TIME–FREQUENCY ANALYSIS OF ACOUSTIC EMISSION PULSES GENERATED BY PARTIAL DISCHARGES

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The subject matter of this paper refers to the improvement of the acoustic emission (AE) method when used for detection, measurement and location of partial discharges (PDs) in oil insulation systems of power appliances. The detailed subject matter refers to the issues connected with the application of modern methods of digital processing of signals obtained during technical high-power measurements. The paper presents the results of measurements and time-frequency analyses of the AE pulses of PDs in oil in the multipoint- plane system. The AE pulses measured were subject to the discrete and continuous wavelet transform and the STFT (Short Time Fourier Transform) analysis.

K e y w o r d s: acoustic emission (AE), partial discharges (PDs), STFT (Short Time Fourier Transform), discrete wavelet transform (DWT) , continuous wavelet transform (CWT)

1 INTRODUCTION

One of the basic causes of the accelerated insulation degradation of high-power appliances are partial discharges (PDs), the evaluation of which can be made using three methods: electric, gas chromatography and acoustic emission (AE). The electric method, due to the high level of electromagnetic interference, cannot be used in industrial conditions during the appliance operation. In the gas chromatography method, the serious problem is the possibility of measurement result adulteration during drawing and transporting the samples of the insulation oil. Only the AE method makes it possible to detect, measure and locate PDs during the operation, without the necessity of disconnecting power appliances [3, 10, 12].

Due to ever higher requirements upon the information obtained by the AE method, it has to be constantly developed and improved. The research carried out so far has focused mainly on the mathematical analysis and explaining the physics of generation and propagation mechanisms of the AE signals in various dielectrics and insulation systems. Also the measuring apparatus has been improved taking advantage of the development of electronics and computer technology. The current research is connected with digital processing of the AE signals measured and with application of the tools of statistical analysis and advanced numerical algorithms in PD evaluation. It also refers to determining such parameters, called descriptors, which would make it possible to correlate the measurement results with the types of defects that are the sources of discharges, and which would characterize the mechanisms of occurrence and the particular stages of PD development [8, 9, 12].

In the research carried out so far the author of this paper concentrated on determining identification possibilities of basic PD forms based on the results of frequency analysis of the AE pulses generated by them. In order to do so the measurements were taken and frequency analysis of AE pulses generated in setups modeling the following PD forms was carried out: point-plane type discharges in oil, multipoint-plane type discharges in oil, multipoint-plane type with a layer of pressboard discharges in oil, surface discharges in oil, gas bubble discharges in oil, discharges in indeterminate-potential particles moving in oil. Analyzing the research results, the author showed that based on frequency spectrum runs, the ranges of dominant frequency bands, peak factor, shape coefficient and median frequency, compared simultaneously, it is possible to identify PD forms. The comparative criteria determined make the identification of PDs possible, however, it refers only to single- source, single, one-type discharges, at strictly defined measuring conditions [5, 6].

The aim of the research carried out by the author of this paper is determining comparative standards, the so-called fingerprints for each of the basic PD forms in such a way that by carrying out the comparative analysis of the AE pulses measured generated by PDs in insulation systems of power appliances it will be possible to identify them uniquely. Apart from determining the place, intensity and size of PDs it is of basic significance in evaluating the condition of the insulation measured and the time of its further failure-free operation.

The aim of the research carried out the results of which are presented in this paper is to determine the range of application of the continuous and discrete wavelet transform and also the STFT in processing the AE pulses generated by six basic PD forms. Also, the possibilities of using the DWT in the analysis of the AE signals are indicated and the runs of the probability density (PDF), normalized autocorrelation functions (NACF), diagrams illustrating the value of the energy transferred which were calculated

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ISSN 1335-3632

separately for the particular details, are shown. For comparison, also Power Spectrum Diagrams (PSD) runs calculated for the AE pulses for each of the PD forms under study have been presented. First of all, the character of frequency structure changes in time of the registered AE pulses generated in model setups was analyzed. Then the set of time approximation runs, and details at various levels obtained for the particular PDs forms underwent a comparative analysis.

Within this paper only the results obtained for the AE pulses generated by PDs of the multipoint-plane type for the positive voltage polarization will be presented. In an analogous way the analyses were carried out separately in the negative and positive voltage half-times for the remaining five PD forms generated in insulation oil.

2 CHARACTERISTICS OF SETUPS USED FOR MEASUREMENT AND ANALYSIS OF AE PULSES GENERATED BY PDS

To generate basic PD forms in insulation oil spark gaps modeling the following PD forms were used: point-plane type discharges in oil, multipoint-plane type discharges in oil, multipoint-plane type with a layer of pressboard discharges in oil, surface discharges in oil, gas bubble discharges in oil, discharges in indeterminate-potential particles moving in oil and the brush. The model setups used were placed in special grips which ensure the repeatability of the PD generation place and fluent adjustment of geometric sizes. The spark gaps made were placed in a transformer tub filled with transformer oil. To carry out the comparative analysis of the results obtained, the measurements of the AE pulses generated in each of the spark gaps under study were taken a voltage which was 80detailed presentation of their supplying system spark gaps, geometric dimensions of the tub and the fixing constructions have been presented, among others, in the works [5, 6].

To measure the AE pulses a piezoelectric wideband contact transducer series WD type AH 17 by the firm Physical Acoustic Corporation was used which was placed on the surfaces of the side walls and the upper lid of the transformer tub. Its application made the measurement of the AE signals possible at a practically flat amplitude characteristics for the frequency in the range (0 - 15) MHz at the maximum value of amplitude drop equal to + 5 dB. The AE signals measured were amplified and then were subjected to initial filtration with a standardizing measuring amplifier Nexus type 26921 - OS1 by the Brel and Kjar firm.

The registration of the AE pulses measured was performed by means of the measuring card National Instruments type NI 5911 compatible with a PC computer. The card is equipped with an A/C transducer of a maximum sampling frequency at an adjustable resolution in the range from 8 to 21 bits and of 100 MHz. The AE pulses registered underwent the analysis in the time, frequency and time-frequency domains and were visualized by the computer programs: Mathcad 2001i and Matlab 6.0. A detailed presentation of the parameters of particular elements that were used in the measuring line and the conditions in which the experiments were carried out have been presented in the works [5, 6].

3 RESULTS OF WAVELET ANALYSIS AND STFT OF AE PULSES GENERATED BY PDS

The evaluation of the time change character of the frequency structures of the AE pulses generated by PDs can be made, among others, using the short-time Fourier transform (STFT), Gabor transform, and wavelet transform [1, 4, 7, 9]. Within the research the wavelet transformation was used due to two basic reasons. Firstly, the use of the wavelet analysis provides the possibility to increase the time-frequency resolution because during signal processing narrow windows can be used at high frequencies, and wide windows for low frequencies. The STFF uses various types of observation windows but a constant time length, and in consequence, time resolution for a given type, which are constant in the whole time-frequency plane. Since the AE pulses generated by PDs can contain both low- and high-frequency components, the wavelet analysis seems useful for evaluating the character of the time-frequency distributions being determined. Secondly, the determining of the frequency structure using the STFT is done by decomposing the signal into a certain number of sinusoid components. In the wavelet analysis, however, the signal distribution is used for a sequence of well-located basic functions called wavelets [2, 11, 13-17].

Table 1. Center frequency and bandwidth for the details analyzed

Detail	Center frequency (kHz)	Bandwith (kHz)
D1	500.0	250 - 750
D2	250.0	125 - 375
D3	125.0	62.5 - 187.5
D4	62.5	31.2 - 93.7
D5	31.25	15.6 - 46.8
D6	15.6	7.8 - 23.4

To analyze the AE pulses measured generated by the PD forms under study a continuous wavelet transform (CWT) with a base Morlet wavelet and a discrete wavelet transform (DWT) with an analyzing simlet wavelet 8 were used. However, for the STFT analysis an observation Hanning window was used. The result of multiresolution analysis application using DWT, a set of time approximation runs, and details at various levels were obtained. The particular levels correspond to the frequency ranges

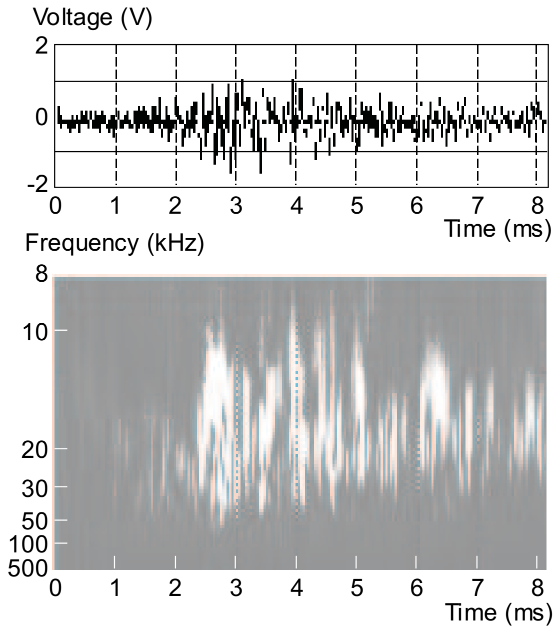

Fig. 1. CWT of a series of AE pulses generated by PDs in oil in the multipoint-plane system during the positive voltage half-cycle and the time interval 4.096 ms.

resulting from the filter bandwidth connected with the analyzed function. The runs obtained constitute a signal decomposition of the pulses measured. The frequency ranges corresponding to the filter bands at various levels are listed in Table 1.

Figure 1 shows the time run and the wavelet distribution of the AE pulse series generated by PDs of the multipoint-plane type for positive voltage polarization.

Figure 1 illustrates a time run of the AE pulse series generated by PD series of the multipoint-plane type at positive voltage polarization. The PD initiation in the run analyzed occurs at around 2.4 ms. The frequency band in which the AE pulses generated by PDs of the multipoint-plane type occur is within the range from 10 to 30 kHz. The PD initiation time is short, of 0.1 ms, compared with the duration time of the whole series of AE pulses generated by PDs, at a given voltage polarization, which is about 5 ms. The relaxation time between these discharges is from 0.05 to 0.5 ms. In order to determine the frequency structure changes in time a wavelet distribution in the time range from 2.2 to 3.7 ms was determined. In the case of AE pulses generated by PDs in the multipoint-plane setup there occur waving structures of the frequency approximately 15 kHz and 22 kHz. These structures are modulated, and in both cases the carrier frequency is approximately 1.5 kHz. The frequency change amplitude is around 10 kHz. In the period analyzed there occur both the component interference, e.g.,

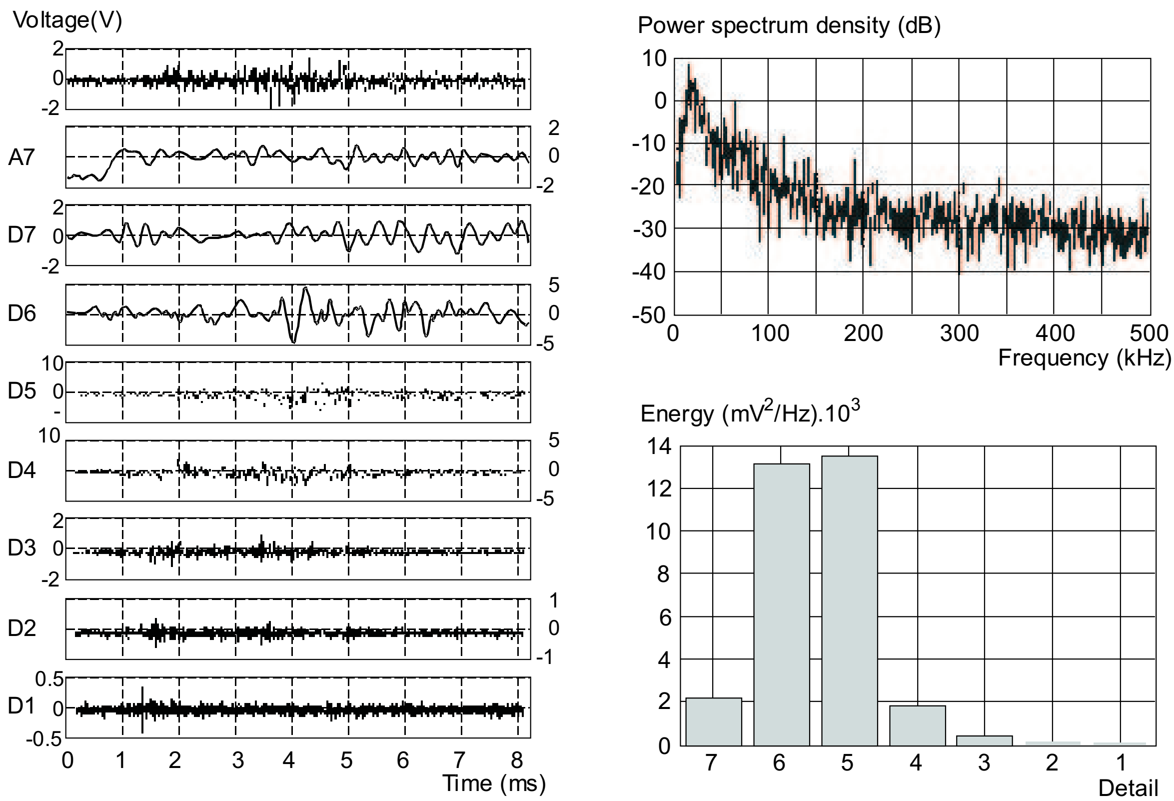

Fig. 2. DWT, PSD, the value of the energy transferred of a series of AE pulses generated by PDs in oil in the multipoint-plane system during the positive voltage half-cycle.

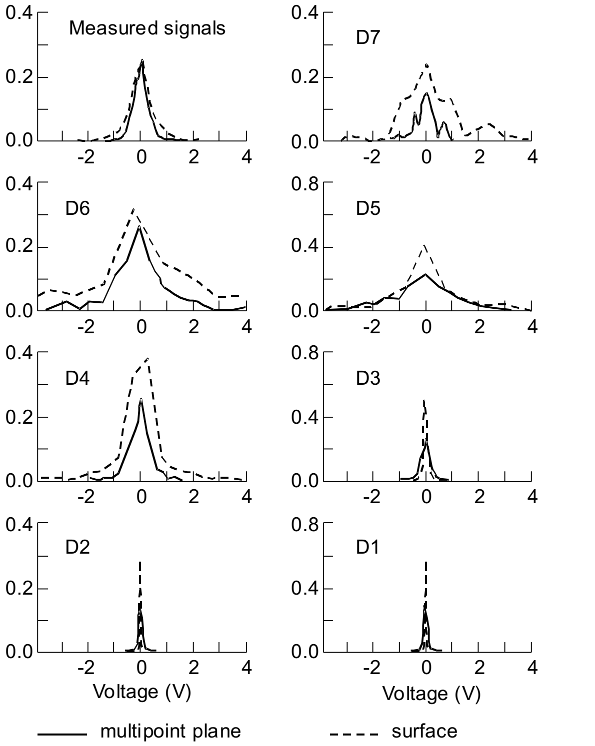

Fig. 3. DWT, PSD, the value of the energy transferred of a series of AE pulses generated by PDs in oil in the multipoint-plane system during the positive voltage half-cycle.

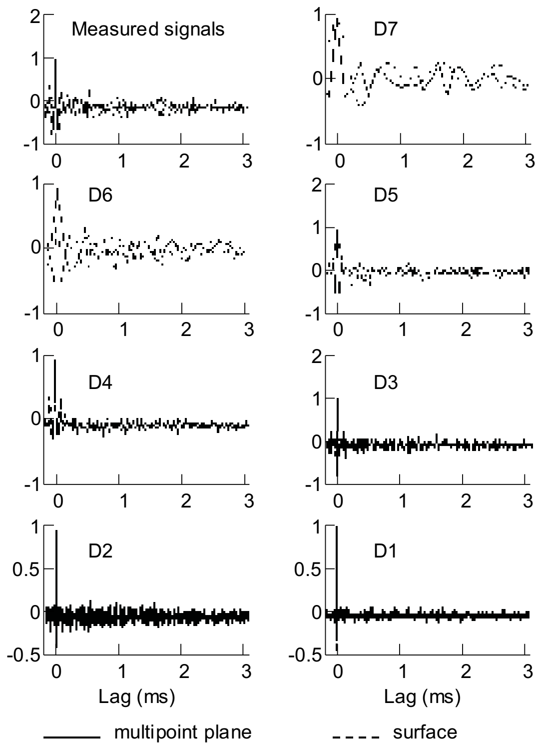

Fig. 4. ACF of a series of AE pulses generated by PDs in oil in the multipoint-plane and surface system during the negative and positive voltage half-cycle.

around 2.7, 2.9, 3.5 ms, and their suppression, which is noticeable at around 3.3 ms.

Figure 2 shows the time run, approximation at the seventh level of decomposition and the runs of details D1-D7 determined for the AE pulses generated at positive voltage polarization by PDs of the multipoint-plane type. For comparison, also PSD runs and diagrams illustrating the value of the energy transferred by particular details have been shown. For the setup of the multipoint type the run of the detail D1 is not as active as the corresponding run D1 determined for the surface setup. It points to a significant decrease of the frequency range in which the acoustic events occur. The expansion of the discharge is initiated in the frequency range represented by the detail D2 (activation in around 1.5 ms). After a short-duration pulse (approximately 0.5 ms) the answers occur in the details D3 - D5. It can be observed that in the time around 3.5 ms an impulse of a slightly lower amplitude occurs in detail D2. This pulse also releases the answer of the details at the higher level of decomposition, which is especially brought out for detail D3 (for the time 3.5 ms). The duration time of acoustic events for details D5 - D6 is significantly longer compared to the events observed for details D2 - D4.

In order to determine statistical properties at the change of voltage polarization, the density probability function PDF (Fig. 3) and the normalized autocorrelation function ACF (Fig. 4) were determined for the details at the decomposition levels from 1 to 7 and for the time run of the AE pulses, for two voltage half-times separately.

Figure 3 shows, for comparison, the PDF diagrams for the discharges of the surface and multipoint-plane types. It can be observed that for both types of discharges the PDF determined for the original runs are very close to each other, like the runs for details D5-D6. However, there are significant differences in the shapes of the PDF runs for the details of a low level of decomposition from 1 to 3, and the PDF diagram determined for detail D7 of the AE pulses generated in the multipoint-plane spark gap is steeper than the analogue run for PDs of the surface type.

The autocorrelation function determined for the runs of details of both PD types (Fig. 4) illustrates similar run features at the low level of decomposition. The ACF runs of details D1- D4 are characterized by a big variance (a high ACF value for the zero log), which indicates a big fraction of noise not connected with discharges in the run. The increased fraction of the determining components occurs for the ACF of details D5-D7. The discrepancies between the ACF functions for PDs of the surface and multipoint-plane types are observed especially for details D6 and D7. The results obtained indicate that it is possible to use them as descriptors in identification of the particular PD forms.

For graphic STFT visualization a spectrogram has been determined which defines changes of the spectrum

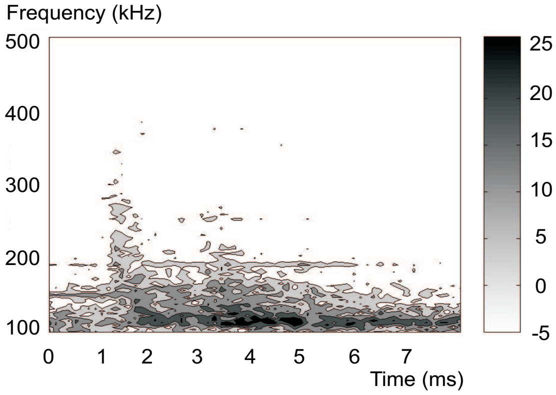

Fig. 5. Spectrogram calculated for the AE pulses generated by PDs in the multipoint - plane system in oil, during the positive voltage half-period.

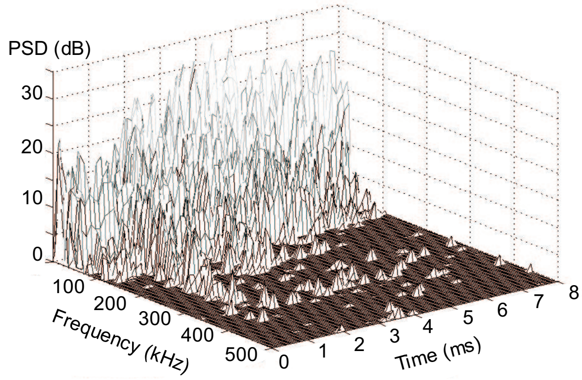

Fig. 6. Three-dimensional spectrogram of power spectrum density calculated for the AE pulses generated by PDs in the multipoint - plane system in oil, during the positive voltage half-period.

density of a signal power in time, and the value of which has been calculated as a STFT module square. This method allows time location of the particular fragments of the signals analyzed, determining the influence of the value change of the AE pulses registered taking place in time on the values of the frequencies transferred, and considerably minimizes the effects connected with the interference of spectrum fragments.

Also three-dimensional spectrograms of the power spectrum density (PDS) and for comparison, an amplitude spectrum spectrogram which was calculated as a STFT spectrum density module were drawn.

Figures 5-7 show the results of the time-frequency analysis obtained for PDs of the multipoint-plane type generated at the positive voltage polarization. The STFT transformation and Hamming observation window were used for calculations.

4 CONCLUSION

In the paper, the results of the time-frequency analysis obtained for PDs of the multipoint- plane type have been presented.It should be stressed that for the remaining five basic PD forms the results were obtained which allow, when combined with the descriptor values characterizing the AE pulses measured in the time domain, the identification of their forms. The current research referring to the AE method focuses namely on the application of modern signal processing techniques in evaluating the AE pulses measured, and in particular they aim at selecting an indicator or a group of indicators, called descriptors, which would best characterize the harmfulness of the PDs measured. It seems to be necessary to correlate the selected descriptors with proper indicators characterizing PDs measured using the electric and gas chromatography methods. Then it will be possible to create and use integrated systems of data acquisition and processing for monitoring power objects, which would result in a complex evaluation of the insulation measured. Taking into consideration during the measurements and on-line analyses all the results obtained by various methods will increase the conclusion reliability on the insulation condition of the objects under study, and thus increase their operational reliability and prevent unexpected failures [3, 10, 11].

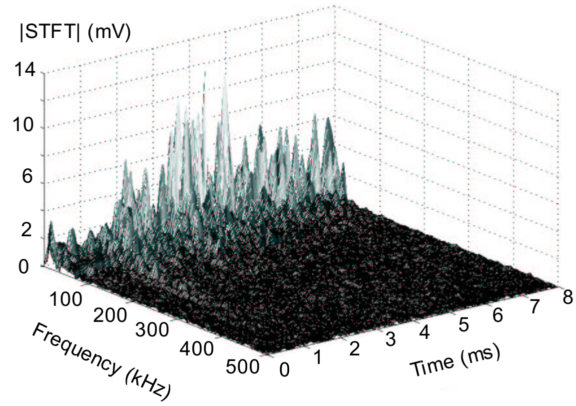

Fig. 7. Three-dimensional spectrogram of amplitude spectrum calculated for the AE pulses generated by PDs in the multipoint - plane system in oil, during the positive voltage half- period.

The paper presents the results of the time-frequency used for processing the AE pulses generated by basic PD forms that can occur in oil insulation systems. Determining the wavelet distributions and spectrograms made it possible to obtain information on the frequency structure change at the particular stages of discharge shaping. The analysis of this type is not possible when the frequency analysis applying the FFT is used, the spectrum for which is averaged in the whole time range analyzed.

Following the time-frequency analysis it was observed that the particular PD forms are characteristic of different frequency structures of the AE pulses generated. Especially the AE pulses generated by PDs of the multipoint-plane type are featured by 2 or 3 structures for the frequencies around 15, 22 kHz (and 30 kHz for negative voltage polarization). These frequencies can change in time, which causes a spectrum broadening when the classic Fourier analysis is used.

The results of the STFT and the wavelet analysis carried out, especially a dissimilar character of the time-frequency distributions determined of the AE, can be used for basic PD form identification. Moreover, a distinct character of the runs of the particular details, the ACF and the statistic properties of the AE pulses generated by basic PD forms. The results obtained should be correlated with the results presented, among others, in papers [5, 6] which refer to the possibilities of PD identification based on the descriptors characterizing the AE pulses measured in the frequency domain. The results presented can be thus taken advantage of in the works aiming at creating expert systems enabling detection, intensity measurement, location defining and identification of PDs occurring in insulation systems of power appliances measured on-line using the AE method.

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Received 12 November 2002

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