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Inactive power in electric-traction DC transport systems

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Abstract. The paper presents a theoretical background to determine the inactive power consumption features, i.e. the reactive power according to S. Fryze approach of the electric transport systems. Traction electric circuits of transport facilities of electric locomotives, feeder traction substations and city trams used in Ukraine demonstrate three features of the reactive power. According to the classical method, the inequality between the active and total power indicates the presence of the reactive power. The second feature is the time variation of an instantaneous impedance or instantaneous conductivity. The third is the inequality between the instantaneous reactive power to zero and the nature of its sign throughout the time of the electric power system consumption. The reactive power consumption gives rise to considerable additional power losses in the electric traction transport systems.

Keywords: inactive power, signs, electric transport, instantaneous, voltage, current, random process, register, power loss, resistance.

Neaktivna moč v električnem vlečnem sistemu za prevoz z enosmernim tokom

V prispevku je predstavljeno teoretično ozadje za določitev značilnosti porabe neaktivne energije (jalova moč pri pristopu S. Fryze) električnih transportnih sistemov z enosmernim tokom. Na podlagi primerov električnih lokomotiv, napajalne vlečne postaje in mestnega tramvaja, ki se uporabljajo v Ukrajini, je bilo dokazano, da imajo vlečni električni tokokrogi transportnih naprav vse tri značilnosti jalove moči. Ugotovljeno je bilo, da je po klasični metodi neenakost aktivne in skupne moči značilnost prisotnosti jalove moči. Druga značilnost je časovna sprememba trenutne impedance, tretja pa neenakost trenutne jalove moči z nič. Poraba jalove moči vodi do bistvenih dodatnih izgub v električnih vlečnih transportnih sistemih.

1 INTRODUCTION

DC electric transport systems are still widely used in European countries. In particular, in Spain, Italy, Belgium, Poland, in the north of the Czech Republic and Slovakia the main systems are powered by a 3 kV DC voltage, and by 1.5 kV in the Netherlands and in the south of France [1]. In the south of Great Britain, the first DC systems with a voltage of 650, 750, and 1200 V with a contact rail are still operating.

In Ukraine, half of the main and suburban, all mine as well as the urban electric transport are also DC driven. Electric locomotives, trains, subway motor cars, trams, and trolleybuses are supplied with a DC voltage of the nominal value from 600 to 3000 V. These electric systems are traditionally believed to not consume the reactive power. This makes their reactive power factor be Q and the power factor λ and determines the energy balance formation only for the active power. As a result, the used analysis methods of energy processes falsely take no account of the continuous and often significant oscillations in the supply voltage and traction current (Figs. 1 and 2 [2]). Namely the DC electric-transport systems are by definition mostly AC systems. Following an in-depth detailed research an analysis should be made of the nature of variation and the level of the reactive power Q_F, as it significantly affects the basic energy indicators, such as:

- the active power loss ΔP

$$\Delta P = \frac{P^2 + Q_F^2}{U^2} \cdot R \qquad \text{(Eq. 1)}$$

- power factor λ

$$\lambda = \frac{P}{\sqrt{P^2 + Q_F^2}} \qquad \text{(Eq, 2)}$$

- reactive-power factor $tg\varphi$

$$tg\varphi = \frac{Q_F}{P} \qquad \text{(Eq. 3)}$$

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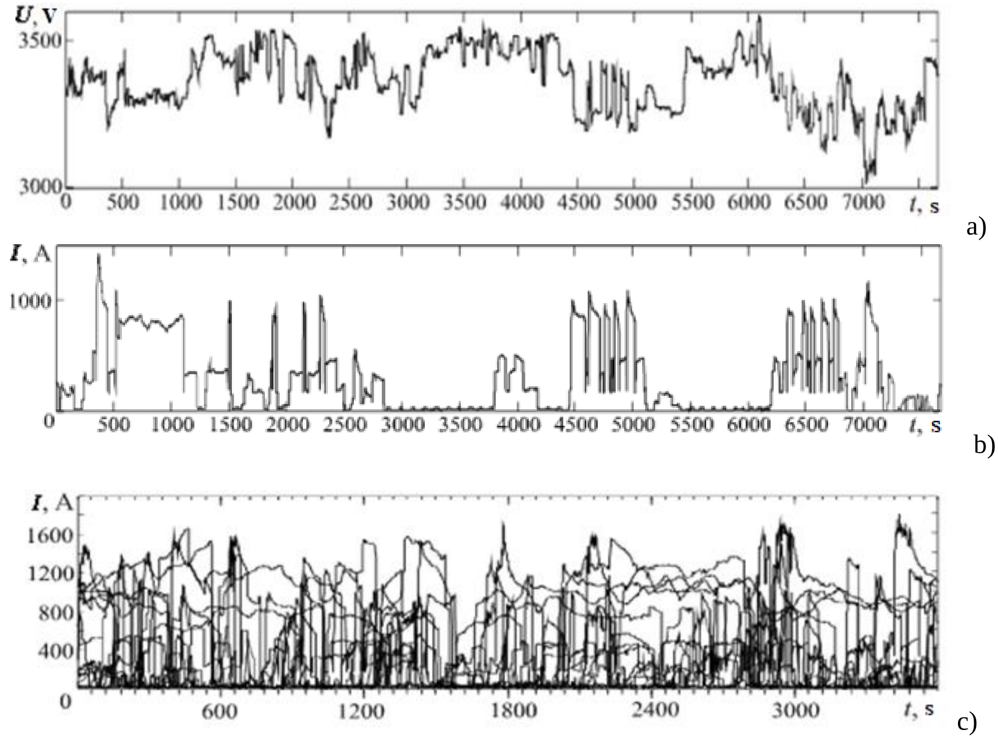


Figure 1. Recorded oscillations (per trip): voltage at the current collector (a), traction current (b) of electric locomotive VL8; traction current (c) - ten implementations of the electric locomotive (DE1)

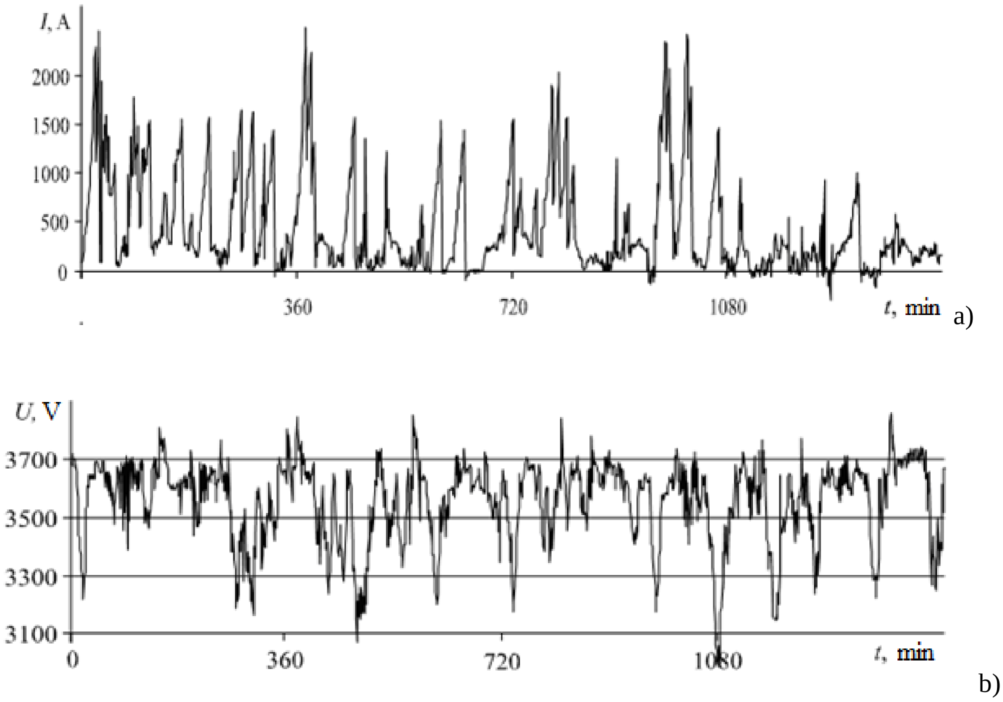


Figure 2. Recoreded oscillations per day: feeder current of substation section AB (a); rectified voltage on the substation A busbars (b)

In 2020 the term "reactive power" as a component of the inactive power was hundred years old [3]. Nevertheless, the scientific discussions on the concepts and formulas to determine the reactive power in electric circuits with nonsinusoidal voltages and currents continue in their current form continue even today [4-16].

The paper discusses the main features of the inactive power present in nonlinear parametric traction circuits of the DC electric transport systems.

2 EXPERIMENTAL RESEARCH

There have been several experimental studies performed in Ukraine for the electrified sections of the Dnieper Railway and urban tram lines in the city of Dnipro.

At the same time, the following was recorded and processed: 20 daily implementations of random processes of feeder voltages and currents of traction substations A and B; 20 implementations of the recorded oscillograms of random voltage processes on current collectors and traction currents of electric locomotives of types DE1, VL8, and trams of type T-3. The voltage and current registration for DE1 and VL8 took 70 minutes and for trams 30 minutes. Electric locomotive voltages and currents were recorded with a microprocessor system. Tram voltages and currents of the were monitored by connecting a personal computer to the onboard control and measuring system of the tram.

Today, the most common methods to determine the components of total power S , and hence inactive power Q_F , are classical, integral, spectral, statistical and instantaneous power methods [6]. In the future, when establishing signs of the presence of Q_F the basic properties of these methods will be used taking into account the fact that voltages and currents in the transport systems under research are stochastic processes.

3 RESEARCH RESULTS

3.1 The classical method

According to Budeanu [17] reactive power Q_B in an electric circuits with periodic non-sinusoidal currents is determined in a form of an integral quantity

$$Q_B = \sum_{l=m=k} U^{(l)} \cdot I^{(m)} \cdot \sin\left(\psi_u^{(l)} - \psi_i^{(m)}\right) \qquad \text{(Eq. 4)}$$

However, this assures no balance between the P , Q_B and S components. So, $P^2 + Q_B^2 \neq S^2$ for which reason on additional power component is introduced known as distortion power D denoting the discrepancy between the square of total power S^2 and the sum of the squares of the active and reactive Q_B^2 power:

$$D = \sqrt{S^2 - \left(P^2 + Q_B^2\right)} \qquad \text{(Eq. 5)}$$

Unlike P and Q_B, distortion power D is determined by the interaction between the voltage and current harmonics of different frequencies and is described by the expression:

$$D = \sqrt{\sum_{m \neq l} \begin{bmatrix} U^{(l)2} \cdot I^{(m)2} + U^{(m)2} \cdot I^{(l)2} - \\ -2 \cdot U^{(l)} \cdot I^{(m)} \cdot U^{(m)} \cdot I^{(l)} \cdot \\ \cdot \cos\left(\varphi^{(m)} - \varphi^{(l)}\right) \end{bmatrix}} \qquad \text{(Eq. 6)}$$

where $\varphi^{(l)} = \psi_u^{(l)} - \psi_i^{(l)}$, $\varphi^{(m)} = \psi_u^{(m)} - \psi_i^{(m)}$.

Fryze [18] disagrees with the introduction of the distortion power. He preserves the functional nature of the description of the energy properties of electric circuits in sinusoidal and non-sinusoidal processes. By the analogy with circuits with sinusoidal voltages and currents he proposes to decompose S^2 into a sum of squares of only two components, i.e. active (effective) P and passive, inactive (fictitious) Q_F powers:

$$S^2 = P^2 + Q_F^2 = P^2 + Q_B^2 + D^2 . \qquad \text{(Eq. 7)}$$

Separating the passive component from the total power instantaneous current is decomposed into two components: active $i_a(t)$ having the same shape as the instantaneous voltage, and reactive having an orthogonal shape. The squared effective values of these components form the effective value of the total current: $I_a^2 + I_p^2 = I^2$. Multiplying both sides by the square of the applied voltage we get: $P = UI_a$, $Q_F = UI_p$ [Eq. 7]. Power Q_F is often known as a reactive power [18]. Its average value for a period is equal to zero and physically it is the energy per unit time oscillating between the source and consumer. Or, it can be assumed as part of the total power that is not transferred to the load due to the consumption process. According to [18] the reactive power is the most complete and effective among the considered ones when defining the unproductive losses in transferring the electric power both in the steady and transient mode of consumer operations.

Based on [Eq. 7] , $Q_F^2 = S^2 - P^2 > 0$ applies when $S^2 > P^2$. According to the classical method, the presence of inactive power Q_F is inequality between the active P and total S power making the power factor less than one.

To demonstrate the above validity, a method to determine powers P , Q , S is presented and their values are estimated for some devices of the electric transport system.

As noted, in Figs. 1 and 2, and [2], the voltages and currents in the studied systems are stochastic processes.

And, as is in [19, and 20], neither the Fourier series nor the integral Fourier transforms can be applied to random functions given on an infinitely long interval. The only exceptions are particular types of the random processes of a specific duration, the spectral analysis of which can be performed by a discrete or fast Fourier transform. The condition to use these methods is duration T of implementations $u(t)$ and $i(t)$ in which there is enough time to determine lack of their most important properties for a practice (at purpose, such as root-mean square values). Then $u(t)$ and $i(t)$ are considered as a deterministic non-sinusoidal function as $a(t)$ which is not on the interval $[0,T]$, but is periodically extended beyond by converting the non-periodic function.

Such spectral method, is based on a digital harmonic analysis of random voltage and current processes performed by a discrete Fourier transform. Instead of actual process *a(t)* (Fig. 3), the stochastic voltage or current is assumed be image a periodic process of an arbitrary period *T*. Non-sinusoidal function *a(t)* is not considered at interval $[0,\tau]$, but as periodically extended outside this interval. That is, non-periodic function *a(t)* is converted into a periodic one with period *T*, for which the Fourier series expansion in a true classical form is:

$$a(t) = A_{m(k)} \sin\left(\kappa\omega t + \psi_{a(k)}\right) \qquad \text{(Eq. 8)}$$

where $A_{m(\kappa)}$, $\psi_{a(\kappa)}$ are the amplitude and initial phase of the *th-th* harmonic of the series determined using complex amplitude $\underline{A}_{m(k)} = A_{m(k)}\,\mathrm{e}^{-j\psi_{a(k)}}$, which is the well-known expression [21]:

$$\underline{A}_{m(k)} = \frac{1}{T}\int_0^T a(t)\mathrm{e}^{-jk\omega t}\,dt \qquad \text{(Eq. 9)}$$

However, function *a(t)* is non-sinusoidal, thus arbitrary, and often very complex, hence making the use of the classical Fourier analysis for a spectral analysis quite difficult. In such a case, using the discrete Fourier transform is preferable. To do this, intervals Δt of function *a(t)* are sampled. Values $a_n = a(n\cdot\Delta t)$ are points of new periodic analog function *a(t)* presented in a form of a sequence of the delta functions and "weighted" by samples $a(n\cdot\Delta t)$ of analog function *a(t)*:

$$a(t) = \sum_{n=1}^{N} a(n\cdot\Delta t)\,\delta(t - n\cdot\Delta t) \qquad \text{(Eq. 10)}$$

Substituting (Eq. 10) into (Eq. 9) gives:

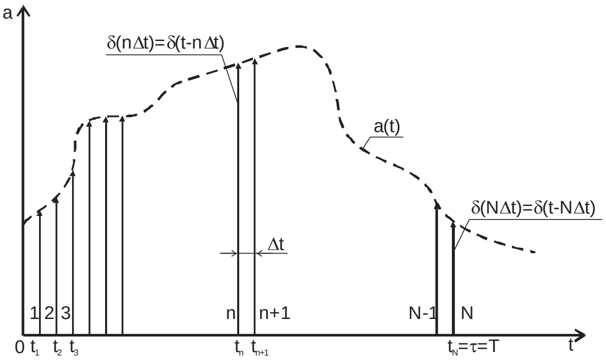


Figure 3. Discretized function *a(t)* in the form of a sequence of delta functions

$$\underline{A}_{m(k)} = \frac{2}{T}\int_0^T \sum_{n=1}^{N} a(n\cdot\Delta t)\,\delta(t - n\cdot\Delta t)\cdot e^{-j\kappa\omega t}\,dt \qquad \text{(Eq. 11)}$$

And, $a(n\cdot\Delta t)$ being constant values (independent on *t*) and function $\delta(t - n\cdot\Delta t)$ zero for any *t* except $t = n\cdot\Delta t$ (Eq. 11) can be rewritten as:

$$\underline{A}_{m(k)} = \frac{2}{T}\sum_{n=1}^{N} a(n\cdot\Delta t)\int_0^T \sum_{n=1}^{N} \delta(n\cdot\Delta t)\,e^{-jk\omega t}\,dt \qquad \text{(Eq. 12)}$$

Taking into account the filtering action of the delta function, expression (12) will take the following form:

$$\underline{A}_{m(\kappa)} = \frac{2}{T}\sum_{n=1}^{N} a(n\cdot\Delta t)\,e^{-j\kappa\omega\Delta t} \qquad \text{(Eq. 13)}$$

Eq. 13 defines the harmonics in a form of complex coefficients containing amplitude and phase. The Fourier series are written using Eq. 14:

$$a(t) = \sum_{k=1}^{S} A_m^{(k)}\cdot\sin\left(k\omega t + \psi^{(k)}\right) \qquad \text{(Eq. 14)}$$

After decomposing into each implementation of random functions $u(t)$, $i(t)$ a Fourier series and determining powers P, Q_F, S is calculated according to the known formulas of the electric circuits theory of the periodic non-sinusoidal current [21]. Power values for the time interval [0, T] is a random variable.

Figure 4 and the Table 1 show the values of active P, inactive Q_F, and total power S consumed by the DE1 and VL8 DC electric locomotives, respectively, which are exploited in Ukrainian electrified areas. Fig. 5 shows the time dependences of the power transmitted from the traction substation A into the traction network of zone AB.

As seen from the above figures, tables and results [22], the first condition for the presence of the inactive power is $P \neq S$ and it applies for main devices (subsystems) of the electric DC transport system. The percentage of power Q_F compared to P is relatively high.

Table 1. Calculations of inactive power Q_F of electric locomotive VL8 .

№ travel	U, kV	I, kA	P,MW	S, MVA	λ	Q_F , Mvar
1	3,366	0.579	1,248	1,949	0.64	1,497
2	3,366	0.516	0.982	1.74	0.565	1,435
3	3,366	0.447	1,023	1,505	0.68	1,103
4	3,351	0.636	1,176	2,134	0.551	1,781
5	3,332	0.755	1,792	2,516	0.712	1,767
6	3,211	0.644	1,151	2,069	0.556	1,719
7	3,316	0.808	1,762	2,679	0.658	2,019
8	3,141	0.754	1,413	2.37	0.596	1,903

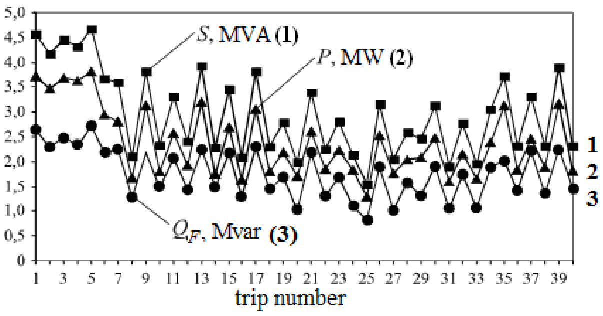


Figure 4. Value of active P, inactive Q_F and the total S power consumed by DC electric locomotives DE1.

3.2 The integral method

This method was proposed in the scientific literature by O.A. Mayevsky [23]. Analysis of the electromagnetic processes in nonlinear electric circuits generating the reactive power show that the classical concept to calculate the reactive power for linear circuits characterizing the oscillating energy between the source and reactive load cannot be used for circuits with nonlinear elements with a variable impedance. Therefore, the reactive power in a nonlinear circuit is expressed by integral quantities of the products of one of the electric magnitudes and the rate of the change of the another:

$$Q_\Pi = \frac{1}{\omega_\Pi T}\int_0^T u(t)\frac{di(t)}{dt}dt = \frac{1}{2\omega_\Pi T}\int_0^T u^2(t)\frac{dy(t)}{dt}dt \qquad \text{(Eq. 15)}$$

$$Q_\Pi = \frac{-1}{\omega_\Pi T}\int_0^T i(t)\frac{du(t)}{dt}dt = \frac{-1}{2\omega_\Pi T}\int_0^T i^2(t)\frac{dz(t)}{dt}dt \qquad \text{(Eq. 16)}$$

where $z(t)=u(t)/i(t)$ and $y(t)=i(t)/u(t)$ are instantaneous impedance and conductivity of the circuit element or section, respectively.

In (Eq. 15) and (Eq. 16), the minus sign denotes the reactive-power generation, and the plus sign its consumption.

For non-sinusoidal voltage *u(t)* and current *i(t)* (in the first approximation, they are assumed to have a sign and stochastic values). After quantization of the voltages and currents at the intervals (Eqs. 15) and (16) are written as:

$$Q_\Pi = \frac{1}{2\omega_\Pi T}\sum_{k=1}^{n}\Delta z_k i_k^2 \qquad \text{(Eq. 17)}$$

$$Q_\Pi = \frac{1}{2\omega_\Pi T}\sum_{k=1}^{n}\Delta y_k u_k^2 \qquad \text{(Eq. 18)}$$

where Δz_k and Δy_k are increments of the resistance and conductivity in the "k" -th quantization point, respectively.

Using Eq.15 and 16 of the integrated method, the following features (necessary and sufficient) of the inactive power consumption are identified [23]:

- the instantaneous impedance (or the conductivity) of the electric circuit (the consumer) changes over time is observed when there is no direct proportionality between the instantaneous values of the voltage and current, i.e. $z(t)\neq \text{const}$, or $dz(t)/dt \neq 0$ (the necessary condition);
- the average value of the product of the rate of the

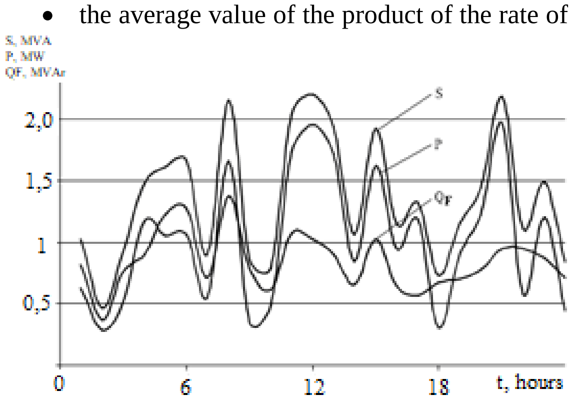


Figure 5. Time dependences of the power transmitted from traction substation B to the traction network of zone B-A

change of instantaneous impedance (or conductivity) $dz(t)/dt$ over time T per square of instantaneous current $i^2(t)$ (voltage) is not equal to zero (a sufficient condition).

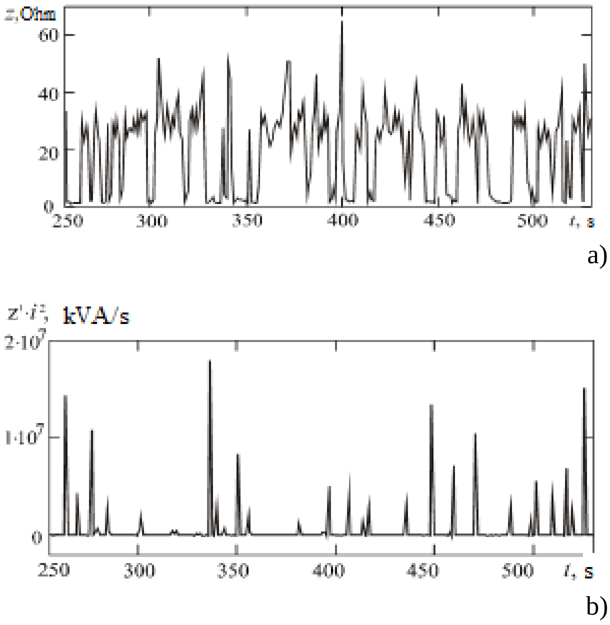


Figure 6. Oscillograms of instantaneous impedance change $z(t)$ in the power circuit of the tram (a) and the product of the rate of the change of instantaneous impedance $z'(t)$ per square of the instantaneous current (b)

For example, instant impedance $z(t)=u(t)/i(t)$ of the power circuit of a tram (Fig. 6, a) and an electric locomotive (Fig. 7, c) undergoes significant fluctuations over time, and the product of the instantaneous resistance derivative over time per square of the instantaneous traction-current $\left[\frac{dz(t)}{dt}i^2(t)\right]$ tram for the considered period of time (Fig. 6, b) is not equal to zero.

3.3 *Instantaneous power method*

The third feature, i.e. the electric power return from the load to the source, is determined by the nature of the change in the sign of instantaneous power *p(t)* which is a real physical quantity. It contains a complete information about the energy processes in electric circuits with an arbitrary form of voltage *u(t)* and current *i(t)*.

Electrical engineering specialists often discuss issues of the reactive power based on classical concepts of linear electric circuits of a sinusoidal current. From the physical perspective the reactive power in such circuits is the exchange of the electromagnetic energy between the source and the load, our case, between the traction substation (TP) and the electric rolling stock (EMF)). For these circuits, the exchange process (and, consequently, reactive power) is the presence of an instantaneous power $p(t)=u(t)\cdot i(t)$. If $p(t)$ changes its sign into a negative one, i.e. ($p(t)$ <0), an exchange process takes place and as a result of the presence of reactive elements in the circuit. At $p(t)$ > 0, there is no exchange processes and no reactive power.

However, in a nonlinear circuit, such as that of the electric transport an inactive power occurs when $p(t)>0$ and in the absence of stored electromagnetic energy [23]. This is due to the powerful nonlinear reactive elements DC power circuits: the inductance of the armature windings, main and additional poles of traction motors and inductive shunts, discrepancy of the instantaneous power sign and the presence of an inactive power in DC electric transport systems show that such an approach using an instantaneous power sign to evaluate the exchange process in nonlinear non-sinusoidal circuits, the current is incorrect [6]. Moreover, in such circuits, even the classical integral expression of the reactive power of a non-sinusoidal current circuit no longer describes a real energy processes occurring between the source and the consumer. In our case of a no-stationary operation mode and stochastic variation of $u(t)$ and $i(t)$, this formula does not apply. Obviously, the possible methods are those that enable finding an inactive power based on the instantaneous values of random voltage functions $u(t)$ and current $i(t)$. To obtain the expression of instantaneous power $q(t)$, it is therefore necessary to consider actual instantaneous reactive power $q(t)$ [16] by using the concepts of an instantaneous voltage, current and power.

A generalized equivalent electrical circuit of an arbitrary load (such as an electric transport system) is assumed in a form of a passive two-port element with input voltage $u(t)$. It is presented in a form of a parallel connection of the active element with conductivity *G*, current $i_a(t)$, of conductivity *B* and current $i_r(t)$. The input current is $i(t)=i_a(t)+i_r(t)$. The active element is the active power loss in the load, and the reactive is the consumption of the inactive power (power of storage and distortion). *B* consumes no energy, or it first consumes it and then returns it to the source.

The decomposition of input voltages $u(t)$ and current $i(t)$ of the above two-port element into orthogonal components using the Gram-Schmidt orthogonalization process [24] runs as follows if { $\vec{A}_1, \vec{A}_2, ..., \vec{A}_k, ..., \vec{A}_n$ }, then any finite or counting system of linearly independent vectors in Hilbert space (basis), is such an orthogonal system $\{\vec{B}_1, \vec{B}_2, ..., \vec{B}_k, ..., \vec{B}_n\}$ which generates the same linear multiplication $\left(\vec{B}_1 = \vec{A}_1\right)$. The $\{\vec{B}_1, \vec{B}_2, ..., \vec{B}_k, ..., \vec{B}_n\}$ system is obtained using the recurrent formulas:

$$\vec{B}_k = \vec{A}_k - \sum_{i=1}^{k-1} \frac{\left(\vec{A}_k \vec{B}_i\right)}{\left(\vec{B}_i \vec{B}_i\right)} \vec{B}_i, \left(k = 2,3,...,n\right) \quad \text{(Eq. 19)}$$

where $\left(\vec{A}_k \vec{B}_i\right)$ and $\left(\vec{B}_i \vec{B}_i\right)$ are scalar products of the corresponding vectors.

With $\vec{A}_1 \sim \vec{U}$, $\vec{A}_2 \sim \vec{I}$, and according to Eq. (19), its general form is

$$\vec{B}_2 = \vec{A}_2 - \frac{\left(\vec{A}_2 \vec{B}_1\right)}{\left(\vec{B}_1 \vec{B}_1\right)} \vec{B}_1$$

or specifically, orthogonal to the voltage $\vec{U}$ current $\vec{I}_{\text{p}}$ component in vector form will be equal to:

$$\vec{I}_{\text{p}} = \vec{I} - \frac{\left(\vec{I}\vec{U}\right)}{\left(\vec{U}\vec{U}\right)} \vec{U} \quad \text{(Eq. 20)}$$

In an integral form for an arbitrary time interval $\left[0..\tau\right]$ it is:

$$i_{\text{r}}\left(t\right) = i\left(t\right) - \frac{\frac{1}{\tau}\int_0^\tau i\left(t\right)u\left(t\right)dt}{\frac{1}{\tau}\int_0^\tau u^2\left(t\right)dt} u\left(t\right) \quad \text{(Eq. 21)}$$

The numerator of the second term in Eq. 21 is active power *P* which consumes the load (transport system), and the denominator is the square of the current value of the input voltage U^2. Eq. 21 now turns into:

$$i_{\text{r}}\left(t\right) = i\left(t\right) - \frac{P}{U^2} u\left(t\right) \quad \text{(Eq. 22)}$$

Multiplying terms of formula (22) by input voltage *u(t)* , the final expression of instantaneous reactive power $q\left(t\right)$ is:

$$q\left(t\right) = p\left(t\right) - \frac{P}{U^2} u^2\left(t\right) \quad \text{(Eq. 23)}$$

where $p\left(t\right) = u\left(t\right)i\left(t\right)$ is an instantaneous load power.

Using the given implementations of random voltage processes *u(t)* and current *i(t)*, the values of instantaneous impedance *Z(t)*, instantaneous active power $p\left(t\right)$ and instantaneous reactive power $q\left(t\right)$ are calculated by Eq. 23. Their time dependences for electric locomotive DE1 are given in Fig.7, and those of the feeder in section AB in Fig. 8.

Based on the sign of the instantaneous power ($p\left(t\right)$ > 0) and the mode of return of the electric power from the loading to the source shows that there are no exchange processes, and, consequently, no inactive power. However, such an exchange process should be affected since the power traction circuits have powerful nonlinear reactive elements, such as inductors of the armature windings, windings of the main and additional poles of the traction motors and inductive shunts. The detected discrepancy between the sign of the instantaneous power and the presence of exchange processes once again confirms that the classical researches should no longer be used for nonlinear circuits with non-sinusoidal currents and voltages. Therefore, to determine the exchange between the electromagnetic processes, it is necessary to consider instantaneous reactive power $q\left(t\right)$ (Fig. 8, c).

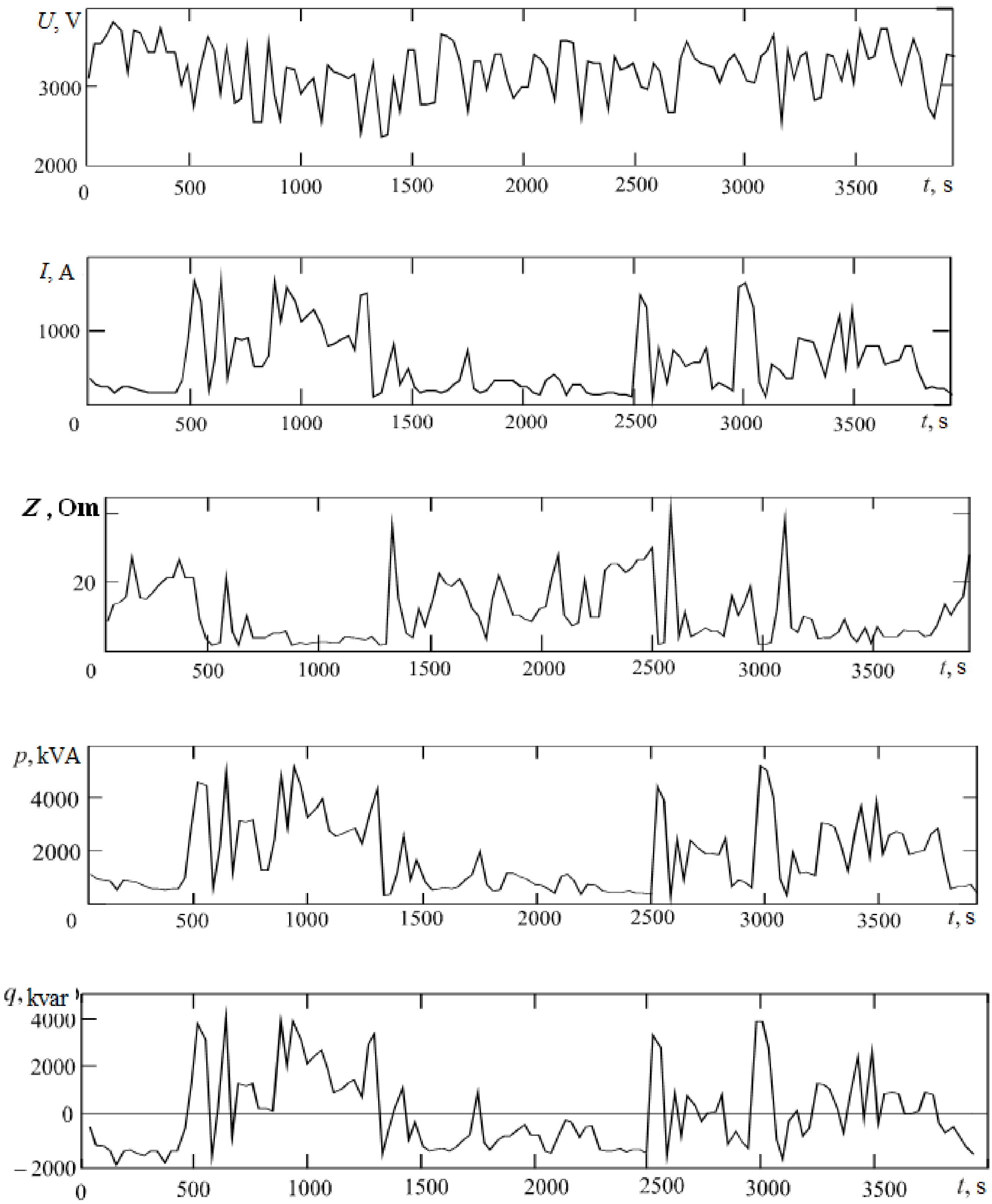
As power $q\left(t\right)$ characterizes the rate of change of the electromagnetic energy $q\left(t\right) = \frac{dW}{dt}$, and when during the time of electric power consumption it is not zero there are exchange energy processes (through the contact network) between the source and the power circuits of the electric locomotive in the electric DC transport system. The directionally variable nature of the change in magnitude $q\left(t\right)$, for example for electric locomotive DE1 (Fig. 7, e) and the TP feeder (Fig. 8, c), indicates that between the TP feeder and the electric locomotive on the one hand, and the electric locomotive (as a consumer) and the catenary (as a source) on the other hand, the exchange of the electromagnetic energy is possible. Exchange processes are absent only if $q\left(t\right) = 0$ during the time of the electric power consumption.

As a result, the power circuits of the DC electric transport systems can be loaded with a reactive current, resulting in additional losses of active power in the active elements of the traction circuit.

Calculations for a series of trips performed by DC electric locomotives and DC trams show that reactive power consumption in the percentage of the total one is from 53.8 to 62.5% for locomotive and from 61.8 to 85.4% for tram respectively. As a result, their power coefficient is less than 1 and is from 0.65 to 0.87 for locomotives and from 0.52 to 0.723 for trams respectively. The consumption of reactive power Q_F calculated according to (Eq. 21) defines nonproductive power losses ΔP in active resistance R of the engine expressed as:

$$\Delta P = \frac{Q_F^2}{U^2} R. \qquad \text{(Eq. 24)}$$

For the electric locomotives this is from 26.86 to 34.28% of the total losses for active resistance R from 5.7… 6.5% of the power consumed by a motor. For the trams this is 43% from 5.9 to 7.1%. So, the variable stochastic nature of change *U (t)* and *I(t)* leads to a reduced efficiency of the electric transport, i.e. electric locomotives of the order 0.737 when the value is 0.891.



a)

b)

c)

d)

e)

Figure 7. Character of variations during one trip of electric locomotive DE1 of: voltage (a), current (b), total instantaneous impedance (c), instantaneous power (d), instantaneous reactive power (e)

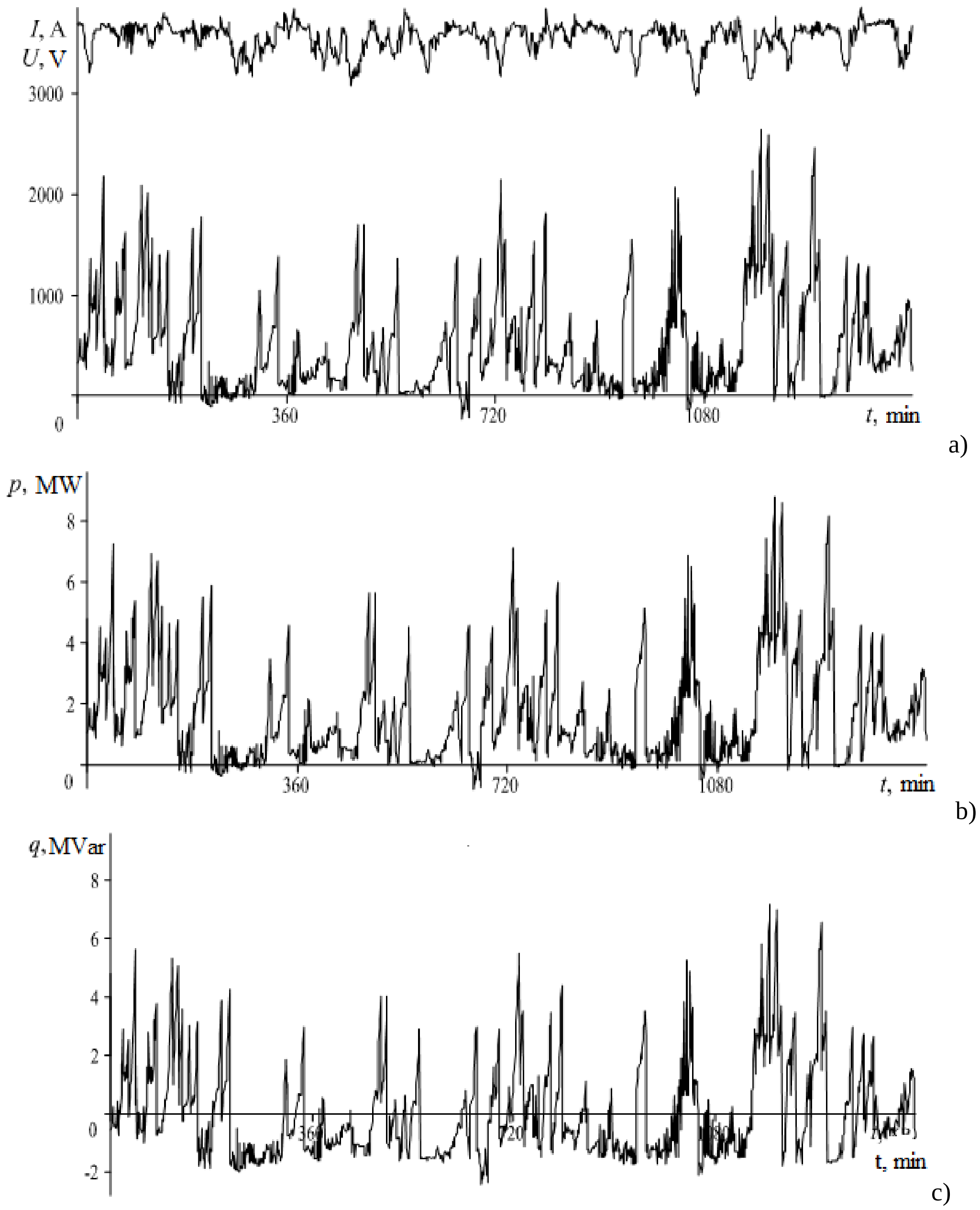


Figure 8. Time dependences per day in the feeder: voltage and current (a), instantaneous power (b), instantaneous reactive power (c)

4 Conclusions

Nonlinear parametric power-traction circuits of electric transport systems, named by the type of the supply voltage of DC circuits, are in fact nonlinear AC circuits caused by continuous changes in the traction current and voltage value.

The most common features of the inactive-power consumption are inequality of the active and total power, changes in the value of the instantaneous impedance (or conductivity) of the device, i.e. the sign of the instantaneous reactive power.

Power-traction electric circuits of the DC electric transport devices have the three features of the inactive power.

Stochastic voltages and currents electric transport systems are nonlinear non-stationary loads that consume a significant amount of the reactive power [18] which reduces the energy indicators of transport systems and is the reason for significant losses of the active electric power in traction circuits.

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