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IMPLEMENTATION OF SYNCHRONOUS ELECTRIC MOTORS WITH PERMANENT MAGNETS IN THE TRACTION ELECTROMECHANICAL SYSTEMS OF TWO-AXLE ELECTRIC LOCOMOTIVES

Annotation. *The article presents a study evaluating the feasibility and effectiveness of using an electromechanical traction complex based on synchronous motors with permanent magnets (SMPM) for two-axle electric locomotives.*

The author proposes a scientific research strategy in line with this topic, which, in order to obtain real scientific results, should be carried out logistically in the following format: starting at a preventive level and then moving on to a qualitative evidence-based level.

It is emphasized that a sufficient level of efficiency in general, and energy efficiency in particular, can be achieved by integrating a corresponding control system (CS) for the speed of these types of traction electric motors (TEM) into the ETS variant with SMPM. An important positive aspect of such a development, taking into account the specifics of the operation of the analyzed types of electric locomotives – as a rule, underground operating conditions and the corresponding requirements for the special design of their equipment – is that a sensorless vector control option should be considered sufficiently feasible.

An effective sub-option for the practical implementation of this idea is the use of high-frequency injection (HFI) to implement this control method. This will allow the necessary condition to be implemented in terms of circuitry – determining the position of the SMPM rotor at low speeds of the electric locomotive, which is characteristic of these types of electric locomotives according to established technologies for their operation. However, as established, the development of an effective algorithm for control actions of the control system in this format of operation requires the study of all factors influencing this process by rebuilding an adequate ETS controllability structure. The logistics for launching this format, as well as the option of the ETS development itself, are presented in this work.

Keywords: *synchronous motor with permanent magnets, energy efficiency, high-frequency injection, sensorless control, electric locomotive.*

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РЕАЛІЗАЦІЯ СИНХРОННИХ ЕЛЕКТРОДВИГУНІВ З ПОСТІЙНИМИ МАГНІТАМИ В ТЯГОВИХ ЕЛЕКТРОМЕХАНІЧНИХ СИСТЕМАХ ДВОСІХ ЕЛЕКТРОЛОКОМОТИВІВ

Анотація. *У статті представлено дослідження, що оцінює доцільність та ефективність використання електромеханічного тягового комплексу на основі синхронних двигунів з постійними магнітами (СДПМ) для двовісних електровозів. Автори пропонують стратегію наукових досліджень відповідно до цієї теми, яка для отримання реальних наукових результатів повинна логістично здійснюватися в такому форматі: починаючи з превентивного рівня, а потім переходячи до якісного рівня, заснованого на доказах. Підкреслюється, що достатній рівень ефективності загалом, та енергоефективності зокрема, може бути досягнутий шляхом інтеграції відповідної системи керування (СК) швидкістю цих типів тягових електродвигунів (ТЕД) у варіант ЕТС з ТВПМ. Важливим позитивним аспектом такої розробки, враховуючи специфіку експлуатації аналізованих типів електровозів – як правило, підземні умови експлуатації та відповідні вимоги до спеціальної конструкції їхнього обладнання – є те, що варіант безсенсорного векторного керування слід вважати достатньо доцільним.*

Ефективним підваріантом практичної реалізації цієї ідеї є використання високочастотної інжекції (ВЧІ) для реалізації цього методу керування. Це дозволить реалізувати необхідну умову в схемотехнічному плані – визначення положення ротора ТВПМ на низьких швидкостях електровоза, що характерно для цих типів електровозів згідно зі встановленими технологіями їх експлуатації. Однак, як встановлено, розробка ефективного алгоритму керуючих дій системи керування в такому форматі роботи вимагає вивчення всіх факторів, що впливають на цей процес, шляхом перебудови адекватної структури керованості ЕТС. У цій роботі представлено логістику запуску цього формату, а також варіант самої розробки ETS.

Ключові слова: *синхронний двигун з постійними магнітами, енергоефективність, високочастотне впорскування, безсенсорне керування, електровоз.*

Relevance of research. Two-axle types of electric locomotives, or as they are classified according to the relevant standardization – mine locomotives, are widely used in underground work at mining enterprises, in construction, in the laying of underground tunnels for subways, high-speed trams, and special-purpose routes [1].

In turn, two-axle electric locomotives are classified according to their ETS power supply type as contact locomotives, which are powered by a contact network, battery locomotives, which are powered by autonomous traction batteries, and mixed contact-battery locomotives [1,2].

To the above fact, for a sufficiently favorable understanding of the problem being analyzed, it should be added that in such a technological line of types and a significant number of operating units of these electric locomotives, all of them are equipped with identical or similar 2-module ETS structures: series-excited traction motors and a central contactor-resistor control unit.

In addition to the moral obsolescence of the existing ETS of the analyzed types of electric locomotives, these complexes are energy-inefficient in the modern sense of the term, since only in the CS regulating resistors, about 40 % of electrical energy is lost at the TEM rotation frequency. In accordance with this odious indicator, at most enterprises where these types of electric locomotives are operated, the level of electricity consumption by the corresponding transport complexes reaches 12–15 % of the total electricity consumed by the enterprises [1,3].

Assessing the not-so-low level of negativity in the technological and technical indicators of the functioning of ETS two-axle electric locomotives, and relying on modern visions and possibilities of circuit implementation, in terms of their current efficiency, in recent years, research has been creatively resumed in the direction of creating new types of traction complexes to replace outdated ones.

This is a necessary logical continuation of scientific research that has been conducted for many years on the development and implementation of new models of two-axle electric locomotives with modern ETS, including energy-efficient ones [4–7]. However, judging by the results, the proper and expected level of implementation of new models has not yet been observed. Therefore, the problem remains unresolved, and the question of the need to create modern ETS for the analyzed types of electric locomotives remains relevant, especially in the context of energy shortages both in the country and in specific industrial enterprises in particular.

Assessing, in a sufficiently accurate manner, new known trends in the study of energy-efficient types of ETS for the analyzed types of electric locomotives, it can be argued that one of the promising areas here should be considered traction electromechanical complexes based on SMPM [4-8].

At the same time, as an important a priori addition, in order to achieve a sufficient level of efficiency of this ETS format, it is advisable to use sensorless control methods in the project [4]. In turn, from the range of these control methods, the CS option with high-frequency injection, better known in the literature as HFI, looks very interesting. This approach to the development of CS ETS will allow additional optimization of the energy consumption level of this format of control systems, increase the positioning accuracy of the SMPM rotor, and ensure the stable operation of the entire electromechanical complex of the electric locomotive in the changing and unpredictable operating conditions of these types of vehicles.

Purpose of the study. Justification and development of a format for building an energy-efficient traction electromechanical system for two-axle electric locomotives based on synchronous motors with permanent magnets, integrating the high-frequency injection method into the process of controlling their rotation speed.

Review of scientific publications. An analysis of well-known scientific publications in terms of the above-mentioned objective of this scientific research shows that the issue of improving the energy efficiency of two-axle electric locomotives and the controllability of traction electric drives has been and remains one of the most relevant and popular problems among researchers in this field of electric drives for a considerable period of time. At the same time, most studies have proven the need to replace outdated, low-efficiency ETS with new, modern versions. Thus, in works [1-4], the possibility of using AC traction electric motors – asynchronous with pulse control methods – in ETS structures was analyzed.

A number of studies of varying variability are also known [4–14]. However, there is still a lack of real solutions for the practical development of ETS for two-axle electric locomotives. The search for such options, taking into account the specifics of the ETS operating technology of these types of electric locomotives, is a necessary and relevant process for evaluating and developing scientific and technical directions in the realities of developing new projects for these types of electric locomotives.

Presentation of the main material. A general analysis of the electromechanical parameters that characterize the energy efficiency of any type of ETS should begin with its main component – the electric motor. The potential capabilities of the ETS variant of a two-axle electric locomotive, formed on the basis of SMPM, analyzed in this study, a priori have a number of advantages over traditional traction complexes with DC motors or asynchronous machines [3,4]. As is known, the main design feature of SMPM is the presence of permanent magnets on the rotor, which eliminates the need for an excitation winding and a DC power source to power it. This makes it possible to reduce energy losses in the motor excitation process, increase the efficiency (EC) of the entire TEP complex, and simplify its ETS design. At the same time, the EC of SMPM can reach 95% or more, which is a significant improvement compared to asynchronous motors, where losses in the rotor and stator windings reduce the efficiency of ETS to 85–90 %.

As is known, SMPM is characterized by relatively high torque per unit mass of the motor and better dynamic behavior due to the synchronous rotation of the stator and rotor magnetic fields [4]. The rotor speed in SMPM is directly proportional to the supply frequency and inversely proportional to the number of pole pairs. The canonical dependence of motor speed on supply frequency actually provides the basis for a physical description of the high-frequency injection (HFI) method studied in this work, which allows determining the position of the SMPM rotor without using physical sensors. HFI is based on the introduction of a high-frequency signal into the stator windings and analysis of the system response, which depends on the anisotropy of the motor's magnetic field. In SDPM, anisotropy arises due to the difference in magnetic resistance along the d-axis (direct – along the magnets) and q-axis (transverse). This difference is due to inductances L_d and L_q, which usually have different values due to the design features of the rotor. For example, in SMPM with surface-mounted magnets, $L_d < L_q$, while in motors with internally mounted magnets, the ratio may be reversed. The principle of operation of HFI is to superimpose a high-frequency voltage U_{hf} with a frequency f_{hf} significantly higher than the operating frequency of the motor on the main control signal. This voltage causes a high-frequency current I_{hf}, the amplitude and phase of which depend on the position of the rotor. Mathematically, the high-frequency component of the voltage in the $d-q$ coordinate system is defined as:

$$U_{hfd} = U_{hf} cos\left(2\pi f_{hf} t\right), \quad U_{hfq} = 0, \tag{1}$$

where U_{hf} −amplitude of the injection signal, f_{hf} −injection frequency (typically 500-2000 Hz). The current feedback in the d and q axes is determined by the inductances:

$$I_{hfd} = \frac{U_{hfd}}{\omega_{hf} L_d}, \quad I_{\text{вч}q} = \frac{U_{hfq}}{\omega_{hf} L_q}, \tag{2}$$

where $\omega_{hf} = 2\pi f_{hf}$ −injection angular frequency. Since $L_d \neq L_q$, the resulting current will have a component proportional to the rotor position angle θ. By analyzing the phase and amplitude of this current, the control system can calculate θ with high accuracy.

In addition, the HFI method is particularly valuable for two-axle electric locomotives, as it eliminates the need for sensors, thereby increasing system reliability. Operating conditions in mines are characterized by high dust levels, temperature fluctuations, and mechanical loads, which complicate the use of traditional sensors. HFI enables sensorless vector control, which ensures optimal current distribution in the motor to maximize torque with minimal losses. Vector control is based on decomposing the stator current into two components: I_d (along the d-axis) and I_q (along the q-axis). Torque:

$$M = \frac{3}{2} p\left[\Psi_{rm} I_q + \left(L_d - L_q\right) I_d I_q\right], \tag{3}$$

where Ψ_{rm} − rotor magnet flux, I_d and I_q −current components in axes d and q. In maximum energy efficiency mode, I_d is often set to zero (for motors with surface-mounted magnets, where $L_d \approx L_q$), which simplifies control and minimizes losses in the windings [5,6].

The energy efficiency of the HFI system can also be achieved through adaptive regulation of the frequency and amplitude of the power supply depending on the load of the electric locomotive. When operating two-axle electric locomotives, the load on their motors can vary significantly: from running an empty locomotive to transporting maximum loads. The HFI method allows dynamic adjustment of angle θ, ensuring stable field synchronization even with sudden changes in torque. For example, when the load increases, the system automatically increases I_q, maintaining optimal engine operation. This reduces power consumption compared to traditional fixed control systems.

An important point in the development of the analyzed ETS variant is also that the practical implementation of HFI in the electric drives of two-axle electric locomotives requires powerful computing resources, since the processing of high-frequency signals and the calculation of angle θ occur in real time. Modern microcontrollers and digital signal processors (DSP) allow these operations to be performed with a refresh rate of up to 10 kHz, which is sufficient to ensure smooth control even at low speeds. At low speeds, where traditional position estimation methods (e.g., based on back EMF) lose accuracy, HFI demonstrates high efficiency, which is critical for maneuvering electric locomotives in narrow mine tunnels. Thus, the integration of the high-frequency injection method into SMPM control systems for two-axle electric locomotives creates the basis for improving energy efficiency and reliability. This approach not only reduces operating costs, but also provides a starting point for preliminary circuit adaptation of the electric drive to specific operations in enterprises where stability and resource conservation are key priorities [5, 8,9].

In other words, drawing certain conclusions from the above, it can be stated that the energy efficiency of control systems for electric drives of two-axle electric locomotives using SMPM and the high-frequency injection (HFI) method is the result of several key factors: minimization of electrical losses, optimal distribution of currents in the motor, and the aforementioned adaptive control of operating modes depending on operating conditions. This is achieved through higher efficiency of converting electrical energy into mechanical energy and reducing heat losses in the motor.

The main sources of losses in electric motors are resistive losses in the stator windings (P_{Cu}), losses in the magnetic circuit (P_{Fe}), and mechanical losses $P_{м}$. For SMPM, resistive losses are:

$$P_{Cu} = 3R_s\left(I_d^2 + I_q^2\right), \quad (4)$$

where R_s – stator winding resistance, I_d and I_q – current components in the d and q axes. In systems with HFI, it is possible to precisely control I_d and I_q, minimizing their values at a given moment. For example, in Maximum Torque Per Ampere (MTPA) mode, the system strives to optimize the angle between the stator current vector and the rotor magnet flux, which reduces P_{Cu}. Losses in the magnetic circuit, which depend on the supply frequency and magnetic induction, are also reduced due to the efficient use of the magnetic flux of permanent magnets, which does not require additional energy to create [7,8].

To evaluate energy efficiency, it is important to consider the dynamic SMPM model in the $d-q$ coordinate system. The voltages on the stator windings are described by the following equations:

$$U_d = R_s I_d + L_d \frac{dI_d}{dt} - \omega L_q I_q, \quad (5)$$

$$U_q = R_s I_q + L_q \frac{dI_q}{dt} + \omega L_d I_d + \omega \Psi_{pm}, \quad (6)$$

where U_d i U_q – axial stresses d and q, ω – angular frequency of the rotor rotation, Ψ_{pm} – permanent magnet flow.

In steady state, the derivatives $\frac{dI_d}{dt}$ and $\frac{dI_q}{dt}$ are zero, which simplifies the model to the expression:

$$U_d = R_s I_d - \omega L_q I_q, \quad (7)$$

$$U_q = R_s I_q + \omega L_d I_d + \omega \Psi_{pm} \quad (8)$$

Equations (7) and (8) allow calculating the power consumption $P_{el} = U_d I_d + U_q I_q$ and optimizing it by adjusting I_d and I_q.. The HFI method plays a key role in this process, ensuring accurate determination of ω and the rotor position angle θ, which is necessary for the correct transformation of coordinates from the abc system to the d-q system.

It should be noted that an important aspect of the energy efficiency of this drive option is the above-mentioned ability of the HFI to operate at low electric locomotive speeds, when traditional sensorless control methods, such as back EMF estimation (Back-EMF), become ineffective, because under such conditions the back EMF is proportional to the rotation speed $\left(E = \omega\Psi_{pm}\right)$ and at low speeds the signal is too weak for accurate analysis. Instead, HFI uses a high-frequency response that does not depend on speed, but only on the anisotropy of inductances. This allows maintaining a stable torque even when the electric locomotive starts from a standstill under load, which often happens in mines when transporting heavy cars.

It is important to note that, compared to other sensorless methods such as model-based adaptive control (MRAS) or extended Kalman filter (EKF) based observation, HFI has the advantage of being simple to implement and less computationally complex. MRAS, for example, is based on comparing the actual and model behavior of the motor, which requires accurate knowledge of the system parameters $\left(R_s, L_d, L_q\right)$, which can change due to heating or wear. EKF, although it provides high accuracy, requires significant computational resources for recursive updating of covariance matrices. The high-frequency injection method, on the other hand, relies on the physical property of anisotropy, which is relatively stable and requires only high-frequency signal analysis, which is easy to implement technically.

The analysis of currents caused by the injection signal is as follows. When applying voltage $U_{hfd} = U_{hf}cos\left(\omega_{hf}t\right)$ to axis d, the resulting current in the rotor coordinate system will be as follows:

$$I_{sqd} = \frac{U_{sq}cos\left(\omega_{sq}t\right)}{\omega_{sq}L_d}, \qquad (9)$$

$$I_{hfq} = 0 \qquad (10)$$

After transformation into fixed coordinates $\alpha - \beta$, these currents depend on angle θ:

$$I_{hf\alpha} = I_{hfd}cos\theta, \qquad (11)$$

$$I_{hf\beta} = I_{hfd}sin\theta \qquad (12)$$

To extract θ, signal demodulation is typically used, for example, by multiplying $I_{hf\alpha}$ and $I_{hf\beta}$ by $sin\left(\omega_{hf}t\right)$ and $cos\left(\omega_{hf}t\right)$, followed by low-frequency filtering. The signal received is proportional to $sin(2\theta)$, which allows the rotor angle to be calculated with an accuracy of several degrees. This procedure is repeated with an update frequency of 5–10 kHz, ensuring smooth control in real time.

We should add that the energy efficiency of HFI also depends on the choice of injection frequency $f_{s\Psi}$.. Too high a frequency (above 2 kHz) can increase losses in the magnetic circuit due to eddy currents, while a low frequency (below 500 Hz) makes it difficult to separate the injection signal from the main motor current. The optimal value of $f_{s\Psi}$. is usually in the range of 800-1200 Hz and depends on the motor design and the operating frequency of the converter. For example, for a 50 kW SMPM with a rated frequency of 50 Hz, an injection frequency of 1 kHz provides a balance between accuracy and losses [8–10].

However, when assessing the overall energy efficiency of the traction electric drive system as a whole, in the context of two-axle mine electric locomotives and for the HFI system option, this positive effect is manifested not only in reduced power consumption, but also in extended battery life, which is the main power source for battery-powered electric locomotives. For example, a 10% reduction in losses in an 8-hour operating cycle can increase the autonomy of an electric locomotive by 30-40 minutes, which is critical for continuous transportation. In addition, stable operation at low speeds reduces wear on mechanical components such as gearboxes and wheels, which also contributes to resource savings.

A comparative analysis with asynchronous motor systems shows that SMPM with HFI provides better specific power (kW/kg) and less sensitivity to temperature fluctuations. In mines, where temperatures can range from +18°C to +40°C, the resistance of asynchronous motor windings increases, leading to additional losses. In SMPM, these effects are less pronounced due to the absence of rotor windings and the stability of the magnetic flux of permanent magnets [5, 11].

While assessing the above as positive in the application of SMPM with HFI control, it is necessary to note some problematic aspects of this method. The widespread implementation of an energy-efficient control system for mine electric locomotives based on SMPM with the HFI method requires a comprehensive approach that includes the selection of hardware, the development of appropriate signal processing algorithms, and consideration of the specific environment in which the system will operate. One of the key elements of the system is a frequency converter, which provides power to the motor and generates a high-frequency signal. Modern converters based on IGBT transistors allow achieving a pulse width modulation (PWM) frequency of up to 20 kHz, which exceeds the typical injection frequency (0,5–2 kHz), ensuring clear separation of the main signal and the injection signal. The output voltage of the converter is formed according to the equation:

$$U_{out} = U_{main} + U_{hf} cos\left(\omega_{hf} t\right), \tag{13}$$

where $U_{main} -$ main voltage for creating a working magnetic field, $U_{hf} -$ injection signal amplitude, $\omega_{hf} = 2\pi f_{hf}$. The amplitude U_{hf} is typically 5–10 % of the nominal motor voltage to avoid a significant impact on the base torque.

High-frequency signal feedback processing is performed by a digital signal processor (DSP) integrated into the control system. The implementation of the HFI algorithm is divided into several sequential stages: injection of the signal, measurement of the resulting currents in the stator phases (I_a, I_b, I_c), conversion of them into the $\alpha - \beta$ coordinate system using the Clarke transformation [8]:

$$I_{hf\alpha} = I_a, I_{hf\beta} = \frac{I_b - I_c}{\sqrt{3}}, \tag{14}$$

with subsequent demodulation to determine the rotor angle θ. Demodulation is based on multiplying the measured currents by the reference sinusoidal signals $sin\left(\omega_{hf} t\right)$ and $\cos\left(\omega_{hf} t\right)$, after which a low-frequency filter separates the components proportional to $sin(2\theta)$ and $\cos\left(\omega_{hf} t\right)$.

Angle θ is calculated as:

$$\theta = \frac{1}{2} arctan\left(\frac{I_{hf\beta}^{filter}}{I_{hf\alpha}^{filter}}\right). \tag{15}$$

The update frequency of this algorithm must exceed the injection frequency by 5–10 times, i.e., reach 5–20 kHz, to ensure smooth control and minimize delays.

It is critically important to achieve high accuracy in determining θ, since any deviation leads to suboptimal distribution of I_d and I_q, which increases losses. In practice, in real mining conditions, HFI accuracy can be degraded by electromagnetic interference, temperature changes, and mechanical vibrations. For example, heating of the stator windings increases R_s, which affects the amplitude of I_{hf}, and dust and moisture can alter the insulation properties, creating noise in the measured signals. To compensate for these effects, adaptive algorithms are used to adjust the model parameters in real time. In particular, the inductances L_d and L_q can be estimated using the following formulas:

$$L_d = \frac{U_{hf}}{\omega_{hf} I_{hfd}}, \quad L_q = \frac{U_{hf}}{\omega_{hf} I_{hfq}}, \tag{16}$$

where I_{hfd} and I_{hfq} measured during test cycles of injection in different directions [9, 14].

Another important aspect is the adaptation of the system to variable load conditions. In mines, electric locomotives can operate in partial load modes (20-30% of the rated torque) or in overload modes (up to 150% of the torque during start-up). The HFI method allows dynamic adjustment of I_q in proportion to the torque:

$$I_q = \frac{M}{\frac{3}{2} p \Psi_{pm}}, \tag{17}$$

where $M -$ required torque. At the same time, I_d – is kept at a minimum level or equal to zero for motors with $L_d \approx L_q$, which reduces resistive losses. In overload mode, the system automatically increases the supply frequency and voltage amplitude, maintaining field synchronization thanks to HFI.

The limitations of the HFI method are also related to its sensitivity to magnetic circuit saturation and nonlinearities in motor behavior. At high currents, inductances L_d and L_q may decrease due to stator steel saturation, which reduces anisotropy and degrades the accuracy of the θ estimate. To solve this problem, modified HFI algorithms are used, which inject into both (d, q) axes and analyze the resulting current ellipse. For example, the injection voltage is set as:

$$U_{hfd} = U_{hf} cos(\omega_{hf} t), \quad U_{hfq} = U_{hf} sin(\omega_{hf} t) \tag{18}$$

and the resulting current forms a trajectory whose parameters correlate with θ. This approach increases the stability of the system but complicates the calculations [7,12-14].

Another challenge in the application of HFI is the "white" noise from the PWM converter, which can be superimposed on the injection signal. To suppress it, bandpass filters with a center frequency f_{hf} are used, as well as synchronization of the injection frequency with the PWM frequency. For example, if $f_{pwm} = 10$ kHz, then $f_{hf} = 1$ kHz is selected as a subharmonic, which simplifies filtering.

As for the future prospects for the development of HFI systems for mine-type two-axle electric locomotives, integration with artificial intelligence systems for load forecasting and operating mode optimization is being pursued. For example, analysis of data on the route, load weight, and rail condition allows for advance adjustment of the I_q and power frequency, further reducing energy consumption. In addition, the use of materials with higher magnetic permeability for the rotor can enhance anisotropy, improving the sensitivity of the HFI [11].

Conclusions. Comparison of the proposed ETS option for two-axle electric locomotives with other technical analogues, such as frequency-controlled asynchronous motors or valve-inductor machines and a number of others, shows that the option with SMPM and HFI has the best energy efficiency and cost ratio for the conditions under analysis.

The traction electric drive control system for two-axle electric locomotives with SMPM and the HFI method is a promising and modern solution for the development of new energy-efficient and flexible control solutions for their operation in the conditions of enterprises where these electric locomotives are used, as it allows to reduce operating costs, increase reliability, energy efficiency, and autonomy of their operation, and adapt the electric locomotive to changing operating conditions.

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