

APPLICATION OF DC-DC CONVERTER IN CONTROLLING THE ELECTRIC DRIVE SYSTEM OF THE CБЩ-250MH ROTARY BLAST HOLE DRILL

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ABSTRACT

Power electronics is currently extensively applied in the area of electric drive control with high efficiency. This paper presents the research on replacing the speed control method for the CБЩ-250MH rotary blast hole drill from a rectifier-motor system to a control method utilizing a DC-DC power converter. The operational results of the drive system using the new method are simulated via MATLAB- SIMULINK software, and simulation results indicate that the system utilizing the DC-DC converter fully meets the operational quality requirements of the rotary blast hole drill, providing flexible voltage regulation, guaranteed continuous current, and rapid speed stabilization. Furthermore, the new solution simplifies the control circuit structure, reduces maintenance costs, and enhances overall energy efficiency. This research opens up prospects for the widespread application of DC-DC converters in replacing the legacy drive systems of rotary drill used specifically in the mineral mining sector generally in industrial electric drive systems.

Keywords: Rotary blast hole drill, Electric drive system, DC-DC converter, Rectifier.

1. INTRODUCTION

Rotary blast hole drill is widely used equipment in the mining industry. Due to the continuously varying loads encountered during operation, these drills require an electrical drive system that adheres to high standards of control performance and dynamic stability. In recent years, advancements in power electronics have enabled the modernization of industrial equipment, leading to enhanced productivity and reduced manual labor. Consequently, the drive systems of rotary blast hole drill have become a primary focus of research and optimization.

Due to the nature of operating in harsh environments with high power capacity and continuously varying loads depending on specific working conditions, the drive system of the CБЩ-250MH rotary blast hole drill requires high standards of control quality. The operation of the electrical drive system involves frequent starting, braking, speed regulation, and reversing over a wide speed range. Furthermore, it must maintain high stability within the working region, while automatically reducing speed during overloads to protect the motor from mechanical damage. To meet the operational requirements of a drive system facing such load types, a specialized drive system is required.[1]

Previously, Thyristor-DC (T-D) regulators were widely employed to control the drive systems of rotary blast hole drills by adjusting the armature voltage and field excitation current of DC motors. Numerous studies from the 1990-2010 [2] period indicated that while the T-D configuration offers a simple structure and high reliability, its primary drawbacks include significant power losses, poor linear adjustment capabilities, low efficiency under light loads,

and difficulties in achieving a fast dynamic response. Furthermore, the pulse-triggering controllers for thyristor must ensure uniform and symmetrical firing pulses; however, the thyristor switching process generates high-order harmonics that inject back into the power grid, causing interference to equipment and transformers. Additionally, during operation, the commutation overlap phenomenon leads to average voltage losses and signal distortion. Particularly at large control angles (α), the voltage waveform becomes spiky and unstable, necessitating high-quality filters and robust cooling systems for semiconductor components in high-capacity mining equipment.

These limitations significantly impact the performance of rotary drill drive systems, which must frequently handle continuously varying loads corresponding to changes in rock hardness. Consequently, it is essential to improve or replace legacy control schemes with more suitable methods, such as DC-DC converters, to enhance productivity, ensure safety, and extend the system's operational lifespan.

Recent studies indicate that utilizing DC-DC regulators can overcome these fundamental drawbacks. By combining a stable DC source with a step-down (Buck) DC regulator using MOSFET or IGBT, the DC voltage can be adjusted without generating electromagnetic interference or harmonics. Notably, the switching process for transistors is relatively simple, and the pulse control circuitry is less complex than that of thyristor, ensuring a stable and continuous current.

In Vietnam, several recent studies [3] have focused on applying DC-DC regulators in machine tool drive systems and hoisting equipment, demonstrating an increase in energy efficiency of 10-15% compared to traditional T-D control methods. These advantages are highly significant for rotary blast hole drill drive systems operating under harsh real-world conditions. When using a DC-DC converter for control, the primary interference in the system arises from continuous load variations rather than the electrical system itself; this interference can be effectively mitigated through the use of voltage and current feedback loops.

Therefore, researching, designing, and evaluating the effectiveness of a DC-DC converter (Buck- Boost converter) as a replacement for the T-D regulator in the electrical drive system of the CБЩ-250MH rotary blast hole drill is essential. This study aims to verify the feasibility, technical efficiency, and energy benefits of the proposed solution, thereby contributing to improved control quality, reduced operating costs, and increased durability of industrial drilling equipment.

2. THE ELECTRICAL DRIVE SYSTEM OF THE CБЩ-250MH ROTARY BLAST HOLE DRILL

2.1. Requirements for the electrical drive system of the CБЩ-250MH rotary blast hole drill

The electrical drive system of the CБЩ-250MH rotary blast hole drill operates according to the mechanical characteristic shown in Figure 1 [1]. This specific profile is known as the 'excavator-type' characteristic, which consists of two sections with different levels of stiffness:

- Region 1 (Working region): When $I_a < I_{cut}$, the system maintains a stiff mechanical characteristic to enhance operational efficiency.

- Region 2 (Overload region): When $I_a \geq I_{cut}$, the system switches to a soft mechanical characteristic to protect the motor from significant overloads, eventually reaching I_{stop} where the motor stalls.

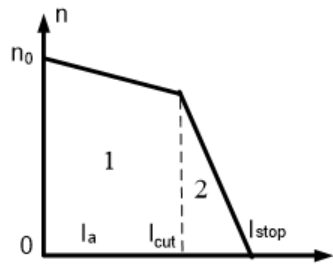


Figure 1. Mechanical characteristic of the CБИЦ-250MH

To generate this 'excavator-type' characteristic, traditional drill drive systems utilize a Thyristor - DC motor (T-D) configuration in a closed-loop system with the following feedback loops:

- Negative voltage feedback to enhance the stiffness of the characteristic in the operating region (Region 1).

- Negative current feedback with cut-off to protect the motor from overloads (Region 2).

The calculation expression for negative voltage feedback is: $U_{V.fb} = \alpha \cdot U_a$

Note that these two feedback loops are mutually exclusive: when the first is operational, the second is disabled, and vice versa

This is case, we have: $U_{ctrl} = U_s - U_{V.fb} - U_{I.fb}$ with:

$$U_{I.fb} = \begin{cases} 0 & \text{if } I_a < I_{cut} \\ \beta (I_a - I_{cut}) & \text{if } I_a \geq I_{cut} \end{cases} \quad (1)$$

During the calculation and simulation process, the unit step function $1(\Delta I)$ is commonly used, with the following values:

$$1(\Delta I) = \begin{cases} 0 & \text{if } I_a < I_{cut} \\ 1 & \text{if } I_a \geq I_{cut} \end{cases} \quad (2)$$

Placing (2) into (1), we have the calculation formula: $U_{ctrl} = U_s - U_{I.fb} - 1(\Delta I) \cdot \beta (I_a - I_{cut})$ (3)

2.2. Schematic diagram of the CБИЦ-250MH rotary blast hole drill drive system

The electrical drive system of the CБИЦ-250MH rotary blast hole drill consists of multiple mechanisms.

- Drill bit rotation mechanism.
- Axial thrust mechanism.
- Pneumatic pulldown mechanism

Among the aforementioned mechanisms, the drill bit rotation mechanism is the most critical, as it directly determines the machine's productivity. Similar to an excavator, a rotary blast hole drill encounters sudden load fluctuations while breaking rock; therefore, its mechanisms must be automatically regulated. Since the drill bit rotation mechanism faces frequent load changes, it requires automatic adjustment devices for both torque and speed.

The electrical drive system for the drill bit rotation mechanism of the rotary blast hole drill (CБИЦ-250MH), as illustrated in Figure 2, is a T-D system. The armature of the DC motor is supplied by a controlled three-phase bridge rectifier. And the motor's separately excited field winding is also powered by a controlled single-phase bridge rectifier.

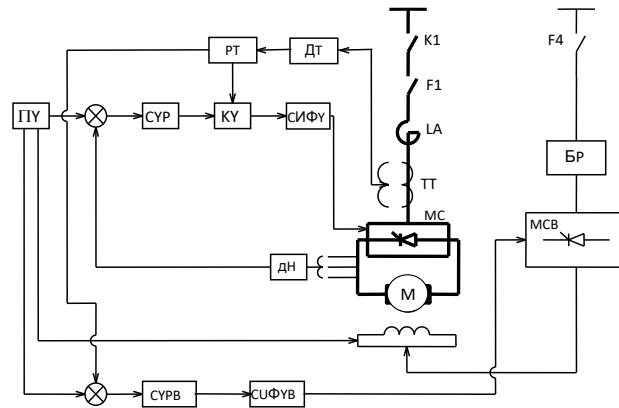
The speed and torque of the DC motor for the drill bit rotation mechanism are automatically regulated in two ways (or directions):

- + Armature voltage control of the DC motor.
- + Field voltage control of the DC motor.

To stabilize the motor speed, a negative voltage feedback loop is employed, while a negative current feedback with fast cut-off is used to limit over-current in the armature circuit.

The motor armature voltage is varied by adjusting the control angle of the controlled three-phase bridge rectifier. Similarly, the excitation voltage is altered by adjusting the control angle of the controlled single-phase bridge rectifier. The controller processes signals from the voltage and current feedback loops to regulate these control angles, thereby adjusting the motor's speed and torque.

The electrical drive system of the drill bit rotation mechanism is represented as a block diagram in Figure 2 [1].



*Figure 2. The diagram of the electrical drive system for the СБЦ-250МН rotary blast hole drill
 LA: inductor; MC, MCB: rectifier converter; M: motor; ДТ: current sensor; РТ: current controller;
 КУ: Correcting element; ДН: voltage sensor; ПГУ: Control table; СУР: Composite Amplifier; СИФУ:
 pulse controller*

During operation, the Thyristor-DC (T-D) drive system demonstrates several advantages, including high power capacity, high reliability, and a control range that meets the operational requirements of the rotary blast hole drill. However, certain drawbacks persist, such as significant power losses and a bulky physical size due to the L-C filters required to ensure DC power quality. Additionally, the system suffers from poor linear adjustment capabilities, a complex pulse-triggering principle, and is primarily operated in step-down mode at low frequencies.

Along with the development of modern power electronics, DC–DC converters utilizing IGBT or MOSFET have been extensively researched and applied in industrial electric drive systems. Buck, boost, and buck–boost DC–DC converters offer continuous output voltage regulation with efficiencies exceeding 90%, while being easily integrated with micro-controllers or digital PID control systems.

In Vietnam, several recent studies have focused on applying DC–DC regulators in machine tool drive systems and hoisting equipment, showing an increase in energy efficiency of 10–15% compared to traditional T–D control methods. However, specific applications for high-capacity rotary blast hole drill remains limited, especially under the harsh working conditions of the mining industry [3].

Based on the aforementioned studies, replacing T–D regulators with DC–DC converters in the electric drive system of the СБЦ-250МН rotary blast hole drill is feasible direction with high practical significance. Nevertheless, detailed research on modeling, dynamic

characteristics, and the ability to respond to varying loads is necessary to ensure the stability and safety of the equipment [4], [5].

2.3. Electric drive system of the СБЦ-250МН rotary blast hole drill using DC–DC converters

The schematic diagram of the rotary blast hole drill’s drive system using a DC–DC converter is shown in Figure 3.

The electric drive system of the СБЦ-250МН rotary blast hole drill requires a highly flexible controller capable of continuous state transitions, frequent starting, speed regulation, braking, and reversing. Therefore, selecting a drive system with an appropriate control method and hardware is a critical requirement. The drive system of the СБЦ-250МН rotary blast hole drill, characterized by continuously varying loads due to diverse geological structures, typically utilizes a separately excited DC motor. The advantage of this motor type is that the excitation and armature circuits are supplied by two independent sources. Consequently, motor speed can be controlled via two approaches: armature voltage control and excitation circuit voltage control. Furthermore, within its operating range, the motor characteristics are linear, making the DC–DC converter control method perfectly suitable [6], [7].

As shown in the schematic, AC power from the source is rectified into DC via a three-phase uncontrolled rectifier. This DC voltage ensures superior stability, minimal ripple, and reduced interference, achieving high operational efficiency as the current remains in phase with the voltage. And it supplies to the DC–DC converter, where it is adjusted to the desired value by varying the pulse width (duty cycle) of the transistors. The underlying switching principle is based on the precise timing control of the power semiconductor switches.

Since the drive motor speed during operation is lower than the ideal no-load speed (n_0), the armature voltage is regulated within the range from 0 to the source voltage (U_s). Therefore, a Buck converter is the appropriate choice for the system's DC-DC regulator, with its schematic diagram illustrated in Figure 3 [8], [9].

The DC–DC converter illustrated in Figure 3 utilizes a power transistor in combination with a DC source derived from an uncontrolled rectifier. The switching process of the transistor varies the DC voltage supplied to the motor armature, thereby enabling control of the motor speed. To achieve this, a pulse generator for the transistor is required, and an appropriate switching frequency must be calculated to obtain the desired control performance.

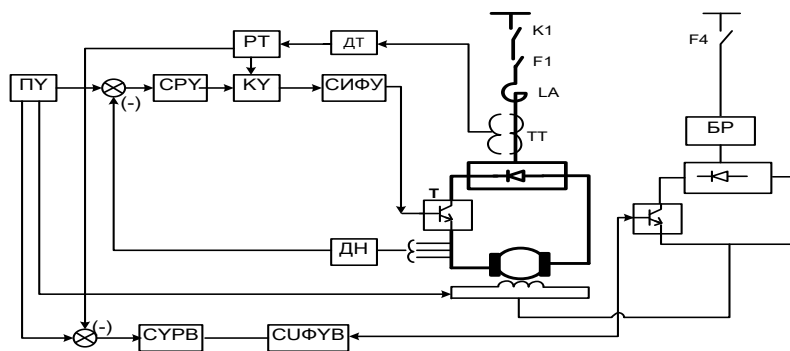


Figure 3. Schematic diagram of the electric drive system for the rotary blast hole drill using a DC–DC regulator.

During the motor starting process, to reduce the starting current, the supply voltage can be adjusted from 0 to U_s by varying the transistor's switching time according to the formula:

$$U_a = \varepsilon \cdot U_s$$

where: $\varepsilon = t_{on}/T_c$

With ε : Duty cycle.

t_{on} : Transistor turn-on time.

$T_c = t_{on} + t_{off}$; T_c : Transistor switching period,

Thus, by varying the transistor's turn-on and turn-off times, the duty cycle can be adjusted from 0 to 1, causing the voltage applied to the motor armature to vary from 0 to U_s , [10], [11].

During operation, as the load may fluctuate continuously, an appropriate motor voltage control strategy is required to enhance productivity and ensure safety. To achieve this, the following control methods can be employed:

-Pulse Width Modulation (PWM): Adjusting the transistor's turn-on time (t_{on}) while keeping the switching period (T_c) constant.

-Pulse Frequency Modulation (PFM) method: Keeping the turn-on time (t_{on}) constant and varying the switching period (T_c).

- Pulse-Time Modulation method: Varying both the turn-on time (t_{on}) and the switching period (T_c).

Within the scope of this report, the PWM method (Pulse Width Modulation) is investigated to regulate the voltage applied to the motor armature for speed control, enabling the drive system to handle varying loads and meet predefined operating characteristics. According to this control method, the pulse duration supplied to the transistor's gate must be adjusted while maintaining a constant switching period. The voltage and current waveforms are illustrated in Figure 4 [3].

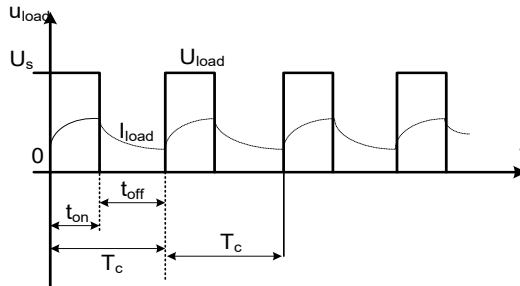


Figure 4. Voltage and current waveforms when adjusting the transistor duty cycle.

The pulse timing and width are adjusted according to the control voltage U_c following the illustrations shown in Figure 4 and Figure 5.

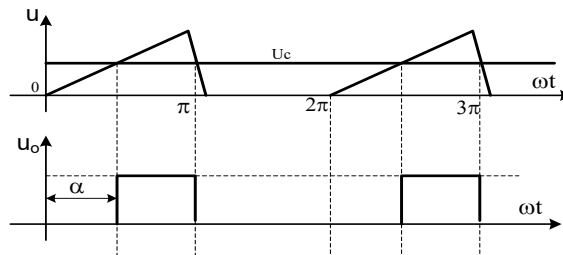


Figure 5. Principle of pulse generation for the transistor.

During the motor speed regulation process, it is crucial to maintain a continuous and stable current while satisfying the "excavator-type" mechanical characteristic requirements of the drive system. Consequently, evaluating the system's dynamic performance through simulation is essential to determine the optimal controller parameters and the ideal switching frequency for the power transistor. This paper presents a simulation of the electric drive system for the

СБЦЦ-250MH rotary blast hole drill using the Pulse Width Modulation (PWM) control method within the MATLAB-SIMULINK software [12].

3. SIMULATION OF THE СБЦЦ-250MH ROTARY BLAST HOLE DRILL'S DRIVE SYSTEM USING THE PWM DC–DC CONVERSION METHOD IN MATLAB -SIMULINK

3.1. Mathematical modeling of components in the rotary blast hole drill's drive system

To simulate the electric drive system of the rotary blast hole drill machine, the author has developed the mathematical models for the components within the drive system as follows [13]:

* The separately excited DC Motor:

$$\begin{cases} R_a I_a(t) + L_a \frac{di_a(t)}{dt} + E_M(t) = U_a(t) \\ J \frac{d\omega(t)}{dt} = M(t) - M_c(t) \\ U_f(t) = R_f I_f(t) + L_f \frac{di_f(t)}{dt} \end{cases} \quad (4)$$

In which: R_a, L_a : Armature Resistance and Armature Inductance (Ω, H)

R_f, L_f : Field Resistance, Field Inductance (Ω, H)

E_M : Back Electromotive Force (V)

U_a, U_f : Armature circuit voltage, field circuit voltage (V)

I_a, I_f : Armature circuit current, field circuit current (A).

* PWM DC–DC chopper: $U_M = \varepsilon \cdot U_S$ (5)

* The negative feedback voltage: $U_{V.fb} = \alpha \cdot U_a$

where α : negative feedback voltage constant.

* The negative current cut off feedback:

$$U_{I.fb} = 1(\Delta I) \cdot \beta(I_a - I_{cut})$$

β : negative feedback current constant.

* Consequently, the input-output relationship equation for the closed-loop system is expressed as follows:

$$\begin{aligned} U_C &= U_S - U_{U.fb} - U_{I.fb} \\ &= U_{Set} - U_{U.fb} - 1(\Delta I) \beta(I_a - I_{cut}) \end{aligned} \quad (6)$$

With: I_a : Armature current of DC motor.

I_{cut} : Cut current.

I_{stop} : Stop current.

U_C : Control voltage.

U_{Set} : Set voltage

$U_{U.fb}$: Feedback voltage.

$U_{I.fb}$: Current Cut off feedback Voltage.

U_S : Source voltage

*The simulation of the rotary blast hole drill drive system was conducted using the following parameters for the separately excited DC motor.

Table 1. Motor data type

Component	Motor type Д 808 Б1			
	P(kW)	U(V)	I(A)	ω (rad/s)
Armature	60	380	160	84
Field circuit		85	25,6	

3.2. Simulation of the CБЦ-250MH rotary blast hole drill machine drive system using PWM DC-DC converter in MATLAB -SIMULINK

* MATLAB-SIMULINK Simulation Diagram

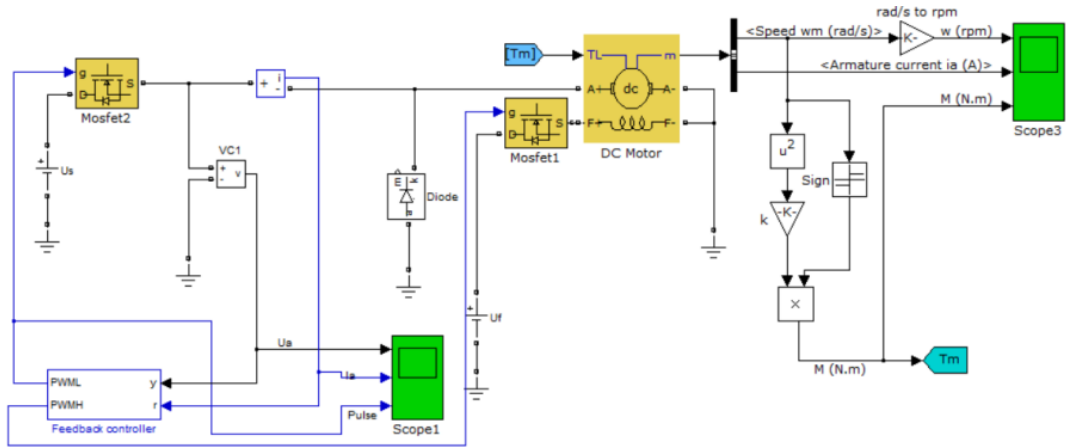


Figure 6. MATLAB-SIMULINK Simulation Model

After developing the system structure in MATLAB - SIMULINK, the simulations were conducted under various switching frequency scenarios. The results determined the optimal pulse frequency that is compatible with $f = 1/T_c = 1/0.0007s$. Based on this frequency, the pulse width was adjusted while maintaining a constant pulse period. The resulting simulation waveform for the armature current, voltage, and motor speed are described follows:

*Case 1 $t_{on} = 1\% T_c$ and $T_c = 0.0007s$: When the pulse width is set to 1% the simulation indicates that the pulse applied to the transistor's base is too small. Consequently, the load current (I_{load}), armature voltage (U_{load}) and speed motor remain at zero, as shown in Figure 7.

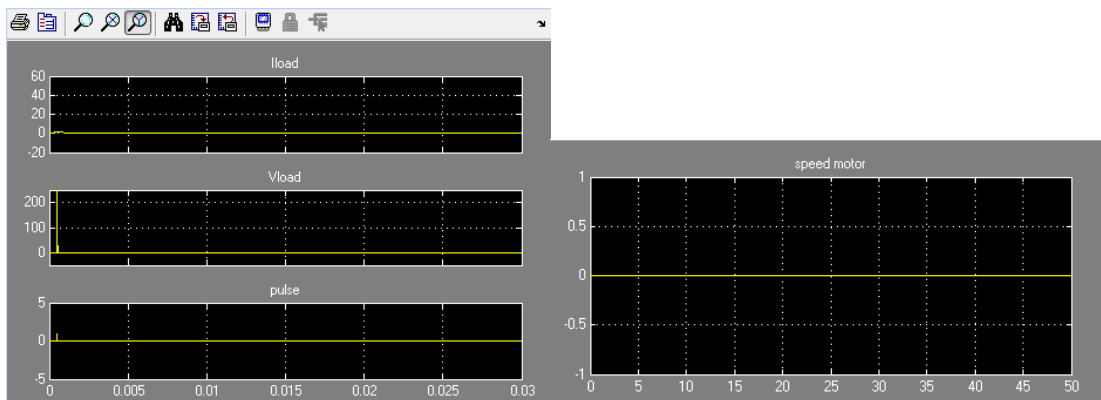


Figure 7. Simulation results of the system when $t_{cut} = 1\% T_c$ and $T_c = 0.0007s$

*Case 2 ($t_{on}=10\% T_c$ and $T_c=0.0007s$): The load current increases to 5.13 A, and the motor speed reaches 6.8 rad/s (Figure 8). This demonstrates that increasing the pulse duration leads to a corresponding rise in voltage and current.

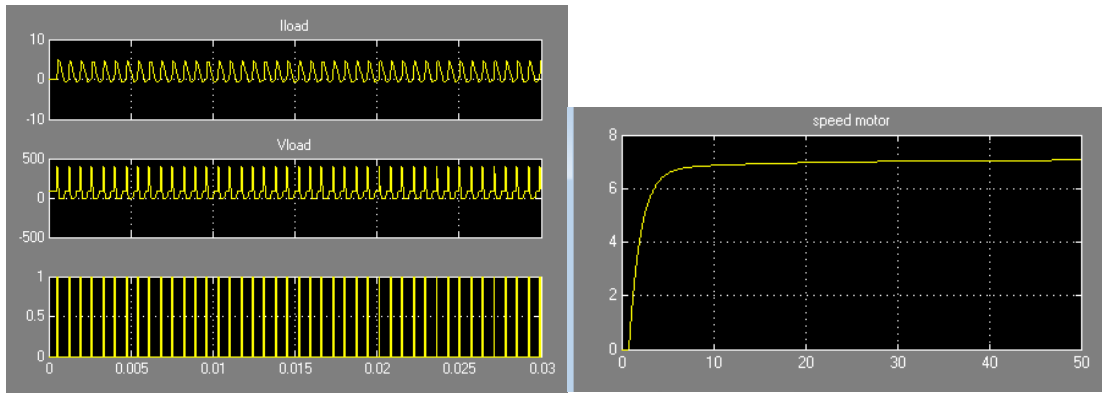


Figure 8. Simulation results of the system when $t_{cut}=10\% T_c$ and $T_c=0.0007s$

*Case 3 ($t_{on}=30\% T_c$ and $T_c=0.0007s$) The results show a load current of 118.7 A and a motor speed of 42.1 rad/s. This indicates that as the pulse duration supplied to the transistor increases, the current, voltage, and motor speed rise accordingly. The simulation results are illustrated in Figure 9.

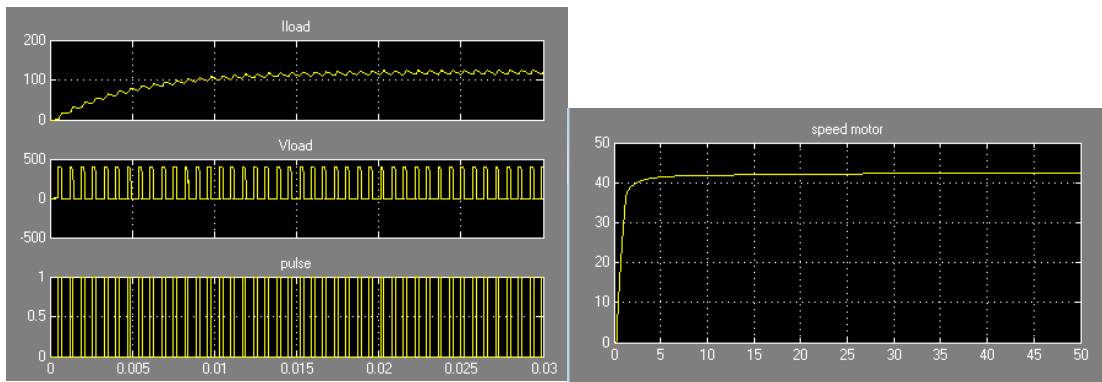


Figure 9. Simulation results of the system when $t_{cut}=30\% T_c$ and $T_c=0.0007s$

Continuing the simulation with $t_{on}=60\% T_c$ and $T_c=0,0007s$, the results yield a load current of 171,2 A and a motor speed of 85,4 rad/s, as illustrated in Figure 10.

*Case 4 ($t_{on}=60\%T_c$ and $T_c=0.0007 s$): The load current reaches 171.2 A and the motor speed increases to 85.4 rad/s as the Figure 10.

Through the sequential simulation cases, it is evident that by utilizing the PWM voltage regulator, the resulting load current is continuous with minimal ripple and high stability. Furthermore, the motor speed reaches a steady-state value with a response time of 10 seconds, satisfying the control quality requirements.

The simulation process under various switching frequency scenarios (optimal at $f=1/0.0007s$) has demonstrated a direct correlation between the pulse width (t_{on}) and the motor's operational performance.

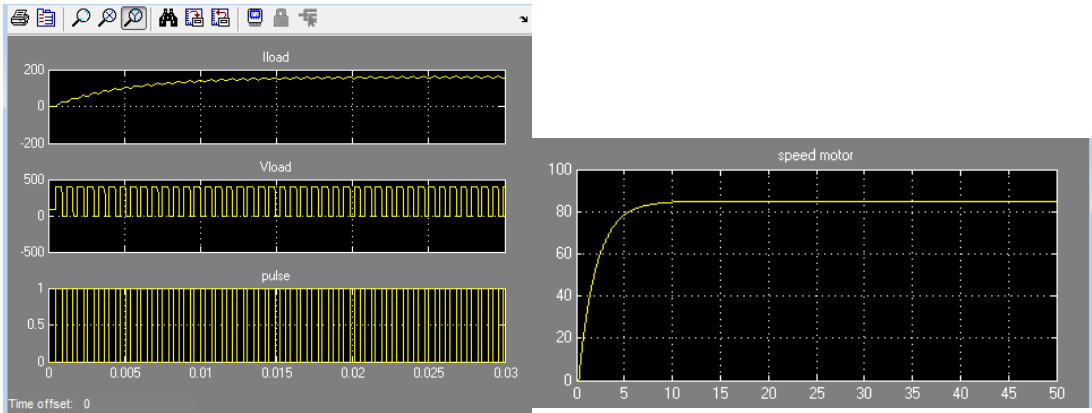


Figure 10. Simulation results of the system when $t_{cut}=60\% T_c$ and $T_c=0.0007s$

When t_{on} is too small ($1\% T_c$): The load current, armature voltage, and motor speed all remain at zero because the pulse supplied to the transistor's base is insufficient to trigger the system.

As t_{on} gradually increases: The output parameters rise proportionally. Specifically:

At $10\% T_c$: The load current reaches 5.13 A, and the speed is 6.8 rad/s.

At $30\% T_c$: The load current rises to 118.7 A, and the speed reaches 42.1 rad/s.

At $60\% T_c$: The load current reaches 171.2 A, and the speed is 85.4 rad/s

Through the simulation case, it is evident that: The current utilizing the Pulse Width Modulation (PWM) regulator enables a continuous load current with minimal ripple and high stability. And the response time: The motor speed reaches its steady-state value with a response time of approximately 10 seconds, satisfying the control quality requirements. The speed motor: The new drive system effectively minimizes speed oscillations, ensuring smooth mechanical operation and reducing wear on the drilling components.

In addition to simulating speed control by varying the transistor's pulse width, the author also conducted simulations under overload conditions. This was done to verify whether the system characteristics meet the requirements of a drive system with continuously varying loads. The simulation results, illustrated in Figure 11, demonstrate that the operating characteristics fully satisfy these operational requirements.

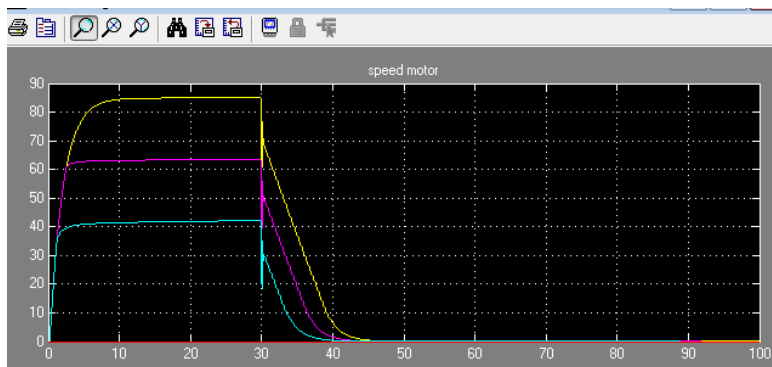


Figure 11. Simulation results of the system under overload conditions

Through the development of the schematic diagram and the execution of MATLAB SIMULINK simulations, the electric drive system of the rotary blast hole drill-utilizing the PWM-based DC-DC voltage regulation method-has demonstrated its ability to meet operational

requirements. These include fast response times, flexible load voltage adjustment, speed stability, and reduced oscillations during regulation. Furthermore, this method helps enhances efficiency efficiency and simplifies the control circuit structure of the drive system.

4. CONCLUSION

This paper has presented a comprehensive study on the replacement of the conventional rectifier-motor (T-D) drive system with an advanced DC-DC power converter for the CБИЦ-250MH rotary blast hole drill. Through theoretical analysis and extensive simulations via MATLAB -SIMULINK, the following conclusions can be drawn:

First, the proposed control method, which integrates negative voltage feedback and an optimized correcting unit, significantly enhances the system's dynamic performance. The DC-DC converter provides a faster transient response and maintains superior voltage stability compared to the traditional T-D system.

Furthermore, the system demonstrates high precision and robustness. Under varying load conditions typical of mineral mining environments, the new drive system effectively minimizes speed oscillations, ensuring smooth mechanical operation and reducing wear on the drilling components.

Finally, the transition to DC-DC technology offers substantial economic and technical advantages, including a simplified control circuit structure, reduced maintenance requirements, and optimized energy consumption. These results confirm that the proposed solution is not only technically feasible but also highly effective for modernizing legacy drive systems.

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