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TECHNICAL LOSSES OF THE RECUPERATED ELECTRIC ENERGY IN A DC TRACTION POWER SUPPLY SYSTEM

Anatoliy Nikitenko

Ac. V. Lazarian Dnipropetrovsk National University of Railway Transport, Ukraine

nikitenko.diit@gmail.com

Abstract: The efficiency of the recuperative braking of DC electric rolling stock is analyzed in the article. The monitoring of voltages and currents is done for EPL2T trains and VL8 locomotives in the traction and recuperative braking modes. Basic, additional and total technical losses of the recuperated energy are calculated for a DC traction power system. The statistical and theoretical distributions of the RMS current, the additional and total losses are drawn, and their basic probabilistic coefficients are calculated.

Key words: recuperation, electrical energy, traction power system, losses, stochastic process, current.

1. Introduction

According to the current State Standard 19350-74 [1], a recuperative braking mode (RBM) is the mode of electric braking in which the electrical energy produced by traction motors is fed back into the traction power supply system. The part of this energy should be consumed by the electric rolling stock (ERS) which moves in the traction mode on the same feeding section. The other part of it flows through the feeder busbars of the traction substation (TS) and spreads through the neighboring feeding sections to the other ERS which moves in the traction mode (if it is available). Finally, the third part of the energy (the excess energy) comes to the TS's inverter or absorbing ballast resistors (if they are available). Thus, in the first case, the energy must be transferred to an external power grid, but in the second case, the energy is needlessly dissipated as heat in the resistors. It is quite clear that in all the cases, the recuperated energy is transported along the traction power system, and therefore there are losses in the network. A theoretical and numerical analysis of these losses is certainly important. The recuperative braking process has been used since the foundation of electric traction, but technical and economic efficiency of this braking is not fully proven, and it follows from [2].

If the total savings due to the recuperative braking equals 100%, then the energy savings are equal to 53%, and the rest 47% are the savings of the brake blocks in the compressed-air brake system. Furthermore, there exist additional operating losses, which are totally equal to 48%, on a track structure, locomotive repairs and sand supply. It is seen that saving of the brake blocks (47%) covers the additional operating losses, but the economic impact can be achieve only through the recuperated energy. The electric efficiency of the regenerative braking is evaluated with electric energy meters. The difference between the consumed and recuperated energies by the ERS and TS is used for this calculation. That is, the influence of the recuperated energy on its power losses in the elements of the traction power system has not been studied yet, and lack of scientific publications on this problem is an evidence of this. Work [3] in which the results of the simulations of the VL10 freight locomotives are presented for different modes of its operation is to some extent, an exception. All these simulations were done for the double-track section Taiga-Mariinsk of the West Siberian Railway (Russian Federation). The calculations show as follows:

1) in accordance with the electric energy meters of TS, the energy losses in the traction power system equal 6,59 % of the total losses (when the locomotive does not use the RBM);

2) for the journeys with RBM, the energy losses are equal to 7,42 %;

3) for the journeys with RBM and the availability of the invertors on the TS, the energy losses are equal to 7,40 %.

Thus, the purpose of this work is to develop the methods for numerical estimation of basic and additional (technical) losses of the recuperated energy which flows through the traction power system from ERS to TS (or the ERS which is moving in the traction mode).

2. Theoretical backgrounds for the power losses calculation

Fig. 1 shows the voltage $U(t)$ and current $I(t)$ records of an EPL2T train (a) and the VL10 freight locomotive (b) in the traction and recuperative braking modes. The EPL2T has the total weight 566,5 tones and 32 axes. The VL8 has the total weight 4500 tones and 236 axes. All the data were recorded in the process of operation at (in) Prydniprovsk Railway. It is seen that in all the modes, the current and voltage are random quantities.

Non-stationary nature of the $U(t)$ and $I(t)$ (or $u(t)$ and $i(t)$) is the cause of losses of the active energy in a traction power network. The losses which appear in the process of the energy transmission and distribution are called technical losses ΔW. They consist of basic losses ΔW_0 and additional losses ΔW_{add}.

The basic losses ΔW_0 are based on the active power transmission and occur when the traction power system operates in sinusoidal, balanced and stable (in the nature of consumption) mode. In fact, these losses are necessary for electricity transmission and therefore they are inevitable.

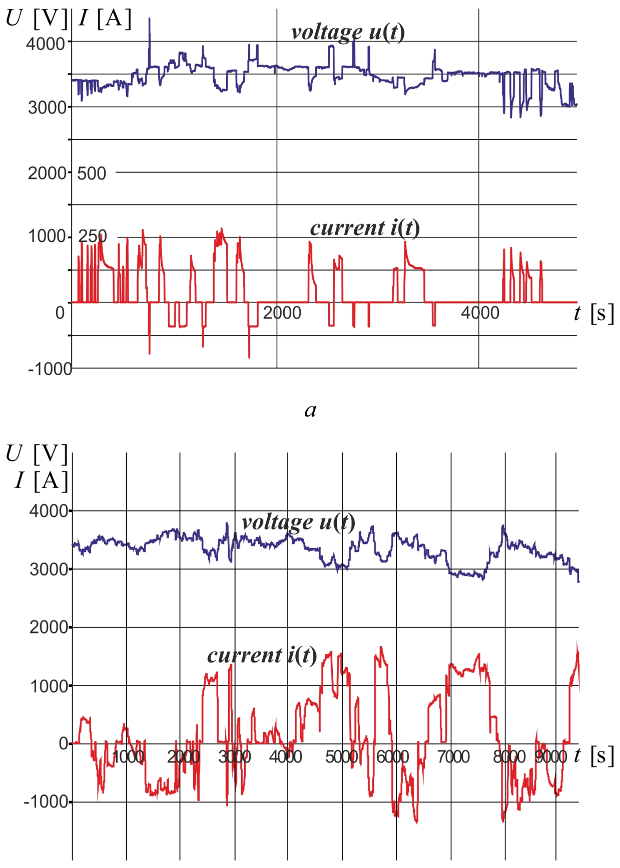

Fig. 1. Voltage U(t) and current I(t) records of the EPL2T train (a) and the freight VL8 locomotive (b) in the traction and the recuperative braking modes.

The additional losses are caused by the reactive power flowing through the power network, that is they are associated with the low quality energy. The problem of estimation and minimization of these losses (as part of the total losses) is an important task for improving the efficiency of the traction power supply system. It is known that there are no devices and methods for the direct or indirect measurement of the basic or total losses (especially in the regenerative mode). Therefore, this paper studies the method for the losses determination, using the time functions of the train voltages and currents which are recorded in the traction and recuperative braking modes.

The additional losses in the power circuit of ERS and the traction power system are studied in works [4, 5] for the traction mode but the analysis of the recuperative braking mode is absent. Therefore, the theoretical aspects of the basic ΔW_0 and additional ΔW_{add} energy losses are considered for this mode in the paper.

In accordance with work [6] and research done in [4, 5], the conception of S. Fryze is the most reasonable and proper. Their decision is based on position of the calculation of the energy losses in the steady state and transient modes of the traction power system.

In accordance with this conception and the theory of electrical engineering, ERS is a passive two-terminal circuit with a current $i(t)$ of any shape. We can represent the circuit by a parallel connection of the resistive element, which characterises the active energy consuming, and the inductive element, which characterises the consumption of the reactive energy. These branches divide the input current $i(t)$ into two componets. One of them is an active componet $i_a(t)$ of the current and flows through the resistor. This current $i_a(t)$ and the input voltage $u_e(t)$ have the same shape. But the other part of the current $i(t)$ is the reactive component $i_r(t)$. It flows through an inductor and has the orthogonal shape in comparison with the input voltage $u_e(t)$. In accordance with Kirchhoff's Current Low, the instantaneous value of the input current $i(t)$ is equal to

$$i(t) = i_a(t) + i_r(t)\,. \tag{1}$$

The squared RMS values of the active and reactive currents give the RMS value of the total current:

$$I^2 = I_a^2 + I_r^2\,. \tag{2}$$

Multiple the both sides of equation (2) by the squared RMS voltage U^2:

$$U^2 \cdot I^2 = U^2 \cdot I_a^2 + U^2 \cdot I_r^2\,,$$

$$S^2 = P^2 + Q_F^2\,, \tag{3}$$

where S is the total power, Q is the reactive power by Fryze. Its average value per period eqals zero. Phisically this power is the energy which oscillates between the source (TS) and consumer (ERS) or is some part of the total energy which is not delivered to the consumer.

Then, in accordance with formula (2), the technical losses ΔW of the regenerated energy in the traction power system over a period of the recuperative braking τ_r can be calculated as follows:

$$\Delta W = R \cdot I^2 \cdot \tau_r = R \cdot I_a^2 \cdot \tau_r + R \cdot I_r^2 \cdot \tau_r , \qquad (4)$$

where R is a resistance of the section of the traction power supply system.

The component $R \cdot I_a^2 \cdot \tau_r$ is based on an active part of the recuperated current which flows through the traction power system. It is named basic losses of the recuperated energy:

$$\Delta W_0 = R \cdot I_a^2 \cdot \tau_r . \qquad (5)$$

Multiple this equation and divide it by U^2. We get a formula for the basic power losses which is based on the active power P:

$$\Delta W_0 = R \cdot I_a^2 \cdot \frac{U^2}{U^2} \cdot \tau_r = R \cdot \frac{P^2}{U^2} \cdot \tau_r . \qquad (6)$$

The second component $R \cdot I_r^2 \cdot \tau_r$ is the active losses of the recuperated energy too. But it is based on a reactive part of the recuperated current and it is known as additional power losses:

$$\Delta W_{add} = R \cdot I_r^2 \cdot \tau_r . \qquad (7)$$

Similarly to the previous formulas, multiple this equation and divide it by U^2. We get a formula for the additional power losses which is based on the Fryze's reactive power Q_F:

$$\Delta W_{add} = R \cdot I_r^2 \cdot \frac{U^2}{U^2} \cdot \tau_r = R \cdot \frac{Q_F^2}{U^2} \cdot \tau_r . \qquad (8)$$

In formulas (6) and (8), the active and reactive powers are used for the basic and additional energy losses calculation. These powers (P, Q_F and S) and the period of the recuperative braking τ_r are defined using the correlation and dispersion method which is specified in work [8].

In accordance with formulas (2), (4), (5) and (7), the total technical losses of the recuperated energy ΔW can be calculated as:

$$\Delta W = R \cdot I^2 \cdot \tau_r . \qquad (9)$$

These losses are the function of random quantity which is the total current I [8, 9], because R and τ_r are the deterministic values. Using the distribution theory of the function of random argument [10] and using formula (9) we get a theoretical law for the distribution of the random quantity ΔW. Imagine that the random quantity of the recuperated current I is distributed in accordance with a certain law $\varphi(I)$. Find the inverse function $I(\Delta W)$ from equation (9):

$$I = \sqrt{\frac{\Delta W}{R \cdot \tau_r}} . \qquad (10)$$

Derive equation (10) with respect to ΔW:

$$\frac{dI}{d(\Delta W)} = \frac{1}{2}\sqrt{\frac{1}{\Delta W \cdot R \cdot \tau_r}} . \qquad (11)$$

Then, the desired law of the distribution of total technical losses of the recuperated energy ΔW can be written as follows:

$$f(\Delta W) = \varphi\left(\sqrt{\frac{\Delta W}{R \cdot \tau_r}}\right) \cdot \left|\frac{dI}{d(\Delta W)}\right| =$$

$$= \varphi\left(\sqrt{\frac{\Delta W}{R \cdot \tau_r}}\right) \cdot \frac{1}{2} \cdot \sqrt{\frac{1}{\Delta W \cdot R \cdot \tau_r}} . \qquad (12)$$

Using formula (9), we can write the probabilistic coefficients of the losses ΔW. These are:

- mathematical expectation

$$M[\Delta W] = M\left[R \cdot I^2 \cdot \tau_r\right] = R \cdot \tau_r \cdot M\left[I^2\right] =$$

$$= R \cdot \tau_r \cdot \left\{\left(M\left[I^2\right]\right)^2 + D[I]\right\} =$$

$$= R \cdot \tau_r \cdot \left(m_I^2 + \sigma_I^2\right), \qquad (13)$$

- dispersion

$$D[\Delta W] = R \cdot \tau_r \cdot D\left[I^2\right] =$$

$$= 2R \cdot \tau_r \cdot \left(M[I]\right)^2 \cdot D[I] + D^2[I] =$$

$$= 2R \cdot \tau_r \cdot m_I^2 \cdot \sigma_I^2 + \sigma_I^4 , \qquad (14)$$

where $M[...]$ or m are the mathematical expectation; $D[...]$ is the dispersion, σ is the standard deviation.

As we can see from expressions (13) and (14), the absolute values and deviations of the energy losses in the traction power system depend on the standard deviation, i.e. the variations of the recuperated current.

3. Calculations and their analysis

The basic, additional and total losses of the recuperated energy are estimated using expressions (6), (8) and (9) which are derived above. All calculations are done for two real zones of the power supply system in Prydniprovsk Railway. For this purpose the voltage and current are synchronously recorded from EPL2T trains and VL8 freight locomotives in the process of real operation in the traction and regenerative modes. The results of the experiments and calculations are shown in the Table 1 below.

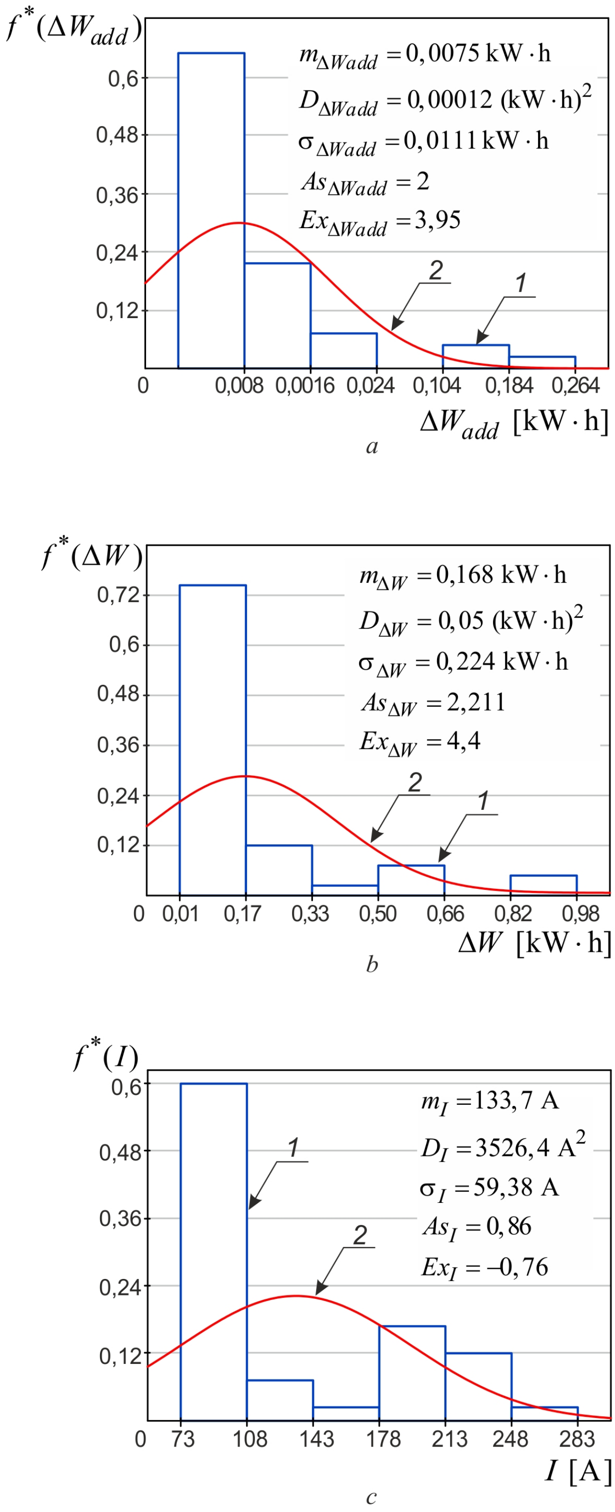

Fig. 2. Statistical (1) and theoretical (2) distributions of additional (a) and total (b) energy losses, current (b) for the EPL2T train in the recuperative braking mode.

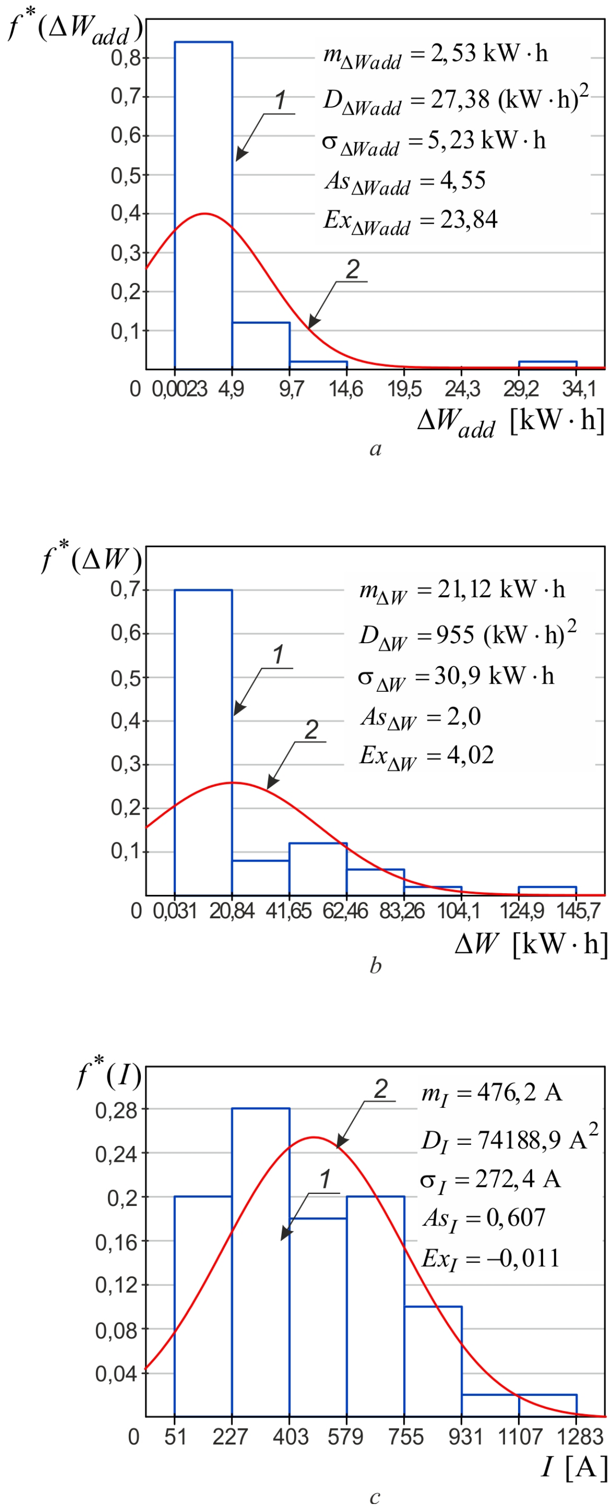

Fig. 3. Statistical (1) and theoretical (2) distributions of additional (a) and total (b) energy losses, current (c) for the EPL2T train in the recuperative braking mode.

Table 1

The technical losses of the recuperated energy in the traction power supply system

Journey's number	W_{rb} [kW·h]	ΔW_0 [kW·h]	ΔW_{add} [kW·h]	ΔW [kW·h]	$\Delta W_0/\Delta W$ [%]	$\Delta W_{add}/\Delta W$ [%]	$\Delta W/W_{rb}$ [%]
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	35,3	1,454	0,015	1,469	99	1	4,2
2	20,256	1,026	0,142	1,168	88	12	5,8
3	46,878	3,624	0,153	3,778	96	4	8,1
4	14,26	0,653	0,007	0,66	98,9	1,1	4,6
12	817	206,6	23,3	229,9	90	10	28,1
31	328,45	45,6	3,7	49,3	92	8	15
37	1034,8	205,2	47	252,2	81	19	24,4
38	2128,5	472,36	52,44	524,8	90	10	24,6

In Table 1: ΔW_{rb} is the recuperated energy of the train for the whole journey (column 2), ΔW_0 is the basic energy losses (column 3), ΔW_{add} is the additional energy losses (column 4), ΔW is the total energy losses (column 5) in the traction power supply system and their percentages (columns 6, 7 and 8).

As it is seen from the table (column 9), the ratio of the total energy losses relative to the recuperated energy is from 4,2 to 8,1% for EPL2T and from 15 to 28,1 % for VL8. This difference is understandable because the trains operate with different loads in the route (and thus they have the different RMS values of the recuperated current which vary to 283 A and 1283 A for EPL2T and VL8 respectively). The percentages of the basic and additional technical losses in the total losses are shown in columns 7 and 8. It is seen that the basic energy losses ΔW_0 are the main part of the total losses ΔW. They are the result of the active energy transfer. However, there are journeys in which the non-stationary (stochastic) nature of the voltage and current is the cause of high additional losses of the recuperated energy. These losses vary from 10 to 20% (column 8: journeys 2, 5, 7, 8).

Stochastic character of the values of the technical losses is confirmed using their histograms and probability values of the coefficients: the mathematical expectation m, the dispersion D, the standard deviation σ, the coefficients of asymmetry As and excess Ex (Fig. 2 and 3). From the histograms and the probabilistic coefficients follow that the statistical distribution of the values ΔW_{add} and ΔW does not obey Gauss's Law. It was eastablish from the following parameters. Firstly, there is a left-side skewness of the distribution with large positive values of the asymmetry coefficient As ranging from 2 to 4,55. Secondly, the coefficient of excess is large and of positive values (≈ 4,0).

Note that all the values in the table and histograms are obtained only for a feeder zone of the traction power system in which the EMF moves in the recuperative braking mode. But, in fact, the recuperated energy flows to the neighboring feeder zones, the invertors in the substations, the external power grid and the technical losses can be bigger in two times or more.

The experimentally obtained values of $D_{\Delta W}$ (Fig. 2b and 3b) confirm theoretically derived expression (14), which shows that the variation of technical losses is strongly depended on the fluctuations of the recuperated current. Indeed, for the EPL2T journeys, the standard deviation of the RMS current is $\sigma_I = 59,38$ [A] (Fig. 2c) and for the total energy losses, it is $\sigma_{\Delta W} = 0,224$ [kW · h] (Fig 2b). But for the VL8, these values are much greater (bigger) than for the EPL2T and are equal to $\sigma_I = 272,5$ [A] (Fig. 3c), $\sigma_{\Delta W} = 30,9$ [kW · h] (Fig. 3b).

4. Conclusion

1. The recuperative braking process has been used since the invention (foundation) of electric traction, but the technical and economic efficiency of this braking is not fully proven.

2. In the process of recuperative braking, the energy flows from ERS to the traction substations. This energy raises technical losses in the elements of the DC traction power supply system which can be over 30% of the total recovered energy.

3. The voltage and current in the recovery mode are stochastic processes which generate energy of low quality, and it is the cause of the additional losses in the power network.

4. Technical energy losses in the power network are probabilistic in nature and they depend upon the standard deviation of the recovered current.

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ТЕХНОЛОГІЧНІ ВТРАТИ РЕКУПЕРОВАНОЇ ЕЛЕКТРОЕНЕРГІЇ В ТЯГОВІЙ МЕРЕЖІ ПОСТІЙНОГО СТРУМУ

Анатолій Нікітенко

Проаналізовано ефективність застосування рекуперативного гальмування електрорухомим складом постійного струму. Моніторинг напруг та струмів виконано для електропоїздів ЕПЛ2Т та електровозів ВЛ8. Розраховано основні, додаткові та повні технологічні втрати енергії рекуперації в тяговій мережі постійного струму. Побудовано статистичні та теоретичні розподіли діючого струму, додаткових та повних втрат енергії рекуперації, а також розраховано основні імовірнісні показники.

Anatoliy Nikitenko was born on September 11, 1989. In 2011 he graduated from Dnipropetrovsk National University of Railway Transport named after Ac. V. Lazarian with the speciality "Electromechanical systems of automation and electric drivers". Since 2011 he has been working at Dnipropetrovsk National University of Railway Transport holding the post of an assistant to a lecturer. In 2013 he took part in an international exchange program studying at Lanzhou Jiaotong University, China. Since 2014 he has been the head of the Polish Center of Education, Science and Culture. Research interests: energy saving technologies, their effectiveness and practical application.