Differential electric drive in the machine industry

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Abstract. This paper is devoted to the search for optimal weight and size parameters of the “power supply - electric motor” system in industrial vehicles. The mathematical formulas describing the differential electric drive based on the simplest planetary gearbox are given. The schemes of parallel and serial connection of differential electric drives are considered. The methods of searching for the optimal laws of control of a differential electric drive based on DC motors are shown. The natural mechanical characteristics of a serial connection of a differential electric drive, as well as its adjusting and artificial mechanical characteristics, are given.

1. Introduction
As is well known, a large number of industrial vehicles (tractors, bulldozers, etc.) are used in the mining industry. Their electrical complex always has a power limit, since the power is supplied from an autonomous source (battery), especially this circumstance affects the electric starter system necessary for starting the internal combustion engine. As a rule, the electric starter system or the “power source - electric motor” system is designed in such a way as to ensure the operational requirements imposed on it and at the same time have optimal weight and size parameters.

Thus, the authors believe that the most rational solution may be power circuits based on differential drives, when the opportunity arises, maneuvering the operating modes of electrical machines as boost-voltage sources of EMF, or drastically reduce the total power of an adjustable power source, or even refuse it.

As a subsequent example of optimizing the “power supply - engine” complex, a serial differential electric drive is used, which is characterized by a very small amount of installed total power of electric machines forming the power source of armature chains.

2. Materials and methods
The main link of the differential electric drive (DED), which determines its most essential features, is the differential gear (DG). It can be made based on either a planetary series or a conical differential. The most widely used gears are in DED with two degrees of freedom. For a planetary differential single-row gear there is the following relationship between the angular velocities of its links [1]:

\[ n_c = n_s \times \frac{i}{i+k} + n_e \times \frac{i}{i+k} \]  

(1)

where \( n_c, n_s, n_e \) are the angular velocities of the carrier, the sun gear, and the epicyclical gear; \( k=z_e/z_s \) is the main gear ratio of the planetary-row, where \( z_e \) is the number of teeth of the epicyclical and sun gears.
In the technical literature devoted to the calculations of planetary gears [1], the magnitudes of the torques applied to the main links of the ideal (lossless) planetary series are usually determined using expressions:

\[-M_c = M_s \times (1 + k) + M_e \times \frac{1+k}{k}\]  \hspace{1cm} (2)

where \(M_c, M_s, M_e\) are the torques applied through gearing to the main links of the planetary series.

If both the magnitudes of the angular velocities of the links, and the torques of their action (reaction) on the shaft of the working mechanism are brought to the shaft of the latter, then equations (1) and (2) are written in the form of the following simple relations:

\[n_1 + n_2 = n_3,\]  \hspace{1cm} (3)
\[M_1 = M_2 = M_3,\]  \hspace{1cm} (4)

where \(n_1, n_2, n_3\) - the angular velocity of the input 1 and 2 and output 3 shafts DG, reduced to the speed of the shaft working mechanism; \(M_1, M_2, M_3\) - torques on the input I and 2 and output 3 shafts DG, reduced to the shaft of the working mechanism.

Relations (3) and (4) are valid for all differential gears with two degrees of freedom, performed based on both the planetary series and the bevel differential.

The technical literature draws attention to a number of valuable advantages of electric drives with DG. Firstly, in the transmission of torque, the planetary gear themselves do not create radial forces in the main links, and the force itself is not distributed in the contact zone of one gear pair, but according to the number of satellites. This facilitates the shafts, support and reduces the magnitude of the contact stresses in the mesh. Due to this, the mass of planetary gears turns out to be 2 ~ 4 times less than conventional (with fixed rotation axes) gears [3, 4].

Due to the summation of the angular velocities of both input branches with perfect alignment of torque, the electric drive with DG receives a number of fundamentally new qualities. Thus, it is important to point out the possibility of obtaining special mechanical characteristics of an electric drive without the use of complex closed-loop control systems [3]. A large control ranges on the speed of the output shaft with limited speed control ranges of each of the electric motors is achieved [5]. There is a perfect alignment of mechanical torques on both shafts with different mechanical characteristics, electric motors [6]. Realization of two-channel electric drives is possible [7]. Low power channels effects on the excitation windings of the ED and improving the reliability of the electric drive, since with the complete failure of one of the EDs, the mechanism can work from another ED.

Due to the two-channel (i.e., according to the parallel connection of the links), the total reduced torque of inertia \(J\) of the entire electric drive is reduced compared to the torques of inertia \(J_1\) and \(J_2\) of its branches. Here there is a certain analogy with the properties of electrical circuits, in which the elements are not connected in series, but in parallel, namely:

\[\frac{1}{J} = \frac{1}{J_1} + \frac{1}{J_2} .\]  \hspace{1cm} (5)

The reduced torque of inertia \(J\) allows to improve the dynamic characteristics of the electric drive in the EDS and, therefore, to improve the control accuracy [8]. In general, industrial electric drives the differential electric drive may be preferred in the case of mechanisms subject to abrupt (including emergency) locking, when In an electric drive with a small torque of inertia, shock loads are significantly reduced [9].

In EDS and electric drives with a deep and ultra-deep speed control range, the use of DEDs, where both EDs rotate in different directions when the output shaft is stopped, improves the accuracy of the electric drive by eliminating the instability of the resistance torque on the shaft of each of the EDs due to the relatively large influence of the torque of friction forces of the brushes [10].
According to their characteristics, electromechanical transmissions are DED, but they must be assigned to a separate class, since in them at least one of the branches of energy transfer remains mechanical.

In autonomous electric drives (especially with an on-board network voltage of 27 V), where a direct start-up of ED is acceptable, additional quite attractive and previously unreachable opportunities open up to DED, when it is possible to completely abandon regulated power sources in ED armature chains and maneuvering the operation of electric machines as booster sources of EMF, to achieve continuous control of the speed of the electric drive in all four quadrants.

In autonomous electric drives, where undervoltage (for example, \( U_s = 27 \) V) of the supply network is often used, direct connection of the armature windings of electric motors to the buses of the autonomous power source is practiced. It is possible to use both parallel and serial DED [11].

In the first case (Fig. 1a), the electric motors \( I_a \) and \( M_2 \) are mechanically connected to the input shafts I and D. The output shaft 3 is connected with the working mechanism. Armature windings MI and M2 are joined in parallel and connected to a constant unregulated voltage source \( U_c \). Control of the DED is carried out by changing the currents in the windings of the excitation ED.

A less well-known scheme of a sequential DED, the idea of which was first expressed in [12], is as follows. ED MI and M2 (Fig. 1b) are mechanically connected with the input shafts I and 2 DG, the output shaft 3 DG is connected with the working mechanism. The armature windings MI and M2 are joined in series and connected to a constant unregulated voltage source \( U_c \). Control of the DED is carried out by changing the currents in the windings of the excitation ED.

In the initial state of the electric drive, the magnetic flux of the ED is equal in magnitude and opposing. ED MI and M2 rotate in different directions, and the speed \( n_3 \) is zero. External stress is divided in half by each of the armatures MI and M2. When the electric drive needs to be given a rotation in a given direction, then one of the electric machines (which rotates in the opposite direction) is re-magnetized so that the magnetic fluxes MI and M2 become consistent. Since in the process of zero crossing of the magnetic flux of one of the ED, the second ED rotates [13].

![Figure 1. Power circuits of parallel (a) and serial (b) DED](image)

The static properties of a sequential DED are described by a system of equations:

- differential gear DG

\[
n_3 = n_1 + n_2
\]

\[
M_3 = n_1 + n_2
\]

- armature chain DED

\[
U_s = E_1 + E_g
\]

- EMF of machines MI and M2
\[ E_1 = n_1 \times \Phi_1 \]  
\[ E_g = n_g \times \Phi_g \]  
- electromagnetic torques of the machines MI and M2  
\[ M_{em1} = \Phi_1 = M_1 + DM_1 \]  
\[ M_{emg} = \Phi_2 = M_g + DM_g \]  
- speed losses in the MI and M2 machines (together with the connected part of the kinematic chain DR)  
\[ DM = k \times n \]  
\[ DM_2 = k \times n_g \]

where \( n_1, n_2, n_3 \) - the angular velocity MI, M2 and the working mechanism, reduced to the shaft of the working mechanism; \( MD_1, MD_2 \) - electromagnetic torques of ED MI and M2; \( M_1, M_2, M_3 \) - torques on shafts 1, 2 and 3, referring to the shaft of the working mechanism; \( F_1, F_2 \) - magnetic fluxes ED MI and M2; \( K \) - coefficient of speed loss.

3. Results and discussion
The analysis of the static DED modes was performed on the basis of the characteristics obtained by solving a written system of equations on a computer. When calculating, the mains voltage \( U_s = I \) was taken, the resistance of the armature circuit was \( R_a = I \). Thus, the adjustable variables were represented in relative units, when \( U_s \) was taken as the basic EMF \( E_1 \) and \( E_2 \), rotation speed \( n_1, n_2, n_3 \) - ideal idle speed of one when the motor is braked with another shaft, the armature circuit current \( I_{ac} \) is the short-circuit current, the magnetic fluxes \( F_1 \) and \( F_2 \) are their nominal values, the torques \( M_{e1}, M_{e2}, M_1, M_2, M_3, AM \) are the electromagnetic torques of the ED at the short circuit current in the armature circuit. The loss coefficient is \( k = 0.05 \), which is typical for a BOT with a power of 0.1 ... 1.0 kW.

Of practical interest are the following static characteristics: natural mechanical, adjusting, and describing the mode of maintaining a given constant speed of the output shaft DR.

Reducing the initial displacements of \( F_1 \) and \( F_2 \) at the point \( U_{in} = 0 \) reduces the inactivity zone of the DED, but this increases the armature current. When the initial displacement flow is not set (\( F_1 = F_2 \)), then we obtain the usual scheme of pole control with short-circuit current in the armature circuit when reversing the drive. Of practical interest are the static characteristics of the DED, operating in a closed system in the mode of maintaining a given speed of the output shaft and loaded with a static torque. In particular, if \( n_1 = 0 \) is supported and the torque \( M_3 \) changes from zero to one (Fig. 2), then the angular velocities \( n_1 \) and \( n_2 \), taking for \( M_3 = 0 \) the values of \( n_1 < r = \pm 5 \), increase in absolute value, reach a certain maximum and then decrease to zero.

In the zone of small and medium torques, when the voltage drop in the armature circuit is small (you can take \( I_1R_a = 0 \)), the state of the DED is determined mainly by a change in the EMF \( E_1 \) and \( E_2 \). Here, when it changes for the purpose of maintaining \( n_1 = 0 \), the absolute value of \( F_2 \) decreases. This causes a decrease in \( E_2 \), resulting in increased voltage at the armature M1, which leads to an increase in \( n_1 \). As a result, the M1 engine is able to overcome not only the torque of its own speed losses, but also “help” the M2 engine in overcoming its speed losses. As a result, the resulting redistribution of energy fluxes increase the torque at the exit of the DS and the velocity \( n_2 \).
In the zone of large $M_3$ values, due to an increase in the armature circuit current, the proportion of the voltage drop across the armature circuit resistivity is significant. This causes a decrease in the total EMF $E_1 + E_2$ and a decrease in the absolute values of $n_1$ and $n_2$. In the short circuit mode of the DED (when $I_{sa} = I$) $E_1 = E_2 = 0$ and all the voltage $U_s$ of the mains supply is extinguished on the active resistance of the armature windings.

The increase in the speeds $n_1$ and $n_2$ is the more significant the smaller the speed loss in the electric drive: with $k = 0.06$ $n_{\text{max}} = 1.7$; with $k = 0.02$ $n_{\text{max}} = 3.6$. When $k = 0$ (ideal drive), the maximum values of $n_1$ and $n_2$ increase infinitely, i.e. the circuit becomes inoperative. The presence of overshoot speed leads to an overestimation of the installed capacity of electric machines in the sequential DED scheme.

When DED is loaded, the $F_2$ flux changes very unevenly: to overcome the increase in $M_3$ from 0 to 0.05 (i.e., only by the value of the owner of the speed losses in the differential branches of the DED). It is required to change the flow $F_2$ from -1 to 0, and with a further increase of $M_3$ from 0.05 to +1, it is necessary to change $F_2$ from 0 to +1.

4. Conclusions

Thus, the analysis of the static modes of the serial DED revealed a number of features of its characteristics, that are significant when developing the considered class of electric drives: the softness of the natural mechanical presence of a dead zone according to the control signal, the overshoot of the rotational speeds of the motors when loading the drive in the output shaft speed maintains continuous control all possible range of changes in the magnetic fluxes of electric cars. Therefore, it is hoped that the deficiencies noted are not unavoidable, and therefore one should somehow try to improve the control characteristic of the serial DED.

As shown by the calculations, then supplemented by experiments on a laboratory model, there is no need to choose the power of the keys, comparable or close to the installed capacity of the electric machines $M_1$ and $M_2$. It is enough to focus on the amount of power speed losses in the differential branches of the electric drive, which in DED with a capacity of up to 1 kW does not exceed 30-40% of the rated power of each of the ED.

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