A Prototype of Diagnostic System of Wind-Driven Power Units

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***Abstract* — The main principles, the structure and the use of the prototype of the system for the technical diagnostics of wind-driven power units are discussed.**

I. Introduction

Novel methods to generate electrical energy including wind, wave, and solar energy sources became more and more important. The main reason is that conventional fuels are limited and expensive, whereas these other forms, known as the renewable sources, are limitless and cheap. It is expected that renewable energy will capture a growing percent of world energy market over the next 20 years. The key drivers of the “Renewable Energy Revolution” are [1]:

– increasing global energy demand;
– concerns about carbon emissions;
– concerns about energy independence;
– falling cost of renewable energy.

Wind is a clean renewable energy source and, if wind power plant is properly sited, it has limited environmental impact. That is why the number of wind power plants is growing in many countries.

Ukraine is participating in this worldwide process too. Ukrainian Complex Program on the construction of wind generators was passed in 1997. The Institute of renewable energy engineering was founded in the structure of the Ukrainian National Academy of Sciences in 2003 and one of scientific areas of the Institute is a development of wind energy systems. The production of several kinds of Wind Energy Conversion Systems (WECS) is established on the enterprises located in Ukraine.

The economic efficiency of a WECS depends on the average strength of wind on the location of wind power plant, efficiency of the energy conversion, and reliability of wind generators. Currently, the reliability is most important problem. One way to improve the reliability of WECS is a development of specific diagnostic systems and their implementation to the wind power plants.

One of the key problems in the development of the diagnostic system is an elaboration of the mathematical models of the real processes, which will be used for the diagnostics, since the method (and algorithm) of the diagnostics significantly depends on those models. Modern WECS is a complex technical object. One of the main peculiarities of its operation is irregular dynamic load applied to its construction and rotating parts. Thus the statistical approach to the diagnostics may give better results than deterministic one.

Within the statistical approach to the diagnostics, the mathematical models for the information signals should be selected from some class of stochastic processes. Let’s examine the main properties of linear random processes [3] in order to show their advantages for this purpose.

II. Linear Random Processes

A linear random process (LRP) $\xi(t), t \in (-\infty, \infty)$, defined in the probabilistic space $\{\Omega, F, P\}$, may be represented by a stochastic functional of the following form [3]:

$$\xi(t) = \int_{-\infty}^{\infty} \varphi(\tau, t) d\eta(\tau), \quad t \in (-\infty, \infty), \tag{1}$$

where $\varphi(\tau, t) \in L_2(-\infty, \infty)$ with respect to τ for all t is a non-stochastic real Hilbert function (a kernel of the process); $\{\eta(\tau), \eta(0) = 0, \tau \in (-\infty, \infty)\}$ is a Hilbert stochastically continuous random process with independent increments that is often called a generating process. While solving numerous problems including statistical simulation, it is convenient to consider the LRP as a response of some linear filter to the influence of white noise $\eta'(\tau)$. In this case $\varphi(\tau, t)$ is a pulse response of this filter and $\eta'(\tau)$ is understood as a generalized derivative of the corresponding process with independent increments.

As it is shown in [3], the LRP is an infinitely divisible process. This means that all its finite-dimensional characteristic functions (CF) are infinitely divisible ones. The CF of any order of the process (1) can be represented through its kernel $\varphi(\tau, t)$ and parameters of its generating process $\eta(\tau)$.

Process (1) can be used as a model of a wide class of real processes. It can be either stationary or non-stationary random process depending on the properties of both $\varphi(\tau, t)$ and $\eta(\tau)$.

If $\varphi(\tau, t) \equiv \varphi(t - \tau)$ and $\eta(\tau)$ is a homogeneous random process with independent increments, process (1) is stationary stochastic process. In this case the process (1) may be represented as

$$\xi(t) = \int_{-\infty}^{\infty} \varphi(t - \tau) d\eta(\tau), \quad t \in (-\infty, \infty). \tag{2}$$

Lets consider two n-dimensional vectors

$$(\xi(t_1), \xi(t_2), \ldots, \xi(t_n)) \tag{3}$$

and

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$$\left(\xi(t_1+T),\xi(t_2+T),...,\xi(t_n+T)\right), \quad (4)$$

where $\xi(t)$ is real random process (1), T – some real constant, and $t_1, t_2, ..., t_n$ belong to a set of separability of the process $\xi(t)$.

According to Slutskiy [7], random process $\xi(t)$ for which such $T > 0$ exists that two vectors (3) and (4) are stochastically equivalent in a wide sense for any integer $n > 0$, is called stochastically periodic. In this case number T is called a period of the process $\xi(t)$.

Recall that two random vectors are stochastically equivalent in wide sense if their distributions are coincided.

Now let’s assume that $\eta(t)$ is a Hilbert process with independent increments for which such $T > 0$ exists that the following relations are satisfied:

$$\begin{gathered} d\kappa_1(\tau) = d\kappa_1(\tau+T); \\ d\kappa_2(\tau) = d\kappa_2(\tau+T); \\ d_x d_t L(x,t) = d_x d_t L(x,t+T) \ \ \forall t \in (-\infty,\infty), \end{gathered} \quad (5)$$

where $\kappa_1(\tau)$ and $\kappa_2(\tau)$ are the first cumulants’ functions of the process $\eta(t)$; $L(x,\tau)$ is a Poisson jump spectrum in Levy formula.

And finally, let $\varphi(\tau,t) \in L_{2,\kappa}$ is a real non-random numerical function of period T such that

$$\int_{-\infty}^{\infty} \varphi(\tau,t) d\kappa_2(\tau) < \infty, \ \forall t \in (-\infty,\infty). \quad (6)$$

Process $\xi(t)$ defined by (1) using generating process $\eta(t)$ satisfying (5) and the kernel $\varphi(\tau,t)$ satisfying (6) is a non-stationary one and is stochastically periodic with period T. Such defined process is called linear periodic random process (LPRP) [2].

Note that stationary LRP is LPRP for any period T. Additionally, Hilbert LPRP is also periodically correlated random process (PCRP). As a rule, PCRP were studied within the L_2 theory framework, and their correlative and spectral structure is known in sufficient detail. The main disadvantage of PCRP is that for such processes the general expression of their characteristic function is difficult to write down.

Properties of LRP and LPRP, as well as peculiarity of their application as information signal models for different diagnostic systems, have been discussed in more details in [2] – [9], and [11], [12]. Briefly described above models of LRP and LPRP constitute the theoretical basis of the designed diagnostic system prototype.

III. The Prototype of the Diagnostic System

The prototype of the diagnostic system for WECS vibrational diagnostics has been developed at the Institute of Electrodynamics of the Ukrainian National Academy of Sciences (Fig.1). It is PC-based and contains special multi-channel device, which performs both preliminary processing (like amplification and filtration) and analog-to-digital conversion (ADC) of input signals.

Fig. 1. A photo of the diagnostic system prototype

The main functions of the developed prototype are following:

– measurement of the set of information signals;
– accumulation and saving of measured data;
– analysis of the measured data.

The prototype supports the measurement of vibrations of the following WECS elements:

– bearings of hub of wind turbine;
– bearings of generator;
– transmission;
– wind tower.

Additionally, it has a capability of the measurement of aerodynamic noise at the wind power plant.

The prototype supports the following sampling frequencies (may be selected by software): 62.5 kHz, 125 kHz, 250 kHz, 500kHz, 1 MHz, 2 MHz. 12-bit ADC and 128 kB buffer storage are embedded to the prototype. Some specifications of the diagnostic system prototype are presented in the Table I.

TABLE I

TECHNICAL SPECIFICATION OF THE SYSTEM PROTOTYPE

Parameters	Values
Frequency range of measuring signals	20 Hz – 30 kHz
Amplitude range of input signals	±1.024 V
Range of sampling frequencies	16 kHz – 2 MHz
Maximum duration of measuring signals	1 sec.
Number of measurement channels	4

IV. Software Description

Original software has been developed for the diagnostic system. A stochastic approach was used. Vibration signals of WECS parts are considered as linear stochastic processes. Early warning of failures (defects) of the WECS parts are based on the changes of statistical parameters of vibration processes, which accompany the WECS operation.

The software includes four modules:

1. Main module.
2. Module of processing and visualization of data.
3. Data storage management module.
4. Interface module for analog signals input.

Fig. 3 shows the structure of the software.

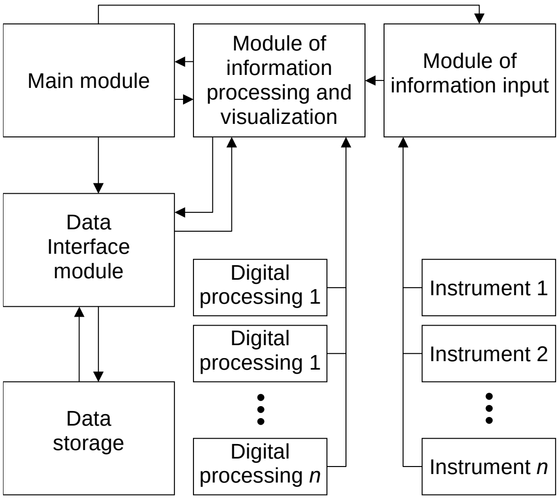

Fig. 2. The structure of the developed software

Main software module connects and controls all others modules. The software interface is based on the «Dock Management» technology. This makes a developing of software quite flexible. Modules of data analysis are the dynamic libraries, which include analysis procedures for determining of the set of statistical parameters and visualization elements. Currently the software includes following signal processing methods:

– histogram analysis with Pearson's smoothing;
– autocorrelation analysis of information signals;
– statistical spectral analysis.

The software also has a decision-making module. Some of the methods are discussed in [2], [4], [7], and [11].

Data storage management module allows long-term data storage and retrieval for the processing. Data sets may be converted to the common format "XY" allowing data exchange with other software packages.

Interface module for analog signals input allows usage of different measurement equipment without changing the software kernel.

V. The Use of the Diagnostic System Prototype

For the concrete definition of the mathematical models of the information signals, which may be used for the diagnostics of WECS, some statistics should be collected form the real equipment. The prototype of the diagnostic system was used for investigation of vibration parameters of USW 56-100 wind turbine at the site of Ukrainian corporation "PO Yuzhmash". Both histogram analysis with Pearson smoothing curves application and statistical spectral analysis of the vibrational signals have been carried out during the experimental investigation. Different types of vibration transducers were used during the research.

Experimental investigations were performed in so-called "engine" mode of operation of wind turbine. This means that electrical power was applied to generator, which worked as engine. The average speed of rotation of the generator's shaft was equal to 1449 turns per minute, and the average speed of rotation of the shaft of wind wheel hub was equal to 72 turns per minute, which are the rated values.

The following transducers were installed at the wind turbine: VT1 (accelerometer of type DN-4), VT2 (accelerometer D-14), VT3 (accelerometer ABC-017), VT4 (seismic transducer SV-10C). Different types of transducers were used in order to select the most effective transducer type for WECS vibrational diagnostics.

Transducers VT1-VT3 were sequentially installed at the different parts of wind turbine. Places of the transducers installation are shows on Fig. 3.

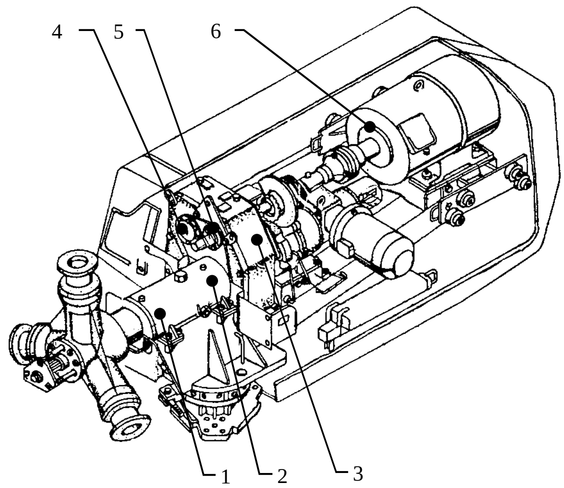

Fig. 3. Places of transducers installation: 1) casing of main shaft in radial direction near bearing at the side of wind wheel hub; 2) casing of basic shaft in radial direction near bearing at the side of transmission; 3) casing of transmission near bearing of low rotating speed shaft in radial direction; 4) casing of transmission near bearing of middle rotating speed shaft in axial direction; 5) casing of transmission near bearing of high rotating speed shaft in axial direction; 6) casing of generator near working end of shaft in radial direction.

Sampling frequency was equal to 15625 Hz during the testing research. Volume of each investigated vibration signal realization was equal to 16000. Estimations of spectral and correlation functions and distribution functions were calculated.

As an example, some statistical parameters of the vibration signal from transducer VT1 installed at the casing of transmission near the bearing of low rotating speed shaft in radial direction were estimated. It was assumed, for the first approximation, that the signal is a stationary linear stochastic process. The estimation of the normalized autocorrelation $R(\tau)$, power spectrum $S(f)$, and the histogram with Pearson's fitting curve (of the type VII) of this signal are shown on the Fig. 4, Fig. 5, and Fig. 6 correspondingly.

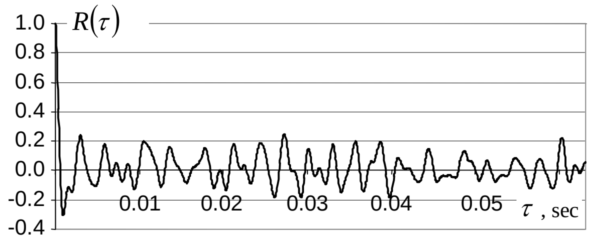

Fig. 4. Estimation of the normalized autocorrelation function of vibration signal on the casing of transmission

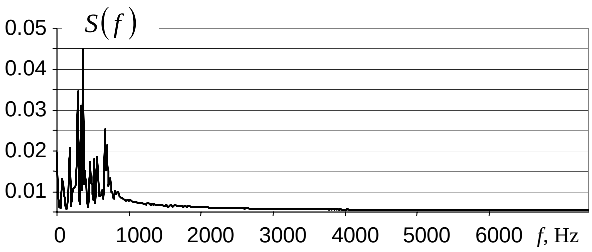

Fig. 5. Estimation of power spectra density function of vibration signal on the casing of transmission

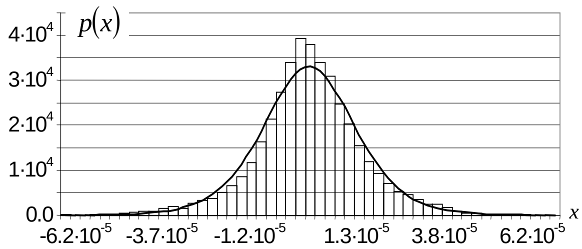

Fig. 6. Histogram and smoothing curve of Pearson's type VII of vibration signal on the casing of transmission

From the oscillations of the autocorrelation, and from the explicit peaks of the power spectrum we can conclude, that the signal has cyclical nature. Since Pearson's fitting curve of this signal is of type VII we can consider that the process has Gaussian distribution, which is infinitely divisible. These facts mean that the model of linear periodic stochastic process with Wiener generating process could be used for the mathematical description of the signal.

VI. CONCLUSIONS

The developing of diagnostic system is a sufficiently difficult problem. It includes both theoretical and experimental investigations. Elaboration of mathematical models of the information signals and investigation of the statistical parameters of the processes are very important for the developing of the diagnostic system. The concrete algorithms of the system operation depend on statistical properties of analyzed and controlled parameters.

We considered the information signals, which could be used for the diagnostics of WECS and have proposed the linear random processes and linear periodic random processes as their mathematical models. It is necessary to remark that these models can be applied not only to the development of diagnostic systems for WECS, but also in the communication systems, control systems, biomedical systems.

Using the developed prototype of the diagnostic system of WECS, some possible diagnostic parameters were estimated. Estimations of diagnostic parameters were analyzed. Obtained results are showing that diagnostic algorithms and software may be developed for the WECS parts with application of statistical methods demonstrated in [2] – [9], and [11], [12].

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