Improving the Efficiency of Electric Rolling Stock Operation Through the Use of Adaptive Filtering Methods for High Harmonic Current Components in Traction Drive Systems

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Abstract. The aim of this work is to investigate the efficiency of various adaptive filtering methods for higher harmonic components of stator currents in a vector-controlled traction drive system to improve the operation efficiency of electric rolling stock. The set goal was achieved by implementing an adaptive filtering block into the basic vector control system, which sequentially employs various adaptive filtering methods. The first harmonic component of stator currents was proposed to be used as the desired signal. An algorithm for determining the first harmonic component under conditions of varying supply voltage frequency was developed. Based on the simulation results, filtration efficiency metrics were established, indicating that the Wiener filter is the most effective for filtering higher harmonic components of stator currents. The most significant results include the algorithm for determining the first harmonic component of the stator phase current and the determination of an adaptive filtering algorithm with the highest convergence rate. The importance of these results lies in identifying the most effective adaptive filtering algorithm for traction drive operation, taking into account the operating modes of electric rolling stock. This will help reduce losses from higher harmonic components in the traction drive and, consequently, increase its energy efficiency.
***Keywords*:** operational efficiency, energy efficiency, vector control, higher harmonic components, adaptive filtering, electric rolling stock.

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Creșterea eficienței de operare a transportului rulant electric prin utilizarea metodelor de filtrare adaptivă pentru componentele cu curent armonic mai mare în sistemele de tracțiune

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Rezumat. Scopul lucrării este de a studia eficiența diferitelor metode de filtrare adaptivă a componentelor armonice superioare ale curenților statorici într-un sistem de antrenare a tracțiunii cu control vectorial pentru a îmbunătăți eficiența de funcționare a materialului rulant electric. Scopul a fost atins prin utilizarea unei unități de filtrare adaptivă în sistemul de control vectorial de bază, care implementează pe rând diferite metode de filtrare adaptivă. Ca obiect de studiu a fost ales tracțiunea unei locomotive electrice din seria DS-3 (Ucraina). Se propune utilizarea primei componente armonice a curenților statori ca semnal dorit al curenților statori. A fost propus un algoritm pentru determinarea primei componente armonice în condiții de modificări constante ale frecvenței tensiunii de alimentare. Analiza rezultatelor obținute a arătat că pentru filtrarea componentelor armonice superioare ale curenților statorici, cea mai eficientă este utilizarea unui filtru Wiener. Cele mai importante rezultate sunt algoritmul de determinare a primei componente armonice a curentului de fază al statorului și determinarea algoritmului de filtrare adaptivă cu cea mai mare convergență. Semnificația rezultatelor obținute este de a determina cel mai eficient algoritm de filtrare adaptivă la operarea unui sistem de tracțiune, ținând cont de modurile de funcționare a materialului rulant electric. Acest lucru va reduce pierderile de la componentele armonice superioare din sistemul de tracțiune și, ca urmare, va crește eficiența energetică a acestuia.
***Cuvinte-cheie*:** eficiență operațională, eficiență energetică, control vectorial, componente armonice superioare, filtrare adaptivă, transportul rulant electric.

Повышение эффективности эксплуатации электроподвижного состава за счет применения методов адаптивной фильтрации высших гармонических составляющих тока в системах тягового привода

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Аннотация. Целью работы является исследование эффективности методов адаптивной фильтрации высших гармонических составляющих статорных токов в системе тягового привода с векторным управлением для повышения эффективности эксплуатации электроподвижного состава. Поставленная цель была достигнута за счет применения в базовой системе векторного управления блока адаптивной фильтрации, реализующего поочередно следующие адаптивные алгоритмы: метода наименьших средних квадратов, нормализованного метода наименьших средних квадратов, разреженного метода наименьших средних квадратов, фильтра Калмана и фильтра Винера. В качестве объекта исследования выл выбран тяговый привод электровоза серии ДС-3 (Украина) с векторной системой управления тяговыми асинхронными двигателями. В качестве желаемого сигнала статорных токов предложено использовать первую гармоническую составляющую статорных токов. Предложен алгоритм определения первой гармонической составляющей в условиях постоянного изменения частоты питающего напряжения. На имитационной модели для установившегося режима были получены временные диаграммы фазных токов статора, крутящего момента и были построены амплитудно-частотные спектры фазных токов статора. На основании полученных результатов, были рассчитаны коэффициент общего гармоничного искажения тока статора, средние абсолютная и относительная ошибки за период, коэффициент пульсации крутящего момента. Анализ полученных результатов показал, что для фильтрации высших гармонических составляющих статорных токов наиболее эффективным является применение фильтра Винера. Наиболее важными результатами являются предложенный алгоритм определения первой гармонической составляющей фазного тока статора в условиях постоянно изменяющейся частоты напряжения питания асинхронного двигателя и определение алгоритма адаптивной фильтрации с наиболее высокой конвергенция (сходимостью). Значимость полученных результатов состоит в определение наиболее эффективного алгоритма адаптивной фильтрации при работе тягового привода с учетом режимов работы электроподвижного состава. Это позволит уменьшить потери от высших гармонических составляющих в тяговом приводе и, как следствие повысить его энергоэффективность.

Ключевые слова: эффективность эксплуатации, энергоэффективность, векторное управление, высшие гармонические составляющие, адаптивная фильтрация, электроподвижной состав.

INTRODUCTION

Increasing the efficiency of electric rolling stock is a relevant task both for the railways of the Ukraine and the railways of European Union countries. One of the components of operational efficiency of electric rolling stock is the energy efficiency of the traction drive. One way to improve the energy efficiency of the electric rolling stock is to reduce the consumption of electrical energy by electric rolling stock for train traction and to reduce the distortions it introduces into the traction power supply system [1].

Vector control systems for traction drives have become extensively used in the electric rolling stock with induction traction motors [2, 3]. In such systems, the induction traction motors are powered by autonomous voltage inverters. The keys of the autonomous voltage inverter are switched according to the pulse-width modulation (PWM) algorithm [4]. With this organization of the power system, the phase voltages of induction motors take the form of a sequence of rectangular pulses of different durations. The repetition period of the sequence of rectangular pulses is inversely proportional to the frequency, and the amplitude of the pulses is the amplitude of the phase voltage supplying the induction motor. The minimum pulse duration is inversely proportional to the PWM sampling frequency. When such a system applies phase voltages to the stator windings of the induction motor, a constant charge-discharge of the stator winding inductances occurs. In this case, the charging time equals the pulse duration, and the discharge time equals the pause between pulses. This circumstance leads to the fact that the stator current of the motor has a non-sinusoidal shape, and higher harmonic components appear in its spectrum.

The presence of higher harmonic components in stator currents leads to the following negative consequences:

- an increase in losses in induction motors and, as a result, an increase in the power consumption of the traction drive [5];
- the appearance of torque pulsations on the motor shaft, which, in turn, leads to increased mechanical losses [6] and deterioration of the overall drive's dynamic properties [7, 8].

To compensate for the higher harmonic components of stator currents, the following methods are used:

- multilevel inverters;
- passive filtering;
- reactive power compensation;
- adaptive selective harmonic reduction.

In his researches, Onishchuk V.I. demonstrated the effectiveness of using multilevel inverters with specialized modulation and control strategies to solve the stated problem. However, the use of multilevel inverters in the railway electric rolling stock would lead to an increase in the overall dimensions of the traction drive, which is an unacceptable factor.

The passive filtering method effectively removes harmonic components with fixed frequencies, but each passive filter can be configured only for one harmonic. Applying a chain of passive filters will result in a significant loss of a transmitted power from the autonomous inverter to the traction motor and increase the overall dimensions of the traction drive. Furthermore, when the operating mode of the traction drive changes, the spectral composition of the stator currents changes as well, rendering the compensation of higher harmonic components ineffective [9].

The method of reactive power compensation employs so-called hybrid filters [10]. The active part of the hybrid filter eliminates the phase shift between phase voltages and the stator current of the induction motor, while the active filters remove the higher harmonic components of stator currents. For the task considered in this study, eliminating the phase shift between phase voltages and the stator current of the induction motor is not a relevant issue. This is because eliminating the phase shift between phase voltages and stator current would lead to a reduction in the reactive current of the motor (magnetic circuit current), which, in turn, would reduce the power factor and, in some cases, even cause the motor stoppage. The set of active filters in this method, like in the previous one, is also configured for fixed frequencies. When the operating mode changes, compensating for higher harmonic components using a set of active filters also becomes ineffective.

The most effective method of compensating for higher harmonic components is adaptive selective reduction (filtering) of harmonic components, which allows for the efficient removal of higher harmonic components even when the operating modes of the electric rolling stock change [11, 12].

According to Parseval's theorem [13], adaptive filtering can be performed in both the frequency and time domains. Algorithms implementing adaptive filtering in the frequency domain are more precise, but their implementation is more complex. This complexity arises from the influence of the distortion magnitude of sinusoidal-shaped stator currents on the stability and convergence time of the algorithms [11]. Filtering in the time domain is less precise but easier to implement since it relies on coordinate transformations of stator currents, which are partially fulfilled in a vector control system [12].

This work is dedicated to investigating the effectiveness of methods for filtering higher harmonic components of stator currents in an induction motor when using vector control in the traction drive of the railway electric rolling stock.

Despite the numerous studies dedicated to filtering higher harmonic components of stator currents in vector control drive systems, most of them focus on the general industrial drives. Traction drives, on the other hand, have a unique characteristic of frequently changing their operating modes (start-up, transition to different motor shaft rotation frequencies, coasting, braking, etc.). This leads to the presence of constant transient processes in the traction drive system [14] and continuous changes in the frequency of stator currents. In contrast, general industrial drive systems use sampling frequencies for PWM ranging from several kHz to several tens of kHz. In traction drive systems, the sampling frequency is within the range of several hundred Hz to one kHz. This limitation in the sampling frequency is due to the switching frequency of power IGBT modules used in the autonomous voltage inverter [15]. A low sampling frequency leads to significant distortion in the sinusoidal shape of stator currents, making it challenging to filter out higher harmonic components.

The goal of this research is to select an adaptive filtering method to develop a compensator for higher harmonic components of stator currents in a vector control traction drive system. This selection is based on the study of the effectiveness of various adaptive filtering methods.

This work distinguishes itself from known studies in that it investigates adaptive filtering methods for higher harmonic components of stator currents of an induction motor in a vector control traction drive system for railway rolling stock using a sampling frequency for PWM organization that is close to what is used in railway rolling stock. Furthermore, an algorithm for calculating desired stator current signals based on Fast Fourier Transform, taking into account changes in the supply voltage frequency, is proposed. These facts allowed for considering the impact of the distortion of the sinusoidal shape of stator currents on the stability and convergence time of various adaptive filtering methods under real operating conditions of railway rolling stock.

DEVELOPMENT OF THE STRUCTURAL SCHEME OF THE VECTOR CONTROL SYSTEM WITH A COMPENSATOR FOR HIGHER HARMONIC COMPONENTS OF STATOR CURRENTS OF THE INDUCTION MOTOR

The research focuses on the traction drive with vector control of induction motors of the locomotive DS-3 (Ukraine).

Due to the high cost associated with studying electromechanical processes in the traction drive system, mathematical and simulation modeling methods were employed in the research.

The following assumptions were made during the development of the mathematical and simulation model of the traction drive and the research process:

- the vector control system is classical.
- the constant voltage at the input of the inverter remains unchanged.
- there are no disturbances in the control system caused by factors such as temperature affecting the motor windings, IGBT modules of the autonomous inverter, etc.
- the load on the motor shaft remains constant.

The classical vector control system for the traction drive [14] is supplemented by the "Adaptive Filtering Block" (Fig. 1). The "Adaptive Filtering Block" implements a specific adaptive filtering algorithm and synthesizes the signals I_{xf}, I_{yf}, ε_{Ix}, ε_{Iy}. The signals ε_{Ix}, ε_{Iy} correct the values of stator currents supplied to the inputs of the corresponding "Current Regulators," and the filtered signals I_{xf}, I_{yf} are fed to the input of the "Cross-Coupling Compensation Block." Since the presence of higher harmonic components in the stator currents of the induction motor leads to torque pulsations on the motor shaft, the system includes torque control on the motor shaft in addition to stator current control, as indicated by "Scope 2."

To implement adaptive filtering methods, it is necessary to have a desired signal for the controlled parameter. It is proposed to use the first harmonic component of the stator currents as the desired signal. For this purpose, the "Fast Fourier Transform Block" is used in the "Adaptive Filtering Block" (Fig 2), which extracts the first harmonic component from the spectrum of the stator current, taking into account the signal frequency proportional to the motor shaft rotation frequency. This is important because the motor shaft rotation frequency and, consequently, the voltage supply frequency change constantly when the operation modes of the rolling stock change. Additionally, frequent changes in the operation modes of the rolling stock induce transient processes in the traction drive system, resulting in the presence of quasi-asymmetric modes [14]. To account for these modes, it is proposed to filter the stator current for each phase ("Adaptive Filters Block"), after which the obtained values are transformed into the αβ coordinate system and subsequently into the xy coordinates.

The frequency of the power supply voltages for the traction motor in the vector control system constantly changes depending on the operating modes of the electric rolling stock. Due to this circumstance, an algorithm of fast Fourier transform with a variable frequency (Fig. 3) is proposed for obtaining the desired signals of the stator phase currents. This algorithm is implemented in the "Fast Fourier Transform Block" (Fig. 2).

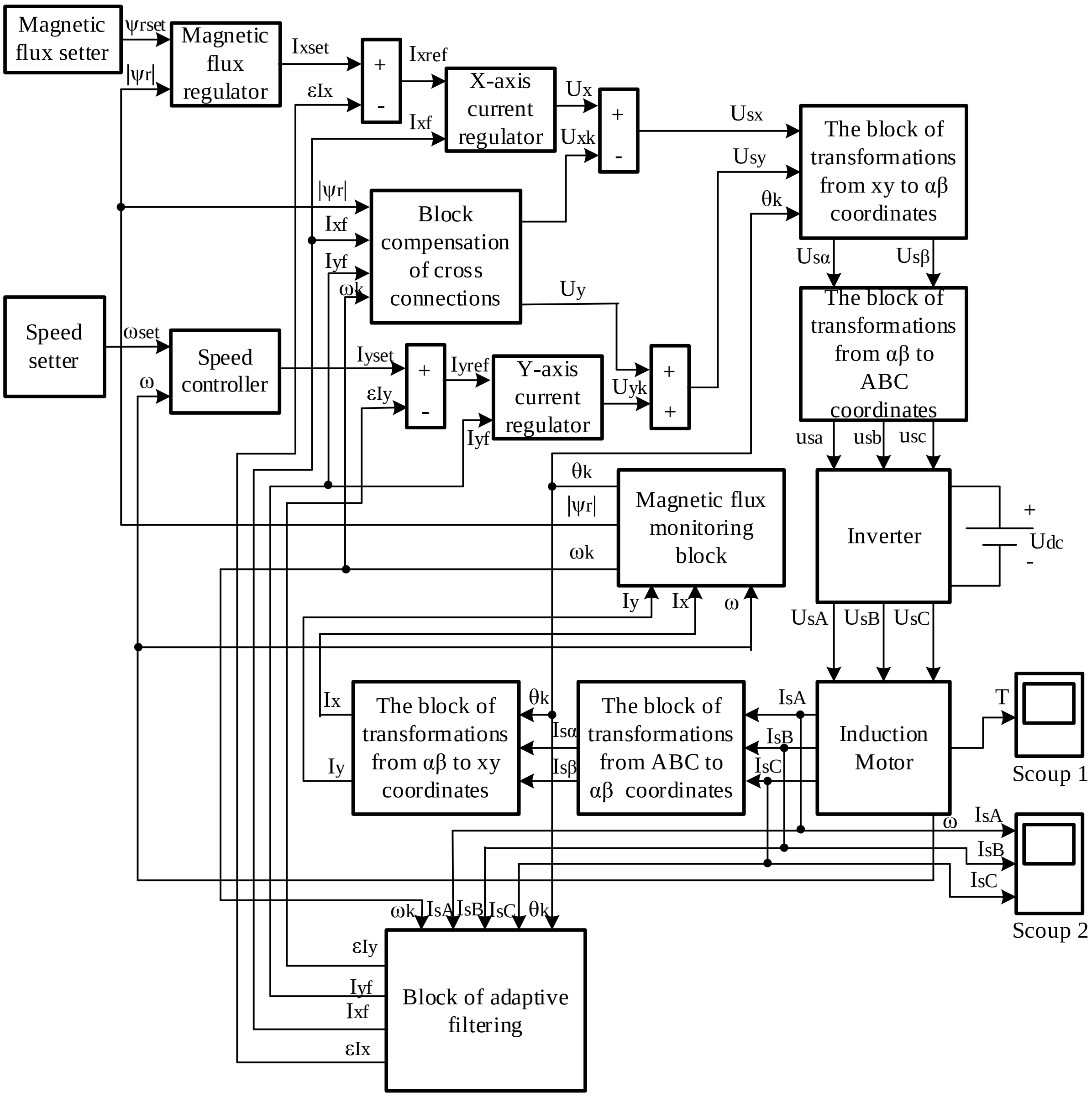

Fig. 1. Proposed Structural Diagram of the Vector Control System for Traction Drive

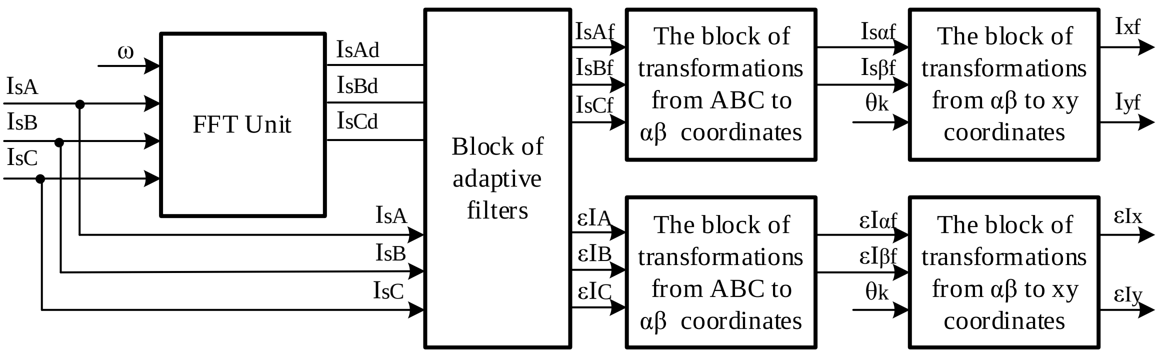

Fig. 2. Structural diagram of the "Adaptive Filtration Block"

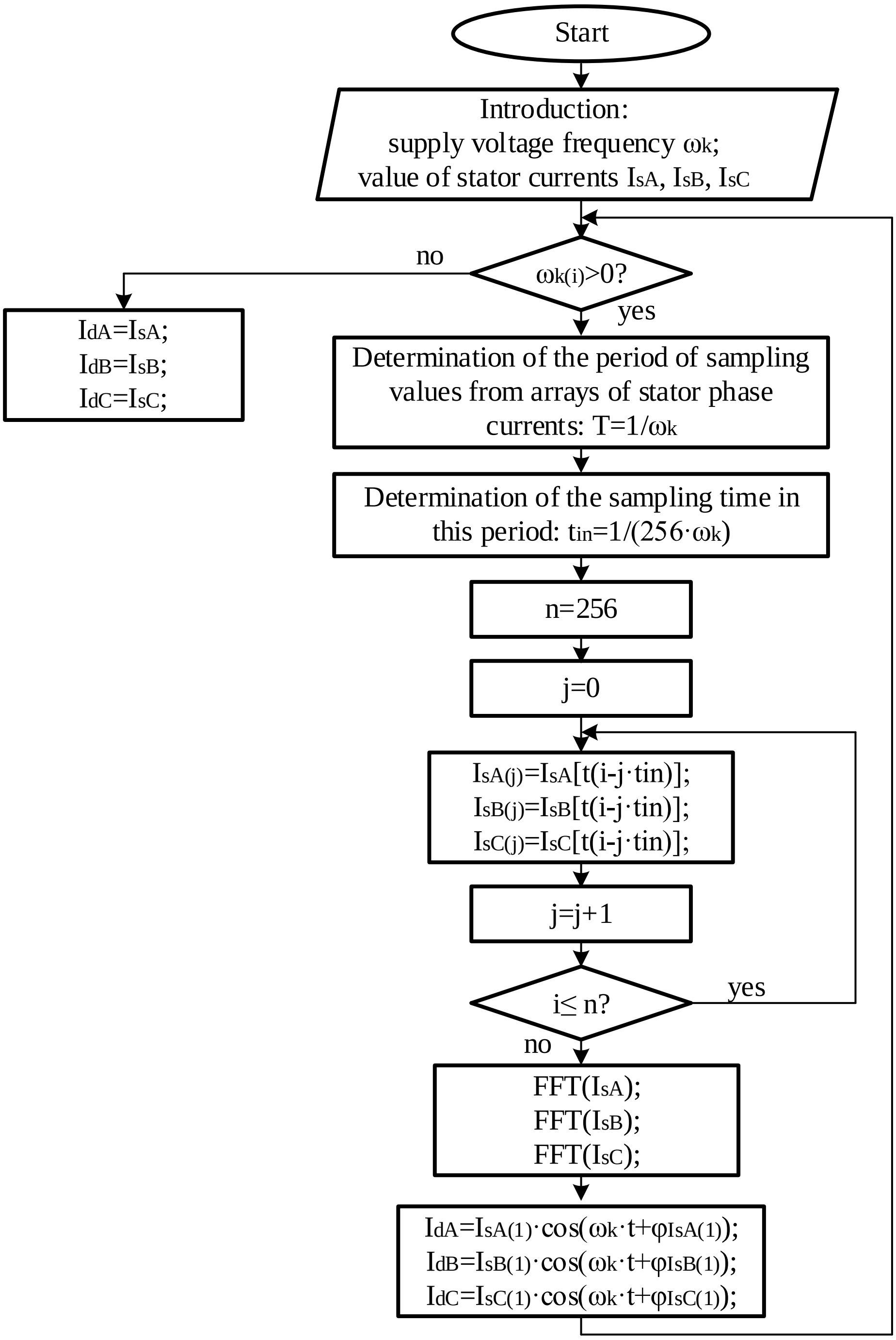

Fig. 3. Algorithm for determining the desired values of stator phase currents

The proposed structural diagram of the vector control system (Fig. 1) is implemented in the MATlab Simulink software environment with the sequential connection of the "Adaptive Filters Block," which implements the studied adaptive filtering algorithm.

MATHEMATICAL MODELS OF ADAPTIVE FILTERING ALGORITHMS

Adaptive filtering methods refer to methods based on the adaptive least mean squares approach [16-18]. Methods of adaptive filtering also include methods that are built on predicting the values of the controlled variable (recursive least squares filters) [19], Wiener and Kalman filtering [20].

In this research, the following methods were considered: classic least mean squares (LMS) method [16], normalized least mean squares (NLMS) method, which has faster convergence compared to LMS [17], leaky least mean squares (LLMS) method, which has faster convergence and accuracy compared to LMS [17], Wiener and

Kalman filtering methods [20]. It was hypothesized during the research that there are no noises in the signal. Under such conditions, the Kalman filter degenerates into the recursive least squares (RLS) filter [19, 20]. Therefore, RLS was not considered separately.

The mathematical model of the least mean squares (LMS) adaptive method

The output signal of the filter is described by equation (16):

$$I_{sf}(n)=\sum_{i=1}^{N} w_i(n)\cdot I_s(n-1), \qquad (1)$$

where I_{sf} – the value of the stator current at the filter's output;
I_s – the value of the stator current at the filter's input;
N – the filter order;
n – the current value of stator current;
w – the filter coefficients.

The filtering error is determined according to the expression:

$$\varepsilon(n)=I_{sf}(n)-I_{sd}(n), \qquad (2)$$

where I_{sd} – the desired value of stator current.

The filter coefficients are determined by the equation:

$$\mathbf{w}(n+1)=\mathbf{w}(n)+2\cdot\mu\cdot\varepsilon(n)\cdot\mathbf{I}_{sf}(n), \qquad (3)$$

where $\mathbf{w}(n)$ – the vector of filter coefficients at the n-th iteration step;
$\mathbf{w}(n+1)$ – the vector of filter coefficients at the n+1-th iteration step;
$\mathbf{I}_s(n)$ – the vector of input values of phase current of the stator;
μ – the step size parameter of the algorithm.

Mathematical model of the adaptive normalized least mean squares (NLSM) method

The output signal of the filter and the filtering error, as in the previous method, are determined by equations (1) and (2) respectively. The filter coefficients are determined by the equation [17]

$$\mathbf{w}(n+1)=\mathbf{w}(n)+\frac{\tilde{\mu}}{\mathbf{I}_{sf}^{T}\cdot\mathbf{I}_{sf}(n)+\psi}\cdot\varepsilon(n)\cdot\mathbf{I}_{sf}(n). \qquad (4)$$

In this recursion $\tilde{\mu}$ и ψ are positive constants that should be appropriately selected. The introduction of the constant ψ is justified to prevent division by a small value when the square of the Euclidean norm $(\mathbf{I}_{sf}(n))^{T}\,\mathbf{I}_{sf}(n)$ is small. This leads to greater stability in the implementation of the NLMS algorithm. Constant $\tilde{\mu}$ can be considered as a step size parameter that controls the convergence speed of the algorithm.

Mathematical model of the adaptive sparse leaky mean square method (LLSM)

The output signal of the filter and the filtering error, as in the previous methods, are determined using equations (1) and (2), respectively. The filter coefficients are determined by the equation [18]

$$\mathbf{w}(n+1)=\left(\mathbf{I}-2\cdot\mu\cdot\gamma\cdot\left[\mathbf{I}_{sf}^{T}(n)\cdot\mathbf{I}_{sf}(n)+\gamma\cdot\mathbf{I}\right]\right)\cdot \cdot\mathbf{w}(n)+2\cdot\mu\cdot\varepsilon(n)\cdot\mathbf{I}_{sf}(n), \qquad (5)$$

where $\mathbf{I}$ – a unit column vector.

Coefficient γ is within the range $0 < \gamma << 1$.

Mathematical model of the Kalman filter

As mentioned earlier, in the absence of noise at the filter input, the Kalman filter has the same structure and, therefore, the same mathematical model as the Adaptive Recursive Least Mean Square (RLS) filter [19]. Therefore, the mathematical model of the RLS filter is adopted as the mathematical model. The output signal of the filter is described by the equation [19]

$$\mathbf{I}_{sf(n-1)}(n)=\mathbf{w}^{T}(n-1)\cdot\mathbf{I}_{s}(n-1). \qquad (6)$$

Filtering Error

$$\varepsilon_{(n-1)}(n)=I_{sd}(n)-I_{sf(n-1)}(n). \qquad (7)$$

The vector of filter coefficients

$$\mathbf{w}(n)=\mathbf{w}(n-1)+\mathbf{k}(n)\cdot\varepsilon(n), \qquad (8)$$

where the gain vector is determined as

$$\mathbf{k}(n)=\frac{1}{\lambda+\mathbf{I}_{s}^{T}(n)\cdot\mathbf{u}(n)}\cdot\mathbf{u}(n), \qquad (9)$$

$$\mathbf{u}(n) = \psi_{\lambda}^{-1}(n-1) \cdot \mathbf{I}_s(n), \quad (10)$$

$$\boldsymbol{\psi}_{\lambda}^{-1}(n) = \lambda^{-1} \cdot \left(\boldsymbol{\psi}_{\lambda}^{-1}(n-1) - \mathbf{k}(n) \cdot \left[\mathbf{I}_s^T(n) \cdot \boldsymbol{\psi}_{\lambda}^{-1}(n-1)\right]\right), \quad (11)$$

$$\lambda = \frac{N-1}{N}. \quad (12)$$

Mathematical model of the Wiener filter

The output signal of the filter and the filtering error are determined by equations (1) and (2) respectively.

The filter coefficients are determined from the equation [20]

$$\mathbf{w} = \mathbf{R}_{Is}^{-1} \cdot \mathbf{p}_{IsId}, \quad (13)$$

where $\mathbf{R}_{Is}$ - the autocorrelation matrix of the input signal I_s;

$\mathbf{p}_{IsId}$ - the cross-correlation matrix between the input signal I_s and the desired signal I_d.

RESEARCH RESULTS

During the modeling, it was taken into account that the nominal frequency of the power supply voltage for the traction motor of locomotive DS-3 is 55.8 Hz. On the other hand, the maximum frequency of the power IGBT modules is 1200 Hz. A sampling frequency of 1116 Hz was chosen for the studies. As a result of the simulation, temporal diagrams of the stator currents and desired stator currents of the induction motor were obtained in the absence of an adaptive filter. Since the case of symmetry of the motor windings and power supply voltages is considered, the analysis was carried out using the time diagrams of phase A stator current for steady-state operation. Figure 4 shows the temporal diagrams of phase A stator current and the desired current for phase A of the motor.

The total harmonic distortion factor (THD) of the stator current was calculated using the formula

$$THD = \frac{\sqrt{I_{sf(0)}^2 + I_{sf(2)}^2 + \ldots + I_{sf(N)}^2}}{I_{sf(1)}} \cdot 100\%. \quad (14)$$

The average absolute error over the period was calculated as

$$\varepsilon_m = \frac{1}{N} \cdot \sum_{i=1}^{N} |\varepsilon_i| \quad (15)$$

and the root mean square error over the period was calculated as

$$\delta = \frac{\varepsilon_m}{I_{sd\,\max}} \cdot 100\%, \quad (16)$$

where I_{sdmax} is the instantaneous value of the desired stator current in a steady-state mode.

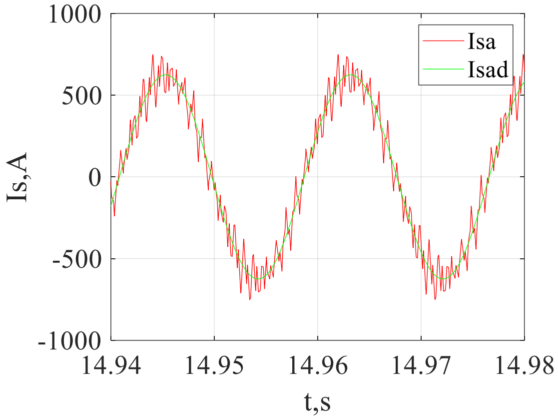

Fig. 4. Time diagrams of phase A stator current and desired current for phase A of the motor for the scheme without an adaptive filter: Isa - stator current of phase A; Isad - desired current of phase A stator

For the steady-state mode, the amplitude-frequency spectrum of phase A stator current was plotted (Fig. 5).

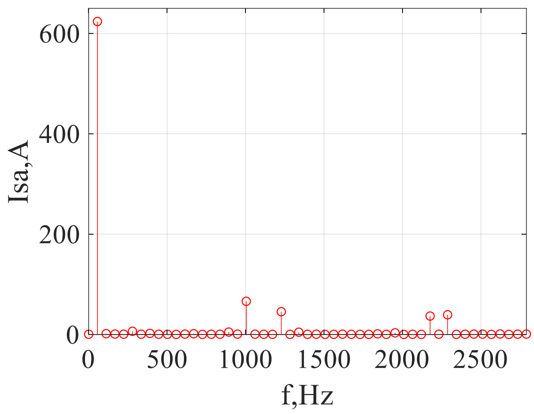

Fig. 5. Amplitude-frequency spectrum of phase A stator current for the scheme without an adaptive filter

From the time diagrams of torque for the steady-state mode, the maximum (T_{max}) and minimum (T_{min}) torque values were determined.

From these values, the average torque value was calculated as

$$T_{midl} = \frac{T_{max} + T_{min}}{2} \quad (17)$$

and the torque ripple factor was determined [14] as

$$k_T = \frac{T_{max} - T_{min}}{T_{midl}} \cdot 100\%. \quad (18)$$

The calculation results are presented in Table 1.

Table 1.

Research results

Method	Parameter						
	THD, %	ε_m, A	δ, %	T_{max}, N·m	T_{min}, N·m	T_{midl}, N·m	k_T, %
Base scheme	16.29	57.8	9.25	13268	7268	10268	29.22
LSM	10.07	36.2	5.8	11750	8516	10133	15.96
NLSM	16.11	56.58	9.07	13100	7270	10185	28.62
LLSM	10.66	36.21	5.8	11670	8560	10115	15.37
Kalman filter	9.62	32.72	5,26	11481	9055	10268	11.81
Wiener filter	0.38	2.46	0.4	10267	10263	10264	0.04

For the scheme with an adaptive filter implementing the least squares method (LSM), time diagrams of stator currents and desired stator currents of the induction motor were obtained. In this case, the filter order was selected as M=31. To ensure filter stability, the algorithm's step size parameter was chosen as μ=2.5·10^{-5}. Figure 6 shows the corresponding time diagrams for the steady-state mode of phase A of the induction motor.

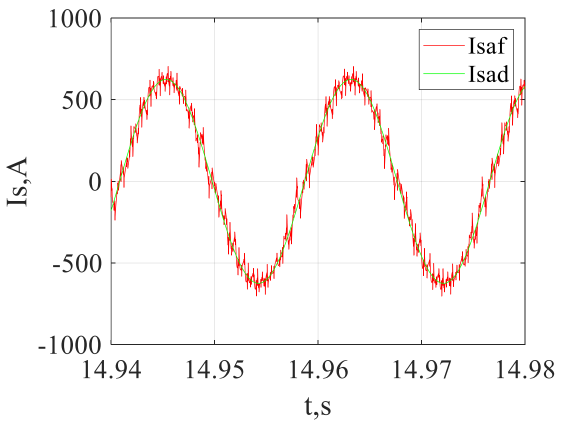

Fig. 6. Time diagrams of phase A stator current and desired current for phase A of the motor for the scheme with an adaptive filter implementing the LMS algorithm: Isaf - stator current of phase A; Isad - desired stator current of phase A.

For the steady-state mode, the amplitude-frequency spectrum of phase A stator current was plotted (Fig. 7).

The following parameters were calculated: the THD t of the stator current (14), the average absolute (15) and relative (16) errors over the period, the average torque value (17), and the torque ripple coefficient (18). The calculation results are recorded in Table 1.

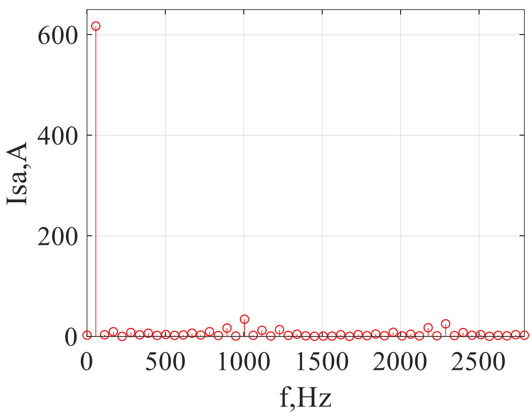

Fig. 7. Amplitude-frequency spectrum of phase A stator current for the scheme with an adaptive filter implementing the LMS algorithm.

For the scheme with an adaptive filter implementing the Normalized Least Mean Squares (NLSM) algorithm, time diagrams of stator currents and desired stator currents of the induction motor were obtained. In this case, the filter order was chosen as M=31. To ensure filter stability, the algorithm's step size parameter was set to $\tilde{\mu}$=2.5·10^{-5}. The coefficient preventing division by zero in formula (4) was chosen as ψ=0.95. Figure 8 shows the corresponding time diagrams for the steady-state mode of phase A of the induction motor.

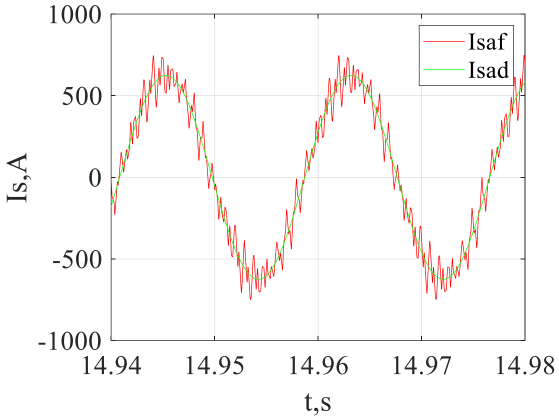

Fig. 8. Time diagrams of phase A stator current and desired current for phase A of the motor for the scheme with an adaptive filter implementing the NLMS algorithm: Isaf - stator current of phase A; Isad - desired stator current of phase A

An amplitude-frequency spectrum of the phase A stator current for the steady-state mode was generated (Fig. 9).

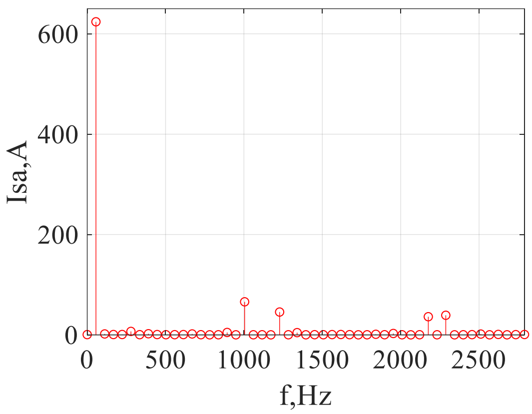

Fig. 9. Amplitude-frequency spectrum of phase A stator current for the scheme with an adaptive filter implementing the NLMS algorithm

The following values were calculated: the THD of the stator current (14), the mean absolute error (15), the mean relative error (16) over the period, the average torque (17), and the torque ripple coefficient (18). The calculation results are presented in Table 1.

For the scheme with an adaptive filter implementing the leaky least mean squares (LLSM) algorithm, time diagrams of stator currents and desired stator currents of the induction motor were obtained. In this case, the filter order was chosen as M=31. To ensure filter stability, the algorithm's step size parameter was set to μ=2.5·10^{-5}. The coefficient, which increases the convergence rate of algorithm γ, was selected as γ=2.5·10^{-4}. Figure 10 shows the corresponding time diagrams for the steady-state mode of phase A of the induction motor.

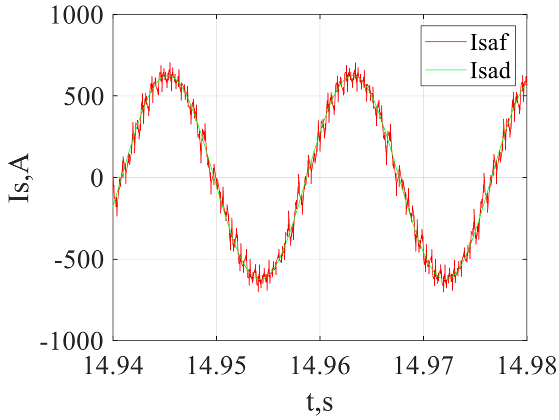

Fig. 10. Time diagrams of phase A stator current and desired current for phase A of the motor for the scheme with an adaptive filter implementing the LLMS algorithm: Isaf – stator current of phase A; Isad – desired stator current of phase A

For the steady-state mode, an amplitude-frequency spectrum of phase A stator current was plotted (Fig. 11).

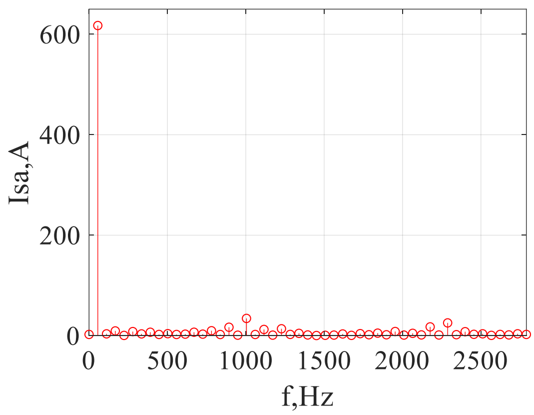

Fig. 11. Amplitude-frequency spectrum of phase A stator current for the scheme with an adaptive filter implementing the LLMS algorithm

The following calculations were made: total THD of stator current (14), average absolute error (15), and average relative error (16) over a period, the mean value of the torque (17), and the torque ripple coefficient (18). The calculation results have been listed in Table 1.

For the scheme with an adaptive filter implementing the Kalman filter, time diagrams of stator currents and desired stator currents of the induction motor were obtained. In this case, the filter order was chosen to be M=11. Figure 12 shows the corresponding time diagrams for the steady-state mode of phase A of the induction motor.

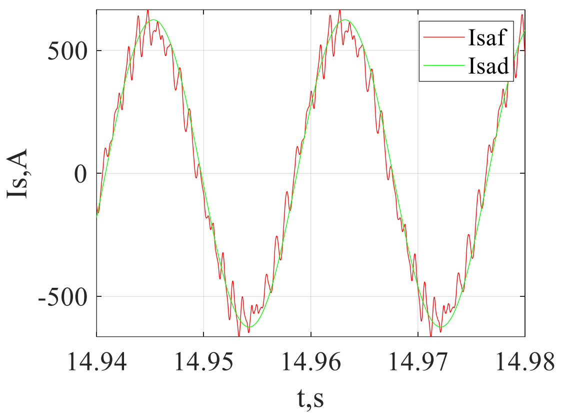

Fig. 12. Time diagrams of phase A stator current and desired current for phase A of the motor for the scheme with the Kalman filter: Isaf – stator current of phase A; Isad – desired stator current of phase A

For the steady-state mode, an amplitude-frequency spectrum of phase A stator current was plotted (Fig. 13).

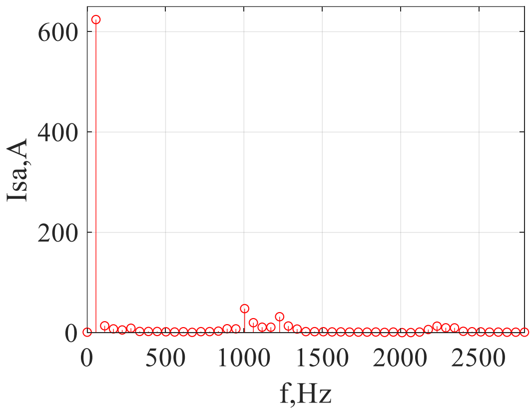

Fig. 13. Amplitude-frequency spectrum of phase A stator current for the scheme with the Kalman filter

The following calculations were made: THD of stator current (14), average absolute error (15), and average relative error (16) over a period, the mean value of the torque (17), and the torque ripple coefficient (18). The calculation results have been recorded in Table 1.

For the scheme with an adaptive filter implementing the Wiener filter, time diagrams of stator currents and desired stator currents of the induction motor were obtained. In this case, the filter order was chosen to be M=11. Figure 14 shows the corresponding time diagrams for the steady-state mode of phase A of the induction motor.

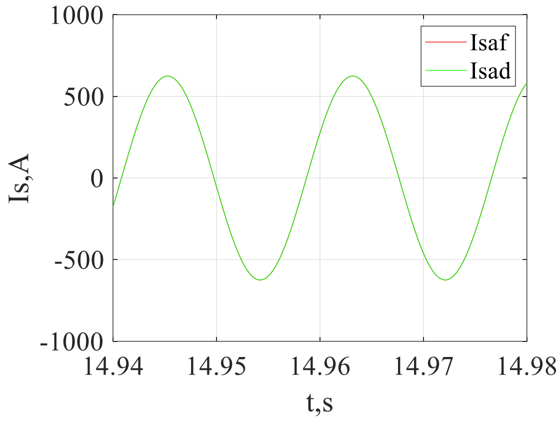

Fig. 14. Time diagrams of phase A stator current and desired current for phase A of the motor for the scheme with the Wiener filter: Isaf – stator current of phase A; Isad – desired stator current of phase A

For the steady-state mode, an amplitude-frequency spectrum of phase A stator current was plotted (Fig. 15).

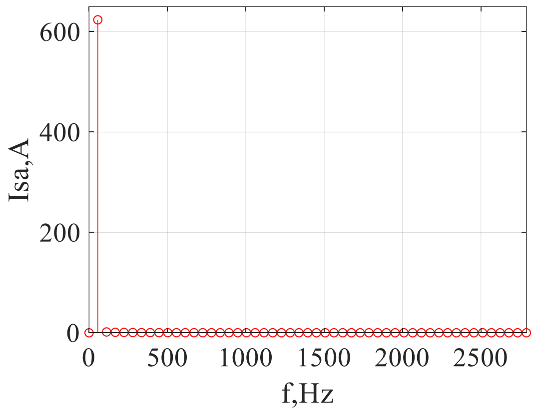

Fig. 15. Amplitude-frequency spectrum of phase A stator current for the scheme with the Wiener filter

The following calculations were made: THD of stator current (14), average absolute error (15), and average relative error (16) over a period, the mean value of the torque (17), and the torque ripple coefficient (18). The calculation results have been recorded in Table 1.

CONCLUSIONS

In this work, it is proposed to enhance the efficiency of operation of electric rolling stock with a vector control system for traction induction motors. Specifically, to improve the energy efficiency of the traction drive and reduce the higher harmonic components of the stator currents of traction motors, adaptive filtration is applied. To solve this task, the following steps were taken:

- through analysis, it was determined that the presence of higher harmonic components in the stator currents leads to increased losses in induction motors and, as a result, increased electrical consumption by the traction drive. This also results in torque pulsations on the motor shaft, which in turn leads to increased mechanical losses and worsens the overall dynamic characteristics of the drive;
- it is proposed to use adaptive filtration in the basic scheme of the vector control system for the traction drive;
- a structural diagram of the adaptive filtration block was developed, which is based on the adjustment of filter coefficients to minimize the error between the motor's stator current and the desired stator current;
- to determine the desired stator current of the motor, it is proposed to use the first harmonic component of the motor's stator current;
- an algorithm for fast Fourier transform (FFT) is proposed to determine the first harmonic component of the stator current under conditions of continuously changing supply voltage frequency;
- modeling of the proposed vector control system for the traction induction motor was carried out in the MATLab/Simulink software environment;
- on the simulation model of the vector control scheme, for cases of the basic control system, a control system with an adaptive LMS filter, an adaptive NLMS filter, an adaptive LLMS filter, a Kalman filter, and a Wiener filter, temporal diagrams of stator currents and torque were obtained, and amplitude-frequency spectra of stator currents were constructed;
- based on the simulation results, the following calculations were made: the THD of the stator current, the average absolute and average relative errors over a period, and the torque ripple coefficient;
- Upon analyzing the obtained results, it was determined that the most effective method for filtering out higher harmonic components of stator currents is the use of the Wiener filter. In this case, the THD of the stator current was 0.38%, the average absolute error over a period was 2.46%, the average relative error over a period was 0.4%, and the torque ripple coefficient was 0.04%. Other types of the adaptive filters showed significantly lower performance. This is because in traction drive systems, the sampling frequency for PWM implementation to control the inverter operation is low (from several hundred Hz to one kHz). Therefore, other types of filters exhibited slower convergence in this case. In the operation of electric rolling stock, high convergence of adaptive filters is crucial.

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