переваг. Зокрема, така модернізація дозволяє підвищити надійність системи, виключаючи ризик аварійних режимів у ланцюзі збудження, а також сприяє оптимізації технічних показників.

Підсилювач забезпечує високий коефіцієнт підсилення сигналу керування, швидкодію, і стабільність роботи в різних умовах, що робить його ефективним для застосування в енергетичних установках. У роботі детально описано конструкцію підсилювача, а також проведено розрахунки, що підтверджують його переваги у тривалих режимах роботи. Завдяки конструктивним особливостям і покращеним експлуатаційним властивостям, підсилювач можна використовувати в автоматизованих електроприводах і промислових автоматизованих системах, де потрібна висока надійність і точність.

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TRANSIENT MODES OF A DIRECT CURRENT TRACTION MOTOR WITH SERIES EXCITATION

Mykola Reutskiy, Ph.D., Anna Shymanska, Ph.D., Olexandr Nofenko, student
Igor Sikorsky Kyiv Polytechnic Institute, Departament of Electromechanics

Introduction. Transient modes of operation occur during starting, braking, reversing, and rapid changes in shaft load of a series-excited DC traction motor. Changes in electromotive force, angular velocity, moment, and current over time are characteristic of the emerging dynamic regimes. The calculation of transient modes is used to determine the power of the electric motor and power equipment, as well as for the development of control systems [1].

Modern schemes for regulating the frequency of rotation of direct current traction electric motors usually contain thyristor pulse-width or phase-pulse converters, a reverse diode and a choke for smoothing out ripples [2].

The aim of the work is study of transient and steady-state operation modes of a 150 kW series-excited DC motor, namely: acceleration and braking; direct and rheostat engine start (with change in starting resistance); instantaneous changes in voltage and engine load; changes in voltage and engine load according to a given law.

Materials of research. When adjusting the frequency of rotation with the help of a pulse-width converter, the voltage takes the form of a series of rectangular pulses with an adjustable ratio of the length of the pulses to the period of their appearance. When the specified ratio changes from 0 to 1, the average voltage value, which determines the engine speed, changes from *0* to *Umax*.

The operation of pulse-width converters is basically based on frequent commutations when adjusting the rotation frequency. The dynamic modes of the source-converter and the motor-load are also affected by the commutation of the current circuit.

The functions of the transient process of the electric motor are the rotation frequency $\omega(t)$ and the current $i(t)$, which are calculated from the initial data, such as the initial values of the frequency and current, parameters of the control circuit (forward resistance of the reverse diode, resistance of the motor circuit and inductance of the motor circuit), relative pulse length, power supply voltage, moment of inertia of the system reduced to the rotation frequency, nominal data of the motor (power, voltage, rotation frequency, torque, current and parameters of the armature and excitation windings).

The transient electromechanical process is described by two systems of nonlinear differential equations.

For intervals of action of voltage pulses $T_k \le t \le t_0 + T_k$ $(k=1,2,3,\ldots)$

$$\begin{cases} \frac{di(t)}{dt} = \frac{1}{L_1}[U_0 - i(t) \times R_1 - e_\omega(t)] \\ \frac{d\omega(t)}{dt} = \frac{1}{J}[M(t) - M_S(t)] \end{cases} \quad (1)$$

For intervals of action of voltage pulses $t_0 + T_k \le t \le T_{(k+1)}$ $(k=1,2,3,\ldots)$

$$\begin{cases} \frac{di(t)}{dt} = -\frac{1}{L_1}[i(t) \times (R_1 + R_0) + e_\omega(t)] \\ \frac{d\omega(t)}{dt} = \frac{1}{J}[M(t) - M_S(t)] \end{cases} \quad (2)$$

where:
$e_\omega(t) = C_E \times \omega(t) \times \Phi(t)$ – rotation EMF,
$M(t) = C_M \times i(t) \times \Phi(t)$ – motors torque.

The non-linear relationship between flux and current of a series excitation motor can be obtained from the universal magnetization curve in relative units [3] $\Phi^* = f(i^*)$, where $\Phi^* = \Phi / \Phi_N$, a $i^* = i / I_N$.

Approximation of the dependent function $\Phi^* = f(i^*)^q$ at $q = 0{,}5$ gives an error of less than 5% in the working range of $0{,}4 \le i^* \le 1{,}4$.

Under such an approximation, the EMF equations of rotation and moment will take the form

$$M(t) = K_M\,[i(t)]^{1,5},$$
$$e_\omega(t) = K_E \times \omega(t)[i(t)]^{0,5},$$

where

$K_M = \frac{C_M \times \Phi_N}{I_N^{0,5}}$,

$K_E = \frac{C_E \times \Phi_N}{I_N^{0,5}} \times \frac{30}{\pi}$ – constant coefficients.

Systems of differential equations for two regimes can be represented by one system that contains parameters dependent on commutation (Table 1).

$$\begin{cases} \frac{di(t)}{dt} = \frac{1}{L_1}[U(t) - K_E \times \omega(t) \times i(t)^{0,5} - i(t) \times R(t)] \\ \frac{d\omega(t)}{dt} = \frac{1}{J}[K_M i(t)^{1,5} - M_S(t)] \end{cases} \quad (3)$$

Table 1

Parameter	Value	
	During the pulse	During the pause
$U(t)$	U_0	0
$R(t)$	R_1	$R_1 + R_0$

At high switching frequencies and low pulsations of the motor current, to solve the system of equations (3), we consider $U = U_{mid}$ for the entire time interval, where $U_{mid} = \gamma U_0$ for pulse-width control and $U_{mid} = U_{max}(1 + cos\alpha) / \pi$ for phase-impulse control.

Solving system (3) under the accepted assumptions makes it possible to investigate transient and stable modes are: acceleration and braking; direct and rheostat engine start (with Rad change); instantaneous changes in voltage and engine load; changes in voltage and engine load according to a given law.

The output data for the calculation is selected taking into account the nominal data of the DC motor with series excitation are

– voltage $U_N = 600\ V$;
– power $P_N = 150\ kW$;
– current $I_N = 275\ A$;
– rotation frequency $n_N = 1480\ rpm\ (\omega_N = 155\ radps.)$;
– moment $M_N = 967\ Nm$.

Parameters

– engine wheel resistance;
– direct resistance of the damping diode;
– inductance of the motor circuit;

Design data

– moment of inertia of the engine;
– constant coefficient;
– constant coefficient;

Initial conditions

– initial start time;
– initial current;
– initial rotation frequency;
– initial pulse length.

When calculating various options, it is possible to determine the parameters of the replacement circuit, which will ensure a high efficiency, low losses and low current ripples in various operating modes.

With the use of calculations of electromechanical processes, it is possible to obtain dynamic mechanical characteristics $\omega = f(t)$ and operating characteristics of the engine, as well as external and control characteristics of the converter, which will allow to evaluate the operational and economic indicators of the engine under study with the selected system of control of its rotation speed.

When solving the system of differential equations (3) under the accepted assumptions, the limit permissible increase in the frequency of rotation of a direct current motor with sequential excitation at start-up is determined for two load modes: $M_C = 0,5\ M_N$ and $M_C = M_N$. The universal magnetization curve is approximated by a power function with $q = 0,5$, calculation step $\Delta t = 0,05$ *s*.

Conclusions. Calculation of the transient characteristics of the change in motor speed and current during acceleration at half and nominal load showed that a further increase in electromagnetic loads would lead to significant deterioration of commutation and thermal operation. Adjustment of the operation mode of the pulse-width converter in the power supply scheme of a DC motor with serial excitation should be carried out taking into account the characteristics of the speed of the voltage rise on the motor under different loads. Forcing the engine start mode can lead to its premature failure.

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