Multipoint Fiber-Optic Hot-Spot Sensing Network Integrated Into High Power Transformer for Continuous Monitoring

A. B. Lobo Ribeiro, N. F. Eira, J. M. Sousa, P. T. Guerreiro, and J. R. Salcedo

Abstract—**A multipoint fiber-optic temperature sensor network integrated inside a power transformer for continuous monitoring of hot-spots on windings, cellulose insulations, and oil, is demonstrated and tested. The temperature sensors are based on proprietary encapsulated fiber Bragg grating (FBG) sensors and the optical interrogation unit uses a special designed narrowband high power broadband fiber source. The fiber-optic sensing network is integrated into a 20 MVA, 345/$\sqrt{3}$ kV −20 kV power transformer (CORE type) having 12 temperature sensing points, distributed over several physical locations inside the transformer (windings, cellulose insulators, magnetic circuit, and cooling oil entrance and exit).**

Index Terms—**Fiber Bragg grating, fiber-optic sensor, power transformer, temperature measurement.**

I. INTRODUCTION

TRANSFORMERS area among the most vital items of equipment in power systems networks, and the consequences of an unexpected failure can cause high financial damage for any energy provider. Loading capability of power transformers is limited mainly by winding temperature. During its entire operation time, a power transformer has to withstand numerous stresses of a thermal, electrical and mechanical nature [1], originating an increasing degradation of the cellulose insulation, which undergoes a depolymerization process. The mechanical properties of the paper (tensile strength and elasticity) degrade, and the paper is not capable of withstanding short circuit forces and even normal vibrations, defining irreversibly by this way, the transformer end of life [2]. Oil-filled power transformers have and additional risk when operating at high temperature, due to the residual water trapped in paper that can reach bubbling conditions. These water vapor bubbles may move with the oil flow, or get trapped in the winding, and in both cases create a threat for insulation breakdown [2]. This is why the so-called hot-spot temperature is of great importance for the transformer owners, and the direct measurement of winding temperature is necessary [3].

There are a number of thermal models for estimating the hot-spot temperature behavior, which uses the temperature measurements obtained outside or inside the transformer by using 1) thermocouple devices or 2) fiber-optic sensors (single-point sensor or by fully distributed sensor). The thermocouple device cannot be used in the winding, but rather at the cooling oil at the bottom and at the top of the transformer, and also suffer from electromagnetic noise interference. The distributed temperature fiber-optic sensor, mainly based on Raman scattering effect, although having enough temperature accuracy for power transformers, they have also a poor spatial resolution (±1 °C/m), long acquisition time and higher cost [4]. On the other end, single-point fiber-optic sensors available on the market, are based on solid-state semiconductor device (GaAs based) glued at the tip of a 200/230 μm optical fiber, with accuracies between ±1.5 °C and ±2 °C [5].

In this paper, the authors demonstrate a real test application of all fiber Bragg grating (FBG) temperature-sensing network embedded inside a 20 MVA, 345/$\sqrt{3}$ kV-20 kV power transformer (CORE type). The temperature change, and consequently, the Bragg wavelength shift of each uniform FBG sensor, is measured using a modified version of a passive all-fiber demodulation scheme previously described by one of the authors [6]. In order to have a long optical sensor fiber link capability (~1000 m) without sacrificing the signal-to-noise ratio of the sensors a proprietary narrowband high power ASE fiber source was fabricated.

II. SYSTEM DESCRIPTION

The configuration of the multipoint fiber-optic sensor (MPOS) unit is shown schematically in Fig. 1. A narrowband and spectrally flat ASE fiber-optic source (shown in Fig. 2), emitting at central wavelength of 1550 nm with ~55 mW output optical power and ~7 nm spectral width (FWHM), was used to illuminate the uniform FBG sensing network in a star-topology which is deployed inside the power transformer.

The optical signal-processing (OSP) module is based on a modified version of the demodulation scheme described in [6]. This OSP module integrates all optical photodetection (two fiber pigtail photodetectors, a 3 dB fiber coupler and a in-house fabricated linear slope fiber filter with a ~1.1 dB/nm centered at 1550 nm), the 13-bit analog-to-digital (ADC) conversion, microcontroller (PIC18F452 of MicroChip) and RS232/RS485

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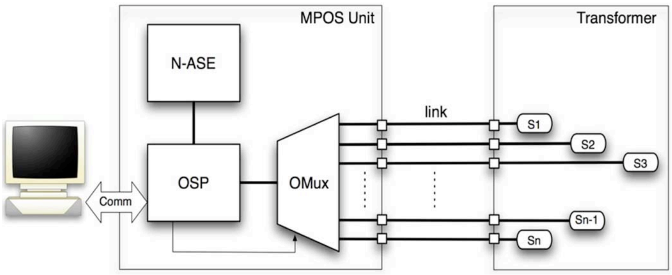


Fig. 1. Schematic diagram of the multipoint fiber-optic sensor unit. (N-ASE: narrowband ASE fiber-optic source, OSP: optical signal processing module, OMux: addressable optical multiplexer, Sn: fiber-optic sensor number n.)

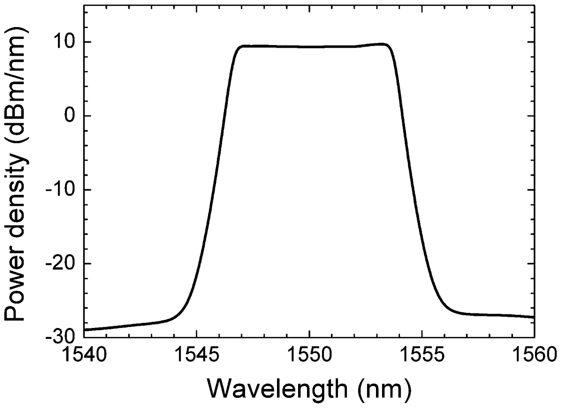
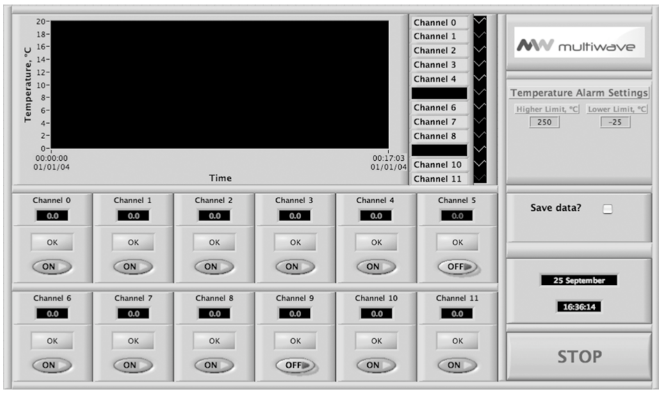


Fig. 2. Emission spectra of the narrowband ASE fiber source [7].

Fig. 3. Photo of the MPOS unit developed.



Temperature Alarm Settings
Higher Limit, °C 250
Lower Limit, °C -25
Save data? ☐
25 September
16:36:14

Channel 0 0.0 OK ON
Channel 1 0.0 OK ON
Channel 2 0.0 OK ON
Channel 3 0.0 OK ON
Channel 4 0.0 OK ON
Channel 5 0.0 OK OFF
Channel 6 0.0 OK ON
Channel 7 0.0 OK ON
Channel 8 0.0 OK ON
Channel 9 0.0 OK OFF
Channel 10 0.0 OK ON
Channel 11 0.0 OK ON

Fig. 4. Graphical user interface of the MPOS unit.

communication interface for external PC unit control and graphical user interface. The presented module has also the option to communicate with a PC via USB and/or GSM interface. This OSP module also communicates with the addressable optical multiplexer (OMux) module through an embedded programming algorithm, which digitally controls independently the optical port for each FBG sensor. This OMux his based on optomechanical switching technology (MOEMS fabricated by IOTech GmbH), with a multiplexing capability of 1 × 12 optical ports, switching time less than 2 ms and insertion loss of 0.7 dB.

All the FBG sensors have an identical nominal Bragg wavelength of 1550 nm at room temperature, with a reflectivity around 98%, wavelength bandwidths of 0.2 to 0.1 nm and a physical length of 10 mm. The FBG sensors where encapsulated in a uniform size protective tubing (special quartz capillary and Teflon tubes from Alpha Wire Co.), which ensure full protection of tip against mechanical stress and potential transformer oil damage. The fiber sensor cable inside the transformer is passed to the outside through a tank wall mounted feed-through vacuum channel, which avoids oil leakage, and is terminated with a FC/APC fiber-optic connector/adapter. For the experimental tests, we have used a two combined fiber-optic cables between transformer and MPOS unit, both of 25 m in length and with six single-mode fiber-optic link each, but the system is capable of reading the signals at longer optical link distances (∼1000 m).

Fig. 3 shows a photo of the developed MPOS unit with capability to multiplex 12 FBG sensors (with expanding capability option up to 36 sensors). The main characteristics of this sensing unit are: temperature accuracy of ±1 °C and resolution of 0.1 °C over the temperature operating range −25 °C to +250 °C; maximum switching channel frequency of 50 Hz and a sampling sensor rate of 150 Hz (limited only by the photodetection electronics and for this particular sensing application).

The LabView™ software package is used to perform real-time data acquisition, signal processing, network communication control and graphical user interface (GUI). Configuration and data files are saved to the user's PC, for later data analysis and temperature history record. Fig. 4 shows the GUI implemented for the present sensing system.

III. RESULTS AND DISCUSSION

The results of the temperature monitoring obtained during a laboratory load test of the 20 MVA, $345/\sqrt{3}$ kV-20 kV power transformer (CORE type), are presented in Fig. 5. The fiber-optic sensors numbered 429 and 411 are mounted in direct contact with the lower and higher voltage bars of the transformer, respectively, and the sensor 404 is glued inside the deflector tube of the high voltage cooper bar. The other sensors numbered 426, 427, 428 are distributed in different locations of the windings; the sensors 418 and 414 are located in the magnetic circuit; the sensors numbered 412, 413, 409, and 403 are glued at different positions of the oil-tank wall. The power transformer was subjected to a 10% overload condition (10% above nominal current) at the ambient temperature of 22 °C.

This continuous temperature monitoring of power transformer provides a clear indication of its real status and aging behavior. During overloaded cycle accelerated aging has to be minimized

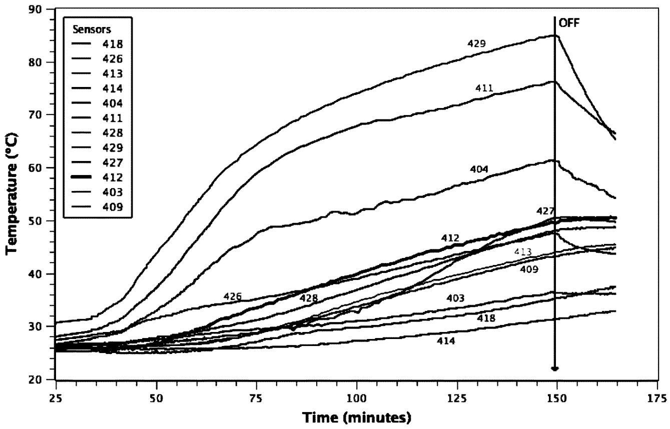


Fig. 5. Hot-spot temperature measured by the MOPS unit during a heating cycle of the 20 MVA, 345/$\sqrt{3}$ kV-20 kV power transformer.

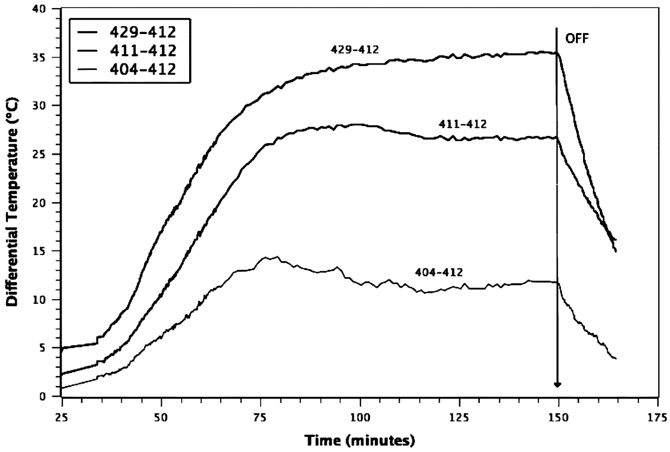


Fig. 6. Differential temperature measured by the MOPS unit during a heating cycle of the 20 MVA, 345/$\sqrt{3}$ kV-20 kV power transformer.

and with these online data, damages can be avoided. It should be mentioned that a hot-spot temperature of 120 °C, which is admissible according to the standard IEC 60354, causes an aging rate factor of 12, and thus its obvious that continuous transformer monitoring of aging is highly recommended.

Fig. 6 shows the differential temperatures between the sensors 429 (low voltage bar), 411 (high voltage bar), 404 (deflector tube of high voltage cooper bar), and the sensor 412 (oil-tank cooling radiator input). As it can be seen from these results the cooling oil circulation system effectively works in order to maintain the differential temperature stable.

It has been recently demonstrated [8], that the transformer oil has no characteristic influence on the mechanical strength of the used optical fiber type and the thermal induced decrease of the refractive index variation in the FBG does not prevent a signal processing with excellent SNR. This clearly indicates that this type of sensor is a real candidate for continuous temperature monitoring of hot-spots on high power transformers.

Fig. 7 shows a photo of the 20 MVA, 345/$\sqrt{3}$ kV-20 kV power transformer (CORE type) used in the temperature cycling test that was performed on the laboratories of EFACEC—Energia S.A. (Portugal).

Fig. 7. Photo of the 20 MVA, 345/$\sqrt{3}$ kV-20 kV (CORE type) power transformer and the MPOS unit at laboratory test facility.

IV. CONCLUSION

The application of fiber Bragg grating sensors for monitoring power transformer hot-spot temperatures has been demonstrated. Laboratory load tests carried on a 20 MVA, 345/$\sqrt{3}$ kV-20 kV power transformer (CORE Type) show a 0.1°C resolution and an overall temperature accuracy of ±1°C to the monitoring unit developed. The sensing system has a multiplexing capability of 12 sensing probes (expandable up to 36 probes), and a real-time probe control and temperature history analysis, providing this way an online indication of the transformer status and aging behavior.

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