Electric traction drive of an agricultural tractor

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Abstract. In the article, the task of expanding the range of work in speed and moment of traction electric drive of an agricultural tractor is considered. We propose to achieve this goal through the use of a two-stage gearbox based on a three-row planetary gear. It is proposed to shift gear ratio by eliminating one row of the gearbox from the process of converting mechanical energy. Evaluation of the effect of the proposed solution was tested on a refined mathematical model, in which the electric drive is presented as a complex "frequency converter with vector control - motor - working body. The obtained simulation results allow us to argue that with the correct operation of the system in long-term operation, energy savings of up to 12% can be achieved (for various types of soil and operating modes: arable land, driving), and for transient processes - 7-8%.

1. Introduction
The tractor is the basic machine in the technological process and it can work only in combination with attachments [1]. Depending on the type of unit, agricultural, road, forest and industrial tractors are distinguished. The difference between the tractor and other traction machines is that for the tractor the soil is not only a surface for movement, but also a working body with which the tractor interacts. Figure 1 shows a qualitative view of the tractor traction characteristics, the dependence of the speed v and power N on the traction force on the hook [2]. The tractor transmission is usually stepwise, so the quantitatively indicated schedule will vary depending on the gear ratio [3].

![Figure 1. Traction characteristic of a diesel tractor.](image)

The transition from a diesel traction engine to an electric one allows to solve a number of problems. The traction drive is virtually silent [4]. This is extremely important in terms of improving working
conditions for workers. The electric drive allows you to provide close to maximum torque in a wide speed range, while for a diesel engine, a high moment is achieved only at 4000 ... 6000 rpm. At low speeds, the moment is about 30% of the nominal [5].

High requirements for handling capacity are imposed on the tractor [6]. When the plough is wedged in solid ground, a short-term effort is required. In the absence of the possibility of such a jerk, the quality of the resulting furrow significantly deteriorates [7].

In addition, since the electric drive tractor is an autonomous vehicle, the efficiency of the energy stored in the battery cells is extremely important [8]. Only a unit that is highly efficient in terms of energy consumption, having a high power reserve, high overload capacity, a wide range of speeds and moments, can be used in agricultural machinery [9].

2. Requirements for electric drive
As a rule, autonomous electric vehicles such as electric cars, buses, snowmobiles, are performed in a gearless design. The lack of transmission due to the above reason. High starting torque does not require additional downshifts. Thus, in autonomous electric vehicles operating under constant conditions in a certain fairly narrow range of load moments, the use of a transmission is impractical and only complicates the design [10].

For a tractor, operating conditions can vary significantly [11]. Viscous wet soil, loose soil, dried stony soil represent a fairly different environment in terms of required effort. On the other hand, high demands on the speed range are set for the tractor [12]. It is important both to ensure the movement of the tractor on the highway or on the stages with high speed, and very slow movement when arable land of fruit crops (berries, vegetables) [13].

To minimize losses in the electric drive, work with maximum efficiency, the engine during operation should be located in the vicinity of the nominal point of static mechanical characteristics for as long as possible. To do this, it is proposed to introduce a two-stage manual transmission [14].

Using a traditional mechanical gearbox in this case does not seem appropriate. Firstly, there is a tendency towards a transition to unmanned control of agricultural machinery based on GIS technologies. Secondly, the requirements of high efficiency of the electrical installation make it necessary to improve its overall dimensions [15]. A traditional gearbox with regard to clutch and gear levers is rather cumbersome [16].

3. Planetary gear
The most compact mechanical transmission is the planetary gear. The main element of its design is the sun gear, which, through the satellites (dependent gears), is mechanically linked to the epicyclic ring, which has teeth on the inside [17]. The axis of the satellites, in turn, are connected mechanically by a rigid carrier. During rotation, this mechanism has two degrees of freedom; it can play the role of an adder of energy or differential [18]. When one of these elements is inhibited, the mechanism has one degree of freedom and performs the function of a mechanical reduction gear [19].

The mathematical description of the relationship of the velocities of the elements is determined by the formula [20]

\[ \omega_C = \frac{\omega_S + g \cdot \omega_R}{1 + g}, \]

where \( \omega_C, \omega_S, \omega_R \) — the angular speeds of the central gear, sun and epicycle, respectively, \( g \) – the planetary gear ratio, which is determined by the ratio of the epicycle diameter to the diameter of the sun [21].

4. Proposed solution
Figure 2 shows a functional diagram of a three-stage planetary gear. At the first stage, the calculations were performed on a simplified model. The speed of the output shaft of the engine was simulated by a constant speed source, which was connected to a single shaft, on which the sun gears of the first and
second rows of the gearbox were located [22]. The ring of the first row PG1 (planetary gear 1) is connected to the disco-brake brake through an electromagnetic clutch F1, which can be in the “closed” and “open” state [23]. The carrier of the first row is mechanically connected to the epicycle of the second row of PG2. This channel can also be inhibited by force [24].

Figure 2. Functional diagram of a three-stage planetary gear.

Braking can be carried out by friction discs or an electromagnetic clutch [25]. A more accurate answer to the question of the appropriateness of using one or another method is possible only with a more detailed design of the mechanical part of the transmission [26].

The first and second brakes F1 and F2 can only be activated alternately. That is, when the first clutch is closed, the second must be open, and vice versa. Let’s consider these two operating modes in more detail [27].

With a braked ring of the first row, it acts as a downshift. Since in this case [28]

$$\omega_{R1} = 0, \text{then } \omega_{C1} = \frac{\omega_{S1}}{1+g}$$

For convenience, we denote the speed of the motor shaft as $\omega_1$.

Then $\omega_{C1} = \frac{\omega_1}{1+g}$, as $\omega_{S1} = \omega_{S2}$.

The speed of the second row central gear in the first case will be equal to [29]

$$\omega_{C2} = \frac{\omega_{S2} + g \cdot \omega_{R2}}{1+g} = \frac{\omega_1 + g \cdot \omega_{C1}}{1+g} = \frac{\omega_1 \cdot (1+2g)}{(1+g)^2}.$$ 

Note that this expression is true when the gear ratios of the first and second row are equal [30]

$$g_1 = g_2 = g.$$ 

The gear ratio of the channel “engine shaft - carrier of the second row” in the first case will be equal $j_1 = \frac{\omega_1}{\omega_{C2}} = \frac{(1+g)^2}{(1+2g)}$.

In the second case, when the ring of the second row is blocked and the first brake is opened, the engine power is directed directly to the solar gear of the second row [31]. In fact, the transmission of the first row in this case does not participate in the conversion of mechanical energy [32].
For the second case $\omega_{c2} = \omega_1 / (1 + g)$. And the gear ratio of the channel "engine central gear of the second row" will be equal to $j_2 = \frac{\omega_1}{\omega_{c2}} = 1 + g$.

Thus, we get different gear ratios in the first and second cases [33]. For example, for $g = 2$, $j_1 = 1.8$; $j_2 = 3$.

The driver of the second row is mechanically rigidly connected to the solar gear of the third row PG3. The epicycle of the third row is always braked [34]. The third row of planetary gear in both the first and second operating modes performs the function of downshift [35].

For clarity, the description of the operation of the planetary transmission is presented in table 1.

| An epicycle of the first row | Operating mode 1 | Operating mode 2 |
|-----------------------------|------------------|------------------|
| An epicycle of the second row | Connected to the central gear of the first row | Braked |
| The speed of the second row central gear $\omega_{c2}$ | $\omega_1 \cdot \frac{(1 + 2g)}{(1 + g)^2}$ | $\omega_1$ |
| Gear ratio of the channel «engine shaft-second row driver» | $\frac{(1 + g)^2}{(1 + 2g)}$ | $1 + g$ |
| Gear ratio of the channel «engine shaft-output shaft (third row driver)» | $\frac{(1 + g)^3}{(1 + 2g)}$ | $\frac{(1 + g)^2}{(1 + 2g)}$ |
| Gear ratio of the "motor shaft – output shaft" channel at $g = 2$ | 5.4 | 9 |

5. Refined mathematical model

At the second stage of the study, the energy efficiency of the proposed solution was evaluated. For this, a refined mathematical model was created in the Matlab-Simulink software environment, in which the electric drive was considered as a "converter - asynchronous motor" complex. The operation of the frequency converter in the vector control mode was simulated. In [36], an updated mathematical model of a traction electric drive using a three-row planetary gearbox is given. The inverter receives power from a direct current source, an analogue of the battery installed on board the tractor body. The speed reference signal “Signal 1” is fed to the input of the inverter key pulse generating unit. The principle of generating control signals for opening and closing keys of a six-pulse circuit is standard and is given in [37].

Measured phase currents $i_a, i_b, i_c$ converted to coordinate system d-q, associated with the longitudinal and transverse axis of the rotor. The formation of the transverse component $q$ allows you to adjust the moment on the motor shaft, and the longitudinal component of the current $d$–flow. On the basis of the reference signals $i_d$ and $i_q$, as well as the angle calculated by the observer $\Theta$ between the specified coordinate axes, currents are formed in a fixed coordinate system associated with the longitudinal and transverse components of the stator, and then phase currents $i_a, i_b, i_c$ are formed [38].

For comparison, a gearless drive model was used, in which the electric drive model was presented similarly, but the transmission in the form of a planetary gear was absent, and the output speed was removed directly from the engine shaft. This model is not provided in the article [39].

Figure 3 shows the oscillograms of starting the traction engine in the system without using the transmission and in the proposed system. The graph shows the oscillograms of the stator current, speed, and torque on the motor shaft. As can be seen from the figure, with the same (set) acceleration time, the system consumes a significantly lower current in its initial stage – 90A versus 185 in a system without
transmission [40]. The difference in the moment is also about 95%. For a comprehensive assessment of efficiency, the indicator of power consumed by the systems was used [41].

![Oscillograms of stator current, speed and electromagnetic moment on the shaft.](image)

**Figure 3.** Oscillograms of stator current, speed and electromagnetic moment on the shaft.

6. **Evaluating the effectiveness of the solution**
   The simulation results showed that the proposed system consumes 18% less energy, all other things being equal, starting conditions. When you actually work in long-term mode, the effect can be about 7-8%.

   It should be noted that the proposed system, the principle of operation of which is largely similar to the automatic transmission of a car, allows you to switch gears without additional pauses for uncoupling with the engine of the mechanical channel.

7. **Selecting the element base**
   In automatic transmissions of cars, the gear ratio is varied according to the principles similar to those presented in this paper. Braking of certain elements of planetary gears is carried out in cars by means of friction discs.

   For a tractor, the torques and therefore the friction forces in the gears are much higher. In this regard, it is more appropriate to use electromagnetic clutches instead of friction disks, the friction in which is significantly less. This will improve the overall reliability of the system. In addition it is necessary to introduce the possibility of mechanical locking when fully engaged in the design of the couplings.

8. **Conclusions**
   The proposed system allows you to control the gear ratio digitally. This allows the system to be used in self-driving tractors.
It should be noted, however, that the proposed solution complicates the drive control system. Makes it less reliable by using additional mechanical components. Management requires experience from the pilot for the correct operation of the system and appropriate switching between modes during long-term operation. In the case of unmanned control, the system needs to be improved in terms of creating an adaptive part to the quality of the soil and other working conditions. If the gearshift is used correctly, it is possible to achieve energy savings of up to 8 ... 12%. Using this system allows you to instantly achieve an increased torque, which is sometimes acutely necessary when working with a plow.

In addition, there may be a problem of overheating of friction disks or electromagnetic clutches at high moments.

References
[1] Baranov L A 2017 Russian Electrical Eng. 88(9) 579-82
[2] Men’shenin A S and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 228-33
[3] Grechishnikov V A, Kurov N D and Vlasov S P 2018 Russian Electrical Eng. 89(9) 507-11
[4] Gulyaev I V, Dar’ enkov A B, Kuzmenkov A N and Titov V G 2017 Russian Electrical Eng. 88(6) 342-6
[5] Lapshina V A, Popov A A and Gulyaev I V 2017 Russian Electrical Eng. 88(6) 347-50
[6] Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 189-92
[7] Shamanov V I 2018 Russian Electrical Eng. 89(9) 536-9
[8] Gryzlov A A, Grigor’ev M A and Imanova A A 2017 Russian Electrical Eng. 88(4) 193-6
[9] Belykh I A and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 234-9
[10] Kosarev A B and Kosarev B I 2018 Russian Electrical Eng. 89(9) 531-5
[11] Shevlyugin M V, Korolev A A, Korolev O A and Aleksandrov I A 2018 Russian Electrical Eng. 89(9) 540-5
[12] Gorozhankin A N, Bukhanov S S, Gryzlov A A and Grigorev M A 2019 Russian Electrical Eng. 90(5) 357-63
[13] Bestem’yanov P F, Van’shin A E and Katkov M V 2018 Russian Electrical Eng. 89(9) 501-6
[14] In’kov Y M, Podovikov O E and Pustovetov M Y 2018 Russian Electrical Eng. 89(9) 555-8
[15] Bestem’yanov P F 2017 Russian Electrical Eng. 88(9) 557-62
[16] Zhuravlev A M and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 222-7
[17] Gryzlov A A and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 245-8
[18] Kavalerov B V and Odin K A 2017 Russian Electrical Eng. 88(5) 310-3
[19] Tyugashev A A, Zheleznov D V and Nikishchenkov S A 2017 Russian Electrical Eng. 88(3) 154-8
[20] Zasov V A, Zheleznov D V, Mitrofanov A N and Belonogov A S 2017 Russian Electrical Eng. 88(3) 115-9
[21] Minullin R G 2017 Russian Electrical Eng. 88(2) 61-70
[22] Khayatov E S and Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 197-200
[23] Chupin E S and Grigorev M A 2019 Russian Electrical Eng. 90(5) 375-9
[24] Gryzlov A A and Grigorev M A 2019 Russian Electrical Eng. 90(5) 364-9
[25] Belykh I A and Grigorev M A 2019 Russian Electrical Eng. 90(5) 370-4
[26] Faizrazhmanov R A Polevshchikov I S Khabibulin A F and Shklyaev F I 2017 Russian Electrical Eng. 88(11) 725-7
[27] Baranov L A and Maksimov V M 2018 Russian Electrical Eng. 89(9) 546-9
[28] Belykh I A, Grigor’ev M A and Belousov E V 2017 Russian Electrical Eng. 88(4) 205-8
[29] Alekseev V M 2018 Russian Electrical Eng. 89(9) 528-30
[30] Naumovich N I and Grigorev M A 2019 Russian Electrical Eng. 90(5) 380-5
[31] In’kov Y M, Kosmodamianskii A S and Pugachev A A 2018 Russian Electrical Eng. 89(9) 512-7
[32] Belousov E V, Grigor’ev M A and Gryzlov A A 2017 Russian Electrical Eng. 88(4) 185-8
[33] Lobnytsev V V, Durakov D N, Ustinov V S and Badyor M P 2018 Russian Electrical Eng. 89(9)
518-24

[34] Gorelik A V, Gorelik V Y and Shalyagin D V 2018 *Russian Electrical Eng.* **89**(9) 550-4
[35] Chupin S A and Grigor’ev M A 2018 *Russian Electrical Eng.* **89**(4) 240-4
[36] Zhuikov A V, Kubatkin M A, Larin V S, Nikulov I I and Khrenov S I 2019 *Russian Electrical Eng.* **90**(8) 579-84
[37] Gorozhankin A N, Gryzlov A A, Tsirkunenko A T and Zhuravlev A M 2018 *Russian Electrical Eng.* **89**(4) 217-21
[38] Gorozhankin A N, Gryzlov A A and Khayatov E S 2017 *Russian Electrical Eng.* **88**(4) 201-4
[39] Gusenkov A V, Lebedev V D, Sokolov A M, Shadrikov T E, Tankoy A and Dyachkov A A 2019 *Russian Electrical Eng.* **90**(8) 599-605
[40] Larin V S and Matveev D A 2019 *Russian Electrical Eng.* **90**(8) 585-90
[41] Kuznetsov K B, Gorozhankin A N, Funk T A *et al.* 2017 *Russian Electrical Eng.* **88**(4) 209-11