Traction Drive Control System for Railway Electric Rolling Stock Based on the Application of Power Factor as an Optimization Criterion

[1]Goolak S., [1]Gorobchenko O., [1]Holub H., [1]Kulbovskiy I., [2]Petrychenko O.

[1]National Transport University, Kyiv, Ukraine
[2]National University "Odessa Maritime Academy", Odesa, Ukraine

Abstract. The objective of this work is to provide theoretical substantiation for the possibility of using power factor as a criterion in the development of optimized automatic control systems for AC electric rolling stock traction drives. The stated objective has been achieved through the solution of the following tasks: development of an algorithm for applying traction drive power factor as an optimization criterion, taking into account stochastic disturbance effects acting on the traction drive from the traction power supply system and mechanical load; development of a structural scheme for an optimized automatic control system of electric rolling stock traction drives, in which the proposed algorithm is implemented. The most important results are: the obtained analytical time dependency of the traction drive power factor, representing a convolution of two-time functions—efficiency and active power utilization coefficient of the traction drive—and the developed algorithm for eliminating stochastic disturbance effects acting on the traction drive from the traction power supply system and mechanical load. The significance of the obtained results lies in improving the quality of AC traction drive control. An electric locomotive traction drive with field-oriented control (FOC) of asynchronous traction motors was selected as the research object. This will enable improved regulation quality in the construction of an optimal automatic control system for traction drives.
***Keywords*:** power factor, energy-efficient traction drive control, time function convolution, microprocessor control system.

DOI: https://doi.org/10.52254/1857-0070.2025.3-67.01
UDC: 621.313.333.2

Sistem de control al tracțiunii pentru materialul rulant electric al transportului feroviar bazat pe utilizarea factorului de putere ca și criteriu de optimizare

[1]Gulac S.A., [1]Gorobcenko O.M., [1]Golub H.M., [1]Kulbovski I.I., [2]Petrâcenko O.O.
[1]Universitatea Națională de Transport, Kiev, Ucraina
[2]Universitatea Națională „Academia Maritimă din Odesa", Odesa, Ucraina
Rezumat. Scopul lucrării este fundamentarea teoretică a posibilității de utilizare a factorului de putere ca și criteriu în dezvoltarea sistemelor optimizate de control automat pentru acționarea tracțiunii materialului rulant electric de curent alternativ. Scopul stabilit este atins prin rezolvarea următoarelor probleme: dezvoltarea unui algoritm pentru aplicarea factorului de putere al acționării tracțiunii ca și criteriu de optimizare, luând în considerare efectele stocastice ale perturbațiilor care acționează asupra acționării tracțiunii din sistemul de alimentare cu energie electrică a tracțiunii și sarcina mecanică; dezvoltarea unei diagrame structurale a sistemului optimizat de control automat pentru acționarea tracțiunii materialului rulant electric, în care este implementat algoritmul propus. Cele mai importante rezultate sunt: dependența analitică de timp obținută a factorului de putere al acționării tracțiunii, care este o convoluție a două funcții de timp - eficiența și factorul de utilizare a puterii active a acționării tracțiunii; algoritmul dezvoltat pentru eliminarea efectelor stocastice ale perturbațiilor care acționează asupra acționării tracțiunii din sistemul de alimentare cu energie electrică a tracțiunii și sarcina mecanică. Semnificația rezultatelor obținute constă în îmbunătățirea calității controlului acționărilor tracțiunii de curent alternativ. Obiectul studiului a fost acționarea tracțiunii unei locomotive electrice cu control orientat pe câmp (COC) al motoarelor de tracțiune asincrone. Acest lucru va îmbunătăți calitatea reglării la construirea unui sistem optim de control automat pentru sistemul de tracțiune.
***Cuvinte-cheie*:** factor de putere, control al tracțiunii eficient energetic, convoluție a funcției de timp, sistem de control cu microprocesor.

Система управления тяговым приводом электроподвижного состава железнодорожного транспорта на базе применения коэффициента мощности в качестве критерия оптимизации

[1]Гулак С.А., [1]Горобченко А.Н., [1]Голуб Г.М., [1]Кульбовский И.И., [2]Петриченко О.А.
[1]Национальній транспортный университет, Киев, Украина
[2]Национальный университет «Одесская морская академия», Одесса, Украина

Аннотация. Целью работы является теоретическое обоснование возможности использования коэффициента мощности в качестве критерия при разработке оптимизированных систем автоматического управления тяговыми приводами электроподвижного состава переменного тока. Поставленная цель достигнута за счет решения следующих задач: разработки алгоритма применения коэффициента мощности тягового привода в качестве критерия оптимизации с учетом стохастических воздействий возмущений, действующие на тяговый привод со стороны системы тягового электроснабжения и механической нагрузки; разработки структурной схемы оптимизированной автоматической системы управления тягового привода электроподвижного состава, в которой реализуется предложенный алгоритм. Наиболее важными результатами являются: полученная аналитическая временная зависимость коэффициента мощности тягового привода, представляющая собой свертку двух временных функций – КПД и коэффициента использования активной мощности тягового привода; разработанный алгоритм устранения стохастических воздействий возмущений, действующие на тяговый привод со стороны системы тягового электроснабжения и механической нагрузки. Значимость полученных результатов заключается в повышении качества управления тяговыми приводами переменного тока. В качестве объекта исследования был выбран тяговый привод электровоза с векторным управлением асинхронными тяговыми двигателями. Имитационное моделирование показало большую сходимость значений коэффициентов мощности, определенных двумя методами: как отношение полезной мощности на валу двигателя к полной потребляемой мощности из контактной сети и как свертки двух временных функций – коэффициента мощности выходной части и коэффициента полезного действия входной части тягового привода. Предложена схема оптимизированного автоматического управления тяговым приводом, в которой в качестве контролируемых параметров используются параметры частот дискретизации входной и выходной части тягового привода, а в качестве критерия оптимизации – коэффициент полезного действия. Это позволит повысить качество регулирования при построении оптимальной системы автоматического управления тяговым приводом.

Ключевые слова: коэффициент мощности, энергоэффективное управление тяговым приводом, свертка временных функций, микропроцессорная система управления.

INTRODUCTION

Due to the trend of constantly rising electricity prices in the global market, reducing electricity consumption is a pressing issue. This topic is particularly relevant for railway infrastructure, as railway electric transport is one of the largest consumers of electrical energy in many countries worldwide.

Directions for improving the energy efficiency of railway traction power supply systems include optimizing train operation and movement, and improving the traction drive systems of electric rolling stock. The largest consumer of energy from railway traction power supply systems is electric rolling stock (ERS), specifically its traction drive.

Among the directions for improving the energy efficiency of railway ERS traction drives, the following can be highlighted: compensation of higher harmonic components of current in the power circuits of traction drives [1], application of onboard energy storage systems [2] and energy-efficient control of electric rolling stock traction drive systems [3], implementation of intelligent traction drive control systems [4].

The power factor is known to serve as an assessment of the energy efficiency of ERS traction drives. On the other hand, the power factor is the product of the active power utilization coefficient and the efficiency coefficient. The efficiency coefficient characterizes active power losses, while the active power utilization coefficient determines the proportion of active power in the total power consumed by the traction electric drive [4]. That is, efficiency is a function of active power losses, while the active power utilization coefficient is a function of the phase shift between supply voltage and current and the distortion coefficient of the sinusoidal form of supply voltage and current.

The application of compensation devices requires the introduction of additional power elements into the traction drive system [5]. This will lead to an increase in the active power utilization coefficient, but to a decrease in efficiency. When using onboard energy storage systems, additional power elements are also necessary to ensure energy exchange between the storage device and traction motors [6]. Energy-efficient control does not require the inclusion of additional power elements in the traction drive system, since such an optimal control algorithm is implemented on the existing microprocessor control system of the ERS traction drive system.

For the implementation of an optimal traction drive control system, an optimization criterion is required [7]. Since energy-efficient control is being discussed, the selection of the power factor as an optimality criterion is quite logical.

The traction drive system belongs to objects whose control must be carried out based on a limited number of decisions obtained at certain points in time. The dynamic programming method is one of the means for solving such problems, the purpose of which is to select such a sequence of decisions for which some quality criterion, reflecting the state function of system parameters, reaches an extremal value. The method is based on R. Bellman's optimality principle [8]. Its essence lies in the fact that optimal control is determined by the final goal and the state of the system at a given moment in time, regardless of how the system "arrived" at this state.

The considered dynamic programming method in the continuous variant does not have strict mathematical justification. The maximum principle is strictly mathematically justified [9]. The main result of this theory is the maximum principle, which defines the necessary optimization conditions that can be solved.

A common feature of these theories is the presence of an objective function (quality criterion) that reaches an extremal value. The criteria by which the effectiveness of controls is judged can be diverse. However, they must satisfy a number of requirements [10]:

- The criterion must have a clear, unambiguous mathematical form of expression;
- The criterion can express technical and economic benefit (productivity, product quality, efficiency coefficient, etc.), losses or costs (electricity consumption, material consumption, system settling time to a specified mode, etc.).

When discussing energy-efficient control of a traction drive system, the selection of its energy indicators as optimality criteria is quite logical. Such indicators include the active power utilization coefficient and efficiency.

The active power utilization coefficient characterizes AC power losses caused by phase shift between voltage and current, and power losses caused by non-sinusoidal voltage and current waveforms. Efficiency characterizes DC losses.

When using the mentioned indicators as criteria for building an optimal automatic traction drive control system, the need arises to implement a solution to a two-criteria problem. To reduce the number of criteria, a generalized energy indicator – the power factor – can be used. The physical meaning of the power factor is the product of the active power utilization coefficient and efficiency at fixed moments in time. Using such an approach to determine the power factor as a criterion for building an optimal automatic traction drive control system is incorrect. This circumstance is related to the fact that such an approach will not account for the inertia of traction drive elements.

Improving the energy efficiency of a traction drive means reducing power losses in its elements. To determine the parameters whose variation can regulate power losses in traction drive elements, the mentioned power losses should be considered and analyzed. The traction drive system can be conventionally represented as a structure consisting of the following elements: input section, DC link, and output section. The input section includes: current collector, traction transformer, input converter, and input converter control system. The DC link is a low-pass filter consisting of a smoothing reactor and capacitor. The output section of the traction drive includes an output converter, output converter control system, and traction motor.

Power losses in the traction transformer consist of power losses in the steel and copper of the primary and secondary transformer windings [11]. Power losses in the steel of traction transformer windings are proportional to the sum of squares of the harmonics of the specified voltages. Power losses in the copper of windings are proportional to the sum of squares of harmonics flowing in the corresponding windings and the active resistances of these windings.

The active resistance of transformer windings is a function of temperature. The presence of higher current harmonics leads to an increase in the active resistance of windings, which, in turn, leads to an increase in power losses in the windings. In other words, the presence of higher voltage and current harmonics in the windings leads to an increase in transformer power losses [11].

Power losses in the input converter (controlled rectifier) are divided into conduction and switching losses. In the on-state, conduction power losses in switches (power transistors and diodes) are proportional to the sum of squares of current harmonics flowing through them; in the off-state – to the sum of squares of voltage applied to them. Switching power losses in converter switches are proportional to the sum of products of corresponding current harmonics flowing through the switch and voltage applied to the switch. Moreover, the presence of higher current harmonics leads to an increase in the active resistance of electronic switches in the open state due to temperature rise, which, in turn, leads to an increase in power losses in the input converter [12].

The DC link is a passive LC low-pass filter, power losses in which are proportional to the sum of squares of current harmonics.

The following induction traction motor control systems can be used on railway ERS: field-oriented control [13] and direct torque control [13, 14]. Reference [13] shows that field-oriented control (FOC) at traction motor shaft rotation frequencies greater than the nominal value maintains the specified frequency value better than the direct torque control system; therefore, FOC application is more appropriate for mainline ERS. Since the traction drive of a mainline electric locomotive will be considered as a prototype traction drive in the following sections, all subsequent discussions will relate to FOC.

An inverter is used as the output converter in the traction drive system. Reference [15] shows that power losses in the inverter consist of conduction and switching losses. In this work, the hypothesis was adopted that the inverter supply voltage is constant. In this case, conduction power losses in the inverter with closed switches are proportional to the square of the voltage applied to them, while with open switches, power losses in the inverter are proportional to the square of the current flowing through the switches.

Switching power losses in switches are determined by the product of applied voltage and current flowing through the switches. In the ERS traction drive, the inverter receives power from the DC link. Under real operating conditions, the DC link voltage is not constant. Higher harmonics are included in its spectral composition. Although their amplitudes are significantly smaller than the DC voltage value, their presence causes additional power losses in the inverter switches. Therefore, the mentioned power losses should be determined through the sum of squares of harmonics of corresponding voltages and currents.

Reference [16] indicated that power losses in an induction motor can be divided into electrical and magnetic losses. Electrical losses in an induction motor consist of losses in stator and rotor windings. These losses are proportional to the sum of squares of harmonics of corresponding phase currents and the complex impedance of stator and rotor phases at corresponding frequencies. Since the active resistance of windings depends on temperature, and winding temperature is proportional to the sum of squares of current harmonics, electrical power losses in an induction motor are proportional to winding temperature.

Magnetic losses in stator and rotor steel consist of energy storage losses, hysteresis losses, and eddy current losses [16]. Energy storage losses are proportional to the sum of squares of magnetizing current harmonics and the angular frequency of corresponding supply voltage harmonics, while eddy current losses are proportional to the sum of squares of magnetizing current harmonics and the square of the angular frequency of corresponding supply voltage harmonics.

The conducted analysis of power losses in ERS traction drive elements showed that all of them depend on the presence and level of higher harmonic components of corresponding currents and voltages.

The sources of higher harmonic components of voltages and currents in the traction drive are the input and output converters. The level of higher harmonics depends on the sampling frequency when implementing PWM in the mentioned converters [17]. In this regard, a dilemma arises: on one hand, the higher the sampling frequency, the lower the level of higher harmonics of corresponding voltages and currents; on the other hand, the maximum switching frequency (PWM sampling frequency) is limited by the design properties of power switches. Thus, IGBT modules are used as power switches on railway ERS, whose maximum switching frequency is 1 kHz, exceeding which will cause their thermal breakdown.

The sampling frequency in the autonomous inverter control system is selected proportional to the nominal supply voltage frequency, while the supply voltage frequency is proportional to the motor shaft rotation frequency. However, the induction motor operates at shaft rotation frequencies different from the nominal. This leads to the fact that when the supply voltage frequency is lower than nominal, there will be more PWM pulses in the supply voltage period. The consequence of this will be a reduction in the level of higher current harmonics. Reducing the sampling frequency will lead to an increase in the level of higher current harmonics, but switching energy losses will decrease. At supply voltage frequencies higher than nominal, there will be fewer PWM pulses in the supply voltage period. This will increase the level of higher current harmonics. Reducing the sampling frequency will lead to a decrease in switching energy losses.

These considerations are also valid for the input converter, since the catenary voltage can vary depending on parameter changes in the traction power supply system.

From the conducted analysis, it follows that there are many publications devoted to optimizing traction drive operation, aimed at reducing energy losses in ERS traction drives. However, there are very few studies that propose reducing power losses in traction drives through optimization of the sampling frequency of input and output converters. This may be related to the fact that in existing traction drive systems, the sampling frequencies of both input and output converters are fixed. Thus, the input converter frequency is proportional to the nominal catenary voltage frequency, while the output converter sampling frequency is proportional to the nominal supply voltage frequency of the traction motor.

This work differs from known approaches in that for building an enhanced automatic ERS traction drive control system, the power factor is proposed as an optimization criterion, whose analytical expression is a convolution of two time functions – efficiency and active power utilization coefficient. In turn, efficiency and active power utilization coefficient are functions of the sampling frequency of the output and input converter control systems of the traction drive, respectively. This will allow minimizing switching power losses in the mentioned converters when building an enhanced automatic traction drive system. As an example, a variant of the structural diagram of an enhanced automatic traction drive control system using the proposed criterion is presented.

DETERMINATION OF THE ANALYTICAL DEPENDENCE OF THE POWER FACTOR

A simplified structural diagram of the AC ERS traction drive system can be represented as shown in Fig. 1.

The active power utilization coefficient, as a function of time, is determined by the expression, is described by the expression as a function of time:

$$k_p(t)=\frac{P_1(t)}{S_1(t)}=\frac{U_d(t)\cdot I_d(t)}{U_1(t)\cdot I_1(t)}, \quad (1)$$

where $S_1(t)$ – the total power consumed by the ERS from the catenary;

$P_1(t)$ – the active power consumed by the ERS from the network;

$U_d(t)$ – the voltage on the DC link;

$I_d(t)$ – the current flowing through the DC link;

$U_1(t)$ – the voltage on the primary winding of the traction transformer;

$I_1(t)$ – the current of the primary winding of the traction transformer.

The efficiency coefficient as a function of time is determined by the expression:

$$EF(t)=\frac{P_2(t)}{P_1(t)}=\frac{T_{em}(t)\cdot \omega_m(t)}{U_d(t)\cdot I_d(t)}, \quad (2)$$

where $P_2(t)$ - useful power at the shaft of the traction motor;

$T_{em}(t)$ – torque at the motor shaft;

$\omega_m(t)$ – mechanical angular velocity of the motor shaft.

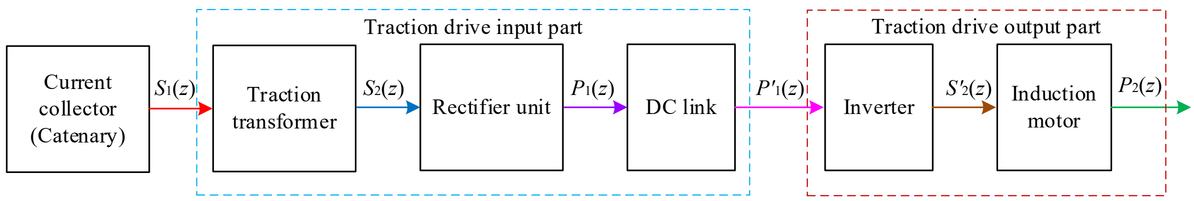


Figure 1. Simplified structural diagram of the traction drive of an electric rolling stock (ERS).

Since the ERS traction drive control system is a microprocessor system, determining the power factor in discrete form is appropriate. Signal processing represented in z-transforms corresponds to signal processing in the frequency domain. Then the active power utilization coefficient can be determined as:

$$k_p(z) = \frac{P_1(z)}{S_1(z)} = \frac{U_d(z) \cdot I_d z}{U_1(z) \cdot I_1(z)}. \quad (3)$$

The efficiency in z-transform form has the form:

$$EF(z) = \frac{P_1(z)}{P_2(z)} = \frac{T_{em}(z) \cdot \omega_m(z)}{U_d(z) \cdot I_d(z)}. \quad (4)$$

The transfer functions $k_p(z)$ and $EF(z)$, defined in equations (3) and (4), are impulse functions.

For convenience of further discussion, the variable z for the impulse function of the active power utilization coefficient is written as z_1, for efficiency – as z_2. That is:

$$z_1 = z_2 = z. \quad (5)$$

Then the impulse function of the power factor has the form:

$$k_p(z_1) = \sum_{i=0}^{N_1} a_i \cdot z_1^{-i}, \quad (6)$$

where a_i - the power factor values taken with a delay of time $i \cdot \Delta T$;
N_1 - the number of samples of the active power utilization coefficient.

The impulse function of the efficiency coefficient has the form:

$$EF(z_2) = \sum_{j=0}^{N_2} b_i \cdot z_2^{-j}, \quad (7)$$

where b_j - the efficiency values taken with a delay of time $j \cdot \Delta T$;
N_2 - the number of efficiency samples.

Thus, the objective function is defined as a transfer function, where the input quantity is the total power consumed by the ERS from the network, and the output is the useful power on the traction motor shaft:

$$k_f(z_1, z_2) = k_p(z_1) \cdot EF(z_2) = \sum_{i=0}^{N_1} a_i \cdot z_1^{-i} \cdot \sum_{j=0}^{N_2} b_i \cdot z_2^{-j} = \sum_{i=0}^{N_1} \sum_{j=0}^{N_2} a_i \cdot b_{N_2-j} \cdot z_1^{-i} \cdot z_2^{-(N_2-j)}. \quad (8)$$

Expression (8) is a convolution operation of two functions k_p and EF, which are written in the form of z-transforms [18].

After substituting expression (5) into expression (8), the objective function expression takes the form:

$$p_f(z) = k_p(z) \cdot EF(z) = \sum_{i=0}^{N_1} a_i \cdot z^{-i} \cdot \sum_{j=0}^{N_2} b_i \cdot z^{-j} = \sum_{i=0}^{N_1} \sum_{j=0}^{N_2} a_i \cdot b_{N_2-j} \cdot z^{-(i+N_2-j)}. \quad (9)$$

The higher the drive efficiency value, the lower the active power losses in it. Correspondingly, the higher the active power utilization coefficient value, the lower the total power losses. That is:

$$p_f(z) = k_p(z) \cdot EF(z) = \sum_{i=0}^{N_1} \sum_{j=0}^{N_2} a_i \cdot b_{N_2-j} \cdot z^{-(i+N_2-j)} \to max. \quad (10)$$

Thus, when using any efficiency criterion to determine optimal values of the active power utilization coefficient and efficiency of rolling stock, it is necessary to monitor the maximum value of the objective function.

Such an approach to determining the power factor is obvious, but using it as an energy efficiency criterion is incorrect. This is related to the following facts. During traction drive operation, various excitation factors act upon it. From the catenary side, the traction drive is influenced by such factors as the conditions of AC ERS passage through the feeder zone, the presence of several ERS units on one feeder zone, current collection quality, etc. From the mechanical side, the traction drive is subjected to disturbance factors that lead to changes in its dynamic properties. These include changes in motion parameters of both the ERS and trailing cars, slip occurrence in one or several wheelsets, track profile changes, etc. In most cases, these influences are stochastic in nature and lead to the power factor variation over time also being stochastic, making it impossible to use as an energy efficiency criterion.

Article [19] demonstrates that the most effective method for solving such a problem is the application of the Wiener-Hopf theorem. The approach to determining the traction drive power factor proposed in work [18] is inconvenient for practical implementation of using the power factor as an energy efficiency criterion. This is related to the fact that different sampling frequencies are used in the input and output converters when implementing PWM. This fact makes it impossible to control the mentioned sampling frequencies when using the traction drive power factor as an efficiency criterion.

The Wiener-Hopf theorem for determining total power for discrete signals has the form [19]:

$$\begin{cases} K_{UI}\left(t-kT,t-nT\right)= \\ =\sum_{i=0}^{N_1}\sum_{j=0}^{N_2}c_{i,j}\cdot K_S\left(t-\left(k-i\right)\cdot T,t-\left(n-j\right)\cdot T\right), \\ k\in N_1, \quad n\in N_2, \end{cases} \quad (11)$$

where $K_{UI}\left(t-kT,t-nT\right)$ - the cross-correlation function of voltage and current signals of the primary winding;

$K_S\left(t-\left(k-i\right)\cdot T,t-\left(n-j\right)\cdot T\right)$ - the autocorrelation function of the total power signal.

The solution of equation (11) for all unknown coefficients $c_{i,j}$, with total unknowns N_1+N_2+2, allows finding the impulse function that minimizes the mean square errors of filtering the random variable of total power.

The Wiener-Hopf theorem for determining useful power on the motor shaft for discrete signals has the form [19]:

$$\begin{cases} K_{T\omega}\left(t-kT,t-nT\right)= \\ =\sum_{i=0}^{N_1}\sum_{j=0}^{N_2}d_{i,j}\cdot K_{P_2}\left(t-\left(k-i\right)\cdot T,t-\left(n-j\right)\cdot T\right), \\ k\in N_1, \quad n\in N_2, \end{cases} \quad (12)$$

where $K_{T\omega}\left(t-kT,t-nT\right)$ - the cross-correlation function of electromechanical torque and mechanical angular velocity signals of the motor shaft;

$K_{P_2}\left(t-\left(k-i\right)\cdot T,t-\left(n-j\right)\cdot T\right)$ - the autocorrelation function of the useful power signal on the motor shaft.

The solution of equation (12) with respect to all unknowns $d_{i,j}$, whose total number will be N_1+N_2+2, allows finding the impulse function that minimizes the mean square errors of filtering the random variable of useful power on the motor shaft.

Then the total power after applying the Wiener-Hopf procedure is determined as:

$$S_1'(n)=\sum_{i=0}^{N_1}\sum_{j=0}^{N_2}c_{i,j}\cdot S_1\left((n-i)-j\right). \quad (13)$$

After applying the Wiener-Hopf procedure, the useful power on the motor shaft is determined as:

$$P_2'(n)=\sum_{i=0}^{N_1}\sum_{j=0}^{N_2}d_{i,j}\cdot P_2\left((n-i)-j\right). \quad (14)$$

The obtained values of total power consumed from the network $S_1'\left(t\right)$ (13) and useful power on the motor shaft $P_2'\left(t\right)$ (14) should be substituted into equations (3) and (4) respectively.

The total power consumed by the traction drive from the catenary and useful power on the motor shaft, determined by expressions (13) and (14), allow eliminating the influence of stochastic disturbances acting on the traction drive when determining the power factor. Thus, the power factor calculated using the Wiener-Hopf theorem for determining total power and useful power on the motor shaft can be used as an efficiency criterion for building an enhanced automatic traction drive control system.

Since the research concerns electric rolling stock traction drives, conducting it on a real object is energy-intensive and thus requires significant capital investments. Due to this fact, it is advisable to conduct the research using simulation modeling.

As indicated above, field-oriented control of induction traction motors is applied as a traction drive in most cases on mainline electric rolling stock. This particular drive was selected as the research object. The simulation model of such a drive is presented in work [13].

To verify the adequacy of the proposed algorithm for power factor determination, the values of U_d, I_d, U_1, I_1, T_{em}, ω_{em} were determined as functions of time through simulation modeling. Based on the values obtained from the simulation, the power factor coefficient values have been calculated using the formula $p_f=P_2/S_1$ and using formula (9) as functions of time. Based on these calculations, corresponding graphs have been constructed (Fig. 2). The convolution of functions was performed under the condition $N_1 = 32$ samples and $N_2 = 32$.

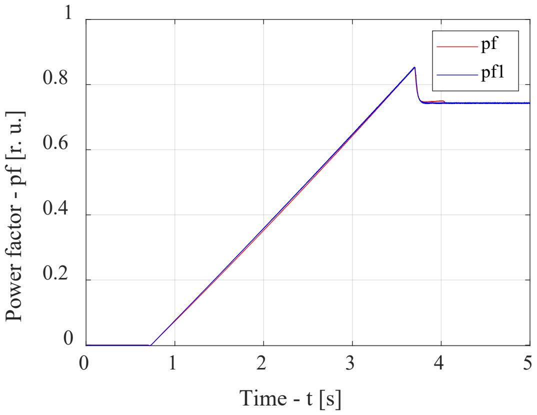


Fig. 2. Temporal characteristics of the traction drive power factor determined according to expression p_f=P_2/S_1 (p_f) and (9) (p_{f1}).

For the steady-state regime, the values $p_f = 0.7395$ and $p_{f_1} = 0.7435$ have been determined from Fig. 2. In other words, the error in determining the power factor using the convolution function of two time functions amounts to 0.54%. Furthermore, analysis of the graphs presented in Fig. 4 shows that the forms and values of p_f and p_{f_1} re almost indistinguishable, which indicates high reliability of the obtained results. It should be noted that the time dependency of the power factor has no physical meaning; it is only necessary for organizing an enhanced automatic control system for traction drive operation.

DEVELOPMENT OF AN ENHANCED AUTOMATIC CONTROL SYSTEM FOR TRACTION DRIVES BASED ON POWER FACTOR AS AN EFFICIENCY CRITERION

An example of an enhanced automatic control scheme for traction drive based on an energy efficiency criterion can be the scheme presented in Fig. 3.

Its operation algorithm is as follows. Based on the voltage signals from the traction transformer primary winding U_1 and the primary winding current I_1, received from corresponding sensors, the total power consumed from the network (denominator of equation (3)) is determined in the "Determination of S_1" unit. In the "Determination of S'_1" unit, the Wiener-Hopf theorem of equations (11), (13) is applied to power S_1.

Based on the voltage signals from the DC link U_d and the traction transformer primary winding current I_d received from corresponding sensors, the active power consumed by the DC link (numerator of equation (3)) is determined in the "Determination of P_d" unit.

Based on the electromagnetic torque signals T_{em} and the mechanical angular frequency of motor shaft rotation ω_m received from corresponding sensors, the useful power on the motor shaft (denominator of equation (4)) is determined in the "Determination of P_2" unit. In the "Determination of P'_2" unit, the Wiener-Hopf procedures of equations (12), (14) are applied to power P_2.

Based on the obtained signals S'_1 and P_d the active power utilization coefficient of the traction drive input part k_{p_in} is determined in the "Determination of k_{p_in}" unit (equation (3)). Based on the obtained signals P'_2 and P_d, the efficiency of the traction drive output part EF is determined in the "Determination of EF" unit (equation (4)). The equation $p_f = P_2 / S_1$ implemented in the "Determination of p_f" unit, and the traction drive power factor p_f is determined. The obtained power factor value p_f is compared with the previous value $p_f(t$-1). The comparison result is fed to the decision-making unit "DMU1", where the comparison result is analyzed: if the previous power factor value is less than or equal to the previous value, the signal s_{pf} at the unit output has a value of 1, which allows changes in sampling frequencies; otherwise, the signal s_{pf} has a value of 0, which prohibits changes in sampling frequencies. The current value p_f is stored in the memory device "MD1".

The current value of the active power utilization coefficient of the traction drive input part k_{p_in} is compared with the previous value k_{p_in}(t-1).

The comparison result is fed to the signum relay "SR1", where the operation sign is determined, after which the signal is supplied to the "Sampling frequency change intensity setter 1" unit.

The current value k_{p_in} is recorded in the memory device "MD2".

The following equation is implemented in the "Sampling frequency change intensity setter 1" unit:

$$\Delta F_{d1} = \frac{F_{dmax}}{k_{p\_in\_max}} \cdot \Delta k_{p\_in}, \qquad (15)$$

where F_{d1max} - the maximum switching frequency of the rectifier IGBT modules ($F_{d2max} = 1000 Hz$ [13]);

$k_{p\_in\_max}$ – the maximum value of the input part power factor of the traction drive (the power factor can have a maximum value equal to 1).

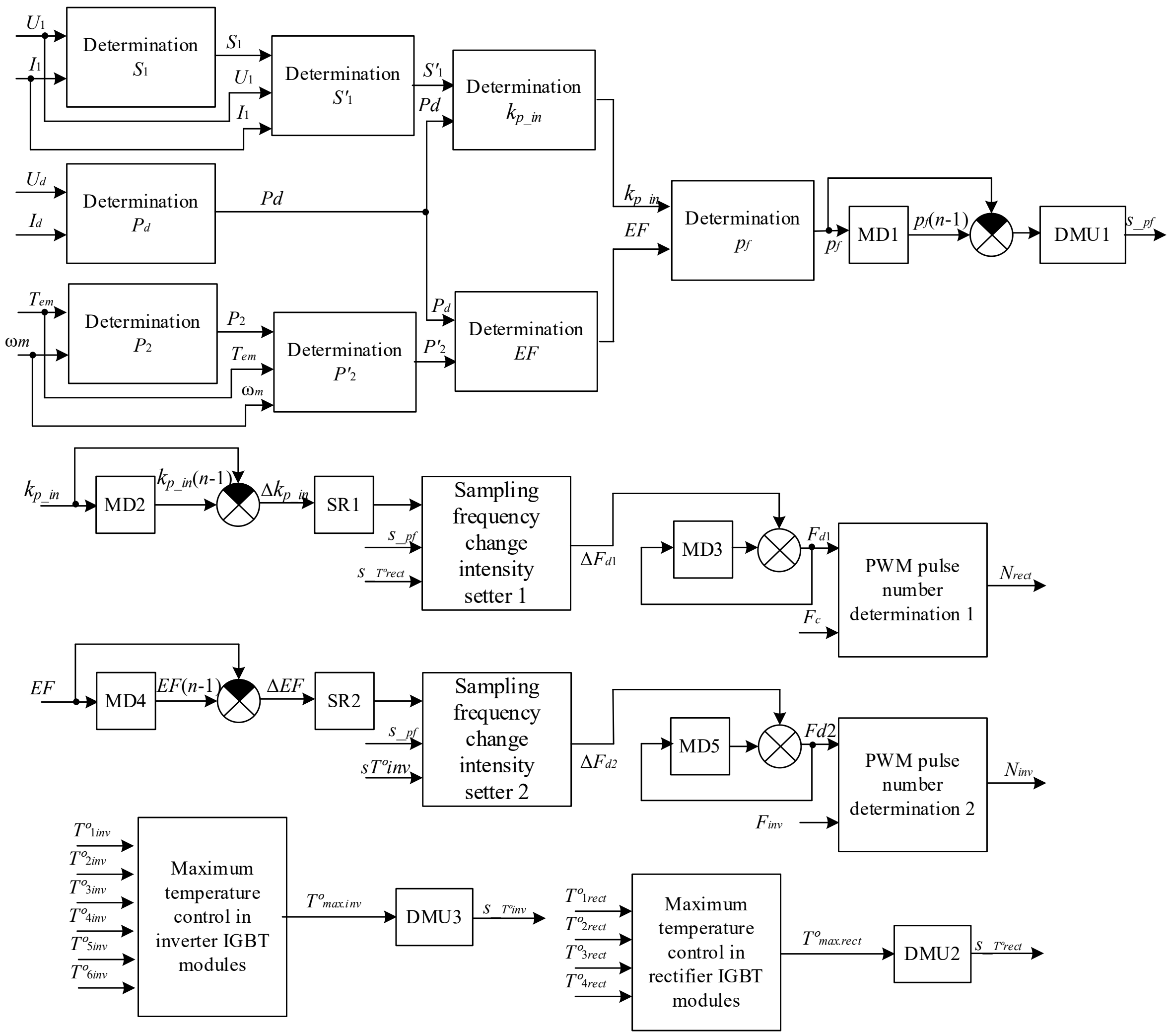


Fig. 3. Example of enhanced automatic control scheme for traction drive based on efficiency criterion.

The "Sampling frequency change intensity setter 1" unit has two control signals that allow determination of the sampling frequency change for the traction drive input part $s_{\_pf}$ and $s_{\_T^o rect}$. The signal $s_{\_T^o rect}$ is generated by the decision-making unit

"DMU2" based on information received from the "Maximum temperature control in rectifier IGBT modules" unit. The "Maximum temperature control in rectifier IGBT modules" unit analyzes signals received from temperature sensors of 4 rectifier IGBT modules and determines the maximum temperature. The decision-making unit "DMU2" determines whether there is temperature exceedance in the rectifier IGBT modules. If there is no temperature exceedance in the rectifier IGBT modules, the signal $s_{\_T^o rect}$ equal to 1 is set at the "DMU2" output; if there is exceedance, the signal $s_{\_T^o rect}$ equal to 0 is set. The "Sampling frequency change intensity setter 1" unit can output the signal ΔF_{d1} when both signals $s_{\_pf}$ and $s_{\_T^o rect}$, are equal to 1. Otherwise, the signal ΔF_{d1} at the output of the "Sampling frequency change intensity setter 1" unit will be equal to 0. ΔF_{d1} is added to the previous sampling frequency value signal received from the memory unit "MD3", the calculation result is stored by unit "MD3" and fed to the "PWM pulse number determination 1" unit, where the number of PWM pulses of the input converter is determined by the expression:

$$N_{\_rect} = \frac{F_{d1}}{F_c}, \qquad (16)$$

where F_{d1} – he determined value of the rectifier sampling frequency;

F_c – the catenary frequency value received from the corresponding sensor.

The current value of the efficiency coefficient of the traction drive output part EF is compared with the previous value EF(t-1). The comparison result is fed to the signum relay "SR2", where the operation sign is determined, after which the signal is supplied to the "Sampling frequency change intensity setter 2" unit. The current value kp_in is recorded in the memory device "MD4". The following equation is implemented in the "Sampling frequency change intensity setter 2" unit:

$$\Delta F_{d1} = \frac{F_{d2max}}{EF_{\_max}} \cdot \Delta EF, \quad (17)$$

where F_{dmax} - the maximum switching frequency of the inverter IGBT modules ($F_{d2max} = 1000 Hz$ [13]);

$EF_{\_max}$ – the maximum value of the efficiency coefficient of the traction drive output part (the efficiency coefficient can have a maximum value equal to 1).

The "Sampling frequency change intensity setter 2" unit has two control signals that allow determination of the sampling frequency change for the traction drive input part $s_{\_pf}$ and $s_{\_T^\circ inv}$. The signal $s_{\_T^\circ inv}$ is generated by the decision-making unit "DMU3" based on information received from the "Maximum temperature control in inverter IGBT modules" unit. The "Maximum temperature control in inverter IGBT modules" unit analyzes signals received from temperature sensors of 6 inverter IGBT modules and determines the maximum temperature. The decision-making unit "DMU3" determines whether there is temperature exceedance in the inverter IGBT modules. If there is no temperature exceedance in the inverter IGBT modules, the signal $s_{\_T^\circ inv}$, equal to 1 is set at the "DMU3" output; if there is exceedance, the signal $s_{\_T^\circ inv}$ equal to 0 is set. The "Sampling frequency change intensity setter 2" unit can output the signal ΔF_{d2} when both signals $s_{\_pf}$, and $s_{\_T^\circ inv}$ are equal to 1. Otherwise, the signal ΔF_{d2} at the output of the "Sampling frequency change intensity setter 2" unit will be equal to 0. ΔF_{d2} is added to the previous sampling frequency value signal received from the memory unit "MD5", the calculation result is stored by unit "MD5" and fed to the "PWM pulse number determination 2" unit, where the number of PWM pulses of the input converter is determined by the expression:

$$N\_inv = \frac{F_{d2}}{F_{inv}}, \quad (18)$$

where F_{d2} is defined as the determined discretization frequency value of the inverter;

F_{inv} – corresponds to the catenary frequency value that may be derived from the FOC signals.

$$F_{inv} = \frac{\omega_k \cdot \Omega_b}{2 \cdot \pi}, \quad (19)$$

where ω_k represents the angular frequency of the coordinate system rotation. The traction drive control system can be implemented when the rectifier and inverter control systems are capable of operating with variable values of catenary frequency and inverter frequency respectively, and with variable pulse numbers of corresponding PWM signals.

CONCLUSIONS

An algorithm for power factor determination has been proposed in this work, and an example of an automated control system has been presented, in which the power factor is applied as an energy efficiency criterion.

It has been proposed to determine the traction drive power factor as a convolution function of two time functions – the input section power factor and the output section efficiency of the traction drive. This approach is determined by the fact that various disturbances of stochastic nature act on the traction drive under operating conditions on one hand, and by the necessity of separate control of discretization frequencies of input and output converters on the other hand. To eliminate the influence of the aforementioned disturbances, the Wiener-Hopf theorem has been proposed to be applied when determining the total power consumed from the network and when determining the useful power at the motor shaft.

As a result of simulation, time dependencies of the traction drive power factor have been obtained and constructed for two cases: calculated as the ratio of useful power at the motor shaft to total power consumed from the network, and calculated as a convolution of two functions of time – the input section power factor and the output section efficiency of the traction drive. Analysis of the obtained dependencies has shown that in stable operating mode, their values differ by no more than 0.54%. In unstable modes, the forms and values of power factors obtained by the two methods differ slightly. This indicates high accuracy of the proposed method for traction drive power factor determination.

As an example, an enhanced automatic control system for traction drive has been proposed, where the power factor is used as an efficiency criterion. Such a scheme, in addition to obtaining maximum power factor, allows monitoring of overheating of power modules of input and output converters. This is necessary since the temperature of the specified modules also depends on the switching frequency (discretization frequency). Implementation of such a scheme is possible when control systems for both input and output converters can operate with variable PWM parameters – signal frequency and PWM pulse number.

The following research topics may be pursued:

- Development of a PWM control system with variable parameters for input and output converters;
- Application of decision theory in the construction of enhanced control systems for traction drives;
- Investigation of the operation of controllers with variable parameters that depend on the discretization frequency parameters of the output converter.

References

[1] Polater N., Tricoli P. Technical review of traction drive systems for light railways. *Energies*, 2022, vol. 15, no 9, pp. 3187. Available at: doi: 10.3390/en15093187.

[2] Fedele E., Iannuzzi D., Del Pizzo A. Onboard energy storage in rail transport: Review of real applications and techno-economic assessments. *IET electrical systems in transportation*, 2021, vol. 11, no 4, pp. 279-309. Available at: doi: 10.1049/els2.12026.

[3] Peng Y., Lu S., Chen F., Liu Z., Tian Z. Energy-efficient train control incorporating inherent reduced-power and hybrid braking characteristics of railway vehicles. *Transportation Research Part C: Emerging Technologies*, 2024, vol. 163, pp. 104626. Available at: doi: 10.1016/j.trc.2024.104626.

[4] Fischer S., Szürke S. K. (2023). Detection process of energy loss in electric railway vehicles. *Facta Universitatis, Series: Mechanical Engineering*, 2023, vol. 21, no, 1, pp. 081-099. Available at: doi: 10.22190/FUME221104046F.

[5] Fomin O., Sulym A., Kulbovskyi I., Khozia P., Ishchenko V. Determining rational parameters of the capacitive energy storage system for the underground railway rolling stock. *Eastern-European Journal of Enterprise Technologies*, 2018, vol. 2, no 1(92), pp. 63-71. Available at: doi: 10.15587/1729-4061.2018.126080.

[6]Domínguez M., Fernández-Cardador A., Fernández-Rodríguez A., Cucala A. P., Pecharromán R. R., Sánchez P. U., Cortázar, I. V. Review on the use of energy storage systems in railway applications. *Renewable and Sustainable Energy Reviews*, 2025, vol. *207*, pp. 114904. Available at: doi: 10.1016/j.rser.2024.114904.

[7] Müller, M. A. Dissipativity in economic model predictive control: beyond steady-state optimality. *Recent advances in model predictive control: theory, algorithms, and applications*, 2021, pp. 27-43. Available at: doi: 10.1007/978-3-030-63281-6_2.

[8] Ding Y., Wang Q., Tian Z., Lyu Y., Li F., Yan Z., Xia X. A graph-theory-based dynamic programming planning method for distributed energy system planning: Campus area as a case study. *Applied Energy*, 2023, vol. 329, pp. 120258. Available at: doi: 10.1016/j.apenergy.2022.120258.

[9] Barrenechea G. R., John V., Knobloch P. Finite element methods respecting the discrete maximum principle for convection-diffusion equations. *SIAM Review*, 2024, vol. 66, no. (1), pp. 3-88. Available at: doi: 10.1137/22M1488934.

[10] Yang C., Xia Y. (2023). Interval uncertainty-oriented optimal control method for spacecraft attitude control. *IEEE Transactions on Aerospace and Electronic Systems*, vol. 59, no 5, pp. 5460-5471. Available at: doi: 10.1109/TAES.2023.3257777.

[11] Steczek M., Jefimowski W., Maciołek T., Barański S. Analysis of energy losses in the novel distributed power supply system for trams. *IEEE Transactions on Transportation Electrification*, 2022, vol. 9, no 1, pp, 1498-1508. Available at: doi: 10.1109/TTE.2022.3165702.

[12] Amry Y., Elbouchikhi E., Le Gall F., Ghogho M., El Hani S. Electric vehicle traction drives and charging station power electronics: Current status and challenges. *Energies*, 2022, vol. 15, no 16, 6037. Available at: doi: 10.3390/en15166037.

[13] Goolak S., Liubarskyi B., Riabov I., Lukoševičius V., Keršys A., Kilikevičius, S. Analysis of the efficiency of traction drive control systems of electric locomotives with asynchronous traction motors. *Energies*, 2023, vol. 16, no 9, pp. 3689. Available at: doi: 10.3390/en16093689.

[14] Zhang K., Yang J., Liu C., Wang J., Yao D. Dynamic characteristics of a traction drive system in high-speed train based on electromechanical coupling modeling under variable conditions. *Energies*, 2022, vol. 15, no 3, pp. 1202. Available at: doi: 10.3390/en15031202.

[15] Hosseinzadeh N., Aziz A., Mahmud A., Gargoom, A., Rabbani M. Voltage stability of power systems with renewable-energy inverter-based generators: A review. *Electronics*, 2021, vol. 10, no 2 pp. 115. Available at: doi: 10.3390/electronics10020115.

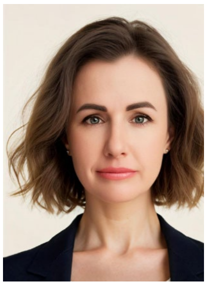
[16] Kosuru V. S. R., Kavasseri Venkitaraman A. Trends and challenges in electric vehicle motor drivelines-a review. *International journal of electrical and computer engineering systems*, 2023, vol. 14, no 4, pp. 485-495. Available at: doi: 10.32985/ijeces.14.4.12.

[17] Balal A., Dinkhah S., Shahabi F., Herrera M., Chuang Y. L. A review on multilevel inverter topologies. *Emerging Science Journal*, 2022, vol. 6, no 1, pp. 185-200. Available at: doi: 10.28991/ESJ-2022-06-01-014.
[18] Xu, Z., Qian S., Ran X., Zhou J. Application of deep convolution neural network in crack identification. *Applied Artificial Intelligence*, 2022, vol. 36, no 1, pp. 2014188. Available at: doi: 10.1080/08839514.2021.2014188.
[19] Subba Rao S., Yang. J. (2023). A prediction perspective on the Wiener–Hopf equations for time series. *Journal of Time Series Analysis*, 2023, vol. 44, no 1, pp. 23-42. Available at: doi: 10.1111/jtsa.12648.

Information about the authors.


Goolak Sergey
PhD, Associate Professor, National Transport University, Kyiv, Ukraine.
Areas of scientific interest encompass mathematical modeling of control systems for electric locomotive traction drives.
E-mail: sgoolak@gmail.com


Gorobchenko Oleksandr
Doctor of Technical Sciences, Professor. National Transport University, Kyiv, Ukraine. Scientific interests – human factor, rolling stock control and diagnostic systems.
E-mail: gorobchenko.a.n@gmail.com


Petrychenko Olga
PhD, Associate Professor, National University “Odesa Maritime Academy”, Odesa, Ukraine.
Scientific interests – mathematical modelling of dynamic systems, game theory in conflict resolution, and development of automated decision-making algorithms.
E-mail: o.petrychenko@onma.edu.ua


Holub Halyna
PhD, Associate Professor. National Transport University, Kyiv, Ukraine.
Scientific interests – control and diagnostics of rolling stock and power supply monitoring systems.
E-mail: holub.hm@gmail.com


Kulbovskyi Ivan
PhD, Associate Professor
National Transport University, Kyiv, Ukraine.
Scientific interests – control and diagnostics of rolling stock and power supply monitoring systems.
E-mail: kulbovskiy@ukr.net