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THE METHOD FOR DETECTING DEFECTS IN MOVABLE ARMATURE OF THE SIGNALLING RELAY

Introduction

Despite significant progress in the development of microelectronic rail automatic systems observed in recent decades, relay-contact devices are still widely used in railway signalling systems, that are fundamental to the safe operation of railways and must perform predictably and reliably [1-6]. Thus, signalling relays used for safety-critical or safety-related applications in railway signalling systems should be properly maintained and tested to ensure their performing safely and reliably throughout their expected service life. Signalling relays should be derived from systems and inspected periodically for any signs of damage, distortion, corrosion, condensation or ingress of moisture, dirt, insects, etc. During relay test sets there should be measured the operating voltage, contact and coil resistances, switching time, etc., and checked the properly operation of the relay armature and contacts, that demands to removing relay cover. Mostly tests are performed manually. Prompt diagnostics of relay fault is critical not only for the safe operation of signalization systems, but also for the reduction of maintenance cost. To automation of the measurements of relay electrical and time parameters the some methods were proposed [1, 4, 6]. The method for relay armature condition monitoring, based on analyzing of transition current flowing in relay coil during its energizing, proposed in [6], showed low sensitivity of transition current characteristic to the armature fault. In order to improve fault feature extraction, the mathematical model of electromechanical processes in the relay during its energizing, was proposed in [4], but simulation results obtained by this model were not accurate enough due to lack of correct analytical expressions for air gap reluctance, magnetic flux leakage, eddy currents in relay core and armature, etc. The artificial neural networks (ANN) used for fault recognition by analysis relay transient currents showed promising results, but a huge amount of experimental data was necessary for ANN learning [1]. Preliminary processing of the transient current for extraction of the relay faults features can accelerate ANN learning process. Last decades the wavelet transform was widely and successfully used for the fault feature extraction.

The purpose of the work is to develop a method for revealing of the movable armature defects of a signalling relay based on the measurement of the transient current when the relay is turned on and off with subsequent currents' processing using wavelet transform.

In this connection, the paper is composed as follows: a brief review of electromechanical processes in the railway signalling relay and wavelet transform theory, measurement technique, results and discussion.

A review of electromechanical processes in the signalling relay

The railway neutral relay consists of a coil with iron core, an iron yoke, a movable iron armature mechanically linked to sets of moving contacts, and contact springs [7, 8]. The contacts of signalling relay has so-called change-over or double-throw structure which include normally open (NO) or front contacts and normally closed (NC) or back contacts, and also a common contacts. Signalling relays differ from most other types of electromagnetic relays by lack of springs, and when relay de-energized the armature returns in initial place by the force of the earth's gravity.

Typical time dependences of the transient current flowed through relay coil during voltage switching is shown in fig. 1.

The transient current plot can be divided into six segments. First three segments (from $t = 0$ to $t = t_3$) correspond to relay energizing, and second three (from $t = t_3$ to $t > t_5$) correspond to its de-energizing. At first segment from moment $t = 0$ to $t = t_1$ the relay's armature doesn't move yet, and relationship for the relay energy balance can be written in a form [7, 8].

$$W_E(t) = W_{EL}(t) + W_{FL}(t) + \\ + W_{FS}(t),\ (t \in t \ldots t_1) \qquad (1)$$

where $W_E = \int_0^t U\, i(t)\, dt$ is a total energy supplied by the electric source; $W_{EL} = \int_0^t i(t)^2 R\, dt$ – the energy that dissipated in the form of heat owing to active coil resistance;

$$W_{FS} = \int_0^{\Psi(t)} U\, d\Psi(t) = \int_0^t U \frac{d\Psi(t)}{dt} dt$$

is the energy stored in the magnetic and electric fields; W_{FL} is the energy loss due to hysteresis, eddy currents, and dielectric losses, etc.; U is voltage applied to relay coil; R is active resistance of relay coil; $i(t)$ is instantaneous current value; $\Psi(t)$ is instantaneous interlinkage flux in relay core.

The transient current $i(t)$ at first segment is increased with time approximately as exponential function. Second segment from t_1 to t_2 corresponds to armature movement, and during this time the part of the total energy, supplied by the electric source W_E and the energy stored in the magnetic and electric fields W_{FS} are transferred into mechanical work W_M of the armature movement. At time t_2 the relay armature is completely attracted to the core and transient current $i(t)$ is increased with time approximately as exponential function again.

The movement of the armature during relay switching can be written in according to Newton's law in the form

$$m_r(x)\ddot{x} + r(x)\dot{x} + f_r(x)x = \\ = \pm\left(F_m(x) - F_c(x)\right), \qquad (2)$$

where m_r is the equivalent reduced mass of all movable relay components; x – instantaneous coordinate of the mass centre; $r(x)$ – equivalent friction force, that reduced to mass center; $f_r(x)$ – equivalent elastic force of the contact springs; $F_m(x)$ – equivalent force of the magnetic attraction of the relay armature to the core; $F_c(x)$ – the mechanical force returning armature to initial place; the sign "+" or "–" is used respectively for the anchor movement toward the core, or in the opposite direction.

During the armature movement, contacts and springs mechanically connected to it are bent and the elastic forces in (2) are changing its values. As a result the some tiny features appear at the second segment of the relay transient current. These features can't be extracted properly by the traditional spectral methods such as fast Fourier transform, short time Fourier transform, etc., because of non-periodic transient current. For analysis such non-periodic non stationary signals the wavelet transform is widely and successfully used last two decades.

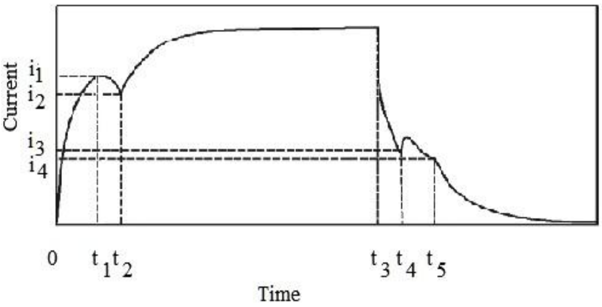

Fig. 1. Typical time dependence of the current in relay coil during relay energizing – de-energizing cycle

Review of wavelet transform theory

The wavelet theory was first put forward by Morlet in 1984 [9]. Wavelets are mathematical functions that cut up data into different frequency components but different from short time Fourier transform (STFT) in that each component is studied with a resolution matched to its scale. They are suitable for analyzing physical situations where the signal contains discontinuities and sharp spikes. The commonly used wavelet algorithms are continuous wavelet transform (CWT) [9-13], discrete wavelet transform (DWT) [14], and discrete wavelet packet transform (DWPT) [15].

Generally, the Continuous Wavelet Transform of a finite energy signal $f(t)$, defined in $L^2(R)$ space, can be written as

$$CWT_\Psi f(a,b)=\langle f(t),\Psi_{a,b}(t)\rangle= \\ =|a|^{-\frac{1}{2}}\int_{-\infty}^{\infty} f(t)\Psi\left(\frac{t-b}{a}\right)dt$$

where b and a are the so-called translation (or time location) factor and the scaling (or dilation) factor, respectively, $|a|^{-1/2}$ is for energy normalization across the different scales, $\Psi_{ab}(t)$ is a function obtained by dilations and translations of a so-called "mother wavelet" $\Psi(t)$. The CWT is characterized as redundant transform over representation of a signal in a form of a two-dimensional array.

In DWT the mother wavelet dilate and translate discretely by selecting $a=a_0^m$, and $b=nb_0a_0^m$, where a_0 and b_0 are fixed values with $a_0>1$, $b_0>0$, $m,n\in Z$, and Z is the set of positive integers. Then the corresponding discrete wavelet transform is given by

$$DWT_\Psi f(m,n)=\langle f(t),\Psi_{m,n}(t)\rangle= \\ =a_0^{-\frac{m}{2}}\int_{-\infty}^{\infty} f(t)\Psi\left(\frac{t-nb_0a_0^m}{a_0^m}\right)dt\,.$$

DWT provides a decomposition of a signal into sub bands with a bandwidth that increases linearly with frequency. In the case of dyadic transform ($a_0=2$ and $b_0=1$), each spectral band is approximately one octave wide. In this form, DWT can be viewed as a special kind of spectral analyzer. The algorithm of multiresolution signal decomposition introduced by Mallat [14] consists of a series decompositions of the signal (with length $2n$) into two components: detail coefficients D_j, which capture the high frequency low-scale information in the original signal and approximation coefficients A_j, which capture the low frequency high-scale information in the original signal, both components with a reduced size of $2n-j$, where j is the decomposition level. Then the detail coefficients D_j remain unchanged while the approximation coefficients A_j are decomposed into new detail and approximation coefficients. This process repeats until the decomposition level reaches.

The wavelet packet transform (WPT) can be viewed as a generalization of the classical wavelet transform, which provides a multiresolution and time–frequency analysis for non-stationary signal. A low and high pass filter is repeatedly applied to the function, followed by decimation by 2, to produce complete sub band tree decomposition to some desired depth. Because WPT not only decomposes the approximations of the signal but also details, it holds the important information located in higher frequency components than WT in certain applications.

Thus, with the use of WPT, a better frequency resolution can be obtained for the decomposed signal. DWPT recursive decomposition can be expressed as [14]:

$$\begin{cases} d_{0,0}(t)=f(t), \\ d_{i,2j-1}(t)=\sqrt{2}\sum_k h(k)\,d_{i-1,j}(2t-k), \\ d_{i,2j}(t)=\sqrt{2}\sum_k g(k)\,d_{i-1,j}(2t-k), \end{cases}$$

where $h(k)$ and $g(k)$ are high-pass and low-pass filter respectively, and $d_{i,j}$ is the reconstruction coefficients of wavelet packet decomposition (WPD) at the i-th level for the j-th node.

Measurement technique

For investigations were taken ten different signalling neutral relays, each of them was in operable condition. After full cycle measurements with them, there were artificially created certain mechanical defects in a form of curved contact springs, or by fixed additional weights on the relay armature, etc. All measurements were repeated for various voltages. In this work there are presented results only for one type of signalling relay. The results for other relays had similar character and were omitted in the work for brevity. The type of investigated relay was NMSH 4-600, with eight double-throw contact sets, nominal coil resistance 600 Ohms, nominal switching voltage 12 V. There were artificially created four types of mechanical defects in the relays: completely dismantled and removed contact sets (type A), with curved all contact springs (type B), with curved common contact spring toward to back contact (C),with curved common contact spring toward to front contact (D).

Relay energized by connecting its coil to stabilized voltage source, and de-energized by disconnecting of the coil from voltage source and short-circuiting coil terminals. Transient currents trough coil and relay contacts were digitized by a multi-channel ten-bit ADC with a sampling frequency 20 kHz and recorded by PC. To measure current trough contacts the front and the back contacts of each group were connected to each other, so the resulting current through the contacts was interrupted only when common contact switched between NC and NO contacts. Obtained results were processed with MatLab.

Results and discussion

The time dependences of the transient currents in the relay coils and contacts during relay energizing – de-energizing are shown in fig. 2. Generally, measured current-time curves have typical form as in fig. 1. For relays of (B), (C), (D) types with curved contact springs some additional features appeared at the second segment of transient current plots. For relays with curved contacts the switching time was different compared to the time for relay without defects.

To compare the transient current behavior for the relays with different faults of contacts their characteristics were shown in the same axes in fig. 3. As can be seen from fig. 3, the transient current for the first and third segments that corresponded to unmovable anchor, increased with time approximately as exponential function. The time constants τ calculated by fitting of the transient current at first segment by exponential function $\left(\exp\left(-t/\tau\right)\right)$ were practically independent on contact springs faults (table 1), but strongly depended on condition of relay coil and magnetic circuit. Also the time constant values were approximately equal to the values calculated as $\tau_c = L/R$, where L is coil inductance. Such behavior allows us to conclude that time constants τ for first segment can be used for monitoring of relay electromagnetic system condition.

Table 1

Time constant values

Relay	(A)	(B)	(C)	(D)
Time constant	0.127	0.134	0.131	0.126

The faults caused by defects of armature and contact springs led to the appearance of additional features on the second segment of the transient current which corresponded to the movement of the armature (fig. 3).

In the case of incipient faults, the features caused by defects of armature and contact springs had small values and for their identification the wavelet transform was used, that allowed to clearly extract diagnostic faults features. The CWT was computed using the "Mexican hat" wavelet, DWT and DPWT by using the "db2" wavelet. The wavelet types were chosen to achieve the high resolution of wavelet transform.

CWTs were carried out at scales 1 to 64, DWTs and DPWTs were performed up to the fourth level of decomposition. CWT of a D1 signal is a matrix containing the wavelet coefficients for the different scale and translation parameters. For better extraction of the faults features, the matrix of the wavelet coefficients energies were calculated as

$$E_{\Psi,a,b} = \left\| CWT_{\Psi} f\left(a,b\right) \right\|^2$$

$$E_{\Psi,m,n} = \left\| DWT_{\Psi} f\left(m,n\right) \right\|^2$$

$$E_{j,k} = \left\| d_{i,j,k} \right\|^2$$

The time dependences of transient current for the relays of (A), (B) types and respective to them energies of the CWT coefficients at scale parameter $a = 64$ are shown in fig. 4.

For the relay with completely dismantled and removed contact sets (type A) the transient current curve was smooth with one singularity at $t \approx 0.19$ sec., which was corresponded to the moment when armature was completely attracted to the core. The CWT energy plot shows the sharp spike at this time. For relay with curved contact springs (type B) some additional features appeared on the transient current plot and their positions are clearly distinguishable by using CWT (fig. 4).

The time dependences of transient currents for the relays of (B), (C), (D) types with different contact springs faults, and respective to them DWT energies of detailed coefficients $E_{\Psi,m,n}$ at fourth level (D4) and DWPT energies $E_{j,k}$ of the coefficients for 2-nd node at 4-th level (4,2) are shown in fig. 5.

The spikes which corresponded to contact springs faults were clearly distinguishable on the DWT and DWPT energy plots. The relative differences in values of spikes for DWT and DWPT energy plots were caused by different scale parameters used in these transforms.

Conclusion

With the purpose of developing a method for detecting defects in movable armature of the signalling relay, the time dependences of transient currents during relays switching have been investigated for relay in various technical conditions: in operable condition, as well as with artificially created defects (bends) of contact springs. The measured data have been analyzed in the time and frequency domain using the wavelet transform modifications (CWT, DWT, DWPT).

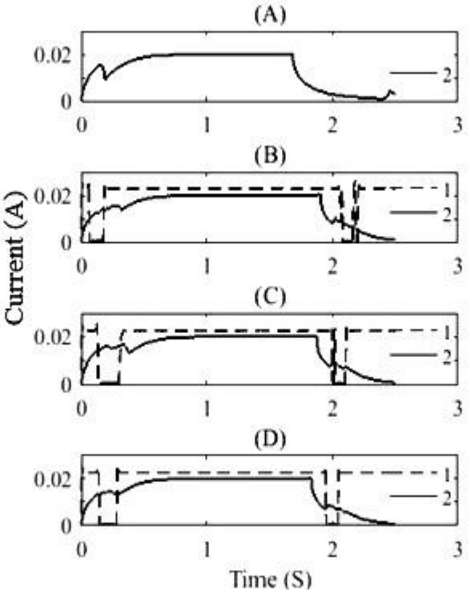

Fig. 2. The time dependences of the transient currents in the contacts *(1)* and relay coils *(2)* during relay energizing – de-energizing. The titles above plots denote relay types

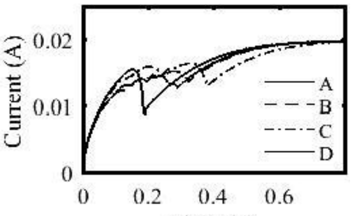

Fig. 3. The time dependences of the transient currents during relay energizing

The analysis of the transient currents was carried out using segmentation of the current characteristics of the relay. The relay transient current at first and third segments which corresponded to unmovable anchor state, increase with time during relay switch-on approximately as the exponential function.

The time constants of the relay current were calculated by approximating the measured cur-rent-time dependences at the first segment of the current curve by exponential function.

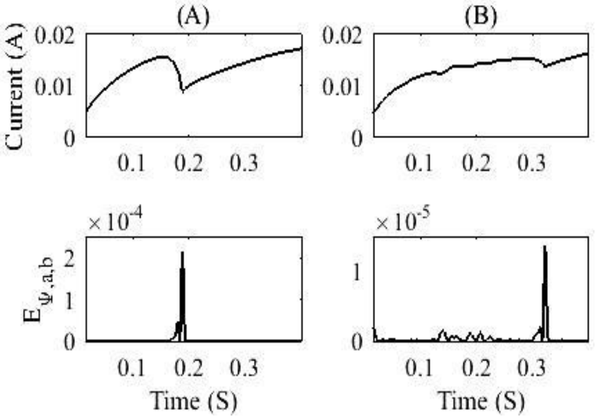

Fig. 4. The time dependences of transient currents for the relays of (A), (B) types and respective to them the energies of the CWT coefficients

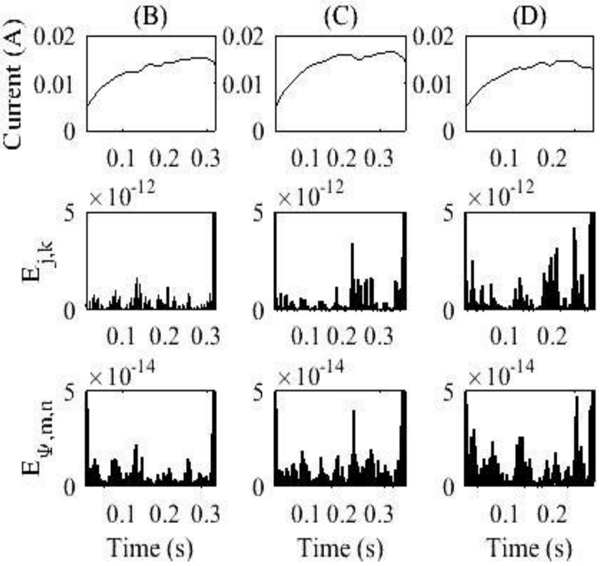

Fig. 5. The time dependences of transient currents for the relays of (B), (C), (D) types and respective DWT energies of detailed coefficients at fourth level (D4) and DWPT energies of coefficients for 4-th level, 2-nd node (4,2)

The presence of defects in the movable armature of the relay had practically no effect on the values of calculated time constants.

However, these values strongly depended on the technical condition of the relay magnetic circuit and the relay coil, as well as on the voltage applied to the coil terminals. This behavior of the relay time constant on the first segment of the relay current characteristic makes it possible to use this parameter to monitor the technical state of the electromagnetic relay system.

Defects of the armature and contact springs led to the appearance of additional features at the second segment of the relay transient current, which corresponded to the movement of the armature. The magnitude of these features on the current curve depended on the value of bending of the relay's contact spring. The width and appearance time of the features at the second segment of the current-switching curve correspond to the non-simultaneous switching of the relay contacts. To determine the amplitude (energy) of these features (peaks) on transient current curve, their duration and the times of appearance, the wavelet transform was used. The results of investigations confirmed the possibility of determining the defects of the relay movable armature by using wavelet analysis of the second segment of the relay transient current characteristic.

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Ключові слова: реле, струмові характеристики, метод визначення дефектів, вейвлет аналіз.

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