INTEGRATED AXIAL WINDING CLAMPING FORCE MONITORING SYSTEM FOR POWER TRANSFORMERS

A. Marinescu
ICMET Research & Testing National Institute for Electrical Engineering,
B-dul Decebal, No.118A, 200746 Craiova, Romania
amarin@icmet.ro

Abstract: The paper presents a new direct measuring system for the axial clamping forces of power transformer windings enabling an objective assessment of their mechanical stability. The system is based on the technology of optical Fiber Bragg Grating (FBG) sensors embedded in the windings pressing rings which does not influence in any way the original mechanical / dielectric design of the transformer. There are presented the principle and application of this smart pressing ring, the performed experiments, the application software enabling measured values correction depending on insulation condition at the measurement moment.

1 INTRODUCTION

Transformers are the most complex and costly components of the electric power system and that is why there are monitoring systems for most operating regimes and for the components that are part of their construction.

The electro-dynamic forces acting on the transformer windings caused by the large short-circuit and inrush currents may seriously damage the insulation, the conducting wires and the clamping system with negative effect on the transformers reliability and its active life[1,2].

At present, the manufacturers use state-of-the-art methods for the calculation of the electro-dynamic forces and have technologies and materials able to stabilize and clamp the windings during and after the manufacturing process[3].

However, the preservation of the initial clamping forces or mechanical stability of the power transformers during their whole active life in very different conditions appearing in operation (mechanical stresses during short-circuits, inrush currents and transportation, heating/cooling processes, paper-oil moisture and ageing) has not been completely kept under control though in the technical literature there are presented and applied many on-line and off-line, intrusive or non-intrusive methods which by means of the offered results try to get into the “black box” represented by the transformer from this viewpoint[4].

Actually, only a direct measurement of the clamping force detects and localizes its dangerous changes or confirms the validity of the applied technical solution for coping with all operating duties during transformer active life.

Beginning with the 70’s, different systems for direct measurement/control of the clamping forces using hydraulic/electric/magnetic transducers were experimented[5,6].

In this paper, it is proposed a new technical solution, which is easily integrated in transformer construction with no change of its mechanical/dielectric design and has a high electromagnetic compatibility. The solution consists in embedding a passive optical FBG sensor in each pressing ring of the windings for the determination of the applied clamping force and so to convert the classical pressing ring into a smart pressing ring (an entirely dielectric clamping force transducer). Application software based on models to relate the remnant measured clamping force to its initial force used by manufacturer was developed.

2 ASSESSMENT METHODS FOR THE MECHANICAL CONDITION OF A TRANSFORMER

The assessment of the mechanical condition of a transformer is necessary both to establish the result of a sudden short-circuit type test in the laboratory and also to detect the windings clamping force drop following the mechanical stresses in operation due to short-circuit and inrush currents, the pure mechanical stresses appearing during shipment to transformer site or following the thermal–oxidative ageing of the paper insulation.

At present, the most used methods are the off-line non-intrusive methods, namely:

- transformer leakage reactance measurement and its comparison with a reference value (fingerprint);

- low voltage impulse (LVI) distortion applied to the transformer related to a reference case;

- frequency response analysis (FRA/SFRA) for the transformer considered as a quadripole related to a reference case too [7].

The last method has been widely spread and at this time special efforts are undertaken within the frame of the scientific community [8,9] to improve result reproducibility.

Other non-intrusive methods that can be applied on-line are:

- vibro-acoustic analysis (VAA) of the transformer attempting to detect, from its vibration spectrum, the part that is affected by winding vibration [10], influenced by a change in winding clamping;

- transient oil pressure (TOP) in transformer tank [11] where the significant increasing values of the current related oil over-pressure are an indication for a critical loss of clamping force inside the transformer without localization, also valid with respect to results measured at former times.

The presented methods can be and are applied, more or less [9,10], for the mechanical condition assessment of power transformers starting from incipient faults to more serious faults that generally develop to mechanical collapse or in a progressive deterioration of the insulation.

The on-line intrusive methods known and applied so far are:

- winding displacement measurement, directly [5] or by acceleration measurement [12];

- recovery of the initial values of the clamping forces by hydraulic or mechanical systems (disc springs) or a combination of them, method used in the 70 - 80's;

-direct measurement of clamping forces[13,14].The method was successfully used for the first time in the 90's to monitor the 600MVA voltage step-up short-circuit transformers built for a High Power Lab[15]. The said transformers are subject to repeated short-circuits at limit values and have the possibility to correct the axial clamping force without un-tanking. Then, magneto-elastic force transducers with high stiffness mounted under the usual clamping bolts were used.

In the last years, although the technology and materials quality have been considerably improved, a proliferation of the monitoring systems at all electrical equipment for the power grid and especially at power transformers occurred, the direct measurement of clamping forces in static and dynamic duty initially used only at special transformers was continuously improved so that today no constructive change of the clamping system to be made and to be applied both at new transformers and at factory or on-site repaired transformers.

In [15], direct monitoring system replaces the usual clamping bolts with bolt sensors having the same dimensions as the original ones.

In other direct measurement system, many SAW (Surface Acoustic Sensors) type discrete sensors are inserted in the pressing rings of the windings together with electronic components and antennas for information wireless transmission to a receiver located outside the transformer tank.

Following consequently the present trend of introducing monitoring systems entirely based on optical fiber into power transformers, the smart pressing ring is presented further on.

3 THE SMART PRESSING RING

This solution applicable for measuring the clamping force of power transformer windings in static and/or quasi-static duty along their active life includes in each pressing ring a FBG strain intrinsic optical sensor [16,17] able to determine after calibration the quasi-distributed force applied to the windings by the mechanical clamping system, irrespective of its achieving way (clamping bolts or wedges).

For this, the original pressing ring is divided in two superimposed identical rings, between which the fibre optic sensor is inserted, as shown in Fig.1. The procedure for placing the FO and fixing the two rings one against the other is patent pending.

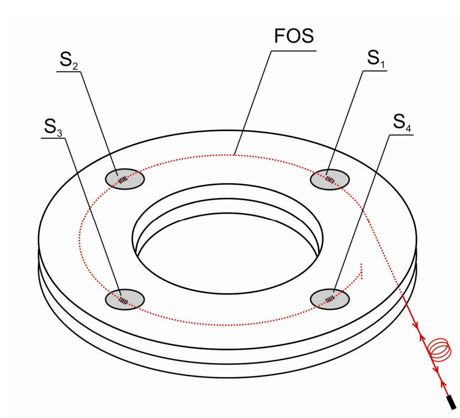

Figure 1: Top view of a smart pressing ring S1, S2, S3, S4 - areas where the controlled axial clamping is achieved, FOS- quasi-distributed strain sensitive FBG optical sensor

As a result of this arrangement, the fiber optic is subjected to compression stress in the areas where the normal clamping force is created on the ring and, in small extent, to bending stress in the space between these areas [18]. These conditions could be fulfilled only by the quasi-distributed FBGs which exploit the FO transverse strain sensitivity instead of the usual axial strain sensitivity [19, 20, 21].

The best accommodation of an optical sensor is the open loop design enabling to exist only one input/output of the optical signal and to make cuts for the electric outputs, holes and vent channels in order to facilitate the extraction of moisture and oil impregnation[18].

The main purpose of this development is to monitor the long-term evolution of the static axial clamping force. The measurement of a pulsating force resulted during the sudden short-circuit test in testing laboratory, respectively within the research for determining the characteristic frequencies of the windings and the influence of static clamping force on them, is also achievable in this way.

Besides, minimize the temperature error and the time stability of the axial force measurement result are fundamental requirements for the new system.

4 FBG SENSORS WITH TRANSVERSE SENSITIVITY TO STRESS

A cross section through the pressing ring in which a FO endowed with a Bragg grating was embedded is shown in Figure 2. The Bragg grating represents a periodical alteration of the FO core refractive index, achieved on a limited section of it, so as the strain could be considered constant there. The grating will reflect light with a peak in amplitude or transmit light signal as an deep of light both centred at the Bragg wavelength λ_B according to [22]:

$$\lambda_B = 2n\Lambda \tag{1}$$

where n is the FO refractive index and Λ is the Bragg grating pitch.

When input of FBG sensor is connected to a wide bandwidth light source (super luminescent diode a.s.o.), the free end is terminated in an anti-reflective manner and the optical grating is transversely stressed, the grating generates a reflection of the light which has two maxima, with other words a splitting of the fibre grating spectral profile. The spectral span between maxima is proportional with the strain and then with the transverse force applied to FO but, unlike the case when the FO is axial stressed(in Z direction), this span is not actually affected by temperature[19].

Additionally, the spectral location of the two maxima could be used, if necessary, for calculating the local temperature.

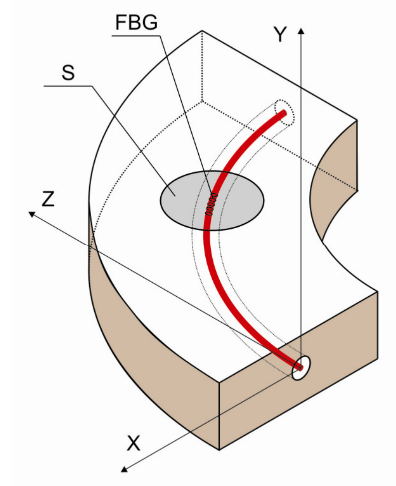

Figure 2: FBG embedded in the pressing ring. Z - the longitudinal direction; X, Y - the transverse directions; Y - the direction on which the pressing force is applied

In our application there are many Bragg gratings (at least in S areas, where the concentrated clamping force is applied) with different Bragg wavelength λ_{B1}....λ_{B4} on a single mode circularly symmetrical, cheap FO used in tele-communications (Corning SMF 28), which has the advantage that the fibre symmetry leads to a transverse sensitivity independent from the stress direction, this simplifying the mounting in the pressing ring. A disadvantage is that for low transverse loads, the splitting of spectral maxima could be extremely difficult to measure due to their coverage by the noise. From the existent experience, it results that this sensitivity threshold is below 10% of the measurement range, fact which could be accepted in our case.

The measuring system was experimented on a linear model put into a compression mechanical test machine (Fig.3). For assuring the mechanical stability of the device, a second passive fiber optic was placed in parallel with the active fiber optic, at a 50 mm distance. The active fiber optic has two Bragg gratings with different wavelengths, λ_{B1} and λ_{B2}. The fiber is located on a flat support, and the concentrated force to be measured is applied above. The material of the support and of the parts on which the force is applied is a 40mm thickness T4 laminated Transformerboard [23]. For interrogating the optical system, an optical sensor interrogator National Instruments PXIe 4844 system[24] with a measurement resolution of 1 pm (1 picometer) equivalent with strain of de 1.2 $\mu\varepsilon$ is used. It contains a light source in the bandwidth from 1510 to 1590 nm, i.e. a 80 nm span in which the wavelength of each Bragg grating could be chosen. At the apparatus output, it is got the electric signal corresponding to the frequency deviation generated by FBG and by means of the

LabView platform, the relative position of the two maxima for each Bragg grating and finally the respective strain expressed in $\mu\varepsilon$. The apparatus can scan optical sensor only up to the frequency of 40 Hz/channel, this making it proper only for static or quasi-static measurements.

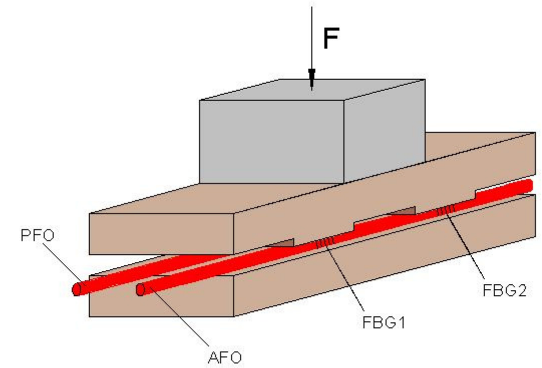

Figure 3: Experimental device for determining the FBG sensor transverse strain sensitivity. AFO-active FO, PFO- passive FO

Under the conditions offered by this experiment, a sensitivity of about 30 pm/MPa and a measurement uncertainty of 1 pm (3%) associated to a temperature error of 1% in the range 20-100ºC are got. The low strain insensitivity domain could be reduced depending on the specific process of FO embedding in the pressing ring.

5 BLOCK DIAGRAM OF THE MEASURING SYSTEM

In Figure 4, the simplified block diagram of this measuring system applied to a three phase power transformer endowed with smart pressing rings is presented. The arrows indicate the mono-or bi-directional information transmission in system, as the case may be.

The equipment contains a broadband light source BOS (laser or LED) regulated by the controller CC, an optical coupler OC enabling the separation between the incident light transmitted to the FBG sensors and the light reflected by Bragg gratings depending on the strain they are subjected to, an optical switch with three ways OS and a digital processor for optical signals OSA (optical spectrum analyzer) which assure, based on WDM (wavelength-division multiplex) technology, the separation of the optical signals reflected with a view to determining the transverse strain in each zone of the smart pressing rings where a Bragg grating is inserted. A system controller SC assures and synchronizes the connection between all the devices from the diagram.

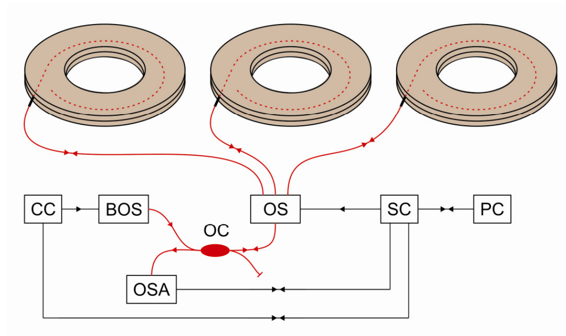

Figure 4: Principle diagram of the axial forces measuring system at a power transformer with smart pressing rings. OS - optical switch 1x3, OC - optical coupler 2x2, OSA - optical spectrum analyzer, SC - system controller, CC -current controller, BOS - broadband optical source, PC - computer, —— FO link, —— electrical link.

At the output of the OSA processor, electric signals proportional with the distribution of the compression force on the pressing ring circumference which are processed, stored and displayed on PC and transmitted through an interface IEC 61850 to the global monitoring system of the transformer are got.

The optical signal processing equipment can be placed in the proximity of the monitored transformer or remotely, in the substation control room, case in which it can process optical signals coming from one or many transformers from the transformer substation. Information on the axial forces time variation can be recorded on-line for the entire life of the transformer or off-line, at longer or shorter intervals depending on the monitoring technology. In this last case, the measuring system can be used at other transformers from that substation or from other substation, by an adequate setting.

Besides the actual measurement of the clamping forces, it should be taken into account that the values measured at certain moment during the transformer operation should be correlated with the oil and winding temperatures, paper-oil insulation moisture and ageing [25,26,27,28], which affect the initial values used by the manufacturing company. In order to relate the real (remnant) measured clamping force $(F_S)_m$ to its initial value $(F_S)_{in}$ used by manufacturer, it was developed a software based on models[19] included in a global correction factor

$$K_{corr} = f(K_T, K_h, K_a, K_m) \qquad (2)$$

where K_T – a model of clamping force variation with temperature at constant moisture, K_h – a model giving moisture influence in paper-oil insulation based on moisture exchange at different temperatures, K_a – a model depending on thermal ageing of the paper insulation and K_m – a model related to a specific transformer manufacturer technology. Depending on the transformer condition when measuring, the global correction factor K_{corr} can have values below/above unit.

In this way, the re-calculated value is :

$$F_S = K_{corr}(F_S)_{in} \quad (3)$$

which should be compared with $(F_S)_m$. If the calculation algorithm of the correction factor is validated, then if

$$(F_S)_m < F_S \quad (4)$$

this means the clamping force was modified due to certain event, for instance as a result of the poor transport conditions, a shortcircuit a.s.o.

6 CONCLUSIONS

The initial adjustment of the axial winding clamping force and the control of its variation during the transformer life can be done on the basis of the smart pressing ring described in this paper. This pressing ring embeds an intrinsic optical strain sensor consisting in fibre optic with transverse strain sensitivity, on which a succession of Bragg gratings (FBG) distributed on the active length of the fibre is inserted, structure enabling by an interrogation system to determine the variation profile for the compression effort on the pressing ring circumference, irrespective of the clamping system used in transformer design.

The smart pressing ring is an entirely dielectric compression force sensor which can be separately characterized and calibrated and which does not influence the mechanical stability and main designed insulation of the transformer, either by installing in the pressing ring or by bilateral optical transmission of the signal carrying information outside the transformer tank.

The measuring/interrogating system utilize optical and electric apparatus and components of common use, the price of which has undergone a dramatic price drop thanks to the telecommunications applications; moreover, one and the same system can be used for monitoring all the transformers in a substation.

Application software which takes into account the insulation condition when measuring (ageing, moisture, temperature etc.) enables correcting the results of the measurements performed for making possible the comparison with the initial clamping forces practiced in the manufacturing company.

7 REFERENCES

[1] Th. Fogelberg:"Surviving a short-circuit", ABB Review, No. 1, pp. 24-28, 2008

[2] R.P.P. Smeets et al: "Thirteen Years Test Experience with Short-Circuit Withstand Capability of Large Power Transformers", 6th Southern Africa Regional CIGRE Conference, Paper 501, 2009

[3] S.V. Kulkarni,S.A.Khaparde: "Transformer Engineering-Design and Practice", Marcel Dekker,Inc.,476pp, 2004, ISBN 0 8247 5653 3

[4] CIGRE WG A2.34: "Guide for Transformer Maintenance", Brochure No. 445, 2011, ISBN:978-2-85873-134-3

[5] P.J. de Klerk et al. :" Winding Slackness Monitoring as a Diagnostic for Insulation Ageing in Oil-Paper Insulated Power Transformers", 11th ISH Symposium pp.1.185-1.188 P4, 1999

[6] A. Marinescu:" Online Measurement of Electro-Dynamic Axial Forces in High Voltage Power Transformers", CIGRE SC 12 Transformer Colloquium, Paper SCP-18, Budapest, 1999

[7] J.Christian, K. Feser, Th. Leibfried: "Die Uebertragungsfunktion als Methode zur Beurteilung der Stosskurzschlusspruefung und vor Ort Diagnose." Elektrizitaetswirtschaft, vol. 9, no.7, pp. 40-44, 1999

[8] P.M.Nirgude et al: " Investigations on Axial Displacement of Transformer Winding by Frequency Response Technique", 14th ISH Symposium, Paper F47,Beijing, 2005

[9] CIGRE WG A2.26: "Mechanical Condition Assessment of Transformer Windings using FRA", Brochure No.342, ISBN:978-2-85873-030-8, 2008

[10] C. Bertoletti et al: "Vibro-Acoustic Techniques to Diagnose Power Transformers" IEEE Transactions on PD, vol.19, No.1, pp.221-229, 2004

[11] Kraetge,A., Kalkner,W., Plath,R., Plath,K.-D. "Diagnostic of the Short-Circuit Duty of PowerTransformers." Proc. of 14th ISH, Beijing, Paper F32, 2005

[12] Y.H.Oh, E.D.Song, B.Y.Lee, K.Y.Park: "Displacement Measurement of High-Voltage Winding for Design Verification of Short-Circuit Strength of Transformer", IEEE PES T&D Conference, Dallas, 2003

[13] E. Marinescu, A. Marinescu, "Measurement of Electro-dynamic Axial Forces in High Voltage PowerTransformers." IMEKO TC3 Proc. of 13th Intl. Conference Force and Mass Measurement, Helsinki, 1993.

[14]A. Marinescu et al :" HV Power Transformer Direct Monitoring of Windings Axial Clamping Forces", In Proc. of CMD Conference, Changoon, 2006

[15]A. Marinescu:" Monitoring of Axial Clamping Forces at Power Transformers", EuroDoble Colloquium, London UK, 2006

[16]J.M. Lopez-Higuera(Editor), Handbook of Optical Fibre Sensor Technology, 795p, Wiley, ISBN 0471820539, 2002,

[17] A.D. Kersey et al: "Fibre Grating Sensors", IEEE Journal of Lightwave Technology, vol .15, No.8, pp. 1442-1463, 1997

[18].M. Biggie, T.A. Prevost: "Calculation Method for Power Transformer Clamping Rings Made from Laminated Insulating Materials",Proc. of Insulation Conf. and Electrical Manufacturing & Coil Winding Conf., pp.567-576, 2001

[19] E. Udd, D. Nelson, C. Lawrence:"Multiple Axis Strain Sensing using Fibre Grating Written onto Birefringent Simple Mode Optical Fibre." Proc. of 12th Optical Fibre Sensor Conf (OFS-12), 1997

[20] K. Okamoto et al:"Stress Analysis of Optical Fibres by a Finite Element Method", IEEE Journal of Quantum Electronics, vol QE-17, No. 10, pp 2123-2127, 1981

[21] M.S. Mueller et al. :" Transfer Matrix Approach to Four Mode Coupling in Fibre Bragg Gratings", IEEE Journal of Quantum Electronics, vol.QE-45, No.9, pp 1142-1148, 2009

[22] E. Udd(Editor) :"Fibre Optic Sensors: An Introduction for Engineers and Scientists", Wiley Interscience, 476p, 2007

[23] Transformerboard TIV url: http://www.weidmann-electrical.com last accessed: April 15, 2011

[24] National Instruments PXIe 4844 url: http://www.ni.com/opticalsensing last accessed: April 15, 2011

[25] C. Krause :"The Change of Clamping Pressure in Transformer Windings due to the Variation of the Moisture Content. Tests with Pressboard Spacer Stacks", CIGRE SC 12 Transformer Colloquium, Paper SCP-12, Budapest, 1999

[26] C. Krause: "Short-Circuit Resistant Power Transformers-Prerequisite for Reliable Supply of Electrical Energy", 6th Southern Africa Regional CIGRE Conference, Paper C01, 2009

[27] T.A. Prevost: "Maintaining Short-Circuit Strength in Transformers" Second Weidmann ACTI Conference, Miami, 2003

[28] M. Koch: "Reliable Moisture Determination in Power Transformers",ELECTRA, No. 255, pp. 4-11, 2011