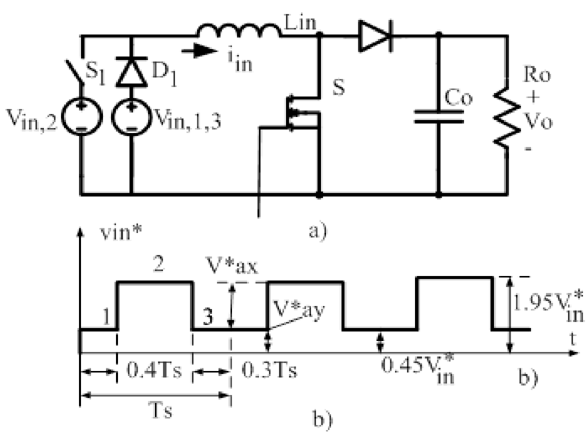
Regime	I^*_{ref}	4.2	5.4	6.3	6.7	10	12
Synchronization by inductance shunting	S^*_E	0.5207	1.4745	1.81	1.9714	3.4418	4.487

Note that in the case under consideration the relative frequency equals one, since no bifurcation modes have been observed. We also see that in this mode in all cases negentropy is considerably higher than in a mode without synchronization, due to which the mode was fully synchronized. For $I^*_{ref} = 4.2$ synchronization was not needed, therefore, there are no changes here.

6. Variations of the reactive Power and Electric negentropy when oscillations are synchronized by a stepwise input voltage

In the previous section we have achieved the synchronization of oscillations by short-duration shunting of the input inductivity resulting in an increase of the reactive power of the input current due to an obvious increase of the area of the limiting cycle of the pulsation of the input current - the input voltage, or in harmonic analysis, increasing the harmonic composition. A question arises, whether is it possible to reach the same aims by feeding the input with a stepwise voltage periodically changing with the frequency of switching of the converter with preserving its average value practically unchanged. A possible diagram of such an input voltage and its form are shown in Fig. 6a, 6b. Below we consider the modes of functioning when the input is supplied with a stepwise voltage formed with respect to its duration and the length of the steps according to Fig. 6b, so that the average value of the supplied voltage remains practically equal V^*_{in}, or more precise, $1.05V^*_{in}$.

Fig. 6c gives in relative units a diagram of variations of the minimal values of the inductivity current in the process of variations of the current I_{ref} in a sufficiently wide range. One can see that due to the introduced stepwise form of the input voltage, the occurrence of bifurcations has been excluded, and thus no transition into the chaotic mode occurs.



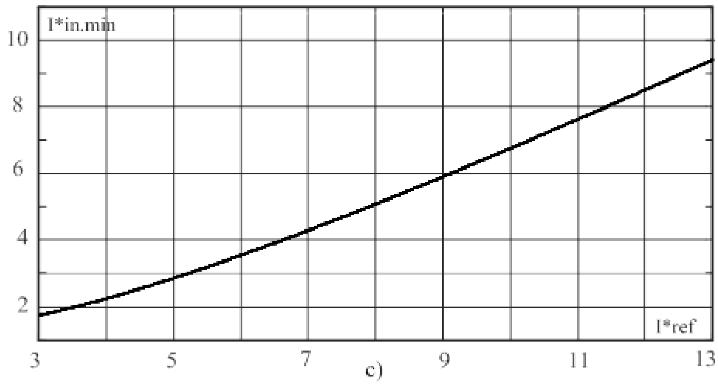


Fig. 6: Boost converter with synchronization of chaotic process with step input voltage-(a), circuit for CMC-above and input voltage diagram -(b), current curve I*$_{L.min}$ =f(I^*_{ref}) –(c).

Fig. 7 shows two limiting cycles constructed for two different values of the current I^*_{ref}, one, which is close to the initial, $I^*_{ref} = 4.2$, (Fig. 7a) and the second, close to the final one, $I^*_{ref} = 12.52$, (Fig.7b).

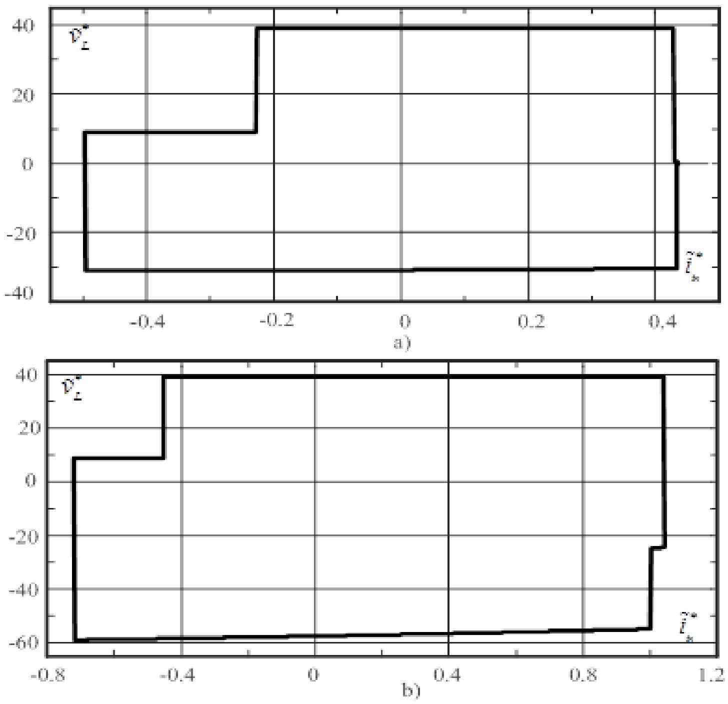


Fig. 7: Limit cycles in the plane $\tilde{i}^*_{in} - \tilde{v}^*_L$, for (a) I^*_{ref} =4.2, (b) I^*_{ref} =12.52.

Table 3 gives the values of negentropy in the case of synchronization of oscillations with a stepwise input voltage and in particular, for the two above values of I^*_{ref} Fig. 7. We see that in this case negentropy is considerably greater than the values in Table 1 for a usual CMC mode, thus explaining the normal functioning of the converter. And we also see that these values are lower than in the shunting of the input inductivity except the first value, for it is of no great meaning, since here no synchronization is needed.

Table 3

Regime	I^*_{ref}	4.2	5.4	6.3	6.7	10.0	12.52
Synchronization by step voltage supply	S^*_E	0.89621	1.1863	1.3934	1.4824	2.1585	2.622

Especially clearly seen is the decrease of the value of negentropy is observed in the last mode when $I^*_{ref} = 12.52$. Note that when we attempted to additionally decrease the amplitudes of steps, especially in this mode there appear signs of the chaotic mode while the normal mode was still present at all the other points.

It is interesting to check which limiting values of negentropy are needed for various values of I^*_{ref} in order to exclude the subsequent occurrence of the chaotic mode. We have checked the action of the stepwise voltage in the form given in Fig. 6b while gradually decreasing the height of the step V^*_{ax} (in the relative units, from the value 1.1 to the value 0.1 by regular steps equal 0.1) while keeping the average value of power supply unchanged by increasing the constant component (in Fig. 6a this component is denoted V^*_{ay} and $V^*_{ay} = 1 - 0.4V^*_{ax}$). As the height of the step V^*_{ax} decreased, the system passed jump-wise into the chaotic mode at the corresponding value of I^*_{ref}. Typical jump-wise transitions into the chaotic mode with the decrease of the steps are shown in Fig. 8, where there are also the values V^*_{ax} и V^*_{ay} for which, beginning with some boundary value $I^*_{ref.b}$, the chaotic mode starts. Obviously, the value of negentropy at that point could be considered minimal for ensuring normal modes for all $I^*_{ref} < I^*_{ref.b}$.

In their turn, for each I^*_{ref} the magnitudes $I^*_{ref.b}$ and negentropy differ at the corresponding point, and decrease with decreasing I^*_{ref}. As a result, we obtain the limit curve of the minimal values of negentropies, Fig. 9, Curve 1. In the same figure, for comparison, we give Curve 2, that has been obtained using Table 3 for the unchanging form of the stepwise voltage.

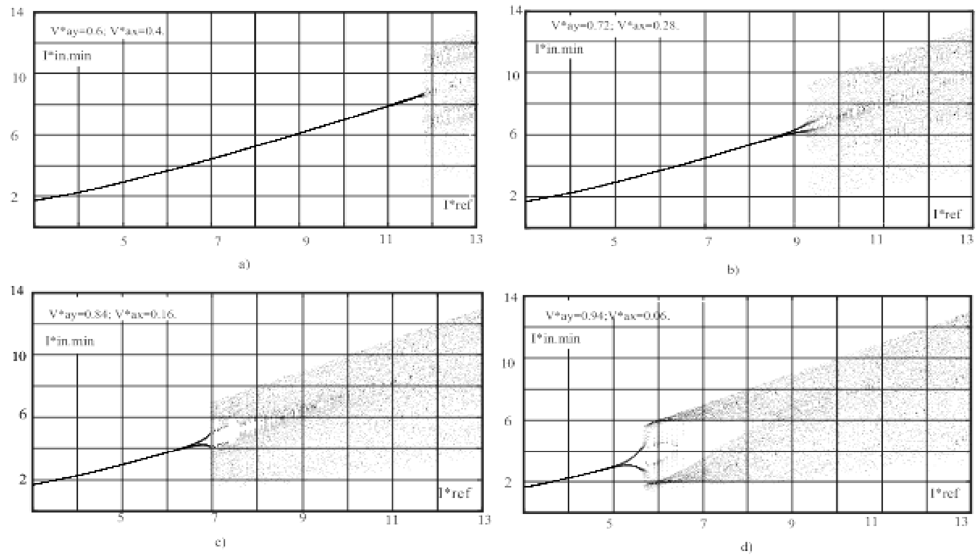


Fig. 8: Current plots I*$_{L.min}$ =f(I^*_{ref}) for various forms of stepped input voltage.

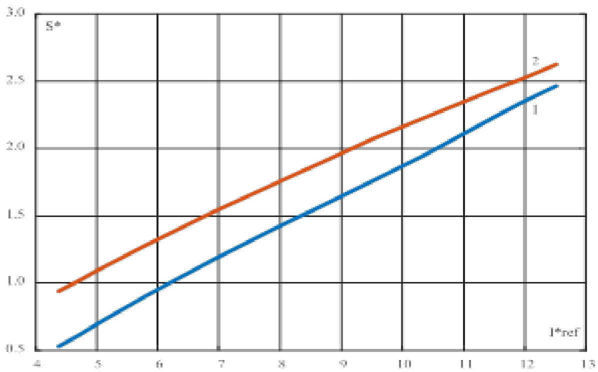


Fig. 9: 1- boundary curve of minimum values of negentropies, 2- negentropy values according to table 3.

A similar picture is observed upon the checking of synchronization when using a supply voltage on the input, which is a sum of the constant voltage $v^*_{in.1} = V^*_{in}$ and a sinusoidal component $v^*_{in.2} = V^*_{in}\cos((2\pi / T_s)t)$, that is, $v^*_{in} = V^*_{in} + V^*_{in}\cos((2\pi / T_s)t)$. Such a form of the input voltage ensures the preservation of synchronization up to $I^*_{ref} = 10$, and, for the sake of comparison, note that for $I^*_{ref} = 10$, $S^*_E = 2.0722$, and that turns out to be insufficient for ensuring synchronization for $I^*_{ref} = 12$. But for V$_{in}$=25 synchronization in ensured over the entire range of variation of I_{ref}. Note that in this Section we did not aim at the optimization of the forms and amplitudes of the steps, it was important for us to show the possibility in principle of ensuring synchronization and to evaluate the changes in negentropy.

7. Changes in the reactive power of the input current pulsations for the Current-Mode Control with Ramp Compensation

The work (Tse, 2004) considers in detail the possibility of expanding the zone of thee normal functioning of a boost converter in the CMC mode by delaying the moment of the occurrence of the doubling of the period. It is achieved by the simultaneous use, along with the linear level I_{ref} , also of a saw-tooth voltage (Fig. 10).

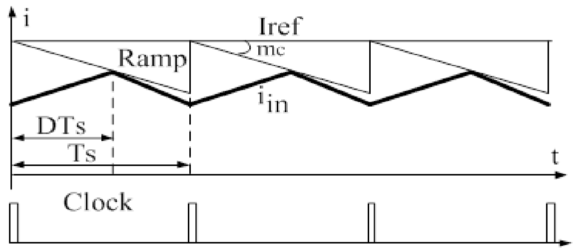


Fig. 10: Diagram of Current-Mode Control with Ramp Compensation.

As is shown in (Tse, 2004), such a CMC mode makes it possible to shift the moment of the occurrence of the doubling of the period from the value $D=0.5$ in the direction of significantly greater values of the duty cycle up to the elimination of bifurcations over the entire working range of the converter, which is achieved by increasing the slope of the saw-tooth voltage m_c. In particular, In the example under consideration of a converter with the CMC-above for $m_c*=1.5$ the normal working mode is preserved until $I_{ref}*=9$ and $D=0.625$ (Fig. 11). Correspondingly, the values of negentropy in the zone of values I^*_{ref} , where chaos earlier occurred, increased from the third to the sixth value **(**Table 4).

Table 4

Regime	I^*_{ref}	4.2	5.4	6.3	6.7	9.0	12.0
CMC with Ramp Compensation	S^*_E	0.4688	0.5906	0.7069	0.7572	1.0253	-

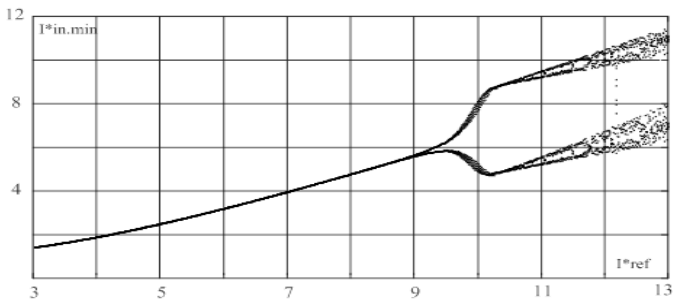


Fig. 11: Current plot I*$_{L.min}$ =f(I^*_{ref}) with Ramp Compensation.

7.1 Note

It can be noted here that to shift the moment of occurrence of the doubling of the period followed by its quadrupling cold be achieved by decreasing inductivity when as a result negentropy increases. Thus in the example of a converter considered here, a decreasing of the inductivity by half results in the shifting of the doubling point to $I^*_{ref} = 4.9$ (instead of $I^*_{ref} = 4.36$) and of the quadrupling point to $I^*_{ref} = 7.9$ (instead of $I^*_{ref} = 5.92$). And the values of the first two values of negentropy in Table 4 have practically doubled.

In (Dongale, et. al., 2015) the authors have checked the influence of the magnitude of the capacitor on the moments of doubling or quadrupling of the period and the durations of these intervals. It has been shown that the increasing of the capacitor magnitude leads to delaying (shifting) of the moments of bifurcations' occurrence. The verification of the changes of the magnitude of negentropy has shown its decrease at the points of bifurcation upon decreasing the magnitude of the capacitor. Until now, we did not consider the issue of the reactive power of the capacitor pulsations, since its magnitude is negligibly small as compared to the power of pulsations of the inductivity current. Thus, for the parameters of the converter assumed here (*Co=5□F*) and the magnitude of negentropy for $I^*_{ref} = 4.36$ $S_E=0.521$ the magnitude of the capacitor's negentropy is only $S_{EC}=-0.044$. However, upon the decreasing of the capacitor's magnitude to *Co=1□F*, the negentropy that is, changes little, $S_E=0.501$, while the capacitors' negentropy yet increases to $S_{EC}=-0.218$ and reduces its summary magnitude do to the negative value. и снижает суммарную ее величину за счет отрицательного значения. This fact explains the more early arrival of the doubling of the period when the magnitude of the capacitor decreases to *Co=1□F* for $I^*_{ref} = 3.1$.

8. The CMC-bottom mode. The changes of the reactive power of the pulsations of the input current and of negentropy in the processes of bifurcations and for various principles of synchronization

Below, using the some example of a converter with the same parameters, but working in the CMC mode but bounded from below (CMC-bottom, Fig. 1b, 1d) (Beck, et. al., 2020), we will analyze its functioning mode when the bounding current I_{ref} varies within the limits from the higher value *2.5A*to the lower *0.5A*. Fig. 10 shows the diagram of bifurcations followed by the transition to the chaotic mode expressed in the relative units while the values of negentropy for various zones are given in Table 5.

Table 5

Regime	I^*_{ref}	3.5	2	1.5	1.35	1.1
Bifurcations and Chaos	T^*	1	2	4	8	32
	S^*_E	0.73	0.63	0.53	0.50	0.34
Synchronization by inductance shunting	S^*_E	-0.6247	-0.2065	-0.1260	-0.1048	-0.0718
Synchronization by step voltage supply	S^*_E	1.7631	1.4896	1.3829	1.3446	1.2723

Let us further consider an application of the synchronization method by periodical shunting of the input inductivity on a short time interval $\approx 0.05T_s$ (Beck, et. al., 2020). Unlike the use of this method in Section 4 in the CMC-above mode here the shunting is performed not when the inductivity current reaches the minimal value, but vice versa when it approaches the maximal level; in that zone the main switch opens and the shunting switch closes for a short time.

This results in the complete elimination of the bifurcation mode and the transition to the chaotic mode over the entire range of variation of I^*_{ref} (Fig. 11a). The fourth row of Table 5 gives for comparison the values of negentropy obtained in this case for the same values of I^*_{ref}. From being of inductive character (consuming reactive power), they pass into a capacitance mode (generation of reactive power).

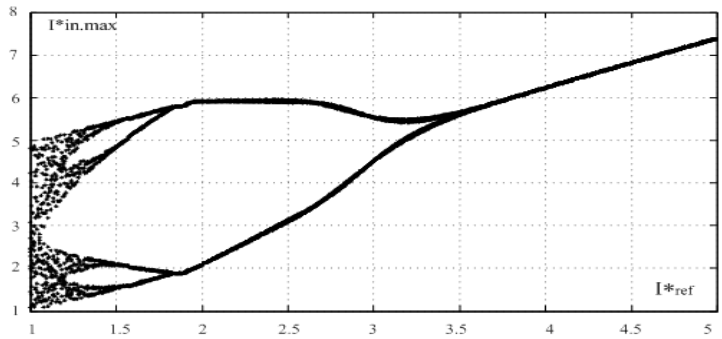


Fig. 10: Plot bifurcation diagrams for different values of I^*_{ref} (CMC-bottom).

We will also carry out the checking of the elimination of anomalous modes by feeding the converter with a stepwise voltage of the form $V_{inx}=V_{in}+V_{ax}$, where $V_{in}=13$, and $V_{ax}=40((-0.8+(t/T_s -floor(t/T_s)))>0)$.

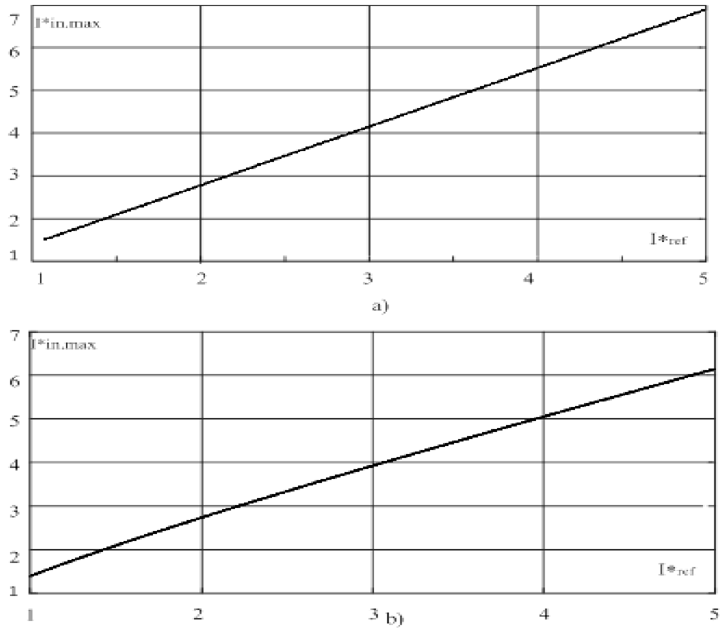


Fig. 11: Plot of variations of the lower limit values of the current I*$_{L.max}$ of the CMC-bottom, a)with pulse synchronization, b) with stepped input voltage.

This change of the input voltage results also in the complete elimination of the bifurcation mode and transition into chaotic mode over the entire range of variations of I^*_{ref} (Fig. 11b). The values of negentropy obtained in this case for the same values of I^*_{ref}, are given for comparison in the fifth row of Table 5; one can see that are considerably greater than the corresponding values in anomalous modes.

9. CONCLUSIONS

1. The reactive power in electric circuits is determining factor in the course of all electromagnetic processes. Being related to the force functions whose formulas contain the magnitudes of the energies of reactive elements, it is the reactive power which according with Hamilton's principle determines the character of the changes of the modes of the electric circuit and is the stabilizing factor in the elimination of the chaotic modes, while reducing the system's entropy.
2. The direct indicator of this effect is the magnitude of negentropy which is the density of the reactive power in the course of the period.
3. In order to verify these assumptions, we have analyzed various methods of synchronization and elimination of chaotic modes in CMC boost converters in two cases – bounded from above and below – and confirmed them The negentropy was determined by the magnitudes of pulsations of the input current..

4. In the CMC mode-above the comparison of the magnitudes of negentropy upon bifurcations and chaotic modes on the one hand and upon the synchronization of them and total elimination by short-duration shunting of the input inductivity shows a considerable increased of the magnitude of negentropy, thus explaining the stabilization of the functioning modes.
5. We have proposed a method of synchronization by the supplying to the converter a stepwise voltage, which also confirms the resulting increase of negentropy ensuring the synchronization process.
6. Besides a stepwise voltage, the possibility of synchronization is pointed out, when a constant voltage is supplied to the converter on which a cosine wave is superimposed whose frequency equals the frequency of the converter's switching, which also is accompanied with an increase of negentropy.
7. In the CMC-bottom mode a comparison of the magnitudes of negentropy in a usual mode and upon the synchronization by short-duration shunting of the input inductivity shows that the reactive power of pulsations assumes a capacitance character instead of an inductive one, that is the reactive power is being generated. We have also shown the possibility of synchronization when a stepwise voltage is supplied to the circuit, and that is accompanied by an essential increase of negentropy.

REFERENCES

1. Haken, H. "Synergetics. An Introduction", Springer, Berlin, 1983.
2. Prigogine, I., Stengers, I. "The Time, Chaos and Quant", 1994.
3. Tse, C. K. and Di Bernardo, M. "Complex Behavior in Switching Power Converters", Proceedings of the IEEE, 2002; 90, 5: 768-781.
4. Nagy, I. "Nonlinear Phenomena in Power Electronics", Journal for Control, Measurement, Electronics, Computing and Communications. Zagreb, Croatia, 2001; 42, 3-4: 117-132.
5. Aroudi, A., Debbat, M., Giral, R. *et al*., "Bifurcations in DC–DC Switching Converters: Review of Methods and Applications", International Journal of Bifurcation and Chaos, 2005; 15, 5: 1549–1578.
6. Deane, J., and Hamill, D. "Instability, subharmonics and chaos in power electronic systems", IEEE Transactions on Power Electronics, 1990; 5, 3: 260–267.
7. Deane, J. "Chaos in current-mode controlled boost DC-DC converter", IEEE Transactions on Circuits and Systems, 1992; 1, 39, 8: 680-683.

8. Hamill, D., Deane J., and Jefferies, D. "Modeling of Chaotic DC-DC Converters", IEEE Transactions on Power Electronics, 1992; 7, 1: 25-36.
9. Tse, C. K. "Chaos in Power Electronics", IEEE ISCAS', Tutorial Notes, 2003; 28.
10. Tse, C. K. "Complex Behavior of Switching Power Converters". CRC Press, 2004.
11. Baranovski, A., and Schwarz, W. "Statistical analysis and design of continuous-discrete chaos generators", IEICE Trans. Fundamentals, 1999; E82: 9, September.
12. Baranovski, A. *et al.* "Chaotic control of a dc-dc converter", In IEEE International Symposium on Circuits and Systems, ISCAS 2000, Switzerland, May, 2000.
13. Woywode, O., Weber, J., Güldner, H. *et al*. "Bifurcation and Statistical Analysis of DC–DC Converters", IEEE Trans. Circuits Syst, 2003; I, 50: 1072-1080.
14. Baranovski, A., Schwarz, W. "Chaotic and random point processes: Analysis, design and applications to switching systems", IEEE Trans. Circuits Syst, 2003; I, 50: 1081-1088.
15. Aroudi, A., Robert, B., and Martinez, L. "Bifurcation Behavior of a Three Cell DC-DC Buck Converter", EPE-PEMC Portorož, Slovenia, 2006; 1994-2001.
16. Benadero, L., Aroudi, A., Olivar, G. *et al.* "Two-Dimensional Bifurcation Diagrams. Background Pattern of Fundamental DC DC Converters with PWM Control", International Journal of Bifurcation and Chaos, 2003; 13, 2: 427–451.
17. Dongale, T. "Investigation of Nonlinear Dynamics in the Boost Converter: Effect of Capacitance Variations", Int. Journal on Computational Science & Applications (IJCSA), 2015; 5**,** 3: 67-76.
18. White D., Woodson H. "Electromechanical Energy Conversion", New York, John Wiley and Sons, Inc, 1959.
19. Hazen, A.M. Introduction of a information measure into the mechanics axiomatic base. (Second updated edition), Moscow, 1998; 242.
20. Berkovich, Y., and Moshe, S. "Study of DC-DC Converters Dynamic Modes Using Energy Functions", WJERT, 2021; 7, 4: 59-89.
21. Emde, F. "Entohmung", Elektrotech.Z., H.15, 1930; S.533-535. (in deutsch)
22. Mayevsky, O. "Energy efficiency of semiconductor converters", Energy, Moscow, 1978.
23. Krogeris, A., Rasevics, K., Sinka, J., Treimanis, E. *AC Power. Power in Circuits of Nonsinusoidal Currents and Voltages*, Institute of Physical Energetics Latvian Academy of Sciences, Riga, 1993; 295.
24. Berkovich, Y. "Electrical Circuits and the Second Law of Thermodynamics", WJERT, 2022; 8, 5: 66-85.

25. Berkovich, J., Ioinovici, A. "Simulation of chaotic processes in boost-converters and their interpretation in terms of information theory", Proc. Int'l. Power Electronics and Motion Control Conf. (PEMC '98), Prague, Czech Republic, 1998; 8: 5-195–5-200).
26. Berkovich, Y., and Moshe, S. "Features of Operation Iin the Van Der Pol Transistor Oscillator", WJERT, 2021; 7, 3: 179-197.
27. Berkovich, Y., "The Van Der Pol Oscillator with a Tunnel Diode", WJERT, 2024, 10, 3: 40-56.
28. Beck, Y., and Berkovich, Y. "A Mathematical Model of Chaotic Processes in a Boost Converter: Generation and Synchronization", WJERT, 2020; 6, 3: 401-419.