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HIGH-ENERGY TRANSFORMER'S SAFETY

Based on many advantages of fiber optic sensor technology, the article presents the possibility of measuring temperature in difficult environmental conditions, for example in a high electromagnetic field. Fabry-Perot interferometers with a short resonant cavity of low resolution are used in these fiber-optic sensors. The advantages of such a solution include simple and compact construction, low price, low temperature effect and no interference loss due to polarization.
Due to the potential of transformer loads, electrical power plants and operating companies test power transformers to assess their condition, set a schedule for maintenance work and plan replacement. Oil temperature measurement is most commonly used using typical sensors. However, this measurement does not reflect the temperature of the winding during the sudden increase in the transformer load.
The proposed method of verifying the parameter, which is the winding temperature, can be very attractive for electricity distributors.

Keywords: power transformer, winding failure, blackout

INTRODUCTION

High energy transformers are among the most valuable equipment of electrical power plants. The production of new transformers and their delivery to the place of operation generates significant costs, however, damage caused by the transformer failure and consequent loss of electricity production may in consequence be much more serious. Therefore, the plants try to maintain the efficiency of the transformers as long as possible. The life of the transformers depends largely on the winding's operating temperature, so it is important to monitor it.

The unique properties of fiber optics, such as the very large information capacity, the ability to transmit signals over long distances, high information rates, insensitivity to electromagnetic interference and reliability make them widely used in telecommunications, signal processing and measuring technology. Fiber optic temperature sensors are measuring transducers that receive information about the measurement size which is the temperature and process it at the transducer output causing an optical signal.

The work presents a method of temperature monitoring in the presence of high electromagnetic radiation using optical fiber sensors. The special technology

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of semiconductor crystals plays an important role in metrology. A method of measuring a sensor based on the use of the Fabry-Pérot interferometer has been proposed.

1. PHYSICAL DESCRIPTION OF THE OPERATION OF A FIBER OPTIC SENSOR

The main component of the measurement system is a fiber optic sensor made in gallium arsenide technology. A great advantage of using gallium arsenide in the device is that it generates less noise than most other types of semiconductors. The gallium arsenide is also completely resistant to electromagnetic induction.

The operating principle of the fiber optic temperature sensor used in the tests is based on the Fabry-Pérot interferometer technology. It is based on the interference of light waves carrying information about temperature. This phenomenon is shown in Figure 1.

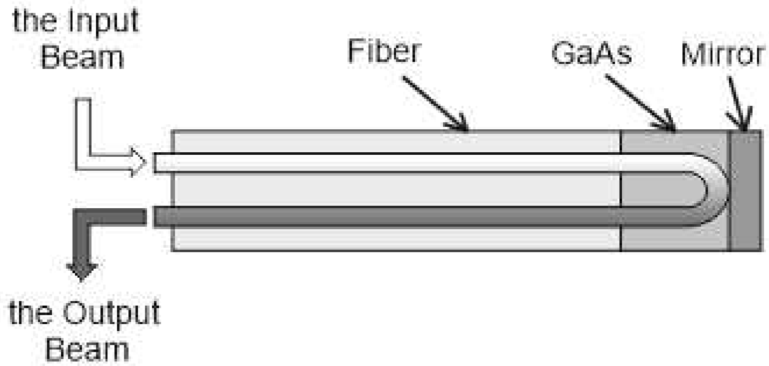

Figure 1. Schematic of the sensor operation based on gallium arsenide technology [1]

A multimode optical fiber uses a continuous broadband light source to illuminate a semiconductor crystal [2-5]. The electrons of the valence band can collide elastically with photons with sufficient energy, which allows to jump to the conduction band. Both bands are separated by an energy gap (E_g expressed in eV). E_g depends not only on the semiconductor structure, but also the hydrostatic pressure and temperature as presented in equation (1) and (2) respectively:

$$E_g(P) = E_g(0) + b \cdot P - c \cdot P^2 \tag{1}$$

where P is the pressure expressed in GPa and for gallium arsenide at 300K:

- $E_g(0) = 1{,}43 \pm 0{,}01\ eV$,
- $b = (10{,}8 \pm 0{,}3)\ eV/GPa$,
- $c = (14 \pm 2) \cdot 10^{-3}\ eV/GPa^2$.

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T} \quad (2)$$

where T is the temperature expressed in K ($0K < T < 10^3 K$) and for GaAs at normal pressure:

- $E_g(0) = 1{,}519\ eV$,
- $\alpha = 0{,}541 \cdot 10^{-3}\ eV/K$,
- $\beta = 204\ K$.

Photons, deriving from a continuous broadband light source, illuminating a semiconductor, can interact with valence electrons depending on their energy:

$$E_\gamma(\lambda) = \frac{h \cdot c}{e \cdot \lambda} \approx \frac{1239{,}84}{\lambda} \quad (3)$$

where:

- E_γ is the energy of the photon expressed in eV,
- λ is the wavelength of the photon expressed in *nm*,
- h is the Planck constant,
- c is the speed of light in a vacuum,
- e is the absolute value of the elementary charge of the electron.

Photons with longer wavelength has lower energy. These photons passed through the semiconductor, return to the optical sensor after reflection from the mirror limiting the system. Only photons with higher energy ($E_\gamma > E_g$) are absorbed. A resultant form of the high pass filter in the wavelengths shown in Figure 2.

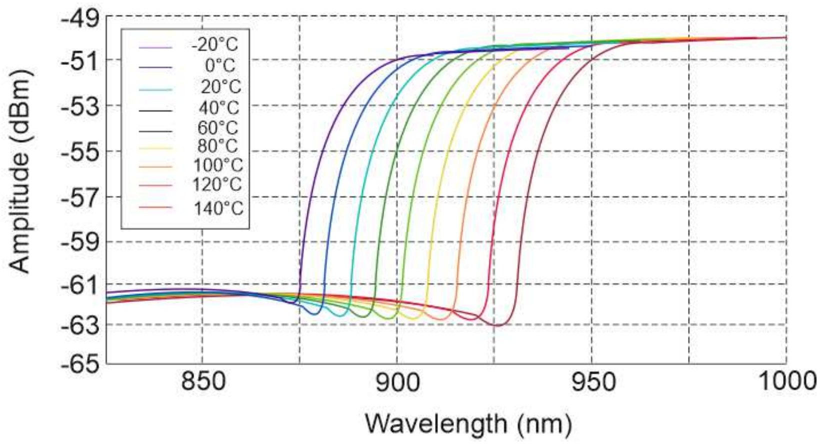

Figure 2. The GaAs sensor spectrum measured by an optical spectrum analyzer at temperatures from -20 to +140 with a difference of 20 [3]

The measurement by means of a fiber optic sensor is based on the use of the Fabry-Pérot interferometer (IFP). Interference image is obtained due to the resonance cavity. In a flat IFP, a parallel beam of light can bounce repeatedly from flat mirrors arranged in parallel or not bounced at all. All rays (reflecting and not reflecting) interfere with each other giving a contribution to the resultant intensity of light passing through IFP. The light intensity at the exit is determined by the formula:

$$I = \frac{I_0}{1+F sin^2 \Phi} \tag{4}$$

where Φ is the phase delay produced by the beam passing through the resonance cavity once, while the

$$F = \frac{4R}{(1-R)^2} \tag{5}$$

is called the slenderness coefficient of interference fringes, R denotes the intensity of reflection coefficient of mirrors [6].

The unique design of the sensor is based on the measurement of the cut-off of the wavelengths of light. Temperature variations create differences in the wavelengths cut off in the Fabry-Pérot cavity and the signal conditioner can continuously measure the wavelength with high accuracy despite any unfavorable environmental conditions (electromagnetic interference, humidity and vibration). Through the use of cross-correlation of white light, signal meters have a surprising speed, providing very accurate and reliable measurements. The principle of IFP's operation is shown in Figure 3.

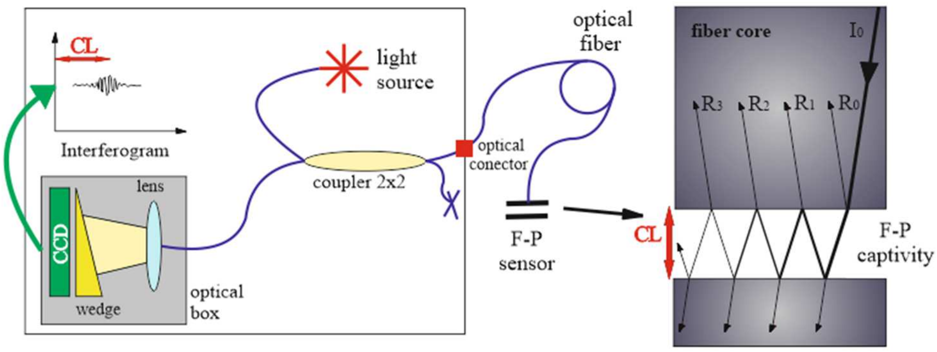

Figure 3. Schematic description of the F-P absolute measurement signal based on white light interference (left) and the structure of the F-P measurement interferometer showing the course of rays obtained by the propagation of the light beam in the optical fiber core (right) [3]

The TPT-62 probe is a robust, fiber-optic temperature probe for use in oil-filled power transformers. It is specially designed to withstand transformer operation conditions, including desorption of kerosene and heat and vibration release during the entire life of the transformer. The geometrical parameters of the sensor are shown in Figure 4:

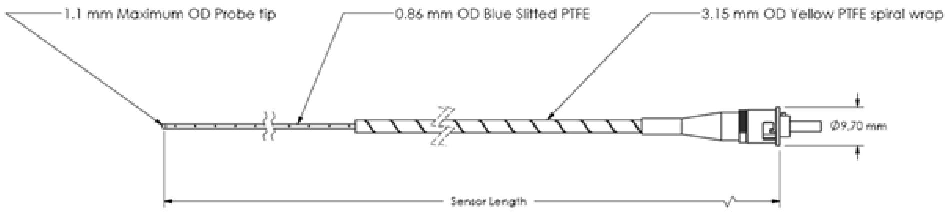

Figure 4. The construction of the TPT-62 measuring probe [1]

The temperature range of the TPT-62 sensor ranges from –40°C to 225°C, 0.1°C resolution, and temperature accuracy of ± 1°C.

Fiber optic sensor is made of insulating materials and is insensitive to electromagnetic interference.

2. HIGH-ENERGY TRANSFORMER TESTING

Power transformers transform electrical energy from one voltage level to another - they increase the transmission voltage to limit losses or power interruptions in the distribution network. The lifetime of the transformers depends largely on the winding operating temperature (Figure 5).

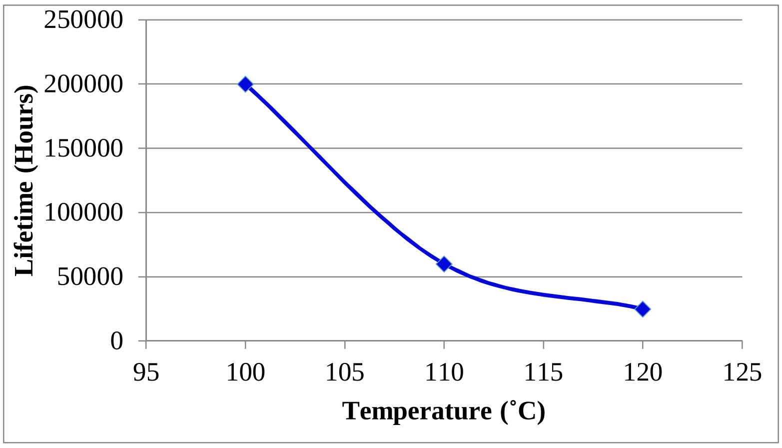

Figure 5. Influence of transformer winding temperature on its lifetime

Internal losses, caused mainly by the load current, have to be discharged. High temperature causes deterioration of transformer insulation materials. Transformer damage caused by these interactions can cause explosion, fire and costly consequences, such as prolonged downtime due to the need to clean and repair the site, as well as the need to wait for new transformers to be delivered.

Figure 6 shows the image of a damaged transformer.

Figure 6. A damaged high-energy transformer

3. THE EXPERIMENTAL METHOD

Testing high power transformers in laboratory conditions is difficult due to the costs. In order to familiarize with the phenomenon from the experimental side, a low power transformer (50W) was tested, immersed in silicone oil [7]. The diagram of the measurement station is shown in Figure 7. One of the sensors measures the temperature directly on the winding, the other measures the oil temperature. The measuring system works via the Nortech Sentinel II interface with a computer program that has the ability to record temperature changes over time. The dynamics of oil temperature changes and the winding of the transformer immersed in it at an exemplary overload 250W is shown in Figure 8.

As can be seen, there are significant differences in the temperature of the winding compared to the oil temperature at a rapid increase in the load. It follows from this conclusion that the oil temperature measurement alone does not show the actual operating condition of the transformer and the temperature measurement should be used directly on the winding. In addition, measuring the temperature in several places of the winding allows to detect the initial phase of damage, for example compact coils and gives the possibility of switching off the transformer before its complete destruction.

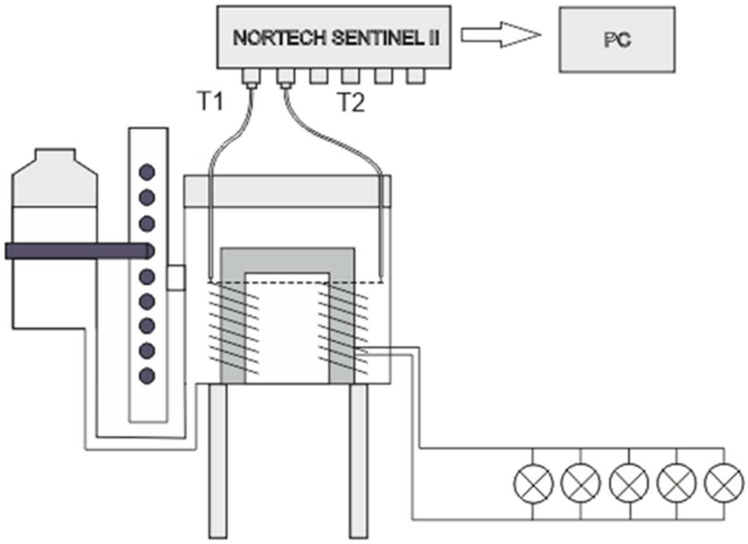

Figure 7. The scheme of measurement

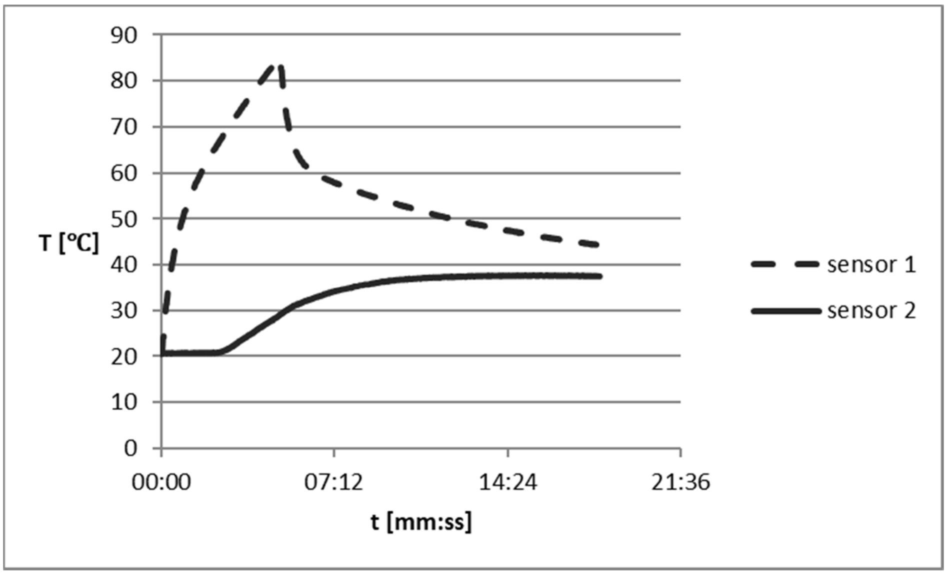

Figure 8. Dynamics of oil and winding of the transformer immersed in oil temperature changes; sensor 1 - winding temperature measurement, sensor 2 - oil temperature measurement

4. CONCLUSIONS

The paper proposes an experiment that allows for temperature measurement in unfavorable environmental conditions. The sensor proved itself and correct measurements were taken in real time.

In the experiment carried out to measure the temperature of the transformer winding and electro-insulating liquid, which was silicone oil as an insulator and coolant of the power transformer. The measurements showed ineffectiveness of the traditional temperature measurement of the oil itself. Spontaneous convection of fluid was noticed, which could additionally confuse potential users and mask the actual temperature of the winding. The presented method of transformer monitoring is extremely useful for electric energy distributors.

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MONITOROWANIE TEMPERATURY TRANSFORMATORA WYSOKOENERGETYCZNEGO Z WYKORZYSTANIEM CZUJNIKA ŚWIATŁOWODOWEGO

Bazując na wielu zaletach technologii czujników światłowodowych, artykuł przedstawia możliwość pomiaru temperatury w trudnych warunkach środowiskowych, na przykład w wysokim polu elektromagnetycznym. W omawianych czujnikach światłowodowych stosuje się interferometry Fabry--Perota, z krótką wnęką rezonansową o małej rozdzielczości. Walorami takiego rozwiązania są m.in. prosta i zwarta budowa, niska cena, mały wpływ temperatury oraz brak zaniku obrazu interferencyjnego wywołanego polaryzacją.

W związku z możliwością obciążeń transformatorów, zakłady elektroenergetyczne oraz firmy prowadzące eksploatację testują transformatory mocy w celu oceny ich stanu, ustalenia harmonogramu prac konserwacyjnych i zaplanowania wymiany. Najczęściej stosowany jest pomiar temperatury

oleju stosując typowe czujniki. Jednak taki pomiar nie odzwierciedla temperatury uzwojenia podczas nagłego zwiększenia obciążenia transformatora.
Zaproponowany sposób weryfikowania parametru jakim jest temperatura uzwojenia może być bardzo atrakcyjny dla dystrybutorów energii elektrycznej.

Keywords: transformator mocy, uszkodzenie uzwojenia, blackout

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