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Control of switched reluctance motors of traction electric drives of railway transport

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Due to harmful emissions from vehicles on fossil fuels, rising prices for petroleum products and natural gas, the use of electric vehicles is on the rise. The rapid growth of electric vehicle production will ultimately satisfy these problems in cities. Outside the city, it is advisable to develop intercity electric transport, primarily rail, which can significantly reduce the cost of passenger and freight transportation. The paper considers the possibility of using switched reluctance motors in the traction drives of railway locomotives to replace less efficient, outdated direct current motors. It was designed in a direct current motor housing to study the static characteristics of the switched reluctance traction motor. A simulation model of a switched reluctance motor was developed, and its static characteristics were calculated at various supply voltages and load torque when operating in traction electric drives of railway transport. A comparison of the traction, mechanical and energy characteristics of a switched reluctance motor and a direct current traction motor at different supply voltages was carried out to assess the efficiency of its application. With this approach, as with direct current motors, the supply voltage of the switched reluctance motors was regulated by changing the wiring diagram. An algorithm for controlling the switched reluctance motor through pulse-width modulation of its phase voltage to form a family of traction characteristics is proposed. The study results showed that the proposed approach to regulating the rotation speed of the switched reluctance motor allows for the formation of the required number of traction characteristics and, if necessary, for performing stepwise or smooth transitions between them to regulate the vehicle speed. The results indicate the efficiency of switched reluctance motors in direct current traction electric locomotives.

Keywords: switched reluctance motor, traction electric drive, railway transport, electric locomotive, pulse-width modulation, rotational speed regulation, efficiency

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INTRODUCTION

The use of intercity wheeled electric vehicles is associated with logistics complications since it leads to the inevitable need to place additional electric filling stations (charging stations) and battery change stations on long routes. In urban conditions, rail transport, primarily intercity trains, trams, and subways, has a greater economic and environmental effect than wheeled electric transport. Therefore, the railway remains the only alternative electric transport for intercity routes. Thus, the task of developing intercity rail electric transport is urgent.

In many countries, railways use various modifications of electric locomotives for multiple purposes (shunting, industrial, mainline freight, freight-passenger, or passenger) and current types (direct, alternating, or multi-system).

Since 1949, railway, shunting and industrial electric locomotives and electro-diesel locomotives of various types of current powered by contact networks, as well as battery and battery-electric locomotives have been produced or modernised on the territory of Ukraine. Among such enterprises, the most famous plants are: Dnipro Electric Locomotive Plant, Luhansk Locomotive Construction Plant, Kharkiv Steam Locomotive Construction Plant, Zaporizhzhya Electric Locomotive Repair Plant, Druzhkivka Machine Building Plant, and others.

Currently, the Ukrainian railways of Joint Stock Company (JSC) Ukrzaliznytsia use various modifications of electric passenger locomotives of the ChS2, ChS4, ChS7, ChS8 series manufactured in former Czechoslovakia and Ukrainian DS3, as well as Ukrainian electric freight locomotives DE1 and 2EL5, and electric locomotives VL8, VL10, VL11, VL40, VL60, VL80, and VL82. At the same time, the most widespread are the VL8 electric locomotives, which are also the oldest of all electric locomotives [1]. A significant number of newer VL10 and VL11 models are often idle, awaiting repairs [2]. Railway locomotives are regularly modernised; in particular, electric locomotives of the VL8, VL11, VL40, VL80, ChS4, and ChS7 series have undergone modernisation over the last 5–10 years.

Currently, new electric locomotives are not mass-produced in Ukraine, which means the need must be met through imports and the extension of service life by modernising existing electric locomotives.

Since most traction electric motors used by DC and AC locomotives in Ukraine are DC machines, their replacement is advisable. Also, considering that most locomotives in JSC Ukrzaliznytsia are DC electric locomotives that have significantly exhausted their service life, they are in the most urgent need of modernisation.

One of the areas in the development of rail electric transport is increasing its energy efficiency, which is achieved by using new types of electric machines with high efficiency and practical algorithms for their control. DC motors are inferior to other types of electrical machines by all indicators except simplicity of control. This is why they were massively replaced in industry by asynchronous motors when it became possible to implement efficient semiconductor converters and vector control. Further development of electric traction drives should be expected through synchronous machines with permanent magnets and switched reluctance machines (SRM), as they have a higher efficiency than other machines. At the same time, synchronous machines with permanent magnets have greater efficiency. However, they have lower reliability and higher cost than SRMs [3–5].

The traction electric drive must provide speed control over a wide range with high energy efficiency and be reliable and easy to maintain. A mandatory requirement is the possibility of energy recovery. In most cases, simplicity and low manufacturing costs are also essential. Thus, it is advisable to consider a SRM that satisfies most of these requirements for electric vehicle driving. Domestic and foreign studies show that switched reluctance motors are superior to DC motors and asynchronous motors in terms of energy, weight, and size indicators [5–7]. At the same time, the cost of their production, which is due to the smaller amount of non-ferrous metals (reduced length of the stator winding frontal parts, absence of a rotor winding), simpler design (absence of a collector, brushes, or slip rings) and a reduction in the number of complex technological operations (coil winding of the stator, absence of casting of the rotor winding), is significantly lower than that of the machines of the specified types [4, 7, 8].

Using such machines is also advisable because of the rising cost of rare-earth permanent magnets and the need to ensure appropriate temperature conditions, which complicate the drive design. At the same time, given their lower efficiency than synchronous machines with permanent magnets, special attention should be paid to developing energy-efficient control algorithms for switched reluctance traction drives. This paper considers these motors as a possible replacement for DC motors when modernising electric locomotives such as the VL10.

The work aims to assess the possibility of using SRMs in traction drives of railway locomotives and approaches to regulating their rotation speed.

LITERATURE REVIEW

The following papers reflect the main directions of SRM research over the past five years. Particular attention is paid to methods for reducing torque pulsations, acoustic noise, and vibrations, which involve the analysis of quasi-steady-state processes, the development of torque control methods [9, 10, 11] and construction, which ensures the improvement of the SRM design [12–14]. Numerous works aim to improve the use of SRMs in electric vehicles [5, 14, 15]. There are known studies on SRM in wheel rail transport drives [13]. In addition to switched reluctance motors, synchronous reluctance machines are also considered traction motors, which also have a passive rotor, a stator winding fed with a three-phase sinusoidal current. At the same time, SRMs were not considered traction motors for railway locomotives. Such studies are of interest because the speed range in such a drive is quite broad and, at the same time, the rotational speed regulation must be carried out while maintaining the traction characteristics of the motor, i.e., stabilisation of the rotational speed is not enough due to the change in the angle of inclination of the railway track, the inconstancy of the movement resistance forces, the presence of limitation on the speed of movement and traction force. In the work of Sreeram et al. [15], an assessment was made of the methods used to control torque and speed and reduce ripples by improving the designs and control strategies of the switched reluctance drives of the electric vehicles. In the work of Li et al. [13], the methods for design, optimisation, and control were presented, the prototype of a linear SRM with a transverse flow, which was intended to replace linear synchronous and induction motors of urban wheel rail transport, was developed and tested. The work of Aiso et al. [12] is devoted to implementing a high-speed switched reluctance motor and using vector control to reduce its vibrations. Masoumi and Bilgin [5] present a comparison of induction, switched reluctance motors, and a synchronous motor with permanent magnets, which are used in electric vehicles: energy and weight and size indicators, natural frequencies of oscillations (determined based on an analysis of radial force density waveforms), as well as the data of vibroacoustic analysis. The work of Jabari and Rad [11] demonstrates the application of optimisation methods aimed at enhancing the performance of speed controllers and reducing torque ripples of SRMs. Rani and Jayapragash [14] proposed a modification of the SRM geometry aimed at reducing the radial force; it consists of using additional holes in the rotor sheets, round or square; the selection of their dimensions and location based on the need to avoid flux saturation. Fang et al. [10] provide an overview of modern SRM control strategies, such as current regulation at low speed, indirect and direct torque control methods aimed at reducing their ripples and suppressing vibrations. Watthewaduge et al. [16] analyse various methods of modelling SRMs: analytical ones, which are based on Maxwell's equations, or methods of interpolation and curve approximation, or numerical ones, based on the finite element method, or the boundary element method, or the magnetic equivalent circuit method. Scalcon et al. [9] devoted their work to optimising analytical torque sharing functions to reduce the current in the DC-link of the SRMs, which will reduce the size (capacity) of the capacitor bank or extend its lifetime. Kawarazaki et al. [17] propose a discontinuous current vector control method for a three-phase SRM, which allows improving the torque per ampere ratio and increasing the efficiency of the SRM in comparison with continuous current vector control, and also reducing vibration and acoustic noise.

Thus, modern and comprehensive research confirms the prospects for using SRMs in electric transport. At the same time, several issues related to their use in railway locomotive traction drives require additional research.

MATERIALS AND METHODS

To assess the advisability of using an SRM as a locomotive traction electric drive, its traction, mechanical, and energy characteristics must be compared with those of the traction motors used.

To study the characteristics of the switched reluctance motor, it was designed in the housing of a TL-2K1 electric motor, which is installed on VL10 DC electric locomotives, with the aim of maintaining the invariability of the kinematic connections of the drive and unified fastening elements. The nominal parameters of both motors are the same.

The motor design is classic: the yokes and teeth of the stator and rotor of the 6/4 configuration are laminated, whereas in the TL-2K1 electric motor, the stator yoke is the motor housing. Although the use of a laminated yoke reduces the maximum possible stator diameter, it is necessary due to the high induction in the yokes and for reducing magnetic losses.

Further studies will consider the issue of choosing the SRM structure and configuration (the presence or absence of a laminated stator yoke, adjusting the dimensions of the housing and magnetic circuits) in the process of its design.

The primary geometric parameters and nominal data of the designed motor are summarised in Table 1. It is worth noting that the obtained efficiency at nominal load can be increased by thorough optimisation of geometric parameters and winding data, and studies [13, 18] indicate this.

Based on previously developed mathematical models, a simulation model was used to calculate the SRM indicators and characteristics [19, 20]. The basic equations of a SRM are as follows:

$$\begin{cases} \dfrac{d\Psi_{ph(n)}}{dt} = U_{ph(n)} - i_{ph(n)} \cdot R_{ph}; \\ i_{ph(n)} = \dfrac{\Psi_{ph(n)}}{L_{ph(n)}}; \\ L_{ph(n)} = f(\theta_{ph(n)}, i_{ph(n)}); \\ \theta_{ph(n)} = (\theta - (q_{(n)} - 1)\dfrac{2\pi}{mZ_R}; \dfrac{2\pi}{Z_R}); \\ T_{ph(n)} = f(\theta_{ph(n)}, i_{ph(n)}); \\ T = \sum_{n=1}^{m} T_{ph(n)}; \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}(T - T_L); \\ \dfrac{d\theta}{dt} = \omega. \end{cases} \quad (1)$$

where $n = a, b, c, \ldots, m$ is the phase designation; m is the number of phases; $U_{ph(n)}$ – the voltage of phase n; R_{ph} – the stator phase resistance; $i_{ph(n)}$ – the stator phase current of phase n; $\psi_{ph(n)}$ – the stator

Table 1. **Geometrical parameters and nominal data of the designed switched reluctance traction motor**

Parameters	Conventional designation and units of measurement	Value
Geometrical parameters of the traction motor		
Stator outer diameter	D_o, mm	975.0
Stator inner diameter (not less than)	D_i, mm	749.0
Rotor inner diameter	D_{Ri}, mm	400.0
Air gap	δ, mm	4.0
Length	l_δ, mm	500.0
Number of stator/rotor teeth	Z_S/Z_R	6/4
Traction motor nominal data		
Nominal voltage	U_d, V	1500
Nominal power (not less than)	P_{nom}, kW	575
Nominal rotational speed	n_{nom}, rpm	830
Current density	j, A/mm^2	7
Efficiency	η, %	92.43

flux linkage of phase n; $L_{ph(n)}$ – the stator phase inductance of phase n; $\theta_{ph(n)}$ – the relative value of the rotor rotation angle for phase n; $(q_{(n)}$-$1)\cdot 2\pi/(m\cdot Z_R)$ – the shift angle of phase n relative to the rotor rotation angle θ, which is equal to 0, $1\cdot 2\pi/(m\cdot Z_R)$, $2\cdot 2\pi/(m\cdot Z_R)$, …, $(m$-$1)\cdot 2\pi/(m\cdot Z_R)$; $q_{(n)}$ is the ordinal number of phase n, which for phases a, b, c, …, m is equal to 1, 2, 3, …, m; $T_{ph(n)}$ – the electromagnetic torque of phase n; T – the total electromagnetic torque; T_L – the load torque; J – the moment of inertia of the aggregate, and ω is the rotor angular frequency.

The calculations were performed using the nominal data of a SRM, which correspond to those indicated in Table 1; the stator winding phase resistance is R_{ph} = 0.0489 Ω, the moment of inertia of the drive J = 20 kg·m^2, and the nonlinear inductance and electromagnetic torque were calculated from a two-dimensional cross-section of the machine using finite element methods for steel grade 2013.

The following assumptions were made during the modelling: the switched reluctance machine windings are identical and symmetrical, there is no mutual induction between the phases, and the change in winding temperature is not considered.

The mathematical model used as the basis for the calculation adequately reflects the processes in the SRM, which is confirmed using the example of a 3 kW nominal power experimental sample: the differences between the calculated phase currents and voltages and the experimental ones do not exceed 7 % and 8 %, respectively [20].

The semiconductor converter (SC) was modelled in the MATLAB–Simulink environment using standard blocks of transistors and diodes from the Simscape Power Electronics library, which allow taking static losses into account. Its scheme corresponds to the given SRM circuit diagram in Fig. 1.

In this case, the transistors and diodes of the upper and lower arms of the simulated SC are three n-channel field-effect transistors with an insulated gate (MOSFET) connected in parallel and three Schottky diodes, respectively, which allows the necessary power to be transmitted and ensures the flow of phase current pulses of the required amplitude. Nominal voltage, average and pulse current, drain-source open junction resistance, maximum dissipated power of MOSFET: U_{DS} = 2000 V, I_{DS} = 123 A (I_{Dsmax} = 282 A), R_{DS} = 0.012 Ohm, P_{tot} = 552 W. Nominal voltage, average and pulse forward current, forward voltage drop, maximum dissipated power of the Schottky diode: U_{Rmax} = 2000 V, I_F = 214 A (I_{Dsmax} = 320 A), U_F = 1.5 V, P_{tot} = 1153 W.

The switching of the SRM phases is positional; they are switched on and off by the control system when the rotor teeth reach the relative angles of switching on (θ_{on} = 45°) and switching off (θ_{off} = 75°), respectively. The start of the rotor rotation angle for a given phase begins from the position in which the axis of the stator teeth of

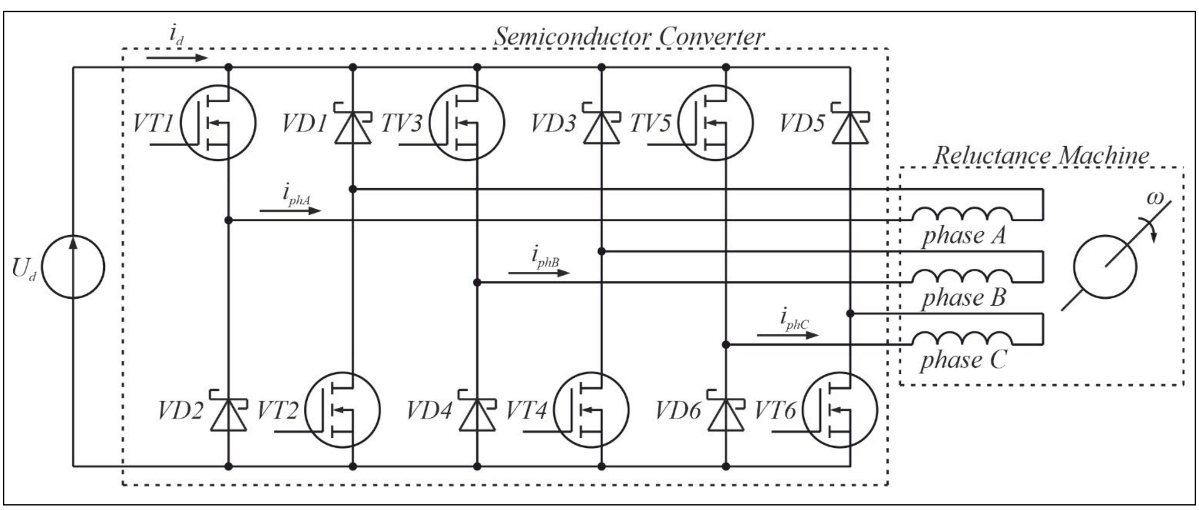

Fig. 1. SRM circuit diagram

Source: compiled by the authors.

a given phase coincides with the axis of the rotor teeth (θ_{ph} = 0°). The value of the rotation angle increases as the phase moves away from the stator teeth and reaches a maximum (θ_{ph} = 90°) when the next pair of rotor teeth coincides with the axis of the phase.

RESULTS AND DISCUSSION

A comparison of the SRM characteristics with the characteristics of the TL-2K1 motor was carried out at a supply voltage of 1500 V, 750 V, and 375 V (Fig. 2). Eight traction SRMs on a tangible object were connected in series, series-parallel, and parallel, which made it possible to obtain three traction characteristics at voltages of 1500 V, 750 V, and 375 V with a network voltage of 3000 V. The traction characteristics of the locomotive indicate the limitations for the operating range of adhesion (maximum traction force $F_{\max}$) and design speed (maximum $V_{\max}$), and the torque-speed and energy characteristics are marked with the corresponding limits of maximum torque $M_{\max}$ and rotation speed $n_{\max}$. The design speed limit is taken, and the adhesion limit is calculated using formulas [21]. The maximum traction force is the maximum force of adhesion of the wheels to the rails, exceeding which would lead to their slipping. This maximum motor torque is proportional to this force. Design speed refers to the maximum speed of the rolling stock for which its mechanical elements are designed (27.8 m/s). This speed of movement corresponds to the maximum rotation speed of the traction motor rotor (1625.5 rpm). The maximum torque of the motor and maximum rotation speed can be calculated using formulas [21, 22].

These SRM characteristics were obtained at constant voltage and switching angles and without influence on the phase current magnitude. It is evident from Fig. 2 and Table 2 that in the SRM, as in the compared DC motor with series excitation, the rotation speed decreases, the phase current, magnetic flux and electromotive force increase with an increase in the motor load torque. The characteristics show that the power of a switched reluctance traction motor increases approximately inversely proportionally to the rotation speed. The nature of the change in the torque-speed and traction characteristics of both motors is practically the same, which allows the proposed SRM to be used as a replacement for the TL-2K1 traction motor or other DC motors of similar purpose. The magnitude of the SRM traction force at the same rotation speed is greater than in the TL-2K1 traction engine (the excess can reach 40%), mainly due to the difference in the motor efficiency and, accordingly, the greater useful power. As shown in Fig. 3c, SRM efficiency at a specific torque is 2% greater than that of the TL-2K1 motor. The SRM efficiency is also higher than that of other electrical machines, except the machines with permanent magnets, which has already been pointed out earlier [6, 7].

The following designations of quantities (average values) are used in the table: U_d, I_d – voltage and supply current of the SRM, respectively; I_{ph} – phase current; P_{mech}, P_{st}, P_a, P_{tran}, P_{diod} – mechanical, magnetic, electrical losses in windings, transistors, and diodes, respectively; P_1, P_2 – consumed and useful power, respectively; n – rotor speed; M_e – electromagnetic torque; V, $F_к$ – locomotive speed of movement and traction force; η – SRM efficiency; j_k – current density in the winding; ψ_{phmax} – phase flux linkage (maximum value).

The SRM efficiency is maximum at a nominal voltage of 1500 V and decreases as the voltage decreases. The higher the rotation speed and the lower the load torque, the greater the value. Thus, for the nominal voltage, with an increase in the load torque from 2 to 9 kN·m, which corresponds to a decrease in the rotation speed within the operating range of 745–1603 rpm (taking into account the design speed limit on one side and the adhesion on the other), the efficiency changes within the range of 93.9–94.5 %. As follows from Table 2, with an increase in the load torque, the useful power produced by the motor increases by 2.1 times, while losses in the windings, steel, transistors and diodes of the converter increase by 6 times, 1.8 times, 5.2 times, and 2.9 times, respectively, and only mechanical losses decrease by 1.7 times. Thus, the decrease in efficiency is caused primarily by the increase in electrical losses in the motor windings, transistors and, to a slightly lesser extent, in the diodes of the semiconductor converter. If desired, the losses in the converter can be reduced

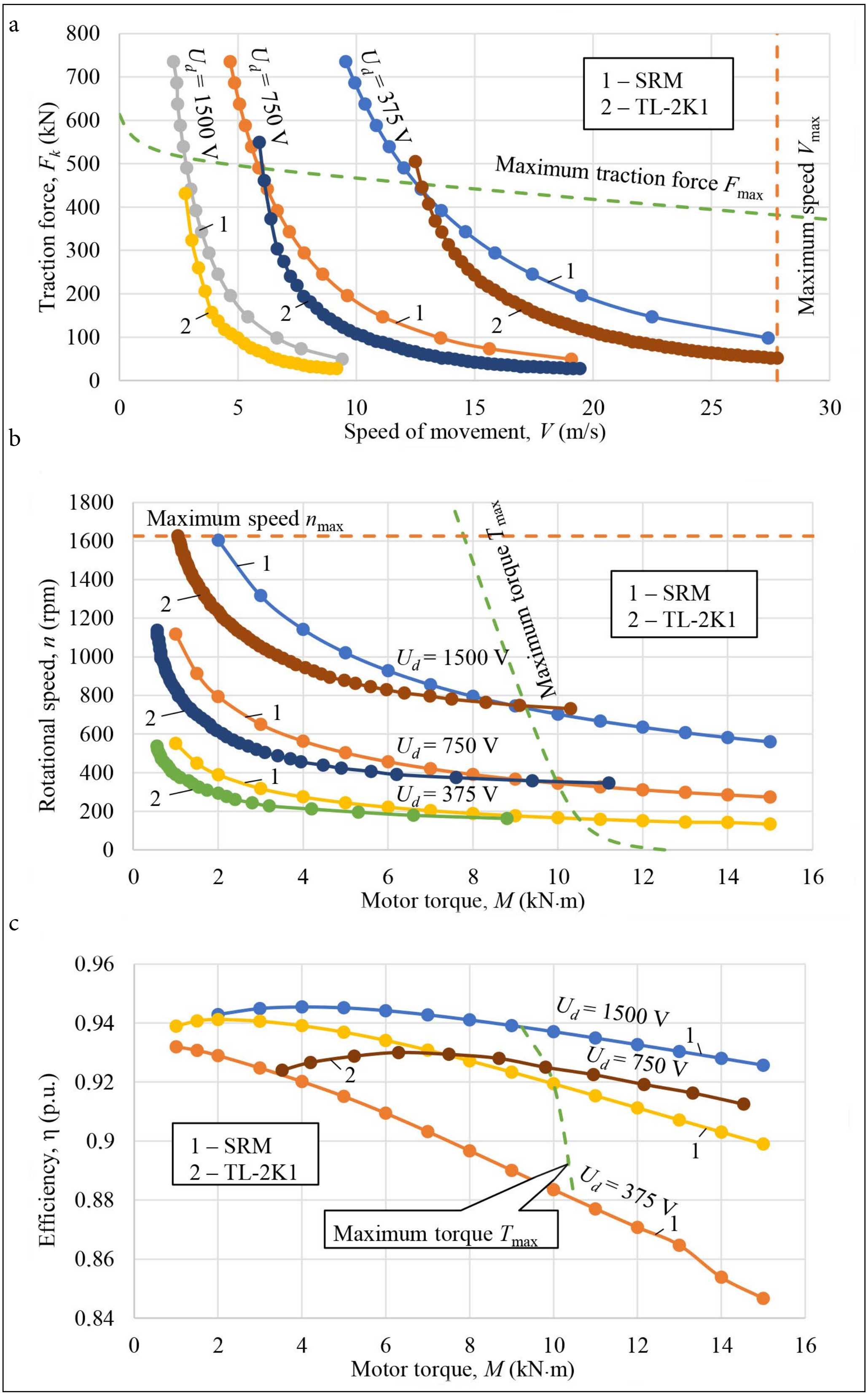

Fig. 2. Comparison of the locomotive traction characteristics (a), torque-speed (b), and energy characteristics (c) of the motors under consideration

Source: compiled by the authors.

Table 2. **Simulation results at supply voltage U_d = 1500 V**

U_d, V	I_d, A	I_{ph}, A	P_{mech}, W	P_{st}, W	P_d, W	n, rpm	M_e, kN·m	Ψ_{phmax}, Wb	j_k, A/mm^2	P_{tran}, W	P_{diod}, W	P_1, kW	P_2, kW	η, %	V, m/s	F_k, kN
1500	237	110	1089	16622	1771	1603	2	4.63	2.2	619	240	356	336	94.29	27.4	98.1
1500	292	135	913	19292	2680	1316	3	5.63	2.71	930	297	438	413	94.49	22.5	147.1
1500	337	157	822	21546	3636	1142	4	6.48	3.16	1250	350	506	478	94.54	19.5	196.1
1500	377	179	765	23559	4690	1020	5	7.24	3.59	1588	407	565	534	94.51	17.4	245.1
1500	412	201	724	25419	5901	928	6	7.94	4.02	1955	472	618	583	94.42	15.9	294.1
1500	443	223	692	27163	7285	855	7	8.61	4.47	2354	545	665	627	94.28	14.6	343.2
1500	472	245	668	28810	8838	795	8	9.24	4.92	2785	623	708	666	94.11	13.6	392.2
1500	499	268	649	30371	10552	745	9	9.84	5.37	3251	705	748	702	93.91	12.7	441.2
1500	524	290	632	31856	12414	703	10	10.41	5.83	3745	789	786	736	93.71	12	490.2
1500	547	313	617	33274	14418	666	11	10.96	6.28	4270	876	821	768	93.49	11.4	539.3
1500	570	335	604	34632	16552	635	12	11.49	6.72	4824	965	855	798	93.27	10.8	588.3
1500	592	357	592	35935	18809	607	13	12	7.17	5405	1054	888	826	93.04	10.4	637.3
1500	613	379	582	37190	21180	582	14	12.5	7.6	6013	1143	919	853	92.81	9.9	686.3
1500	633	400	572	38400	23657	559	15	12.98	8.03	6645	1233	949	879	92.57	9.6	735.4

Source: compiled by the authors.

proportionally by increasing the number of parallel-connected switches, if any. In contrast, the losses in the windings can only be reduced by increasing the wire cross-section or the number of parallel conductors of the coils, which is highly limited by the stator slot sizes. It should be noted that even with an ideal converter, the efficiency increases by only 0.3–0.5% at nominal voltage (at U_d = 750 V and U_d = 375 V by 0.5–1.1% and 0.9–2%, respectively).

A decrease in the rotation speed reduces mechanical losses, and an increase in phase currents increases electrical losses in the windings and the elements of the converter, magnetic flux, and consequently magnetic losses.

Since, as in the case of TL-2K1 traction motors, the use of only three torque-speed characteristics obtained by changing the motor wiring diagram does not allow complete control of the rotation speed for train control, it is necessary to find control methods that would enable the formation of a larger number of traction characteristics.

In DC traction motors, stepwise excitation regulation (magnetic flux reduction) is used for this purpose by shunting the excitation winding with an adjustable resistor. This allows the implementation of five mechanical characteristics within each wiring diagram: one with a full field and four with different field weakening coefficients.

Thus, in two-unit four-axle DC electric locomotives, such as the VL10, 15 traction characteristics are formed, which simplifies train control, softens the transition processes between serial, serial-parallel, and parallel connections of traction motors, and improves the quality of the contact network voltage. However, significant current surges, voltage drops, etc., still increase energy losses in the contact network. In order to reduce current surges when switching from one traction characteristic to another, it is necessary to use starting resistors and inductive shunts, which also reduce the efficiency of traction motors. To achieve a smooth transition between traction characteristics, it is essential to increase their number, which is possible through semiconductor converters in the anchor circuits of traction motors. In this case, the structure of such a drive will be in many ways similar to a switched reluctance drive. However, the efficiency of a DC motor will still be lower than when using more efficient types of electrical machines, such as SRMs.

Depending on the SRM operating mode, various methods of influencing its rotation speed can be applied: changing the switching angles, adjusting the phase current limit level, regulating the phase voltage or supply voltage [20]. Due to the wide range of torque and rotation speed changes, the most straightforward and expedient method is to use motor voltage regulation. Moreover, considering that the power of the transmitted energy is quite significant, the most economical option would be to implement a pulse-width modulation (PWM) algorithm using the switches of the available semiconductor converter (phase voltage regulation) instead of an additional converter (supply voltage regulation). In this case, the control system operation algorithm has the following form shown in Fig. 3.

The rotation speed is regulated by changing the duty cycle of forward applied phase voltage pulses, while the switching angles are set constant (θ_{on} = 45 deg., θ_{off} = 75 deg.). The switching control unit (SCU) receives signals of the instantaneous value of the rotor rotation angle θ_{ph} from the rotor position sensor RPS and, in accordance with the specified duty cycle *D*, generates a control action on the semiconductor converter switches (the reference signal frequency of the PWM controller f_{PWM} = 20 kHz). The train driver sets the duty cycle manually and can change it stepwise or smoothly. Such regulation makes it possible to avoid the need for regrouping motors, simplifying electrical wiring diagrams, and reducing switching devices.

To assess the efficiency of rotation speed control by changing the duty cycle stepwise, the locomotive traction characteristics (Fig. 4a), torque-speed (Fig. 4b), and energy (Fig. 4c) characteristics of the SRM were calculated. The SRM wiring diagram is a connection in four parallel branches, when two motors are included in each of them, with a maximum voltage of 1500 V on each motor.

It is evident from the figure that even for the proposed steps of duty cycle change (0.6, 0.67, 0.7, 0.75, 0.8, 0.87, 0.93, 1), which allows the formation of an eight torque-speed characteristics, relatively smooth regulation of the train speed of movement is possible while providing a traction force in the range of 98–206 kN. Using a smooth duty cycle change will expand this range and significantly improve the smoothness of train movement. The increased traction force (up to 451–520 kN for smooth regulation of the duty cycle) obtained as a result of the application of phase voltage regulation of switched reluctance motors of a VL10 locomotive will speed up the train acceleration process and reduce current surges caused by transient processes in the future.

An analysis of the energy characteristics (Fig. 4c) allows us to state that in the working area at a speed of 2.8–27.8 m/s, the efficiency is 89.7–94.5%. Moreover, the lower part of the range corresponds to low speeds of movement, which are used for a short time, and already at a speed of 5.6 m/s, the efficiency exceeds 92.5%.

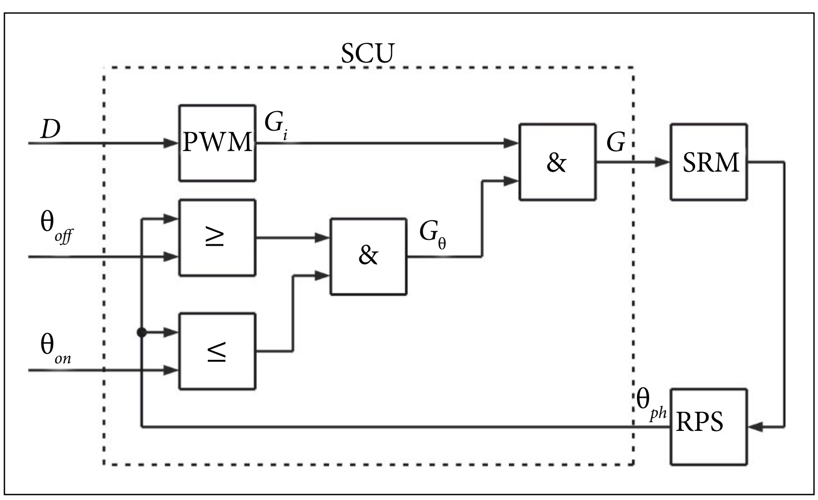

Fig. 3. Block diagram of the control algorithm of a switched reluctance motor

Source: compiled by the authors.

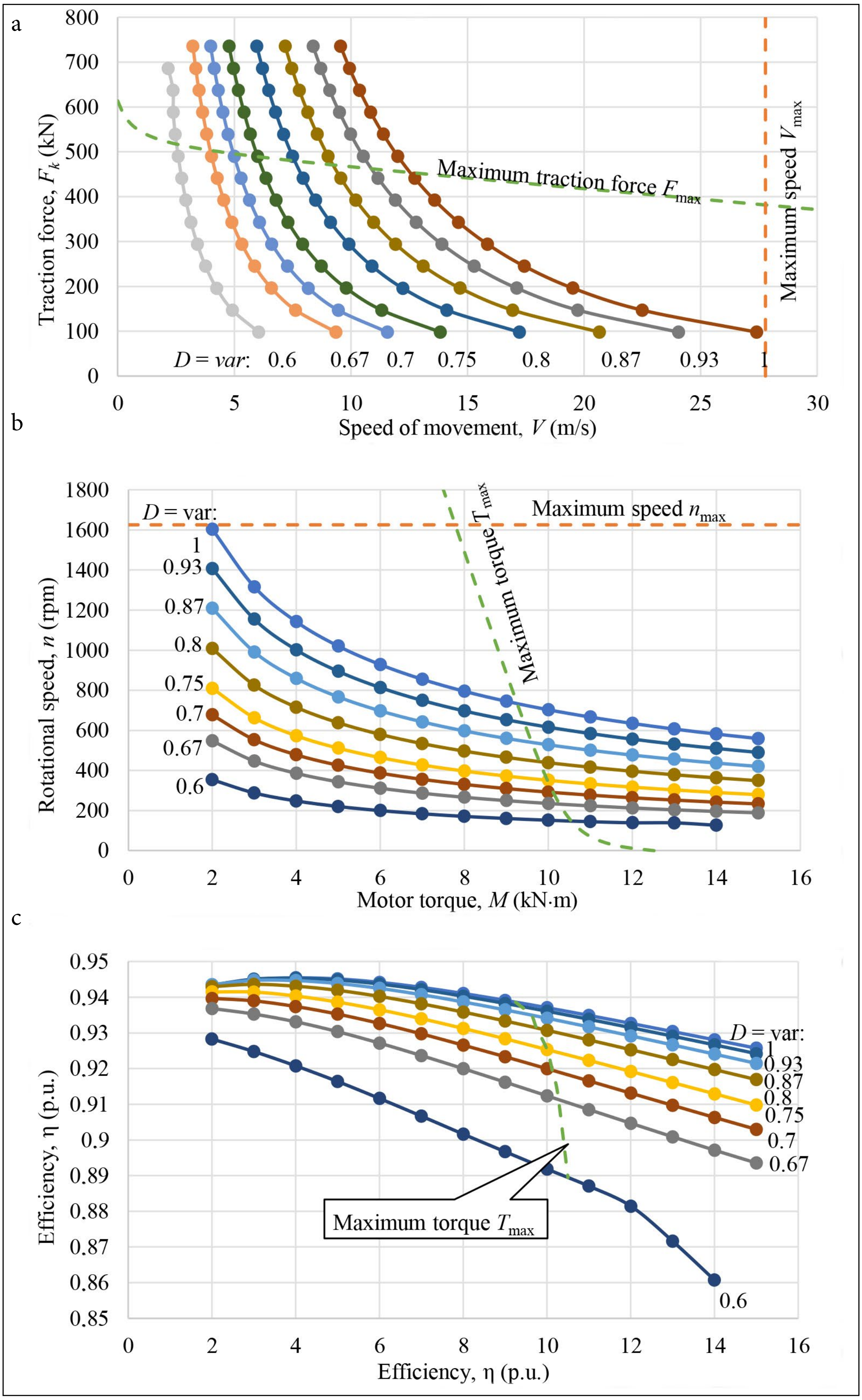

Fig. 4. Locomotive traction characteristics (a), torque-speed (b) and energy (c) characteristics of switched reluctance motors at PWM

Source: compiled by the authors.

CONCLUSIONS

Using the example of VL10 DC electric locomotives, the advisability of using SRMs in traction electric drives of railway transport has been determined by comparing the characteristics of a TL-2K1 DC motor and a SRM designed in its dimensions.

Two approaches to creating traction electric drives based on SRMs are proposed. According to the first approach, eight traction SRMs of an electric locomotive, as in the case of using DC motors, can be connected in series, series-parallel, and parallel, which makes it possible to obtain three traction characteristics at voltages of 1500 V, 750 V, and 375 V with a network voltage of 3000 V. It was established that the nature of the change in the traction and torque-speed characteristics of SRM and TL-2K1 at the specified voltages is similar. However, at the same rotation speed, the SRM traction force exceeds the DC motor traction force (the excess can reach 40%). This is due to the higher efficiency of the SRM (at some torques about 2%), which does not contradict the scientific results presented in technical literature, where a comparison of this energy indicator of different types of machines is performed. To regulate the smoothness of an electric locomotive movement, it is necessary to obtain several additional traction characteristics within each voltage step by changing the switching angles, regulating the phase current limit level, supply voltage, or phase voltage.

According to the second approach, the SRM wiring diagram is a connection in four parallel branches, when two motors are included in each of them with a maximum voltage on the motor of 1500 V. It is proposed to form traction characteristics and regulate the SRM rotation speed in a wide range using pulse-width modulation of the phase voltage by changing the duty cycle of the control pulses with a constant angular switching zone.

The results indicate the efficiency of using SRMs in traction electric drives of DC electric locomotives.

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GELEŽINKELIO TRANSPORTO PRIEMONIŲ TRAUKOS ELEKTROS PAVARŲ SU PERJUNGIAMAIS REAKTYVIAISIAIS ELEKTROS VARIKLIAIS VALDYMAS

Santrauka

Elektriniai automobiliai vis plačiau naudojami siekiant mažinti taršą, kurią sukelia degalais iš iškastinio kuro varomos transporto priemonės. Jų populiarėjimą skatina ir didėjančios naftos produktų ir gamtinių dujų kainos. Sparčiai auganti elektrinių automobilių gamyba ilgainiui padės spręsti šiuos iššūkius miestuose. Už miesto ribų patartina plėtoti tarpmiestinį elektrinį transportą, visų pirma geležinkelius, kurie gali reikšmingai sumažinti keleivių ir krovinių pervežimo sąnaudas.

Straipsnyje nagrinėjamos galimybės geležinkelio lokomotyvų pavarose naudoti perjungiamus reaktyviuosius elektros variklius kaip alternatyvą mažiau efektyviems, pasenusiems nuolatinės srovės varikliams. Toks variklis buvo suprojektuotas nuolatinės srovės variklio korpuse, siekiant ištirti jo, kaip traukos variklio, statines charakteristikas. Sukurtas perjungiamo reaktyviojo elektros variklio matematinis modelis ir apskaičiuotos jo statinės charakteristikos įvairioms maitinimo įtampoms bei apkrovos sukimo momentams, būdingiems geležinkelio transporto traukos elektros pavaroms. Siekiant įvertinti šio variklio darbo efektyvumą, buvo palygintos jo traukos, mechaninės ir energetinės charakteristikos esant skirtingoms maitinimo įtampoms su atitinkamomis nuolatinės srovės traukos variklio charakteristikomis. Taikant šį palyginimo metodą maitinimo įtampa buvo reguliuojama keičiant sujungimų schemą. Be to, pasiūlytas algoritmas perjungiamo reaktyviojo elektros variklio valdymui, taikant fazinės įtampos impulsų trukmės moduliavimą ir sudarant traukos charakteristikų šeimą. Tyrimo rezultatai parodė, kad siūlomas metodas tokio variklio sukimosi greičiui reguliuoti leidžia gauti reikiamą traukos charakteristikų skaičių ir atlikti žingsninius arba sklandžius perėjimus tarp charakteristikų. Gauti rezultatai patvirtina perjungiamų reaktyviųjų elektros variklių efektyvumą nuolatinės srovės traukos elektriniuose lokomotyvuose.

Reikšminiai žodžiai: perjungiamas reaktyvusis elektros variklis, traukos elektros pavara, geležinkelio transportas, elektrinis lokomotyvas, impulsų trukmės moduliavimas, sukimosi greičio reguliavimas, efektyvumas