PROGRAMMABLE STATIC CONVERTERS FOR INTELLIGENT ELECTRICAL NETWORKS

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ABSTRACT

The authors consider the basic operations of implicative algebra for the choice of the logical-algebraic modeling of static converters, provided that the objective and predicate variables are identified with the parameters of the energy and information processes. The possibility of formalizing the problems of synthesizing static converters based on logical-algebraic models, which are reproduced instrumentally in the elemental basis of single-channel relators, is substantiated. Examples of logical-algebraic models of typical energy transformations are given. A generalized logical-algebraic model is proposed that allows one to formalize the procedure for synthesizing a programmable static converter. The examples of the program specification of the type of the electric energy conversion being carried out are given.

Keywords: Programmable Static Converters, Intelligent Electrical Networks, Implicative Algebra, Logical-Algebraic Modeling, Single-Channel Relators.

1. Introduction

Intelligent electrical networks, characterized by the use of mechanisms for obtaining, storing and processing knowledge to implement the necessary modes of operation and control algorithms, impose stringent requirements on static converters (SC) of types and parameters of electrical energy. Among the traditional requirements for increasing the energy and mass-dimensions, improving the dynamic characteristics, the indicators of multifunctionality, invariance, robustness that predetermine the stability of SC to damage, malfunctions and failures, the ability to adapt to changes in the type and quality of the input electric power, to introduction of new components. Satisfying the above criteria, the SC acquires the properties inherent in intelligent systems, for the creation of which the principles of situational management and such information technologies as expert systems, artificial neural networks, fuzzy logic, genetic algorithms [1, 2] are used.

The design of programmable, intelligent static converters requires the solution of problems not only of system analysis, but also of circuit synthesis. The task of the analysis is to determine the output coordinates of SC with respect to a given structure and input variables, is completely formalized and is always solvable either by analytical methods [3] or by numerical computations [4]. The synthesis problem consists in determining the internal structure of SC on the given sets of input and output variables. In this formulation, the synthesis problem is not formalized and requires the use of heuristic techniques, which predetermines the ambiguity of the solutions obtained.

For a formalized description of the SC, the concept of a commutation function connecting the input u_{input}, i_{input} and output u_{output} , i_{output} coordinates [3.5]

$$u_{\text{output}} = \Psi_{\text{SC}} \cdot u_{\text{input}}, \; i_{\text{input}} = \Psi_{\text{SC}} \cdot i_{\text{output}} \qquad (1)$$

and determining the type and quality of the transformation.

However, the switching function does not reflect the structure of the power part and the control system of the SP and does not allow solving the problems of circuitry synthesis.

In [5], for a systematic description and formalization of synthesis problems, it is suggested to treat the SC as a functional system that realizes some set of transformation operators. However, to describe the transformation operators, an adequate mathematical apparatus is not proposed that would allow one to establish a one-to-one correspondence between the form of the transformation operator and the circuit structure for its implementation, and hence completely formalize the synthesis problems of SC.

At the same time, it is widely known that two-valued algebraic logic (Boolean algebra) serves as a theoretical basis for the formalized solution of problems of analysis and synthesis of digital systems. This gives grounds for assuming the expediency and the prospects for the extension of logical-algebraic methods to continuous-discrete systems, including SC.

In the present work, for the formalization of synthesis problems, a logical-algebraic method of system description of SC is proposed, based on the laws and properties of continual algebraic logics developed by L.I. Volgin and combined by a function - the axiom of weighted power means in a single metasystem, including classical two-valued algebraic logic [6].

The most implementative tasks of the system description and formalization of the SC synthesis procedures are the implicative choice algebra (ICA), the domains of which are two sets of analog variables, subject $Y = \{y_1, y_2, \ldots, y_n\}$ and predicate $X = \{x_1, x_2, \ldots, x_n\}$, and the basic operations are physically reproduced by single-channel relators. This allows, subject to identification of object variables with parameters of the energy process, and predicate variables with parameters of the information process, to form a system description of the SC in the form of logical-algebraic (LA) models written in the basis of the ICA operations, which can then be converted into electrical circuits by means of an elemental basis of relators [7]. As a result, the problem of synthesizing the SC is completely formalized.

2. Basic operations of the implicative selection algebra.

Basic for ICA are binary operations

$$\mathrm{V}(y_1, y_2) = y_1 \cdot I(x_1 - x_2) + y_2 \cdot I(x_2 - x_1), \qquad (2)$$

$$\Lambda(y_1, y_2) = y_1 \cdot I(x_2 - x_1) + y_2 \cdot I(x_1 - x_2), \qquad (3)$$

where y_1, y_2 - subject variables, which can serve as mathematical objects and physical parameters that satisfy the conditions of separation $y_i \cdot 1 = y_i$ and absorption $y_i \cdot 0 = 0$; x_1, x_2 - predicate variables (real numbers); $I(x)$ - the unit function (Heaviside operator), equal to 1 for $x > 0$ or 0 for $x < 0$.

Analysis (2), (3) allows us to conclude that the basic binary operations of ICA have implicativity properties, which is an analogue of the Boolean "EXCLUSIVE OR" function in the continual domain, and perform an alternative choice of one of the objective variables, either y_1, or y_2. It should also be noted that the procedure for identifying objective and predicate variables, for example $y_1 = x_1$, $y_2 = x_2$ is accompanied by binary values of the latter $x_i \in \{0,1\}$ by the degeneration of the basic ICA operations (2), (3) into logical operations of Boolean disjunction $x_1 \vee x_2$ and conjunction $x_1 \wedge x_2$, respectively.

Hardware implementation of basic ICA operations (2), (3), and when the above constraints and Boolean disjunctions and conjunctions are fulfilled, the analog logic element is implemented - a single-channel relator RL that contains a DA differential comparator that controls the two-operation keys of the closing S and breaking $\overline{S}$ types forming depending on the method of connection, the switching channel of the multiplexer (M-relator) or demultiplexer (D-relator) types, shown in Fig. 1a, b, respectively [6]. The single-channel RL relator has a wide adaptive capability. In particular, increasing the load capacity of keys $S, \overline{S}$ and expanding, by introducing a digital element DD, algorithms for operating a switching channel in accordance with a family of reproducible ICA functions

$$W(y_1, y_2) = D_L \cdot [D_R \cdot \mathrm{V}(y_1, y_2) + \overline{D}_R \cdot \Lambda(y_1, y_2)], \qquad (4)$$

allows to transform a single-channel RL relator into a power relator RLF (Fig. 1c) [8]. As can be seen from (4), the digital signal D_L blocks $(D_L = 0)$ or permits $(D_L = 1)$ the execution of ICA operations (2), (3), and the digital signal $D_R = \{0,1\}$ ensures the interchange of ICA operations ($\mathrm{V} \leftrightarrow \Lambda$).

Analysis of (2), (3) and (4) allows us to note the principal possibility of simulating the simultaneous energy and information processes taking place in the SC in the basis of ICA operations, thanks to the use of two sets of variables that do not intersect in the general case - subject and predicate ones. It is sufficient to consider physical parameters of the energy process as objective variables, and control (information) signals as predicate variables.

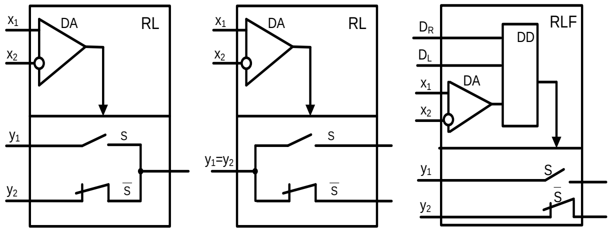

Fig.1. Structural diagrams of single-channel (a, b) and power (c) relators.

3. Logical-Algebraic models of energy transformations.

In the most typical for most single-phase SP case, only one source of input voltage is used and, accordingly, the following variants of identifying object variables

$$y_1 = e(t), \qquad y_2 = 0, \qquad (5)$$

$$y_1 = e(t), \qquad y_2 = -e(t), \qquad (6)$$

where $e(t)$ is the input voltage of the SC, variable

$$e(t) = e(t + T) \qquad (7)$$

With a period of variation of T or a constant

$$e(t) = \pm E. \qquad (8)$$

When identifying subject and predicate variables

$$y_1 = e(t); \quad y_2 = 0; \quad x_1 = y_1; \quad x_2 = y_2, \qquad (9)$$

with input variable with the change of the sign of the voltage $e(t)$ basic binary ICA operations

$$\mathrm{V}(y_1, y_2) = \mathrm{V}(e,0) = e(t)\cdot I[e(t) - 0] = \begin{cases} e(t) & \text{при } e(t) > 0 \\ 0 & \text{при } e(t) < 0 \end{cases}, \quad (10)$$

$$\Lambda(y_1, y_2) = \Lambda(e,0) = e(t)\cdot I[0 - e(t)] = e(t)\cdot\{1 - I[e(t)]\} = \begin{cases} 0 \\ e(t) \end{cases}$$

for $\begin{matrix} e(t) > 0 \\ e(t) < 0 \end{matrix}$, (11)

determine the nature of the change in the output voltage of the SC and reproduce the LA models of uncontrolled single-phase half-wave rectification with positive and negative polarity of the rectified voltage, respectively. Analysis (10), (11) shows that the interchange of the basic binary operations $\mathrm{V} \leftrightarrow \Lambda$ by, as follows from (2) and (3), the interchange of either subject variables $y_1 \leftrightarrow y_2$, or predicate variables $x_1 \leftrightarrow x_2$, is accompanied by a reversal of the polarity of the rectified voltage.

Based on the LA models (10), (11), the ICA functions can be obtained

$$\mathrm{V}(e,0) - \Lambda(e,0) = e(t)\cdot I\ [e(t)] - e(t)\cdot\{1 - I\cdot[e(t)]\} = e(t)\cdot Sign\ [e(t)] = |e(t)|, \quad (12)$$

$$\Lambda(e,0) - \mathrm{V}(e,0) = e(t)\cdot\{1 - I[e(t)]\} - e(t)\cdot I[e(t)] = -e(t)\cdot Sign[e(t)] = -|e(t)|, \quad (13)$$

which reproduce the LA models of unregulated single-phase full-wave rectification with positive and negative polarity of the rectified voltage, respectively. Here

$$Sign[e(t)] = \begin{cases} +1 & \text{for} & e(t) > 0 \\ -1 & & e(t) < 0 \end{cases}$$

there is a sign function.

A similar result can be obtained for modified conditions for identifying subject and predicate variables

$$y_1 = e(t); \quad y_2 = -e(t); \quad x_1 = y_1; \quad x_2 = y_2 \quad (14)$$

In this case, the basic binary ICA operations (2), (3)

$$\mathrm{V}(y_1, y_2) = \mathrm{V}(e,-e) = e(t)\cdot I[2\cdot e(t)] - e(t)\cdot I[-2\cdot e(t)] =$$
$$= e(t)\cdot Sign[e(t)] = |e(t)|, \qquad (15)$$

$$\Lambda(y_1, y_2) = \mathrm{V}(e,-e) = e(t)\cdot I[-2e(t)] - e(t)\cdot I[2\cdot e(t)] =$$
$$= -e(t)\cdot Sign[e(t)] = -|e(t)|, \qquad (16)$$

also reproduce the LA models of unregulated single-phase full-wave rectification with positive and negative polarity of the rectified voltage, respectively.

Despite the same final result, the transformations (12), (13) and (15), (16) reflect different ways of realizing rectification processes. The rectified voltage under the conditions of identification (9) is formed by inversion according to the criterion of the sign of the input alternating voltage, which requires simultaneous execution of binary operations (2), (3) as follows from (12), (13). This method of conversion is carried out in bridge rectifiers. To form the rectified voltage under the identification conditions (14) it is sufficient, as follows from (15), (16), to perform one binary operation to carry out only an alternative choice by the criterion of the sign of one of the two antiphase variable voltages, since the inversion procedure was performed previously. This method of conversion is carried out in rectifiers with an average point.

4. Logical-Algebraic models of programmable electricity transformations.

Typical control algorithms of SC for different purposes are based on the procedure for comparing the reference signal $u_0(t)$ of the unfolding view and the signal of regulation $u_r(t)$, which generated by the automatic controller or specified by the operator [8]. Such a comparison will be carried out in the process of implementing the basic binary operations (2), (3), if these signals are identified with predicate variables, for example, $x_1 = u_0(t)$. The reference signal in the general case can be represented as a composition of two functions

$$u_0(t) = U_0(t)\cdot Sign[e(t)], \qquad (17)$$

where $U_0(t)$ is the modulation function determining the shape of the reference signal;

$Sign[e(t)] = \begin{cases} +1 & \text{for} & e(t) > 0 \\ -1 & & e(t) < 0 \end{cases}$ - sign function that synchronizes the reference signal with the supply voltage.

When $U_0(t) = U_0 = const$ the reference signal has the form of a meander and provides only synchronization of the switching channels of the power RLF relator with the transitions of the input voltage through zero values. By choosing the law of variation $U_0(t) = \mathrm{var}$, it is possible to give the reference signal practically any shape, which necessary for the formation of a given transfer characteristic of SC. Under the conditions (8), the reference signal, as follows from (9), must perform the function of the reference signal

$$u_0(t) = U_0(t) = U_0(t + T_{\text{con}}) = u_{\acute{K}}(t) \quad , \ (18)$$

which determines the switching frequency of the switching channel of the power RLF relator and, correspondingly, the frequency of conversion of electrical energy $f_{\text{con}} = 1/T_{\text{con}}$.

If the objective (y_1, y_2) and predicate (x_1, x_2) variables satisfy the identification conditions $y_1 = e(t)$, $y_2 = 0$, $x_1 = u_0(t)$, $x_2 = u_r(t)$, then the basic binary operations (2), (3) reproduce the functions

$$\vee(y_1, y_2) = y_1 \cdot I(x_1 - x_2) = e(t) \cdot I \left[u_0(t) - u_r(t)\right], \quad (19)$$

$$\Lambda(y_1, y_2) = y_1 \cdot I(x_2 - x_1) = -e(t) \cdot I \left[u_0(t) - u_r(t)\right], \quad (20)$$

half-wave rectification with pulse-phase regulation of the output voltage, positive (19) or negative (20). The interchange of predicate variables ($x_1 \leftrightarrow x_2$) is accompanied, as can be seen from (19), (20), by reversing the polarity of the rectified voltage.

Under the constraints (14) for object variables (y_1, y_2) and preserving the identification conditions for predicate variables $x_1 = u_0(t)$, $x_2 = u_r(t)$, the basic binary operations (2), (3) reproduce functions

$$\vee(y_1, y_2) = y_1 \cdot [I(x_1 - x_2) - I(x_2 - x_1)] = e(t) \cdot Sign \left[u_0(t) - u_r(t)\right], \quad (21)$$

$$\Lambda(y_1, y_2) = y_1 \cdot [I(x_2 - x_1) - I(x_1 - x_2)] = -e(t) \cdot Sign \left[u_0(t) - u_r(t)\right], \quad (22)$$

full-wave rectification with pulse-phase regulation of the output voltage of positive or negative polarity, respectively. In the particular case where the regulation signal $u_r(t) = 0$, expressions (21) and (22) degenerate into (15), (16), respectively, determining the limiting value of the rectified voltage.

The analysis (19), (20) under the conditions of identification of objective variables

$$y_1 = |e(t)| \quad \text{or} \quad y_1 = -|e(t)|$$

and the identification of the predicate variable $x_1 = u_3(t)$ with the reference signal $u_3(t)$ of the unfolding form, whose frequency should exceed the frequency of the input voltage $e(t)$, shows that the basic operations (2), (3)

$$\vee(y_1, y_2) = |e(t)| \cdot I[u_3(t) - u_r(t)] = \frac{1}{2} \cdot |e(t)| + \frac{1}{2}|e(t)| \cdot Sign[u_3(t) - u_r(t)] = \begin{cases} |e(t)| \\ 0 \end{cases} \text{for} \begin{matrix} u_3 > u_r \\ u_3 < u_r \end{matrix}, \quad (23)$$

$$\Lambda(y_1, y_2) = -|e(t)| \cdot I[u_3(t) - u_r(t)] = -\frac{1}{2} \cdot |e(t)| - \frac{1}{2} \cdot |e(t)| \cdot Sign \cdot [u_3(t) - u_r(t)] = \begin{cases} -|e(t)| \\ 0 \end{cases} \text{for} \begin{matrix} u_3 > u_r \\ u_3 < u_r \end{matrix}, \quad (24)$$

reproduce the functions of pulse-width regulation (PWR) of the rectified voltage of positive (23) or negative (24) polarity. The relations (23) and (24) are LA models of rectifiers with a PWR on the DC current side.

The analysis of (19), (20) when the condition (8) is satisfied for the subject variable y_1 and condition (18) for the predicate variable x_1 shows that the operations of the IAA disjunction (2) and the ICA-conjunction (3)

$$\vee(y_1, y_2) = E \cdot I[u_3(t) - u_r(t)] = \frac{1}{2} \cdot E + \frac{1}{2} \cdot E \cdot Sign[u_3(t) - u_r(t)] = \begin{cases} E \\ 0 \end{cases} \text{for} \begin{matrix} u_3 > u_r \\ u_3 < u_r \end{matrix}, \quad (25)$$

$$\Lambda(y_1, y_2) = -E \cdot I[u_3(t) - u_r(t)] = -\frac{1}{2} \cdot E - \frac{1}{2} \cdot E \cdot Sign[u_3(t) - u_r(t)] = \begin{cases} -E \\ 0 \end{cases} \text{for} \begin{matrix} u_3 > u_r \\ u_3 < u_r \end{matrix}, \quad (26)$$

reproduce the functions of pulse-width regulation of a constant voltage of positive (25) or negative (26) polarity.

Analysis (21) and (22) also allows us to note that each of the basic ICA operations (2), (3) under conditions (8), (18) reproduces the function of converting a DC voltage into an AC voltage with amplitude E and repetition period TR. The mutual replacement of predicate variables ($x_1 \leftrightarrow x_2$) and basic ICA operations ($\vee \leftrightarrow \Lambda$) is respectively accompanied by a change in the phase of the output alternating voltage to the opposite one.

Based on (21) and (22) with the use of (4), a generalized LA-model of the full-wave SC is formed as a function of the instantaneous values of the output voltage recorded in the predicate-logical form

$$u_{\text{output}}(t) = D_L \cdot \left\{ D_R \cdot \left[e(t) \cdot Sign\ \left(u_0(t) - u_r(t)\right) \right] + \overline{D}_R \cdot \left[(-1) \cdot e(t) \cdot Sign\ \left(u_0(t) - u_r(t)\right) \right] \right\}. \quad (27)$$

The generalized LA-model (27) shows the principal possibility of not only regulating the output voltage of the SC with the help of analog signals u_0, u_r, but also setting (programming) the required type of current conversion by interrupting, inversion, switching the level of the input voltage at individual time intervals in accordance with the formation algorithm of digital signals D_R, D_L.

The obtained LA models of various methods of unregulated and regulated rectification can be converted by means of an elemental basis of relators into electrical schemes of power and information structures of the SC, allowing to formalize the problems of circuit engineering synthesis [9,10].

5. Examples of programming of energy transformations.

Analysis of the LA model (27) shows that the regulated rectification is provided by specifying digital signals $D_L = 1,\ D_R = 1$ or $D_R = 0$ depending on the required polarity of the rectified voltage, forming the in-phase with the supply voltage of the reference signal of the deployment form in accordance with (17) and fixing the operating point control signal u_r on the regulated characteristic, whose form is determined by the law of change of the modulation function $U_0(t)$.

The formation of a digital signal D_R in the form of a single function

$$D_R = I[e(t + nT)] \quad \text{at n = 2, 3, 4}$$

allows to transform the ICA function (27) into the LA model

$$W(y_1, y_2) = D_L \cdot |\, e(t) \,| \cdot Sign[e(t + nT)],$$

frequency conversion and generation of an output AC voltage, with a frequency "n" times lower than the frequency of the input voltage of the power supply.

An unregulated DC to AC conversion is provided by specifying digital signals $D_L = 1,\ D_R = 1$ or $D_R = 0$ by fixing a predicate variable $x_2 = u_r = 0$ and generating a reference signal in the form of a periodic function of arbitrary shape (18), for example, a meander that determines the switching frequency $f_{\text{con}} = 1/\ T_{\text{con}}$ of the switching channel. At the same time, an output alternating voltage of rectangular shape with amplitude E and a repetition period $T_П$ is formed.

For pulse-width regulation of the output voltage, it is necessary to provide the formation of a reference signal not only, for example,

$$u_0(t) = U_0 \cdot [1 - Sin(4\pi \cdot \frac{t}{T_П})], \qquad u_r = c\ o\ n$$

but also digital signals in the form of single functions

$$D_R = Sign[Sin \frac{2\pi}{T_П} \cdot t], \qquad D_L = I[u_0(t) - u_r].$$

Then the ICA function (27) takes the form

$$W(y_1, y_2) = E \cdot Sign[Sin 2\pi \cdot \frac{t}{T_{\text{con}}}] \cdot I[u_0(t) - u_r]$$

As can be seen, only when $u_0(t) > u_r$ basic ICA operations are reproduced and an output voltage equal to $+E$ or $-E$ is generated. On the intervals $u_0(t) < u_r$, the switching channel is blocked, because $D_L = 0$, by interrupting the output voltage. The modulation of the digital signal D_R ensures a periodic interchange of the basic ICA operations ($\mathrm{V} \leftrightarrow \Lambda$), which is accompanied by an inversion of the polarity of the output voltage U_{output}. The change in the control signal in the range $0 \le u_r \le 2 \cdot U_0$ is accompanied by a change in the half-wave length of the AC voltage from 0 up to $T_{\text{con}}/2$ and the output voltage from zero to the maximum value. The examples considered do not exhaust the possible combinations of the values of the master information signals u_o, u_r, D_R, D_L.

6. Conclusion.

A new approach to the system analysis of energy and information processes in single-phase static converters based on the logical-algebraic apparatus of implicative selection algebra is proposed. Its basic operations extend to the binary, discrete, continual range of values of variables and are instrumentally reproduced by universal circuit elements, single-channel relators.

The method of logical and algebraic modeling of single-phase static converters is developed in the basis of binary operations of the implicative choice algebra based on the procedures for identifying object and predicate variables with the parameters of information and energy processes and allowing to formulate on a single methodological basis logical-algebraic models reflecting the types of reproducible energy transformations, methods of program task of the current transformation, the structure of the electrical circuit.

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