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An Effective Mathematical Modeling Method for Designing a Three-phase Parallel Inverter With Shut-off Valves

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ABSTRACT: This paper presents the results of efficient mathematical modelling for the design of a three-phase parallel inverter with shut-off gates by applying a universal matching matrix. The model is developed on the basis of Laplace transform and provides the choice of optimum parameters of inverter power circuit elements with high accuracy as it takes into account possible dynamic modes at start-up, load switching, reduction or increase of input voltage value. Phase topological symmetry, which is inherent in three-phase converter circuits, can be used in the calculation for switched gates with different numbers. This fact is the basis for a universal matching matrix. This matrix can be used to calculate transient and steady-state processes in three-phase autonomous current inverters (ACI) of different configurations: parallel ACI, parallel-series ACI, series-parallel ACI, serial ACI, ACI with cut-off gates and ACI with two-stage switching.

KEY WORDS: valve converter, autonomous current inverter, mathematical modeling, autonomous current inverter with cut-off valves

I. INTRODUCTION

As is known, when designing complex electrical systems, including electromechanical systems based on valve converters, special attention is paid to the issue of ensuring a high level of reliability of their operation under various conditions [1-3]. This provides the ability of the developed model to take into account with high accuracy not only the variety of switching circuits, different operating modes both with constant load parameters and input voltage, but also the almost continuous change in the structure of the power circuit as valves of various groups are turned on and off. Thus, the design stage based on the use of an accurate model necessarily goes through the analysis of many possible equivalent circuits that describe the type of converter mode as a nonlinear circuit [4-9].

II. METHOD

One of the promising types of converters that are often used in AC electric drive systems are valve converters based on three-phase current inverters with different circuit configurations. The main advantage of such converters is their use for widespread and economic speed control of the most popular, cheap and reliable asynchronous motor with a squirrel-cage rotor. One of the most widely used in practice and which is successfully used to ensure reliable power supply.

The circuit of an asynchronous electric drive with adjustable frequency is a circuit of a three-phase autonomous current inverter with cut-off valves [2, 10], which is shown in Fig. 1, where T1 ÷ T6 are the main thyristors, D1 ÷ D6 – cut-off diodes.

The method for analyzing transient processes in converter circuits proposed in the article and used below is based on the rules of the piecewise linear approximation method and is described in the author's works [4, 6, 10].

Despite the method being somewhat cumbersome in terms of task preparation, it has serious advantages:

- does not require large machine resources;
- ensures analysis accuracy within the capabilities of the machine, independent of the time step, as is inherent in various digital models of electrical circuits;
- does not require the development of a special programming language, is based on the separation of the functions of a developer and a programmer, which corresponds to the current trend in organizing the work of computer centers;
- in the procedure for searching for moments of fulfillment of boundary conditions that determine the change of types along the path of development, the method allows the use of not only step-by-step analysis with clarification of the

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moments of type change, but also iterative methods for finding these moments by solving not systems, but individual transcendental equations.

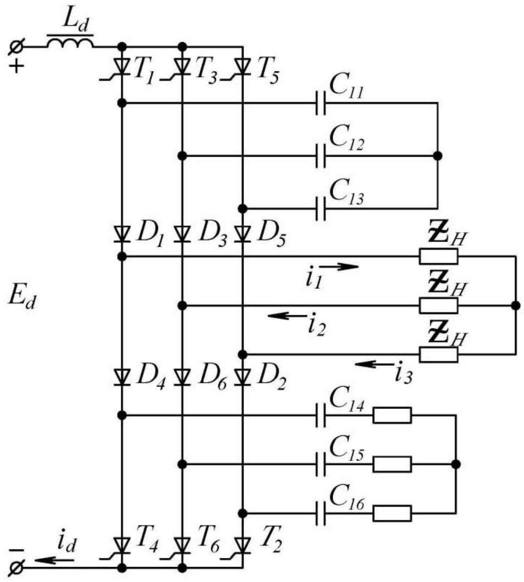

Fig 1: Current inverter with cut-off diodes

In three-phase converter circuits, due to topological symmetry in phases, the same equivalent circuit, as a type, turns out to be valid and can be used to analyze processes with the same combination of switched on valves having different numbers. Therefore, operator equivalent circuits are compiled for certain combinations of numbers of switched on valves and are used to calculate the process at the required stage for all phases, that is, all elements of the circuit. To facilitate the programming and calculation procedure, it is very convenient to use the correspondence matrix presented in Table 1.

Table 1

t / $t\,\varphi$ (t)	$0 \div \pi/3\omega$ T_1, T_2	$\pi/3\omega \div 2\pi/3\omega$ T_3, T_2	$2\pi/3\omega \div \pi$ T_3, T_4	$\pi \div 4\pi/3\omega$ T_5, T_4	$4\pi/3\omega \div 5\pi/3\omega$ T_5, T_6	$5\pi/3\omega \div 2\pi$ T_1, T_6
i_1 U_1 U_{21}	i_1 U_1 U_{21}	i_2 U_2 U_{22}	$-i_3$ $-U_3$ $-U_{23}$	$-i_1$ $-U_1$ $-U_{21}$	$-i_2$ $-U_2$ $-U_{22}$	i_3 U_3 U_{23}
i_2 U_2 U_{22}	$-i_2$ $-U_2$ $-U_{22}$	i_3 U_3 U_{23}	i_1 U_1 U_{21}	i_2 U_2 U_{22}	$-i_3$ $-U_3$ $-U_{23}$	$-i_1$ $-U_1$ $-U_{21}$
i_3 U_3 U_{23}	$-i_3$ $-U_3$ $-U_{23}$	$-i_1$ $-U_1$ $-U_{21}$	$-i_2$ $-U_2$ $-U_{22}$	i_3 U_3 U_{23}	i_1 U_1 U_{21}	i_2 U_2 U_{22}
U_{11} U_{14} U_{c1}	U_{11} U_{14} U_{c1}	$-U_{15}$ $-U_{12}$ $-U_{c2}$	$-U_{13}$ $-U_{16}$ $-U_{c3}$	$-U_{14}$ $-U_{11}$ $-U_{c1}$	U_{12} U_{15} U_{c2}	U_{16} U_{13} U_{c3}

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U_{12} U_{15} U_{c1}	U_{12} U_{15} U_{c2}	U_{16} U_{13} U_{c3}	U_{11} U_{14} U_{c1}	$-U_{15}$ $-U_{12}$ $-U_{c2}$	$-U_{13}$ $-U_{16}$ $-U_{c3}$	$-U_{14}$ $-U_{11}$ $-U_{c1}$
U_{13} U_{16} U_{c3}	$-U_{13}$ $-U_{16}$ $-U_{c3}$	$-U_{14}$ $-U_{11}$ $-U_{c1}$	U_{12} U_{15} U_{c2}	U_{16} U_{13} U_{c3}	U_{11} U_{14} U_{c1}	$-U_{15}$ $-U_{12}$ $-U_{c2}$

The same matrix can also be used in calculations of clock intervals containing a repeating sequence of types. It also uses the fact that during the clock interval, processes in different load phases can be described by the same relationships, taking into account permutations of notations and signs determined by the properties of the three-phase system.

In Table 1, the column φ (t) contains functions in the notation corresponding to the analysis of an operator substitution scheme of any type. The remaining six columns establish the correspondence of the functions of the first column with each other at six clock intervals of the operation of the three-phase ACI circuit.

The correspondence matrix is used when analysing transient processes of inverters, taking into account the following notations:

$i_1 \div i_3$, $U_1 \div U_3$ - load phase currents and voltages; $U_{11} \div U_{16}$ - voltage of parallel capacitors;
$U_{21} \div U_{23}$ - voltage of series capacitors;
$U_{c1} \div U_{c3}$ - voltages on capacitors in ACI with cut-off diodes.

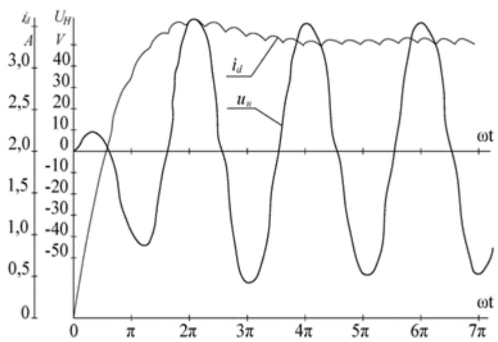
For all current inverters under consideration at t = 0, the currents in the inductances and the voltages on the plates of the commutating capacitors are assumed to be zero.

The transient process of starting an ACI with cut-off diodes according to a control system when operating on an active-inductive load is distinguished by the variety of equivalent circuits, the dependence of their type and order on the parameters of the smoothing choke, switching capacitors, load and frequency of the inverted voltage.

The calculation of the transient process of ACI with cut-off diodes is based on six types of equivalent circuits, various combinations of which represent the paths of development of the process at clock intervals. In this case, the following are accepted as boundary conditions for equivalent circuit transitions:

a) $i_1(\tau) = i_d(\tau)$; b) $i_2(\tau) = 0$; c) $u_1(0) + u_2(0) + u_{c2}(0) < U_{c1}$;
d) $u_2(\tau) + u_{c2}(\tau) = 0$; e) $i_1(0) = i_2(0)$.

Using the developed mathematical model, time diagrams for the launch of ACI with cut-off diodes were obtained. In Fig. 2, *a* shows the curves $i_d(\omega t)$, $u_H(\omega t)$ of ACI with cut-off diodes at $r_H = 10$ *Ohm*, $L_d = 0.1$ *H*, $L_H = 0.011$ *H*, $C = 40$ *μF* and $Ed = 100$ *V*. In Fig. 2, *b* shows oscillograms of $i_d(\omega t)$, $u_H(\omega t)$.



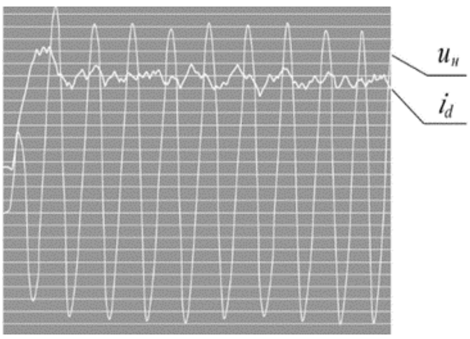


Fig. 3. Calculated (a) and experimental (b) curves of instantaneous values of currents and voltages of the transient process of ACI with cut-off diodes

III. CONCLUSION

It is shown that analysis of the development paths of the transient process in three-phase converters at all stages in clock intervals can be provided using the proposed special correspondence matrix.

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Due to the topological symmetry in phases in the circuits of three-phase converters, the same equivalent circuit turns out to be valid for several topologies of the power circuit and can be used to analyze processes with the same combination of switched on valves having different numbers.

The good agreement between the instantaneous values of currents and voltages of the transient process obtained in experiment and calculation confirms the correctness of the initial provisions of the method and the developed algorithms and models for calculating transient processes.

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