SIMULATION OF TRACTION WORK TO RATIONALISE THE WEIGHT DISTRIBUTION OF THE 4WD ELECTRIC TRACTOR

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Abstract - Electric tractors, as the latest direction in agricultural machinery, have recently attracted considerable attention due to their environmental, economic and technological advantages. With the global transition to renewable energy sources and the tightening of requirements to reduce greenhouse gas emissions, electric tractors are a promising option for improving the agricultural sector. The aim of this type of material is to increase the overall efficiency of the four-wheel drive mini-electric tractor through the rational selection of the weight that falls on the tractor axle and the amount of internal pressure in agricultural tires. The objective was achieved by using a simulation model of the operation of a permanent magnet synchronous machine in Matlab and by incorporating the most loaded test cycles of DLG-PowerMix. The practical significance of the presented work consists in determining the change in the range of values of the weight distribution on the axle of the 4WD electric tractor and the pressure in the tires during aggregation on the most heavily loaded agricultural works, which will be useful when performing plowing and cultivation works on farmland. The scientific novelty of the work is the establishment of a relationship between the weight distribution on the axle of a 4WD electric tractor and the pressure in the front and rear tires of the driving wheels when simulating traction work according to the DLG PowerMix cycles of plowing and cultivation.

Keywords: Electric tractor 4WD, Energy indicators, Efficiency, Weight distribution, Tire pressure, Traction cycles, Matlab modeling.

1. Introduction

The electrification of wheeled machinery has become widespread throughout the world in order to solve the problems of environmental degradation caused by polluting emissions and the depletion of fossil fuel reserves [1, 2]. Manufacturers of tractor equipment are experimenting with various electric drive technologies to improve modern equipment, because the implementation of this technology will ensure an increase in energy efficiency and allow the creation of universal equipment for agricultural activities.

The use of electric traction on low horsepower tractors, which are widely used in agriculture, is becoming increasingly popular. Compared to traditional (combustion engine) tractors, all-electric tractors have a compact structure, maximum torque at low rpm and high efficiency. The use of low power tractors is due to their versatility, as they are used in a complex with variable mounted, semi-mounted and trailed agricultural units, so the design of the electric tractor must ensure the implementation of traction and energy indicators.

The rationalization of the design parameters that ensure the overall weight distribution of a low-power electric tractor [3] will allow an improvement in the traction and energy indicators of the machine-tractor unit, contributing to the growth of energy efficiency that will allow the creation of universal machines for agricultural activity, is an urgent scientific and practical task that has determined the direction of this research.

2. Literature Review

With the global transition to renewable energy sources and increasing requirements to reduce greenhouse gas emissions, electric tractors are a promising option for improving the agricultural sector. Thus, according to [4], there is now a global move to reduce greenhouse gas emissions, reducing the negative impact of exhaust gases from wheeled machines during operation, which is leading to an increased demand for the introduction of more ecological technologies. In [5] a review was made of the decisions taken to control exhaust emissions from agricultural tractors and similar self-propelled machinery [6, 7]. The authors [5] highlighted the need to increase the efficiency of fuel use, the implementation of technical solutions for the latest pollutant emissions and the introduction of alternative biofuel blends [8 - 10].

Scientific works dedicated to the study of electrification and hybridisation of agricultural machinery are now gaining great popularity. For example, according to [11, 12], the introduction of an electric drive as a power plant in agricultural tractors is a promising and urgent need. In [13], the authors emphasise that the hybridisation of agricultural tractors is a fast-growing sector with great prospects, as it can provide high productivity, fuel economy and low pollutant emissions. When researching the operation of tractors with a power plant based solely on battery electric architecture, it is necessary to consider both the advantages (local environmental issues) and disadvantages (operational limitations). From [14] it was found that the modern development of the technology of the structure of storage batteries is not yet perfect and leads to the introduction of bulky batteries in order to satisfy the performance indicators of the equipment. The analysis of the work [15] showed that an electric four-wheel drive tractor with speed control is susceptible to slipping, and further research is needed to improve the performance of the four-wheel drive system with speed and slipping control.

Taking into account the experience of the authors [16], it should be noted that the modernisation of any agricultural machine requires a detailed study of changes in traction and energy indicators. The study of the traction and energy indicators of a wheeled tractor is based on the determination of the kinematic and power characteristics of the interaction between the wheel drive (tyre) and the deformed soil environment [17]. In [17] it is stated that the numerical study of tyre-soil interaction is reduced to the construction of empirical, semi-empirical and models based on the physics of the process or on modern intelligent technologies. The construction of empirical models is reduced to the systematisation of experimental data and the correlation of the obtained data [18, 19]. This method of modelling was quite popular, but with the development of technologies, semi-empirical models have gained relevance, using not only experimental results together with empirical formulas, but also analytical models. Thus, in [20] a comparative analysis of the methods of determining the characteristics of the tyre interaction model with the soil environment based on the Becker equation was carried out, the development of this work was the study [21], in which numerical models were formed for the quantitative assessment of soil characteristics. In [22], the authors developed a synthesised semi-empirical model which shows good convergence with the experimental values of slipping. The third group of constructional models of tyre-soil interaction is largely based on finite element methods [23] and discrete element methods [24].

Today, there is also a tendency to use artificial neural network models [25, 26] that summarise the physical and geometric parameters of the tyre. The use of photogrammetric to develop a 3D model [27, 28] of the tyre contact patch on the ground, and the subsequent evaluation of the accuracy of the 3D model, is becoming more widespread. For example, in [29] an approximate digital photogrammetric of a tyre is presented which showed an effective and more accurate assessment of the depth and volume of the tyre contact patch in the ground.

3. Materials and Methods

3.1. A Model for Determining the Overall Efficiency of a Tractor

When studying the energy indicators of an agricultural tractor, it is impossible to avoid the question of its efficiency. The efficiency criterion is based on determining the change in the overall efficiency of the tractor, which is determined by considering the energy balance. The construction of such a balance is based on the determination of all component capacities and losses that occur during the operation of the tractor and ploughing units when performing technological (traction) work.

Let's create a mathematical algorithm to construct the tractor's energy balance, taking into account the operation of agricultural implements

$$N_e=\begin{cases} N_{\text{tr}}+N_{\delta}+N_{f}+N_{\text{PTO}}+ \\ +N_{\text{hd}}+N_{\text{agro}}+N_{V\text{un}}+N_{f\text{un}}, \end{cases} \tag{1}$$

where N_{tr} is the power realised for losses in transmission; N_{δ} is the power applied to compensate for skidding of the drive wheels; N_f is the power spent on rolling resistance of the wheels; N_{PTO} is the power transmitted by the PTO shaft to the agricultural implement drive (PTO); N_{hd} is the power that is realized to drive the agricultural implement through the hydraulic system; N_{agro} is the power required to perform agricultural technical work; $N_{V\text{un}}$ is the power generated by increasing resistance as speed increases; $N_{f\text{un}}$ is the power that is realized to move the agricultural implement on the basis of the rolling losses of the running system and the forces of friction of the elements with the soil environment.

Let's look at the complete energy balance of a wheeled tractor, which differs from the existing ones by taking into account the electric drive instead of the power of the combustion engine. The structure of using the power of the electric motor in the tractor during technological work is shown in Fig. 1.

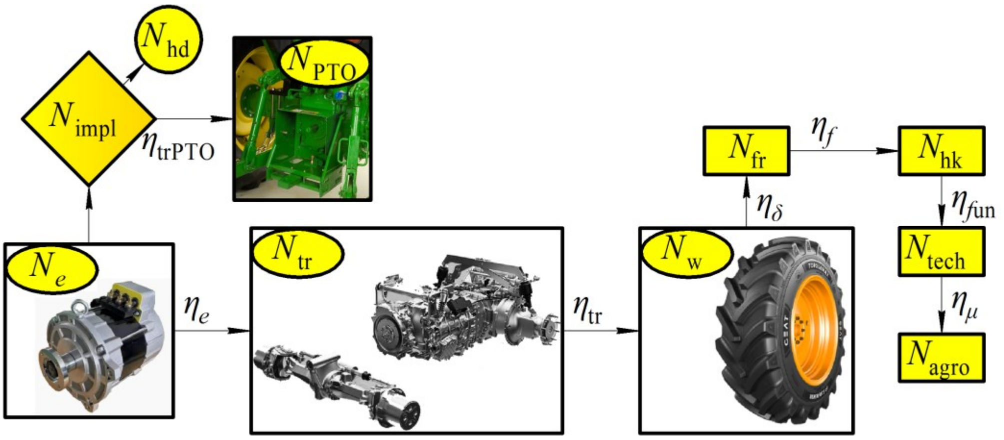


Figure 1: Simplified scheme for realising the power of the power unit of an electric tractor when working with agricultural implements:
N_{impl} is the power that is realized on the drive of the agricultural implement; N_w is the power delivered to the wheels of the tractor from the side of the transmission; N_{fr} is the power that flows to the frame of the tractor during the implementation of the tangential traction force and the process of towing, which pushes the frame in the direction of movement; N_{hk} is the power generated on the tractor hook; N_{tech} is power that is realized directly on the technological process of movement of the soil environment during tractor operation; η_e is the effective efficiency of the power unit; η_{tr} is the overall efficiency of the transmission of the wheeled tractor; η_δ, η_f are efficiency, which collectively take into account skidding losses and rolling resistance of the tractor; η_{fun} is efficiency, which takes into account the losses due to the resistance to the movement of agricultural implements in the case of rolling losses of the running system and friction of elements with the soil environment; η_μ is efficiency, which takes into account power losses due to an increase in traction resistance with increasing speed; η_{trPTO} is the overall efficiency of the PTO gearbox transmission

Calculating the overall efficiency of a wheeled electric tractor has several components, let's look at them:

– Transmission efficiency

$$\eta_{\text{тр}} = \frac{N_{\text{w}}}{N_e} = \frac{\left(P_{\text{w1}} + P_{\text{w2}}\right)\cdot V_{\text{т}}}{N_e} = \frac{N_{\text{w}}}{N_{\text{w}} + N_{\text{tr}}}. \tag{2}$$

– Drive wheel slipping efficiency

$$\eta_\delta = 1 - \delta = \frac{N_{\text{fr}}}{N_{\text{w}}} = \frac{V}{V_{\text{T}}}, \tag{3}$$

where V_{T} is the theoretical speed of the tractor.

- Efficiency, which takes into account the rolling resistance of the wheels of the driving axles of the tractor

$$\eta_f = \frac{N_{\text{hk}}}{N_{\text{fr}}} = 1 - \frac{N_f}{N_{\text{fr}}}. \tag{4}$$

- Efficiency, which takes into account losses due to resistance to the movement of agricultural implements

$$\eta_{f\text{un}} = \frac{N_{\text{tech}}}{N_{\text{hk}}} = 1 - \frac{N_{f\text{un}}}{N_{\text{hk}}}. \tag{5}$$

- Efficiency, which takes into account the loss of speed due to the increase in traction resistance of the unit as the speed of technological work increases:

$$\eta_\mu = \frac{N_{\text{agro}}}{N_{\text{tech}}} = 1 - \frac{N_{V\text{un}}}{N_{\text{tech}}}. \tag{6}$$

One of the important components in determining the overall efficiency of the tractor is the efficiency, which provides information on the proportion of useful power delivered to the drives (wheels) that can be realized as useful hook power:

$$\eta_{\text{ch}} = \eta_\delta \cdot \eta_f = \eta_\delta - \frac{N_f}{N_{\text{w}}}. \tag{7}$$

You can then calculate the efficiency of the tractor without taking the power plant component into account.

$$\eta_{\text{trr}} = \eta_{\text{ch}} \cdot \eta_{\text{tr}} \cdot \lambda_{\text{tr}} + \eta_{\text{PTO}} \cdot \lambda_{\text{PTO}} + \eta_{\text{hd}} \cdot \lambda_{\text{hd}}, \tag{8}$$

where λ_{tr} is power fractions that are components of the power flowing from the power unit to the transmission; λ_{PTO} is power fractions that are components of the power flowing from the power unit to the PTO reducer; λ_{hd} is power fractions that are components of the power flowing from the power unit to the hydraulic system.

$$\lambda_{\text{tr}} = \frac{N_{\text{w}}}{\dfrac{N_{\text{w}}}{\eta_{\text{tr}}} + N_{\text{PTO}} + N_{\text{hd}}}. \tag{9}$$

$$\lambda_{\mathrm{PTO}} = \frac{N_{\mathrm{PTO}}}{\dfrac{N_{\mathrm{w}}}{\eta_{\mathrm{tr}}} + N_{\mathrm{PTO}} + N_{\mathrm{hd}}}. \tag{10}$$

$$\lambda_{\mathrm{hd}} = \frac{N_{\mathrm{hd}}}{\dfrac{N_{\mathrm{w}}}{\eta_{\mathrm{tr}}} + N_{\mathrm{PTO}} + N_{\mathrm{hd}}}. \tag{11}$$

- Tractor efficiency including electric motor efficiency

$$\eta_{\Sigma} = \eta_{\mathrm{trr}} \cdot \eta_{\mathrm{e}}, \tag{12}$$

where η_e is the efficiency of the electric motor.

The efficiency of an electric motor is measured as a percentage and can range from 10 to 99%. Electric motors up to 100 kW have an efficiency of 75-90%, while more powerful units have an efficiency of 90-97%. The higher the efficiency, the better and more efficient the electric motor works, the more efficiently electricity is used and the more mechanical energy is available for electric drives.

$$\eta_{\mathrm{e}} = \frac{N_{\mathrm{meh}}}{N_{\mathrm{elec}}} = \frac{M_{\mathrm{elec}} \cdot \omega_{\mathrm{elec}}}{m \cdot U \cdot I \cdot \cos\varphi}, \tag{13}$$

where M_{elec} is the torque on the electric motor shaft; ω_{elec} is angular velocity on the electric motor shaft; m is number of phases of the stator winding; U is on the stator terminals; I is current intensity; φ is phase shift angle between the stator voltage and current.

To summaries, the design of a low-power wheeled tractor with electric traction requires careful research to ensure that the maximum traction and energy indicators are respected, especially when carrying out traction (field) work.

3.2. Imitates the Traction of an Electric Tractor

Today, when designing or modernizing tractor equipment, it is necessary to carry out traction/transport tests to determine the efficiency of the nodes and aggregates of the agricultural implement. For this purpose, official tractor test standards are implemented by the Organization for Economic Co-operation and Development (OECD [30]). The most popular test standards for agricultural tractors are NTTL (Nebraska Tractor Test Laboratory) in the USA and DLG-PowerMix (Deutsche Landwirtschafts-Gesellschaft) in Germany.

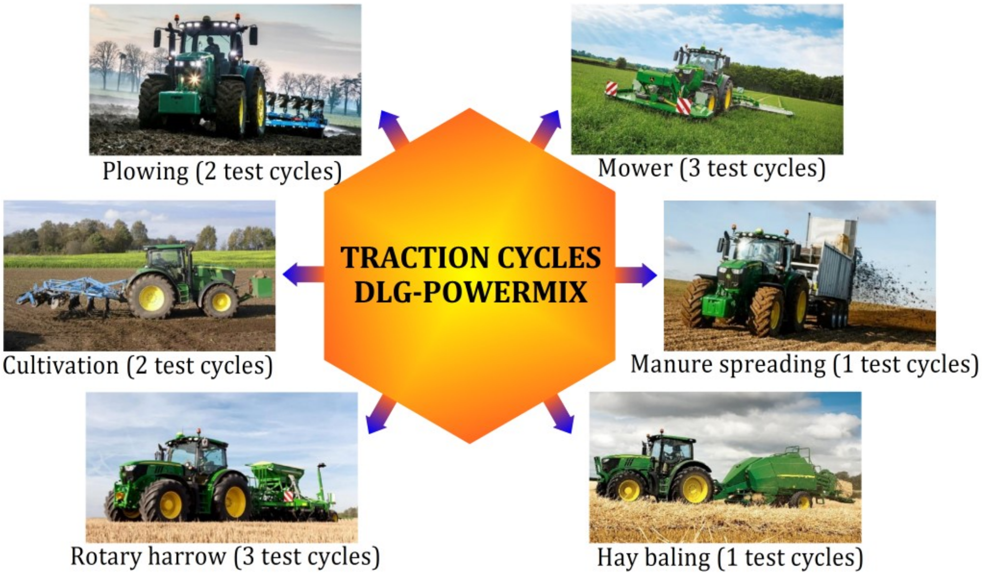
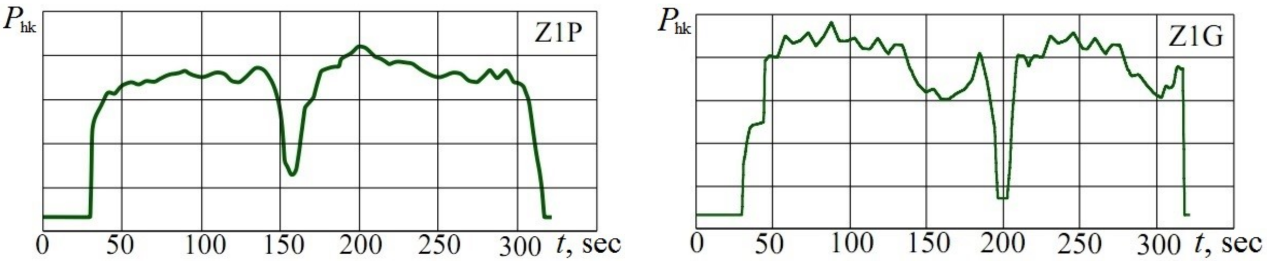


Figure 2: Various traction cycles DLG PowerMix



a

b

Figure 3: Hook pull P_{hk} as a function of time t according to the DLG-PowerMix test procedure of aggregation with a Z1P plow (a) and aggregation with a Z1G cultivator (b)

In [31] it is claimed that the use of DLG-PowerMix cycles is more efficient than NTTL cycles. This is justified by the fact that the DLG-PowerMix cycles (Fig. 2) have a wider range of the list of typical agricultural technological operations (traction and traction-drive) [32, 33], which are carried out at full and partial load of the combustion engine. This result in greater thoroughness compared to the NTTL cycles, which apply traction to the tractor hook at 50%, 75% and 100% of maximum engine power.

In [30, 32] the output data of the DLG-PowerMix test cycle procedure are described. We will select the traction work (plowing Z1P (Fig. 3a) and cultivating Z1G (Fig. 3b)) as the most loaded and perform a numerical experiment based on them.

Let's note that the dependence of $P_{\mathrm{hk}}(t)$ from Fig. 3 must be adapted to a specific agricultural tractor.

3.3. Simulation Model of an Electric Tractor in Matlab

To date, a sufficient amount of information has been accumulated and a lot of experience has been gained on the issue of studying electromechanical systems that are part of various energy facilities with the disclosure of internal processes.

This is also true for electrical propulsion systems, where complex non-linear processes take place, involving energy transfer, electromagnetic and electro-mechanical energy transformations. Most scientists make certain assumptions when forming non-linear systems, which allows the mathematical model to be simplified. This makes it possible to improve the efficiency of the model being studied during a numerical experiment, or to stop studying the phenomena and processes in the system in detail.

One of the most effective ways to model the operation of an electric drive is to use powerful mathematical and object-oriented software packages: Mathematica, MatLab, Mathcad, Model Vision Studium, WorkBench, Modelica with the Dymola application, Comsol Multiphysics, etc. One of the most popular software packages with integrated simulation tools is the MatLab interactive system with the Simulink subsystem and the Simscape Electrical application. Thanks to this software, it was possible to simulate the operation of a permanent magnet synchronous motor [33] as part of a wheeled tractor (Fig. 4). The simulation uses an electric synchronous motor with permanent magnets. The motor presented is tabular and was selected from those proposed in the MatLab system.

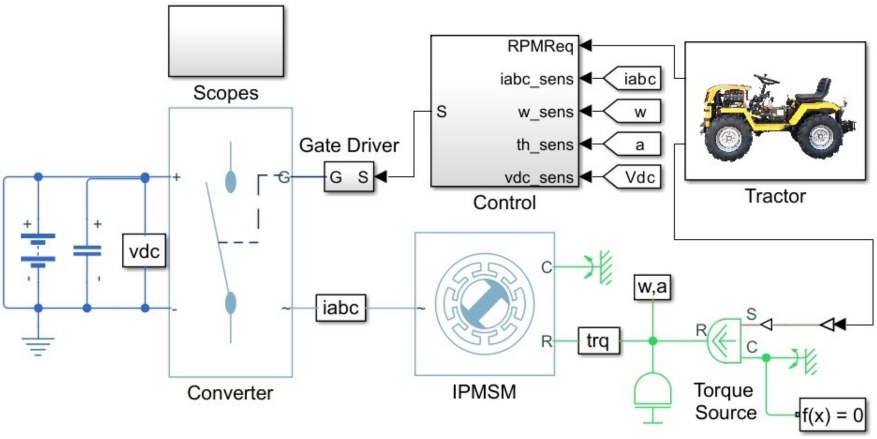


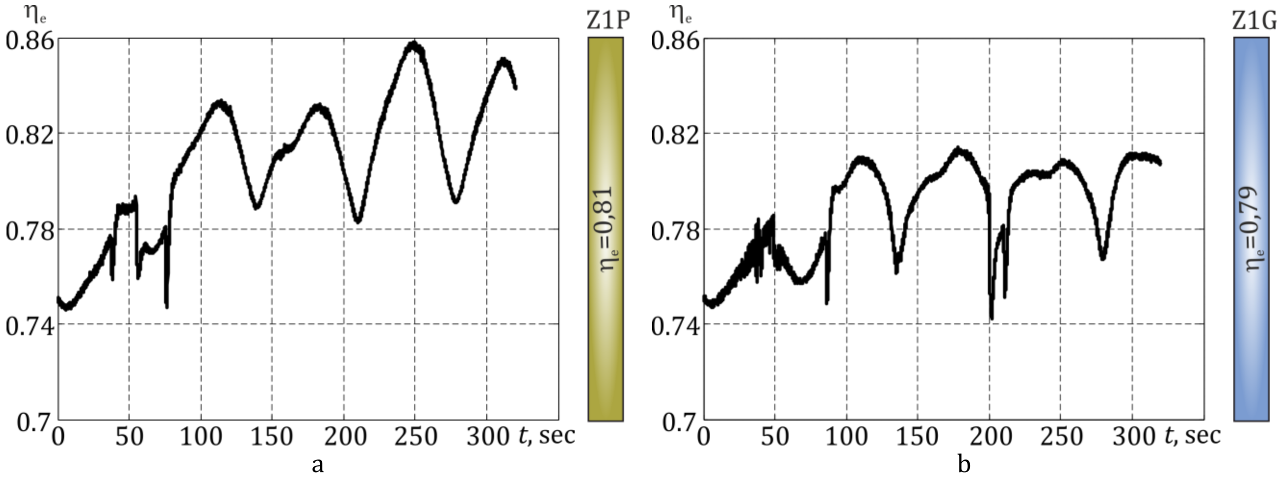
Figure 4: Implementation of a wheeled tractor model with a permanent magnet synchronous motor using MatLab / Simscape Electrical

The control subsystem (Fig. 4 "Control" block) comprises a PI-based multi-speed cascaded control structure with an outer angular velocity control loop and two inner current control loops.

4. Results

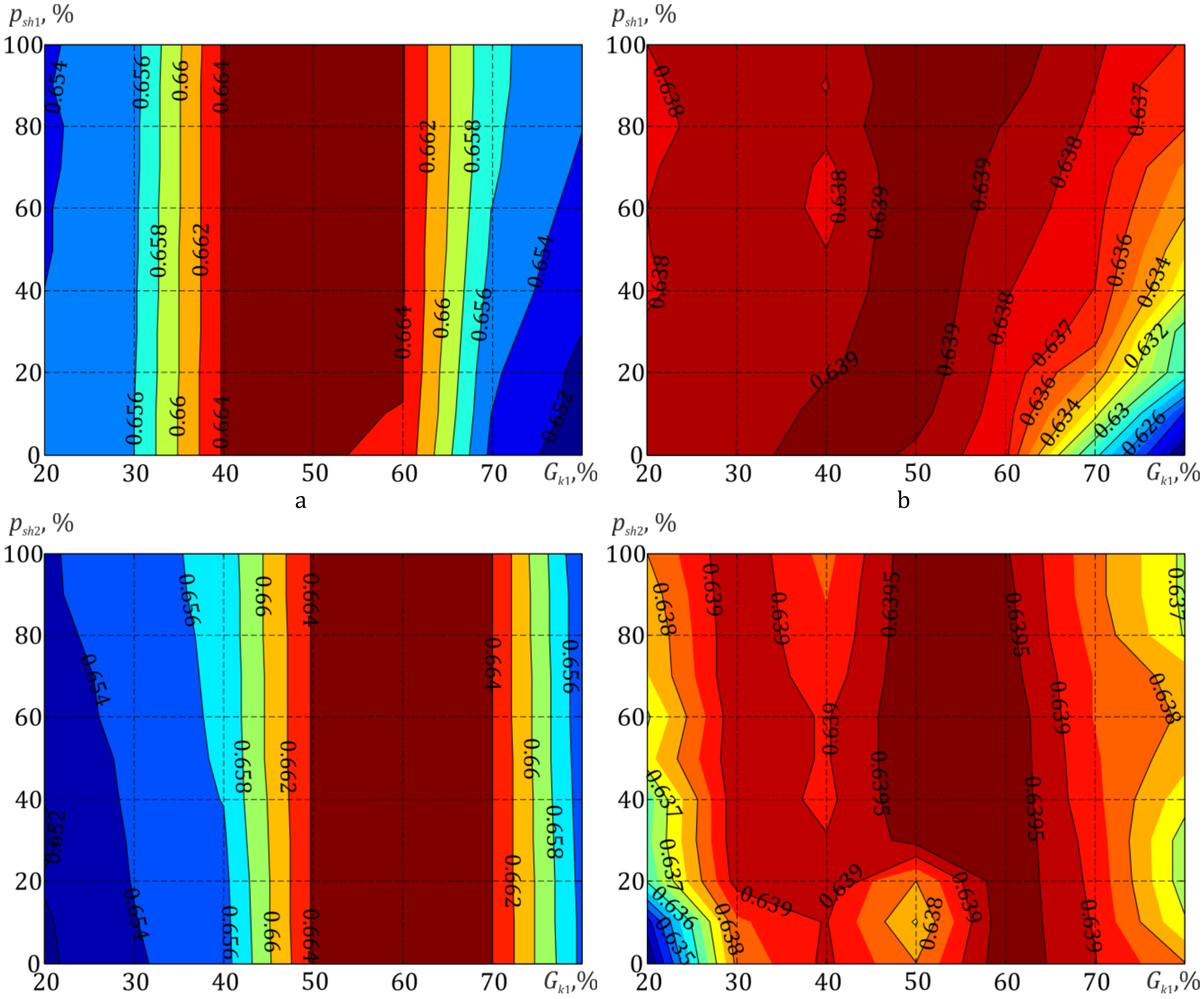
On the basis of the formed simulation model of the tractor with electric drive, it is possible to determine its energy indicators when using the procedure of DLG-PowerMix test cycles. Fig. 5 shows the change in the efficiency of a synchronous motor with permanent magnets used as a power unit when simulating traction work according to the most loaded DLG-PowerMix cycles. As can be seen from Fig. 5, the dependence $\eta e(t)$ has a significant variability, so for a better understanding we will accept the estimation of this indicator by the average integral indicator.

Figure 6 shows the change in overall efficiency of the 4WD electric tractor with changes in tyre pressure and different weight distributions along the tractor axles during the Z1P ploughing and Z1G cultivating test cycles. As can be seen from Fig. 6, the variability in the selection of the value of the weight distribution along the tractor axles has a wide range, so when making recommendations we will take into account the change in the traction of the tractor wheels (Figs. 7 - 10).



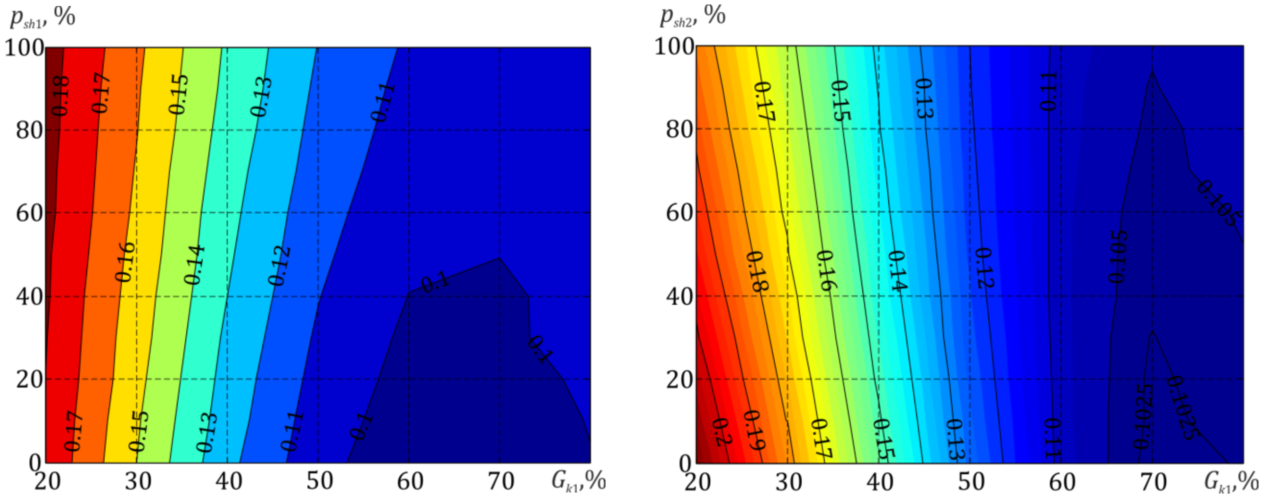
a b

Figure 5: Efficiency η_e of the synchronous motor as a function of the time of traction work according to the DLG-PowerMix plowing Z1P(a) and cultivation Z1G(b) cycles.



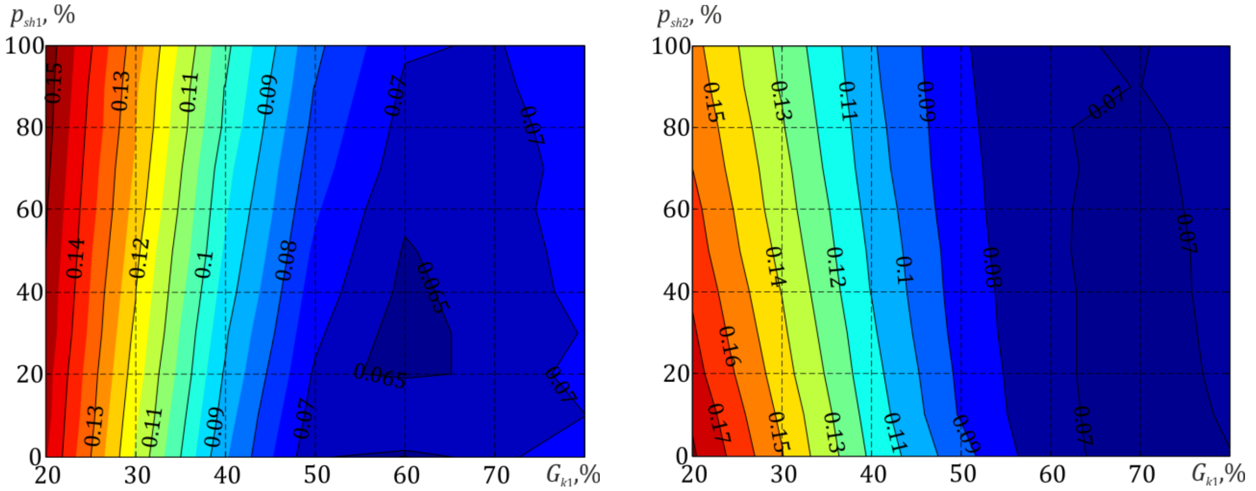
a b c d

Figure 6: Dependence of the overall efficiency of the electric tractor on the variation of the internal pressure in the front (a, b) and rear (c, d) tires, taking into account the variation of the weight distribution on the front axle G_{k1} of the tractor during the simulation of plowing Z1P (a, c) and cultivating Z1G (b, d).



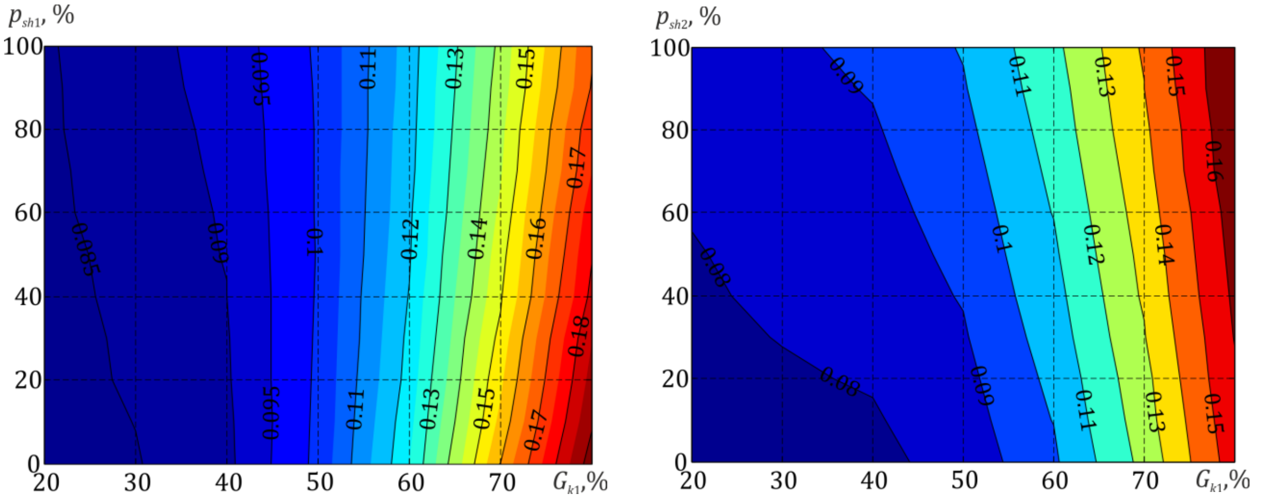
a b

Figure 7: Dependence of the front wheel slip on the variation of the internal pressure in the front (a) and rear (b) tires, taking into account the variation of the weight distribution on the front axle G_{k1} of the tractor when simulating plowing Z1P



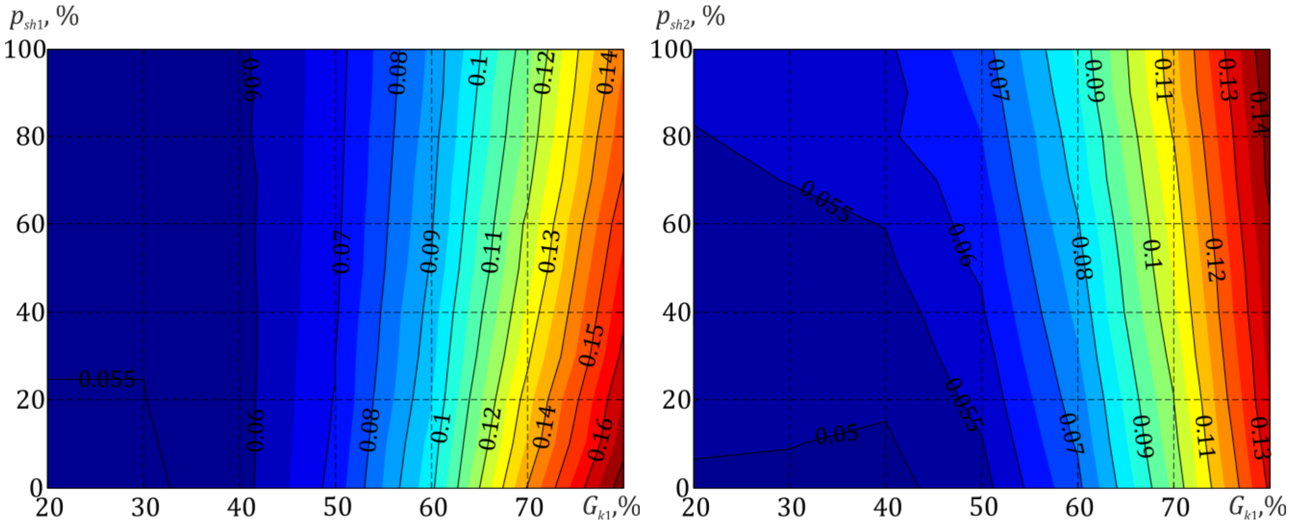
a b

Figure 8: Dependence of the front wheel slip on the variation of the internal pressure in the front (a) and rear (b) tires, taking into account the variation of the weight distribution on the front axle Gk1 of the tractor when simulating cultivation Z1G



a b

Figure 9: Dependence of the rear wheel slip on the variation of the internal pressure in the front (a) and rear (b) tires, taking into account the variation of the weight distribution on the front axle Gk1 of the tractor when simulating plowing Z1P



a b

Figure 10: Dependence of the rear wheel slip on the variation of the internal pressure in the front (a) and rear (b) tires, taking into account the variation of the weight distribution on the front axle G_{k1} of the tractor during the simulation of the Z1G cultivation

In Fig. 6 - 10, the display of the internal pressure in the front and rear tyres varies from 0 ÷ 100%, i.e. the percentage of tyre pressure filling. This is because we have used standard size 6.00-12 bias-ply tyres in the simulation, which have a minimum internal pressure of 1.7 bar and a maximum of 2.8 bar.

5. Discussion

During the simulation of the operation of an electric tractor with a synchronous motor with permanent magnets using MatLab / Simscape Electrical, the average integral values of the efficiency of the synchronous machine were obtained (Fig. 5), which are Z1P η_e = 0.81 when simulating the ploughing operation with an electric tractor, and Z1G η_e = 0.79 when simulating the cultivation operation. The obtained result is further used to determine the overall efficiency of the electric tractor in Fig. 6.

Evaluating the results in Fig. 6, it can be seen that the tire pressure has practically no effect on the overall efficiency of the 4WD electric tractor. When simulating the plowing operation Z1P, the influence of the internal pressure in the tires is not observed, and when simulating the cultivation operation Z1G, the overall efficiency indicator changes by 0.3%. Analyzing the value of the total efficiency of the electric tractor when the distribution of the weight falling on the tractor axle is changed, it changes within

- for Z1P $\eta_e \in [0.6507; 0.6642]$;
- for Z1G $\eta_e \in [0.6208; 0.6399]$.

Considering the results from Fig. 6, the maximum values of the total efficiency of the electric tractor occur when the weight distribution changes to the front axle $G_{k1} \in$ [50%; 60%].

Fig. 7 - 10 show the results of changing the front and rear tires on a 4WD electric tractor, taking into account the change in tire pressure and weight distribution on the tractor axle. The amount of slippage varies within

- for the front wheels at Z1P $\delta \in [0.0936; 0.2104]$;
- for rear wheels at Z1P $\delta \in [0.0741; 0.1927]$;
- for front wheels with Z1G $\delta \in [0.0624; 0.1818]$;
- for rear wheels at Z1G $\delta \in [0.0483; 0.1733]$.

6. Conclusions

An approach to determine the overall efficiency of an agricultural tractor by constructing an energy balance that takes into account the efficiency of the transmission, wheel slip, rolling resistance of the wheels, useful power delivered to the drivers (wheels), etc. is given. The relationship between the weight distribution on the axle of the 4WD electric tractor and the pressure in the tyres of the driving wheels during the simulation of traction work according to the DLG-PowerMix cycles of plowing Z1P and cultivation Z1G has been established. From a practical point of view, the presented work will be useful in the design of low-power 4WD agricultural electric tractors.

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