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FAULT DIAGNOSIS FOR ELECTROMAGNETIC RELAY USING DISCRETE WAVELET TRANSFORM AND WAVELET PACKET ENTROPY

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ABSTRACT

In order to fault features extraction for neutral electromagnetic relays of railway automatics, the time dependences of the relays transient currents during relays switching have been measured. The results of measurements, performed for the relay in operable condition and for relays with artificially created defects, were analyzed in the time and frequency domains. The discrete wavelet transform (DWT), discrete wavelet packet transform (DWPT) and wavelet packet energy Shannon entropy (WPESE) were used for relay fault feature extraction. Increased values of the WPESE of the transient current for electromagnetic relay with armature defects as compared with the value for the relay in operable condition, provides an integrated assessment of the relay fault existence. Analysis of relay transient currents by using DWT and WPT allows to identify the defects of the relay contacts and armature. Defects of the relay electromagnetic system can be revealed by measuring the time constants of the transient current when the relay is energized but the anchor does not move yet, because it is in one of the two end positions.

KEYWORDS

relay, fault diagnosis, wavelet transform, Shannon entropy

INTRODUCTION

Despite of significant progress in development of microelectronic railway 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]. So, signalling relays used for safety critical and safety related applications in railway signalling systems must be properly maintained and tested to ensure that they perform safely and reliably throughout their expected 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 to the armature fault because of weak influence fault on the transient current characteristic. 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 because of lack 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 for the fault feature extraction, the wavelet transform was widely and successfully used.

The aim of the work is the fault features extraction for the diagnosing of railway signalling relay that based on measuring of relay transient currents with using wavelet transform and wavelet energy packet Shannon entropy.

In this regard, the paper will appear as follows: a brief review of electromechanical processes in the railway signalling relay and wavelet transform theory, measurement technique, results and discussion. The last section concludes the paper.

1. A REVIEW OF ELECTROMECHANICAL PROCESSES IN THE SIGNALLING RELAY

The railway signalling 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 signalling relay has so-called change-over or double-throw contact sets 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 in that 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 in relay coil during voltage switching are 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]

$$W_E(t)=W_{EL}(t)+W_{FL}(t)+W_{FS}(t), \quad \left(t \in t..t_1\right) , \tag{1}$$

where $W_E=\int_0^t U\,i\left(t\right)dt$ is a total energy supplied by the electric source;

– the energy that dissipated in the form of heat owing to active coil $W_{EL}=\int_0^t i\left(t\right)^2 R\,dt$

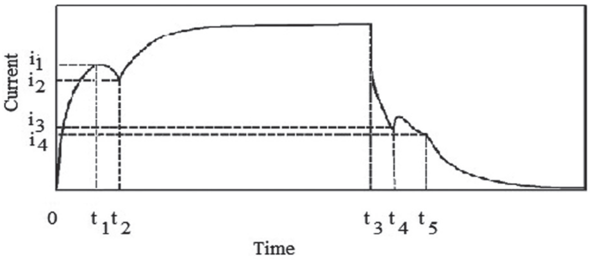

Fig. 1. Typical time dependence of the current in relay coil during relay energizing – de-energizing cycle

resistance; $W_{FS}=\int_0^{\Psi(t)} U\,d\Psi(t)=\int_0^t U\frac{d\Psi(t)}{dt}dt$ – energy stored in the magnetic and electric fields; W_{FL} – energy loss due to hysteresis, eddy currents, and dielectric losses, etc.; U – voltage applied to relay coil; R – active resistance of relay coil; $i(t)$ – instantaneous current value; $\Psi(t)$ – 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

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

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.

2. A 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) [15-18].

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

$$CWT_{\Psi} f(a,b) = \left\langle f(t), \Psi_{a,b}(t) \right\rangle = |a|^{-\frac{1}{2}} \int_{-\infty}^{\infty} f(t)\Psi(\frac{t-b}{a})\,dt \quad , \tag{3}$$

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 $b = nb_0 a_0^m$, 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

$$DWT_{\Psi} f(m,n) = \left\langle f(t), \Psi_{m,n}(t) \right\rangle == a_0^{-\frac{m}{2}} \int_{-\infty}^{\infty} f(t)\Psi(\frac{t - nb_0 a_0^m}{a_0^m})\,dt \quad , \tag{4}$$

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 multi-resolution 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, 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 the 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 subband 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 [14,18]:

$$\begin{cases} d_{0,0}(t) = f(t), \\ d_{i,2j-1}(t) = \sqrt{2}\sum_k h(k)\, d_{i-1,j}(2t-k), \\ d_{i,2j}(t) = \sqrt{2}\sum_k g(k)\ d_{i-1,j}(2t-k), \end{cases} \tag{5}$$

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.

One of the quantitative measures associated with WPT is entropy [19, 20]. Entropy provides valuable information for analyzing nonstationary signals. Last years the wavelet energy packet entropy was used for fault diagnoses that allow to derive from WPD coefficients some high-level features for better classification. Different types of entropy such as log, norm, Shannon, and threshold can be used to characterize the transient current features. However, for this study the wavelet energy packet Shannon entropy (WPESE) was used. The information of the k -th coefficient of the j -th node at i -th level WPD can be expressed as

$$E_{i,j,k} = \left\| d_{i,j,k} \right\|^2 \tag{6}$$

The probability of the k -th coefficient can be calculated by

$$p_{i,j,k} = {E_{i,j,k}} \big/ {E_{i,j}} , \tag{7}$$

where $E_{i,j} = \sum_{k=1}^{N} E_{i,j,k}$ is the total energy for the j -th node at i -th level; N is the number of the corresponding coefficients in the node. WPESE can be calculated as

$$WPESE = -\sum_{k=1}^{N} p_{i,j,k} \log\left(p_{i,j,k}\right) . \tag{8}$$

3. MEASUREMENT TECHNIQUE

For investigations were taken ten different railway 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 four types of artificially created mechanical defects in the relays: completely dismantled and removed contact sets (type A), all curved contact springs (type B), curved common contact spring toward to back contact (C),curved common contact spring toward to front contact (D).

Relay energizing was carried out by connecting of the coil to stabilized voltage source, and its de-energizing was realized by disconnecting of the coil from voltage source and then it's short-circuiting. Transient currents in relay coil and in relay contacts were digitized by a multi-channel ten-bit ADC with a sampling frequency 20 kHz and recorded by PC. During measurements the front and the back contacts were connected to each other, so resulting current through the contacts was interrupted only at time, when common contact switched between NC and NO contacts. Obtained results were processed with MatLab.

4. 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 characteristics had 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 presented in the same axes in fig. 3. As can be seen from fig. 3, the transient current on the first and third segments which corresponded to unmovable anchor, increased with time approximately as the exponential function. The time constants τ calculated by fitting of the transient current at first segment by exponential function $\exp\left(-t/\tau\right)$ 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 constant τ for first segment can be used for monitoring of relay electromagnetic system condition.

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).

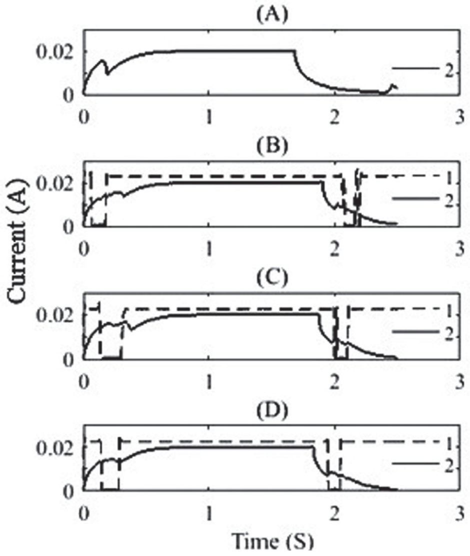

Fig. 2. The time dependences of the transient currents in the contacts (1) and relay coils (2) during relay energizing –de-energizing. The titles above plots denote relay types

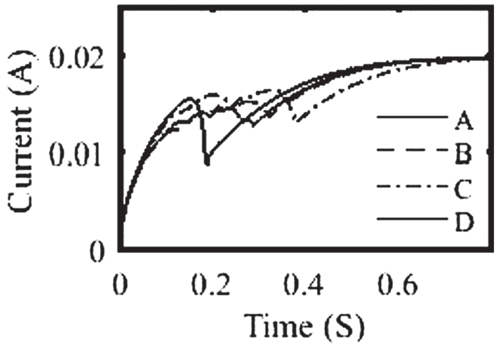

Fig. 3. The time dependences of the transient currents during relay energizing

Table 1. Time constant values

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

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 – 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 1D 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

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

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

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

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.

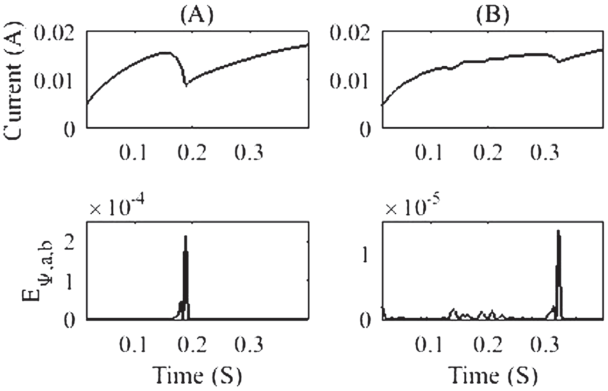

Fig. 4. The time dependences of transient currents for the relays of (A), (B) types and respective to them the energies of the CWT coefficients

For the relay with completely dismantled and removed contact sets (type A) the transient current curve was smooth with one singularity at $t \approx 0.19\,c$, 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.

Since the number and amplitude of spikes on DWPT energy plots increased with increasing of armature and contact springs faults, it allows us to use single integrated parameter for the fast monitoring of the relay armature and contacts condition. For these purposes, as noted above, can be used entropy, which characterizes a degree of signal disorder. The calculated values of the wavelet packet energy Shannon entropy (WPESE) for DWPD node (W1,0) are given in table 2.

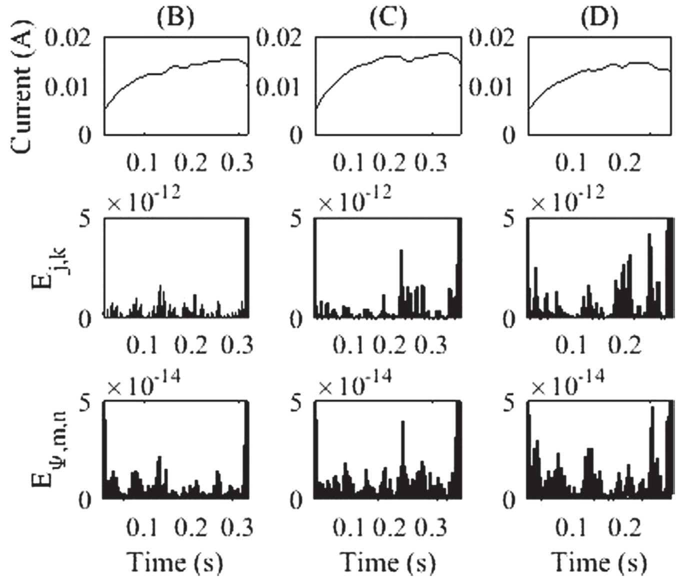

Fig. 5. The time dependences of transient currents for the relays of (B), (C), (D) types and respective DWT energies of detailed coefficients at fourth level (*D4*) and DWPT energies of coefficients for 4-th level, 2-nd node (4,2)

The WPESE values strongly depended on the faults of relay contact springs. The minimum of WPESE values was for (A) type relay with completely dismantled and removed contact sets, and the maximum value was for relay of (B) type with all curved contact springs.

Table 2. The WPESE values

DWPD node	Relay			
	(A)	(B)	(C)	(D)
W(1,0)	94.1	108.8	106.1	103.9

CONCLUSION

With the aim of the fault features extraction for the diagnosing of the railway signalling relay the time dependences of transient currents during relays switching have been investigated for relays in operable condition and for relays with artificially created defects of contact springs. The measured data have been analyzed in time and frequency domain with using the wavelet transform modifications (CWT, DWT, DWPT), and with wavelet energy packet Shannon entropy (WEPSE).

Analyses of the transient currents were performed by using of segmentation of the relay current characteristics. The transient currents at the first and third segments that corresponded to unmovable anchor, increased with time approximately as the exponential function.

The time constants calculated by fitting of the transient current at first segment by using of the exponential function were practically independent on contact springs faults but strongly depended on condition of relay coil and magnetic circuit. Such behavior allows us to conclude that time constants for first segment can be used for monitoring of relay electromagnetic system condition.

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 In the case of incipient faults these features are small and for their identification were used wavelet transform modifications (CWT, DWT, DWPT), which allowed to clearly extract fault features.

Since the number and amplitude of spikes on DWPT energy plots increased with increasing of armature and contact springs faults, it allows us to use single integrated parameter for the fast monitoring of the relay armature and contacts condition. It was shown that for these purposes can be used the WEPSE of transient current, which values increased with the increasing of the faults in relay contact springs.

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DIAGNOZOWANIE WAD PRZEKAŹNIKA ELEKTROMAGNETYCZNEGO PRZY UŻYCIU TRANSFORMATY FALI ELEMENTARNEJ I ENTROPII PACZKI FAL ELEMENTARNYCH

STRESZCZENIE

Aby wykryć oznaki wad neutralnych przekaźników elektromagnetycznych automatyki kolejowej, zmierzono zależności prądów przejściowych, przekaźników w czasie ich przełączania. Wyniki pomiarów, wykonanych w stanie roboczym przekaźnika i dla przekaźników ze sztucznie stworzonymi wadami, przeanalizowano w zależności od czasu i częstotliwości. Do wykrycia wady przekaźnika użyto dyskretnej transformaty fali elementarnej (DWT), dyskretnej transformaty paczki fal elementarnych (DWPT) oraz entropii Shannona energii paczki fal elementarnych (WPESE). Zwiększona WPESE prądu przejściowego dla przekaźnika elektromagnetycznego w porównaniu do wartości w stanie roboczym zapewnia kompleksową ocenę występowania wady przekaźnika. Analiza prądu przejściowego przy użyciu DWT i DWPT pozwala na identyfikację i lokalizację w czasie wad kontaktów i zwory przekaźnika. Wady układu przekaźnika można ujawnić mierząc stałe czasowe prądu przejściowego, kiedy przekaźnik jest włączony, ale zwora się nie porusza, ponieważ znajduje się w jednym z dwóch położeń końcowych.

SŁOWA KLUCZOWE

przekaźnik elektromagnetyczny, diagnostyka usterek, transformata falkowa, entropia Shannona