APPLICATION OF FIBER OPTIC INTEGRATED FABRY-PEROT INTERFEROMETER FOR NON ELECTRIC QUANTITIES MEASUREMENT IN ELECTRICAL ENGINEERING

Gheorghe OPRAN, Mircea TEODORESCU, Andrei MARINESCU

ICMET Research Development and Testing National Institute for Electrical Engineering, Craiova, amarin@icmet.ro

Abstract **– The non-electric quantities measurement technologies widely used in the present technique are based on conventional technologies known for many years, which lead to reliable and reproducible results.**
With a view to measuring the non-electric quantities in high power equipment, irrespective of the environment in which they occur with as close as possible results, it was necessary to find a technology with high electromagnetic compatibility, able to work in intense electric and magnetic fields and at high potential.
With that end view, the modern technology based on transducers achieved with optic sensors has imposed itself for measuring and monitoring some important parameters (mechanical stresses, temperatures etc.) during the operation of some important equipment under heavy operating conditions, under high potential, in disturbing electromagnetic fields, corrosive or explosive environment.
In this paper, the operation principle of the fiber optic (FO) integrated Fabry Perot interferometer is presented, also its practical application and experimental results demonstrating that in this way, measurement uncertainties with the same magnitude order as in classical technologies can be got, the essential advantage of those optic sensor being the lack of metallic parts in their construction and the isolation achieved by the transmission from the measurement site by the fiber optic.

Keywords: *non-electric quantities measurement, fiber optic, Fabry-Perot interferometer.*

1. INTRODUCTION

The measurement principles most frequently used for measuring electrically some non-electric quantities (force, mass, strain, temperature, pressure etc.) are known from literature [1,2,3].
During the last decade, important mutations happened at the same time with the development of smart micro-electronic systems, of embedded systems to which miniature sensors based on micro and nanotechnologies have been associated.
One of the most promising ways to progress in sensorics is represented by the sensors based on optical phenomena, but also the sensors integrated in fiber optic modified for becoming sensitive to different electrical, mechanical or thermal excitations [2].
The special development of this technology has led to the industrial manufacture of some optic sensors with high repeatability able to be used in industrial applications.
ICMET Craiova has a significant experience in signal acquisition and transmission through fiber optic under high potential [3,7].
Under these circumstances, it is possible to approach some non-electric quantities in optoelectronic technology, in accredited measurement and calibration laboratories in the mechanical and thermal field, where the proposed technical solutions can be practically verified and certified for industrial measurements [4 - 6].
For measuring and monitoring some important parameters during the operation of some important equipment in the national power grid, like power transformers, high voltage apparatus and power transmission cables, simple, accurate and reliable measuring equipment and systems are necessary, which should work under heavy operating conditions (under high potential, in disturbing electromagnetic fields, corrosive or explosive environment a.s.o.).
These considerations have led to the implementation and use of fiber optic sensor for different industry and laboratory applications regarding some non-electric quantities measurement and/or monitoring.
The present paper presents the studies which have been performed for demonstrating the metrological characteristics of some transducers based on the technology of fiber optic integrated Fabry-Perot interferometer and the prospects of applying this technology.

2. FO SENSORS FOR NON-ELECTRIC QUANTITIES MEASUREMENT

In principle, any system which measures optically a physical quantity (electric/non-electric), consists of the optic sensor itself, intrinsic or extrinsic to the optic fiber for information transmission and the system for acquisition, processing, displaying and transmission of the signal proportional with the

measurand (system for interrogating the optic sensor - SISO).
SISO contains also the light signal source which the optic sensor modulates depending on the measurand variation.
The optic signal modulation is carried out depending on the nature of the optic sensor used, namely:
- optic sensor with intensity modulation of the optic signal
- optic sensor with phase modulation of the optic signal (interferometric sensor). Phase modification can be determined, as the case may be, by different types of interferometers (Michelson, Mach-Zehnder, Sagnac or Fabry-Perot)
- optic sensor with polarization modulation of the optic signal. An example of this kind is the electric current measurement by Faraday effect
- optic sensor with spectrum (color) modulation of the optic signal.

Irrespective of the measurand (M) the input-output relation has the form

$$x = S \cdot M + x_0 \qquad (1)$$

where S is the sensitivity, and x_0 is the zero signal of the sensor.
Another quantity important for characterizing a transducer is its resolution, given by the relation

$$(\Delta M)_{min} = (\Delta x)_{min} / S \qquad (2)$$

An optic sensor can be used in practice as the transducer of some measurand only through its attaching or proximity to a “test body” which is the carrier of the information on the measurand. In case of optic sensors for force and strain, they are fixed by bonding to the test body.
When choosing the types of optic sensors for the practical achievement of some transducers for non-electric quantities measurement, the authors have considered the price/performance ratio and the universatility degree (common technology for achieving and interrogating all types of sensors) in order to get a solution comparable with the resistive strain gauging based on strain gauges with many other advantages.
Under these circumstances, optic sensors based on phase modulation and white light interferometry (technology WLPI – White-Light Polarisation Interferometry), technology applied by many companies, like OpSens [4], Fiso [5] and Neoptix [6], in a structure similar to the Fabry Perot interferometer integrated in sensor.

3. DESCRIPTION OF SOME FO STRAIN AND TEMPERATURE SENSORS. MEASUREMENT SYSTEM

3.1. FO STRAIN SENSOR

As strain sensor, a sensor type OSP-A was used (Fig.1).
The white light transmitted by fiber optic reaches the interferometric sensor, where is divided into two beams. The length difference between the two beams (LS) varies depending on the strain the transducer undergoes.

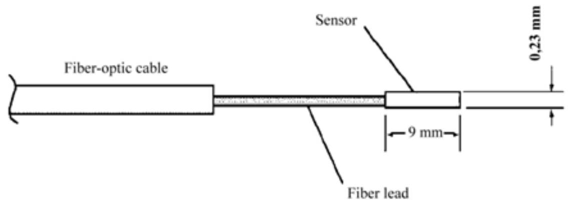

Fig. 1. – Strain sensor type OSP-A.

Then the two beams are recombined and reflected back to the processing (interrogation) unit, where the optic signal is transformed into an electric signal, proportional to the sensor micro-strain (Fig. 2).

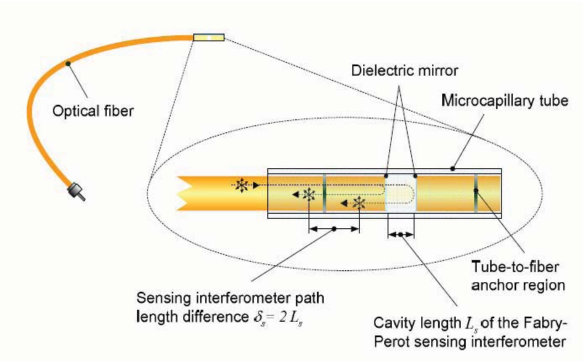

Fig. 2. – Principle of strain sensor integrated in fiber optic

By micro-strain it is understood the relative variation of the length of the sensor or test body on which it is fixed, in accordance with Hooke’s law

$$1\mu\varepsilon = (\Delta L / L_0) \cdot 10^{-6} \qquad (3)$$

OSP sensors have a high resolution (0.15 to 0.5 με) for a measurement range between ±1000 με and ±5000 με, can operate in a wide temperature range (-40 ºC to +250 ºC), have no metallic component are entirely immune to electromagnetic fields.
The response rate of OSP sensors assures a measurement of the strain variation with frequency of al least 10 kHz, which finally depends on the interrogation unit used.

3.2. FO TEMPERATURE SENSOR

For temperature measurement, the sensors type OTP-A were used (Fig.3).

The OTP-A sensors have a resolution of 0.1 ºC and an accuracy of 1 ºC for a measurement range between -40 ºC and 250 ºC, having a response time of about 1.5 sec and all the advantages specific to FO sensors.
The temperature sensor is based on the polarization interferometer manufactured from a birefringent crystal whose variation with temperature is at the basis of the sensor.

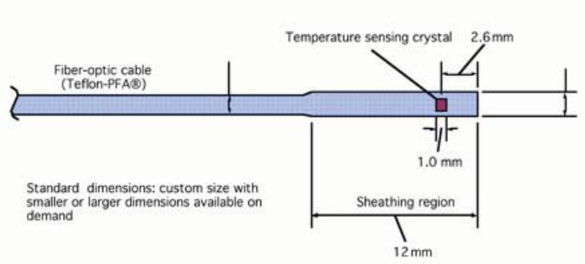

Fig. 3. – Temperature sensor type OTP-A.

The input face of the birefringent crystal is a linear polarizer, and the output one is a dielectric mirror.

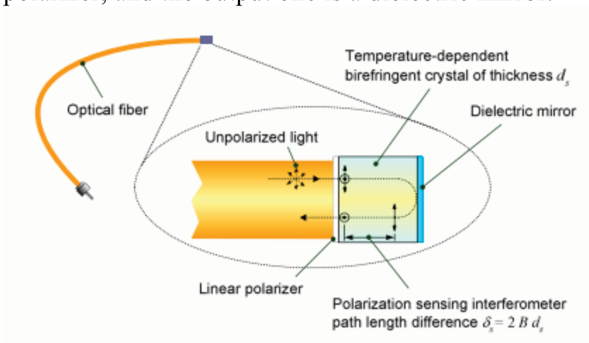

Fig. 4. – Principle of interferometric temperature sensor integrated in fiber optic

These components form a polarizing interferometer with 2 beams, having the path length difference

$$\delta_S = 2 \cdot B \cdot d_S \tag{4}$$

where B is the crystal birefringence depending on temperature, and d_S is the crystal thickness.
As SISO, there were used 2 separate channels (for strain and for temperature) of a signal interrogation system WLPI with 4 channels MultiSens (Fig. 5).

Fig. 5. – MultiSens : 4 channels WLPI Signal Conditioner

3.3. TEMPERATURE COMPENSATION OF A FORCE TRANSDUCER

The authors have tested the FO sensor characteristics in the field in which they had maximum experience and adequate measuring means, namely the field of force/mass/strain and temperature.
The purpose was to determine and correct the temperature influence on some industrial force transducers achieved by placing a pair of fiber optic sensors, a strain one and a temperature one, on the same test body (Fig.6).

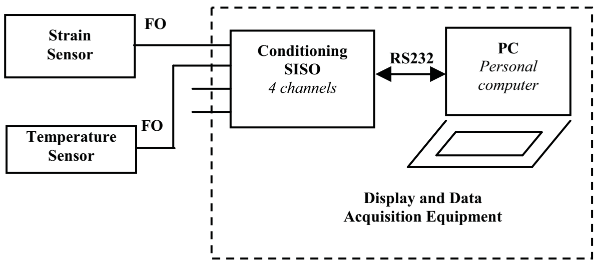

Fig.6. – Fiber Optic Industrial Force/Mass measurement with temperature compensation.

The information from the two sensors has been brought on two separate channels to the signal conditioning system SISO which was serially connected (RS232) to a personal computer where it was done the software correction, displaying and storage of the information determined in this way.

4. TESTS AND EXPERIMENTAL RESULTS

In order to get some conclusive results on the use of FO strain sensors for force measurement, the authors have built and tested two force transducers of 100 kN tension and 200 kN tension - compression.
These force transducers have been achieved by applying (bonding) some strain sensors type OSP-A to the test bodies made of alloy steel [6]. In Fig. 7 and 8, the force transducer of 100 kN tension achieved by using a FO sensor of ± 5000 με (bonded to a test body with 3000 mm length and 13,7 mm diameter) and the 200 kN tension/compression transducer achieved by using a FO sensor with ± 2500 με (bonded to a cylindrical test body with 130 mm length and 48 and 38 mm diameter).
Both transducers are provided with threads at their ends (outside or inside) for being mounted in the test machines.
The technology of bonding the FO sensors on the test body and the used additives are similar to the bonding technology and materials used for strain gauges.

The tests and experiments of the two force transducers have been performed by means of two standard force machines from the endowment of ICMET Craiova: a 1000 kN machine for tension and compression with weights loading and amplification by lever, and a 10000 kg machine for tension with direct loading of weights.

Fig. 7 – 100 kN force transducer with FO sensor (tension).

Fig. 8 –200 kN force transducer with FO sensor (tension/compression).

The machines (qualified with a measurement uncertainty of $\leq$ 0,05 % for the working ranges of 5 - 1000 kN and 100 - 10000 kg) and the test setup for force transducers are presented in Fig. 9 and Fig.10.
For determining the strain variation of the force transducer test body at the working temperature with a view to compensating the variation of their zero signal, experiments and measurements have been performed in a climatic chamber Vőtsch type VC4060 (600 l volume) with the 100 kN force transducer– Fig. 11, to its test body being attached a temperature sensor type OSP-A, with the measurement range between -40 ºC and + 250 ºC

Fig. 9 – Test setup for the de 200 kN transducer in the 1000 kN machine

Fig. 10 – Test setup for the de 100 kN transducer in the 1000 kg machine

Fig.11 – Temperature variation test in climatic chamber Vőtsch.

In order to determine the performances and to characterize metrologically the experimental models of force transducers achieved, they have been tested in accordance with national and international norms (SR 11852/4-1993 and ISO 376-2004) specific to load cells for measuring force and/or mass.
The results got at the environmental temperature of the 100 kN transducer for tension (linearity 0.2 %, repeatability 0.3 %, hysteresis 0.5 %) have been thoroughly presented in the paper [7].
Further on, the results got by the tests, experiments and measurements performed with the two force transducers experimentally achieved, regarding their metrological performances with a view to utilizing them in measurements for different industry and/or laboratory applications are presented.

4.1. Tests and experiments at temperature variations with the 100 kN transducer (tension)

For assessing the behavior of the 100 kN tensile force transducer with the temperature within a range from 0ºC to 50ºC, this has been mounted in a climatic chamber, located in the chain for weight loading of the 10000 kg machine with direct loading (Fig. 10).
The got results are presented in Table 1 as average values for 3 – 4 measurements.
From the tests and measurements performed according to SR 11852/4-1993 and presented in Table 1, it is found that the achieved 100 kN force transducer maintains its metrological characteristics (3273 με sensitivity and the measurement errors) at an environmental temperature of 21ºC ±2ºC, but it changes its temperature sensitivity in a range between 0ºC and 50ºC, namely 3061 με at 50ºC (about – 7% /ΔT=30ºC) and 3368 με at 0ºC (about + 3% /ΔT=20ºC) , and the errors increase (especially the hysteresis error).
The errors related to the rated load of 100 kN (according to SR 11852/4-1993) are given in Fig. 12 as average values at environmental temperature of 21ºC ± 2ºC and at temperatures of 0ºC and 50ºC.
For determining and compensating the temperature influence on the 100 kN transducer, on the body of which a strain sensor type OSP-A of ± 5000 με was bonded, no-load measurements have been performed in a climatic chamber (Fig.11), for a temperature range between -40ºC and 60ºC. The body of the 100 kN force transducer and 3 strain sensors OSP-A of ± 1000 με, ± 2500 με and ± 5000 με connected to a SISO type MultiSens4 have been put in the climatic chamber, starting from a temperature of 20ºC.
From the performed measurements, it was found that the transducer body (alloy steel bar with 13.7 mm diameter) undergoes a strain depending on temperature, of about 10-11 με/ºC [measured values: -710 με at -40ºC, -205 με at 0ºC, 0 με at 20ºC and +405 με at 60ºC], unlike the strain sensors themselves, the signals of which do not vary by more than ± 10 με on the whole temperature range.

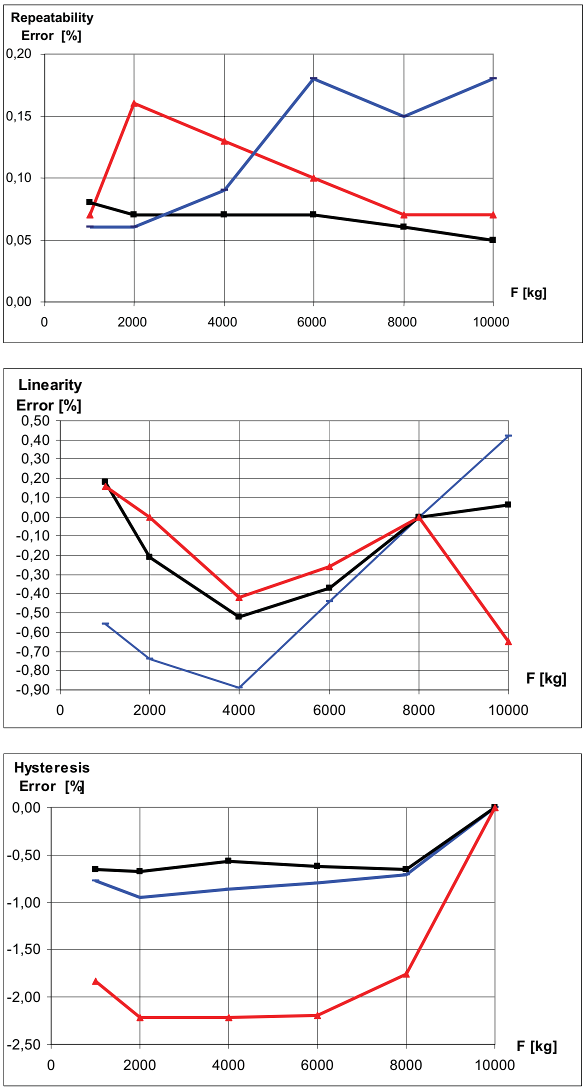

Fig.12 - Measurement errors of the 100 kN transducer (T) (blue - 0ºC ± 1ºC, black - 21ºC ± 1ºC, red - 50ºC ± 1ºC)

On the basis of the above measurement data, a temperature compensation of force transducers fitted out with FO strain sensors in a diagram like that one from Fig.6 can be achieved, knowing both the no-load strain of the transducers and their sensitivity change with temperature.

4.2. Tests and experiments at environmental temperature with the 200 kN transducer (tension/compression)

The 200 kN fiber optic transducer has been tested in accordance with SR 11852/4-1993 for determining is metrological performances (linearity, repeatability and hysteresis), at an environmental temperature between 20ºC and 24ºC.

In Table 2, the results of some cycles of tension and compression tests achieved in different days are presented. The series of value M1 (T/C) - M3 (T/C) represents the average of 3-4 measurements.

The average errors for the series of values M1- M3 (tension) and M1 - M3 (compression), determined according to SR 11852/4-1993 and related to the rated load of 200 kN (+1276 με for tension and -1311 με for compression), are given in Fig.13.

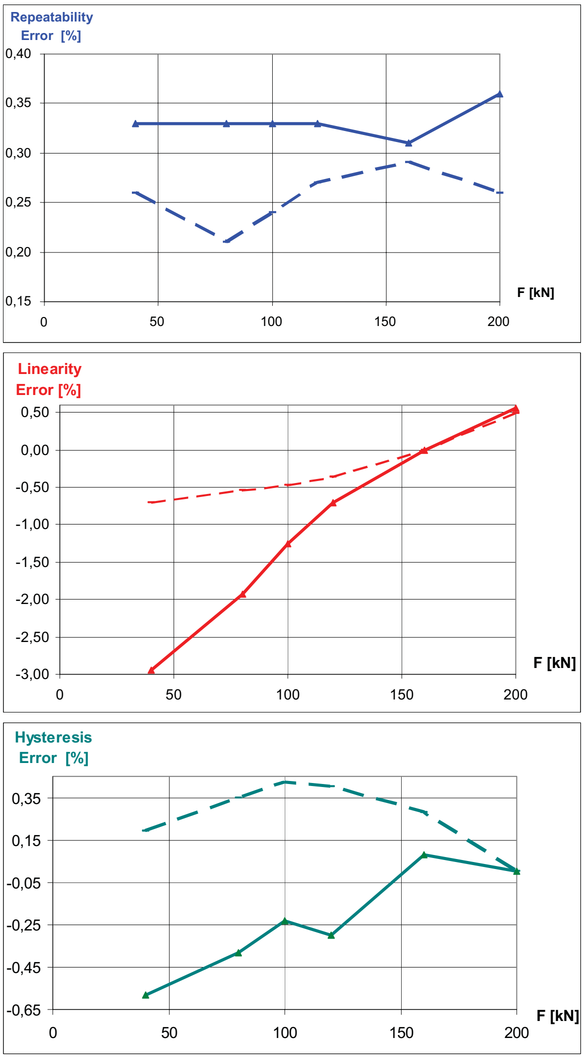

Fig.13-Measurement errors of the 200 kN transducer (T/C) (solid line - compression, dotted line - tension)

The results for this type of combined (hybrid) tension/compression transducers are promising from the point of view of the repeatability and recovery (hysteresis) errors – values up to 0.5% being got, but the linearity error of this type of transducer is higher than 1.5% at compression, which probably is due to the transducer body geometry.

5. CONCLUSIONS

The got experimental results demonstrate that by the new measurement technology, uncertainties with the same order of magnitude as in classical technologies can be got – in this case up to 1%.

The use of optic sensors represents an excellent alternative to the sensors with strain gauges, due to some advantages like: lack of metallic parts, immunity to electromagnetic disturbances, possibility to use them at high voltage and under other difficult operation conditions (explosive, corrosive media etc.).

At the same time, their miniature size, low dependence to the transversal strain, the relatively reduced cost and the possibility of software compensation for temperature influence, recommend them for utilization in different industry and laboratory applications for monitoring and measuring some non-electric physical (mechanical and thermal) quantities.

References

[1] E. Marinescu, A. Marinescu, *Introducere in magneto-elasticitate*, Editura ICPE București, 1997.

[2] T.S. Francis, L. Y. Shizhuo, P.B. Ruffin, *Fiber Optic Sensor*, CRC Press, 1993.

[3] A. Marinescu, *Non Conventional Measuring Systems Based on Optoelectronic Technology. ICMET Experience*, Proc. of ICATE Conference, Craiova 2008.

[4] Opsens , *Fiber Optic Strain Gauge* (available on *www.opsens.com).*

[5] Fiso , *Fiber Optic Sensors with Polarization Interferometry Technology*(available on *www.fiso.com)*

[6] Neoptix , *Sensors based on Polarization Interferometry Technology* (available on *www.neoptix.com)*

[7] A. Marinescu, G. Opran, M. Teodorescu , *Optical sensors application for strain and force measurement in installations used in high potential environment,* Proc. OptoTech Symposium of Cheia, 6-8 May 2009.