Evaluation of energy-economic parameters of tractor with electrically driven power unit

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Abstract. The development of agro-industrial complex in modern conditionsneeds a large share of low traction class tractors. Manufacturers in their turn strive to fill the market with tractors with good consumer properties. The use of electric drive on tractors is a relatively new trend with many unresolved issues in various areasof this subject. In this paper the questions on prospects of using electric motors as a drive of tractor power unit are touched upon. Energy equipment and general preparedness for transition of tractors to such systems are considered. The question of comparison of basic parameters of electric and diesel engines, consisting in one power category, is considered. The methodology of estimation of energy-economic characteristics of a tractor with electric drive power unit in relation to a conventional tractor with dieselengine and argumentation of the given parameters are given. The usefulnessof the introduced index is shown, as well as the necessity of its use in order to evaluate the efficiency of engines of different types in a comparative analysis. This paper will be useful in the engineering and design field of knowledge related to the design and development of electric drive technologies for mobile machines.

1 Introduction

In modern conditions of agricultural tractors operation there are a number of disadvantages, which are caused directly by their power unit. One of the negativefactors generated by the tractor is toxicity of exhaust gases (EG) of the diesel engine,as well as comparatively low efficiency of the power unit, for the current period, which is about 40-50%, in the modes of maximum efficient operation [1].

In addition to the above-mentioned problems, the impact of toxic emissions limits tractor operation in areas with limited air ventilation, such as farms, greenhouses, etc. In spite of the fact that small capacity tractors are used for such premises, the problem remains actual, as it is scientifically proved that human and animal health is harmed by toxic emissions. The main toxic element in diesel engines along with soot [2] is the emission of nitrogen oxides NOx, the formation of which is inevitable and associated with various physical processes in the combustion chamber of the engine [3]. The mechanisms of their formation have long been known, and it has been shown that their prolonged effect on living organisms, including plants, both depresses their growth and has a negative impact on their structure.

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To solve the problems of toxicity of internal combustion engines there is a largenumber of ways, up to the addition of water into the combustion chamber together with diesel fuel [4] or alternative fuels [5]. Solutions to the complex problem, which involves bothincreasing the efficiency of the machine and improving its consumer properties is more difficult to realize. One of such solutions is the use of electric drive of the tractor power unit. The absence of harmful emissions into the environment and comparably high efficiency of 80-96% [6], open the possibility for its use as a source of mechanical energy in order to fulfill the functional purpose of the machine [7].

The electric motor used to drive the power unit has a number of advantages overthe tractor equipped with a basic diesel engine. One of the most important featuresis the possibility of energy recovery in case of dynamic changes in the drive system.The flexibility of the electric drive control will also significantly increase the tractor's efficiency.

The best choice as a source of mechanical energy to drive the power unit of thetractor is supposed to be a brushless synchronous DC motor, also called a valve motor. This choice is justified primarily by the absence of contacting elements in the motor design, good load characteristics and flexible control with acomparatively high specific power of such a motor [8].

Considering the situation, in which the tractor will work in poorly ventilated rooms, it should be taken into account that its dimensions as well as engine power should not be large. For tractors of small traction class for such tasks the engine power can be in the range of 10-60 kW. Therefore, when comparing the parameters of different types of engines, it is necessary to consider the same categories of tractors operated under identical conditions. Analyzing different groups of diesel engines [1] and valve motors [7, 9], which are possible to use as a machine drive, it is possibleto compare their main parameters (Table 1).

Table 1. Comparison of main parameters of diesel and electric motors.

Parameter	Type of engine to drive the power unit	
	Diesel engine	**Electric motor**
Maximum efficiency	40-50%	80-96%
Specific power	0.1-0.6 kW/kg	2-5 kWh/kg
Market price per kW	1.5-8 thousand rubles/kW	3.5-15 thousand rubles/kW
Operating temperature	80-100 C°	-50-80 C°
Temperature limit	120-140 C°	90-250 C°

Source: (Compiled by the authors).

From the review analysis of motors in the same power ranges it is clear, that theirmain parameters and price categories are different. The efficiency of the valve motor is almost 2 times higher than that of the diesel motor, and the specific poweris 5-10 times higher. Operating and limit temperatures of such electric motors are within adequate values, so to ensure their maintenance does not require large laborinputs. This justifies the prospect of using valve motors as a drive of power units ofmobile machines.

2 Materials and methods

The market cost of the considered electric motors is 1.5-2 times higher and has a range of about 11.5 thousand rubles/kW, which is explained by differences in manufacturing materials, service life, manufacturer of the product and components,etc. A higher price than diesel per kilowatt of power is not the main problem whenintroducing valve motors in tractor production. The problems of mass use of electricmotors are connected primarily with electric energy storage on board the tractor, aswell as with the low world electric power potential, which currently amounts to approximately 1200 billion kWh in the Russian Federation, while the marginal electric power consumption limited by power plants is about 1500 billion kWh [10]. Thus, the notional stock of electricity consumption is about 300 billion kWh, which can potentially be used for the operation of electric drive tractors at the moment. Based on data for 2017, diesel fuel consumption in Russia according to the Ministry of Energy keeps practically atthe same level and amounts to 33 million tons per year. The share of fuel used in agriculture is approximately 18-25% of the total volume, i.e. 5.9-8.3 million tons per year. When a diesel engine is running, it is possible to determine the amount ofenergy required to convert into mechanical work from the fuel consumed by knowing the basic parameters of the process.

$$W_{max} = \frac{H_u \cdot G_w \cdot \eta_d \cdot \eta_e}{K_t}, \quad (1)$$

where: Hu is the lowest specific heat of combustion of diesel fuel (Hu ≈ 42 MJ/kg); Gw is the weight consumption of fuel per year, kg; ηd is the efficiency of the diesel engine (ηd ≈ 0.4); ηe is the efficiency of the electric motor (ηe ≈ 0.9); Kt is the time factor for conversion to the SI system (t = 3600).

Thus, the amount of electrical energy converted into mechanical work by dieselfuel for a year in the agricultural sector can be estimated at 24.8-34.9 billion kWh, which is approximately 10% of the stock of electricity production. Taking into account the dynamics of agricultural machinery use by months, it is known that upto 60% of the total amount of work falls on the spring period and the beginning of the fall period. At the same time, the maximum monthly share of fuel from the totalannual volume can reach 35%. Based on these data it is possible to determine the maximum monthly energy consumption.

$$W_{max} = \frac{H_u \cdot G_w \cdot \tau \cdot \eta_d \cdot \eta_e}{K_t}, \quad (2)$$

where: τ is the share of fuel consumed in the busiest month (τ = 0.35).

In this case, the maximum energy consumption may be 8.7-12.2 billion kWh for1 month. It should be taken into account that the energy produced by power plants per month is 1/12th of the total free volume and amounts to 25 billion kWh, whichis 2-3 times more than the maximum monthly energy consumption. This indicates the possibility of transition of tractors to electric drive of the power unit, however, without further development of energy complexes the use of electric motors in tractors when consuming energy from the external network will be impossible.

The use of combined power units on tractors is a less demanding option, as it does not require constant charging from the external network. Such a tractor can contain a diesel and electric engine in the power plant, working together, so in thiscase there is only the problem of selecting electric charge accumulators and the layout of machine elements [11, 12].

The operation of a hybrid or all-electric tractor is limited to a specific set of operations, including indoor operations. In order to eliminate toxic exhaust emissions in areas with limited ventilation, the tractor must be powered by an electric motor. Its working functions must be ensured. All tractor performance, including traction performance, depends primarily on engine characteristics, its parameters and mode of operation.

The analysis of the issue of energy consumption estimation should be consideredon the base model. For a tractor of low traction class, capable of working in greenhouses or in farms on forage distribution it is possible to choose the engine power of 20 kW and take as a prototype tractor VTZ-2032, corresponding to this parameter. To evaluate the parameters of tractor efficiency, it is necessary to analyze the characteristics of the valve motor in comparison with the characteristicsof the diesel engine of equivalent power, as it is basic in the tractor equipment. Characteristics of the valve electric motor and diesel engine are different, but they can be approximated based on physical laws and approximation by empirical indicators [1, 14]. It is most convenient to consider the speed characteristic of the engine (Figure 1) with the change of various indicators from the speed n, rpm. The characteristics of diesel engine D-120 and brushless DC motor with neodymium magnets type HPM20KW with nominal power of 20 kW were taken as a base for modeling, respectively.

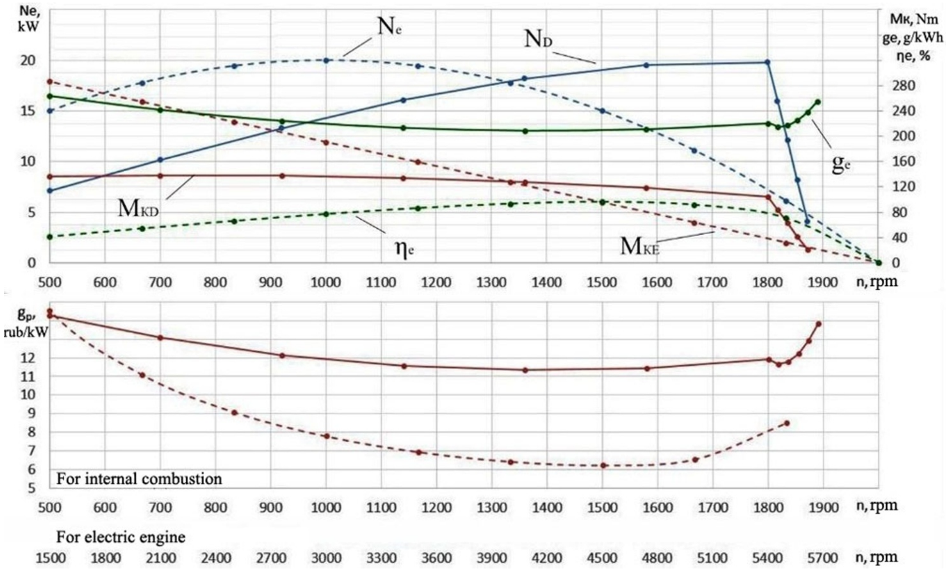

Fig. 1. Speed characteristics of diesel and electric brushless motor. Where: dotted line (- - - - - - -) denotes the characteristics of electric motor, solid line (———) denotes the characteristics of diesel engine; Ne, N_D - output power of diesel and electric motor respectively; Mk - torque of motors; g_e - specific effective fuel consumption of diesel engine; η_e - efficiency of electric motor; g_p - specific energy cost. *Source:* (*Compiled by the authors*).

One of the main indicators of engine performance is the energy consumption toproduce a unit of power. For internal combustion engines, efficiency is evaluated by specific effective fuel consumption g_e, showing the amount of fuel required to produce a unit of power per unit time [1]. There is no such indicator in electric drive, and its efficiency is usually evaluated by efficiency (η_e). Unlike power and torque, which are easy to compare with each other, there is a problem of a unified approach to the evaluation and comparison ofefficiency indicators of motors of different types.

3 Results

To solve the problem, a general concept of approach to this issue has beendeveloped. The concept is the use of a single coefficient g_p, which characterizes theefficiency of an engine by estimating the specific material costs of energy or fuel toproduce a unit of power. This coefficient may vary with changes in fuel prices or electricity tariffs for the same categories of engines, so it is of an applied nature andis convenient for comparing their efficiency under specific conditions (Figure 1). For a diesel engine, the specific energy cost is determined by the formula:

$$g_p = \frac{P_D \cdot G_D}{\rho \cdot N_D}, \quad (3)$$

where: PD - price per liter of diesel fuel, rub/l; GD - hourly fuel consumption, kg/hour; ρ - fuel density, kg/l; ND - current engine power.

For an electric motor powered by a battery or other electrical energy storagedevice, the specific energy cost is determined in a different way:

$$g_p = T_E \frac{P_e}{N_t} \eta_B, \quad (4)$$

where: TE - tariff rate for electric power, rub/kWh; PE - electric power supplied to the electric motor, W; Ne - mechanical power at the output, W; ηB - charging/discharging efficiency of electric energy storage and converter.

According to the obtained characteristic, it can be seen that the specific energy cost of diesel engine is higher than that of electric engine by maximum 6-7 rub/kWh at medium and low loads. As the load increases, the specific energy cost convergestowards 15 rub/kWh for both types of engines. The initial cost of diesel fuel is assumed to be 45 rub/l, and the cost of electricity is assumed to be 6 rub/kWh, in accordance with real conditions.

Similar coefficient is convenient to use when comparing traction and economic characteristics of the tractor using different types of power unit drive. In the basic version for the tractor there is an indicator g_{tr} - specific effective hook fuel consumption, by which the amount of fuel consumed to produce a unit of power onthe tractor hook per unit of time is estimated [13]. For electric drive this indicator is not relevant and in this case it is convenient to use a generalizing indicator $g_{кр}$ - specific hook energy cost, which shows the cost of produced poweron the hook per unit of time. In general, it can be determined by the formula:

$$g_{кр} = \frac{g_p}{\eta_{tr}} = g_p \frac{N_e}{N_{tr}}, \quad (5)$$

where: ηtr - traction efficiency of the tractor; Ne - engine output power; Ntr - traction power of the tractor on the hook.

Thus, the proposed indicator allows to estimate the specific energy cost not only considering the engine operation, but also considering the tractor using different types of engines, as well as to give a comparative assessment of their efficiency parameters.

4 Discussion

When considering the problem of electric power consumption of electrically powered tractors, it is necessary to take into account the fact that the agro-industrial sector is not a privileged one. Therefore, when such technologies are introduced into mass use, the main share of electric drive power units will be used by buses, cars and trucks. In this case, the energy reserves of 300 kWh power units will be insufficient, which will entail the need to increase the amount of electricity produced.

It is believed that the problem of electricity reserve limitation can be solved by using a hybrid propulsion system, which should contain an internal combustion engine and an electric transmission. If electric energy storage devices are used, they shouldnot be charged from the grid, but from the converted energy of the engine. Not onlylithium-ion batteries can be used as energy storages, but also supercapacitors (ultracapacitors), which have been actively introduced in recent years and are considered as temporary charge storages with good characteristics [15, 16]. These factors are the determining factors in the concept of the electric tractor, but there remain many problems related to the selection and mutual arrangement of electrical engineering units, as well as their control algorithm. These problems are currently promising and are solved by various firms such as John Deere, Claas, Tesla, Toyata [12], Drive Electro, etc. in the course of realization of their products.

In spite of the problems of electric tractor utilization solved by various researchers,many questions remain open and this topic has not been widely spread yet. This study analyzes the issue of using an electrically powered tractor, including its comparison with a classic tractor containing a diesel engine. However, the proposedenergy consumption indicators g_p and g_{tr} evaluate the economic component when comparing tractors with different type of drive. Therefore, to solve applied engineering tasks when using tractors with different types of power unit drive, it ismore convenient to operate with energy indicators measured in Joules or Watts.

5 Conclusion

During the review analysis it is shown that the efficiency of the valve electric motoris about 2 times higher than that of the diesel engine and reaches about 95-96% in modern models. In addition, the specific power in relation to the weight of the motormotor reaches 5 kW/kg, which is 7-10 times higher than the basic internal combustion engine used on tractors. These factors, as well as affordable price (3.5-15 thousand rubles/kW) open the possibility of using brushless DC electric motorsas a power unit drive for tractors.

The analysis of power equipment on the territory of the Russian Federation wascarried out in order to use electric tractors powered from the external network. In the course of the study of materials it was established that for 2019. In Russia, the stock of energy resources received in total from all power plants is about 300 billionkWh, which according to calculations exceeds the energy costs for the possible supply of electric tractors and other agricultural machinery in the agricultural sectoralmost 10 times. It is shown that in more loaded months the energy consumption will not exceed 12.2 billion kWh, which is not critical.

In this paper, a specific energy cost indicator was proposed to summarize the concept of diesel and electric engine efficiency. This indicator is convenient for comparative analysis. Thus, when modeling the parameters of 20 kW motors, it wasshown a reduction in specific energy cost when using a valve electric motor compared to diesel by 5-7 rub/kWh or 30-50%, at medium and low loads. At further load increase the indicators tend to the equivalent value of about 15 rub/kWh.

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