Mykolay KOSTIN, Anatoliy NIKITENKO

Dnipropetrovs'k National University of Railway Transport named after Ac. V. Lazaryan (DIIT)

Statistics and Probability Analysis of Voltage on the Pantograph of DC Electric Locomotive in the Recuperation Mode

***Abstract**. The statistical analysis and probability characteristics of voltage random variation on the pantograph of DC electric locomotive in the recuperation mode are presented in the article.*

***Streszczenie.** Praca przedstawia analizę statystyczną zmian napięcia pantografu maszyny stałoprądowej stosowanej w lokomotywach podczas pracy systemu w trybie odzyskiwania energii podczas hamowania. Analizie statystyczne poddano przebiegi uzyskane w rzeczywistych warunkach pracy elektrycznej lokomotywy VL8 (**Analiza statystyczna napięcia pantografu w trybie odzyskiwania energii lokomotywy elektrycznej DC**).*

Keywords: recuperation, probability laws, voltage, DC electric locomotive, statistics.
Słowa kluczowe: odzyskiwanie energii w maszynie elektrycznej, statystyka, metody probabilistyczne.

Introduction

There are two electric traction power systems: direct current (DC) and alternating current (AC) on electrified railways in the world. In Ukraine nearly 50% of railways are electrified by DC. But DC traction power system is DC system only by name. In fact (from Fig. 1) voltage $U(t)$ of this traction power supply system isn't direct but is varying direct quantity.

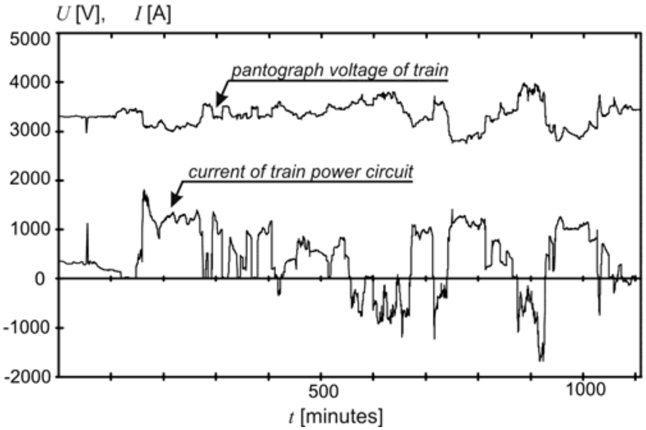

Fig.1. Pantograph voltage $U(t)$ and current $I(t)$ of train power circuit recorded from locomotive VL8

From the early beginning of the railway electrification it was established that one of the factors, which influences on the effectiveness of the recuperative braking of DC electric rolling stock (ERS) is the voltage on the pantograph and the voltage of the traction power system. This fact is described not only in the fundamental works by L. Trahtman and V. Tulubov, but also in the recent investigations by G. Korepanov, V. Nerubatskiy, E. Duranin, Y. Shcherbak, A. Beliaev, L. Petrovich and others.

The authors of these investigations study the voltage level on the pantograph of the DC electric locomotive VL8 from the position of appearing the collector ring fires of drives [1]. They also investigate the voltage oscillation and the facts of voltage form distortion of the traction power system [2]. The in-depth analysis of the recuperation braking process of DC ERS the effective voltage range was defined in the work by Y. Shcherbak [3]. The voltage must be from 2500 V till 3700 V for the possible recuperation mode. But these works don't have analysis of statistics and probability. Only some histograms are represented in the work by S. Sulima [4].

Thus, the first purpose of this work is the sufficient analysis of statistics and probability of pantograph voltage in the recuperation mode of DC electric locomotive.

Experimental research methods

Experimental research and analysis were accomplished for the electric locomotives VL8. All oscillograms of the pantograph voltage level $U(t)$ of the electric power system and the current level $I(t)$ (one of them is presented in Fig.1) were recorded from the locomotives in the process of operation in Prydniprovs'k Railway. To obtain these characteristics we used the special designed hardware and software system for measuring the parameters of the train electric circuits. This system consists of 4 parts: the normative database; the module of inputting and correcting the normative information; the calculation module; the registration module of the train motion rates and the conditions of railway section motion (or the hardware module HWM). We used HWM for recording the necessary characteristics $U(t)$ and $I(t)$.

Experimental research results

On the $U(t)$ and $I(t)$ oscillograms it is depicted that the voltage in the recuperation mode is characterized by significant time variations. This fact shows that pantograph voltage U is a stochastic function from the time (or chance processes $U(t)$). Each oscillogram is analyzed with a sampling interval of time by the theory of random quantity. Voltage histograms received by discretization of each oscillogram separately [5].

The analysis of oscillograms, histograms and tables testifies that measured values of voltage vary over a wide range from 3014 V to 3989 V (Fig. 1). Minimal U_{MIN}, maximal U_{MAX} and medium U_{MED} voltage considerably exceed nominal voltage U_{NOM}=3000 V (see Table 1).

The shapes of histograms (Fig. 2) and the skewness coefficients As and the coefficient of excess Ex (Table 1) allow to make a conclusion that the Gauss law is the main characteristics for train journeys (№ 4, 5, 6). In other cases (journeys 1-3) statistical distribution has negative (right-side) skewness and negative (oblate) excess without normal law regularity.

Table 1. Probability parameters of chance pantograph voltage level in recuperation mode

Journey number	U_{MIN} [V]	U_{MAX} [V]	m_U [V]	σ_U [V]	As [r. u.]	Ex [r. u.]
1	3014	3534	3310	126,6	-0,702	-0,544
2	3074	3671	3392	147,9	-0,031	-0,689
3	3434	3989	3688	140,3	0,02	-0,989
4	3289	3978	3667	153,9	-0,2	-0,377
5	3077	3805	3469	131,6	-0,4	-0,269
6	3426	3590	3524	42,4	-0,274	-0,881

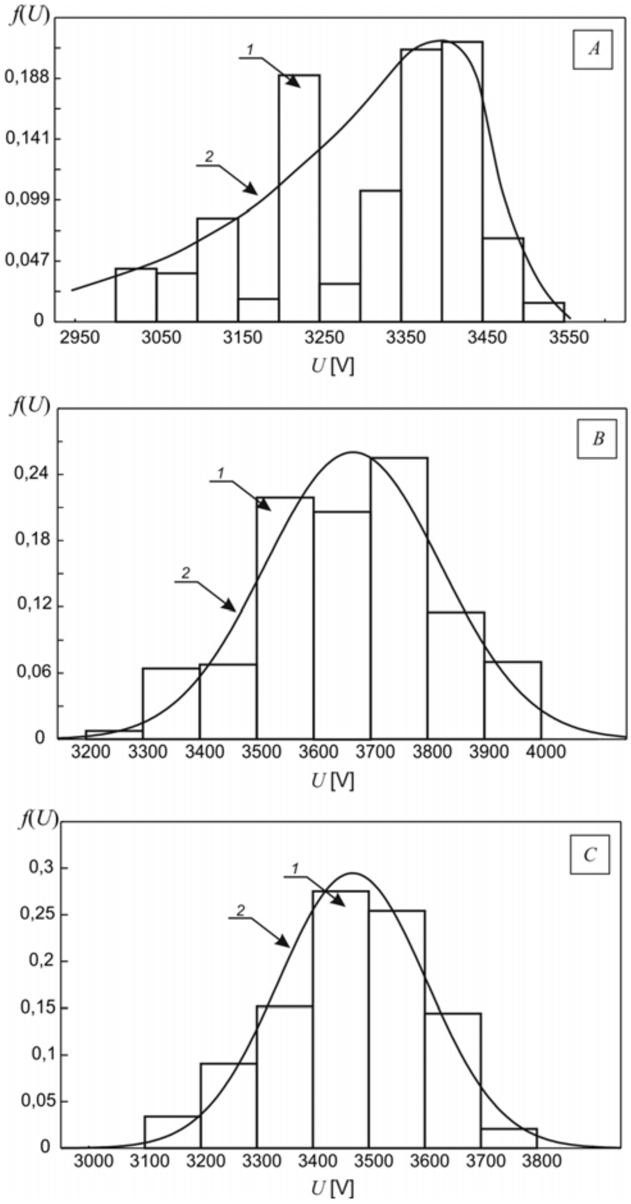

Fig.2. Statistics (histograms "1") and theoretical "2" distribution of pantograph voltage of locomotive VL8 in recuperation mode (A, B, C – different journeys)

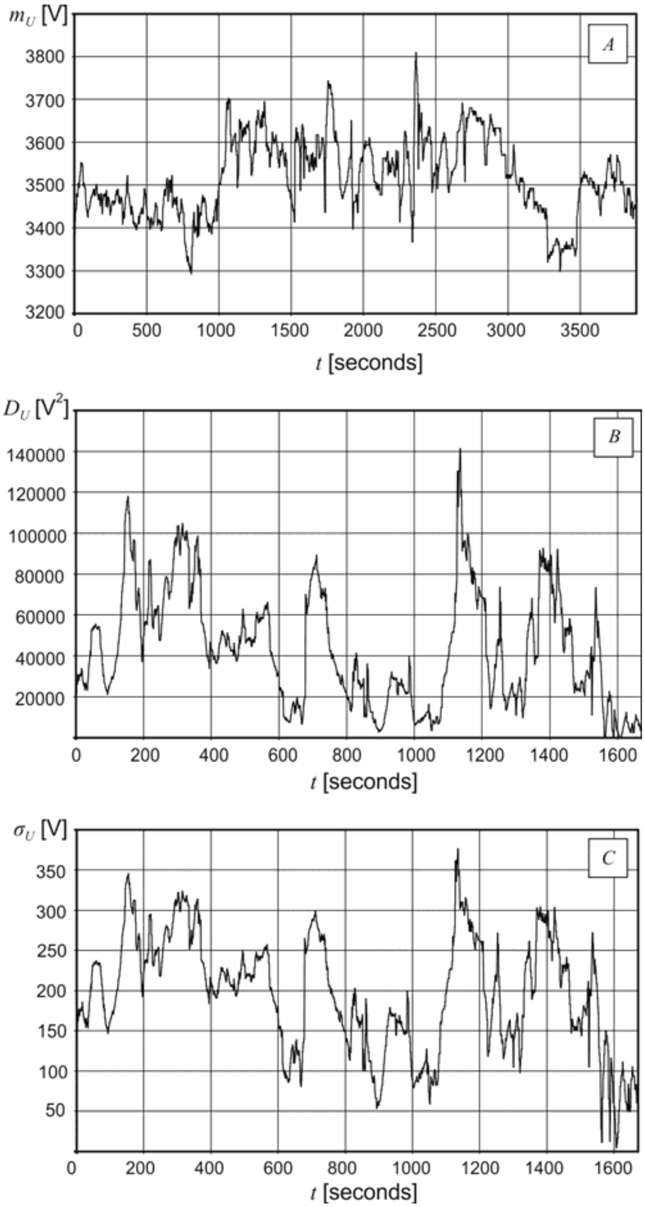

Fig.3. Functions of mathematical expectation $m_U(t)$ – "A", dispersion $D_U(t)$ – "B" and standard deviation $\sigma_U(t)$ – "C" of pantograph voltage of locomotive VL8 in recuperation mode

According to Fig. 3, the functions of mathematical expectation $m_U(t)$, dispersion $D_U(t)$ and standard deviation $\sigma_U(t)$, which obtained by quantization of many characteristics $U(t)$ aren't constant but they oscillate relatively some constant value. So voltage stochastic process $U(t)$ isn't stationary one, but according to [6] it can be reduced to stationary: limited quantity $U(t)$ of characteristics is conditioned by availability of significant probability element in the obtained estimates functions of the mathematical expectation and dispersion. Therefore these visible deviations in Fig. 4 don't have regular character and so $m_U(t)$, $D_U(t)$ and $\sigma_U(t)$ can be averaged.

Abovementioned makes it possible to suppose stationary stochastic process of pantograph voltage in the first approximation.

Conclusion of statistics and probability analysis

Pantograph voltage in the recuperation mode is not the constant rate. It is the dynamics chance process. Those voltage variations negatively influence the quality coefficients of power indices of rolling stock and additionally, the traction power supply system [2].

About recuperation mode

As it is known, the recuperative braking process of the electric rolling stock (ERS) pursues two objectives: firstly, reducing the speed of the train (about to 10 km/h); secondly, solving the problem of energy-saving. In this mode the current flow reversing during the drive ("generator mode") increases oscillation of the current flow in comparison with its oscillation in the "traction mode". This current reversing in the traction mode is to reduce the power indices and increase incidental losses of the rolling stock. The dynamics of the current flow by recuperative braking (and inertia running too) is to reduce power indices more not only of the rolling stock but, in addition, of the elements of the traction power system.

Thus, the second purpose of this work is to estimate the voltage and current influence of recuperative braking on the sections of DC traction system in the first approximation.

Calculation of oscillograms

The generator modes are calculated. Each oscillogram is analyzed with a sampling interval of time Δt. In accordance with the Kotelnikov's theorem it goes as:

$$\Delta t = \frac{0{,}5}{f_{top}},$$

where f_{top}=1/2…1/3 s^{-1} – the maximum spectrum frequency of the experimental functions $U(t)$ and $I(t)$.

According to the calculation quantization the step is one second. The oscillograms enable calculation total power S and its ingredients, active power P and reactive power Q by Frize (in accordance with the work [7]), true power factor λ (TPF) and reactive power factor tgφ (in accordance with formulas [8]).

Results of calculation and its analysis

Powers and their indices of electric locomotive VL8 in recuperation mode are presented in Table 2. The energy of recuperative braking and inertia running is of bad quality thus the true power factor is λ=0,790…0,934 (but standardized λ=0,92…0,95). The reactive power factor is tgφ=0,384…0,777. It is quite clear that low-quality recovering energy will increase incidental losses of the rolling stock and wires of the traction power system [9].

Table 2. Powers and their indices of electric locomotive VL8 in recuperation mode

Journey number	S [kVA]	P [kW]	Q_{Frize} [kVAr]	λ [r. u.]	tg φ [r. u.]
1	714,32	564,153	438,16	0,790	0,777
2	2222,9	1926,83	1108,43	0,867	0,575
3	1673,18	1562,27	599	0,934	0,384
4	2569,86	2231,86	1273,96	0,868	0,571
5	2276,09	1972,43	1135,8	0,866	0,576
6	2422,09	2102,14	1204,9	0,867	0,573

As an example of the influence of inertia running there are some additional power losses ΔP in the active resistance of traction engines locomotive VL8 in characteristics of 6 journeys (Table 3).

Table 3. Additional power losses ΔP in the active resistance of traction engines DC locomotive VL8

Journey number	$\frac{\Delta P}{P}\cdot 100$ [%]	With inertia running		Without inertia running	
		$\frac{\Delta P_p}{P}\cdot 100$ [%]	$\frac{\Delta P_\sim}{P}\cdot 100$ [%]	$\frac{\Delta P_p}{P}\cdot 100$ [%]	$\frac{\Delta P_\sim}{P}\cdot 100$ [%]
1	6,25	12,32	21,61	12,32	12,45
2	5,76	12,21	19,10	12,21	10,21
3	5,92	13,47	24,14	13,47	13,62
4	6,51	12,24	22,60	12,24	11,32
5	5,85	13,80	23,51	13,80	12,74
6	6,17	14,03	20,25	14,03	12,83

In comparison with data in columns 4 and 6 in Table 3 it is seen that inertia running increases the reactive component of traction current, that leads to the losses of electricity 12…14 % more than without taking into consideration the time of the inertia running.

It is known that the locomotive exploitation is impossible without inertia running, so pauses in traction current and unstable consumption of locomotive energy from the traction power system is specific technological character of traction voltage. Therefore it is necessary to pay attention to the question of implementation energy storage system of large power on the rolling stock. This energy storage system in inertia running mode will store energy, but in the time of locomotive transition into traction mode this device will work in discharge profile and with the help of this inject locomotive power circuit. In this case locomotive in traction mode will consume current less than before without storage system, as the part of energy was stored in inertia running mode. Energy of device storage before will be completely given to the locomotive and so, in traction mode two flows of energy will supply the locomotive – the first flow will be from the power system, and the second one from storage device system.

Conclusion

Firstly, during recuperative braking of ERS energy of low-quality is generated and it leads to incidental losses of the rolling stock and elements of traction system. Secondly, inertia running of ERS reduces its power factor too. Thirdly, consequently, recuperative braking and inertia running are very important and cost-effective modes for solving the problem of energy-saving in the electric transport. Therefore its detailed theoretical and experimental analysis is necessary for improving its efficiency.

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Authors: *prof., doctor of technical sciences Mykolay Kostin (e-mail: dnuzt_toe@mail.ru); assistant lecturer Anatoliy Nikitenko (e-mail: nikitenko.diit@gmail.com), Dnipropetrovs'k National University of Railway Transport named after Ac. V. Lazaryan (DIIT), Faculty of Railway Electrification, Department of Electrical Engineering, Ac. V. Lazaryana str. 2, room 238, Dnipropetrovs'k, 49010, Ukraine. Web site of University: http:\\diit.edu.ua*