Chapter

Hybrid Electro-Optic Capacitive Sensors for the Fault Diagnostic System of Hydrogenerator

Ievgen O. Zaitsev and Anatolii Levytskyi

Abstract

This chapter presents one of the ways of solving a problem ensuring reliability reducing instability and emergence of the power generators during its work. Its way use hybrid electro-optic sensors (HFOS) with capacitive mechanical sensors at their structure of the fault diagnosis system of hydro generators for measurement parameters of machine mechanical defects as quality parameters of air gap, shaft out, core compression ratio and other. So this chapter also contains: principle of measurement of the sensor, which based on measuring the mutual displacement of the flatness of the generator structural element relative to coplanar sensor electrodes surface; the design principle for developing HFOS with capacitive mechanical sensor which combines the benefits of microelectronic and fiber-optic technology; determination response characteristics of the sensitive sensor (capacitive sensors with coplanar electrodes) of HFOS for monitoring air gap defects and power accumulators of core clamping system and system of control; analytical calculations and experimental studies of air gap HFOS with the AD7746 at its operating excitation frequency using; optimum geometry calculation of air gap sensor electrodes for bulb hydro generators type SGK 538/160-70M; analyze application the air gap HFOS for the control system in the bulb hydro generators type SGK 538/160-70M.

Keywords: hydro generator, air gap, hybrid, measurement, capacitive sensor, displacement

1. Introduction

Hydroelectric power plants (HPP) are an important part of generating capacities that are capable not only for generating electricity but also due to the high mobility of hydraulic units and the pumped storage power plants use to provide a balanced load on the unified power grid during peak hours. Most of the hydroelectric power plants that are part Ukrhydroenergo PJSC have worked for a long time, more than 20 years. Only 45 hydraulic units from 103 were reconstructed in 2018, which made it possible to extend their lifespan by at least 40 years [1].

So, an important problem to be solved during the reconstruction of existing hydroelectric units as the design of new is to increase the reliability of operation and determine the actual technical condition of the hydraulic unit as a whole mechanical system. The solution to this problem requires a range of specialized measuring instruments for registration of diagnostic parameters, characterizing the flow of work processes in the hydraulic unit systems of their technical diagnostics.

Vibration diagnostics systems are widely used to obtain information on the state of the hydraulic unit. Sensors of this system mounted directly on the machine body for measured vibration parameters [2]. But, monitoring only the vibration parameters makes it possible to identify not all defects in various machine components. This is due with inaccuracy of diagnosis is often associated with measurement errors and incorrect interpretation of vibration measurement results, caused by insufficient temperature stability of vibration transducers, high noise levels, neglecting the features of machine vibration in the high-frequency and low-frequency areas, errors in the determination of discrete components of vibration during spectral analysis, and also due insufficient consideration in diagnostic systems specificity of stochastic fluctuations of the electromechanical equipment [3].

So, an important aspect to improve the performance of electric machines at the electricity generating station (thermal, atomic, hydro) it is the monitoring of their mechanical parameters. Change of mechanical parameters characterizes technical condition of the electric machine's equipment and exerts impact on the main energetic affectivities of working the generating station [4, 5].

Detection of defects which appear in the operating time of the machine at an initial stage of their emergence and timely acceptance the right decisions on their elimination before the emergence of an emergency situation provides a high level of readiness, reducing of downtime, lowering of costs of repairs.

Nowadays the usual ways to improve the performance of new and existing electrical equipment is design and realized new instruments for monitoring mechanical parameters of electrical equipment of the power generator [6–9].

2. Air gap as crucial parameters for characterizing technical condition of HPP

One of the major mechanical parameters that characterize the technical condition of electric machines equipment is its air gap. In hydro generators it is provided, the air gap is small in small as compared with the stator bore diameter. The air gap is a nominal or measured value between the hydrogenerator rotor and stator, or literally speaking it is the "heart" of a hydrogenerator, because in the air gap the mechanical energy is transformed into the electric energy [10]. While machine work it is difficult to obtain stable size and uniformity of the air gap. The air gap deviations from nominal value are resulting of distortion of the air gap between the stator core and rotor. The air gap deviations from nominal value are resulting of distortion of the air gap between the stator core and rotor. The air gap deviations may be caused by deviations of machine construction, static or dynamic eccentricities, cone rotor, ellipse-shaped surfaces of the stator and rotor and other factors [11]. Technological inaccuracies resulting in an eccentricity are practically impossible to avoid in a production process of the power generators for HPP [12, 13].

Therefore control and monitoring of the air gap that is one of the most important quality parameters of HPP is very important. For doing this usually way it is the air gap sensors use [6–9]. Information's from the sensors in automated measuring systems used to simplify testing and minimize repair time, to avoid accidents during machine operation. Capacitive sensors for measuring air gap in hydrogenerators are represented by the following companies:

- Vibro-Meter LS120 for range 2–33 mm [14]

- Iris Power for different ranges from 5 to 47 mm [15];

- Bently Nevada offers a 4000 Series Air Gap Sensor System with an air gap sensor up to 20 mm [16];
- HUBER+SUHNER has developed the air gap sensor consisting of a fiber-optic loop [17].

All existing sensors are designed to be used only on definite types of generators. Sensors adaptation underuse into a definite type generator requires considerable financial costs [16, 18]. So promising for the construction of technical diagnostics of power equipment is used HFOS [4, 16]. HFOS combines the benefits of fiber optic and microelectronic technologies [8, 9, 19].

3. Air gap parameters and their influence on key characteristics of hydrogenerators

The air gap between the rotor and the stator is one of the most important parameters of a powerful generator. The size of the air gap largely determines the characteristics of the machine and its behavior during operation.

Due to the irregularity of the air gap, an asymmetry of electromagnetic forces occurs in the GG, which in turn leads to the appearance of vibration and an increase in the surface temperature of the rotor. One of the signs that the vibration has arisen due to the uneven gap is its dependence on the excitation current. When the excitation is removed, the vibration disappears completely.

The small size of the pole distributions of the hydrogenerators causes large scattering of their pole system, high inductions in the cores of the poles and causes difficulty in placing the required volume of the excitation copper winding at the poles. This leads to hydrogenerators resort to reduce air gaps. In practice, given the above factors, the values of air gaps are taken in one thousandth of the rotor diameter.

The value of the air gap also significantly influences a number of other characteristics of hydrogenerators, namely: the end magnetic fluxes of losses in the extreme packets of the core and the stator pressure plates, the vibrational state of the machine during operation. Thus, both the thermal state of the hydrogenerators as a whole and the level of local heating are largely determined by the value of the air gap. In addition, the areas of acceptable modes of operation of hydrogenerators (with the condition of non-excitation) are also determined by the value of the air gap [20–30].

Distortion of the rotor and stator shape of the hydrogenerators, which leads to an uneven air gap, can cause accidents (due to rotor engagement on the stator), failure of the windings, steel cores, and poles. It is especially difficult to achieve a stable operating gap even if the air gap is small (compared to the stator bore diameter). Creating a design that resists the magnetic pull in such a machine configuration is one of the most difficult tasks in the development of hydrogenerators.

Often, damage caused by a change in shape or a violation of the alignment of the stator and rotor cores has been observed. Thus, the largest at one time HG HPP Grand Coulee Dam (USA), having an air gap of 25 mm with a rotor diameter of 19 m, repeatedly failed due to the displacement of the active parts of the machine. At the same time, there was even engagement of the rotor for the stator, which led to the need for their reconstruction with increasing the air gap and increasing the strength of the stator core [20]. Serious problems with deformation of the rim of the rotor were on the hydropower generators Mica Creek (Canada). These machines, with a diameter of 14 m, have a nominal air gap value of 20.6 mm [20].

The difficulties with maintaining the air gap within the acceptable limits for the hydrogenerator is illustrated by the example given by a representative of Alstom Jeumont [20]. When the stator core is heated, the diameter of 17 m will expand by 5 mm and the rotor by 5.3 mm (the estimated air gap for this machine is 24 mm). Considering also the magnetic pull forces between the stator and the rotor, which are aimed at reducing the air gap, the designer has a difficult task to maintain the cylindricality of the rotor rim, the uniform expansion of the stator and the spokes of the crosspiece.

During operation of capsule SGs type SGK 538/160-70 of Kyiv and Kaniv hydroelectric power stations, due to the distortion of the stator shape and imperfect rotor shape, the air gap between the rotor and stator varied in both radial and axial direction: at a nominal value of 5 mm the gap did not exceed 3.5 mm [24, 29]. Due to the significant reduction of the air gap, the load on the damper winding, which it was not designed for, increased sharply. In the end, this led to the destruction of the damper system: there was a rupture of the cores, the burning of core steel and the fall of the damper rods from the core into the air gap, as well as significant damage to the core and stator winding. During the reconstruction of these hydropower generators, the following was done to prevent such accidents: the nominal air gap between the rotor and the stator was increased to 6 mm, the adjusting gaskets for the rotor poles were introduced, and the requirements for the correct form of the stator bore were increased.

The irregularity of the air gap, accompanied by the deviation of the bore of the stator core and the bypass pole of the rotor from the cylindrical shape, can occur during the installation, after it, as well as under operating conditions of the generator. Electromagnetic forces of the mutual attraction of the stator and rotor, as well as redistribution of internal stresses, can lead to deformation of the stator and rotor core. Uneven heating of the stator packs and rotor poles can also contribute to the deformation of the generator units.

It is also known that the irregularity of the air gap in height and radius of the magnetic system of the hydrogenerator is the cause of the vibration of the stator and rotor and the cause of additional losses on the surface of the rotor poles [30].

The deviation of the air gap from the nominal value can also be caused by defects in the design of fastening elements, violations of the technology of assembly of the hydrogenerator at the station, degradation processes during operation of the unit under the action of electromagnetic and thermomechanical loads [20].

Analyzing the above, it can be argued that to control the air gap in powerful GH requires reliable high-performance devices, designed with the design features of the machine.

4. The architecture of the control system with HFOS for electric machine faults monitoring system

The architecture of electric machines faults diagnostic system incorporates a wide range of mechanical sensors to control many technological parameters. However, in practice, during operation of the machine, external influences (electromagnetic fields, temperature, etc.) act on the measuring equipment. For avoiding external influence on the sensor and control systems operation unit is used fiber optic and other electro-optical components. The benefits of the optics components make possible to use HFOS in applications for measurement parameters of mechanical faults in working environment of large generator with high-EMI field, temperature, pressure, explosive, noisy, etc. [9].

The HFOS structure for large generator faults monitoring system shows on **Figure 1**, has following notation: PSCS – primary special capacitive sensor of the mechanical parameters with capacitance-to-digital converter on board; SigPr – microcontroller unit or signal processing unit; SW – switch; OPS – converter optical energy to power supply of HFOS unit; OF – optical fiber; OCS CMP – control systems operation unit for large generator fault diagnostic system; Optical Tx/Rx – indirect way its converter optical digital code to electrical digital code with digital controller and reversed way its electrical to optical digital code.

Figure 1 shows a simplified structure of control system processing tools with a complete mapping of the structure of the HFOS microelectronic and optoelectronic components in functional groups. The system consists of two parts: HFOS in isolated area and processing tools of the monitoring system. The monitoring system processing tools located in isolated areas on safe distance which provides a low level of external influences (electromagnetic fields, temperature, etc.) [8, 9].

Group of unit of HFOS in isolated area integrates a capacitance-to-digital converter (CDC) AD7745/AD7746 from Analog Devices, Inc. (Norwood, MA, USA) [31] on primary capacitive sensor circuit board material made from FR4 copper clad laminate printed circuit board (PCB) [32], optical Tx/Rx implementations by analogy described in [33] with low power microcontroller and vertical-cavity surface-emitting semiconductor laser with very low threshold current, semiconductor photovoltaic energy converter (labeled as the "OPS").

In the system described in the work [9], a pair of optical fibers connects the OPS and vertical cavity surface emitting semiconductor laser to the external system to receive power energy by optical cable and measurement data by fiber optic. Moreover, one optical fiber to receive control data to microcontroller from main system used.

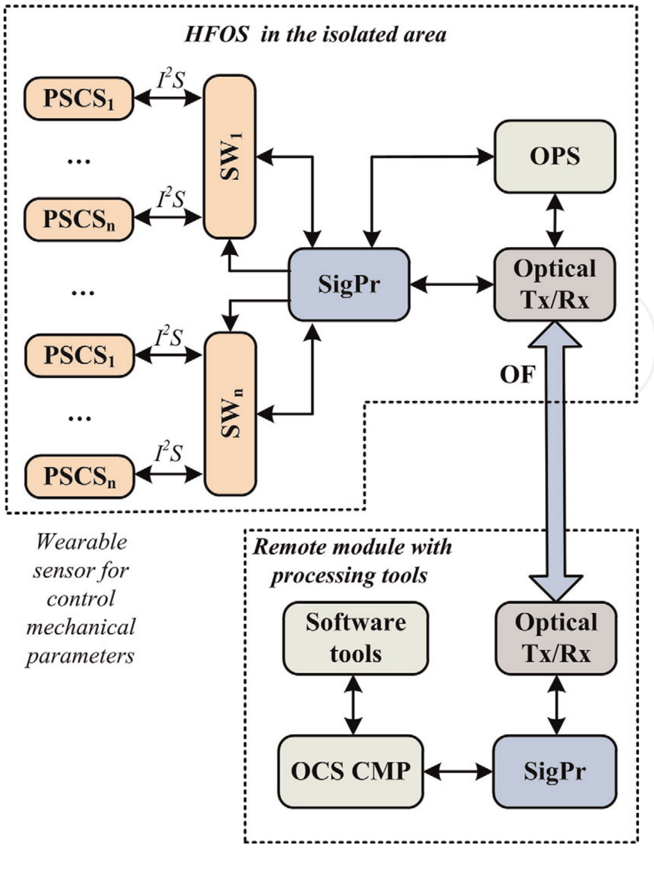

Figure 1.
Control system with HFOS.

The group of blocks in a safe area integrates "optical Tx/Rx," SigPr system and digital part with a special software solution for detection and monitoring mechanical faults of the electric machines. In the remote zone there is a user interface through which the operator controls the operation of the system and receives information about the state of the object.

5. Work principle by HFOS for large generator faults monitoring system

5.1 Principle of work primary capacitance sensor for electric machines mechanical faults monitoring system

Capacitive sensors can be applied for measuring a different kind of non-electrical quantities [34, 35], such as mechanical parameters of electric machines equipment: geometrical dimensions change, displacement and vibration of grounded surfaces, air gap, and position of the object, core compression ratio and others. Capacitive mechanical sensors are the most widely used non-optical sensors in short-range positioning applications owing to their excellent resolution [18].

The principle of measurement of a capacitive sensor is based on the change in the capacitance with the distance of the capacitor with parallel electrodes coplanar witch are located in one place. **Figure 2** has shown the typical design of coplanar sensor. The coplanar sensor consists of the following parts: hi-potential electrode 1; low-potential electrode 2; low-potential guarding electrode 3; dielectric substrate 4; metal substrate 5, which is installed on a grounded surface special elastic element which is located on the stator between stator bore and rotor polys [36].

Electrical capacity C of the coplanar sensor between electrodes 1 and 2 will change when change air gap between rotor and stator bore of the hydrogenerator [8] and can be calculated as [32, 36]:

$$C = f(d) \tag{1}$$

where d is a distance between the electrodes of the capacitance sensor.

Based on this principle was implemented mechanical sensor for measuring the value of air gap and other in the hydrogenerator.

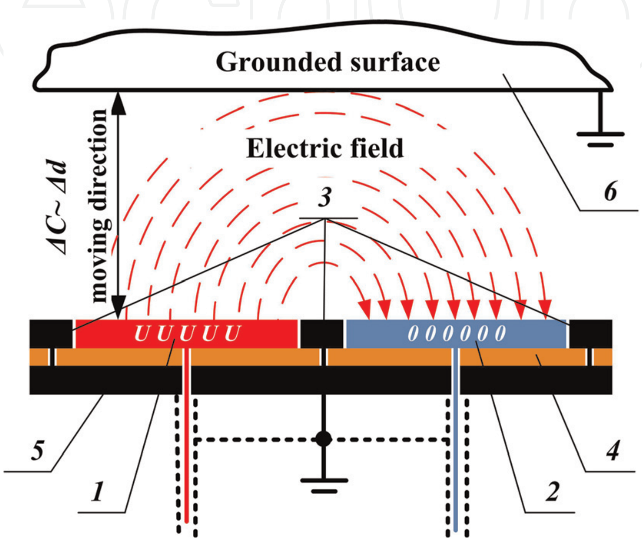

Figure 2.
Capacity sensor with coplanar electrodes.

DOI: http://dx.doi.org/10.5772/intechopen.88947

5.2 Principle of work microelectronic components

The base of the principle of operation the system shown in **Figure 1** is described in [9] and is as follows: the primary measuring transducer (sensing element PSCS) converts the value of a controlled parameter of a mechanical defect into a digital code like NRZ. Then the SigPr communication subsystem collects measurement information from the PSCS and converts the information data into a modulated optical signal [9]. The signal is transmitted by optic fiber-cable (OF) to optical Tx/Rx module where optical signal converted into an electrical signal. The electrical signal as digital code like NRZ send to processing tools as data information processing system OCS CMP and use for analysis with special software tools. In the case of the transmission of digital control data signals for PSCS transducers, the OCS CMP system works in the similarly [9]. The architecture of HFOS was detail analysis in work [8, 9].

For converter capacitance value of the primary sensor to digital code chosen capacitance-to-digital converter (CDC) AD7745/AD7746 (Analog Devices, Inc., Norwood, MA, USA) with temperature sensor. The use of a 24-bit sigma-delta converter allows the resolution of the measurement range of an informative capacity of 4fF [31].

5.3 Principle of work power optoelectronics components

The benefits of fiber optics make it possible to use the capacitive sensor in applications for measurement mechanical parameters of power generator in their working environment with high-EMI and magnetic field, temperature, pressure, hazardous, explosive, noisy and etc. Data sent by data optic fiber. Power supply for primary measuring converters HFOS in an isolated area can transmit by the following ways [19, 33, 34, 37–45]:

a. with the autonomous power supply:

- using battery power directly adjacent to the meters;
- with the help of energy from power sources realized by technology "Energy Harvesting" and located directly adjacent to and / or component of the meters;

b. powered by a fiber optic line:

- energy transmitted through the power optical line, which can be used:

  i. single-mode fiber;

  ii. multimode fiber;

  iii. optical harness;

- using the energy transmitted through the information-power optical line, implemented on the basis of "Wavelength-Division Multiplexing" technologies (multimode fiber).

In the system that we are reporting, the second option was used when light connected to one optical fiber with a unique photovoltaic converter on the one hand, and a powerful laser that was located in SigPr on the other was used to power it. For photovoltaic energy converter it proposed to use semiconductor photovoltaic cells based on crystalline GaAs.

5.4 Principle of work software solution

Remove module of the monitoring system consist of optical converters with microcontroller for communication and a personal computer, which functions under the control of specialized software. Its functions designed for [5]:

- the definition of the class of possible defects (the most important or most frequently encountered) that must be identified;
- selection of diagnostic signals available for measurement, and control points on the object under study;
- development of a mathematical model of the diagnostic object, the analysis of which allows substantiating possible diagnostic parameters;
- development of algorithms for obtaining numerical values of selected diagnostic parameters;
- construction of decisive rules for identifying and classifying defects; creation of means implementing certain steps of the diagnostic process from the selected measurement and diagnostic signals before making diagnostic solutions.

The system software (primary data acquisition and processing module) consists of the following parts: a data processing software module from CDC and CDC control, a microcontroller configuration module, a primary data processing module [46].

The CDC control module algorithm for converter capacitive value to code and receive the digital data to the monitoring system use algorithm from [31] for "AD7746," the data exchange for designed to provide the organization of data exchange between hardware and software monitoring system and CDC.

Operations of calculating the value of the mechanical parameters special software solution is used. Processing of the received data in the control module of mechanical parameters state of the control is used for the value of the mechanical parameter and analyzed its status and changes. In turn, obtained at the work of the module of mathematical processing and module of automatic control of the state of the electrical equipment node is transferred to the data storage organization module for database management based on the history of measurements. In this case, it is possible to create knowledge bases with diagnostic features, which depend on the value of the physical parameter that is control of the certain state of the power equipment.

The connection of the monitoring system and HFOS module in the isolated area is transfer with a developed communication protocol for the fiber-optic line communication. In addition, the module for input and output information SigPr is designed for organizing the exchange data between the modules of the system.

6. Sensitive elements of air gap HFOS for the hydrogenerator faults monitoring system

6.1 Basic principle of the air gap control in the large hydrogenerator

Nowadays the usual method for the designed and realized sensor for the air gap measurement in the powerful hydrogenerator is a capacitive method [4, 10, 47–49], now. When you use the method of capacitive sensors mounted on the bore of the stator core.

In this method, the electrical C capacitance sensor depends on the size of the air gap d and can be calculated by Eq. (1).

In [50] present variant when the two capacitive sensors are mounted on the same plane with the angle between them is 90 degrees. **Figure 3** shows example of the installation air gap sensor with the control system on the stator core of the bulb hydro generators type SGK 538/160-70M. **Figure 3** has the following notation: 1 – stator core; 2 – air gap capacitive sensor; 3 – connecting cable between the sensor and the converter; 4 – secondary transmitter; 5 – connecting cable between the converter and the computer; 6 – computer with processing tools.

6.2 Influence on the measurement accuracy of the air gap of the skew of the sensor electrode relative to the surface of the stator core

Influence on the measurement accuracy can be calculated by use obtaining results in the paper [49–51] by the equations

$$\Delta C_{12i} = \frac{\varepsilon_0 \varepsilon}{\pi} \Delta y_i \ln \frac{\left(\mathrm{th}\frac{\pi s}{4z_i} + \mathrm{th}\frac{\pi(s+2b)}{4z_i}\right)^2}{4\mathrm{th}\frac{\pi(s+2b)}{4z_i}\mathrm{th}\frac{\pi s}{4z_i}}, \quad (2)$$

where b – width of the electrodes 1 and 2; s – the distance between the electrodes 1 and 2; z_i – the distance between the plane and the plane of the strips **5** and **4** after the onset of warp (**Figure 4**).

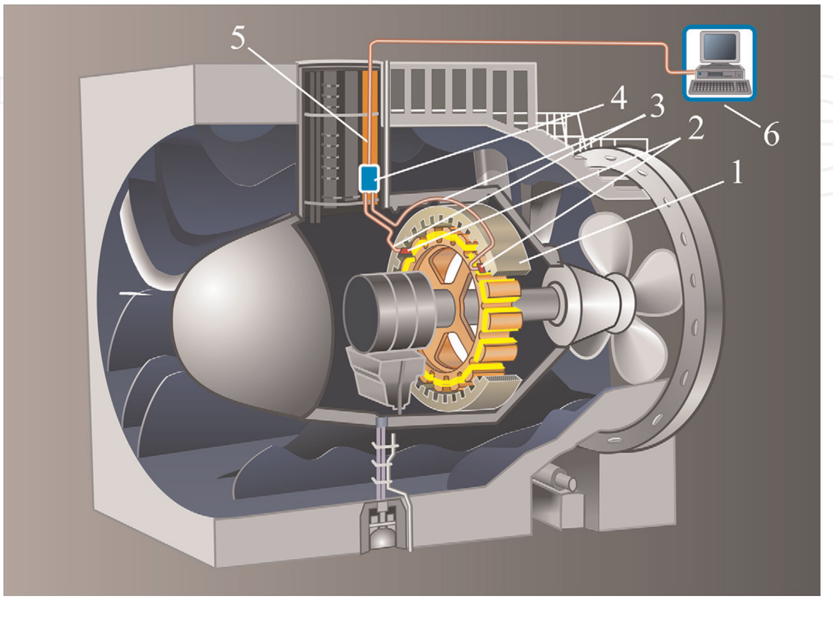

Figure 3.
Example of an installation control system with two HFOS.

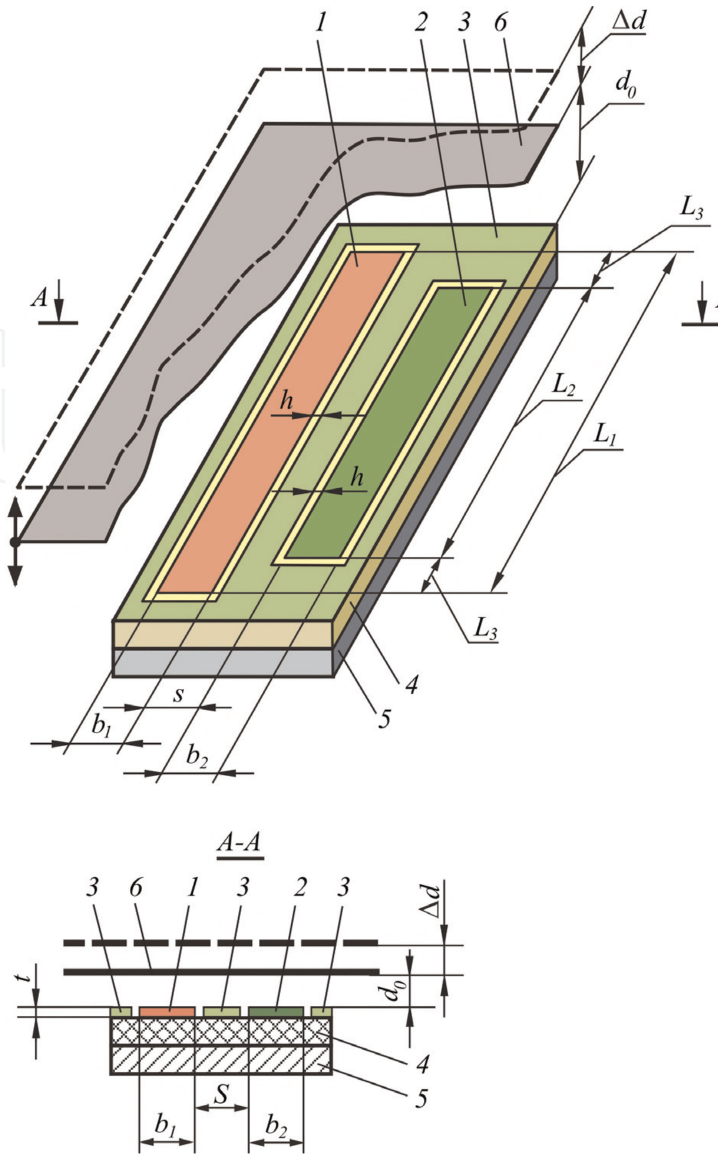

Figure 4.
Scheme for calculating the influence of plane electrode sensor.

Considering $A_0A_1 = d0$, $A_1A_2 = \Delta z_i$, $\Delta z_i/y_i = tg\alpha$, z_i defined as:

$$z_i = d_0 + \Delta z_i = d_0 + y_i \text{tg}\alpha, \tag{3}$$

where y_i – the distance between 5 and point of start coordinates O; d_0 – the distance between the plane and the plane of the electrodes 4 before warp; α – the angle between the plane and the plane of the electrodes 4, resulting warp.

The capacity $C_{12\Sigma}$ of the sensor use Eqs. (2) and (3) can calculate as:

$$C_{12\Sigma} = \sum_{i=1}^{i=\infty} C_{12i} = \sum_{i=1}^{i=\infty} \frac{\varepsilon_0 \varepsilon}{\pi} \Delta y_i \ln \frac{\left(\text{th}\frac{\pi s}{4(d_0 + y_i \text{tg}\alpha)} + \text{th}\frac{\pi(s+2b)}{4(d_0 + y_i \text{tg}\alpha)}\right)^2}{4\text{th}\frac{\pi(s+2b)}{4(d_0 + y_i \text{tg}\alpha)}\text{th}\frac{\pi s}{4(d_0 + y_i \text{tg}\alpha)}}. \tag{4}$$

Without warp capacitance C_{12} between electrodes **1** and **2** is defined by Eq. (4) [50].

The error of warp δ_Π defined by using Eqs. (2) and (3) as:

$$\delta_\Pi = \frac{C_{12} - C_{12\Pi}}{C_{12}} \cdot 100\% = \left(1 - \frac{\frac{\varepsilon_0 \varepsilon}{\pi} \int_0^L \ln \frac{\left(\text{th} \frac{\pi s}{4(d_0 + y\text{tg}\alpha)} + \text{th} \frac{\pi(s+2b)}{4(d_0 + y\text{tg}\alpha)} \right)^2}{4\text{th} \frac{\pi(s+2b)}{4(d_0 + y\text{tg}\alpha)} \text{th} \frac{\pi s}{4(d_0 + y\text{tg}\alpha)}} dy}{L \frac{\varepsilon_0 \varepsilon_r}{\pi} \ln \frac{\left(\text{th} \frac{\pi s}{4d_0} + \text{th} \frac{\pi(s+2b)}{4d_0} \right)^2}{4\text{th} \frac{\pi(s+2b)}{4d_0} \text{th} \frac{\pi s}{4d_0}}} \right) \cdot 100\% \qquad (5)$$

Define capacity $C_{12\Sigma}$ and C_{12} sensor gap [50], for use in capsule hydrogenerators SGK 538/160-70M with next parameters b = 12 mm, s = 2 mm, L = 180 mm, using Eq. (4) and [32]. Result defines capacity $C_{12\Sigma}$ and C_{12} shown in **Figure 5**.

Using Eq. (7), determine the numerical value of warp error for the hydrogenerators SGK 538/160-70M and plot them in **Figures 6** and **7**.

6.3 Experimental studies

6.3.1 Design of the sensitive elements of air gap HFOS

The air gap sensor for the control system in the hydrogenerator is designed and realized in the Department of electric and magnetic measurements of the Institute of Electrodynamics of the NAS of Ukraine. The development sensor with processing unit was shown in **Figure 8**.

6.3.2 Temperature stability

Generally, the coplanar air-gap sensor is developed and designed for work in temperature range from −30 to +80°C. The low-limit of temperature can be during

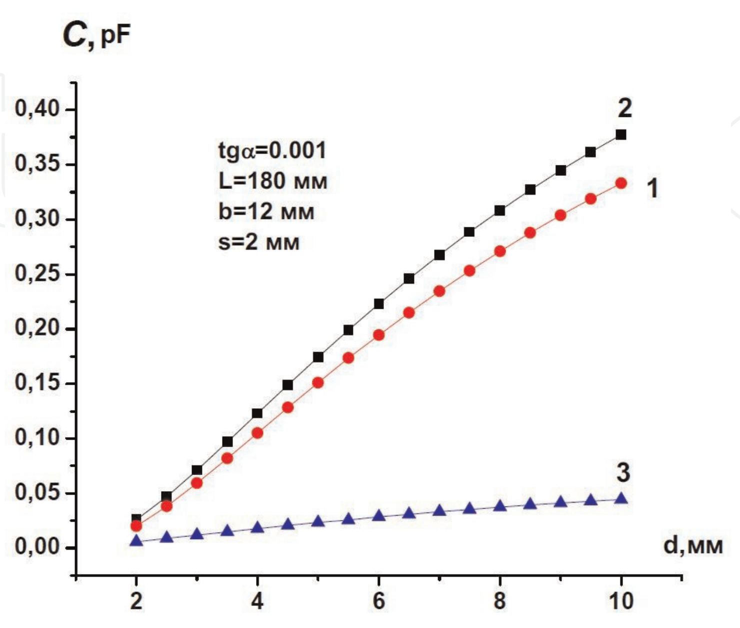

Figure 5.
Capacity $C_{12\Sigma}$ and C_{12} as measurement range: 1 – Change of capacitance $C_{12\Sigma}$ in a nominal measuring range from 2 to 10 mm with warp; 2 – change of capacity C12 without warp; 3 – the capacities difference $\Delta C = C_{12} - C_{12\Sigma}$.

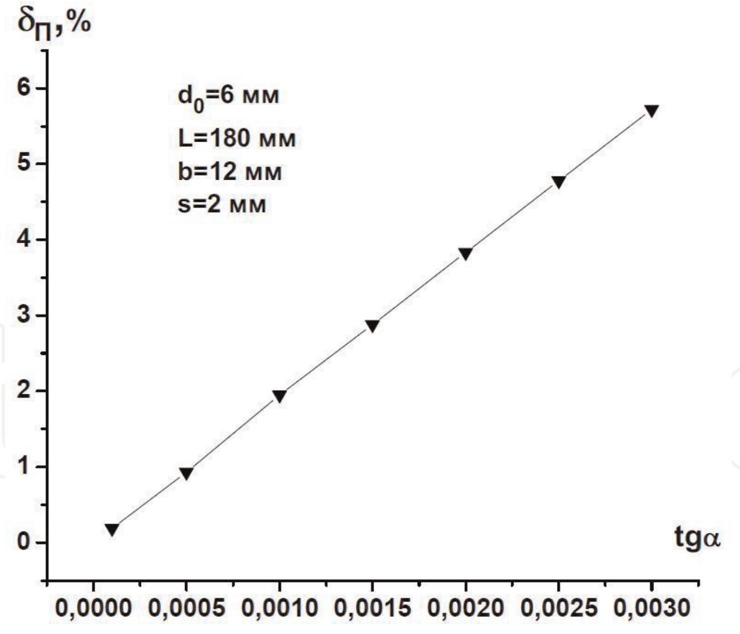

Figure 6.
Angle warp as error for d_o = 6 mm.

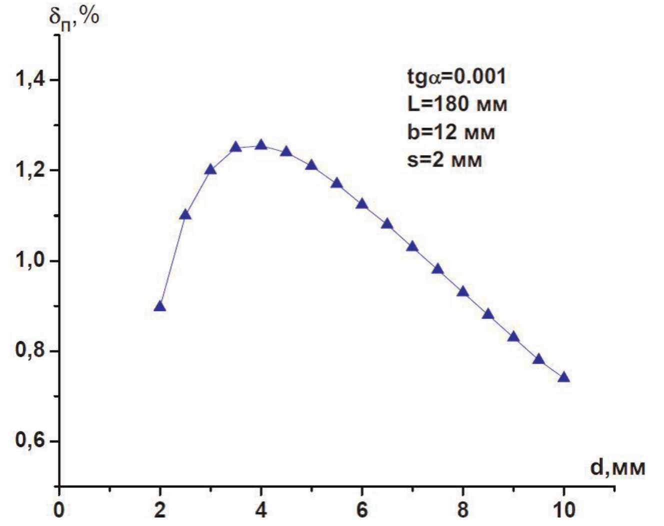

Figure 7.
Air gap as error for warp $\alpha \approx tg\ \alpha = 0.001$.

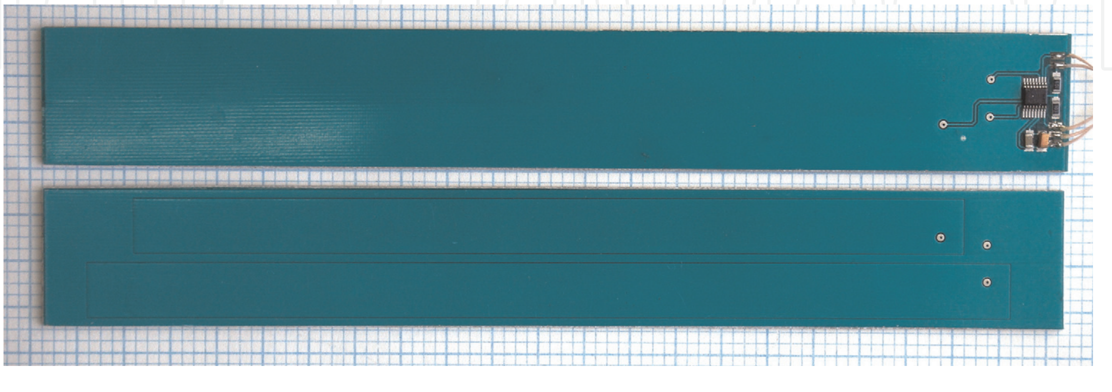

Figure 8.
Realized sensors in the department of electric and magnetic measurements of IED NASU: top – reverse side of the sensor; bottom – operational side of the sensor with working electrodes.

an initial setup or during a planned inspection of the hydrogenerators. In the operator the hydrogenerators have temperature nearly 70–80°C.

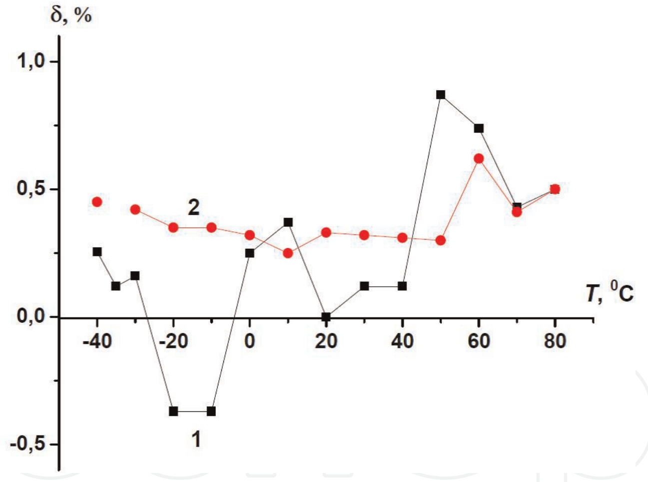

Figure 9.
A plot of the capacitance values in the temperature range from −30 to +80°C: 1 – the curve of capacitance C12P for the direct change; 2 – the curve of capacitance C12Z for the reverse change.

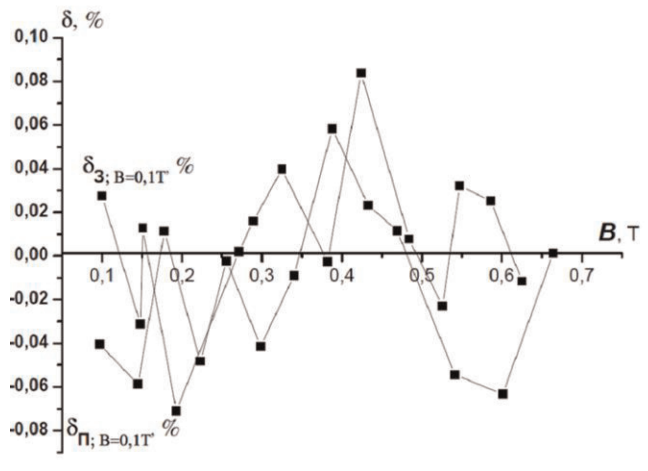

Figure 10.
The test sensing element for air gap HCS: $\delta_{\Pi;B=0,1\ T}$ for the direct change induction of electromagnetic field and $\delta_{3;B=0,1\ T}$ – for the reverse change induction of electromagnetic field.

Study influence of temperature stability is described detail in work [51]. And obtained result of the study's influence of the temperature on the stability of the air gap sensor was shown in **Figure 9**.

6.3.3 Electromagnetic stability

For experiments was designed special stand. The values of electromagnetic field industrial frequency are described in the works [52, 53]. The stand works as follows: variable voltage from the source is creating magnetic field in the air gap of coil. This magnetic field is modeling of electromagnetic field industrial frequency in turbo generator. In experiment values of electromagnetic field varied in range between 0.1 and 0.68 T. The principle of operation and the scheme of a special stand are described detail in following works [54].

The results of the natural experimental study of electromagnetic field influence on the measurement accuracy error of the air gap sensor shown in **Figure 10**.

Study industrial frequency magnetic field influence on microcontroller functioning stability is described as detail in work [55].

7. Conclusion

1. The structure and principle of operation of hybrid electro-optical sensors for the fault diagnosis system of large generators presented. Using fiber optic for data transmission allows you to easily and economically solve the implementation of anti-noise sensors for monitoring, control and measurement systems that are not subject to electromagnetic interference, electrical interference, explosive, can work in high-voltage or high-temperature environments. The hybrid sensor of the proposed design can be easily adapted to measure various parameters of mechanical defects in large generators.

2. It is shown that the skew of the sensor plane relative to the stator bore leads to technological errors.

3. The obtained experimental results confirm the possibility of using the proposed coplanar air gap sensor for air control systems in capsular hydrogenerators of the SGK 538/160-70M type.

The obtained results set the efficiency of the capacitive air gap sensor under the influence of industrial frequency magnetic field from 0.1 to 0.63 T.

Author details

Ievgen O. Zaitsev* and Anatolii Levytskyi
Department of Electric and Magnetic Measurements, The Institute of Electrodynamics of the NAS of Ukraine, Kyiv, Ukraine

*Address all correspondence to: zaitsev@i.ua

References

[1] Rassovsky VL. Ukrhydroenergo 15 years old. Hydroelectricity in Ukraine. 2018;**3-4**:4-7

[2] Chepulsky YP, Zamaraev KS. Vibration Diagnostics of Machine Parts. Moscow: MIIT; 2009. 75p

[3] Zaitsev IO. Opto-electronic transducer for large hydro generator shaft run-out fault diagnostic system: Design and measurement principle [thesis]. Kiev: IED NANU; 2019

[4] Levytskyi A, Fedorenko G, Gruboi O. Control of the State of Powerful Hydro and Turbogenerators by Means of Capacitive Measuring Instruments of Mechanical Defects Parameters. IED NANU: Kiev; 2011. 242p

[5] Babak SV, Myslovich MV, Sysak RM. Statistical Diagnostics of Electrical Equipment. IED NANU: Kiev; 2015. 456p

[6] Rolim F, Tetreault A, Marshall R. Air Gap Monitoring System Key Element to Correctly Diagnose Generator Problems. Belém city, Para state, Brazil: ENAM; 2004. 9p

[7] Date sheet: Using the VM600 System to Measure Air Gaps on Hydro Turbine. London: Zeefax Inc; 2012. 43p

[8] Zaitsev IO. Electric machines faults monitoring system with hybrid electro-optic capacitive mechanical sensors. In: Abstracts of the 2017 IEEE International Young Scientists Forum on Applied Physics and Engineering (YSF-2017); 17-20October 2017; Ukraine, Lviv: IEEE; 2017. pp. 15-18

[9] Zaitsev IO, Levytskyi AS, Kromplyas BA. Hybrid capacitive sensor for hydro- and turbo generator monitoring system. In: Proceedings of the International conference on modern electrical and energy system (MEES-17); 15–17 November 2017; Ukraine. Kremenchuk: IEEE; 2017. pp. 288-291

[10] Griščenko M. Air gap monitoring unit generator to advance vibration diagnostic procedure: Summary of the Doctoral Thesis. Riga: RTU; 2015. 20p

[11] Mikalauskas R, Volkovas V. Air gap modelling and control possibilities in rotary systems. Ultragarsas. 2003;**1**(46): 7-11

[12] Volkovas V, Gečys SJ. Increase the initial eccentricity of electric cars in experimental working conditions. Elektrotechnika : mokslo darbai. 1988; **15**(24):37-52

[13] Jonušas R, Jurkauskas A, Volkovas V. Rotorinių sistemų dinamika ir diagnostika. Kauno technologijos. 2001;**1**:213-228

[14] Date sheet: Air gap measuring system LS 120–121 transducers & ILS 730–731 conditioners. Vibro-Meter [Internet]. 2019. Available from: https://www.ahrinternational.com/PDF_catalogues/SKF/058406.pdf [Accessed: 30-06-2019]

[15] Manual: Iris Power Capacitive Air Gap Sensor. Catalog Qualitrol [Internet]. 2019. Available from: https://irispower.com/wp-content/uploads/2016/11/Iris-Power-CGS-Brochure-Capacitive-Gap-Sensor-1.pdf [Accessed: 30 June 2019]

[16] Date sheet: 4000 Series Air Gap Sensor System. Bently Nevada* Asset Condition Monitoring Specifications and Ordering Information [Internet]. 2019. Available from: https://www.industrial.ai/sites/g/files/cozyhq596/files/2019-06/4000_series_air_gap_sensor_system-167885f.pdf [Accessed: 30 June 2019]

[17] Air gap monitoring in generators with fiber based sensor [Internet]. 2017. Available from: http://fo4energy.hubersuhner.com/en/News/1868 [Accessed: 20 July 2017]

[18] Gorbova G, Gorbov M, Meyer M. Precise capacitance calculation of sensing elements capacitive sensors by method of direct field strength determination. In: Proceedings of the lEfct Sensor 2002; 12–14 June 2002; USA, Orlando; 2002. pp. 1239-1243

[19] Turan J, Ovseník L, Turán J. Optically powered fiber optic sensors. Acta Electrotechnica et Informatica. 2005;**5**:7

[20] Alekseev BA. Determination of the State (Diagnosis) of Large Hydrogenerators. Moscow: ENAS; 2002. 144p

[21] Potashnik SI, Fedorenko GM, Vaskovsky YN, et al. Problems of increasing the reliability of powerful hydrogenerators with instability of the air gap. Hydroelectricity in Ukraine. 2006;**3**:6-10

[22] Vaskovsky YN, Fedorenko GM, Voshchinsky KV, et al. Modeling of electromagnetic and thermal processes in the damper of the rotor of a hydrogenerator with an uneven air gap between the rotor and the stator. Hydroelectricity in Ukraine. 2006;**3**: 11-17

[23] Kuzmin VV, Vakulenko AN. Operating modes and the most common damage to hydro generators of hydroelectric power plants of the Dnieper cascade. The influence of the parameters of the air gap between the rotor and stator of the hydrogenerator on the reliability of its operation. Hydroelectricity in Ukraine. 2005;**2**: 22-30

[24] Pasko VE, Fedorenko GM. The introduction of continuous monitoring of hydrogenerators is a revolutionary step in improving their reliability and efficient operation. Hydroelectricity in Ukraine. 2005;**2**:37-40

[25] Petrov YV. Unevenness of the air gap of the hydrogenerator and its effect on the stator vibration. Electric Stations. 1974;**1**:25-28

[26] Fedorenko GM, Saratov VO, Chernish VV. Having inflated the parameters of the gap to the characteristics of the hydro generator. Hydroelectricity in Ukraine. 2005;**4**: 26-33

[27] Fedorenko GM, Vaskovsky YN, Saratov VA, et al. Modeling the electromagnetic load of the damper system of the rotor of a hydrogenerator in synchronous modes with an eccentricity of the air gap. Hydroelectricity in Ukraine. 2006;**1**: 25-32

[28] Azuare C, Millan A. Stator deformation of large hydrogenerators and its effects on the machines. In: Proceedings of the International Council on Large Electric Systems (CIGRE 2004); 29 August–3 September 2004; France, Paris; 2004. pp. 1-7

[29] Kuzmin VV, Vakulenko AN. Hydrogenerator poles damage by electrical erosion-pattern, cause, diagnostics and failure prevention. In: Proceedings of the International Council on Large Electric Systems (CIGRE 2006); 26 August–1 September 2006; France, Paris; 2006. pp. 1-9

[30] Netseevsky AB, Geller AB, Schetinin AD. Elimination of the asymmetry of the air gap in the hydrogenerator type SV1340/150-96. Electric Stations. 1975;**1**:45-49

[31] AD7745/46 24-Bit Capacitance-to-Digital Converter with Temperature Sensor [Internet]. 2019. Available from: https://www.analog.com/media/en/tech

nical-documentation/data-sheets/AD7745_7746.pdf [Accessed: 30 June 2019]

[32] Zaitsev IO, Levytskyi AS. Determination of response characteristic of capacitive coplanar air gap sensor. In: Proceedings of the 2017 IEEE Microwaves, Radar and Remote Sensing Symposium (MRRS-2017); 30 June–2 August 2017; Ukraine, Kiev: IEEE; 2017. pp. 85-88

[33] Sunmee P, Borton D, Kang M, Nurmikko A, Song Y. An implantable neural sensing microsystem with fiber-optic data transmission and power delivery. Sensors. 2013;**13**: 6014-6031

[34] Levytskyi A, Zaitsev I. Hybrid fiber-optic measuring tools for control and diagnostic parameters of hydrogenerators. Hydroelectricity in Ukraine. 2016;**3-4**:32-33

[35] International Measurement Confederation (IMEKO) [Internet]. 2009. Available from: www.imeko.org [Accessed: 30 June 2019]

[36] Zaitsev IO, Levytskyi AS, Kromplyas BA. Capacitive distance sensor with coplanar electrodes for large turbogenerator core clamping system. In: Proceedings of the 2019 IEEE 39th International Conference on Electronics and Nanotechnology (ELNANO); 16–18 April 2017; Ukraine, Kiev; 2017. pp. 644-647

[37] Zadvornov SA. Issledovaniye metodov postroyeniya gibridnykh volokonno-optikoskikh izmeritel'nykh sistem. Moscow: MPEI; 2009. 119p

[38] Rosolem JB, Floridia C, Sanz J. Optical system for hydrogenerator monitoring. In: Proceedings of the International Council for Power Electroenergetical Systems CIGRE 2010; France, Paris; 2010. pp. 1-8

[39] Riesen S, Schubert U, Bett AW. GaAs photovoltaic cells for laser power beaming at high power densities. In: Proceedings of the 17th European Photovoltaic Solar Energy Conference; 22–26 October 2001; Germany; pp. 182-185

[40] Peña R, Algora C, Anton I. GaAs multiple photovoltaic converters with an efficiency of 45% for monochromatic illumination. In: Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion; 11–18 May 2003; Japan, Osaka: Arisumi Printing Inc. pp. 228-231

[41] Dakin J, Brown R. Handbook of Optoelectronics. Boca Raton: CRC Press; 2006. 1563p

[42] PV-Cells for Optical Power Transmission [Internet]. 2019. Available from: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/infomaterial/brochures/photovoltaik/14e_ISE_Flyer_III-V_OpticalPowerTransmission.pdf [Accessed: 30-06-2019]

[43] Herb J. Commercialization of New Lattice-Matched Multi-Junction Solar Cells Based on Dilute Nitrides. Subcontract Report NREL/SR-5200-54721. San Jose, California: NREL; 2012. 28p

[44] Wang MR, Chen RT, Sonek GJ, Jannson T. Wavelength-division multiplexing and demultiplexing on locally sensitized single-mode polymer microstructure waveguides. Optics Letters. 1990;**15**(7):363-365

[45] Haid M, Armbruster C, Derix D, Schöner C, Helmers H. 5 W Optical Power Link with Generic Voltage Output and Modulated Data Signal. In: Proceedings of the 1st Optical Wireless and Fiber Power Transmission Conference (OWPT2019); 23–25 April 2019; Japan, Yokohama

[46] Zaitsev IO, Levytskyi AS, Sydorchuk VE. Air gap control system for hydrogenerators. Devices and Methods of Measurements. 2017;**8**(2): 122-130

[47] Manual: VMTM Air Gap. Capacitive Measuring Chains [Internet]. 2019. Available from: http://vibrosystm.com/wp-content/uploads/9628-25D1A-103.pdf [Accessed: 30 June 2019]

[48] Volkovas V, Mikalauskas R, Eidukeviciute M. Air gap measuring system for purpose of diagnostics and condition monitoring [Internet]. 2019. Available from: http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-article-BAT3-0033-0039/c/httpwww_bg_utp_edu _plartdiagnostyka2004volkovas.pdf [Accessed: 30 June 2019]

[49] Manual: Air Gap Monitoring System [Internet]. 2019. Available from: https://www.giga-tech.it/media/prodPdf/Doc.%20AirGap_93_AyIM6_it.pdf [Accessed: 30 June 2019]

[50] Levytskyi A, Zaitsev E, Kromplyas B. Determination of the response characteristic of the capacitive sensor of the air gap in the hydrogenerator СГК 538/160-70M. The Institute of Electrodynamics of the National Academy of Sciences of Ukraine. 2017;**43**:134-137

[51] Zaitsev IO, Levytskyi AS, Kromplyas BA. Characteristic of capacitive sensor for the air gap control system in the hydrogenerator. In: Proceedings of the First Ukraine Conference on Electrical and Computer Engineering (UKRCON); 29 May–2 June 2017; Ukraine, Kyiv: IEEE; 2017. pp. 390-394

[52] Milykh VI, Vysochin AI. Principles of calculation of the magnetic field in the end of the turbo generator in various regimes of its work. Electrical Engineering. 2010;**3**:19-24

[53] Milykh VI, Dubinina ON. Numerical calculation of the magnetic field in the end zone of the turbogenerator under load conditions. Electrical Engineering and Electrical Mechanics. 2003;**1**:64-69

[54] Zaitsev I, Levytskyi A, Kromplyas B, Panchyk M, Bereznychenko V. Study influence industrial frequency magnetic field on capacitive pressing sensor for large turbogenerator core clamping system. In: Proceedings of the Ukraine Conference On Electrical And Computer Engineering (UKRCON); 2–6 July 2019; Ukraine, Lviv: IEEE; 2019

[55] Zaitsev I, Levytskyi A, Kromplyas B, Panchyk M, Bereznychenko V. Study industrial frequency magnetic field influence on STM32F051K8T6 microcontroller functioning stability. The Institute of Electrodynamics of the National Academy of Sciences of Ukraine. 2019;**52**:80-86