Measurements of Mechanical Vibrations at Magnetic Cores of Power Transformers with Fiber-Optic Interferometric Intrinsic Sensor

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***Abstract*—A fiber-optic interferometric sensor with intrinsic transducer along a length of the fiber is presented for vibration measurements of the magnetic core inside an oil-filled power transformer. The sensor is designed for high sensitivity measurements into the harsh environment of electromagnetic fields, wide temperature change, and in oil immersing. This sensor allows e nough sensitivity for the application, for which vibrations amplitudes are due to submicron displacements at frequencies of 100 Hz and its harmonics. in addition, the accessibility to the sensing region is guaranteed by low size immune fiber-optic cables as well as optical phase-based transducer/carrier of the sensor outpu. Thus, it is ideal for the requirements of the remote operation. The transducer size is a few mm in length, and is compact and rugged. Our results show that the vibrations of the elements constituting a power transformer are directly measured, improving the indirect techniques actually available. Finally, the measurements inside a medium power transformer at site are obtained for its application in electric plants.**

***Index Terms*—Dynamic strain and mechanical vibration measurements, interferometry, fiber-optic sensors, harsh-environments, power transformers.**

I. INTRODUCTION

TECHNOLOGICAL advances in on-line monitoring are actually arriving to electric power plants and power transmission systems for measurements and diagnosis tests. Since power transformers are among the most expensive elements of the high-voltage power system, the monitoring of such equipment realizes in significant costs saving due to maintenance [1], [2]. The data that are actually most often used for both diagnosis and analysis of transformers are obtained through indirect measurements and an estimation of the parameters in study. For example, measurements of temperature are accomplished at accessible points and then a modeling of the gradient induces the maximum temperature in some areas. Furthermore, the vibrations of the magnetic core are deduced from vibration measurements at the external surface of the transformer. However, the measurement of these parameters and others performed at significant regions inside the transformer are being attractive for on-line monitoring and diagnosis, as well as for further modeling and analyzing its behavior in service [1], [2].

Traditionally, electric parameters and analysis of moisture content of the cooling oil are performed for transformer maintenance and diagnosis [1], [2], with requency response analysis (FRA) of electric characteristics being common. Nevertheless, recent efforts have been made to deal with measuring other parameters as temperature and vibrations [3], [4] and for example partial discharges (PD) [5]. These are stretching related to the performance of the transformer. The temperature gives information of the isolation accuracy and cooling effectiveness, particularly where hot spots are detected. The vibrations of the magnetic core and of the windings could characterize transitory overloads and permanent failures before any irreparable damage occurs [1].

Different fiber-optic sensors are available for temperature, some of which are proposed for measurements inside a transformer [6], [7], while to our knowledge, no attempts have been made for vibrations with this application. The best demonstrated application in real transformers is for temperature measurements based on the fluorescence of an optical fiber probe [8], [9]. First results with Bragg gratings have also been obtained [7]. Others, such as intensity modulation of light and a fiber-optic Fabry-Perot, are being proposed for applying in electric exploitations, but not into transformers.

On the other hand, several results have been obtained with fiber-optic sensors for vibration measurements applied to rotating electric machines [10]–[13]. They are mainly based on intensity modulation of light in a cantilever configuration. Although these accelerometers take advantage of immune fiber-optic technology, they cannot be installed into the environment of a filled oil transformer, especially for being in contact with the core and windings that are difficult to access. Moreover, higher sensitivity of the sensor is required for the typical amplitude of vibrations in this kind of applications. The aforementioned sensors are fine for rotating machines in power electric generation, as it was proposed. In this application, the amplitudes of vibrations are large at low frequencies of interest. Only interferometric techniques are able to achieve the sensitivity requirements for measuring the small amplitude of vibrations found in power transformers.

The techniques that have potential use in transformer applications are based in sensing dynamic strain in contact with the core and windings. Actually, only the interferometric fiber-optic intrinsic transducer is available [14]. Other techniques such as Bragg gratings-based ones, have not enough sensitivity for a few $\mu\varepsilon$, which would imply better than 10 pm resolution in wavelength measurement, which is difficult to obtain with practical instrumentation [15], [16]. Probably only the Fabry-Perot is accurate in sensitivity compared with the fiber optic as intrinsic

Manuscript received July 17, 2000; revised September 18, 2000. This work was supported by Unión Fenosa, S.A. under the FUTURE Project.

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Publisher Item Identifier S 1077-260X(00)11294-8.

1077–260X/00$10.00 © 2000 IEEE

transducer [15], [16]. However, in the case of the latter, the length of the sensing head enhances the intrinsic transducer sensitivity. In fact, the length required for submicron measurements of dynamic strain is not practical for a fiber cavity [17].

The main characteristics of the environment inside the transformers cause the measurements to be in harsh conditions. These conditions of operation are as follows. Electromagnetic fields are of high intensity, not only at accessing cables or electronic units, but also at the regions where sensors must be placed. Therefore, the sensors and patch cords must be immune, and remote operation is necessary for placing the electronic processing units far from the sensing area. On the other hand, the sensors need to be in contact with magnetic cores and windings, so compact solutions and low weight are recommended. Finally, the sensor heads and accessing cables are oil immersed because oil is used in high power transformers for cooling purposes. A wide temperature range, up to 100 °C from environmental temperature, could also be found. Consequently, fiber-optic sensors are ideal for these applications because they are even immune to these external fields, whereas the light propagating along the fiber should be an intrinsic transducer of the useful parameters. Electronic sensors as piezoelectric or semiconductor-based ones are not feasible in these conditions.

In this paper, we propose an interferometric sensor that is based on an intrinsic transducer for vibrations through the path change of the sensing fiber. Our interest for this application is devoted to measurements of vibrations inside transformers, though it also concerns the temperature impact. Since temperature and vibrations are clearly frequency separated for this application, the cross sensitivity of the interferometric sensor is far softened. However, the characteristics of temperature measurement are taken into account for desensitizing the sensor and for disturbance impact purpose. On the other hand, the vibrations in study are due to the magnetic field at the transformer core and due to loading effects at windings. In both cases, they are due to submicron displacements at frequencies related to the electric excitation (50 Hz–60 Hz). These conditions deal with high sensitivity sensors in the presence of temperature changes as well.

In this paper, we present a novel experimental setup for vibration measurements in a medium-power (25 KVA) transformer. Measurement of vibrations at magnetic cores is demonstrated using this fiber-optic interferometric sensor with short sensing fiber. We describe the bases of the fiber-optic interferometric sensor, its calibration, the behavior of the mechanical vibrations of transformers in vacuum tests, and the results obtained in field installation of the vibrations at the magnetic core of a medium power transformer. The sources of disturbance are identified and softened, and conclusions about the feasibility of the sensor are analyzed with the application.

The paper is organized as follows. Section II is devoted to the principle of sensing and the optoelectronic arrangement. The calibration of the interferometric sensor and the tests in the laboratory are presented in Section III. In Section IV, the blocks of the interrogation system at site and the operation procedures are described, as well as the tests concerning the installation in the power transformer. The experimental results of this sensing system are presented in Section V for measurements inside a medium-power transformer. They are focused on vibrations of the magnetic core in vacuum tests and parameters of influence. Finally, the conclusions are discussed in Section VI.

II. PRINCIPLE OF SENSING AND INTERFEROMETRIC SYSTEM

A. Principle of Sensing

The intrinsic transducer is a piece of optical fiber in contact with the vibrating surface (the magnetic core or the windings of the transformer). In the case of mechanical vibrations at the magnetic cores, they are induced by magnetostrictive forces. A periodic change of dimension of the ferromagnetic material is produced because of the magnetic fields in the transformer. This dynamic strain is sensed by changes in the optical path length of the light crossing the sensing fiber, and it is accomplished by interferometric interrogation. In this case, the interference intensity output in homodyne detection is

$$I(t) = I_o\{1 + V \cdot \cos[\phi(t)]\} \tag{1}$$

where

$I(t)$	intensity dependence with time;
I_o	mean of optical power from the source at the interferometer;
V	visibility;
$\phi(t)$	optical phase;

which is modulated by the stimuli.

On the other hand, the amplitude of the mechanical strain induced inside the transformer is up to a few microstrains. For a sensing length of a few centimeters, the induced optical phase change is up to π rad (half a fringe of the interferometric output). In addition, other parameters influence the sensor, especially the drift of phase due to temperature changes. Thus, the optical phase is modulated by several parameters that can be grouped as follows:

$$\phi(t) = \phi_O + \phi_{\mathrm{MV}}(t) + \phi_D(t) \tag{2}$$

where

ϕ_O	phase difference constant term between reference and sensing fiber;
$\phi_{\mathrm{MV}}(t)$	due to mechanical vibrations inside the transformer;
$\phi_D(t)$	term of disturbance.

The impact of this external disturbance is far slower than the dynamic behavior of the vibrations. Hence, although measurements of the strain would be strongly affected by the sensitivity to temperature, the measurement of the induced dynamic strain could be performed separately in frequency. However, the low frequency disturbance affects the initial phase of measurement and the sensitivity to the dynamic parameter. This effect is commonly named the optical phase drift. Thus, let us identify the quasistatic optical phase as ϕ'_O, equivalent to the point around the optical phase is modulated by the mechanical vibrations. Then the resulting interference output is

$$I(t) = I_o\{1 + V \cdot \cos[\phi'_O + \phi_{\mathrm{MV}}(t)]\}. \tag{3}$$

In (3), ϕ'_O is the initial phase, and $\phi_{\mathrm{MV}}(t)$ represents a low signal modulation. The maximum sensitivity is obtained around the quadrature point ($\phi'_O = \pi/2$ rad).

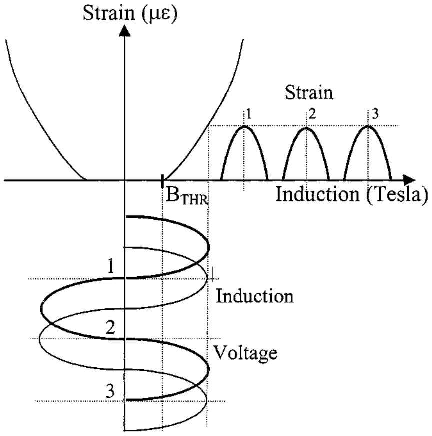


Fig. 1. Dynamic strain at the transducer related to the voltage input and induced by the magnetostrictive behavior of the magnetic core inside the transformer.

The characteristics of the mechanical vibrations measurements inside transformers confer benefits to the interferometric technique [3]. First, the stimulus dynamically modulates the optical phase and second, the frequencies of the mechanical vibrations can be accurately studied. Finally, the amplitude of these vibrations inside the transformer needs a high sensitivity sensing to measure up to a few $\mu\varepsilon$.

Fig. 1 is a schematic of the magnetostriction effect of the material. The magnetic field is modulated in quadrature with the voltage and thus, the magnetic forces are maximum when the voltage excitation gets nulls (Fig. 1). Moreover, the mechanical response of the material is independent of the magnetization sign. Consequently, the dynamic strain has a sinusoidal rectified shape (Fig. 1). Besides, the mechanical response of the material to the magnetization has a threshold. For example, for induction amplitudes less than 0.2 Tesla with silicon steel alloy, the induced strain is negligible, while a quasilinear response is observed in the region of interest between the threshold and the saturation (1.6 Tesla). These data are experimental observations of the effect at ferromagnetic materials [18]. Concerning the fiber-optic transducer, the optical phase is linear with the stimulus [19], so the modulation of phase can be expressed as follows:

$$\phi_{\mathrm{MV}} = \begin{cases} ABS[K_{\mathrm{MV}} \cdot l \cdot \sin(2\pi \cdot f_e \cdot t)], & |B| > B_{\mathrm{THR}} \\ 0, & |B| \leq B_{\mathrm{THR}} \end{cases} \tag{4}$$

where

K_{VM} sensitivity of the optical phase transducer expressed in rad/nm;

l amplitude of the periodical change of the optical path-length in the fiber;

f_e frequency of the voltage excitation.

For amplitude of the induction (B) less than the threshold (B_{THR}), the strain is negligible (Fig. 1).

The input voltage in the transformer to strain is depicted in Fig. 1, which also shows the induction at the magnetic cores. As can be seen, in practice, the magnetostriction has a main frequency two times faster than the voltage excitation and approximately in quadrature. For typical frequencies of the voltage in power transformers, 50 Hz for example (60 Hz in other cases), the vibrations modulate the optical phase at the sensing head at 100 Hz and its harmonics. In fact, since the magnetostriction is similar to a rectified sinusoidal excitation with a dead zone, harmonics of $2f_e$ are present. Moreover, the excitation, which is easily measured, gives a reference for synchronization of interferometric demodulation. However, other effects are expected, as the magnetostriction at the core material also produces transversal contraction.

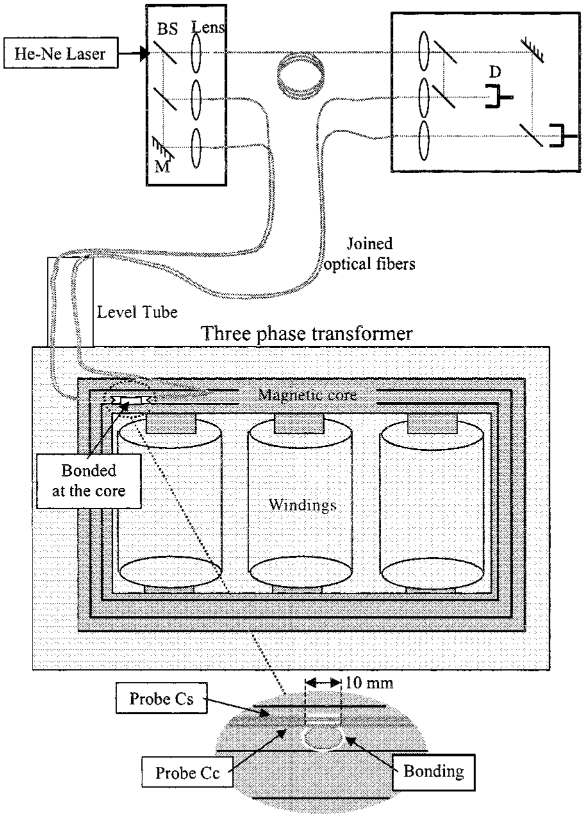


Fig. 2. Optoelectronic setup for interferometric measurements inside the power transformer.

Concerning the interferometric output demodulation, a first approach is by working with the interferometer in quadrature $\phi'_O = \pi/2$ rad, and for very low amplitudes of the dynamic optical phase. In this case, the sensitivity of $I(t)$ to the modulation $\phi_{\mathrm{MV}}(t)$ is maximum. Note that for this approach, the fiber-optic transducer is quasilinear. Thus, no linearity is only caused by the characteristic voltage to magnetostriction (double frequency and harmonics).

B. Optoelectronic Setup

The instrumentation system is based on a Mach–Zehnder interferometer for interrogating the fiber-optic arms. The disturbance is reduced with a common addressing path of the fibers to the sensing region, and the measurement is performed in differential means [3]. The optical fibers of the interferometer access to the vibrating surface stretchy joined and they are separated at the sensing region (Fig. 2).

The light source is an He–Ne laser (633 nm), and single-mode fibers are the optical paths of the interferometer. Splitting and recombining light is performed remotely at the optoelectronic unit. A piece of the optical fiber is the transducer due to strain in contact with the magnetic core surface of the transformer. The optical phase of the light travelling the sensing head is modulated, and the information is carried out to the processing unit. On the other hand, although both paths of the interferometer are joined, residual fluctuations of the optical phase occur because of the parameters influencing the patch cords. These effects are neglected by isolation of the cables from external disturbance.

Changes in the visibility of the interference output are observed. They are caused by misalignments of the optical setup and mainly by changes in the polarization stage of the fibers. This change of polarization is due to the birefringence of the fibers, mainly affected by temperature, though the setup was partially isolated from temperature, and patch cords were paired for accessing the sensing region. Polarization-maintaining fibers provide a partial solution to this problem, usually named polarization-induced signal fading. However, these fibers present softened sensitivity [20] to strain, and the optical components required increase costs and complexity. Other techniques of polarization control are proposed [21], but in fact, the adopted setup solution is low cost and quite enough for the application, in which visibility change was characterized up to 50%. The signal processing and demodulation of the optical phase is able to recover from these levels.

III. LABORATORY TESTS OF THE FIBER-OPTIC SENSOR

A. Calibration of the Sensor

A characterization system was developed in the laboratory for calibrating the fiber-optic interferometric sensor [22]. It was intended to reproduce the environmental conditions as in the transformer before the field installation. The experimental tests for the calibration concern the following concepts. The transducer sensitivity was characterized for dynamic strain of the surface in contact with it. The desensitization by bonding the sensor and immersing it in oil was studied, as well as the reliability of the fixing in these conditions. The temperature impact at the sensor was also studied. Other tests of isolation and pairing the accessing fibers were carried out, but they are out of the focus of this paper. Finally, previous results of vibrations at the magnetic core of a low power transformer were accomplished.

The optoelectronic setup for the characterization in laboratory is depicted in Fig. 3. The scheme is a fiber-optic interferometer in a Mach–Zehnder configuration. The reference path is insulated from the physical parameters to be applied. The sensing fiber is divided in several sections for testing separately the response to vibrations and the temperature impact at the accessing fibers immersed in oil used in power transformers. The patch cords of the sensing fiber are 250 cm in length, and a separation of 125 cm of fiber was used between the vibration probe and the temperature probe. The former is a section where dynamic strain is applied with a piezoelectric material and the later is a section affected by temperature. The lengths of the sensing and reference fibers are about 1100 cm. Some tolerance in the path difference was considered, thinking about the field practical installation as well as the long paths reproduce the conditions of remote operation in power transformers.

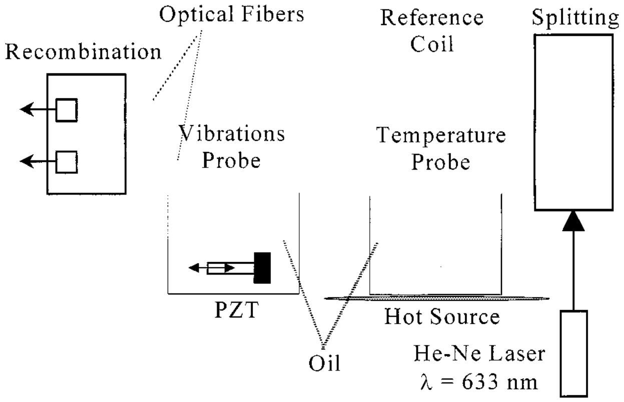


Fig. 3. Setup for the calibration of the interferometric sensor in laboratory tests.

The piezoelectric material (PZT) elongation with the applied voltage was characterized using a free space Michelson interferometer where the PZT supports a moving mirror. By applying high voltage ramps, the optical phase change was measured. In this case, the optical phase modulation is due to changes in the physical path of the arm where the PZT is used. Thus, elongation is obtained with regard to the wavelength of the source. It was characterized at about 1.25 μm elongation/100 V for a PZT length of 36 mm (i.e., 34.7 $\mu\varepsilon/100$ V). The frequency response of the PZT allows up to 200 Hz of signal bandwidth (3 dB cut-off frequency).

A segment of the optical fiber was bonded to the PZT with epoxy (vibrations probe). Twelve loops of 150 mm were used, from which, 13×17 mm are of the bonded section to the PZT. Several turns were used for enhancing the transduction at the fiber, resulting an expected sensitivity about π rad/5 volt. The probe was about 190 cm of length with exactly 221 mm of the sensing head. Although this size is unfeasible for real application, it is a compromise between the enhancement of the sensitivity through the probe length and minimizing loading effects from the PZT-free response. During the experiments of characterization, the PZT and the joined fiber were immersed in the oil that is usual in high power transformers for cooling purposes (Fig. 3). Several cycles of PZT excitation were applied with ramps of 20 Hz and 20 V of amplitude. The PZT response at this frequency is the aforementioned. In these conditions, the equivalent elongation of the PZT is 250 nm over 36 mm (i.e., 1.53 μm over 221 mm of bonding section: 6.9 $\mu\varepsilon$).

The optical phase output in these conditions of bonding and immersing in oil, was characterized experimentally as 10.27 rad with the fiber-optic interferometer. Therefore, the sensitivity of the fiber is 6.71 rad/μm (0.067 rad/$\mu\varepsilon$ for a sensing length of 10 mm). It indicates that the elongation observed at the optical fiber transducer is about 0.65 times the elongation of the surface at which it is bonded, by comparing with the results obtained in [19]. It was assumed that the strain is mainly applied axially with the light propagation. This difference of 35% between the elongation of the PZT and the strain sensed by the optical fiber represents the strain transfer efficiency, which is mainly caused by the

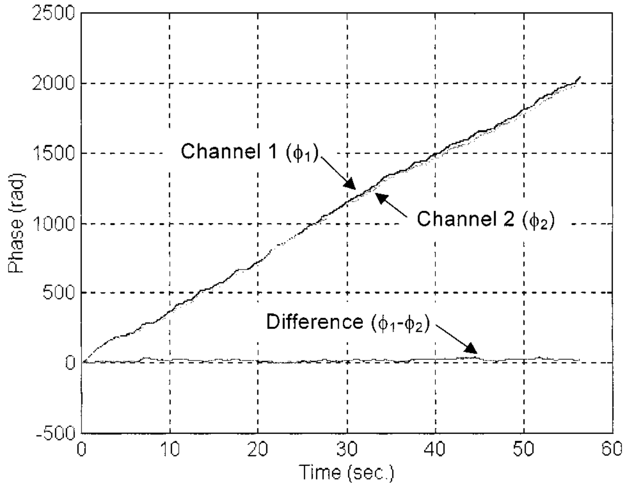


Fig. 4. Rejection of disturbance with common path: optical phase response with time of two fiber-optic channels to a common temperature stimulus and the phase difference between them.

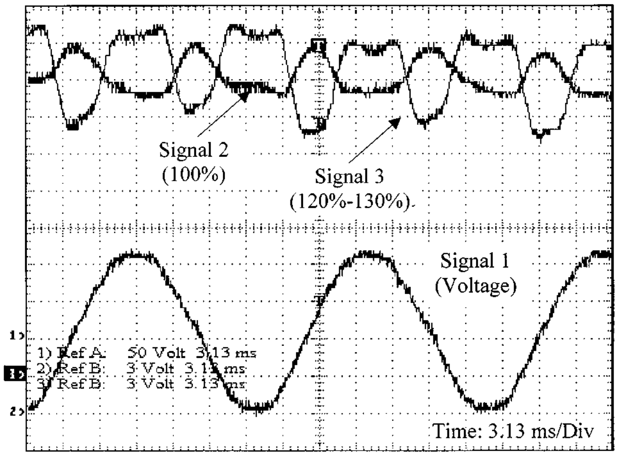


Fig. 5. Response of the sensor to two different amplitudes of vibrations (signals 2 and 3) at the low power transformer with two signs of transducer slope. The reference of synchronism is the voltage applied to the transformer (signal 1).

performance of the bonding to the surface. No additional effects were observed with the oil immersing conditions. The transmission of the strain from the monitored surface to the sensing fiber is limited by the practical bonding in this case. Finally, periods as long as months were used for observing the ruggedness of the optical fiber bonding in these conditions. No significant changes were observed in the results of sensitivity.

On the other hand, temperature impact and disturbance at the patch cords were studied, and particularly, experiments of desensitization to temperature with common path-accessing fibers (paired) were done. In Fig. 4, an example of the characterization of two paired fibers (250 mm length) with temperature are shown. They are two sensing paths of a two-channel interferometer with a common reference path [3]. The evolution of the cumulated phase with time is compared for the two outputs with the fibers immersed in oil, where temperature changes in the typical range at the transformer are applied during the experiment (cycles of 100 °C). The induced optical phases represented in Fig. 4 are of several fringes. The interference intensity outputs of two channels were sampled, resulting about 34 samples/period. The optical phase is calculated using fringe counting and fraction excess. The optical phase fraction excess was obtained by using $\cos^{-1}$ function at any instant of time, except when the first derivative of the interference intensity signal is close to null [23]. The correction from the fluctuations of amplitude (visibility changes) is implemented with the normalization performed before the signal processing. All these tasks are carried out by a computer. The results show that the optical phase difference between both paired fibers is characterized as less than 1% for bare fibers when they lay closely.

B. Characterization of Vibrations in Low Power Transformers

Before any further installation, we have tested the sensor with a low power transformer (220 V/3.5 A). It allows electrical tests to be easily performed, especially if extreme regimens of operation are demanded in safety conditions. For example, overloads and excitation voltages higher than the nominal operation are considered. In this case, the tests can cause damage in the medium power transformer installation.

A segment of approximately 20 mm in length was bonded to the visible surface of the magnetic core of the low power transformer. The sensing region was selected attending recommendations about where the measurement of vibrations is significant, but the amplitude is more realistic for future needs of sensitivity. The transformer ran with load and in vacuum tests. For the loaded tests, the response of the sensor was negligible, as was expected. In this case, the magnetic fields are minimized, so the effects of magnetostriction are insignificant at the transformer core.

On the other hand, the magnetostriction at the transformer core is better observed in vacuum tests, as well as its amplitude depending on the amplitude of the excitation voltage. The response of the sensor was observed operating at nominal voltage (220 V) and with 20%–30% above, in order to compare the response proportional to the magnetic field. In these cases, we have observed enough sensitivity with the transducer length used. In Fig. 5, the response of the sensor can be compared for both cases in relative means. It can also be observed that the input voltage signal (50 Hz) is a reference of the resulting frequency of vibrations, in which the main harmonic is of 100 Hz. The transducer output signal was observed linear with the excitation (low optical phase at the quasilinear region of the interference output), though two signs of the transducer slope were used (signal 2 is inverted to signal 3 in Fig. 5). The resultant signal shows two effects. First, the electric-mechanical characteristic causes the induced strain to have a shape of a signal input rectified (Fig. 1). Second, the dead zone caused by the magnetostriction of the magnetic material has a threshold (see signal 2 in Fig. 5). It is observed that the output signal gets its maximums synchronously with the nulls of the voltage. In addition, each period of the output signal starts with a maximum or minimum of the voltage and finishes at the next one (Figs. 1 and 5).

The vacuum tests were extended for other regimens of excitation: 100%, 110%, 120%, and 130% of the voltage in nom-

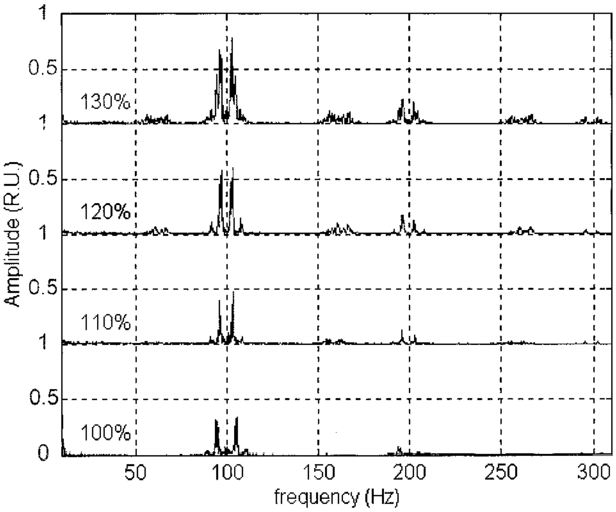


Fig. 6. Spectral characterization of vibrations at different regimes of excitation in vacuum tests. The optical phase is modulated at low frequency (3 Hz to 5 Hz) with a PZT in the reference arm.

inal operation. The interferometer was modulated at low frequency in order to have a reference of the intensity amplitude for normalization. The purpose is to analyze the spectral output for four cases of different excitation amplitude. The modulation aids the FFT processing of the acquired signals by providing a reference of the interferometric signal amplitude and the initial phase around the vibration is transduced but includes new components of the harmonic output. A PZT is used for modulating the optical phase with an amplitude of 2π rad at 3–5 Hz in the reference arm. The sensing fiber is modulated by the magnetostriction at the core of the transformer with phase amplitudes up to $\pi/2$ rad at higher frequency (0.6 rad, 0.84 rad, 0.96 rad, and 1.17 rad, respectively, for 100%, 110%, 120%, and 130% of the voltage in nominal operation). The spectral response of the sensor to the excitation is presented in Fig. 6. Good correlation of the frequency response with 100 Hz and harmonics was obtained, and the amplitude of the signal detected increases with the induced magnetic field, as is expected. In Fig. 6, amplitudes are depicted in relative units to which corresponds π rad optical phase change. The double side band without carrier around the frequency of vibrations is due to the low frequency modulation of phase (±3 Hz to ±5 Hz, depending on the experiment). This represents a change of the initial phase, around which the vibrations are transduced. Thus, it produces changes of the output signal amplitude due to vibrations. Second and third harmonics are also observed, though in this case, a cross talk is present for these frequencies between the vibrations at the transducer and the signal fading of the first harmonic. These frequency components are observed especially for higher amplitudes of vibrations when the voltage is 120% and 130% of nominal operation (Fig. 6).

IV. IMPLEMENTATION IN A MEDIUM POWER TRANSFORMER

The interferometric sensor was installed in a medium power transformer for monitoring the vibrations of the magnetic core. The transformer with 25 KVA of power was opened, and nine optical fibers were bonded to different points inside it (Fig. 7).

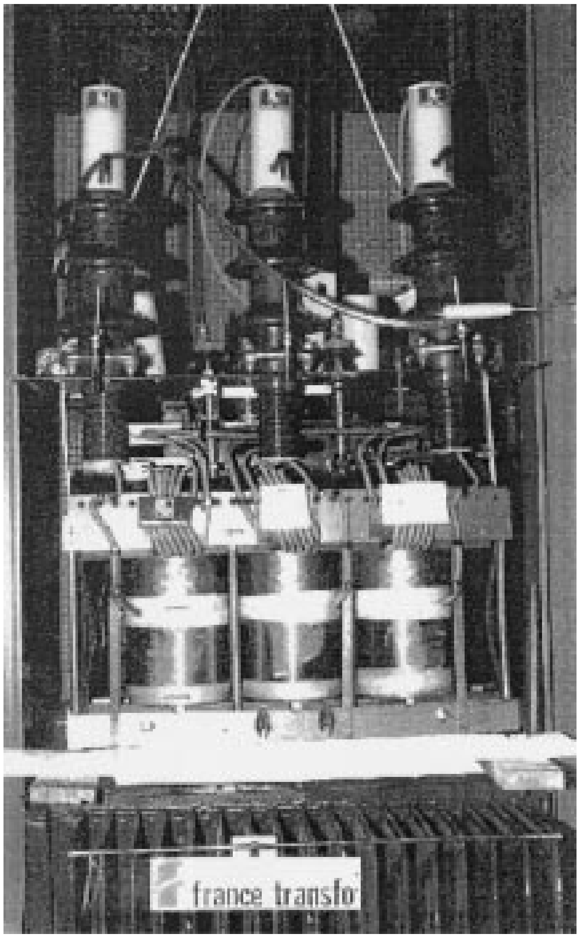


Fig. 7. Front view of the opened transformer. Experimental setup in field of the fiber-optic installation (nine fibers) for interferometric measurement inside the power transformer.

Although the application of some of these fibers is out of the focus of this paper, they are described as follows. Two are placed at the magnetic core for monitoring vibrations, five are around the windings at different heights for monitoring electrical loading effects, and two are where it is expected to have a hot spot inside the transformer [14]. Only the first pair of fibers was used for measuring vibrations.

The characteristics of the fibers are the same as in the laboratory test. They are single mode for interferometric measurement. Bare fibers were used for implementing the transducer in contact with transformer elements. The total length of the fibers from the processing unit to the sensing points and back is about 1100 cm as well. The patch cords were guided to the transformer input through flexible plastic tubes in order to isolate them from the environment. The access to the transformer barrel is performed using the drill hole available for the oil-level lecture. The fibers lay stretching joined accessing the transformer, as well as remaining paired inside the transformer, except at the sensing surface where the transducer segment is bonded. The vibration sensing fibers were bonded at the transformer core with two different shapes (Fig. 8). Probe C_S is a segment of 10 mm, and probe C_C is a circumference of 15 mm diameter. Both have a common path, including 10 mm bonded to the surface, except at the perimeter of the circumference. They can be observed in

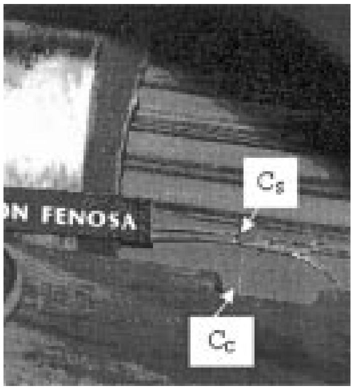


Fig. 8. Detail of the vibration probes installation at the core. Probe C_s is a segment bonded straightly, and probe C_c has a curved geometry. Probes are in contact with the core surface.

Fig. 7, where the transformer being tested is open for the installation of the optical fibers. Fig. 8 is a detail of the probes at the core.

The optoelectronic processing unit is separated from the transformer room and the optical setup is isolated with a plastic case from room fluctuations. Electrical isolation is also assured, because an electrically grounded Faraday case is used, as well as the power supply of the electronics being independent and the sensor cables being dielectric. A He-Ne laser (633 nm) for light source and bulk optics for splitting and recombining the light that travels along the optical fibers were used for interferometric interrogation. A spatial filtering of fringe pattern output was implemented for focusing only the main disk onto the detector.

Differential measurements between two probes at the transformer were performed but also between a probe and an isolated reference, depending on the test. In the former, common optical phase disturbance is compensated, and the phase change at the sensor segment is mainly selected. Although the interferometer integrates the optical phase changes along all fiber branches, in this case, the common path reduces the influence of the common mode in the fiber sensor.

The transformer being tested (three phases) has an input of 15 500 V and an output of 220 V between each phase and ground. The magnetization current was monitored with a Hall Effect current probe instead of the input voltage. It was used as a reference of frequency excitation in field tests. This installation is constrained for also being used with other tests, where loads are designed mainly for line power input (220 V output at the transformer).

However, the transformer was tested in a vacuum regimen. For this operation, the transformer presents better characteristics for vibration measurements, as was mentioned before. The load effects are neglected, separating different sources of vibrations. In addition, the dynamic strain due to magnetostriction is dominant at the core and a main axis of strain is expected following the lines of magnetic flux.

Though the conditions inside the transformer are of high electromagnetic fields, their direct effects to the optical fibers are negligible. This is especially true for this implementation. The geometry of the probes and the installation of the optical fibers were selected for sensing magnetostriction of the core material mainly in the axial direction. Other effects due to magneto-optic properties of the silica fibers (Faraday Effect) and electro-optic effect [24] do not affect the sensor for the implementation and geometry used.

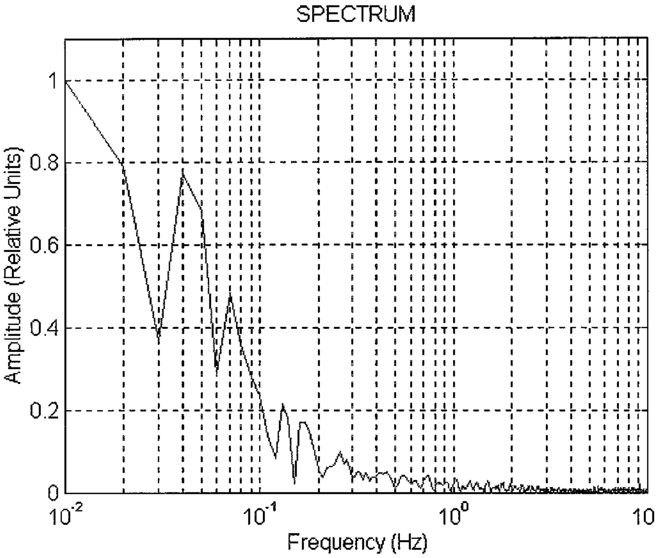


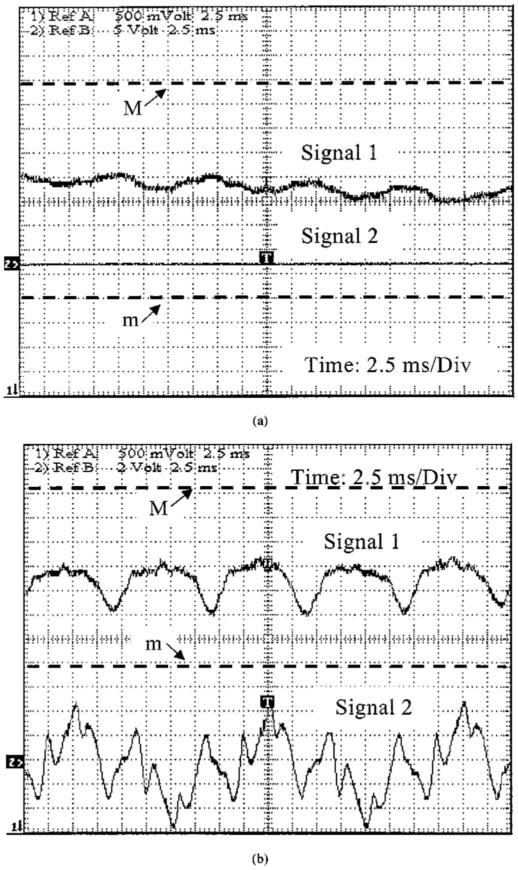
Fig. 9. Spectral characterization of the optical phase drift measured at the in-field installation. Amplitude is in relative units to the maximum.

V. Experimental Results

First characterization of the interferometric sensor installed in the core of a medium power transformer is centered on the system response to external parameters affecting the measurement. As mentioned previously, the main sources of disturbance are the drift of phase due to environmental temperature and the ground vibrations that are also detected. In both cases, the effect is mainly observed at the accessing fibers and at the remote optoelectronic setup.

Although the disturbance was quite reduced with the mechanical isolation performed during the installation in field, residual thermal drift is present, but its impact is negligible. In Fig. 9, it is presented the spectral characterization of low frequency fluctuations up to 10 Hz in relative units to the maximum amplitude. 0.7 rad of optical phase drift ($1/9$ of a fringe) was calculated as the standard deviation in periods of 100 s. The spectral response indicates that the amplitude is up to 1% for frequencies higher than 3 Hz ($\approx 10^{-3}$ of a fringe) and about 3% for 1 Hz. These results were obtained using the differential measurement of the probes C_S and C_C with common path (Fig. 8).

The ground vibrations in the bandwidth of measurement were also studied. In this case, the response of probe C_S was analyzed using an isolated reference path in the interferometer. Fig. 10(a) is a plot of residual vibrations, where signal 2 (monitoring of the magnetization current) indicates that the transformer is off. The interferometric output is near the quadrature point of operation. The amplitude of the main frequency was obtained by normalizing the interference output monitored for 2π rad of phase change. Optical phase from the signal in Fig. 10(a) is up to 0.055 rad of amplitude (8.7×10^{-3} of a fringe). Its main frequency



(a)

(b)

Fig. 10. Measurement of vibrations with probe C_s (10 mm) around quadrature. Dashed lines denoted as M and m delimit the amplitude of interference output signal. (a) Residual ground vibrations detected at the sensor. Signal 2 of current monitoring indicates that the transformer is off. (b) Axial vibrations measured at the core surface inside the transformer. Signal 2 is due to the magnetization current, used for synchronization of frequency.

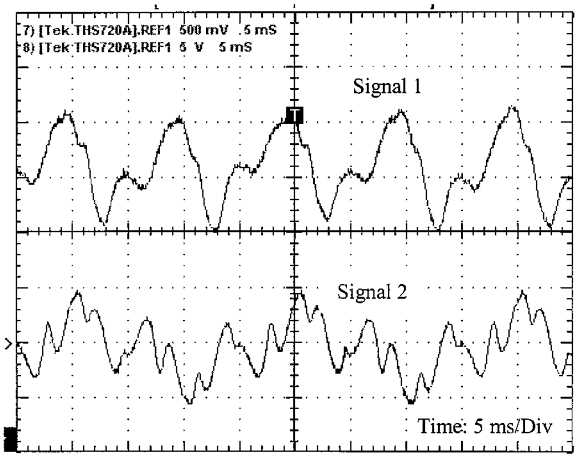


Fig. 11. Axial and transversal vibrations measured differentially with probes C_s and C_c around quadrature. Frequency reference is obtained from the magnetization current (Signal 2).

is 100 Hz, and the minimum signal detected is about 0.014 rad (2.2×10^{-3} of a fringe).

The results obtained with the probe C_S are presented in Fig. 10(b), in which signal 1 is the sensor output and the signal 2 is the magnetizing current. The measurement is performed from the isolated reference path, and it represents the axial dynamic strain (see Fig. 8). The interferometer is operating next to quadrature, and the signal is inverted because the interference intensity is in the negative slope. The phase change due to vibrations is of low amplitude, and the drift of phase is observed very slowly. This permits the read out of the sensor to be obtained when the low frequency drift of phase of the interferometer places the optical phase next to quadrature. The drift phenomenon is quasistatic for periods of observation up to 1 s, and no fading exists in these conditions. The signal fading is not suppressed actively, but it is avoided in the point of observation. The shape of the output is similar to the results with the low power transformer (see signal 2 in Fig. 5). Note that the response is almost null during half a period of the output (dead zone), while it is linear with the rectified sine at the remainder. The current is monitoring for a reference of main frequency and it is presented in Fig. 10(b), where a fractional delay of about 20° appears between the strain at the transducer and the monitored current. This delay comes from the relation of the current with the voltage, in extension with the magnetic flux, and it depends on the ratio of reactive/resistive electrical components. In addition, only the first harmonic of voltage is significant, though current harmonics of higher orders are observed. The spectral response of the optical phase output includes harmonics of 100 Hz (double frequency of the excitation voltage), originated by the nonlinear (rectified) response of the dynamic strain. These results are observations of the strain induced by magnetostriction. The interest is about these signals with time in different regions instead of the spectral response. The harmonics appear as a result of the transference function of magnetostriction (rectified with a dead zone, Fig. 1). The range of the optical phase change due to the strain is 0.29 rad for 10 mm of the probe, which corresponds to 43.2 nm (4.3 $\mu\varepsilon$). These results are in good agreement with expected strain of 6 $\mu\varepsilon$ in iron with induction of 1.6 Tesla [18]. In fact, the magnetic core at the transformer supports 1.5 Tesla, which does not saturate the magnetostriction characteristic. In addition, the material of the core is silicon steel alloy typical in transformers and presents a softened magnetostrictive nature (about 4.5 $\mu\varepsilon$ is expected for 4% of silicon) [18]. With an SNR better than 15 characterized at the output signal in Fig. 10(b), the resolution is up to 3 nm of elongation (0.3 $\mu\varepsilon$) and the dynamic range (in the quasilinear region of $\pi/2$ rad optical phase) is 234 nm (23.4 $\mu\varepsilon$).

Finally, tests between probes C_S and C_C were done for studying the behavior of axial and transversal strain (Fig. 8). In this case, a differential segment between both probes senses axial strain along the axis of magnetic flux. In addition to this, transversal strain is only sensed by probe C_C. Therefore, axial and transversal strains are obtained in this scheme through the probe C_C. Fig. 11 shows the results, where a part of the signal is observed, as in Fig. 10(b) (axial strain). They were obtained with a differential configuration of both probes as arms of the interferometer. The signal depicted is directly related to the interference intensity output with passive homodyne detection when, as before, the drift places the optical phase around quadrature. In addition, other components appear at the dead zone trace of Fig. 10(b), which correspond to a transversal strain with the new configuration. Its main frequency is also 100 Hz.

VI. DISCUSSION

From the aforementioned experimental results, it can be concluded that this fiber-optic interferometric vibration sensor has enough good performance for practical applications. It will be implemented in the near future for monitoring a high power transformer (1500 KVA, ABB), which was designed custom for tests of performance and failure within the project FUTURE. The main characteristics of this work are that the transformer is custom designed for testing aging and typical failures, as well as the field environment is partially controlled because of the researching nature of the project.

According to this application, future important subjects for practical use of the sensor are centered in the compensation of external parameters and the adjustment of sensitivity for calibrating the measurements. The parameters of influence are mainly determined by mechanical and thermal affection of the sensor system. Their effects are located at the interrogation unit and at the transmission fibers. A first approach is to design a compact system based on all-fiber components that reduce the mechanical perturbations of the remote optical interrogation. This unit could be isolated and placed far from the transformer environment, where similar conditions as in laboratory tests are expected.

In addition, different technical designs are anticipated that will refer to the fiber cables. The sensor head and the accessing fibers are actually one cable, and bare fibers are used for enhancing the sensitivity of the sensing segment in contact with the monitoring surface. The immunity of the accessing fibers to mechanical and thermal affections would be obtained practically with jacketed cable. Teflon jackets and multilayer configurations isolate it from temperature and reduce the stress induced to the fibers. However, the main technical advance is centered in pairing fibers that cross an identical path for compensating temperature. The study mentioned before reveals that with two bare fibers without jacketing that lay stretchy joined, the thermal influence is reduced to 1% in a temperature range of 100 °C used for the application. For cables of paired fibers with jacket, better results are expected. This approach apparently increases the number of fibers for each sensor that access to the sensing area. But if a multichannel configuration with a common reference is used for different points that are related [3], only one cable with one fiber for each sensor and one for the reference would be used. In this case, all fibers are joined except at the sensing regions.

As mentioned earlier, thermal magnitude was characterized in a range of frequency clearly separated from the vibrations signal. Since temperature is a slow parameter, its influence is soft for the dynamic sensing scheme. In fact, these two parameters could be separated by filtering frequency components of a processed phase output without the intrinsic difficulties observed in quasistatic discrimination of two parameters. The prediction of the vibration bandwidth for this application, along with the fundamental and harmonics decomposition, allows this approach. Since the cross talk of the quasistatic thermal effects and the dynamic parameter sensed is negligible, the sensor maintains the high sensitivity of interferometric measurements. Nevertheless, the drift produces change in the interferometric sensitivity for the vibration induced optical phase signal, but active techniques for locking the phase in quadrature (homodyne detection) or others based in modulating the phase (pseudo-heterodyne or heterodyne detection) could be used for solving this problem.

Finally, our interest in the future is to increase the length of the sensing fiber for enhancing the sensitivity and the ratio of the vibration signal to external parameters affection. The purpose is to obtain a dynamic response that induces a displacement of several fringes. In these conditions, a multifringe signal processing technique as the aforementioned of fringe counting and fraction excess is used for demodulating the optical phase [23], and no initial phase adjustment is necessary. Moreover, the range of the sensor can be increased and is only limited by the bandwidth of the signal processing. Since the magnetostriction of the material and the sensor output are related to the electrical excitation, as was analyzed and observed in this work, it confers a way for synchronously referencing of the initial optical phase and the change of sign.

VII. CONCLUSION

A fiber-optic interferometric sensor was developed for measurements of vibrations at the magnetic core of power transformers. The sensor is designed for high sensitivity measurements. The sensitivity to dynamic strain, the frequency response of transformer vibrations, and the disturbance impact, mainly centered in temperature, were characterized in laboratory tests. The sensor is based on a segment of fiber bonded to the core surface as an intrinsic transducer. It senses the dynamic strain due to magnetostriction of the core through the changes of the optical path length, which is dynamically modulated.

The complete process from characterization to field installation was carried out and is presented in this paper. The results have shown a high sensitivity measurement of vibrations in the presence of low drift temperature fluctuations. Submicron measurements in a range of 43 nm (4.3 $\mu\varepsilon$) were achieved for the axial dynamic strain of the core inside the power transformer with 10-mm-length probes. They are in good agreement with the expected values in silicon steel sheets. Those measurements were obtained with an SNR better than 15. The behavior of vibrations due to magnetic flux through the core was identified, and the sources of mechanical response were analyzed. Axial and transversal strains at the magnetic core were also observed at the same time. These are to our knowledge the first results of low amplitude vibrations in magnetic cores of power transformers.

ACKNOWLEDGMENT

The authors wish to gratefully acknowledge Unión Fenosa, S.A. for supporting this work under the FUTURE Project.

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