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APPLICATION OF SOFT STARTING AND BRAKING FOR ELECTRICAL DRIVES OF BOOM MECHANISM OF SHIPBOARD CRANES

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Abstract- When calculating the elements of ship crane mechanisms, a method is used, which is usually called the calculation of permissible stresses. The method is based on the determination of the safety factor, which is the ratio of the maximum value of material stresses, loads or deformations to the maximum design stresses, loads, deformations. The coefficient of safety margin should not exceed certain values inherent in the accepted materials or operating conditions of the elementsof mechanisms. A verification calculation is being performed. The current state of electrical drive, which changes the crane radius in shipboard crane, is analyzed in the paper. The necessity of application of squirrel-cage induction motor in the mentioned drive and choosing a modern control system for its control was shown. The analysis of different types of control systems built on the basis of semiconductors was carried out, and the control system chosen for its economic and technical advantages was presented.

Keywords: ship, crane, electrical drive, semiconductor, soft starter, frequency converter.

1. INTRODUCTION

Electrical drives of ship's hoisting mechanisms are prepared using specialized electrical machines and devices that meet the requirements of operation in ship conditions. On many crane ships, the power of the electric motor of the hoisting mechanisms is equal to or close to the power of one generator of the power plant. The basis of the requirements for electrical drives of hoisting winches and cranes is ensuring of high capacity [1].

The requirements for the electrical drives of the ship's hoisting mechanisms are determined by the Rules of the Maritime Registry, the standards and norms of the relevant departments. Fulfillment of all the formulated requirements was proposed, first of all, to ensure high capacity of mechanisms, more effective organization of cargo operations and their safe operation.

The general requirements for the technical operation of electrical equipment, including the automation system, determine the rules for the technical operation of the ship's electrical equipment. By following these rules and providing regular maintenance of electrical equipment, it is possible to ensure reliable and safe operation of electrical drives of hoisting mechanisms (and meeting modern requirements).

Ship's hoisting machines play a major role in the normal operation of a sea vessel. Ship's hoisting machine is a complex of means installed on a ship (on floating structure) and specified for carrying out loading operations, unloading and transporting operations, as well as for transporting people (ship's cargo derricks, ship cranes, hoists, ship elevators, lifting ship platforms, superstructures of crane ships).

Ship's hoisting mechanisms are divided into *hoisting-shipping* (cargo and rescue boat winches) and *shipping* (carrying out onboard operations, various types of conveyors, elevators, hoists, lifts, etc.) mechanisms.

Usually, boom ship cargo cranes have 3 mechanisms, and these mechanisms have separate electric drives:
- Electric drive of the hoisting mechanism;
- Electric drive of the turning mechanism;
- Electric drive of the boom mechanism.

The main difference between the electric drives of the ship's hoisting mechanisms and the drives of the cargo gears used on the shore is that they are fed from approximately the same powerful power plant. It should also be noted that overloads occur regularly in electrical drives during cargo operations on board in seaway conditions. For this reason, there is a need to find a way to solve complex issues such as the selection of appropriate electric motors and control systems for electric drives of hoisting machines, allowing for decreasing of peak loads occurring in dynamic modes.

2. DATA AND METHODS

In ship cranes the crane radius is the maximum distance between the center of gravity of the lifted load and the vertical axis of the swiwel pin. In the electrical drives of the mentioned mechanisms, DC motors or asynchronous motor, which is economical and reliable due to its simple design, are used [1].

The disadvantage of asynchronous motors is the presence of large values of impact electromagnetic torques and starting currents, which negatively affect the reliability and long-term operation of mechanical transmissions.

It should be taken into account that the cost of the power of the ship's hoisting mechanisms, including other large-power ship electrical drives, is close to the power of generators of the ship's power plant. The reason for this is the decrease in the quality of the energy produced by the ship's power plant as a result of the large shock currents that occur during the starting of the drives. This, in turn, has a negative impact on the activity of many ship operators and other responsible energy consumers. In electrical drives that do not require long-term operation at intermediate speeds due to technological reasons, the economic efficiency of the drive, the smoothness of the starting and braking processes, the limitation of impact moments and starting currents, the requirements for obtaining stable small speeds for accurate stopping, can be ensured by applying soft starting and braking devices [2].

By means of the control system, the value of the first harmonic of the supply voltage of the asynchronous motor at the output of the soft starter is changed at maintaining of constant frequency. With the application of a certain control algorithm, at the output of soft starters, as well as before the precise stop of electrical drive, it is possible to get a low-frequency voltage for the obtaining of a steady-state low speed. It is also possible to use a frequency converter to solve the mentioned problems, but it should be taken into account that the price of the frequency converter is 3-5 times higher than the price of the asynchronous motor. In turn, the price of currently series-produced thyristor soft starters is approximately two times lower than the price of the frequency converter of the same power. Therefore, according to the technical and economic indicators, the "frequency converter - asynchronous motor" system for the above conditions is considered out of competition, in addition to wasteful consumption. For this reason, the paper is devoted to the review of various soft starters for an asynchronous motor.

In the current electrical equipment market, there is a wide range of thyristor-based soft starters, mainly presented by foreign manufacturers: Siemens, Danfoss, ABB, Control Techniques, Allan Bradley, General Electric, etc. Due to the variety of control types, there are currently two methods of voltage control for soft starters: phase control (thyristor) and pulse (transistor). Let's compare these two control methods.

2.1. Phase Voltage Control of Asynchronous Motor

The power circuit of series-produced standard soft starters assembled on a thyristor (Figure 1a) consists of 3 pairs of thyristors connected in parallel and provides for adjustment of the value of the output voltage by changing the firing angle of the thyristors (Figure 1b). In the starting and braking modes of the asynchronous motor, the value of the supply voltage supplied to the stator is changed according to a certain law. For example, linear or exponential [2].

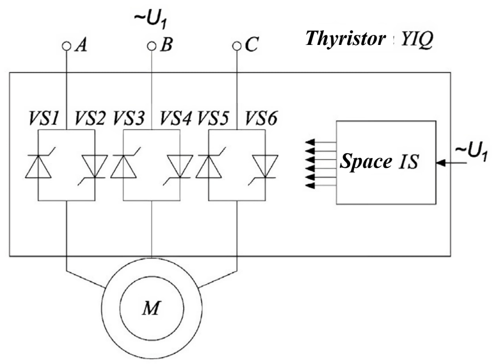
During the use of a special control algorithm, it is possible to realize quasi-frequency control to achieve the steady-state low speed before accurate stopping of the electric drive. Phase-controlled soft starters are characterized by a simple power scheme (in total six thyristors), lack of output chokes and capacitors, operational reliability, low power losses in the voltage regulator (there is a double conversion of energy in the frequency converter, while soft starters have a single conversion) and ease of installation. At the same time, phase-controlled thyristor soft starters have some shortcomings.

The occurrence of excess energy losses during the start-up of an asynchronous motor [2], the existence of an additional slip angle of the first harmonic of the current in voltage depending on the firing angle α of the thyristor; the disturbance of the harmonicity of the supply voltage curve (the formation of high voltage harmonics: 5-; 7-; 11-; 13th, etc. the occurrence of interference in communication and control circuits, static noise, vibrations and additional heating of electrical equipment.

In order to eliminate the main shortcomings of phase-controlled thyristor soft starters, it is proposed to apply voltage pulse regulators built on the basis of fully controlled power elements [3, 4].

2.2. Pulse Voltage Regulation of Asynchronous Motor

Pulse regulation of motor voltage (Figure 1d), fully controlled power elements, e.g. IGBT (Insulated-gate bipolar transistor) transistors are implemented by changing the voltage pulse width with a certain regularity at a certain switching frequency [3, 4].



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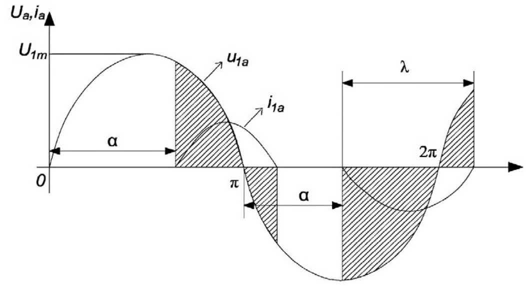

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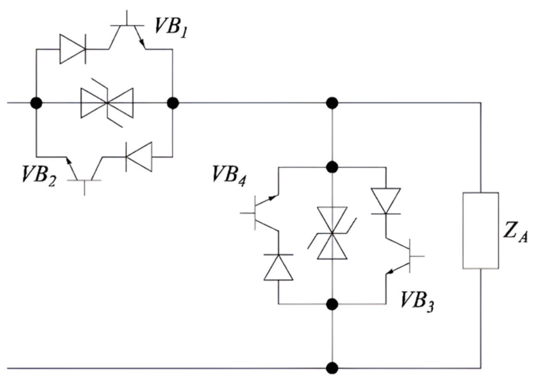

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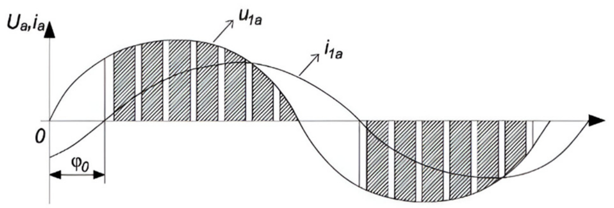


(d)

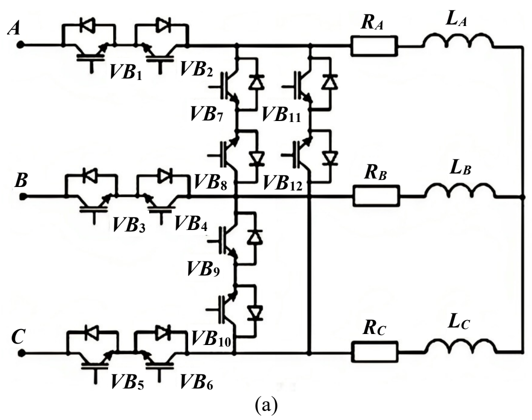
Figure 1. a) main circuit of three-phase soft starter with thyristor; b) output voltage and current during phase control; c) single-phase pulse voltage regulators; d) output voltage and current during pulse control

It is possible to obtain a more perfect harmonic composition of the output voltage curve in pulse voltage regulators by increasing the number of pulses in one- half period [3]. Also, as mentioned in [3], due to the application of pulse voltage regulation, a decrease in the cost of energy losses during the transient processes of an asynchronous motor is observed compared to phase regulation.

The power circuit diagram of single-phase voltage pulse regulators is shown in Figure 1c. More detailed explanation of the device's main circuit and working principle are given in [4].

Depending on the number of main power switches (for example, transistors VB1, VB2 in Figure 1c) and shunt switches of the stator windings of the asynchronous motor (transistors VB3, VB4), which are specified for the formation of the output voltage of the pulse voltage regulator, various options for the structure of the power part of the device are possible [5].

Options of main circuits of pulse voltage regulation considered by the author are shown in Figure 2a, 2b, 2c.



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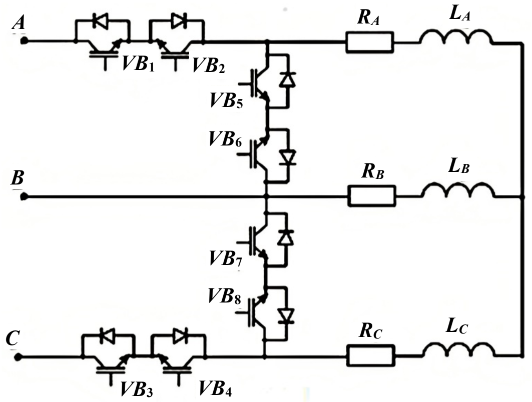

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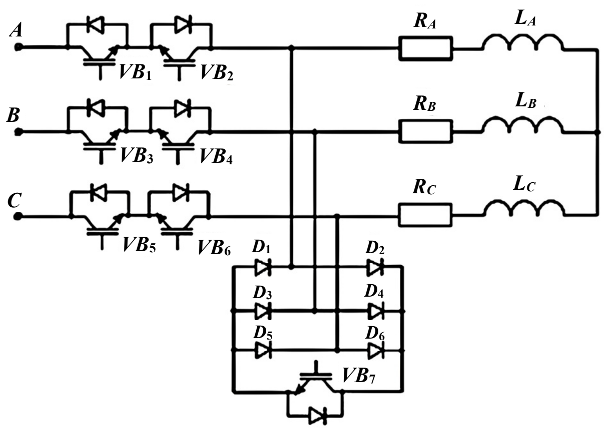


(c)

Figure 2. Scheme of the power circuit of three-phase voltage pulse regulation a) consisting of six power switches; b) consisting of four power switches; c) consisting of three power switches with diode bridge and unidirectional transistor

The model of the pulse voltage regulator is developed according to the scheme with three power switches, shunting diode bridge and unidirectional transistor (Figure 3).

Diagrams of phase voltages and currents at the output of the pulse voltage regulator are presented in Figures 4a and 4b, respectively.

The first main circuit (Figure 2a) is built on 6 switches, with three switches per phase and three shunt switches for each winding of the stator of the asynchronous motor (a total of 12 IGBT transistors). This circuit works on the following principle. When the main transistors VB1÷VB6 are connected, energy is exchanged between the load and the grid; If the VB1÷VB6 switches are open, the VB7÷VB12 transistors shunt the load phases so that a continuous current flow to be provided in the power circuit. Such a structure of the power circuit allows for obtaining completely symmetrical output voltages and currents relative to each other (Table 1), and is also characterized by the simplicity of the transistor control algorithm. However, compared to all considered options, it is considered the most economically unfavorable option due to the larger number of power switches of the circuit.

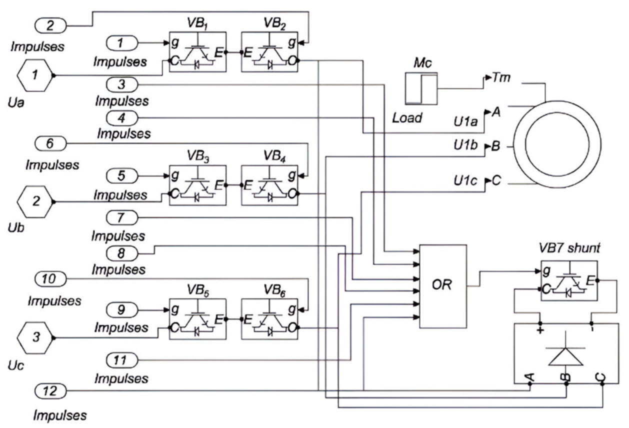
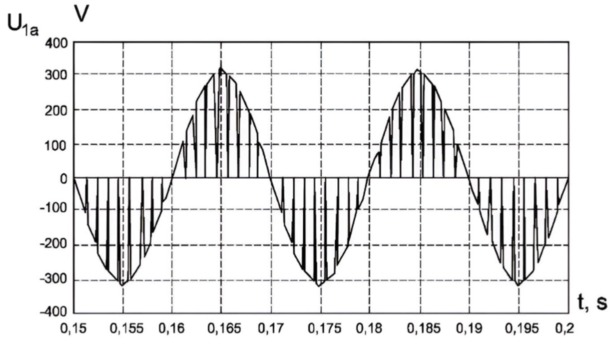


Figure 3. MatLab simulation model of pulse voltage regulator power circuit with three power switches

In the second option of the power circuit of pulse voltage regulation, a shunt switch is provided, which provides interphase shunting of 2 main and 2 stator windings of the asynchronous motor. The scheme of the power circuit of the pulse regulation of the given voltage consists of 4 main IGBT transistors, with 2 transistors VB1÷VB4 and shunt transistors VB5÷VB8 in both phases. Despite the asymmetric structure of this circuit, the asymmetry of the output voltages and currents caused by the absence of power semiconductors in the uncontrolled phase (Table 1), it is considered cost-effective compared to the 6-switch circuit. Another disadvantage is the presence of an uncontrolled phase in the circuit. As a result, the regulation of the braking time is not ensured and the braking time increases (Figure 5a, curve 1).

To eliminate this, it is necessary to separate that phase with a contactor or other separator (Figure 5a, curve 2).



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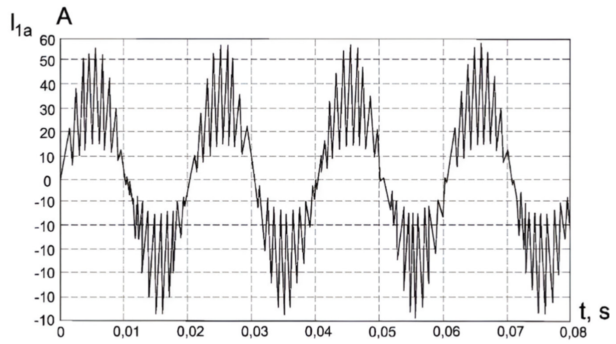
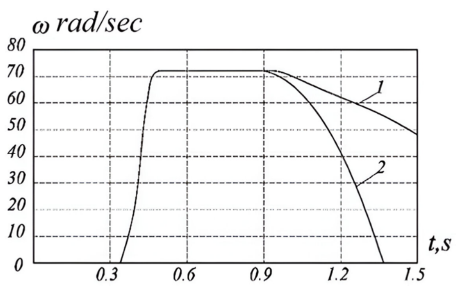


(b)

Figure 4. Time diagrams of the output voltage - (a) and current – (b) of the voltage pulse regulation consisting of three power switches

Time diagrams of rotation speed at different adjustment values of asynchronous electric drive, starting current limitation are shown in Figures 5a and 5b.



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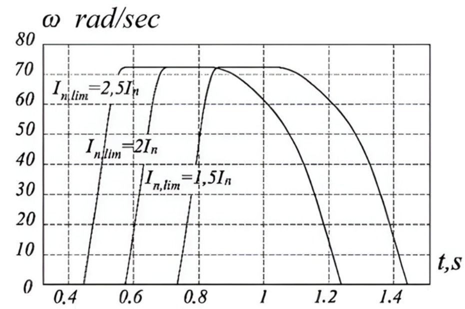

(b)

Figure 5. Time diagrams for pulse voltage adjustment of the boom mechanism of the asynchronous motor speed with a) four and b) three power switches

In the 3rd main circuit of pulse voltage regulation, three switches are provided, 1 power switch per phase. The circuit also includes a transistor diode bridge that provides interphase shunting of the stator windings of the asynchronous motor. Transistors VB1÷VB6 provide energy exchange between the load and the ship network. When one of the mentioned transistors is closed, the unidirectional transistor VB7 turns on, which shunts the corresponding windings of the asynchronous motor by means of diode bridge D1÷D6. The circuit has a symmetrical structure, providing almost completely symmetrical phase voltages and currents relative to each other (table 1), combining the advantages of the other two circuits. Considering the number of power switches in the circuit, this also seems to be cost effective.

Table 1. Asymmetry of phase currents and power losses of power circuits with different structures of pulse voltage regulation

	$I_{or.kv(R)}$, %	$I_{or.kv(S)}$, %	$I_{or.kv(T)}$, %	ΔA*, n.v.
With 4 switches	1.4	12.2	11	1.15
With 5 switches	1.68	5.7	4.1	1.06
With 6 switches	–	–	–	1
With diode bridge and 3 switches	0.13	0.11	0.17	1.02

The asymmetry of phase currents (in%) of main circuits of various structures, taking into account phase currents in a circuit consisting of 6 fully symmetrical switches is shown in Table 1.

As we know [2, 3], during the start-up of the asynchronous electric drive, the increase of energy losses is observed, however, the losses during smooth braking decrease, codering the start-up and braking at the rated voltage. A comparative analysis of losses during start-up and braking was carried out for the considered main circuits with different structures.

The study of the asynchronous motor of the 4MTKF160LB8 type crane electric drive (11 kVt, $380/220$ V, $IM\,40\%$, $k_j = 1.6$, $M_c = M_{nom}$, $t_0 = 0.4$ sec) has shown that the increase of energy losses in the stator windings during transient processes is directly proportional to the asymmetry of the phase currents. Also, due to greater asymmetry of the phase currents, higher losses are manifested in the scheme of pulse voltage regulation with 4 power switches. More comprehensive information about the comparison of main circuits with different structures is presented in [5].

Thus, based on the results of the conducted study, the circuit with 3 power switches, shunting diode bridge and transistor was chosen as the most cost-effective solution to the problem of the power part of the pulse voltage regulator. Compared to other schemes, the indicated scheme is characterized by a simpler control algorithm of power switches, the absence of asymmetry of phase currents and voltages, and a minimal level of losses in the asynchronous motor during transient processes.

The study of smooth start-up and braking of asynchronous electrical drive of the boom mechanism, at phase- and pulse voltage regulation was carried out in the MatLab environment by means of "Soft starter - asynchronous motor" type models developed by the authors. The model of the pulse voltage regulator is developed according to the scheme with three power switches, shunting diode bridge and unidirectional transistor (Figure 3).

4MTKF160LB8 type asynchronous motor (11 kVt, $380/220$V, $IM\,40\%$, $k_j = 1.6$, $M_c = M_{nom}$, $t_0 = 0.4$ sec) was applied for the simulation of all operating modes and different control methods. The control of phase rotor asynchronous motor at both pulse and phase control is studied for the first harmonic of the voltage.

3. CONCLUSIONS

In the electric drives of the boom mechanisms of the ship crane, which do not require the speed regulation, the smoothness of starting and stopping of the control motor, as well as the obtaining of stable small speeds for the purpose of accurate stopping of the drive can be ensured by the application of pulse voltage regulators. Compared to frequency converters with thyristors, the following advantages are obtained by applying pulse voltage regulators:
- energy losses in the transient processes of crane drive decrease;
- the harmonic content of the current and voltage of the electric motor improves;
- additional deviation of the first harmonic of current in voltage is prevented;
- electric drive stops the crane mechanism without additional travel;
- during commissioning, the negative effects on the power quality of the ship's power plant are reduced.

Pulse voltage regulators to be used in ship's electrical drives that do not require the rotation speed regulation are recommended to be manufactured according to a scheme with 3 power switches and shunt semiconductor bridge, which ensures the symmetry of phase currents and voltages and has superior economic indicators compared to other pulse voltage regulators.

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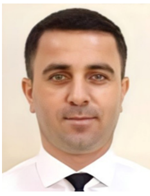

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