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Research and Simulating Electric Drive System of ЭКГ–10 Excavator by Matlab Simulink Software

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***Abstract*— The ЭКГ - 10 is a new Russian excavator that uses a converter generator motor drive system. It replaces traditional drive systems: magnetic amplifier- generator-motor by a motor-generator-converter system. The electric drive system of the ЭКГ - 10 excavator uses a converter-generator-motor with a flexible working model, which meets high requirements according to the "excavator type" working characteristics. This drive system uses microcontrollers combine closed-loop control method to change the control angle of the converter therefore it changes the generator's voltage and motor to adjust the speed of the motor. That it has marked a new turning point in the automation of the control process to production, the Excavator drive system is very complex, consisting of many mechanisms structures, so the system's operation requires a perfect controller in both parameters and control techniques. In other words, to improve the productivity and quality of operation of this type of excavator, it is necessary to find a suitable working parameter for the controller of the electric drive system. The article has researched and simulated the converter-generator-motor drive system of the ЭКГ - 10 excavators by Matlab Simulink software to find out the optimal parameters to meet the operation requirements of the system and have the direction of control match the load object when they constantly change, thereby helping the system operate stably and achieve the desired control quality.**

***Keywords*— ЭКГ – 10 excavators; optimal operating parameter; the converter generator motor drive system.**

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I. INTRODUCTION

In recent years when power electronics developed, it has improved the drive control system of the excavator from magnetic amplifiers-generator-motor in the direction of using converter- generator-motor [1]. The synthesis of signals using magnetic amplifiers has the advantage of a high gain simple control, but with big inertia, slow impact, and difficulty in automation. To overcome this drawback, the ЭКГ-10 excavator has synthesized the control signal, and the rectifier has controlled the feedback by closing the α angle to change the set voltage value up the excitation wire. Adjusting the opening α angle is handled by pre-programmed microcontrollers. The problem is to find reasonable working parameters for the controller to install. The article performed the simulation using Matlab Simulink software, the converter-generator-motor electric drive system of the ЭКГ - 10 excavators, to find these optimal parameters.

II. MATERIALS AND METHOD

A. The Requirements of the Electric Drive System of an Excavator

The electric drive system of excavator requires high quality in working process, wide adjustment range, frequent start, brake, speed adjustment and rotation reversal. In the workspace, the system has a high requirement for speed stability. When falling into an overloaded area, the system must automatically reduce the characteristic hardness to protect the motor and other mechanical structures [2]. To meet these requirements, the working characteristics of an excavator electric drive system are in the form shown in Fig. 1, this characteristic line is called an "excavator type" characteristic, which consists of two parts with different stiffness [3].

The first area is the working area when $I_a < I_{cut}$, stiffness of characteristic to increase the working efficiency of the system. The second region: overloaded area, when $I_a \geq I_{cut}$, characteristic is soft to protect the motor from overloading. The problem of current limitation is set because when calculating, the design of the electric drive system uses feedback to reduce speed errors and increase hardness characteristics, but also it increases the short-circuit current and short-circuits torque of the motor. The result will be dangerous to the motor when a large overload and damage to the drive system by excessive acceleration when starting and braking. To solve the conflict between the requirements of working speed stability and the requirement of limiting the current, people often use the partitioning method. In the allowable variation region of the torque and armature current of the motor, the characteristic has a high stiffness to ensure a small speed error. When the current and the torque exceed this range, the hardness of the characters must be sharply reduced to limit the current.

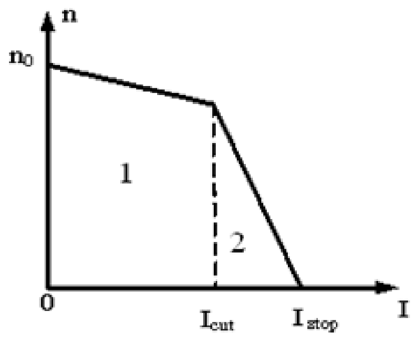

Fig. 1 “Excavator type” of characteristic

This “excavator-type” characteristic ensures that the electric drive system changes the load to operate stably. In large rigidity, the system works with high efficiency, called the working area of the system. When overloaded special features automatically soften to protect. This type of working characteristic is applied not only for excavators but also for many machines operating with constantly changing loads such as drilling machines, cutting machines, etc. Modern machines often use the working characteristics as shown in Fig. 2. Areas 2 and 3 with the meaning as in Fig. 1, and area 1 is the work area with a very small load allowing the drive system to accelerate to increase productivity.

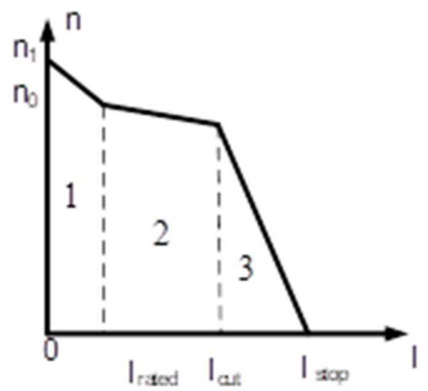

Fig. 2 “Excavator type” of characteristic

To be able to create this "excavator type" characteristic, the electric drive system of ЭКГ-10 excavator uses a convertor-generator-motor system that uses a closed-loop system with feedback loops: Negative feedback of voltage to improve property stiffness in the work area (area 1 Fig. 1). The fast-cut negative feedback of armature currents protects the motor from overload (area 2-Fig. 1). It should be noted that when the first feedback is active, the second feedback does not work and vice versa. Then we have $U_c = U_s - U_{fbU} - U_{fbI}$ with:

$$U_{fbI} = \begin{cases} 0 \; if \; I_a < Ic \\ \beta(I_a - Ic) \; if \; I_a \geq Ic \end{cases} \tag{1}$$

In the process of calculations and simulations it is often used with the value of 1 (ΔI) function:

$$1(\Delta I) = \begin{cases} 0 \; if \; I_a < Ic \\ 1 \; if \; I_a \geq Ic \end{cases} \tag{2}$$

Replace (2) in (1) we have the formula to calculate:

$$Uc = Us - UfbU - 1(\Delta I).\ \beta(Ia - Ic) \tag{3}$$

With: U_c: control voltage (V)
U_s: setup voltage (V)
U_{fbU}: feedback voltage (V)
U_{fbI}: feedback voltage according to armature currents (V)
I_a: armature currents (A)
I_C: cut currents (A)
β: feedback coefficient according to current.

B. The generator-motor system.

A Generator-motor system is an electric drive system in which the converter is an independent magnetic dc generator. This generator is usually due to a rotating three-phase synchronous primary motor (for high-powered machines) or asynchronous motors (for small-capacity machines) and considers the rotating speed of this generator to be constant. Two characteristics determine the characteristics of a generator: the no-load characteristic is the dependence between the electromotive force of the generator and the excitation current, and the load characteristic is the dependence of the voltage on the two poles of the generator into the load current.

The generator-motor system has the principle diagram shown in Fig. 3, an electric drive system consisting of an independent magnetic DC generator. This generator powers an independent DC motor to drive the load. The control is carried out via generator and motor excitation control.

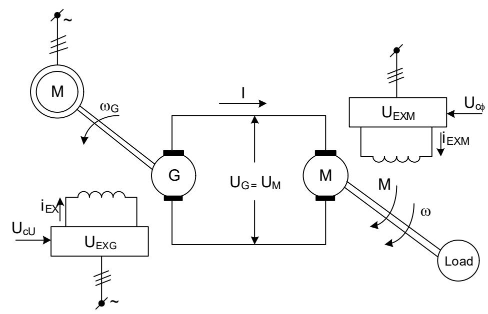

Fig. 3 The generator-motor system

The outstanding advantage of the generator-motor system is the flexible working state transition large overload, so it is often used for mining machines [2]–[4]. To control the speed motor of the generator-motor drive system, we can control in two directions: Control the generator voltage by changing the voltage applied to the generator excitation circuit; Control the excitation current of the motor by changing the voltage applied to the motor excitation circuit.

People used magnetic amplifiers or machine power amplifiers to implement ways to control the speed motor using the generator-motor drive system. However, with the development of power electronics, they have replaced them with thyristor rectifiers.

C. The electric drive system of ЭКГ – 10 excavators.

Control the main electric drive system of the ЭКГ – 10 excavators using a digital control system: generator- motor-rectifier with voltage feedback and rapid cut-off according to the armature current. The use of a thyristor converter to adjust the speed of the drive motor for the excavator ЭКГ – 10 has overcome some basic disadvantages of the system using generator- motor-magnetic field amplifier (or machine power amplifier) such as bulky, large inertia, slow and inaccurate action. The requirements for electric drive systems for ЭКГ – 10 excavators have been met with greater efficiency: Reduce the variation of the armature current allowed according to the switching value; Limiting the maximum acceleration of the drive during idling and torque of electric drive during overloading; Reduce the current and torque when the foundation is subsided during the stopping process; Reduce the phenomenon of shock when releasing cable during lifting and contacting.

Reference [5] shows ЭКГ-10 excavator has many structures such as lifting mechanism, rotating, moving, and opening of bucket bottom. The electric drive of the ЭКГ - 10 excavator devices use the converter- generator-motor system as shown in Fig. 3, including an independent excitation generator for powering an independent excitation motor to drive the load. The excitation part of the generator and motor gets power from controlled three-phase rectifiers.

To adjust the drive speed for ЭКГ- 10 excavator structure used in two directions: Control the output voltage of the generator by changing the excitation circuit voltage; Control according to the excitation circuit voltage of the motor.

To stabilize the motor speed using negative feedback voltage, limit overcurrent using fast-cut negative feedback of armature current as in Fig. 4. The excitation voltage generator is controlled by adjusting the opening angle α of the three-phase rectifier using a thyristor with a neutral point. This rectifier has capable of reversing current. The excitation for the motor is taken from the controlled three-phase bridge rectifier, which cannot change polarity. In terms of structure, the force circuit of the rectifier supplies power to the excitation part of the generator, and the motor's excitation can be assembled by the same type, using a microcontroller to adjust the opening α angle to the synthesis of a feedback signal.

The function of the current sensor is to take the armature current signal to the microcontroller in case the current increases to the value I_{stop}. Then the microcontroller will perform open α angle control to adjust the voltage signal excitation circuit, which drives the speed motor to zero. The function of the voltage sensor is to take the voltage signal from the generator to the microcontroller. If the voltage is wrong with the stability value, the microcontroller will issue a signal to adjust the α angle to adjust the value of the excitation circuit voltage of the generator, thereby changing the motor voltage.

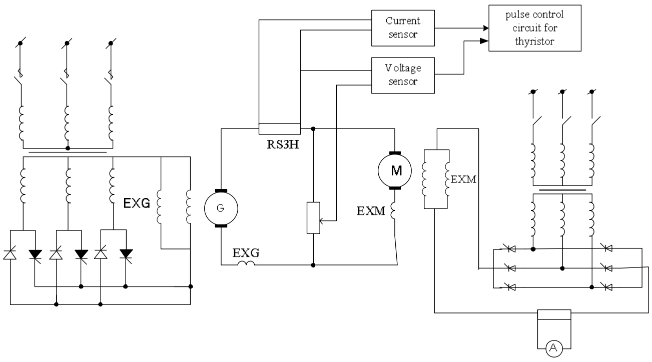

Fig. 4 Electric drive system of ЭКГ–10 excavator

III. RESULTS AND DISCUSSION

The converter- generator-motor system of the excavator ЭКГ-10 is a nonlinear system due to the excitation part of the generator. The motor has a relationship between the excitation current and the flux of the magnetic excitation pathway curved magnetization. While simulating based on nonlinear equations will face many difficulties. Thus, the author performs the simulation by linearizing around the working point based on the control theory linear system for making equations [3], [7]–[10]. Details of linearization were done. Consider generator G. The formula represents the relationship between flux and excitation current:

$$\Phi G = f(IexG) \quad (4)$$

According to the magnetization curve, this relationship is nonlinear. However, in the small I_{exG} segment, we can use the approximate calculation method by linearizing each segment and obtaining: $\Phi_G = a.I_{exG}$, is a linear relationship. Then the mathematical description of the generator is expressed as follows:

$$E_G(s)(T_G s + 1) = K_G.U_{\mathrm{exG}}(s) \quad (5)$$

Do the same with the rest of the system, we have:

1) Motor:

$$\begin{cases} R_a I_a(s) + L_a s I_a(s) + E_M(s) = U_a(s) \\ Js.\omega(s) = M(s) - M_{opt}(s) \\ U_{\mathrm{ex}}(s) = R_{\mathrm{ex}} I_{\mathrm{ex}}(s) + s L_{\mathrm{ex}} I_{\mathrm{ex}}(s) \end{cases} \quad (6)$$

2) Rectifier:

- The rectifier for power excitation of generator:

$$T_{cG} s.\alpha_G(s) + \alpha_G(s) = 1{,}17 U_{cG}(s) \quad (7)$$

- The rectifier for power excitation of motor:

$$T_{cM} s.\alpha_M(s) + \alpha_M(s) = 2{,}34 U_{cM}(s) \quad (8)$$

3) Feedback circuit:

- Negative feedback of voltage: $U_{fb.U} = \alpha.U_M$ (7)
- The fast-cut negative feedback of armature current:

$$Ufb.I = 1(\Delta I).\beta(Ia\text{-}Ic) \quad (9)$$

We have built a structure diagram of the system from the mathematical model in the cases. "Reference [2],[5],[6],[11] -When adjusting the generator voltage as Fig. 5:

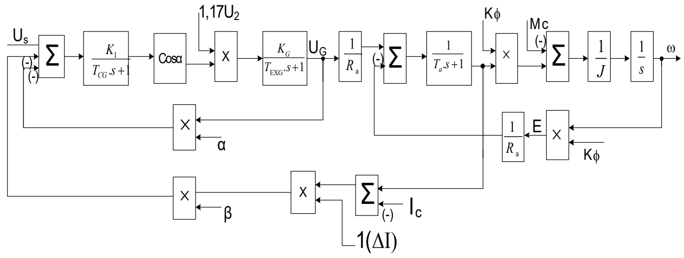

Fig. 5 Structure diagram of the circuit when adjusting generator voltage

When changing flux magnetic circuits of the motor as shown in Fig. 6.

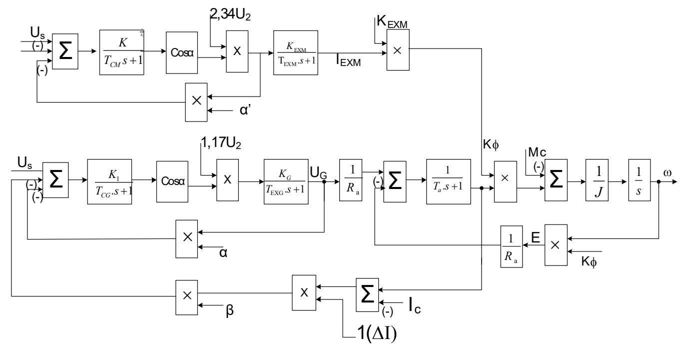

Fig. 6 Structure diagram of the circuit when changing magnetic flux circuit of the motor

Perform the simulation according to the following Table. 1 data:

TABLE I
ELECTRIC DRIVE SYSTEM PARAMETER

	Type of generator 4ГПЭМ 600-1/1Т2		Type of motor ДЭ 818 Т2		3-Phase bridge rectifier	
	Armature	*Excitor*	*Armature*	*Excitor*	*Neutral*	*No neutral*
P(kW)	600		270			
U(V)	750	57	375	85	440	220
I(A)	800	64	770	25.6	60	30
n(r/m)	1000		800		$\alpha = 30^0 \div 60^0$	

From the construction math model, we moved to simulate on Matlab Simulink [3], [7]–[22].

A. Find the Optimum for the Generator Voltage Regulator

Diagram of Matlab Simulink simulation structure shown in Fig. 7.

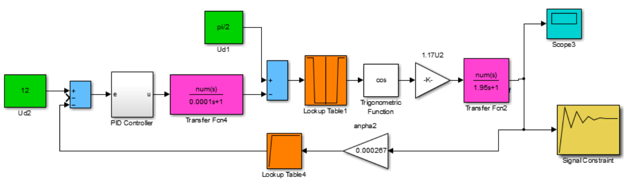

Fig. 7 Matlab Simulink structure diagram of the generator

The simulation run results are shown in Fig. 8. The coefficients to find KP = 15,1971 and KI = 0.5534.

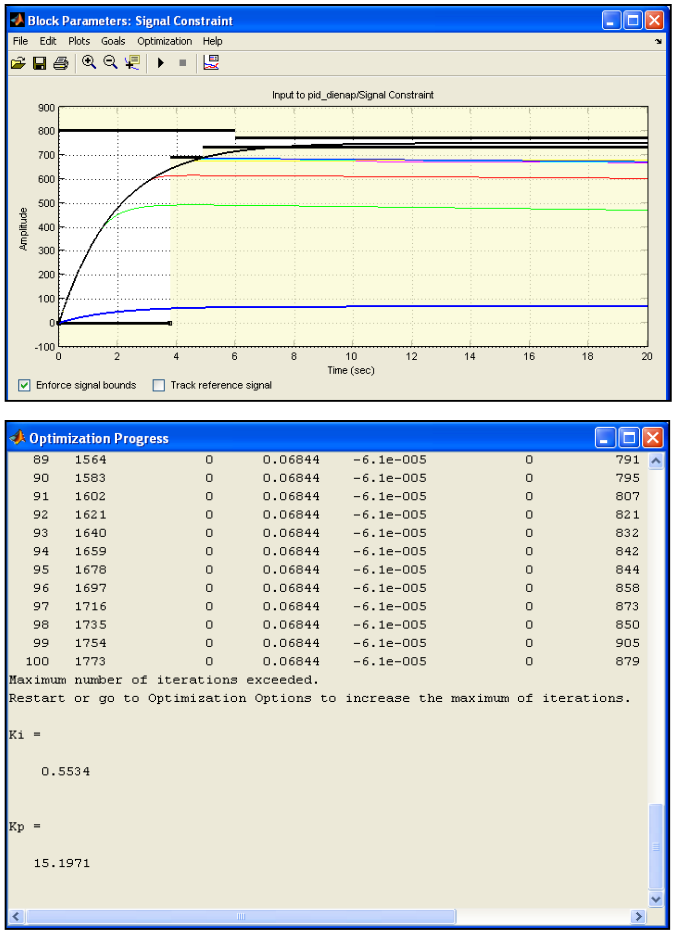

Fig. 8 Results of simulating to find the optimal parameters for the generator controller

After running the program to find parameters for generator voltage regulators, the results found the coefficients K_P = 15.1971 and coefficients K_I = 0.5534. These coefficients respond to the transitional process of the system within the permissible parameters of the excitation circuit and the armature circuit of the generator.

B. Find The Optimum for the Motor Current Regulator

After finding the optimum parameters for the generator excitation voltage regulator, the next goal is to simulate the armature current adjustment system and the rotation speed of the dc motor to find the optimal parameters of the motor's regulators. The diagram of Matlab Simulink structure to find the optimum for the motor current regulator as Fig. 9.

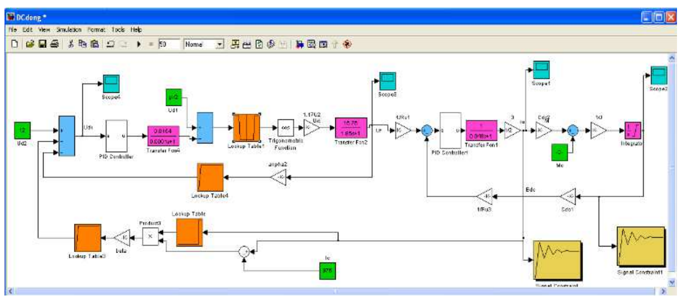

Fig. 9 The diagram of Matlab Simulink structure of the converter-generator – motor system

The simulation results are shown in Fig 10. The coefficients to find: $K_P = 0{,}1046$; $K_I = 0{,}017$ and $K_D = 0{,}0021$.

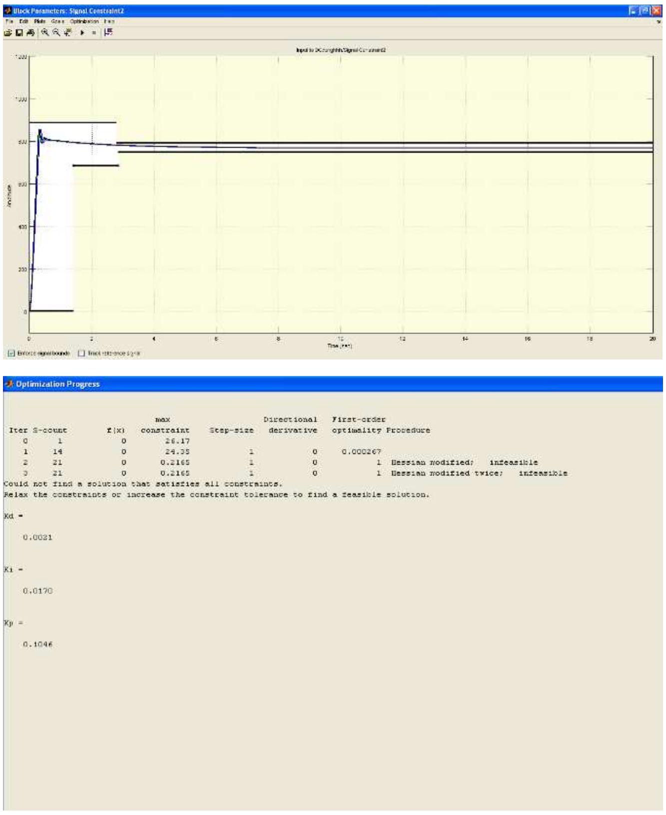

Fig. 10 Results of running the simulation to find the optimal parameters for the current of motor controller

After finding coefficients: $K_P = 0.1046$, $K_I = 0.017$, $K_D = 0.0021$, replace these results into PID regulator of armature current motor, conduct system survey with U_{sG} signals turn 12V, 9V, 6V, 3V, we see that the adjust time of the generator voltage characteristic line are relatively large, thus affecting the stable working time of the system. Therefore, it is necessary to adjust the factors of the voltage generator regulator and the armature current regulator of the motor so that the system meets stability requirements with the control levels. By re-running the simulation program, we can adjust the optimal PI and PID coefficients found above: Coefficients for the generator controller: $K_P = 15{,}1971$ and $K_I = 0.97$; Coefficients for the current motor controller; $K_P = 0.1046$; $K_I = 0{,}08$ and $K_D = 0{,}0021$.

C. Find the Optimum for The Regulator from Motor Excitation

The motor flux regulator of the motor is to change the voltage applied to the converter of the motor's circuit excitor to increase the speed of the motor over the idle speed, ideally when the excavator works in idle or light load mode. However, reducing the flux (or increasing the speed of the motor) cannot be stepless because the engine speed cannot be increased. Therefore, this section performs a limiting survey of the flux and simulates the excavator's electric drive system when changing the flux of the motor. The simulated structure diagram on Matlab Simulink is shown in Fig. 11

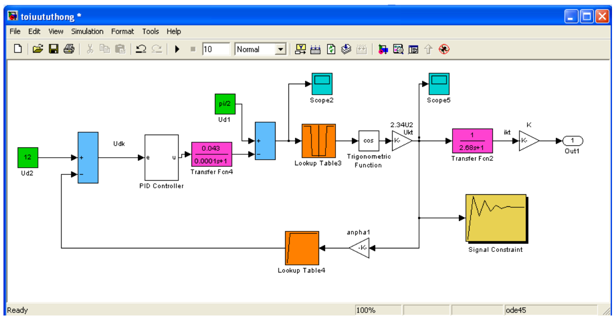

Fig. 11 Matlab structure diagram to find the optimal of the flux regulator of the motor

Results obtained when finding the optimum for the circuit flux regulator of the motor with the values $K_P = 3.1$ and $K_I = 1.4761e\text{-}005$.

D. Response System with the Optimal Values of The Regulator Has Been Found When Adjusting Voltage Generator

Changing voltage values sets the rectifier supply power to the exciter circuit of the generator (U_{EXG}) with values of 3V, 6V, 9V, 12V, respectively. It will change the voltage emitted by the generator. Then it will receive the characteristic curve that simulates the speed and current motor, as shown in Figures 13 and 14.

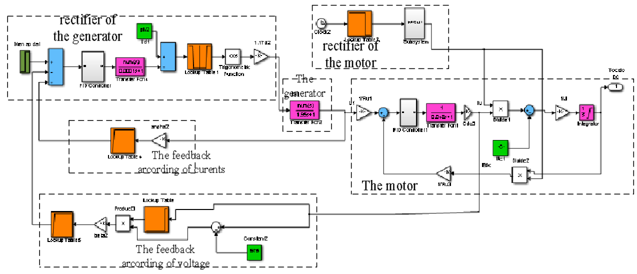

Fig. 12 The diagram of Matlab Simulink structure of the converter-generator –motor system

Simulation results when we adjust the speed and current of the motor according to the armature voltage are shown in Table. 2. From the simulation results of the speed and current of the motor in Fig. 12 and Fig. 13, when using the optimal parameters for the regulators just found, we find that the system's response is completely satisfactory.

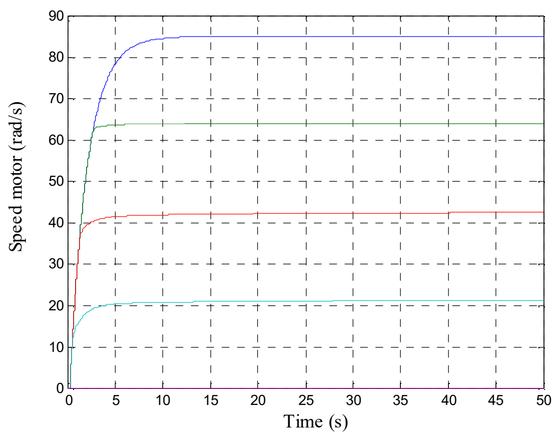

Fig. 13 The simulation results in speed of the motor when changing armature voltage

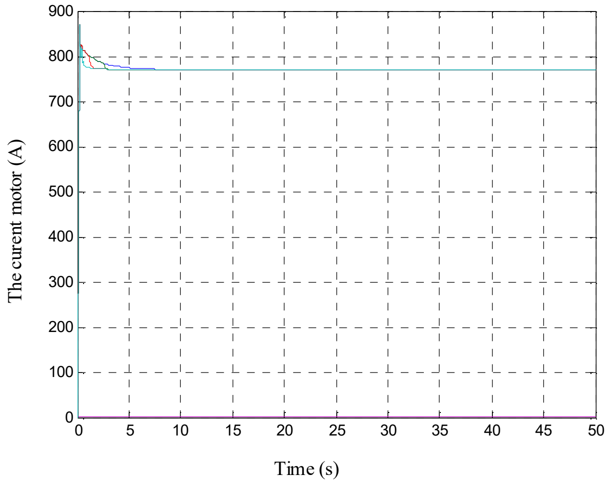

Fig. 14 The simulate results current of the motor when changing armature voltage

TABLE II
THE RESULT SIMULATION

M_C (Nm)	U_{sG}(V)	U_G(V)	I_a(A)	ω(rad/s)
$M_C = M_{Crated}$	3	748,9	770	84,93
	6	561,8	770	63,71
	9	374	770	42,42
	12	186,8	770	21,19

E. Perform System Simulations when Changing Flux Magnetic Circuits of the Motor

When changing the voltage values of the input of the rectifier of the motor's excitor with the values of 3V, 6V, 9V, 12V, respectively, speed motor will increase the value greater than the speed value Ideal load usually applies in case of no load. The speed results obtained in Fig. 15 completely meet the control requirements.

Fig 15. System simulation results when changing the flux exciter of the motor

F. Perform System Simulations when an Overload Occurs

When a large overload occurs, the armature current is too high, which will cause a fire to the motor, so it will be possible to limit the current by using negative feedback according to the current, and in this area, the negative feedback according to the voltage will not be active.

Assuming a large overload, opposing torque (M_{opt}) increases rapidly, armature current increases to a value of 1750A as the Fig.16, the speed of the motor in the cases is reduced to 0 in turn to protect the motor. Through simulating the speed characteristics in Fig. 17, we see that the drive system completely meets the requirements.

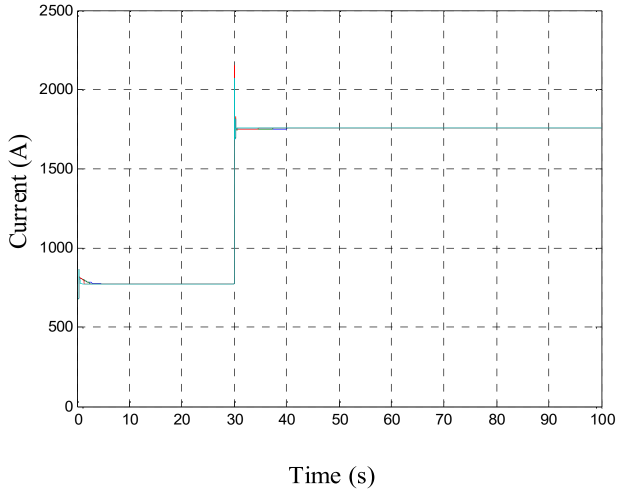

Fig 16. Simulation results of current motor when overload occurs

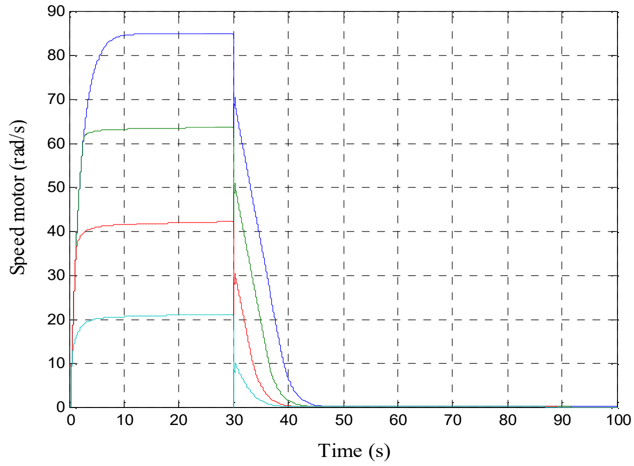

Fig. 17 Simulation results of speed motor when overload occurs.

IV. CONCLUSIONS

The electric drive system of the ЭКГ - 10 excavator uses a converter-generator-motor with a flexible working mode, which meets high requirements according to the "excavator type" working characteristics. The simulation method with Matlab Simulink software has found the optimal parameters for the regulators in the system. The simulation results have shown that the system's operation is completely in line with the requirements. However, these results are only the initial results of the survey in certain conditions while the actual production has many objective factors affecting, so, in the operation process, there still needs to be adjustment be suitable.

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