Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 25 (2023), Issue 1

journal homepage: http://www.ein.org.pl

Article citation info:
Kenessova P, Kaverin V, Tatkeyeva G. Variable-speed drive with series-excited motors in dynamic braking mode. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2023: 25(1) http://doi.org/10.17531/ein.2023.1.9

Variable-speed drive with series-excited motors in dynamic braking mode

Indexed by: Web of Science Group

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Highlights

- The research problem was to consider determine the dynamic characteristics of a variable direct current drive.
- In this study was developed two models of an electric motor with subsequent excitation.
- There has been proposed technical implementation of the power section of a variable-speed electric drive.
- The article has not only theoretical, but also visual and practical significance.

Abstract

Variable-speed DC drives with series-excited motors are widely used in the mining industry, transport and lifting equipment. The purpose of the study is to determine the dynamic characteristics of a variable direct current (DC) drive with a series-excited motor in the dynamic braking mode. In the article, there have been developed schematic diagrams of the power section that ensure stable braking of a variable-speed electric drive with a series-excited motor. The requirements for the braking mode have been developed. The studies have been carried out for a saturated and unsaturated magnetic circuit of an electric motor. The scientific novelty of the work consists in determining the zone of stable operation of the dynamic braking mode. As a result, there has been proposed technical implementation of the power section of a variable-speed electric drive with a series-excited motor that ensures stable braking. A special place in the study is the development of two models of an electric motor with subsequent excitation taking into account the saturation of the magnetic circuit - mathematical and simulation. Thus, the article has not only theoretical but also visual and practical significance in the context of already conducted studies on the subject. Options for the technical implementation of the braking regime were also considered in the course of the sequential implementation of the planned stages of the study.

Keywords

electric motor; power section; direct current drive; alternating current drive; circuit design.

1. Introduction

Variable-speed DC drives with series-excited motors are widely used in the mining industry, transport and lifting equipment. The works of many scientists such as C. Asok and M.U. Deepa [4], J. Nevrl et al. [27], F.Y. Grepe [15] are dealing with the issues of technical solutions of dynamic braking modes for a DC electric drive with a series-excited motor. The authors consider the issues of technical implementation of dynamic braking modes for an unregulated electric drive. At present, variable-speed electric drives are produced by well-known world manufacturers such as Siemens, Danfoss, Mitsubishi Electric, Schneider Electric Companies, etc. [Okojie]. At the same time, the analysis shows that the generator modes of a variable-speed electric drive, the need for which is caused by the requirements of safety standards and increasing reliability, have been insufficiently studied [Menon].

Serious problems that prevent developing control systems for a variable-speed DC electric drive with series-excited motors in the dynamic braking mode, taking into account the requirements of its safe operation, are as follows: the possibilities of realizing dynamic braking modes in a wide range of speeds have not been studied; there have not been taken into account the dynamic features of the series-excited motor associated with nonlinear links and variable parameters; the design features of electric motors have not fully been taken into

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account; mathematical and simulation models that adequately describe the physical processes occurring in a variable-speed electric drive in a controlled dynamic braking mode have not been developed; there are no technical solutions for the power section of the electric drive that provide stable braking [7, 46]. This work is aimed at solving the problems mentioned.

Analysis of existing technical solutions and theoretical studies of the braking modes of a DC electric drive with a series-excitation motor was conducted as well [16]. There are formulated problems that prevent the development of control systems for a variable-speed DC electric drive with series-excited motors in the dynamic braking mode. The article includes an analysis of the requirements of safety standards for braking modes of industrial machines and mechanisms. There are considered variants of technical implementation of braking modes. The analysis of the methods of theoretical research of the controlled electric drive in the dynamic braking mode is carried out. Also, there is information about an equivalent circuit of an electric drive with pulse converters that provides control in the motor mode and the dynamic braking mode. A mathematical model has been developed for a series-excited n electric motor, taking into account the magnetic circuit saturation. A simulation model of an electric drive has been developed. Technical characteristics of the electric motor have been determined. Taking into account the results of simulation experiments, technical implementation of an adjustable electric drive has been developed, which provides stable controlled braking. The purpose of the study is to determine the dynamic characteristics of a variable direct current (DC) drive with a series-excited motor in the dynamic braking mode.

2. Review and analysis of the existing technical solutions to dynamic braking modes

The semiconductor of alternating current (AC) and DC electric drives are widely used in the mining industry, in transport and lifting equipment, and the motor modes of their operation have been comprehensively studied [1, 18, 30, 36-37]. Industrial safety regulations require braking distances during emergency braking [44]. For in-plant electric transport including electric cars, electric forklifts and electric tractors, the requirements for limiting the braking distance depending on the speed of movement have been established in the range of 1-2 m [12-14]. For the feed mechanism of the shearer, the safety requirements regulate the braking distance that should not exceed 0.4 m [45]. Requirements for the provision of the braking torque with the braking safety factor of at least 1.5 in the mechanisms for lifting the load, which ensures reducing the braking distance, are imposed on lifting mechanisms [43]. For generator operating modes of electric drives with separately excited motors, a large amount of research has been carried out, and various developments have been made including analyzing the operation in normal modes, as well as in case of failures [5, 8, 9, 17, 20, 42]. As generator modes of semiconductor direct current electric drives with series-excited motors have not been sufficiently studied [33, 35, 54]. The best-known technical solutions are those for uncontrolled dynamic braking systems for traction electric drives of direct current [32; 34]. The disadvantages of these methods consist of the fact that they can only be implemented in a limited range of motor speed that is close to the nominal value [40; 41]. This is unacceptable for variable-speed drives of machines with an operating range of speed variation in the motor mode of more than 1:5 [21].

At the same time, series-excited electric motors are widely used in the mining industry as electric drives for contact electric locomotives, in railway, city and factory transport, and in lifting equipment [26, 31, 47, 50, 51]. There are developments in the use of such electric drives in coal shearers and conveyors [11, 19, 22-25, 29]. The known methods for implementing dynamic braking modes consisting in connecting braking resistors to limit the armature current [2] are ineffective for machines with an operating speed range in motor modes of more than 1:5. Studies of pulse control of the series-excited DC motor in the dynamic braking mode are of great interest [3, 10].

The analysis of the requirements for the braking modes of the adjustable electric drive of mining machines and mechanisms shows that to ensure the safety of their operation, it is necessary to equip the braking mode. This provides effective braking both in technological mode and in the presence of electricity in the power supply system of the electric drive, as well as in emergency mode with its automatic shutdown [48, 29, 53]. For structural and parametric optimization of the ACS (Automatic Control System) of an electric drive in the controlled braking mode, it is necessary to analyze the physical processes occurring in it. The principle of dynamic braking is used as the basis for the implementation of controlled braking.

An important stage in the process of theoretical research of an electric drive is the development of equivalent circuits for its power unit. The principle of operation of a variable-speed electric drive in the dynamic braking mode is to control the transfer of energy stored in the flywheel masses of the mechanical part of the electric drive into thermal energy. In connection with the above, the automatic control system should provide: emergency braking mode, taking into account the limitation of the parameters of the electric drive; stabilizing the braking torque at the level of the maximum permissible value; control of the output coordinates of the electric drive in the working area limited by the nominal parameters of the electric drive [6].

Dynamic braking control depending on the mode is carried out in two ways. The first way, in the emergency braking mode, the energy stored in the mechanical section of the electric drive is spent for heating the active resistances of the power section of the electric motor, while control is realized by using the energy stored in the elements of the power section of the electric drive. The second way, in the technological mode, mechanical energy is converted into thermal energy in the current-limiting resistor of the power circuit of the electric motor, and dynamic braking is controlled utilizing a controlled converter in the power electric circuit of the electric motor.

One of the issues that need to be addressed when switching from the motor mode to the emergency braking mode in the event of an unauthorized power outage is the electric drive activation. The method of activating the electric drive consists of the sequential use of electromagnetic energy. This energy is stored in the reactive elements of the power part of the electric drive, for powering the information part and excitation with subsequent switching to the source, which is formed by the electric motor, during regenerative braking. To study the static and dynamic characteristics of a controlled electric drive in the dynamic braking mode, and to determine the requirements for the power section of an electric drive, it is necessary to develop mathematical and simulation models.

3. Developing models of an electric drive with a series excited motor

In the works S.N. Veshenevsky [52], D.M. Smith [49] for an electric drive with a series-excited motor it is proposed to implement the requirements of safety standards and standards governing the requirements for regenerative braking using the dynamic braking mode with self-excitation. The basis of the circuit design of the power unit of a two-quadrant electric drive in a variable-speed electric drive with a series-excited motor is proposed to use a variant based on bypassing the armature circuit with a series-excited winding by a pulse converter. The equivalent circuit of the electric drive in the controlled braking mode is shown in Figure 1.

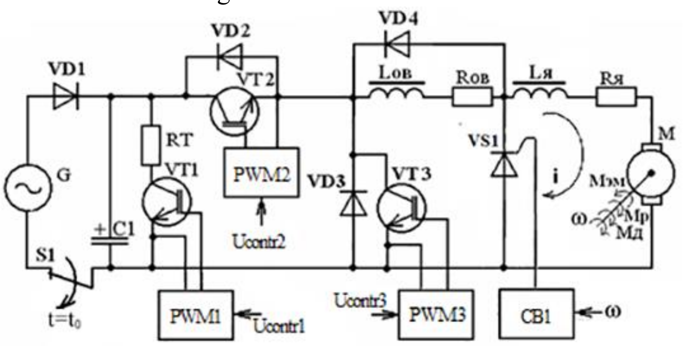

Figure 1. The equivalent circuit of the electric drive in the controlled braking mode with self-excitation.

In the technological mode, the electric drive receives energy from a three-phase transformer substation with subsequent voltage rectification by a three-phase full-wave uncontrolled rectifier. Since at each moment the load is connected between the phases of the substation, in the equivalent circuit it is represented by a single-phase source G with the effective value of the line voltage. Since at each moment, in a three-phase rectifier assembled in a bridge circuit, the current flows through two diodes connected in series, the rectifier is represented by a VD1 diode in the equivalent circuit. To reduce the ripple amplitude and compensate for the reactive component of the transformer substation, a capacitive C1 filter is installed at the rectifier output.

The electric drive is controlled in the motor mode utilizing the VD2-VT2-PWM2 pulse converter. The dynamic braking mode is controlled by two pulse converters. A circuit consisting of a VT1-PWM1 converter and a current-limiting resistor RT limits the voltage across the C1 capacitor, and through the VD3-VT3-PWM3 converter, the dynamic braking mode is controlled. Energy generated by the electric drive in the generator mode is consumed for heating the braking RT resistor. A feature of this circuit design is the use of inductive components of the armature and the excitation winding in the power circuit to control the dynamic braking mode.

In the time interval of the closed state of the VT3 key, electromagnetic energy is accumulated in the inductive components of the motor circuit. At this time, the VD2 diode and the transistor, the pulse converter VT2 of the motor mode are closed. After closing the VT3 transistor, and shunting the motor circuit, the EMF (Electromagnetic force) of self-induction of the inductive components is added to the EMF of the motor armature and opening the VD2 diode charges the capacitor of the capacitive C1 filter. The active resistance of the power circuit of the series-excited electric motor is so small that when the EMF of the armature decreases tenfold, it will provide a current of the nominal value over the time interval of the closed state of the VT3 transistor. Since the EMF of self-induction of the inductive components of the motor in amplitude, in the interval of the open state of the VT3 transistor is several orders of magnitude higher than the EMF of the armature of the electric motor, this will allow realizing a wide range of regulation of the armature circuit of the electric motor current at low values of speed.

The processes occurring in the electric motor in the generator mode are described by the following system of differential equations in relative units [52]:

$$E_a^* = i^* r_a (1 + \mathrm{T}_e r), \qquad (1)$$

where E_a is an electromagnetic force of the armature of the electric motor; T_e is an oscillation period in the electric motor, r_a is a radius of the armature.

$$\Phi^* = \begin{cases} i^* (\text{for unsaturated magnetic circuit}) \\ 1 (\text{for saturated magnetic circuit}) \end{cases}, \qquad (2)$$

$$E_a^* = \Phi^* \cdot \omega^*, \qquad (3)$$

$$\mathrm{M}_{ЭД}^* = \Phi^* \cdot i^*, \mathrm{T_M p}\omega^* = \mathrm{M}_\mathrm{P}^* - \mathrm{M}_{ЭД}^*, \qquad (4)$$

where: $\mathrm{M}_{ЭД}^* = \Phi^* \cdot i^*$; $\mathrm{M}_\mathrm{P}^* = \frac{\mathrm{M_P}}{\mathrm{M_H}}$; $i^* = \frac{i}{i_\mathrm{H}}$; $E_a^* = \frac{E_a}{E_\mathrm{H}}$; $E_a = \mathrm{C}\Phi_\mathrm{H}\omega_\mathrm{H}$; $\omega^* = \frac{\omega}{\omega_\mathrm{H}}$; $\Phi^* = \frac{\Phi}{\Phi_\mathrm{H}}$; $T_\mathrm{M} = J\frac{\mathrm{M_H}}{\omega_\mathrm{H}}$; $M_{эм}$ is the electromagnetic moment developed by the electric motor; M_p is the moment from the load side, unwinding the shaft of the electric motor; i is the current of the electric motor; Φ is the magnetic flux; ω is the angular speed of the engine; C is the constructive constant of the electric motor; J is the moment of inertia of the electric motor; $i_н$, $Φ_н$, $ω_н$, $M_н$ are the nominal parameters of the electric motor, current, magnetic flux, angular frequency of rotation of the armature and electromagnetic moment, respectively.

To determine the dynamic characteristics of the electric drive in the controlled dynamic braking mode, based on the mathematical model (equations 1-4), a simulation model has been developed using the MATLAB (Matrix Laboratory) application package, taking into account the equivalent circuit (Figure 1) that is shown in Figure 2. Theoretical studies with the use of simulating static and dynamic characteristics have been carried out using the example of a series-excited electric motor of the DP-62 type, the technical characteristics of which are presented in Table 1.

The study of the stability of the power section of an electric drive with a series-excited motor in the dynamic braking mode has been carried out using the equivalent circuit shown in Figure 1 and the simulation model shown in Figure 2. Simulation experiments have been carried out using the example of an electric motor of the DP-62 type, the technical characteristics of which are presented in Table 1. The simulation results are shown in Figure 3.

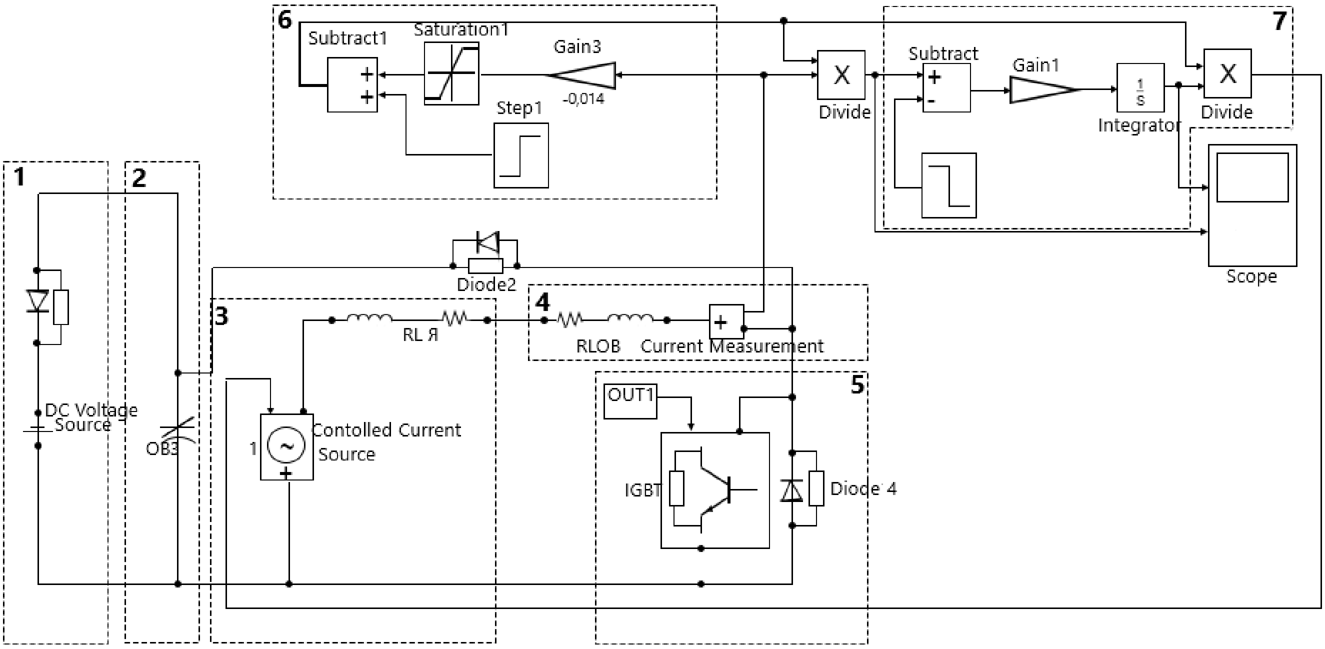

Figure 2. Imitation model of the electric drive in the dynamic braking mode.

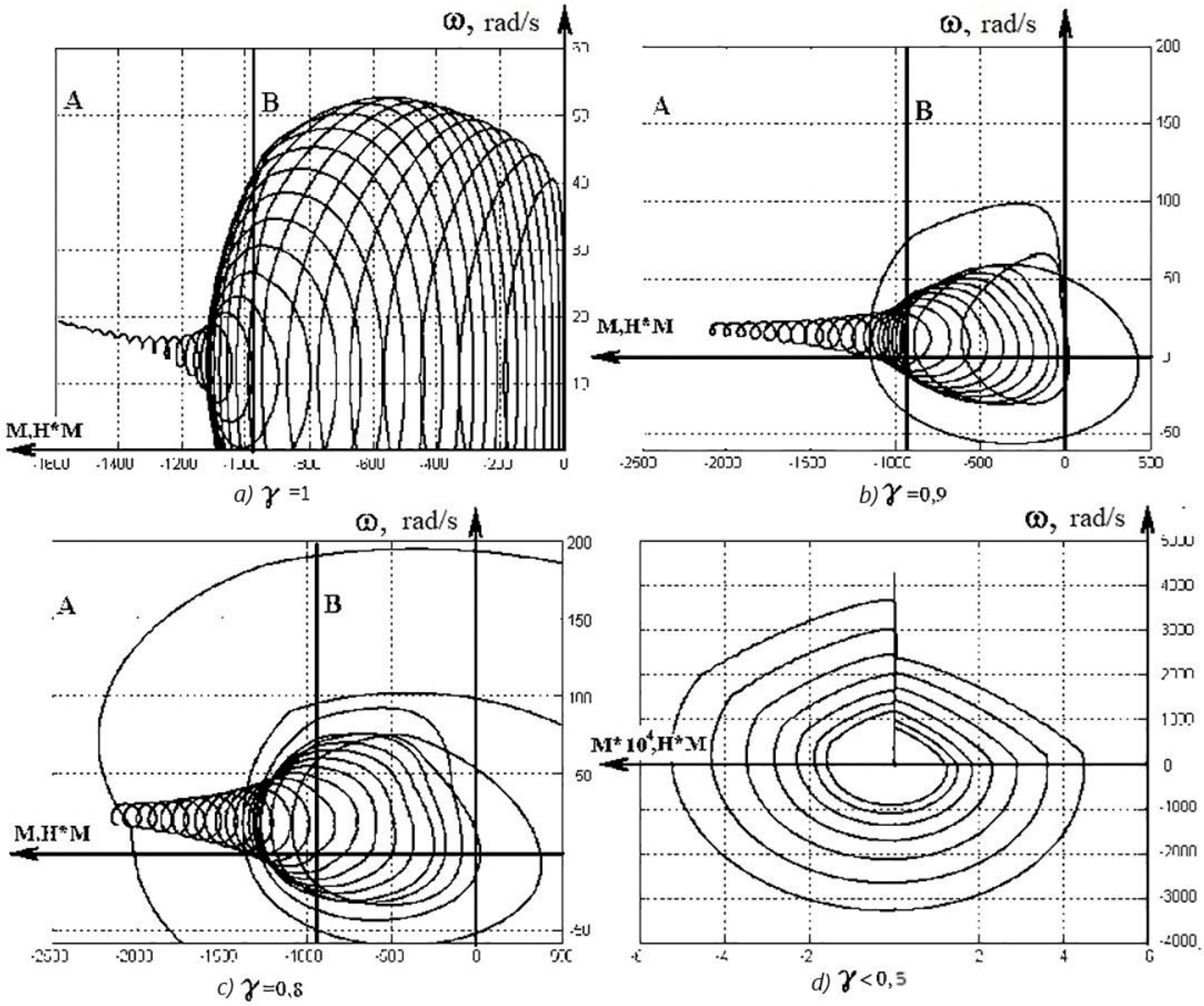

Figure 3. Mechanical characteristics of a DC drive for various values of the duty cycle of the VD3-VT3-PWM3 pulse converter.

All the characteristics are obtained for a torque changeable in the range from 0 to 2 Nm. At this, decreasing the duty cycle of the pulse converter shunting the armature circuit VD3, VT3, and PWM3 (Figure 1), leads to decreasing the current in the armature circuit. In Figure 3a, the duty cycle of converter $\gamma = 1$, where γ means the duty cycle, which corresponds to the completely closed state of the transistor VT3. In the case when there is a torque moment, and accordingly, the current strength of the electric motor is below the nominal value, which corresponds to the unsaturated state of the magnetic circuit of the electric motor, the dynamic characteristic has a self-oscillating character. The oscillatory process in the angular velocity corresponds only to the region of the unsaturated state of the magnetic circuit. This fact is explained by the presence of a positive feedback loop in the power section of the electric drive formed by links 3, and 4 that simulate electric circuits of the armature and field winding, respectively, 6 simulating the magnetic circuit of the electric motor and 7, the model of the mechanical part (Figure 1).

In the positive feedback loop, one of the links with variable parameters is the nonlinear dependence of the magnetic flux on the motor current. With the saturation of the magnetic circuit, the structure of the model changes, while the positive feedback loop is broken and the model becomes stable. With decreasing the duty cycle, the amplitude of the velocity fluctuations increases (Figure 3a, b, c, d). With the duty cycle of $\gamma<0.5$, the transient process in the angular speed of the electric drive becomes divergent. Since in the proposed circuit design, dynamic braking is controlled by reducing the motor current, in this technical solution, the implementation of stable controlled dynamic braking in the entire range of the duty cycle of the pulse converter is impossible. To implement stable controlled braking, it is advisable to switch to a circuit design with separate excitation, which is shown in Figure 4.

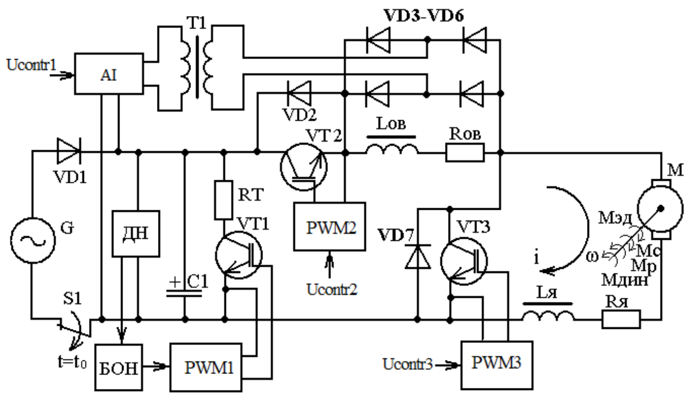

Figure 4. Equivalent circuit of the series-excited electric drive power section in the controlled dynamic mode.

A feature of the circuit design of an electric drive with a series-excited motor is the presence of a high-frequency autonomous inverter (AI) that receives power from a capacitive C1-type energy storage device. The T1 transformer matches the voltage and current on the C1 capacitor with the required voltage and current of the field winding. Additionally, AI can be used to control the current of the field winding, taking into account the fact of decreasing the voltage on the capacitor, which will expand the capabilities of the electric drive. Thus, for the organization of stable controlled braking of a series-excited electric drive in the technological and emergency modes, it is advisable to switch to a separately-excited circuit.

4. Conclusions

The proposed circuitry solution will make it possible to implement the braking technological and emergency modes in case of unauthorized power outages. The graphical dependences of series-excited electric motor’s electromechanical characteristics are presented as a function of power, which will subsequently make it possible to develop self-adjusting automatic control systems for an electric drive in the dynamic braking mode.

Simulation experiments have been carried out for different duty cycles of a pulse-width converter shunting a series-excited electric motor in the dynamic braking mode. The areas of unstable operation of the electric drive have been determined, and recommendations for changing the schematic diagram of the power section of the electric drive have been proposed. A schematic diagram of a variable-speed electric drive with a series-excited motor in the modes of emergency and technological braking has been developed.

In the course of the study, many technical tasks related to the work topic were implemented. Among them is the setting of tasks developed for the development of a control system for a controlled direct current electric drive with subsequent excitation in the dynamic braking mode. Also, this is an analysis of already frequently repeated solutions on the topic, braking modes of an electric drive with an increased level of constant excitation. Analysis of safety rules when working with braking modes of industrial mechanisms and machines. Development of the technique of theoretical control of the electric drive in the dynamic braking mode. Also, options for the technical implementation of the braking mode were considered. The practical operation of this network ensures the development of a mathematical and simulation model of an electric motor with subsequent excitation, taking into account the saturation of the magnetic circuit. The prospects of this study consists in studying the dynamic characteristics of a variable direct current for other types of magnetic circuit of an electric motor.

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