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CONTROLLING ELECTRICAL CIRCUIT OF ELECTRIC MOTOR ON IGBT TRANSISTORS

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Purpose. *Development and analysis of the operation of an electrical circuit for controlling a 700 W direct current electric motor using a contactor on IGBT transistors for operation in diesel locomotives.*

Methodology. *Analytical and computational methods for developing and analyzing the operation of an electrical circuit using a contactor on IGBT transistors.*

Findings. *An electrical circuit for controlling a 700 W DC motor using IGBT transistors was developed. The circuit allows you to replace electromagnetic contactors with IGBT transistors to improve the technical characteristics and performance of the electric motor. The use of IGBT transistors allows you to avoid burning of contact groups in comparison with an electromagnetic contactor. A graphical analysis of the transient processes during switching on and off of the electric motor using a circuit based on IGBT transistors was carried out. The analysis of the load characteristic of the electric motor at start-up shows that in the initial section the voltage increases according to a linear law. After the initial increase in voltage, it reaches the set value and the electric motor operates in the operating mode. The analysis of the load characteristics of the electric motor when it is turned off shows, that when the power is turned off, the motor can't stop immediately, as the phenomenon of self-induction occurs. When the external voltage is turned off, its change on the electric motor occurs according to the exponential law. It is shown that for controlling the operation of the electric motor, it is more appropriate to use an electric circuit based on IGBT transistors, which provides conditions for more stable and safe operation of the electric motor. Using the electrical circuit allows you to find quickly malfunctions for their further elimination. The electrical circuit allows you to avoid physical wear of its electrical elements.*

Originality. *An electrical circuit for controlling an electric motor based on modern electronic components has been developed, which allows the use of IGBT transistors instead of electromagnetic contactors. On the basis of the analytical and calculation method and graphical analysis, the expediency of using IGBT transistors instead of electromagnetic contactors has been proven.*

Practical value. *The developed electrical circuit can be applied to control a 700 W direct current electric motor for operation in diesel locomotives. The proposed electrical circuit allows to increase the mobility of repairs in the event of a malfunction by replacing the corresponding unit.*

Keywords: electric motor control circuit; contactors; IGBT transistors; DC electric motor.

I. I. INTRODUCTION

In modern engineering, different types of switching devices are used: electromagnetic and electronic. The electromagnetic contactor has positive aspects: low price, ease of installation and repair. But it has a number of disadvantages: burning of contacts, electric arc, weakening of the return spring, as a result of which the power contacts are de-energized with a delay, or at all remain under a high current, large weight and size of the contactor, no possibility of operation at high switching frequencies. Today, electronic switches are widely used. For example, modern electronic switches based on IGBT transistors do not have the disadvantages inherent in electromechanical contactors.

II. ANALYSIS OF RESEARCH AND PUBLICATIONS

Electromagnetic contactors are the most common types of switching devices used in modern electrical engineering. Many works describe the principle of operation, types and examples of application in various electrical installations [1] - [5]. Commutation of electric circuits by contacts in electromechanical devices is carried out by closing and opening them. One of the main disadvantages of electromechanical contactors is burning of contacts. In low-voltage devices with operating currents of more than 1000 A and in some types of medium and high-voltage devices (including those with lower operating currents), in addition to the main contacts designed to carry operating currents in the closed state, additional - arcing contacts (arcing) are used in the main circuits contact), on which

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an electric arc is established when the electric circuit is opened. The arc extinguishing contact is always electrically parallel to the main contact, and the design of the contact system is built in such a way that the arc extinguishing contact closes before and opens later than the main contact. In the vast majority of switching devices, their main contacts also perform the functions of arc extinguishing contacts [4].

Contact resistance is formed due to two reasons: 1) narrowing or tightening of current lines in the contact zone of contacting parts, and 2) the presence of oxide, sulfide, and other films in the contact zone. The effect of current line contraction on contact resistance is explained by the fact that due to the roughness of contact surfaces (even those that at first glance seem perfectly smooth), the real contact area is one to two orders of magnitude smaller than the imaginary contact area. The effect on the contact resistance of micron-thick films is explained by the fact that these films have a very high specific resistance, which is many orders of magnitude (up to 10^{15}) higher than the specific resistance of pure metals [4].

A new closed-loop sensorless method for reducing contact bounce on closure of a contactor has been proposed. Several approaches to the problem have already been described; most of them use some kind of sensor to establish the position and speed of the contacts in real time, whereas in our approach, the position and speed of the moving armature and contacts are calculated by using only the current and voltage values of the contactor coil as control inputs. A fuzzy controller takes as input the position and velocity of the armature and provides as output an intensity set point that controls the velocity of the closure of the contacts. Inexpensive electronic modules have been developed that implement the control system and integrate it into the contactor. The module eliminates the bounces completely and thus prevents the contacts from repeatedly making and breaking the circuit [6].

The authors of the article [7] gave a numerical assessment of the effect of pressing the contactor contacts in the power circuits of electric rolling stock on their plastic deformation and melting using the proposed engineering method.

Article [8] is devoted to experimental studies and numerical modeling of pulsed heating of high-current electrical contacts in a wide temperature range - up to the melting temperature. It is established that electrode welding begins when the temperature is significantly lower than the melting temperature. Features of the processes of softening and melting of the contact zone are described.

In the article [9], a mathematical model of a high-speed drive based on an IDM and a bistable mechanism was developed, which includes the equation of the electromagnetic field of an electric circuit and the equation of motion. The model correctly describes physical processes and can be used to develop and study the design of high-speed wires. On the basis of variable calculations, it is possible to solve the problems of finding the necessary parameters of the drive with the aim of obtaining: a) a small value of the closing time of the contacts and avoiding "rattles" when switched on; b) high initial speed and overall low value of contact opening time (less than 1 ms), reduce dynamic loads and drive elements and contact system.

The article [10] discusses the method of determining the surface temperature of high-current breaking contacts operating with arcless alternating current commutation. The determination of the temperature was based on the numerical solution of the limiting inverse problem of thermal conductivity. Calculations of the temperature of the contact surfaces as a function of time have been obtained. The calculation was performed using the MathCAD application program package. The obtained temperature values using this technique are more accurate than when using the existing ones.

The article [11] presents the results of studies of electrothermal processes in the contacts of switching devices. The cause-and-effect factors of failure of switching devices of transformer equipment are analyzed. Methods of probabilistic analysis and experimental studies of contact resistance depending on non-sinusoidal current and the number of commutations are proposed.

Solving the problem of contacts, which are characteristic of electromagnetic contactors, is achieved by using electronic contactors using IGBT transistors. The IGBT transistor is a three-electrode power semiconductor device that combines two transistors in one semiconductor structure: bipolar (forming a power channel) and field (forming a control channel). This device has absorbed the positive properties of a bipolar transistor (high voltage between the collector and the emitter) and a field transistor (control is by means of an electric field, not by current as in a bipolar transistor) [12] - [16].

The development and improvement of circuitry using IGBT transistors is important. The authors of the article [17] proposed an improved hybrid direct current contactor, in which the introduction of new structural elements and connections allows for arc-free switching of the circuit when the device is turned on and off; allows you to use it in reversible switching schemes, to ensure the absence of a zone of possible switching with an arc, to ensure low dimensions, weight and cost of the contactor, to increase the reliability of its operation.

The IGBT transistor has a number of positive properties: light weight, not large size, power, high switching frequency, lack of physical wear, longer shelf life. Disadvantages include: price, a more complicated installation and debugging process, passive cooling is required for heat removal, power is lost at high switching frequencies (approximately 20-50 kHz) [18].

Analysis of research and publications devoted to various types of electric and electronic contactors allows us to consider the development and improvement of control schemes using IGBT transistors as relevant.

III. FORMULATION OF THE WORK PURPOSE

The purpose of this work is to develop and analyze the operation of a circuit for controlling a 700 W direct current electric motor using a contactor on IGBT transistors for operation in diesel locomotives.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

The use of electromagnetic contactors in electric motor control circuits has the following features. When the control voltage is applied to the contactor coil (electromagnet), it immediately enters the saturation state and attracts the armature to the core, which in turn closes the contacts, and an electric current begins to flow in the electric power circuit. But it should be noted that when the voltage is turned off, the magnetic field of the coil changes slowly, an EMF of self-induction occurs, under the influence of which the current will decrease slowly. Due to this, the time of switching off the contacts increases, or in general the armature can be kept in the closed position, and this can lead to the failure of the equipment, or even cause a fire.

To prevent the negative consequences that arise when using electromagnetic contactors, we have developed a basic electrical circuit for controlling an electric motor using IGBT transistors (Fig. 1). Such an electrical circuit can be used to control the operation of a direct current electric motor, namely, turning on or off a 700 W electric motor when working in a TEM-2 diesel locomotive.

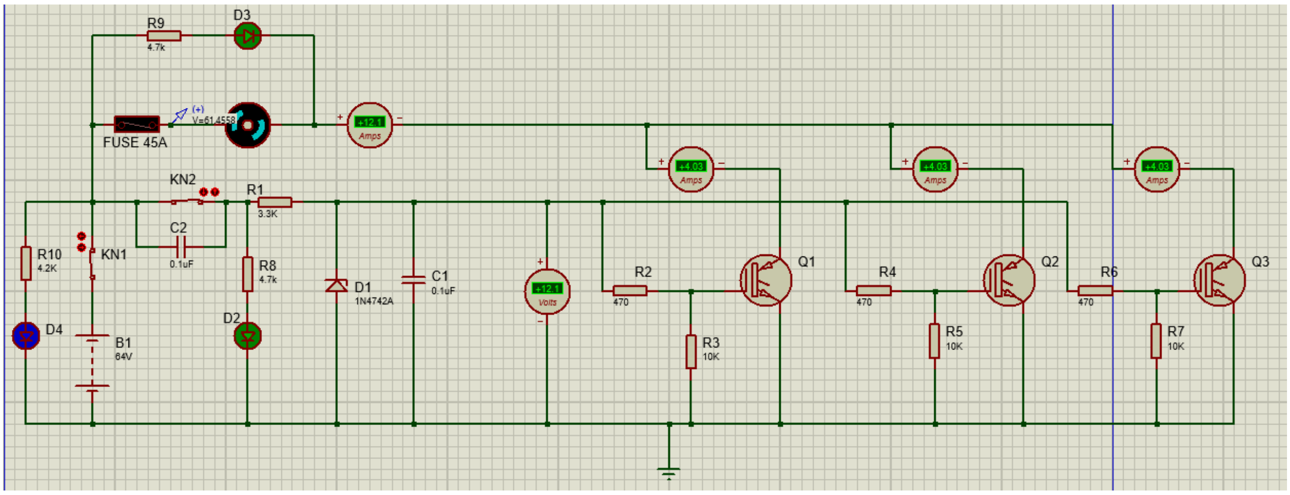

Figure 1. The basic electrical circuit for controlling a 700 W direct current electric motor using a contactor on IGBT transistors for operation in a TEM-2 diesel locomotive

The principle of operation of the electrical circuit is as follows. When the KN1 button is closed, the power indicator D4 lights up (blue color), which signals the operation of the battery. To turn on the electric motor, you need to close the KN2 button, the D2 indicator lights up (green color), which signals that the voltage is supplied to the parametric voltage stabilizer D1 through the resistor R1, which sets the stable operation of the Zener diode. The stabilization current is I = 0.02 A. After the Zener diode, we get a constant stabilized voltage of 12 V. The control voltage of 12 V is supplied through resistors R2, R4, R6 to the gates of the IGBT transistors, which are connected in parallel to distribute evenly the load between them. The transistors enter the saturation state and open, as a result of which the electric circuit of the motor is closed to minus (Ground) and an electric current begins to flow in the power electric circuit.

It can be seen from the diagram that the electric motor is supplied with a voltage of 60 V, a current of 12 A, that is, the total power of the electric motor will be equal to

$$P = 60 \text{ V} \cdot 12 \text{ A} = 700 \text{ W}.$$

The load is evenly distributed on the IGBT transistors, as an electric current of 4 A flows through each IGBT transistor. Let's determine how much power each of them can withstand. As you know, the FGA25N120ANTD IGBT transistor dissipates 312 W of power. Since the power of one IGBT transistor is equal to:

$$P_{IGBT} = 700/3 = 233 \text{ W},$$

then there is a power reserve. But you should not forget about the cooling system of IGBT transistors, as it will ensure the prevention of possible emergency situations.

In the basic electrical circuit for controlling the electric motor, the D3 indicator is installed parallel to the motor. This is done for safety purposes: if the KN2 button is open (there is no control voltage on the gates of the IGBT transistors), and the engine continues to work, it means that there is a short circuit to the ground (Ground), or the transistors have failed, or for some reason, the transistor does not enter the cutoff (opening) state.

Figure 2 shows graphs of the dependence of the voltage change on the IGBT transistors on the time during switching on and off.

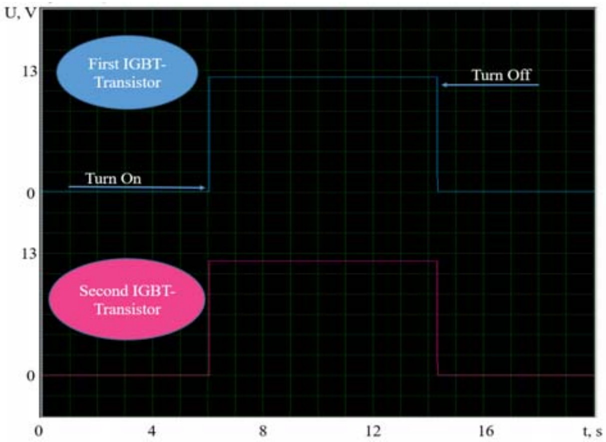

Figure 2. Graphs of the dependence of the voltage change on IGBT transistors on time during switching on and off.

The use of IGBT transistors in comparison with electromagnetic contactors shows a completely different result: switching on occurs almost instantly, and the voltage acquires the required value, that is, the IGBT transistor opens. This type of voltage change does not affect the operation of the equipment. When turned off, the IGBT transistor is completely closed, but no electric current flows through it. In this way, a safer mode of operation of the load is achieved.

Figure 3 shows the graph of the dependence of the voltage change on the electric motor when it is turned on.

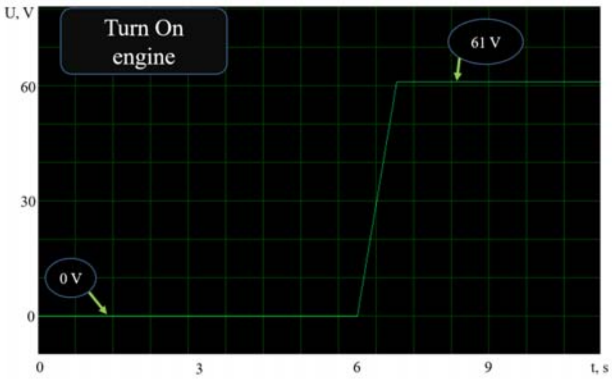

Figure 3. The graph of the dependence of voltage change on time for the electric motor when it is turned on.

The analysis of the load characteristics of the electric motor when it is turned on (Fig. 3) shows that in the initial section the voltage increases according to a linear law:

$$U = kt,$$

where k – the coefficient of proportionality, t – time.

After the initial increase in voltage, it reaches the set value and the electric motor operates in the operating mode.

Figure 4 shows the graph of the voltage change versus time on the electric motor when it is turned off.

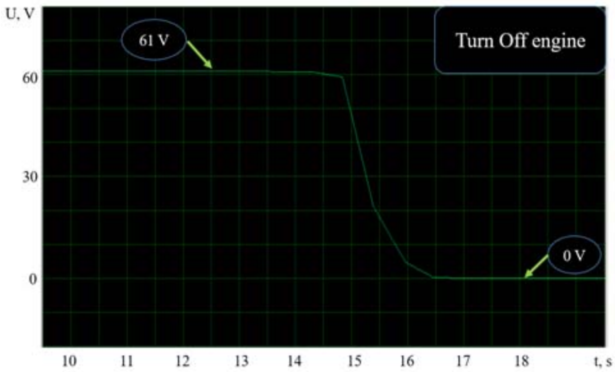

Figure 4. The graph of the dependence of voltage change on time for the electric motor when it is turned off.

Analysis of the load characteristic of the electric motor when it is turned off (Fig. 4) shows that when the power is turned off, the motor can't stop immediately; as the phenomenon of self-induction occurs (it becomes a generator). At the same time, self-induction voltage occurs, which falls on the collector of the transistor and can cause damage to it. But modern field-effect transistors have a diode in their structure that protects against such dangerous situations.

When the external voltage is turned off, its change on the electric motor occurs according to the exponential law:

$$U = U_0 e^{-\frac{t}{\tau}},$$

where U_0 – the saturation voltage, τ – the relaxation time.

The relaxation time characterizes the rate of change of the current in the circuit and, accordingly, the voltage on the electric motor and is determined by the value of the inductance and active resistance of the electric circuit:

$$\tau = L / R,$$

where L – circuit inductance, R – active circuit resistance.

This nature of the voltage change on the electric motor is explained by the fact that when the external voltage is turned off, the current through the inductance coil of the electromagnetic contactor decreases, which leads to the emergence of an EMF of self-induction, which will prevent the current from decreasing according to Lenz's rule.

Analysis of the graph of the voltage change versus time on the electric motor when it is turned off, shown in Figure 4, shows that when the external voltage on the IGBT transistor is turned off, its value decreases to zero almost instantly. That is, there are no transient processes that occur on the electromagnetic contactor. Thus, the use of an IGBT transistor to control the operation of an electric motor can't lead to equipment failure and is safer.

V. CONCLUSIONS

1. An electrical circuit for controlling a 700 W DC motor using IGBT transistors was developed.

2. A graphical analysis of the transient processes during switching on and off of the electric motor using a circuit based on IGBT transistors was carried out.

3. The analysis of the load characteristic of the electric motor at start-up shows that in the initial section the voltage increases according to a linear law.

4. The analysis of the load characteristics of the electric motor when it is turned off shows that when the power is turned off, the motor can't stop immediately, as the phenomenon of self-induction occurs. When the external voltage is turned off, its change on the electric motor takes place according to the exponential law.

5. It is shown that for controlling the operation of the electric motor, it is more appropriate to use an electrical circuit based on IGBT transistors, which provides conditions for more stable and safe operation of the electric motor.

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ЕЛЕКТРИЧНА СХЕМА УПРАВЛІННЯ ЕЛЕКТРОДВИГУНОМ НА IGBT-ТРАНЗИСТОРАХ

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Мета роботи. *Розробка і аналіз роботи електричної схеми для керування електродвигуном постійного струму на 700 Вт із застосуванням контактора на IGBT-транзисторах для роботи у тепловозах.*

Методи дослідження. *Аналітико-розрахункові методи для розробки і аналізу роботи електричної схеми із застосуванням контактора на IGBT-транзисторах.*

Отримані результати. *Розроблена електрична схема керування електродвигуна постійного струму на 700 Вт із застосуванням IGBT-транзисторів. Схема дозволяє замінити електромагнітні контактори на IGBT-транзистори для покращення технічних характеристик та продуктивності роботи електродвигуна. Застосування IGBT-транзисторів дозволяє уникнути підгоряння контактних груп в порівнянні з електромагнітним контактором. Проведено графічний аналіз перехідних процесів при вмиканні і вимиканні електродвигуна із застосуванням схеми на IGBT-транзисторах. Аналіз навантажувальної характеристики електродвигуна при вмиканні показує, що на початковій ділянці зростання напруги відбувається за лінійним законом. Після початкового зростання напруги відбувається вихід його на задане значення і робота електродвигуна проходить у робочому режимі. Аналіз навантажувальної характеристики електродвигуна при вимиканні показує, що при відключенні живлення, двигун одразу зупиниться не може, так як має місце явище самоіндукції. При вимиканні зовнішньої напруги її зміна на електродвигуні відбувається за експоненціальним законом. Показано, що для керування роботою електродвигуна більш доцільно використання електричної схеми на IGBT-транзисторах, що забезпечує умови більш стабільної та безпечної роботи електродвигуна. Застосування електричної схеми дозволяє швидко знайти несправності для подальшого їх усунення. Електрична схема дозволяє уникнути фізичного зносу її електричних елементів.*

Наукова новизна. *Розроблена електрична схема для керування електродвигуном на сучасних електронних компонентах, яка дозволяє застосувати IGBT-транзистори замість електромагнітних контакторів. На підставі аналітико-розрахункового методу і графічного аналізу доведено доцільність використання IGBT-транзисторів замість електромагнітних контакторів.*

Практична цінність. *Розроблена електрична схема може бути застосована для керування електродвигуном постійного струму на 700 Вт для роботи в тепловозах. Запропонована електрична схема дозволяє збільшити мобільність ремонту в разі несправності шляхом заміни відповідного блоку.*

Ключові слова: ***електрична схема керування електродвигуном; контактори; IGBT-транзистори; електродвигун постійного струму.***