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Vibration Method for Monitoring the Technical Condition of Support-Rod Insulators Using Non-Contact Laser Vibrometry Methods

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Abstract – **A new method of non-contact vibration control of the technical condition of support-rod insulators, which are in operation under operating voltage, is developed. Theoretical studies were carried out in the ANSYS software complex to determine the information frequencies of natural oscillations of support-rod insulators associated with certain types of defects. A new measurement and diagnostic complex and software for implementing a new method for contactless monitoring of the technical condition of the support-rod insulators using laser vibrometry methods have been developed and created. Experimental studies of the parameters of natural oscillations of the of support-rod insulators on the operating substation under operating voltage have been carried out, and the operability of a new method for contactless monitoring of the technical condition of the support-rod insulators has been tested.**

Index Terms – **laser vibrometer, isolator, spectrum, signal.**

I. Introduction

THE urgency of the developed vibration method for monitoring the technical condition of the support-rod insulators (SRI) using contactless methods of laser vibrometry was determined by the need for timely diagnosis of the technical condition of the SRI in order to prevent emergencies and outages of electrical networks, modern, reliable, effective non-destructive monitoring methods that allow remote measurements. This problem is due to the fact that for remote monitoring of the technical condition of SRI there are no specialized complexes and measurement techniques.

II. Problem Definition

At present, for the control of the mechanical condition of the SRI of high-voltage switching equipment under operating conditions, many methods widely differing in their methodological nature and hardware implementation have been distributed. None of the existing methods of diagnosis can not be called fully remote. Virtually all devices for monitoring the technical condition of the SRI are used in close proximity to the facility, which leads to large labor costs for maintenance personnel and a decrease in the reliability of the results obtained. One of the main drawbacks of existing methods is the need to shutdown and decommission the SRI. Unlike other methods, the method of free oscillations using contactless laser vibrometers allows controlling the technical condition of the insulators remotely under operating voltage.

III. Theory

With the purpose of developing a method for contactless vibration control of the state of SRI, theoretical studies have been carried out to determine the informative frequency interval, which makes it possible to detect defects in SRI by analyzing the frequency spectrum of natural oscillations.

To plan the experiment and obtain an informative part of the spectrum, it is necessary to model the forms of the natural oscillations of the object of investigation. The sample has a complex structure, this significantly limits the possibility of using analytical methods for estimating natural oscillations. This task allows us to solve engineering computer analysis. An analysis of existing methods for solving problems associated with the modeling of defects of SRI has shown that it is expedient to use the finite element method to determine the informative harmonics of spectra [1]. For this purpose, the frequencies of the natural oscillations of the object of investigation are calculated in the ANSYS finite element simulation software.

Modal analysis was applied, the calculation was carried out using the Lanczos algorithm. The type of insulator under consideration is SRI-35-500-01. The finite element model of the SRI is shown in Fig. 1.

The following defects were considered as defects:

– cracks in the barrel of the insulator near metal caps (with 10, 50 and 80% overlap from the cross section of the trunk, Fig 1);

– cracks of the edges of the insulator (with 50% overlap along the simulation curve, Fig 1).

At the stage of defining the boundary conditions, the displacement model (hard sealing) was applied to the design model in the place shown in Fig. 1. Two variants of rigid sealing were considered:

– along the edges of the lower hood;

– along the edges of the lower and upper hoods at the same time.

The calculation was carried out for various combinations of defects and mounting options (Fig 1).

The analysis of the results of calculations confirmed the possibility of monitoring the technical condition of the SRI by vibration parameters. The defects considered lead to a

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change in the oscillation frequencies of the SRI in a wide range of the spectrum.

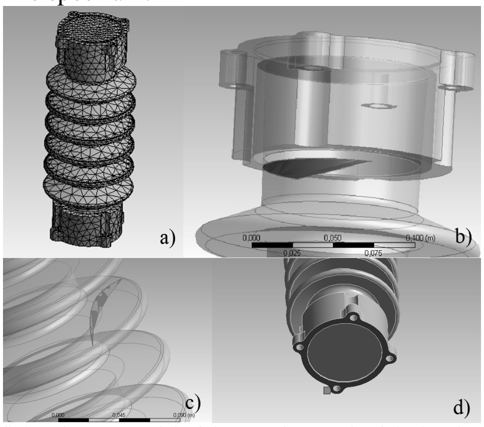

Fig.1. a – finite-element model of the SRI, b – crack of the insulator's trunk, c – crack of the insulator rib, d – hard seal.

Analyzing the results of calculations and waveforms, such informative frequency ranges can be identified as follows:

- from 0.2 to 4.5 kHz;
- from 9.5 to 11.5 kHz;
- from 12.6 to 15.3 kHz.

The results obtained in the course of numerical modeling can not be considered final and require experimental confirmation and supplementation on field samples.

To implement the proposed method of non-contact vibration control of the SRI condition, the measurement and diagnostic complex (MDV) and software using contactless methods of laser vibrometry were developed, and experimental studies of the parameters of natural oscillations of the SRI were carried out.

IV. MEASURING-DIAGNOSTIC COMPLEX WITH THE USE OF LASER VIBROMETERS AS MEASURING ELEMENTS

The measuring and diagnostic complex [2, 3] (Fig. 2) is designed for contactless monitoring of the technical state of SRI at an electrical substation and (or) in a laboratory environment in order to prevent emergencies and disconnections of electrical networks. The MDC includes a laser vibrometer 1, a multifunction input / output module 2, a personal computer (PC) 3, and a software 4 developed in a graphical programming environment LabVIEW 13.0 [4, 5].

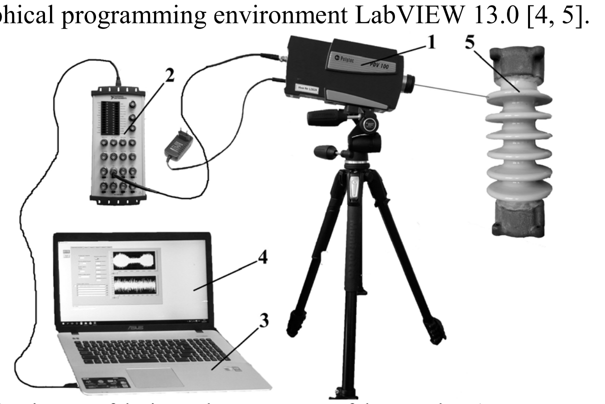

Fig. 2. Diagram of device and measurement of the complex: 1 - Laser Vibrometer PDV-100; 2 - multi-function input-output module (BNC 6212); 3 - personal computer; 4 - software; 5 - object of study

A special feature of the developed measuring equipment is the use of laser vibrometers as measuring sensors. Laser vibrometers allow you to remotely and quickly measure vibration parameters at various points of the product in a zone hazardous to the personnel (chemically aggressive, with high temperature, radiation, etc.), measure vibration parameters of objects of small size and complex shape, work with high-risk objects under operating voltage) without preliminary preparation of the surface of the object.

Non-contact vibrometry methods are the most accurate in comparison with other measurement methods. Laser vibrometers are exemplary meters and are used for metrological certification of vibration measurement and vibration testing equipment.

The laser vibrometer (PDV-100) registers vibrations at a distance of up to 30 meters and converts them into an electrical signal proportional to the vibration speed of the research object that is fed to the multifunction input-output module where it is digitized and transferred to a PC with the software installed.

The digitized signal received from the multifunction input-output module is converted to an amplitude spectrum using the Fast Fourier Transform (FFT) procedure and analyzed by software.

V. DESCRIPTION OF THE SOFTWARE FOR THE ANALYSIS OF VIBRATION SIGNALS OF THE MDC

1. Rejection principle products.

The rejection of products is performed depending on the results of comparison of the reference and current spectra by the values of the five objective comparison functions:

- correlation coefficient
- Spearman's nonparametric rank estimate;
- the assessment of Iman-Konover;

To calculate the correlation coefficient, use the following relationship:

$$r = \frac{\sum a_i\, a_{si} - \left(\sum a_i \sum a_{si}\right)/n}{\sqrt{\left(\sum a_i^2 - \left(\sum a_i\right)^2/n\right)\cdot\left(\sum a_{si}^2 - \left(\sum a_{si}\right)^2/n\right)}},$$

where a_i – the amplitude of the i current at a frequency spectrum; a_{is} – the amplitude at the frequency of the reference spectrum, n – the number of spectra compared with the standard.

In addition to assessing the correlation between the test and the reference spectrum, a nonparametric rank estimate of Spearman is calculated:

$$r = 1 - \frac{6}{n\,(n^2-1)} \sum_{i=1}^{n} \left(rank\, a_i - rank\, a_{si}\right)^2 ,$$

where rank a_i – the rank of ai amplitude variations in the amplitude range of the spectrum verifiable; rank a_{si} – is also for the reference spectrum.

The Iman-Conover approximation for large samples is calculated by the following formula:

$$J_r = \frac{r}{2}\left(\sqrt{n-1} + \sqrt{\frac{n-2}{1-r^2}}\right)$$

To classify products as "fit" or "defective" (Fig. 3), an approach is used that is typical for the procedures for rejecting anomalies: the program interprets a set of computed values of some statistics (p_1, p_2, ..., p_m) as a set of measured values of an abstract parameter and applies to this set of values the following procedure:

1) calculate the position estimate;
2) calculate the spread scatter S;
3) for a given level of significance α build a confidence interval [6]:

$$\bar{p} \pm S \cdot t(1-\frac{\alpha}{2}, m-2),$$

where t (α, m) is the α-quantile of the Student's distribution with m degrees of freedom.

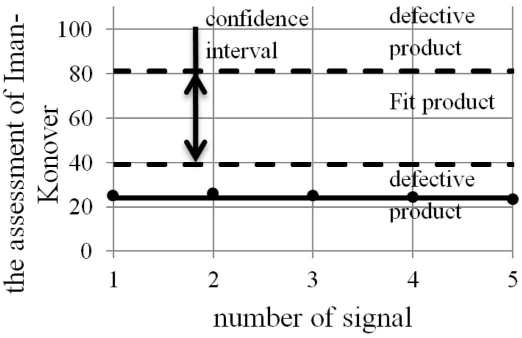

Fig. 3. The principle of constructing the decisive "fit-defective" rule by the example of the Iman-Konover estimate

If the comparison coefficients lie within the limits of the confidence interval, then the object of the study is considered "fit", if they exceed the limits of the confidence interval, then the product is recognized as "defective".

2. The structure of the developed software complex.

The software package includes the following main parts:

– subroutine control;
– subroutine for the formation of reference spectra;
– subroutine comparing the spectra with the standard.

All these components are combined in one integrated shell, logging is provided with the ability to further view the results of recording and signal processing modes.

The conclusion about the state of the product is done automatically without the user's participation, which excludes subjectivity in making a decision.

2.1. The subroutine diagnostic.

The subroutine provides registration - conversion from analog form to digital signals with a specified number of samples and a sampling interval value. On the front panel of this subroutine, the user sets:

– number and code of the controlled product;
– sampling rate;
– recording time;
– way to the reference for each measuring channel;
– parameters of the pulses of the detected signal.

When the subroutine is started from the measuring channels, vibrational responses of the beats are recorded (the file name and the product code, the .txt file format are prescribed in the file name). After the end of the recording, the subroutine automatically generates a spectrum for each signal by the FFT algorithm, calculates the target comparison functions of the reference and current spectra, and compares them with the confidence interval boundary.

2.2. Subroutine for the formation of reference spectra.

The subroutine for the formation of reference spectra is intended for the formation of a standard and a confidence interval. The problem is that the formed spectrum should be the most "typical" for the set of spectra over which it is formed, i.e. included the most common characteristics of the spectra, and excluded the individual characteristics of each spectrum.

The front panel of this subprogram the user sets the number of reference will be made to a signal processing (default zero count), the length of the signal sample to obtain a spectrum (default 2048), the frequency interval in which the processing of the spectra is carried out. In addition, there is the possibility of normalizing the spectrum. Normalization means the division of each spectral component by the maximum amplitude of the spectrum. As a result of this operation, the influence of the impact force on the result of comparing the spectra is excluded.

The subprogram for generating reference spectra operates in the following sequence (Fig. 4).

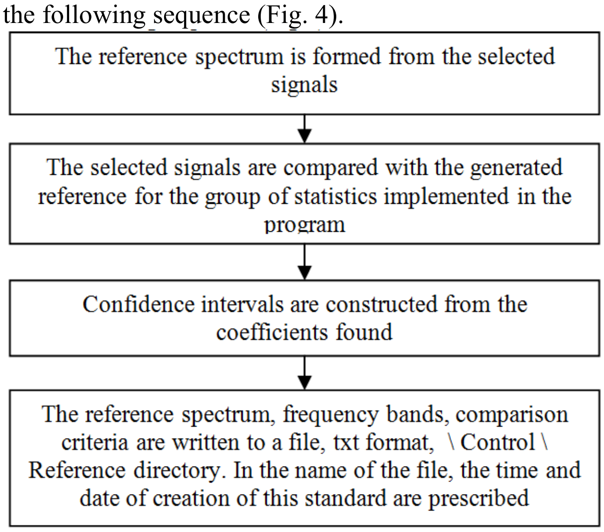

Fig. 4. Sequence of work of the subprogram "Formation of reference spectra".

When forming the reference spectrum, an algorithm of robust (noise-immune) weighing is used [7], which makes it possible to divide the spectral components into three categories: plausible data, the area of doubt, and explicit explicit values (deletion area). Observations from the field of plausible data are considered valid, observations from the field of doubt are given a reduced weight, which is less, the further the data is removed from the region of plausible data, the observations from the removal area are considered to be emissions, they are assigned zero weights, thus they are excluded from the estimation.

2.3. Subroutine for comparing spectra with a standard.

The subroutine for comparing the spectra with the standard (Fig. 5) is designed to estimate the differences of each initial spectrum of the recorded signals from the reference.

On the front panel of this subroutine, the "Parameters" tab allows the user to select the reference spectrum (by default the last used standard is set), here you can see the settings accepted during the formation of the standard.

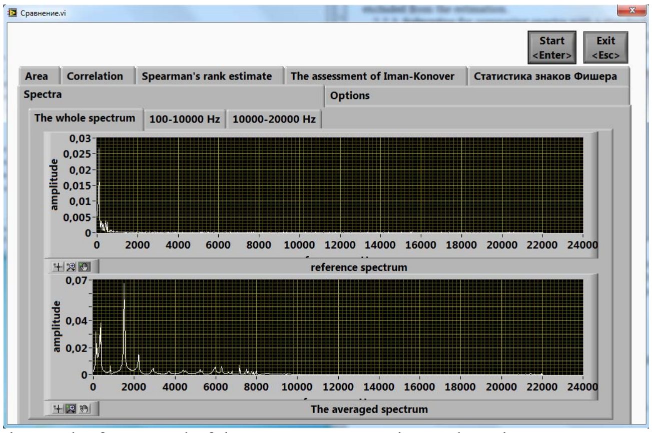

Fig. 5. The front panel of the spectrum comparison subroutine.

The subroutine works in the following sequence:

– a reference file and signals are read;
– for each signal a spectrum is formed;
– for each spectrum, objective functions are calculated that are compared with the confidence interval boundary.

VI. THE METHODOLOGY TO HOLDING THE TESTS

1. Requirements for testing conditions.

a) the tests should be carried out under normal climatic conditions:

– ambient temperature from + 5 ° C to 40 ° C;
– relative humidity of air from 45% to 80%;
– atmospheric pressure from 630 to 800 mm Hg. p.

b) tests are carried out only in dry weather, it is forbidden to test at approach of a thunderstorm and a rain, at a fog, a snowfall, a strong wind, the begun works should be suspended.

2. Preparation of the MDC for testing.

2.1. The laser vibrometer is installed at a distance of 5 to 15 meters to the test object and connected via a multifunction input-output module to a personal computer (laptop).

2.2. The laser vibrometer is focused. The minimum allowable focusing of the PDV-100 laser vibrometer is 5 units from the 10 focus scale.

2.3. The point of guidance of the laser vibrometer beam and the location of excitation of free oscillations is shown in Fig. 6.

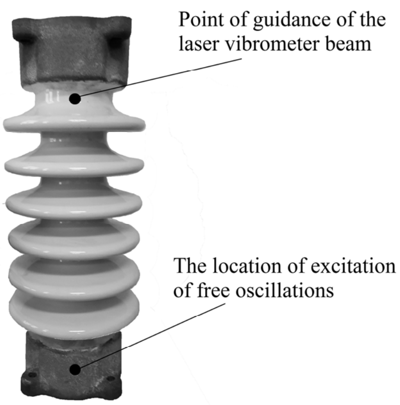

Fig. 6. Point of guidance of the laser vibrometer beam and the location of excitation of free oscillations

3. Conducting measurements.

According to the SRI, two measurements are made in each of which 5 mechanical strikes are made by an isolating rod (SHO-10) (under operating voltage) for 10 seconds.

4. Processing and analysis of vibration characteristics of SRI.

The parameters of the oscillations from the object of investigation are recorded by a laser vibrometer (PDV-100). Signals from the sensor are fed to the multifunction input / output module (NI BNC 6212), where they are digitized and transferred to a personal computer (laptop), with the software installed. The digitally recorded signal is converted into an amplitude spectrum by the FFT procedure, the values of the target comparison functions are computed for each spectrum. A comparison of the spectra and calculation of the values of the objective functions of a defect-free and controlled SRI of 35 kV, based on the theoretical study carried out at ANSYS, is performed in the frequency range 0 – 4.5 kHz.

5. Decision-making ("fit", "defective").

The test object is recognized as "fit" if the values of the objective functions in two dimensions are within the confines of the confidence interval, if they go beyond the confidence interval, then the product is recognized as "defective" (Fig 1.5).

VII. EXPERIMENTAL RESULTS

Experimental studies were carried out at the existing substation No. 126 35/6 kV OGPD Leninogorskneft (Almetyevsk) with the use of the MDC, taking into account the requirements presented in paragraph 4.

The objects of the investigation are a defect-free and defective support-rod insulator of 35 kV (IOS-35-500-01) installed on an iron beam above the transformer. As defective insulators SRI was used:

- with a main crack of the insulator stem near the upper flange;
- with a defect in the form of a crack in the lower edge.

As a result of the studies, vibration signals of defect-free and defective SRI were obtained. On the defect-free insulator, a reference spectrum and confidence intervals were generated to determine the defectiveness of the product. With the help of objective functions, the reference spectrum was compared with the spectra of defective SRI.

To form the reference spectrum and the confidence interval, the following parameters were set:

- zero reference number;
- sampling frequency - 44100 Hz;
- length of the signal sampling for obtaining the spectrum - 2048 samples;
- Confidence level - 0,95;
- normalization of the spectrum into the "on" mode.

The results of comparisons of the values of the target functions of the defective (trunk trunk of the insulator near the upper flange) and the reference defect-free SRI are shown in Fig. 7.

In Fig. 7, the numbers of mechanical shocks (signal number) are plotted along the abscissa axis, the values of the objective comparison functions are dashed along the axis, the dashed lines are the boundaries of the reference confidence interval, the solid line is the median value for all the measurements of the defective SRI.

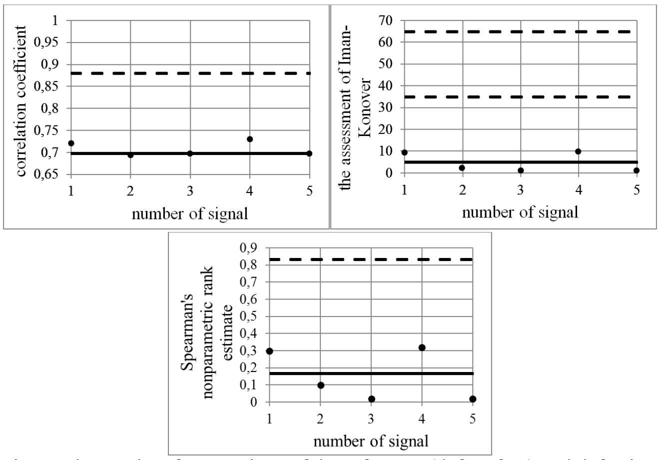

Fig. 7. The results of comparison of the reference (defect-free) and defective (trunk core of the insulator near the upper flange) SRI

The solid line and the values of the objective comparison functions are either below the dashed line (the boundary of the confidence interval of the defect-free (reference) SRI) or outside its limits, respectively, the spectra have significant differences, that is, the SRI is recognized as defective.

The results of comparisons of the values of the target functions of the defective (crack of the lower edge) and the reference defect-free SRI are shown in Fig. 8.

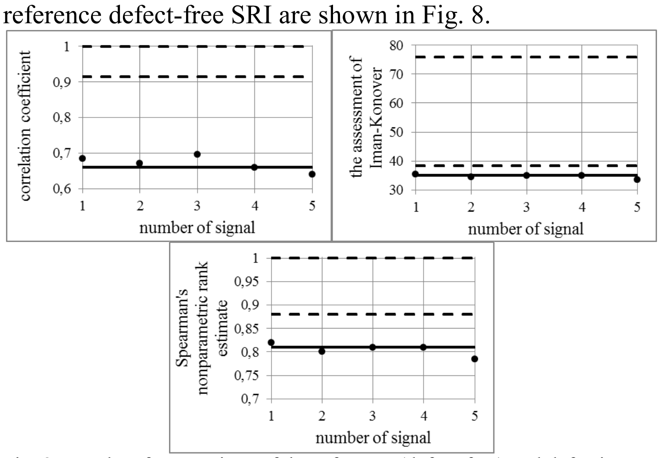

Fig. 8. Results of comparison of the reference (defect-free) and defective (crack of the lower rib) SRI

The solid line and the values of the objective comparison functions are outside the boundaries of the confidence interval (dashed lines) of the defect-free (reference) SRI, respectively, the spectra have significant differences, that is, the SRI is recognized as defective.

VIII. DISCUSSION OF THE RESULTS

Analysis of the experimental data showed a stable determination of the defects (crack of the lower rib and main crack of the insulator stem near the upper flange) in the SRI using the developed MDC for 3 objective functions (“Correlation coefficient”, “Spearman rank”, “Estimate of Iman-Conover ”)and confirmed the possibility of using this method to monitor the technical condition of the SRI in automatic mode.

Thus, it can be concluded that contactless monitoring of the technical condition of the SRI can produce free vibration methods using a measuring and diagnostic complex, excite vibration in the SRI by means of an impactor in the form of an insulating rod, both under operating voltage.

IX. CONCLUSION

The measuring and diagnostic complex was approved within the framework of the contract for research and development work with LLC "TagRas-EnergoService" on the topic "Development of a technique for monitoring the technical condition of core insulators using laser vibrometers".

The measuring and diagnostic complex allows:

- contactlessly and promptly monitor the technical condition of the SRI at the electrical substation and (or) in the laboratory;
- exclude subjectivity in assessing the technical condition of products;
- use statistical methods of information processing and decision making;
- apply computer technologies in the tasks of their implementation;
- exclude dependence on control conditions, measurement errors and information processing;
- automate the diagnostic process;
- receive an opinion on the existence of a defect in documentary form.

The developed technique allows noncontact monitoring of the technical state of the SRI with a voltage class of 20, 35 and 110 kV.

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