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Selecting Mother Wavelet for Wavelet Analysis of On-Load Tap Changer Acoustic Emission

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Wavelet transformation is one of the most popular tools for acoustic signal analysis. It provides good resolution both in time and frequency domains as well as wide choice of mother wavelets — this makes wavelet transformation a choice when flexible approach is required. However, selecting parameters of analysis can be difficult, especially regarding mother wavelet as different mother wavelets have various properties regarding number of vanishing moments and symmetry. This paper presents studies to determine the possibility of on-load tap changer wear detection by applying wavelet transformation. In research, different mother wavelets were selected and their usefulness was examined. Signals to be analyzed were obtained during on-load tap changer operation in different mechanical conditions — simulating devices wear in service. All measurements were performed on model very similar to real industrial on-load tap changer. Tests were conducted in controlled laboratory environment, reducing most of the possible disruptions.

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1. Introduction

Acoustic signals generated by on-load tap changer (OLTC) can be analyzed with many different mathematical tools. Among the most popular are wavelet transformations (WTs). Main advantages of WT over other time-frequency transformations are: temporal resolution and possibility to use different mother wavelets to analyze signal. These two features are important due to complicated structure of OLTCs acoustic emission as it consists of sequence of acoustic events.

Possibility of WT application in OLTCs diagnostics was investigated in papers [1–3]. In all mentioned studies accelerometer was used to measure signals. Paper [1] presents study aimed to determine technical condition of selector type tap changer based on continuous wavelet transformation. Analysis is based on envelope of acoustic emission signal, and quadratic spline wavelet was used. In Ref. [2] authors introduced discrete wavelet transformation (DWT) to obtain acoustic signature of OLTC in different technical conditions. Proposed analysis was based on approximation and detail coefficients. They used daubechies 1 wavelet in their studies. In paper [3] researchers performed study to determine wavelet most suitable for describing signature of OLTC vibration signals. Different wavelets from biorthogonal, coiflet, daubechies and symlet families were used to calculate DWT coefficients of signals envelope. Most suitable wavelet was selected basing on energy of signals components. Other works considering diagnosis of electrical power devices are described among other in [4–11].

Work reported in this paper focuses on approach aimed to determine possibility of OLTCs wear detection. Signals to be analyzed were obtained during two series of measurements. First of them was performed on OLTC model with power switch in good technical condition while during the second one researchers obtained acoustic signals generated by device with simulated wear of main contacts. Signals were registered with usage of narrow band resonant sensor with operational frequency up to 400 kHz.

Main parameter to be analyzed was energy spectral density (ESD) — this was done by calculating energy on every level of signal decomposition. Mother wavelets from symlet and biorthogonal families were used in study. Due to fact, that signals were not repeatable, statistical analysis was introduced. Obtained results were compared in terms of energy median values, energy spread, and observed energy changes between two simulated technical conditions of OLTC.

2. Laboratory setup

To conduct research on OLTC diagnostics, research work station was created in laboratory belonging to Opole University of Technology. Work station was created around full physical model of OLTC. The model consisted of tank filled with transformer oil, switching mechanism, and electric drive. Main part of the model — power switch and tap selector — were type VEL-110 made by ELIN. This type of OLTC is classified as device of divided power switch and selector.

Changing of taps could be done in semi-automatic manner or manually. During tests switching process was done semi-automatically by activating relay controlled electric motor.

During measurements transducer R15α manufactured by PAC was used. It is general purpose, narrow band resonant sensor enclosed in stainless steel case and epoxy sealed. Sensor is insulated from measured object by thick ceramic shoe. Proper insulation between object and measuring circuit is especially important during tests in industrial environment. This fact caused that sensor capable to be used in harsh industrial environment was selected to perform measurements.

Sensor operational frequency range is defined by manufacturer as 50–400 kHz with resonant frequency at 75 kHz. Figure 1 depicts frequency characteristics of used sensor.

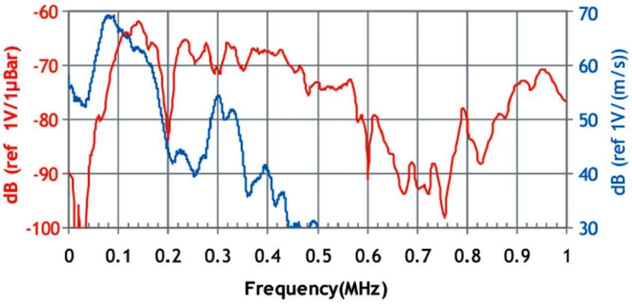

Fig. 1. Frequency characteristics of R15α.

Besides R15α sensor, measuring circuit was built by connecting 2/4/6 preamplifier, amplifier with band-pass filter and data acquisition computer. Measurements were performed in 0–500 kHz frequency range.

3. Experiment description

Technical condition of OLTCs power switch was changed during measurements. Two technical conditions were simulated:

1. power switch in good technical condition,
2. power switch with simulated wear of main contacts.

To simulate wear of power switch main contacts, pieces of sheet metal were placed between main contacts and support structure to which they were mounted. Then main contacts were tightly attached to support structure by screw connections. This was done to eliminate all possible clearances between mechanical elements as they could lead to movement of main contacts during OLTC operation. Figure 2 shows view of power switch main contact with piece of sheet metal attached to it. In each of the examined OLTC technical conditions thickness of all main contacts was similar. It is very important due to fact that uneven thickness of main contacts may lead to non-symmetrical switching process.

In discussed experiment no current was passing through OLTC main circuit contacts as no external electrical source was connected, therefore only acoustic emission (AE) from mechanical events during switching process were measured. This approach was selected to observe AE from mechanical events separately from AE generated by electrical events.

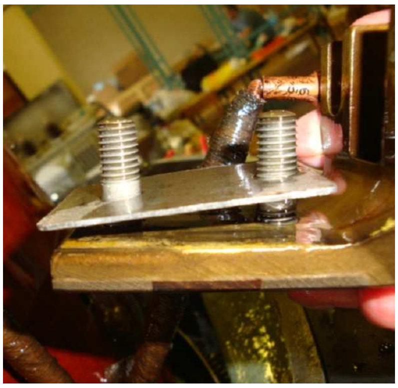

Fig. 2. View of power switch main contacts.

Type of model used in experiments, similar to real industrial OLTC installed in transformer, provided good possibility to evaluate influence of some factors on measured AE. During operation, OLTC was driven by electric motor via series of gears and shafts — this created a background that interfered with AE generated by main contacts. Furthermore, tank of model was filled with large volume (around 1 m^3) of transformer oil. It made observation of acoustic wave propagation effects on measured AE possible. Most suitable place to attach sensors on model tank was selected basing on signal strength. It was done before main experiments have been conducted, and location of sensor was unchanged during all measurements. Additionally, tap selector present in close vicinity of power switch acted like separate source of AE.

4. Methods of signal analysis

One of first tasks was to standardize obtained data. This was done by cutting part of registered AE containing all acoustic events generated by power switch for further processing. As a point of reference, to find beginning of the standardized signal, major acoustic event present in signal was selected. All signals to be analyzed were standardized in the same manner, so they would have the same length.

Signal processing was performed with the use of DWT. DWT is mathematical operation which can be compared to signal filtering in a filter bank. On each level of filtering half of frequency spectrum is cut. This means that input signal with frequency spectrum in range between 0 and 500 kHz enters first level of filter bank. Upper half (this means between 250 and 500 kHz) of spectrum is processed and wavelet coefficients are calculated. Remaining part of signal (below 250 kHz) is passed further and cut in half in second decomposition level. Process continues until calculation on last assumed level of decomposition is finished. In presented study seven levels of decomposition were taken into consideration. Information about frequency ranges and middle frequency of each level of decomposition can be found in Table I.

TABLE I

DWT levels of decomposition, their ranges and middle frequencies.

Level of decomposition	Range [kHz]	Middle frequency [kHz]
1	250–500	375
2	125–250	187.5
3	62.5–125	93.75
4	31.25–62.5	46.87
5	15.63–31.25	23.43
6	7.81–15.63	11.71
7	3.91–7.81	5.86

After DWT calculations with the use of appropriate mother wavelet are finished, energy of signal on every level of decomposition is calculated. Mother wavelets used in research were from symlet (2 and 7) and biorthogonal (1.1, 1.3, 3.1 and 3.3) families. Biorthogonal (referred further as bior) wavelet family originates from Haar wavelet, with bior 1.1 is actually the same as Haar wavelet. Presented symlet wavelets are near symmetrical while biors are symmetrical. Wavelets used in study are presented in Fig. 3.

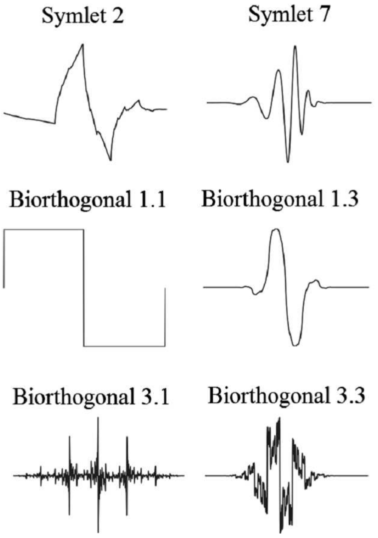

Fig. 3. Mother wavelets used in research.

Bior 3.1 and bior 3.3 are the most complex wavelets used in study. They contain large number of pulses while remaining wavelets are rather simple with less number of zero crossings.

5. Results

As a result of measurements, information about AE during sixty switching sequences was gathered — thirty for power switch in good technical condition, and thirty for power switch with simulated wear of main contacts. Figure 4 depicts exemplary AE signal after standardization process.

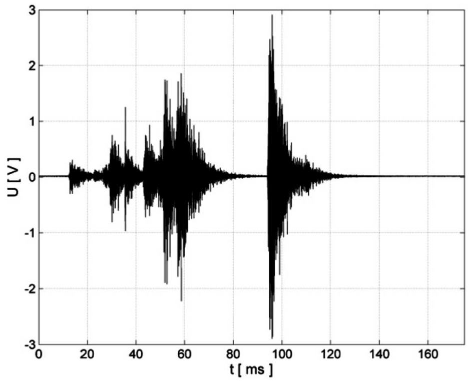

Fig. 4. Exemplary AE signal registered.

After obtaining results it becomes apparent that recorded AE is not repeatable even when switching occurred between two consecutive taps. Therefore it was decided that statistical analysis is required. Table II illustrates computed median values of ESD for series of measurements (OLTC in good technical condition).

TABLE II

Median of ESD for series of thirty measurements. OLTC in good technical condition.

Level of	ESD [mV^2/Hz]					
decomp.	Symlet 2	Symlet 7	Bior 1.1	Bior 1.3	Bior 3.1	Bior 3.3
1	880	739	1 254	1 286	290	277
2	3 744	3 056	4 168	4 895	4 180	3 751
3	12 489	14 001	10 909	14 635	38 100	42 151
4	9 908	12 110	8 415	11 432	48 800	30 145
5	4 507	3 019	5 681	4 554	192 280	55 924
6	654	16	1 527	262	254 700	25 656
7	196	2	895	52	789 960	24 927

Calculated ESD is different for each type of wavelet used. In case of symlet 2, symlet 7, bior 1.1 and bior 1.3 energy is in range from 2 to about 14.6×10^3 with maximum values on 3rd level of decomposition (this means 62.5–125 kHz). It should be noted that for mentioned wavelets, energy has its maximum in the middle parts of frequency spectrum with minimum values on both ends of spectrum. In case of bior 3.1 wavelet energy is in the range from around few hundred to 0.79×10^6, and for bior 3.3 obtained energy maximum is 56×10^3. It is clearly visible that for bior 3.1 maximum energy is several times larger than for other wavelets and is located on 7th level of decomposition (3.91–7.81 kHz). For bior 3.3 wavelet maximum of energy is located in middle of spectrum with minimum at 1st level of decomposition (250–500 kHz).

In Table III median values of ESD for OLTC with simulated wear of main contacts are presented.

It can be observed (Table III) that locations of maximum energies in spectrum did not change when compared to previous example (Table II). Locations of ESD

TABLE III

Median of ESD for series of thirty measurements. OLTC with simulated wear of main contacts.

Level of decomp.	ESD [mV^2/Hz]					
	Symlet 2	Symlet 7	Bior 1.1	Bior 1.3	Bior 3.1	Bior 3.3
1	567	506	962	962	190	185
2	3 213	1 923	3 898	4 331	2 320	2 077
3	15 594	17 971	12 959	17 684	36 010	40 814
4	12 849	15 742	10 424	13 780	45 660	33 846
5	5 381	2 847	7 028	4 501	270 005	75 226
6	911	24	2 070	376	277 365	37 617
7	218	2	979	58	713 465	31 871

minimal values are also unaffected. The only parameters that changed are values of energies. To better assess variations of ESD with OLTCs technical condition deterioration relative change of ESD was calculated. This was done in accordance to Eq. (1):

$$\Delta\mathrm{ESD}_{\%} = \frac{\mathrm{ESD}_2 - \mathrm{ESD}_1}{\mathrm{ESD}_1} \times 100\%. \tag{1}$$

In Eq. (1) ESD_1 and ESD_2 are values stored in Tables II and III, respectively.

Figures 5 and 6 illustrate relative changes of ESD (ΔESD in %) between two simulated states of OLTC. In general, shapes of presented curves are similar, however some important differences can be observed.

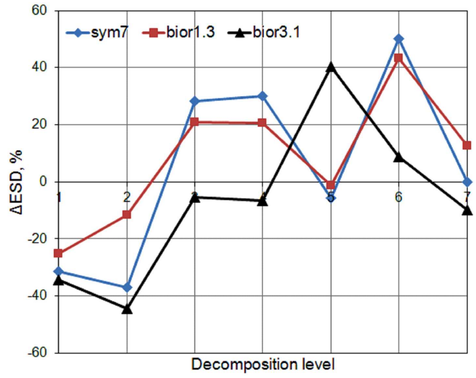

Fig. 5. Relative changes of ESD with OLTCs technical condition deterioration. Data for sym 7, bior 1.3 and bior 3.1 wavelets.

Figure 5 shows ΔESD calculated for symlet 7, bior 1.3 and bior 3.1 wavelets. At 1st and 2nd level of decomposition (frequency from 125 to 500 kHz), energy decreases with technical condition change for all wavelets. For decompositions levels from 3rd to 7th curves of symlet 7 and bior 1.3 are very similar — differences between them are below 10% of ΔESD. However shape of curve for bior 3.1 is different. At 5th level of decomposition it has its maximum value of 40%. Besides mentioned levels it takes values from −10 to +10%.

ΔESD calculated for symlet 2, bior 1.1 and bior 3.3 are presented in Fig. 6. Just like for previously presented wavelets (Fig. 5) at 1st and 2nd level of decomposition energy decreases with technical condition change. Curves for symlet 2 and bior 1.1 are similar for almost all decompositions levels with difference between them not exceeding 15% of ΔESD. Plot for bior 3.3 have two extreme values of around −45% at 2nd and +45% at 6th level of decomposition.

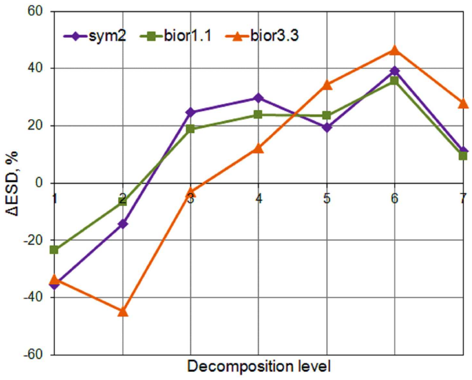

Fig. 6. Relative changes of ESD with OLTCs technical condition deterioration. Data for sym 2, bior 1.1 and bior 3.3 wavelets.

Besides median values also spread of ESD for series of measurements was calculated. Figure 7 illustrates example of ESD spread calculated for series of thirty measurements. Vertical bars indicate spread between minimal and maximal values for series of thirty measurements, and horizontal cross line indicates average value on level of decomposition.

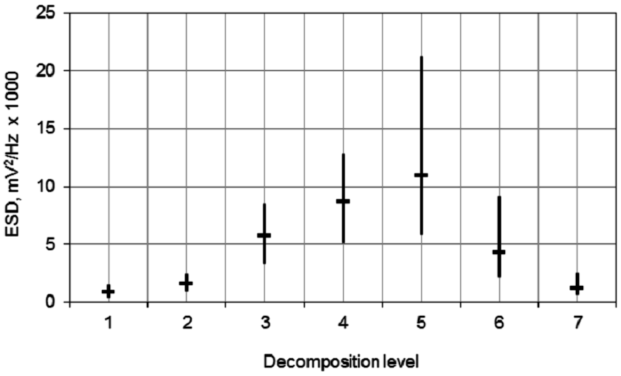

Fig. 7. Exemplary ESD spread for series of thirty measurements (bars indicate minimum and maximum values with average value as cross line in the middle).

As it can be seen (Fig. 8), spread of results is significant. Absolute deviation was calculated for each level of decomposition and each wavelet for series of thirty results, as Eq. (2) denotes. Value of calculated absolute deviation was then related to average value of energy on appropriate level of decomposition (3). This was done due to fact that ESD for different mother wavelets was in range from around 0 to 1.5×10^6:

$$D=\frac{1}{n}\sum_{i=1}^{n}\left|E_i-E_{\rm avg}\right|, \tag{2}$$

$$D_{\rm rel}=\frac{D}{E_{\rm avg}}. \tag{3}$$

Table IV shows calculated values of relative deviation of ESD in case of OLTC in good technical condition. It can be seen that calculated values are rather uniform as they are in 0.14–0.28 range. Average values of parameters presented in Table IV is 0.21.

TABLE IV

Values of ESD relative deviation ($D_{\rm rel}$) for OLTC in good technical condition.

Level of decomp.	$D_{\rm rel}$					
	Symlet 2	Symlet 7	Bior 1.1	Bior 1.3	Bior 3.1	Bior 3.3
1	0.22	0.21	0.22	0.20	0.21	0.20
2	0.25	0.28	0.23	0.21	0.25	0.26
3	0.22	0.22	0.21	0.19	0.25	0.24
4	0.17	0.18	0.17	0.14	0.20	0.17
5	0.18	0.20	0.17	0.17	0.20	0.20
6	0.22	0.23	0.22	0.18	0.28	0.22
7	0.22	0.21	0.20	0.19	0.25	0.24

Table V shows calculated values of relative deviation of ESD in case of OLTC with simulated wear of power switch main contacts. Presented values are between 0.11 and 0.25 with average value of 0.16. After comparing calculated values, it is evident that they are considerably lower than those presented in Table IV.

TABLE V

Values of ESD relative deviation ($D_{\rm rel}$) for OLTC with simulated wear of main contacts.

Level of decomp.	$D_{\rm rel}$					
	Symlet 2	Symlet 7	Bior 1.1	Bior 1.3	Bior 3.1	Bior 3.3
1	0.16	0.20	0.14	0.14	0.19	0.18
2	0.14	0.16	0.12	0.13	0.15	0.14
3	0.13	0.13	0.11	0.12	0.16	0.16
4	0.14	0.14	0.13	0.14	0.14	0.15
5	0.19	0.23	0.13	0.19	0.14	0.15
6	0.18	0.19	0.15	0.18	0.15	0.17
7	0.21	0.15	0.17	0.18	0.25	0.16

6. Summary

Wavelet transformations applied to OLTC diagnostic purposes is a promising technique. It allows different approaches to observe changes of devices technical condition. Nevertheless, caution is advised as results depend on adopted parameters of analysis. One of the important factors that will have impact on analysis is selection of mother wavelet.

It was found that value of ESD depends on type of mother wavelet used during calculations. For one of the mother wavelets maximum of ESD was found several times larger than for other ones. Also location of energy maximum in frequency spectrum appears to be connected with type of wavelet used. For wavelets with small number of vanishing moments maximum was found to be located between 62.5 and 125 kHz while for more complex ones it was located below 31.25 kHz.

Spread of calculated energies was found to be significant, reaching 21% in average. After modification of OLTC model setup (simulating wear) average spread decreased to 16%. Spread of results is most probably connected with both technical condition of switching mechanism and type of wavelet used.

Calculating relative changes of ESD between two simulated conditions of OLTC gave information about usefulness of proposed wavelets in diagnostics. It was discovered that apart from maximum values of ESD also ability to detect changes in frequency spectrum should be taken into account when selecting wavelet.

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