Losses of Recovered Electric Energy in the Elements of a DC Electric Transport System

Adam Szelag[1], Mykola Kostin[2], Anatolii Nikitenko[1]
[1]Electric Traction Division, Warsaw University of Technology, Pl. Politechniki, 1, Warsaw, 00-661, Poland
E-mail: adam.szelag@ee.pw.edu.pl , anatolij.nikitenko@ee.pw.edu.pl
[2]Department of Electrical Engineering and Electromechanics, Dnipropetrovsk National University of Railway Transport
named after Academician V. Lazaryan, Lazaryan Str., 2, room 238, Dnipro, 49-010, Ukraine
E-mail: nkostin@ukr.net

***Abstract* – The regenerative braking is one of the most attractive ways for energy saving in electric transport. It has many advantages and its effectiveness is discussed in numerous researches, but there are no significant publications, which describe the power losses in the way of recovered current flowing. The paper describes an alternative method for estimating recovered energy losses in the elements of a DC electric transport system. In comparison with existing methods, it is based on the correlation theory of stochastic processes and takes into account the Fryze's concept for reactive power. The method is verified by the experimental researches, which are performed for the VL8, VL11M, VL11M6 locomotives, EPL2T multiple-unit train and T4D tram, which operate in DC sections, Ukraine. The losses are calculated for different elements of an electric transport system, and their theoretical and statistical distributions with basic probabilistic characteristics are shown. The results prove the validity and applicability of the method.**

***Keywords* – power losses; regenerative braking; stochastic process; electric transport.**

I. INTRODUCTION

Possibility of electric rolling stock (ERS) operation in a regenerative braking mode (RBM) is treated as one of significant advantages that electrified transport systems [1, 2] have to offer. However, three important issues of its power effectiveness must be taken into account: the conditions of reliable and stable realization of the RBM, the amount of recovered electric energy and the state of its effective usage [3]. A significant role here plays the possibility of transmission, distribution and energy consumption with the lowest energy losses [4, 5], which are known as technical energy losses ΔW and consist of basic ΔW_0 and additional ΔW_{add} energy losses [6]. The basic losses ΔW_0 are caused by transmission of active power and they occur when the traction power system (TPS) operates in a sinusoidal, balanced and stable (in the nature of consumption) mode. Such losses are necessary for energy transmission and distribution, so they are inevitable. The additional losses ΔW_{add} are caused by reactive power flowing through a power network, that is they are associated with the low quality energy. Furthermore, there are no devices and methods for direct measurement of the basic ΔW_0, additional ΔW_{add} or total ΔW energy losses, especially in the regenerative braking modes.

Therefore, the main aim of the paper is to develop methods and numerical calculation of recovered energy losses in the elements of the electric transport system in case of energy transmission from the ERS, which operates in the RBM, to a traction substation (TS) and then into the AC grid.

II. RECOVERED ENERGY EVALUATION

In practise, the effectiveness of energy recovering is estimated as an energy saving, which is calculated using a difference between the active power meters (APM) of consumed energy in the traction mode and recovered energy to the overhead contact system (OCS) in the regenerative braking mode. Hence, the influence of recovered energy on its losses in the elements of the electric traction system has not been studied yet and the researches of such problem are absent, with the exception of papers [6-10], which cover the issue to some extent. It should be noted that in these papers energy losses are calculated only for the overhead contact system, while papers discussing pulsation of power in traction vehicles are available [11]. The results of investigation in [8-10] are obtained using simulation modelling. Only researches [6, 7] use real data, which were measured by the APM in traction substations or other way.

The voltages and currents are the stochastic processes (Fig. 1), especially in the RBM [12-14]. The DC locomotives and multiple-unit trains are equipped with the AMPs of electromagnetic or ferrodynamic types, while new vehicles are equipped with digital meters [15].

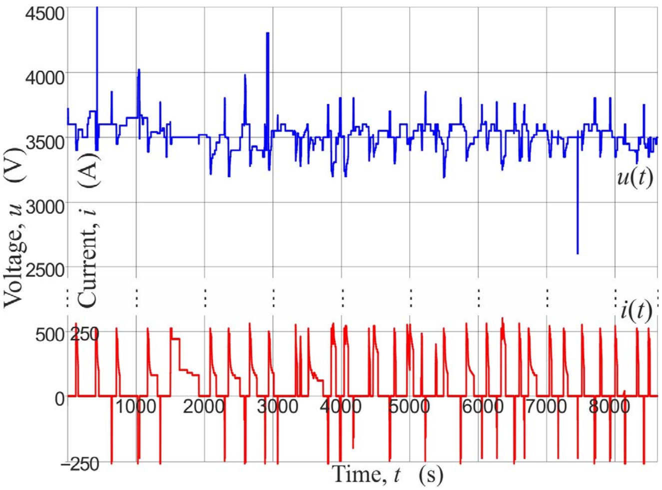

Fig. 1. Voltage $u(t)$ and current $i(t)$ recorded in a motor car of the EPL2T multiple-unit train in the traction and regenerative braking modes.

978-1-5090-1798-0/16/$31.00 ©2016 IEEE

For example, the EPL2T multiple-unit train has AMPs of SKVDT621 type. These AMPs provide accuracy of 2.5 and are intended for measuring DC values. In fact, the voltage and current are varying direct quantities [12]. The non-steady consumption of electric power creates an inaccuracy of measurements; therefore, the AMPs show inexact data in the process of electric transport system operation. Such inaccuracy may to be sorted to the category of dynamic errors. It rises, when the measured quantity is a function of time. As it is known, the dynamic error of measuring devices may to be standardized similarly to the static mode of operation and for concrete (deterministic) dependence $x = F(t)$ of a measured value. In such case the measured data should be divided into the parts and the dynamic mode of each part may to be described using a linear differential equation. Its solution identifies the inaccuracy. However, if the measuring device has non-linear sections, which dynamic modes are described with non-linear differential equations, the task will be complicated. The task has no practical solution, if the measured value corresponds to the stochastic process. In such case the investigation of dynamic errors must be performed using the methods of the theory of stochastic functions [12, 16-19].

The active power meters of DC electric rolling stock may to be calibrated in order to ensure the precise measurement. But all calibrations of the APM under operating conditions are done for the stationary mode of power consumption, that is with the fixed load, therefore they do not include the specificity of non-stationary energy consumption. This influences strongly on the wide disagreement between the really consumed and measured energies. Thereby, random character of the voltage and recovered current significantly increases the dynamic error of the APM. As a result, the mean error of the APM of D621 type increases to -17…+19% with standard deviation at the level of 58…62% [16]. Application of the smart digital meters allows to solve these problems [15].

The series of experimental researches with the EPL2T multiple-unit train and VL11M6 locomotive were conducted in the Prydniprovsk railway (Ukraine). Practical exploitation of the DC ERS showed that the measurement devices give understated (incorrect) results. Compare for the trip from Dnipropetrovsk to Piatykhatky, the APM of the EPL2T train measured 330 kWh in regenerative braking mode, when real recovered energy was equal to 424 kWh. In the trip from Piatykhatky to Dnipropetrovsk the AMP showed 260 kWh, when real energy was 345.4 kWh. The energy recovered by the VL11M6 locomotive was measured 1900 kWh, but real energy was equal to 2378 kWh in the section between Nyzhniodniprovsk-Vuzol and Piatykhatky stations.

The above shows the reason for developing a method used to estimate the recovered energy losses and calculate them, not only for the overhead contact system, but also for all elements of a traction power supply system.

We strongly believe that for energy losses evaluation the experiment-calculated method is the most effective and reasonable one. It uses the records of voltage across the current collector and current in the power circuit of the ERS, which are random functions and recorded in the real conditions.

III. METHODS FOR CALCULATION OF RECOVERED ENERGY LOSSES

According to [20] and researches [16, 19], the Fryze conception [21] is the most effective and appropriate one from the perspective of effective energy losses estimation.

Any element of the electric transport system may to be represented by a passive two-terminal circuit with the current $i(t)$ of an arbitrary shape, and consists of the parallel connection of resistive and reactive elements. The resistive element determines the consumption (loss) of the active power, which was recovered in the RBM. The reactive element characterizes the reactive and low quality powers. The branch with a resistive element has the active component $i_a(t)$ of the recovered current. Its shape coincides with the shape of the applied voltage $u_e(t)$. The reactive component $i_r(t)$ of the recovered current flows through the reactive element and is orthogonal with the applied voltage $u_e(t)$. Then, the instantaneous value of the current is calculated according to Kirchhoff's First Law

$$i(t) = i_{\mathrm{a}}(t) + i_{\mathrm{r}}(t). \tag{1}$$

The rms values of the above mentioned components can be squared and written as

$$I^2 = I_{\mathrm{a}}^2 + I_{\mathrm{r}}^2. \tag{2}$$

If multiply (2) to squared rms value of voltage U^2 applied to the elements as

$$U^2 \cdot I^2 = U^2 \cdot I_{\mathrm{a}}^2 + U^2 \cdot I_{\mathrm{r}}^2,$$

we get the expression for powers

$$S^2 = P^2 + Q_{\mathrm{F}}^2, \tag{3}$$

where S is a total power, P is an active power and Q_F is a reactive power, which is frequently called Fryze's reactive power. Then, according to (2), the technical losses of the recovered energy ΔW in an element of the system per the time of RBM τ_{rb} are defined as

$$\Delta W = R \cdot I^2 \cdot \tau_{\mathrm{rb}} = R \cdot I_{\mathrm{a}}^2 \cdot \tau_{\mathrm{rb}} + R \cdot I_{\mathrm{r}}^2 \cdot \tau_{\mathrm{rb}}, \tag{4}$$

where R is a resistance of an element of electric transport system.

Here, the energy $R \cdot I_a^2 \cdot \tau_{rb}$ is based on the active component of the recovered current and represents the basic losses of the recovered energy:

$$\Delta W_0 = R \cdot I_{\mathrm{a}}^2 \cdot \tau_{\mathrm{rb}} = R \cdot I_{\mathrm{a}}^2 \cdot \frac{U^2}{U^2} \cdot \tau_{\mathrm{rb}} = R \cdot \frac{P^2}{U^2} \cdot \tau_{\mathrm{rb}}. \qquad (5)$$

Energy $R{\cdot}I_{\mathrm{r}}^2{\cdot}\tau_{\mathrm{rb}}$ in (4) also represents the active energy losses, but it is based on a reactive component of recovered current, so it is the additional loss of recovered energy:

$$\Delta W_{\mathrm{add}} = R \cdot I_{\mathrm{r}}^2 \cdot \tau_{\mathrm{rb}} = R \cdot I_{\mathrm{r}}^2 \cdot \frac{U^2}{U^2} \cdot \tau_{\mathrm{rb}} = R \cdot \frac{Q_F^2}{U^2} \cdot \tau_{\mathrm{rb}}. \qquad (6)$$

Expressions (4)-(6) allow to calculate the recovered energy losses using the duration τ_{rb} of RBM, the rms values of the currents I, I_{a}, I_{r}, or the active P and reactive Q_{F} components of the total power S. These values can be calculated in different manners, which depend on the type (behaviours) of stochastic processes of the voltage $u(t)$ and current $i(t)$ in the RBM. There are stationary or non-stationary, ergodic or non-ergodic processes. They are defined below.

According to the references [17, 18], if some stochastic process is a stationary ergodic process, then its probabilistic characteristic may to be received using only one characteristic of such process.

Let us assume that $u(t)$ and $i(t)$ are stationary ergodic processes, which are recorded synchronously for a certain period of time τ_{rb} (for example, for a phase of regenerative braking) and their curves have arbitrary shapes (Fig. 2). If discretized with the interval of time Δt using Kotelnikov's Theorem [12], then the values of currents and powers can be calculated for the period of time τ_{rb} according to "discrete electrical engineering" [22] using expressions for:

- *the active power P*:

$$P = \frac{1}{N}\sum_{k=1}^{N} u_k \cdot i_k = \frac{1}{N}\sum_{k=1}^{N} p_k, \qquad (7)$$

where p_k is an instantaneous value of active power of the k-th point of the voltage and current curves (Fig. 2);

- *the rms values of the voltage U and current I* for the period of time (phase of regenerative braking):

$$U = \sqrt{\frac{1}{N}\sum_{k=1}^{N} u_k^2}, \quad I = \sqrt{\frac{1}{N}\sum_{k=1}^{N} i_k^2}; \qquad (8)$$

- *the total power S*:

$$S = U \cdot I; \qquad (9)$$

- *the reactive power Q_{F} by Fryze*:

$$Q_{\mathrm{F}} = \sqrt{S^2 - P^2}; \qquad (10)$$

- *the components of rms value of current*:

$$I_{\mathrm{a}} = \frac{P}{U} = \sqrt{\frac{P}{R}}, \qquad (11)$$

$$I_{\mathrm{r}} = \frac{Q_{\mathrm{F}}}{U} = \sqrt{\frac{Q_{\mathrm{F}}}{R}}. \qquad (12)$$

In this case, if the voltage and current in the phase of regenerative braking are non-ergodic processes, the task may to be solved using "n" numbers of the voltage $u(t)$ and current $i(t)$ records (Fig. 3).

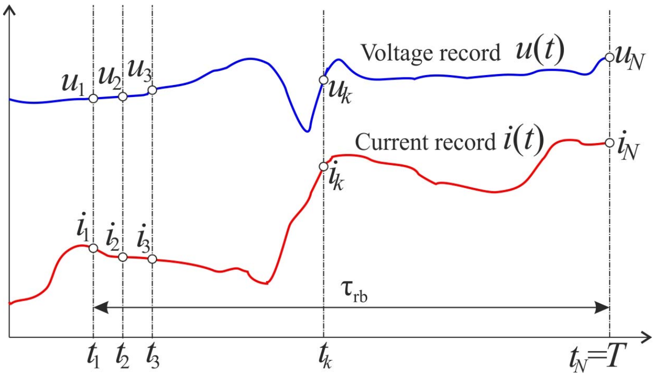

Fig. 2. Time dependences of stationary ergodic processes of the voltage $u(t)$ and current $i(t)$ for the period of regenerative braking τ_{rb}.

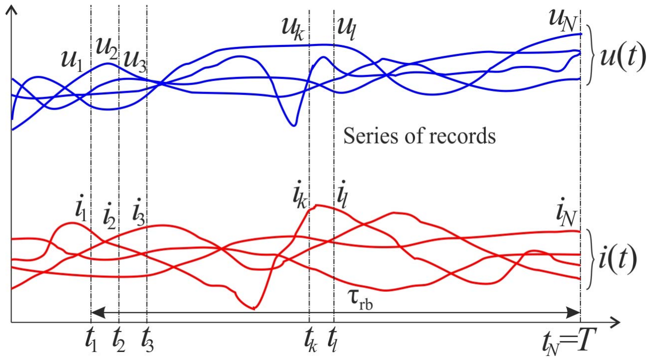

Fig. 3. Series of the voltage $u(t)$ and current $i(t)$ records for the period of regenerative braking τ_{rb}.

Then, the unknown values in (4)-(6) have to be found using the correlation-dispersion method according [23]. For this, all "n" records of $u(t)$ and $i(t)$ may to be discretized with the step $\Delta t = \tau$ using Kotelnikov's Theorem, and then it is important to write the auto- and cross-correlation functions for the nonstationary stochastic processes of the voltage $u(t)$ and current $i(t)$ [17, 18]. Subsequently, the correlation function is written as

$$K_U(t_k, t_l) = \frac{\sum_{i=1}^{n} u_i(t_k) \cdot u(t_l)}{n-1} - m_U(t_k) \cdot m_U(t_l) =$$

$$= \frac{\sum_{i=1}^{n} u_i(t_k) \cdot u(t_l)}{n-1} - m_U(t_k) \cdot m_U(t_k + \tau), \qquad (13)$$

where m_U is a mathematical expectation at the moments t_k and t_l. If $t_k = t_l$, that is $\tau = 0$, then the correlation function can be written as

$$K_U(t_k, \tau = 0) = U^2(t_k) - m_U^2(t_k), \qquad (14)$$

where $U(t_k)$ is an rms value of voltage at the moment t_k; this allows to write voltage as

$$U(t_k) = \sqrt{K_U(t_k, \tau = 0) + m_U^2(t_k)}. \qquad (15)$$

Analogically, the expression of nonstationary stochastic process of the current $i(t)$ may to be written as

$$I(t_k) = \sqrt{K_I(t_k, \tau = 0) + m_I^2(t_k)}, \qquad (16)$$

where $K_I(t_k, \tau=0)$ is a correlation function of the current $i(t)$.

Then, the total power at the moment t_k is calculated as:

$$S(t_k) = U(t_k) \cdot I(t_k) =$$

$$= \sqrt{\left[K_U(t_k, \tau = 0) + m_U^2(t_k)\right] \cdot \left[K_I(t_k, \tau = 0) + m_I^2(t_k)\right]}. \qquad (17)$$

Above mentioned expressions allow creating the characteristics of $K_U(t)$, $m_U(t)$, $K_I(t)$, $m_I(t)$ using the values of K_U, m_U, K_I, m_I. These characteristics can be approximated, and then (15) and (16) can be rewritten as the functional dependencies as

$$U(t) = \sqrt{K_U(t) + m_U^2(t)}, \qquad (18)$$

$$I(t) = \sqrt{K_I(t) + m_I^2(t)}. \qquad (19)$$

Then the functional dependence of the total power have to be written for the time interval $[0\ldots T]$ as

$$S(t) = U(t) \cdot I(t) =$$

$$= \sqrt{K_U(t) + m_U^2(t)} \cdot \sqrt{K_I(t) + m_I^2(t)}. \qquad (20)$$

The cross-correlation function of the stochastic processes of $U(t)$ and $I(t)$ may to be evaluated as [17, 18]

$$K_{UI}(t_k, t_l) = \frac{\sum_{i=1}^{n} \left[U_i(t_k) - m_U(t_k)\right] \cdot \left[I_i(t_l) - m_I(t_l)\right]}{n} =$$

$$= \frac{\sum_{i=1}^{n} U_i(t_k) \cdot I_i(t_l) - U_i(t_k) \cdot m_I(t_l) -}{n} \ldots$$

$$\ldots \frac{-I_i(t_l) \cdot m_U(t_k) + m_U(t_k) \cdot m_I(t_l)}{n}, \qquad (21)$$

and after some transformation it can be rewritten as

$$K_{UI}(t_k, \tau = 0) = P(t_k) - m_U(t_k) \cdot m_I(t_k). \qquad (22)$$

This expression allows to calculate the active power for the time $t = t_k$ as

$$P(t_k) = K_{UI}(t_k, \tau = 0) + m_U(t_k) \cdot m_I(t_k). \qquad (23)$$

Using (23), one can obtain the values of $P(t_1)$, …, $P(t_k)$; $K_{UI}(t_1)$, …, $K_{UI}(t_k)$; $m_U(t_1)$, …, $m_U(t_k)$ and $m_I(t_1)$, …, $m_I(t_k)$. The approximation of these values within the range $[0\ldots T]$ allows it to simplify and rewrite (23) as

$$P(t) = K_{UI}(t) + m_U(t) \cdot m_I(t). \qquad (24)$$

Finally, one can write the functional dependence of Fryze's reactive power using the expressions for the total energy (20) and active energy (24) as:

$$Q_{\mathrm{F}}(t) = \sqrt{\begin{array}{l}\left[K_U(t) + m_U^2(t)\right] \cdot \left[K_I(t) + m_I^2(t)\right] - \\ -\left[K_{UI}(t) + m_U(t) \cdot m_I(t)\right]^2\end{array}}. \qquad (25)$$

IV. EXPERIMENTAL RESEARCHES

The method is verified by the numerous experimental researches, which use the different types of ERS with DC motors such as the VL8, VL11M, VL11M6 locomotives, EPL2T multiple-unit train and T4D tram. The voltage across the current collector and the current in the power circuit of the ERS are recorded by an on-board control system or using a laboratory car. All ERSs operate in the DC supplied sections of Prydniprovsk and Lviv railways of Ukraine and have real conditions and weights. The examples of voltage and current records are shown in Fig. 4 for the VL11M6 freight locomotive.

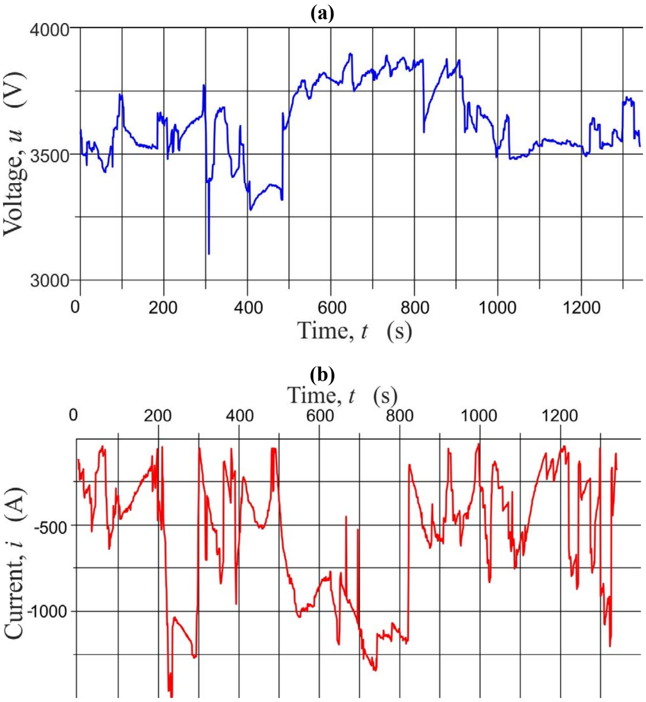

Fig. 4. Voltage (a) and current (b) records of the VL11M6 locomotive in the regenerative braking mode only.

V. NUMERICAL EVALUATION AND ANALYSIS OF RECOVERED ENERGY LOSSES

Now, let us define the losses of recovered energy using the expressions and methodology mentioned above. The calculations are performed only for the RBM and use the voltage *u*(*t*) and current *i*(*t*) records.

A. Total Losses of Energy Recovered by the EPL2T Multiple-Unit Train

Find the recovered energy losses in case of the EPL2T train operates in the section between substations A and B. The main parameters of train are shown in Table I.

TABLE I
PARAMETERS OF THE EPL2T MULTIPLE-UNIT TRAIN

Quantity	Value
Maximal speed	130 km/h
Number of cars	8
Empty weight	460 t
Power	0.96 MW
Average traction acceleration	0.7 m/s^2
Average braking acceleration	-0.8 m/s^2

Let us describe the path of recovered current using Fig. 5. The distance between the substations is 15.2 km. The inverter is installed in the substation B. In such case, the recovered current flows through the power and return feeder lines (FL), thyristor of the inverter (TI), smoothing reactors (SR), step-up transformers (ST), booster transformer (BT), three-phase power transmission lines (PTL) to AC grid. The following is description of their characteristics.

The type of catenary is M-120+2MF-100+A-185 and it has electrical resistivity of R_{0ct} = 0.0578 Ohm/km. The total length of the power and return feeders is l_{FL} = 1 km. They consist of four wires. The type of wires is A-185 and has electrical resistivity of R_{0FL} = 0.042 Ohm/km. The inverter is VIPE-2UZ type with parameters: the maximal voltage is 4000 V, the nominal current is 1600 A and the efficiency is 98%. The power losses of inverter equal $\Delta P_{ST} = 0.02 \cdot P_{RB}$, where P_{RB} is the power of regenerative braking. The smoothing reactors are made from the winding wire of A-240 type with resistivity of 0.12 Ohm/km, hence the resistance of reactors equals R_{SR} = 0.336 Ohm. The type of the reactors is RBFA-U-65001. The smoothing reactors are connected to two step-up transformers of UTMRU-6200/10 type. The total nominal power of each of them equals S_{ST} = 3700 kVA. The type of a booster transformer is VTMR-3200/10 and its total nominal power is S_{BT} = 2400 kVA. The transformers' parameters are the current of 3000 A, power factor λ=0.9, efficiency of 98%. The nominal power losses equal 54.4 kW for ST and 28.8 kW for BT in case, when current is 3000 A. Therefore, they have to be calculated for a certain current in the RBM.

Traction substation B is supplied from the district substation by two triple-core cables of ASB-3-240 type and nominal voltage 10 kV. The lengths of the cables are 735 m and 727.3 m. The resistivity of a core equals 0.129 Ohm/km.

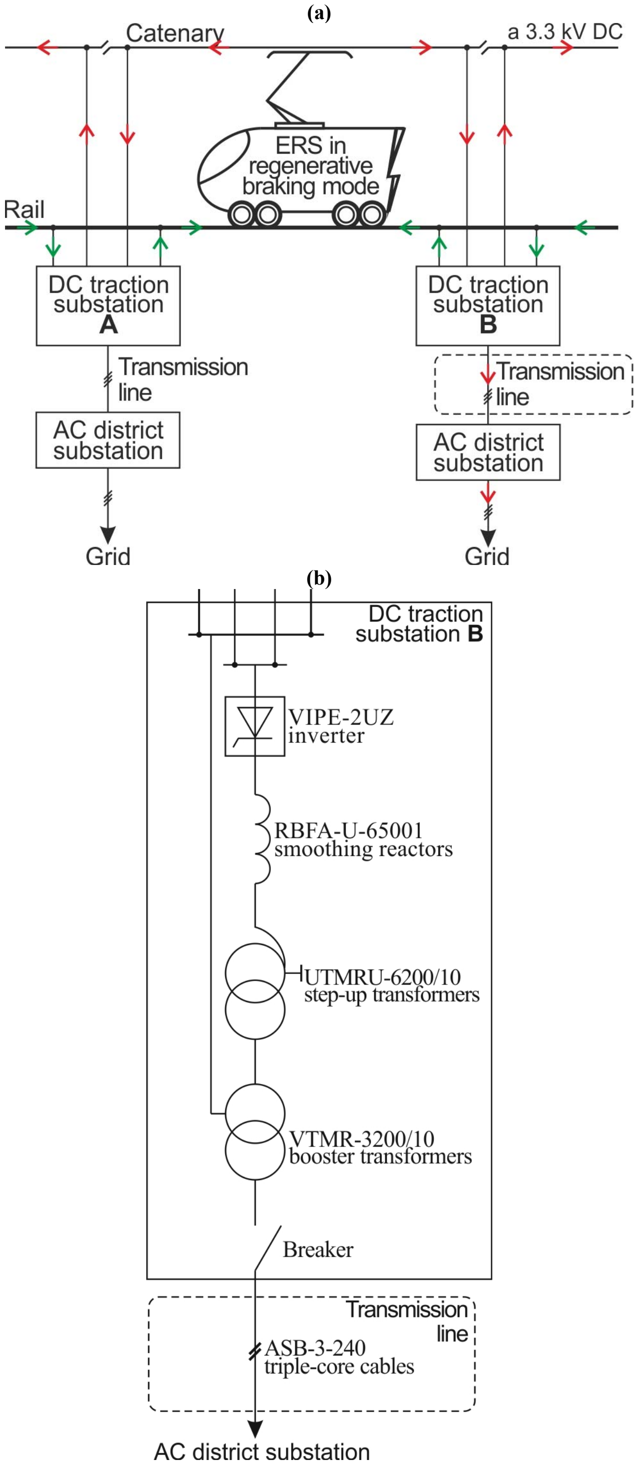

Fig. 5. The way of recovered current flowing (a) and the scheme of traction substation B (b).

The results of calculation are presented for all experiments in Table II. It shows that total losses of recovered energy by the EPL2T train in the section between substations A and B are at the level of 13.31%, including the losses in the overhead contact system and feeders of 6.32%, in the traction substation of 6.57% and power transmission lines of 0.41%.

TABLE II
TOTAL LOSSES OF RECOVERED ENERGY

Section	Recovered energy, kWh	Losses of recovered energy, kWh					
		OCS	FL	Traction substation			PTL
				TI	SR	ST+BT	
A – B	60.96	3.52	0.336	1.216	1.348	1.44	0.252
F – G	878.0	89.5	13.55	17.56	1.45	21.0	4.27
M –N	998.4	184.2	12.7	19.97	2.63	24.6	0.29

B. *Total Losses of Energy Recovered by the VL8 Locomotive*

Calculate the losses of recovered energy for a train with 236 axles, total weight Q = 4500 t and driven by the VL8 locomotive. The main parameters of locomotive are shown in Table III. The experiment was done in the F – G section , where the traction substation F has inverter. Its scheme is similar with the substation B, but in this case it is supplied from district substation through the three-phase transmission line, which has the following parameters: U = 35 kV, wire of 3xAS150 type with resistivity of 0.21 Ohm/km. The scheme of substation G is a similar to substation B. The results of calculation are shown in Table II. The losses of recovered energy in the overhead contact system are 10.2%, the losses in the OCS including FL are 11.74%, the total losses for the whole path of recovered current flow are 16.78%.

TABLE III
PARAMETERS OF THE VL8 AND VL11M FREIGHT LOCOMOTIVES

Quantity	VL8	VL11M
Maximal speed	100 km/h	100 km/h
Number of sections	2	2
Weight	180 t	184 t
Power	4.2 MW	5.2 MW

C. *Total Losses of Energy Recovered by the VL11M Locomotive*

The losses are calculated for a train with 57 cars, total weight of 4900 t and two VL11M locomotives operating in the M – N section. The first locomotive operates in the head of the train and the second operates at the end. The main parameters of locomotive are shown in Table III. Both substations M and N have inverters and their schemes similar with the substation B, but with the exception of some details. The distance between them is 11 km. The type of catenary is the same as in previous experiments. The total length of the power and return feeder lines is 1 km. The type of inverters is I-PTP-M-2,0k-3,8k-50-12-UZ and consist of T553-800-42-6N2-UH8 thyristors. The substation has ROSV-2000 and RBFA-U-6300/3000 reactors, UTMRU-6300/35 step-up transformers, UTMR-3500/35zh booster transformers. The nominal total power of step-up transformer is 3700 kVA and total losses are 54.44 kW for the case of nominal load. The booster transformer has the total nominal power of 100 kVA and the total losses of 28.8 kW. The traction substation N is supplied from district substation through the 35 kV three-phase transmission line, which consists of three different sections. The first section has the length of 50 m and the wire of M-7 type with resistivity equal to 0.267 Ohm/km. The parameters of the second section are the following: length of 50 m, wire of M-120 type, resistivity of 0.154 Ohm/km. The third section has the length of 100 m, wire of A-240 type, resistivity of 0.12 Ohm/km. The resistance of one line equals 0.0331 Ohm.

The results of calculation are shown in Table II. The losses of recovered energy are 18.46% in the overhead contact system only; 19.67% in the overhead contact system including power and return feeder lines; and total losses 24.43%

D. *Other Results*

The example of theoretical and statistical distributions of the losses in the overhead contact system are shown with some probabilistic coefficients in Fig. 6-8 for the VL11M6 locomotive. The numerous experiments show that relation of the total losses to the total recovered energy is changing within limits of 2…43.1% for the VL8 locomotive, 1.6…38% for the VL11M6 locomotive, 2…17% for the EPL2T multiple-unit train and 2.6…32.9% for the T4D tram. Where the basic energy losses ΔW_0 play a dominating role. But the additional energy losses have enough influence and are equal to 33%, 49%, 20% and 18.5% of the total energy losses for different types of the ERS respectively.

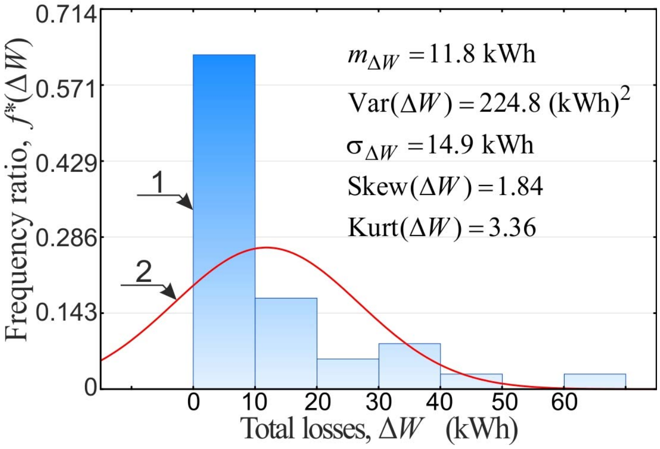

Fig. 6. Statistical (1) and theoretical (2) distributions of the total losses ΔW of energy recovered by the VL11M6 locomotive.

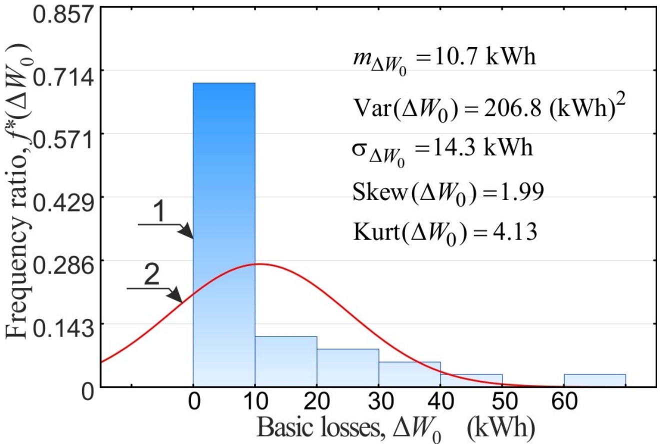

Fig. 7. Statistical (1) and theoretical (2) distributions of the basic losses ΔW_0 of energy recovered by the VL11M6 locomotive.

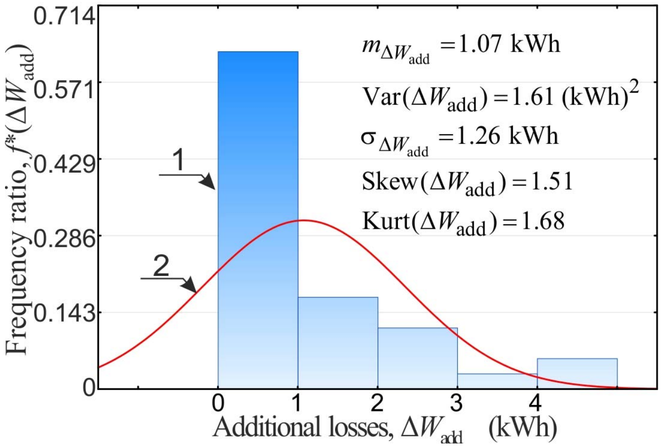

Fig. 8. Statistical (1) and theoretical (2) distributions of the additional losses ΔW_{add} of energy recovered by the VL11M6 locomotive.

VI. CONCLUSIONS

Currently, there are no methods or devices for direct measurement of recovered energy losses, and this factor leads to the necessity of developing the experimental-calculation methods [6, 7]. Application of modern metering systems as [15] in vehicles and traction substations of modernized lines [24] could create opportunity of obtaining detailed information on effectiveness of energy recuperation. Till implementation of such systems, the presented method of analysis may be used with the real records of random voltage and current, which are recorded in the process of real operation of the ERS, taking into account their stochastic character. The method of a "discrete electrical engineering" has to be used for ergodic processes of voltage and current and the correlation-dispersion method may be used in case of non-ergodic processes. The last one is based on the application of auto- and cross-correlation functions [13]. This method allows to estimate the effectiveness regenerative braking and energy loss in the electric transport system with high precision. Moreover, the estimation of power losses is frequently necessary for optimal design of new sections of power supply system.

The results of calculation show, that the total losses are varying within the limits from 1.5 to 43.1% of recovered energy in the elements of the electric traction system and from 6.3 to 20% in the overhead contact system. The basic losses significantly influence on the total losses and vary within the limits from 51 to 97%.

REFERENCES

[1] A. Szeląg and L. Mierzejewski, "Ground transportation systems," in *The Encyclopedia of Electrical and Electronic Engineering. Supplement I*, NY, USA: John Wiley & Sons Inc., 1999, pp.169-194.

[2] JeeHo Lee *et al.*, "A study for improvement performance of electric brake for electric train," in *International Conference on Control, Automation and Systems*, Seoul, Korea, 2008, pp. 1345-1348.

[3] Xubin Sun *et al.*, "Regenerative braking energy utilization by multi train cooperation," in *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, Qingdao, PR China, 2014, pp. 139-144.

[4] D. Gonzalez and F. Manzanedo, "Optimal design of a D.C. railway power supply system," in *Electric Power Conference EPEC-2008. IEEE Canada*, Vancouver, Canada, 2008, pp. 1-6.

[5] S. Sagareli and V. Gelman, "Implementation of new technologies in traction power systems," in *Proceedings of the 2004 ASME/IEEE Joint Rail Conference*, Baltimore, USA, 2004, pp. 141-146.

[6] A. Nikitenko, "Technical losses of the recovered electric energy in a DC traction power supply system," in *Computational Problems of Electrical Engineering*, Lviv, Ukraine, 2013, vol. 3, No 2, pp. 71-76.

[7] Taichi Hirano *et al.*, "Evaluation of energy loss in d.c. traction power supply system," in *17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, Geneva, Switzerland, 2015, pp. 1-6.

[8] Falvo *et al.*, "Energy storage application in trolley-buses lines for a sustainable urban mobility," in *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS*), Bologna, 2012, pp. 1-6.

[9] V. Cheremisin *et al.*, "The influence of regenerative braking on the traction power supply system," in *Locomotive*, Ukraine, 2013, vol. 18, pp. 5-8.

[10] M. Steiner and J. Scholten, "Energy storage system with ultracaps on board of railway vechicles," in *European Conference on Power Electronics and Applications,* Aalborg, Denmark, 2007, pp. 1-10.

[11] A. Szeląg and G. Skarpetowski, "Power pulsation in converter traction drives," in *TTS Technika Transportu Szynowego*, Poland, ISSN 1232-3829, 2015, 10, pp. 184-189.

[12] M. Kostin and A. Nikitenko, "Statistics and probability analysis of voltage on the pantograph of DC electric locomotive in the recuperation mode," in *Przegląd Elektrotechniczny*, Warsaw, Poland, 2013, No 2a, pp. 273-275.

[13] A. Nikitenko, "Methods of spectral analysis of traction voltage and currents as random functions," in *16th International Conference on Computational Problems of Electrical Engineering CPEE-2015*, Lviv, Ukraine, 2015, pp. 135-138.

[14] A. Szeląg and K. Buchta, "Application of statistic and probabilistic methods for assessment of quality of 3kV DC network energy delivery to traction vehicles," *in Modern Electric Traction. Volume 2. Power supply*, Gdansk, Poland, ISBN 83-911669-7-X, 2009, pp. 33-46.

[15] Elester-PKP. (2015). *DC energy metering system: i-LE 3000 smart energy meter; Falko zone-based analysis system for traction energy consumption* [Online]. Available: http://www.elester-pkp.com.pl/dc_energy_metering_system_.php

[16] O. Sablin, "Improvement of the consuming efficiency of DC electric rolling stock," Ph.D. dissertation, Dept. Elect. Transp., Dnipropetrovsk National University of Railway Transport, Dnipropetrovsk, Ukraine, 2009.

[17] A. Sveshnikov, *Applied Methods of the Theory of Random Functions.* 1st English ed. Oxford: Pergamon Press Ltd., 1966.

[18] Lonnie C. Ludeman, *Random Processes:Filtering, Estimation, and Detection*. New York: Wiley-IEEE Press, 2003.

[19] A. Petrov, "Ineffective losses of electric energy in DC traction power supply system," Ph.D. dissertation, Dept. Elect. Eng., Dnipropetrovsk National University of Railway Transport, Dnipropetrovsk, Ukraine, 2011.

[20] V. Tonkal *et al.*, *Energy Balance in the Electric Circuits.* Kyiv, Ukraine: Naukova Dumka, 1992.

[21] S. Fryze, "Active, reactive and apparent power in electrical circuits with non-sinusoidal current and voltage," in *Przegląd Elektrotechniczny*, Poland, 1932, No 7, pp. 193-203; No 8, pp. 225-234; No 22, pp. 673-676.

[22] M. Kostin, "The methods for powers determination in the systems with stochastic electric processes," in *Technical Electrodynamics*, Kyiv, Ukraine, 2006, vol. 6, pp. 6-8.

[23] A. Nikitenko and M. Kostin, "The method of the correlation and dispersion defining of the total power components in the electric transport devices," in *Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport*, Dnipropetrovsk, Ukraine, 2013, vol. 1(44), pp. 64-75.

[24] A. Szeląg and T. Maciołek, "A 3 kV DC electric traction system modernisation for increased speed and trains power demand – problems of analysis and synthesis," in *Przegląd Elektrotechniczny*, Warsaw, Poland, 2013, No 3a, pp. 21-28.