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Pressure Monitoring in Medium-Voltage Vacuum Interrupters

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Abstract: Innovation in the economy is closely tied to energy development, encompassing the exploration of new energy sources, increased energy production efficiency, and the integration of diverse energy sources for safe and effective supply to industries and households. Outdated energy infrastructure disrupts electricity continuity and hampers economic innovation. Power interruptions lead to higher SAIDI and SAIFI reliability indices. Quality and reliability requirements have sparked interest in enclosed energy devices. Vacuum technology has been pivotal in electrical switchgear insulation and arc-quenching for over four decades. However, the lack of real-time pressure monitoring systems for vacuum equipment, especially enclosed disconnectors, limits their use as isolation connectors. Potential insulation failure poses risks to power line maintenance teams and can lead to unplanned shutdowns, further compromising energy supply quality. This article explores an innovative pressure monitoring system for vacuum interrupters, utilizing fiber optic Bragg grids as a measuring sensor, enabling pressure measurement within the vacuum chamber ranging from 2×10^1 Pa to 5×10^5 Pa.

Keywords: fiber Bragg grating; fiber optic sensor; pressure measurement; dielectric strength; vacuum technology; vacuum interrupter

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1. Introduction

An innovative economy requires the development of energy, from the search for new energy sources and ways of using them through increasing the efficiency of energy production and mutual integration of sources to the safe and effective supply of energy to industry and households. The objectives and assumptions of the infrastructure are related to the development challenge of providing the economy, institutions, and citizens with stable and optimally adapted energy supplies at an economically acceptable price. As part of this challenge, it is necessary, among other things, to ensure energy security related to the diversification of energy sources and raw materials or to introduce new technologies allowing for an increase in the efficiency of energy installations based on conventional and renewable energy sources. Most of the network infrastructure operating in the power system reaches the age of 30–35 years, which is the declared operating time of the devices installed in it, and in extreme cases, this time has expired [1].

Outdated energy equipment has a negative impact on the continuity of electricity supply, gradually hindering the building of an innovative and thriving economy for the country. Interruptions in electricity supply cause an increase in reliability coefficients, the average system duration of long and very long breaks (SAIDI), and the average system frequency of long and very long breaks (SAIFI) [2,3], for exceeding which distribution system operators pay financial penalties. During the last decade, reliability factors in Poland have gradually decreased. The exception was 2017, when the indicators of almost all operators increased significantly. The reason for this state of affairs was the increased number of extremely adverse weather conditions, which caused many faults in overhead lines. However, with the onset of the COVID-19 pandemic and the associated cost cuts for

the modernization of power grids, reliability factors have recently significantly increased again. Both in 2021 and 2022, increases in reliability factors were recorded in the five largest distribution system operators in Poland. Changes in the SAIDI and SAIFI coefficients over the last decade are shown in Figure 1.

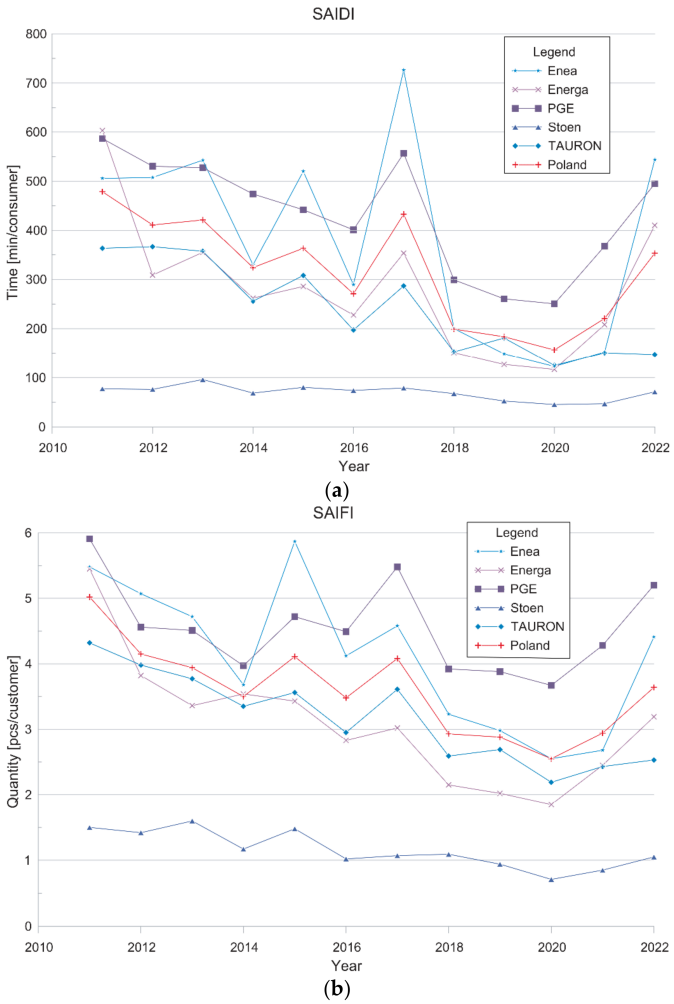


Figure 1. Changes in reliability coefficients in Poland (**a**) SAIDI and (**b**) SAIFI over the past decade [1].

The requirements regarding the quality of supplied energy and the continuity of its supply have resulted in an increase in interest in devices with a closed structure. Over more than four decades, vacuum has reached its greatest importance as an insulating medium. In 2020, slightly more than 95% of newly installed switchgears in medium-voltage networks used vacuum as an insulating medium [4], as shown in Figure 2.

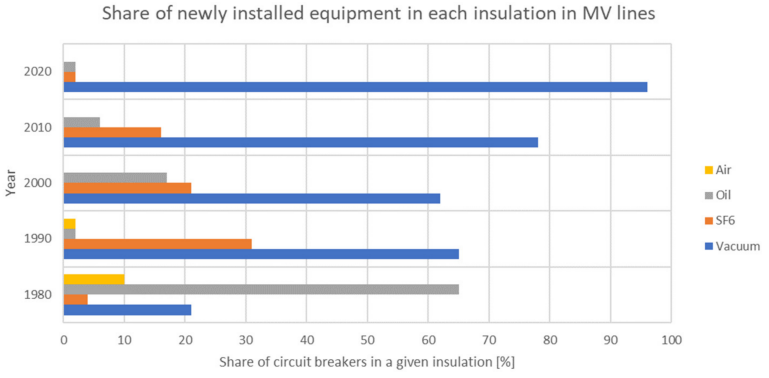


Figure 2. Participation of individual insulating media in newly installed equipment [4].

The growing importance of vacuum equipment m.in is related to tightening environmental regulations. The latest regulations of the European Parliament [5] require that newly installed or replaced medium-voltage circuit breakers with a voltage of up to 24 kV and a voltage above 24 kV to 52 kV for equipment placed on the market after 1 January 2026 and 1 January 2030, respectively. Equipment should be equipped with a greenhouse potential (GWP_{100}) not exceeding 10. Similarly, this provision also applies to high-voltage equipment operating at voltages between 52 kV and 145 kV and above 145 kV. In addition, in devices placed on the market after 1 January 2028 and 1 January 2031, an insulating medium with a GWP_{100} exceeding 10 should not be used.

Bearing in mind ecological aspects and the need to modernize the network infrastructure, the research group to which the authors of the article belong has successfully developed an innovative medium-voltage overhead vacuum disconnector in a closed housing, designed for smart grid (EKTOS) networks in which the dielectric strength of connecting chambers has been increased by using low-pressure helium admixtures as a medium to extinguish the electric arc [6]. Thanks to this solution, the device meets the latest ecological standards and also retains the required dielectric strength over a larger pressure range. The comparison of the dielectric strength of vacuum and helium is shown in Figure 3.

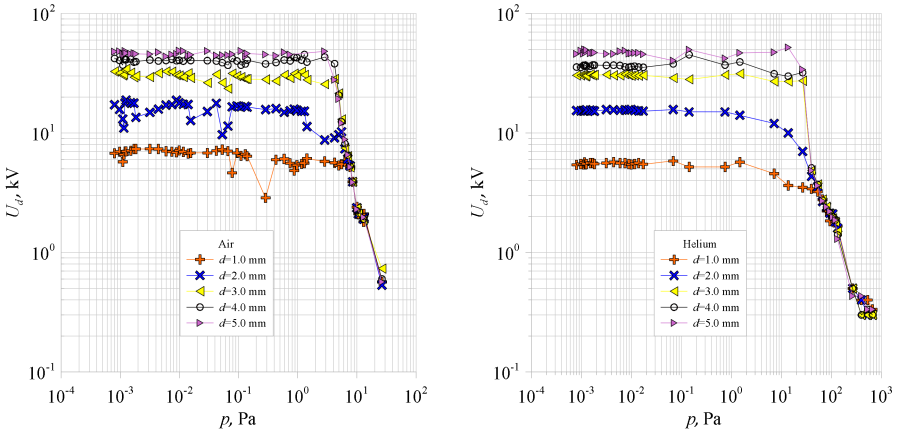


Figure 3. Dielectric resistance of (**a**) air and (**b**) helium for different interstitial distances [6].

As can be seen from the figure above, the device using helium as an insulating medium retains adequate electrical strength at a pressure of over 2×10^1 Pa, which significantly facilitates the tightness of vacuum devices used in switchgear, and the values of switching overvoltages occurring in power systems will be limited.

Vacuum devices with a closed structure have many advantages such as lack of susceptibility to weather conditions, neutrality for the environment or no need to carry out maintenance work in the declared service life, but the closed design of these devices makes it impossible to observe a safe insulation break as well as to measure the pressure in the device without interfering with its operation. The measurement of the pressure inside the device, according to Figure 3, is extremely important for maintaining the appropriate dielectric parameters [7].

Traditional pressure sensors are subject to technical limitations, such as single-point measurement, poor immunity to electromagnetic interference, and the inability to remotely transmit and monitor measurement signals online [8–11]. Due to the above limitations, the attention of the world of science and industry has been directed to the use of fiber optics for the construction of pressure sensors [12].

Researchers devoted much attention to fiber optic sensors, including the Fabry–Pérot interferometer (FPI), Bragg mesh (FBG), polymer FBG, and other fiber optic configurations to detect deformations caused by pressures [13–22]. These sensors are small, lightweight, and resistant to electromagnetic interference and have high sensitivity. Fiber optic technol-

ogy provides many benefits, but its significant disadvantage is its sensitivity to temperature. As a result, compensation systems are needed, and sensors and measurement systems must be enriched with additional components for monitoring the reference temperature.

The scale of the problem of pressure monitoring in vacuum equipment is also reflected in the number of publications in recent years concerning pressure monitoring systems in gas-insulated devices [23] as shown in Figure 4. Unfortunately, despite the significant involvement of researchers and manufacturers of vacuum equipment, according to the knowledge of the authors of the article, there is currently no system designed to monitor the parameters of pressure devices with vacuum insulation in real time [24–33]. The lack of such a solution negatively affects the continuity of electricity supply because the inability to control the state of pressure in vacuum equipment significantly hinders the prediction of switchgear failures, which leads to a greater number of unplanned interruptions caused by network failures and to an increase in the number of planned interruptions caused by the need to perform conventional tests of vacuum chambers determining their suitability for further operation [34–38].

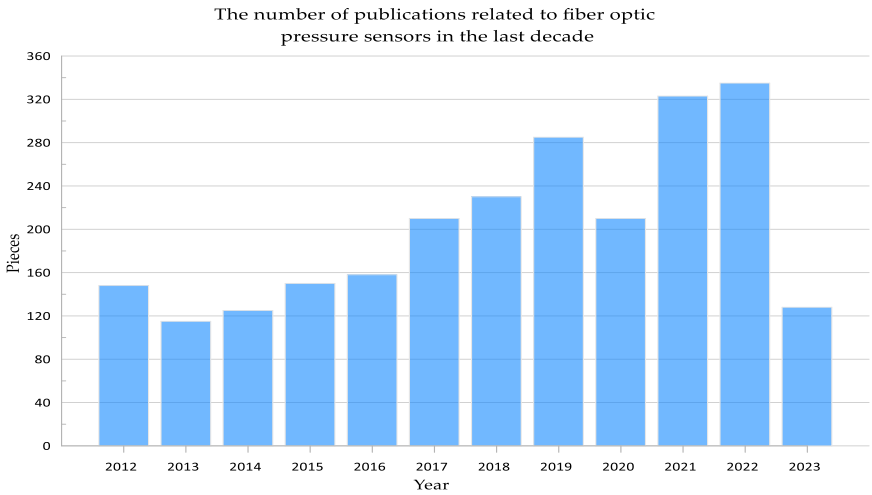


Figure 4. Chart of the number of publications related to fiber optic pressure sensors in the last decade [23].

Therefore, the authors of the article undertook intensive research work on the development of a sensor for real-time pressure measurement, designed for vacuum switchgear and switchgear. This article presents an innovative design of a measuring system combining fiber optic technology using Bragg grids and a mechanical structure in the form of a metal elastic element susceptible to deformation caused by the pressure prevailing inside the medium-voltage vacuum interrupters.

2. Research Stands, Materials, and Methods

The test stand used during empirical work (Figure 5) bases its operation on the so-called dismantling chamber [39–41], which, thanks to its innovative design, allows the implementation of the tested measuring heads into a real vacuum system.

The optical schematic of the measurement system is shown in Figure 6.

The configuration of the measuring system required the selection of an appropriate set of elements allowing for fixing the measuring head in a hermetic manner, as well as changing the pressure prevailing in the system. Therefore, it was necessary to develop and manufacture an appropriate mounting base for the tested systems, ensuring the tension of the fiber optic Bragg grid and a tight connection of the element susceptible to pressure loads with the vacuum system. At the same time, work was carried out to study light sources and develop models of photonic structure characteristics with optimized parameters that meet the requirements of the pressure measurement system.

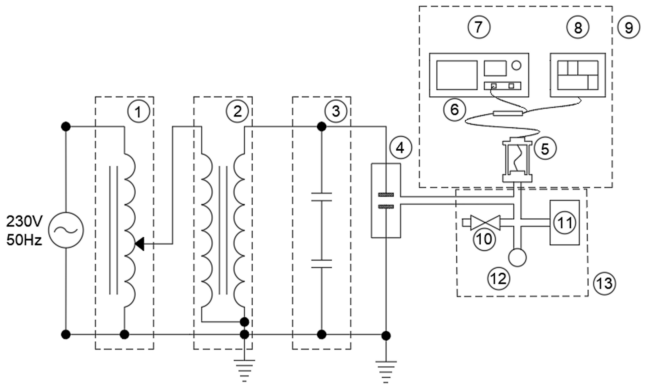


Figure 5. Diagram of a measuring station equipped with a dismantling vacuum chamber intended for empirical tests of vacuum sensors. 1—control panel, 2—test transformer, 3—capacitive divider, 4—removable vacuum chamber, 5—tested measuring head, 6—measuring circulation system, 7—optical spectrum analyzer, 8—broadband light source with superluminescent diode, 9—fiber optic measuring system, 10—precise dosing valve, 11—pump set, 12—vacuum meter, 13—vacuum system [42].

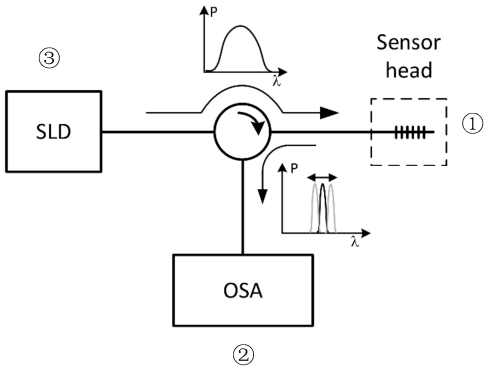


Figure 6. Optical schematic of the measurement system. ①—superluminescent diode, ②—optical spectrum analyzer, ③—measurement sensor.

The light source is one of the most important elements of the optoelectronic system, containing a fiber optic sensor. The stability of the parameters of the light source and the power of its emission affects the characteristics of the measuring system in which it is used. In amplitude-based measurement systems, the spectral stability of the light emitted by the source is particularly important because fluctuations strongly affect the output signal of the sensing system. In addition, light sources used in measurement systems should be able to be replaced by other sources, often with different spectral parameters. As part of the preparatory work for the construction of the pressure measuring head, spectral characteristics of a laboratory light source with a wide band in the form of a superluminescent diode were tested.

Numeric calculations have shown the possibility of significantly reducing the so-called side mods, while maintaining a very high transmission rate. The results from the numerical calculation phase contributed to determining the optimal physical parameters of the pressure sensor, thanks to which the mentioned spectral characteristics were achieved. As a result, this enabled the sensors to function properly in the form of fiber optic Bragg meshes, serving as pressure, deformation, temperature sensors and special optical filters for these sensors. The developed models allow the selection of optimal photonic parameters of sensors in the form of fiber optic Bragg meshes. Modeling the characteristics of the Bragg structure at the numerical design stage, even before actual production, significantly reduced the time and costs of producing full-fledged sensors. This method also minimizes material consumption and allows you to predict most sensor properties without having to produce sensors with different parameters. Thanks to extensive research, it is possible to determine a specific type of Bragg fiber optic mesh.

The effect of numerical and design work was the production of the Bragg grid using the phase mask method in the excimer laser system. Exposure wavelength 248 nm, phase mask period 1068.97 nm, structure length Bragg 12 mm. Mesh with a reflectance of approx. 0.5. Half width (FWHM) 0.07 nm. These parameters ensure a grid spectrum with a low FWHM factor and no spectrum distortion. Importantly, a basic peak with a distribution similar to Gauss with side mods with a small amplitude less than 20% was obtained.

3. Test of the Measuring Head with a Spring Membrane

In the first stage of work related to the development of the measuring head structure, it was decided that a special spring diaphragm would act as a pressure-sensitive element. During the research, measuring heads using membranes made of stainless steel and INCOTEL 718 alloy were made and tested. The membranes had a thickness of 2 µm and a diameter of 25.4 mm. The pressure values at which the membrane deforms and the size of this deformation are presented in Table 1.

Table 1. Technical parameters of the elastic membranes used.

No	Pressure [Pa]	Membrane Deflection [mm]	
		Stainless Steel	INCOTEL 718
1	6.89	2.0×10^{-5}	9.0×10^{-5}
2	68.95	5.0×10^{-5}	1.0×10^{-4}
3	689.48	3.0×10^{-4}	3.0×10^{-4}
4	2757.92	1.3×10^{-3}	1.2×10^{-3}
5	4826.36	2.3×10^{-3}	2.2×10^{-3}
6	6894.80	3.3×10^{-3}	3.1×10^{-3}
7	34474.00	1.56×10^{-2}	1.38×10^{-2}

After the execution of a hermetic system equipped with an elastic membrane with an attached fiber optic Bragg grid, a series of conditioning measurements were carried out, limiting the impact of gassing of pump system materials. Specific tests of the measuring heads were performed in the pressure range from 8×10^{-4} to 5×10^{5} Pa in steps of two units in each pressure row, observing changes in the optical spectrum using an analyzer.

The configuration of the test stand for the membrane test head is shown in Figure 7, while the results of the optical spectrum analysis of selected test heads are shown in Figure 8.

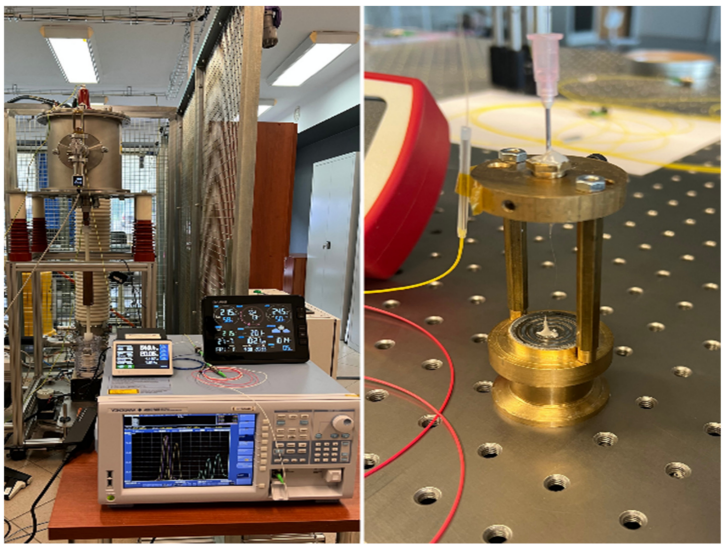


Figure 7. A view of the measurement station and the measurement head.

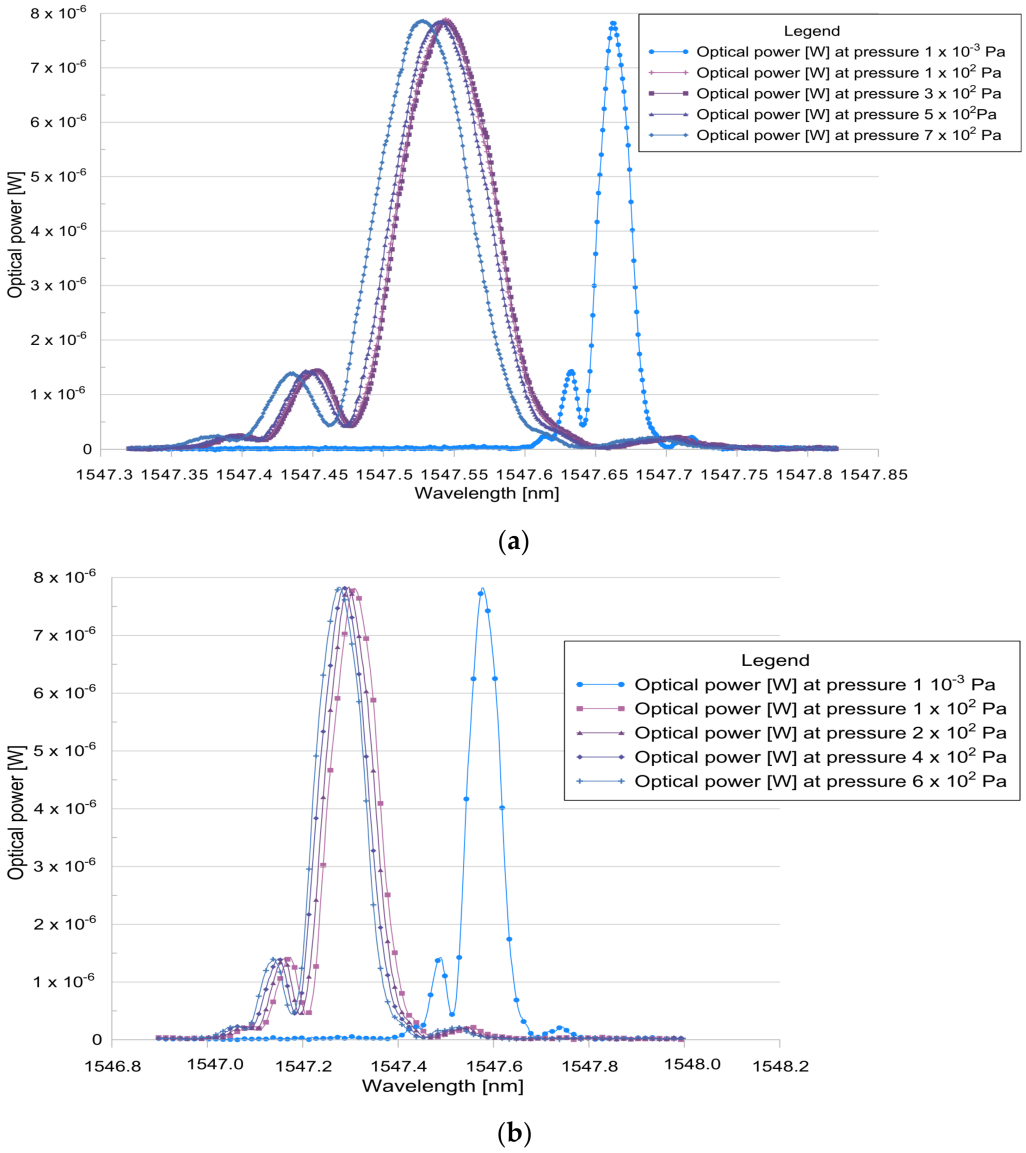


Figure 8. Pressure-load-induced response of the measuring head examined with an optical spectrum analyzer: (**a**) measuring head with a membrane made of stainless steel; (**b**) measuring head with a membrane made of INCOTEL 718 alloy.

The measurements showed the ability of the developed measuring heads to measure pressure in the range from 5×10^2 to 5×10^5 Pa and from 1×10^2 to 5×10^5 Pa for heads using a stainless-steel membrane and an INCOTEL 718 alloy, respectively. Such results were considered unsatisfactory, and it was decided that a measuring head based on the solution of the so-called spring bellows should be developed. Based on a thorough analysis of the physical properties of available materials, it was assumed that in the case of this solution, the range of transmitted changes caused by the applied pressure will be greater, and thus the pressure level detection range and the sensitivity of the measuring head will be increased.

4. Testing of the Measuring Head with Elastic Bellows

Work on the development of a measuring head using elastic bellows as a pressure load transfer element began with the verification of the deflection level of a set of elastic bellows characterized by various mechanical parameters as shown in Table 2.

Table 2. Technical parameters of spring bellows used for testing.

No	Material	Outer Diameter	Inside Diameter	Effective Area	Number of Coils	Length of the Coil Area	Coefficient of Elasticity	Maximum Deflection	Maximum Working Pressure	Wall Thickness
		mm	mm	cm^3	-	mm	N/m	mm	MPa	mm
1	Bronze and Brass	22.00	15.00	2.69	9.00	15.00	8.30	4.50	0.10	0.13
2		12.00	8.00	0.80	19.00	29.50	-	9.16	1.80	0.11
3		10.00	6.00	0.50	28.00	31.00	3.00	8.00	2.00	0.10
4		12.00	8.00	0.80	18.00	22.20	-	6.00	1.80	0.11
5		16.00	10.50	1.61	6.00	8.40	9.00	3.00	0.65	0.10
6	Stainless steel	7.00	4.65	0.27	12.00	12.30	55.00	1.90	18.00	0.10
7		38.10	25.00	7.93	13.00	41.17	1.90	13.70	0.35	0.13
8		13.20	9.40	1.01	13.00	14.20	19.00	3.90	3.00	0.10
9	Monel400	50.80	34.67	14.34	14.00	47.60	5.00	9.00	0.20	0.18

Due to the significant number of selected bellows intended for the development of the measuring head, it was decided to make an initial selection of bellows by performing control measurements using a vacuum system and a Mitutoyo small shift meter and vacuum meter. The stand for initial verification of the deflection of bellows is shown in Figure 9.

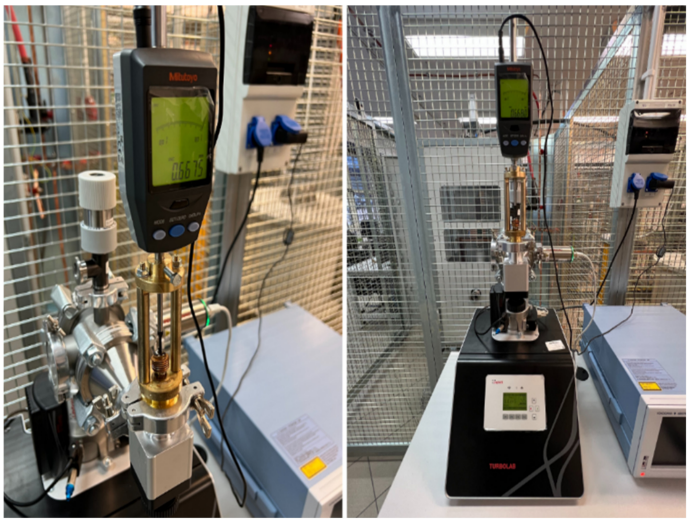


Figure 9. Test stand for verifying the deflection of spring bellows.

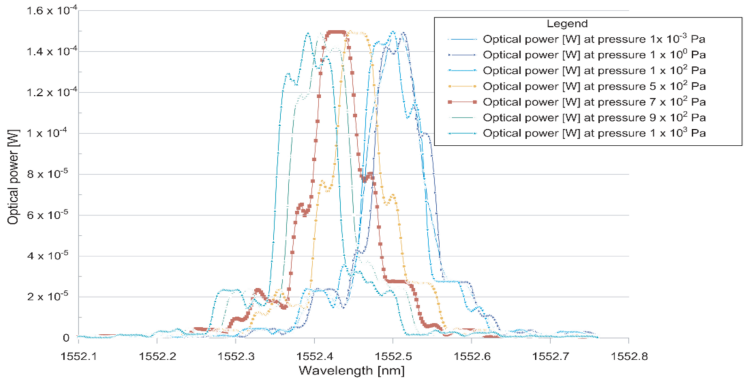
Carrying out a series of measurements for each type of housing allowed to choose the optimal structure for developing a measuring head in the form of a flat made of bronze and brass with a declared deflection of 6 mm. Based on the obtained test results, measuring heads using spring bellows made of brass and bronze alloy were developed and made.

It is worth noting that two types of measuring heads using spring bellows have been developed. The first of them based its action on a bellows, which was compressed under pressure, while the second version was made in such a way that the application of pressure load would cause the flat to lengthen. The measuring heads and test stand configured for testing empirical measuring heads with spring bellows are shown in Figure 10, and the obtained results of measuring the response of the measuring head to the applied pressure load are shown in Figure 11.

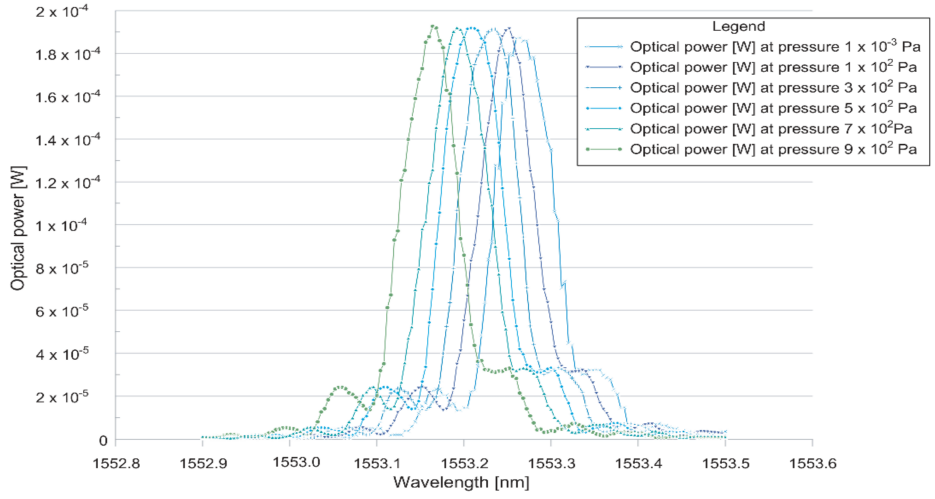
Thanks to the appropriate modeling and design of the fiber optic Bragg grid, the influence of side modes on the measurement result was reduced, as shown by the obtained light spectra. Deformation of the elastic element constituting the mechanical structure of the measuring head causes changes in the optical spectrum shift. Measurements carried out using an optical spectrum analyzer allowed to link the optical spectrum shift with the pressure prevailing in the vacuum system.



Figure 10. A view of the measurement heads and test stand.



(**a**)



(**b**)

Figure 11. Pressure load response of the measuring head tested with an optical spectrum analyzer: (**a**) head with a bellows to be compressed; (**b**) head with bellows subjected to elongation.

As a result of the measurements, it was shown that the measuring head, whose elastic bellows is subjected to compression, has reactions to pressure loads in the range from 1×10^2 to 5×10^5 Pa, while the head containing the bellows subjected to elongation during pressure load, allows to detect pressure changes in the range from 2×10^1 to 5×10^5 Pa as shown in Table 3.

Table 3. Summary of the basic parameters of the developed measuring heads.

No	Type of Head	Measuring Range [Pa]	Operational Use	Determination of Pressure Values	Repeatability
1	Head with stainless steel membrane	5×10^2–1×10^5	Yes	Yes	95.88%
2	Head with INCOTEL 718 membrane	1×10^2–1×10^5	Yes	Yes	96.80%
3	Head with compression bellows	1×10^2–1×10^5	Yes	Yes	98.56%
4	Head with extension bellows	2×10^1–1×10^5	Yes	Yes	98.77%

5. Summary

The result of the construction and research works are four measuring heads that can be successfully used to detect leakage and measure the pressure prevailing in vacuum interrupters of switchgear and switchgear with increased dielectric strength. Measuring heads are a combination of selected elastic elements and fiber optic Bragg grid with strictly defined parameters defined by numerical modeling. Depending on the design, they allow the detection of pressure with values ranging from 2×10^1 to 1×10^5 Pa. It is well known that fiber optic Bragg grids are susceptible to temperature changes, which forces the development of a system compensating for the influence of temperature on the measuring head. In addition, research is being carried out in parallel on the development of an interrogation system that is designed to convert changes in the optical parameters of the photonic sensor (based on a fiber optic Bragg grid) into changes in radiation power and ultimately changes in the voltage signal. It is important that the designed detection system meets several key criteria, such as high measurement accuracy, appropriate measuring range adapted to the expected changes in measured quantities, reliability, and minimization of production costs compared to conventional measurement methods that use optical spectrum analyzers. Since the use of complex electronic and optoelectronic components sensitive to temperature changes can introduce great uncertainty in the demodulation of the sensor signal, it is necessary to ensure the stability and reliability of the system operation under different temperature conditions in order to ensure the economics of the solution prototype.

The location of the pressure level sensor is significant here, which is why the research team also carried out advanced computer simulations concerning, among others the temperature distribution in vacuum chambers, both under idle conditions, under load and in the event of a short circuit. The simulation results will allow us to precisely determine the optimal location of the measuring head. The result of the simulation work will be empirical verification of the correct operation of the measuring head depending on the place of installation of the sensor.

Author Contributions: P.W. proposed the topic and problem area of the article; D.K., M.L. and C.K. reviewed, compared and contrasted the state of knowledge on vacuum sensors and proposed type of sensor; D.K., M.L., C.K. and A.Z., develop the test stand. All authors have taken measurements. P.W. and D.K. analyzed the results obtained; D.K., M.L. and A.Z., developed the graphic part of the article; P.W. revised the paper and contributed to the discussion increasing the merit of the paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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