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RESEARCH ON BATTERY-OPERATED ELECTRIC ROAD VEHICLES

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16. Abstract

A mathematical analysis of battery-operated electric vehicles is presented. Attention is focused on assessing the influence of the battery on the mechanical and dynamical characteristics of dc electric motors with series and parallel excitation, as well as on evaluating the influence of the excitation mode and speed control system on the performance of the battery. The superiority of series excitation over parallel excitation with respect to vehicle performance is demonstrated. It is also shown that pulsed control of the electric motor, as compared to potentiometric control, provides a more effective use of the battery and decreases the cost of recharging.

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RESEARCH ON BATTERY-OPERATED ELECTRIC ROAD VEHICLES

V. S. Varpetian

Currently, electric road vehicles (ERV) which operate on chemical storage batteries (SB), such as electric cars, electric locomotives and electric loaders, are fairly widespread. /43*

The design of the electric equipment for these vehicles must be comprehensive in order to ensure the required static and dynamic characteristics of the ERV with specific limitations.

The SB of limited energy capacity, whose power is commensurate with the load, confers on the system a number of features governed by the fact that the energy source and the other electrical equipment of the given vehicle (electric traction motor, systems of control and power transmission, etc.) are closely interconnected. Therefore, the selection of the ERV electrical equipment must be made with consideration for the mutual effect of its individual components.

In this respect, this work examines the following topics:

1. The effect of the storage battery on the mechanical and velocity characteristics of dc traction electric motors (TM) with series and parallel excitation;

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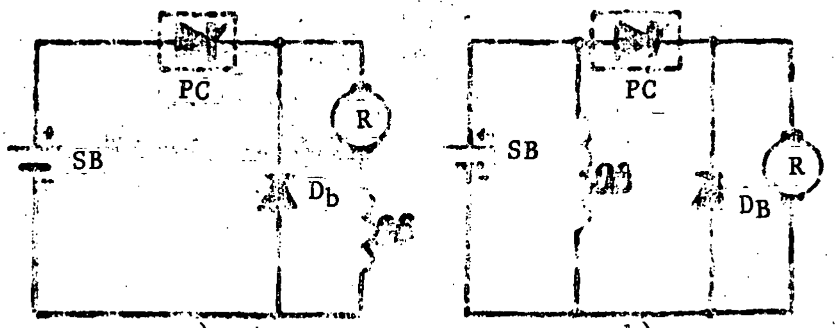
*Numbers in the margin indicate pagination in the original foreign text.

2. The effect of the TM excitation method and the speed control system on the performance of the storage battery from the standpoint of the best utilization /44 of the latter.

A schematic diagram of the TM charging is given in Figure 1, where the voltage regulator is a pulse converter conventionally designated by equivalent adjustable keys. The study was made using electrical equipment for the electric car developed and manufactured in the applications laboratory of the Yerevan Polytechnical Institute.



a) b)

Figure 1. Schematic diagram of TM charging: a — with series excitation; b — with bypass excitation. IC — pulse converter; D_b — bypass diode

The primary information for the electrical equipment of the electric car is:

SB — consists of 18 series-connected storage batteries of type 6ST-68;

TM — two dc machines of series P-42 with voltage 220 V, total rated power 16 kW, and revolution rate of 3000 rpm. The traction motors are charged from the SB through individual thyristor-pulse converters operating synchronously. At the same time, the quantities we are interested in are determined in relative units which makes it possible to extend the main results of the research to the electrical equipment of other ERV as well.

In studying the TM characteristics, the following assumptions were made:

a) the effect of the switching processes of the pulse converters (PC) is not taken into account;

b) it is assumed that the period of the pulse cycle of PC operation is much less than the electromagnetic time constant of the load circuit [1], i.e., pulsation in the load current is not taken into account.

The TM performance rate [1]

$$\omega = \frac{U_{av} - I_{av} R}{k_1 \Phi}, \tag{1}$$

where ω — TM revolution velocity; U_{av}, I_{av} — average values, respectively, of voltage and current of the TM during the pulse cycle; R, k_1, Φ — resistance of power circuit, design constant and magnetic flux of TM, respectively.

The average vlaue for voltage U_{av} is defined from [1] as

$$U_{av} = \gamma U_a, \tag{2}$$

where γ — on-off time ratio of the pulse converters;
U_a — voltage amplitude of the storage battery in the conducting state of the IC.

In order to describe the discharge characteristics of the SB, the equation from [2] is used in the following form:

$$U_c = U_0 - Ni - c_0 q - k \frac{1}{1-q} \tag{3}$$

where U_0 — constant potential; N — coefficient representing the internal resistance of the storage battery; c_0 — coefficient representing the drop in potential during the discharge due to the reduction in density of the electrolyte; /45 k — coefficient representing polarization; $q = it/Q_0$ — capacitance yielded by the storage battery in relative amounts; i and t — current and time of discharge, respectively; Q_0 — maximum discharge capacity governed by the active masses of the storage battery.

The coefficients of Equation (3) are determined according to the experimentally plotted discharge curve the the technique described in detail in [2].

The amplitude of the battery current during the conducting state of two PC will be:

$$I_a \quad 2I_{\text{av}}.$$

With consideration for the latter and Equations (2) and (3), Expression (1) will have the following form:

$$\omega = \frac{\gamma\left[n\left(U_0 - NI_a - c_0 q - k\frac{1}{1-q}I_a\right)\right] - I_{\text{cp}}R}{k_1\Phi}. \tag{4}$$

where n — number of series-connected storage cells in the battery.

The effect of the storage battery on the TM characteristics at a given moment in time is determined by the amount of capacitance of the battery before this time, which in Equation (4) is taken into account by q, which also determines the charge state of the SB.

With series excitation of the TM, in a specific charge state of the storage cell (q), with a given on-off time ratio γ of the pulse converters, I_{av} varies. This is used to determine the magnetic flux Φ from the curve of motor magnetization and the voltage of the battery with current I_a.

During bypass excitation of the TM, its exciting current (see Figure 1,b) does not remain constant due to the change in voltage of the SB at current I_a and capacitance q. In this case the quantity Φ is determined from the magnetization curve using the excitation current

$$i_{\text{в}} = \frac{U_{\text{а.ср}}}{R_{\text{в}}},$$

where R_B — resistance of the by-pass coil of excitation;
$U_{\text{a.av}}$ — average value of voltage for the SB during the pulse cycle PC of operation.

Usually under operating conditions i_B ...* I_{av}. Therefore, one can disregard the effect of i_B on the SB voltage. At the same time, from the accepted assumption (b) it follows that one can completely disregard the pulsation in the current of the excitation bypass coil, since the electromagnetic time constant of the bypass coil is much greater than that of the armature.

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*Translator's note. Illegible in foreign text.

The battery voltage at current I_a equals U_a, while in the nonconducting PC state $I_a=0$ and the SB voltage from (3) equals $(U_0 - c_0q)$. Consequently, the average value for the battery voltage is defined as: /46

$$U_{a.av} = U_a\gamma + (U_0 - c_0q)(1-\gamma) = \gamma\left(U_0 - NI_a - c_0q - k\frac{1}{1-q}I_a\right) +$$

$$+ (U_0 - c_0q)(1-\gamma) = U_0 - c_0q - \gamma I_a\left(N + \frac{k}{1-q}\right). \qquad (5) \qquad (5)$$

The torque of the traction motors is defined as $M=k_1\Phi I_{av}$.

On the basis of the aforementioned, with consideration for (4) and (5), Figures 2, 3, and 4 present the calculated velocity $\nu(i_{av})$ and mechanical $\nu(\mu)$ characteristics of the pulse-controlled motor P-42 with different types of excitation during various charged states of the battery. The rated data of the motor were taken as the reference values. The characteristics were computed in the range of permissible motor overload using current $i_{av} \leqq i_{per} = 2.5$. At the same time, four characteristics for the charged state of the battery q=0, 0.25, 0.5, 0.75 correspond to each value γ (with an increase in q, the characteristics are shifted along the ν axis).

The TM characteristics during bypass excitation obtained are nonlinear due to the change in current (Φ) of the motor with a change in the SB voltage. In addition, with specific charged SB states the torque of the traction motor during bypass excitation is reversed. This is explained by the fact that in a velocity reduction the torque is more strongly affected by a drop in the excitation current of the TM than an increase in the armature current. Reversal in the TM torque during bypass excitation is extremely undesirable, insofar as in this case the dynamic characteristics of the ERV are strongly impaired.

Analysis of the dependence of the average value for the SB current $i_{a.av}$ on the torque μ of the TM during bypass and series excitation, which can be constructed with consideration for the characteristics given in Figures 2, 3, and 4, shows that during starting and overcoming the overloads, i.e., in the range $\mu<1$, at the same torque the current $i_{a.av}$ which is demanded of the battery during series excitation is always less than during bypass. At the same time, the average value for the SB current should be defined as: /47

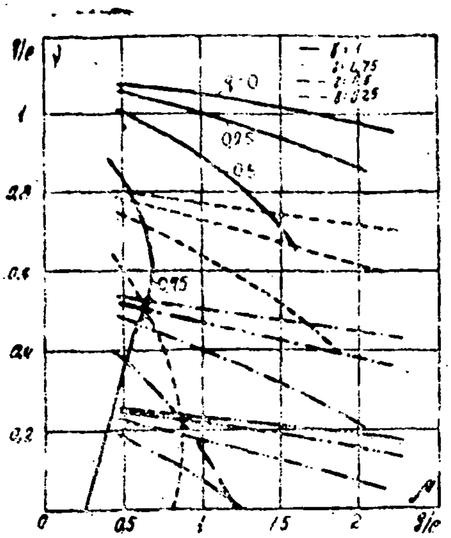

Figure 2. Mechanical characteristics of TM during bypass excitation

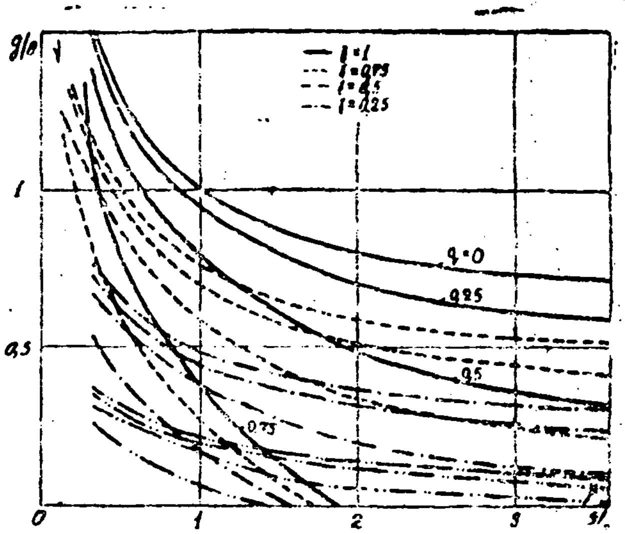

Figure 3. Mechanical characteristics of TM during series excitation

$$i_{a.av} = \gamma(2i_{av}) \qquad (6)$$

In addition, from Figure 4, with consideration for (6) it follows that during the pulse-controlled start of the TM with bypass excitation and maintenance of a constant current of the motor (i_{av}) with an increase in the TM velocity its torque is reduced depending on the charged state of the SB. For example, during the start of the TM by current i_{av}=2 to velocity ν=0.6 when q=0.5, the torque is diminished from 2.25 to 1.7. This is explained by the fact that under the condition i_{av}=const starting occurs by a smooth increase in the on-off time ratio γ which results in an increase in the current and a drop in the battery voltage. As a result of this, with an acceleration in the TM the current in the bypass coil of excitation is reduced. A decrease in the torque due to the bypass excitation of the TM in turn impairs the dynamics of the ERV.

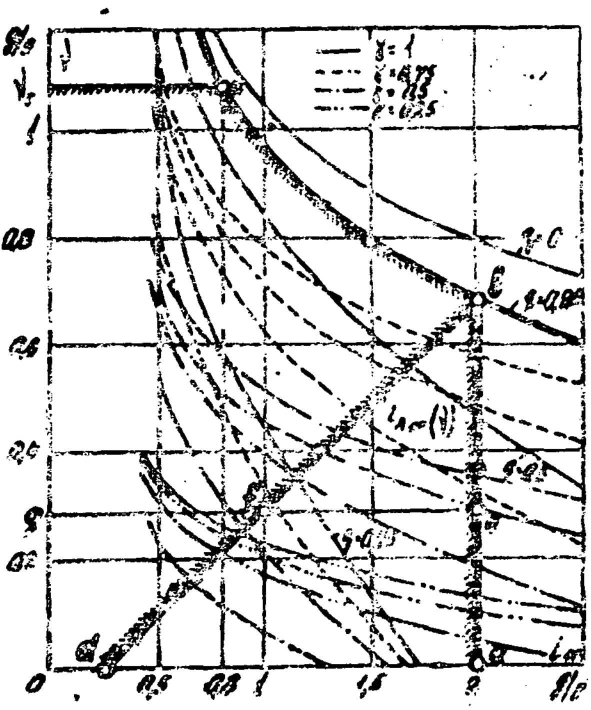

Figure 4. Velocity characteristics of TM during series excitation

Analysis of the dependence of the maximum power determined from Figures 2, 3 as $P = \omega M$ and the maximum TM torque for the charged state of the battery shows that the maximum torque and power of the TM during series excitation are greater than during bypass excitation for all practical values of q.

It follows from the aforementioned that in series excitation of TM, in comparison with the bypass, not only the acceleration of the ERV improves but also — according to [3] — the use of the SB improves with a reduction in $i_{a.av}$.

During series excitation, the effect of the control system of the TM on the degree of SB use under the same conditions of ERV movement can be evaluated by comparing the pulse and rheostat control methods which are employed in ERV dc electric drives.

For this purpose we will determine the discharge capacitance of Q_0 of the battery for one traction motor for pulse starting with a constant value of current i_{av} for a given characteristic (here we will disregard the change in the charged state of the SB and will examine the ERV starting with constant acceleration). We will assume that in the charged state of the battery $q = 0.25$, the traction motor is started by current $i_{av} = 2$ to $\gamma = 1$ (section ab on characteristic abc, Figure 4), after which the startup continues according to characteristic bc to point c corresponding to the static load of the motor $i_{av} = 0.8$ (according to the data of [4], the current of each motor during the uniform movement of the electric car is roughly 80% of the rated). Along section bc the pulse converter is completely open ($\gamma = 1$) and, according to (6), $i_{a.av} = 2i_{av}$. On section ab, /48 where $\gamma < 1$, according to Expressions (4) and (6) under the condition $i_{av} = \text{const}$ the relationship $i_{a.av}(\nu)$ is represented by the straight line bd. In order to construct straight line bd, its second point j is located as follows: from point e of the intersection of the straight line ab with the intermediate characteristic $\gamma < 1$ (on Figure 4, the characteristic is selected with $\gamma = 0.5$) for given $q = 0.25$, a horizontal is marked containing the section gf which is equal to current $i_{a.av} = \gamma i_{av} = 1$. By joining points b and f by a straight line, we obtain the relationship $i_{a.av}(\nu)$. In this case the discharge capacitance Q_0 of the battery will be proportional to the shaded area limited by line dbc and axis ν.

During the formation of the starting characteristic abc by a change in the rheostat resistance in the motor circuit, the current of the battery will everywhere be equal to $i_{a.av} = 2i_{av}$, i.e., with rheostat control the amount of discharge battery capacitance Q_R will be proportional to the area limited by the actual starting characteristic abc and the axis ν. The relationship of the discharge capacitances during pulse and rheostat starting, calculated by graphic integration of the appropriate curves dbc and abc according to the variable ν in the examined case, equals $\alpha = Q_0/Q_R = 0.69$.

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It follows from Figure 4 that at the assigned static load the value α depends on the position of the starting characteristic (i_{av}, ν). The latter is determined by the required conditions for ERV starting. For the two charged states of the battery, using the indicated graphic method one can plot the dependence of α on the conditions of ERV starting with the same static load $i_{av} = 0.8$ (Figure 5). The amount γ_k determines the position of the final characteristic $\nu(i_{av})$ during the start of the TM.

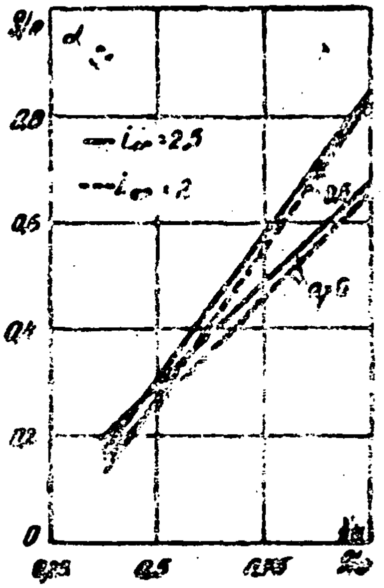

Figure 5. Comparison of discharge capacitance of storage battery during pulse and rheostat startings of TM. k — final value of on-off time ratio used to control the average voltage on the TM by maintaining the constant current $i_{av} = \text{const}$

If one considers that during the movement of the ERV under city conditions the value γ_k on the average is 0.5 - 0.7, then it follows from Figure 5 that in comparison with the rheostat, during pulse TM starting the discharge capacitance taken from the SB is reduced roughly by 60%. This improves the use of the SB and increases the capacitance reserve with further travel of the ERV after starting.

On the basis of the aforementioned, one can draw the following basic conclusions:

1. The method of bypass excitation of traction electric motors using direct current which operate on storage batteries is inferior to the method of series excitation in terms of ensuring the required dynamic characteristics of the electric vehicle.

2. Series excitation of electric motors in comparison with bypass excitation results in an improved use of the storage battery during starts and permissible overloads of the motors.

3. With battery operation of the traction electric motors, the use of pulse control results in improved operation and saving in capacitance of the storage battery during starting and movement of the electric road vehicles in modes $\gamma < 1$.

The results of the study can be used for designing battery-operated electric road vehicles.

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