ISSN 1726-5479

SENSORS & TRANSDUCERS

9/08
vol. 96

IEEE

TEDS Sensors, IEEE 1451 Standards

International Frequency Sensor Association Publishing
IFSA

Sensors & Transducers

Volume 96
Issue 9
September 2008

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA). Available in electronic and CD-ROM. Copyright © 2007 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

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Volume 96
Issue 9
September 2008

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 96, Issue 9, September 2008, pp. 81-92

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Direct Monitoring and Control of Transformer Temperature in Order to Avoid its Breakdown Using FOS

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Received: 8 July 2008 /Accepted: 19 September 2008 /Published: 30 September 2008

Abstract: This manuscript focuses on Direct Monitoring & Control of Transformer Temperature in order to avoid its Breakdown Using FOS (fiber optic sensor). Although there are various reasons for failure of transformer operation but mainly it is due to conductor loss and hysteresis losses which causes temperature rise in the internal structures of the transformer leading to burning of windings. A system for monitoring the temperature of transformers is required. Existing sensors cannot be used for monitoring the temperature of transformers because they are sensitive to electrical signals and can cause sparking which can trigger fire since there is oil in transformers cooling coils. Distributed FOS based on microbend is simulated on MATLAB7.5 in order to check the effectiveness of this sensor. Results in the form of graphs i.e., intensity modulation vs. the temperature has been shown in the manuscript. *Copyright © 2008 IFSA.*

Keywords: Generic microbend sensor, Hot spot monitoring, Direct temperature monitoring, Bending loss

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1. Introduction

From the survey [1], Fig. 1. it is very clear that the temperature is one of the prime factors that affect a transformer's life. In fact, increased temperature is the major cause of reduced transformer life. Further, the cause of most transformer failures is a breakdown of the insulation system, so anything that adversely affects the insulating properties inside the transformer reduces transformer life. Such things as overloading the transformer, moisture in the transformer, poor quality oil or insulating paper, and extreme temperatures affect the insulating properties of the transformer. Most transformers are designed to operate for a minimum of 20-30 years at the nameplate load, if properly sized, installed and maintained.

Winding temperature sometimes called ‘hot spot-temperature’ this is a criteria regarding the best time at which to replace a power transformer due to load growth i.e., to minimize the cost without significantly increasing the risk.

Over the long term, it is the peak hot-spot (winding) temperature that matters, and whether or not it has caused undesirable contaminating products to form. Load growth causes increased loading on transformer or necessitates the procurement of new transformer.

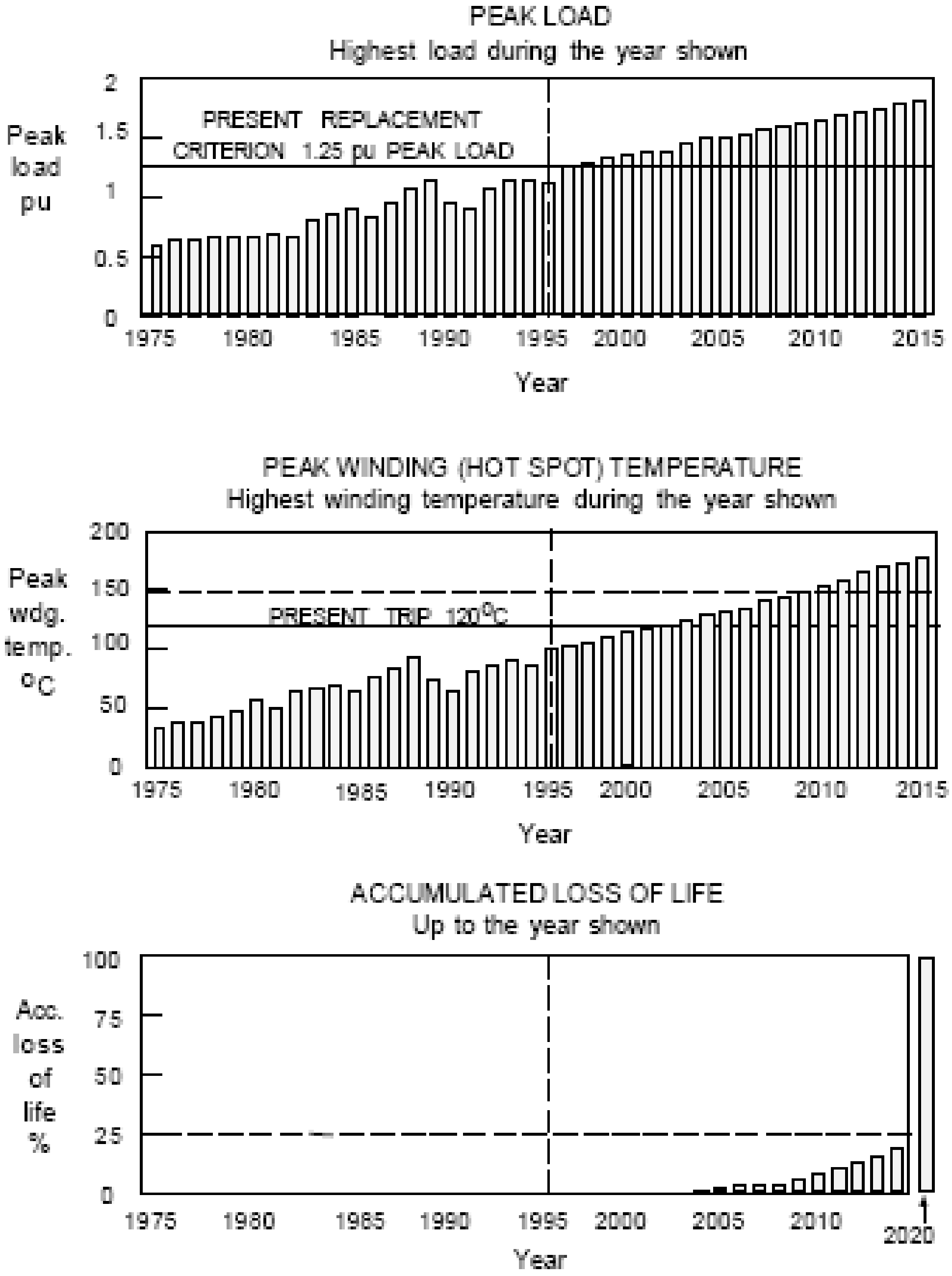
The winding hot spot temperature is usually the principal factor limiting the load ability of a power transformer. Higher winding hot spot temperatures cause degradation of the winding insulation material and can result in the formation of gas bubbles which facilitate the dielectric breakdown characteristic of the transformer oil. The loss of life is related to the thermal degradation of the insulating paper. For paper insulation, the end of life is defined at the degradation point where the paper has lost half of its mechanical strength. The life of the paper insulation is then only 7.42 years at a continuous winding hot spot temperature of 110 °C which increases to 50 years with a continuous winding hot spot temperature of 92 °C. Industry standards recommended that during rated load, the temperature of the winding hot spot should not exceed 110 °C. or 80 °C rise above ambient.

1.1. Causes of Failures in Transformers

Power Transformers are vital links in the chain of components constituting a power system, the failure of which affects the supply of electric power to the consumers. Internationally, the transformers are found to be very reliable but in our country the failure rates are quite high. Failure analysis quotes a host of reasons behind the failure of power transformers. These may include abused operations inept maintenance, substandard techniques adopted during manufacturing, testing and commissioning, substandard input materials, inconsistency environment, design deficiencies, abnormal operating conditions, over voltages, system short circuits etc. The main causes of failures of transformers in service as shown in Table 1.

Table 1. The main causes of failures of transformers in service.

Cause	**% of cases**
Design	36
Manufacturing problem	28
Material defects	13
Poor maintenance	5
Lightning surges	4
Short circuits	2
Components	**% of cases**
Winding	29
Terminal	29
Tank and dielectric fluid	13
Magnetic Circuit	11
Other accessories	5



PEAK LOAD
Highest load during the year shown

PEAK WINDING (HOT SPOT) TEMPERATURE
Highest winding temperature during the year shown

ACCUMULATED LOSS OF LIFE
Up to the year shown

Fig. 1. Market Survey of Peak Load, Peak Hot Spot Temperature and Accumulated Loss of Life of Power Transformer.

The causes of failure may be many, but the effect is burning of windings. So, the conclusion of above topic is that the major cause of failure of transformers is burning of windings of transformers. This gives a rise to overheating and fire hazards. So, a proper technique is required to monitor the temperature of transformer by which the transformer shuts down whenever there is increase in temperature.

1.2. Benefits of Accurate Winding Temperature Measurements

Various Benefits of accurate Winding Temperature measurements is listed below:

- Higher safe loading
- Efficient use of cooling equipment

- Reduce cooling prediction of remaining insulation life
- Reduced physical stress on winding
- Operational conditions assessment
- Load planning
- Asset management
- End-of life determination

1.3. Consequences of Inaccurate Winding Temperature Measurement

Various Consequences of Inaccurate W.T Measurement is listed below:

- Underutilization of assets
- Higher running and maintenance costs
- Physical/thermal stress on winding insulation
- Shortened insulation life due to overheating cycles

1.4. Comparison of Conventional Methods

Comparison of Conventional Methods to Measure Temperature in Transformer Windings is listed in Table 2.

Table 2. Comparison of Conventional Methods to Measure Temperature in Transformer Windings.

SENSOR	ADVANTAGE	DISADVANTAGE
Thermocouple	Simple, rugged, high temperature operation, low cost, no resistance lead wire problem point temperature sensing, fastest response to temperature change.	Least stable, least reproducible low sensitivity to small temperature changes, extension wire must be of the same thermocouple type wire may pick up radiated electrical noise if not shielded.
RTD	Most stable over time most accurate most repeatable temperature measurement very resistant to contamination/corrosion of the element	High cost slowest response time low sensitivity to small temperature change, bulky size, errors are caused due to conduction effect, lead resistance error possibility of self-healing and consequent change in temperature as current passes through the element when its resistance is measured using bridge circuits.
THERMISTOR	High sensitivity to small temperature changes. Temperature measurements become more stable with the use of copper or nickel extension wires can be used	Limited temperature range, fragile, non linear temperature range some initial accuracy “drift” Decalibration if used beyond sensors temperature ratings, lack of standard for replacement.
INFRARED	No contact with product required response times as fast as or faster than thermocouple no connection or oxidation to affect sensor accuracy, good stability overtime high repeatability.	High initial cost, measurement accuracy more complex -support electronics required emissive variations affect temperature field of view & spot size may restrict sensor application, measuring accuracy affected by dust ,smoke, background radiation, etc.

1.5. Advantages of Fiber Optic Temperature Sensors

Various advantages of fiber Optic temperature sensors are listed below:
- Resistant to electro magnetic interference
- Better response time
- No secondary junction problems
- No reversal of thermocouple material at termination point.
- No worries of mixing sensor materials
- No reference junction needed
- Sensor identification embedded during manufacturing, by wavelength
- Multiple sensor types can be mixed on the same fiber, strain, pressure and temperature
- Fibre optic cable is less susceptible to signal degradation than copper wire.
- Fibre optic cables weigh less than a copper wire cable, small size.
- Data can be transmitted digitally.
- Lower-power transmitters can be used instead of the high-voltage electrical transmitters used for copper wires.
- Unlike electrical signals in copper wires, light signals from one fibre do not interfere with those of other fibres in the same cable.
- Because no electricity is passed through optical cable it is non-flammable, and immune to lightning, immunity to interference
- Impossible to tap into a fibre optics cable, making it more secure.
- Signal security, Abundant raw material

1.6. Why Monitoring Temperature of Transformer?

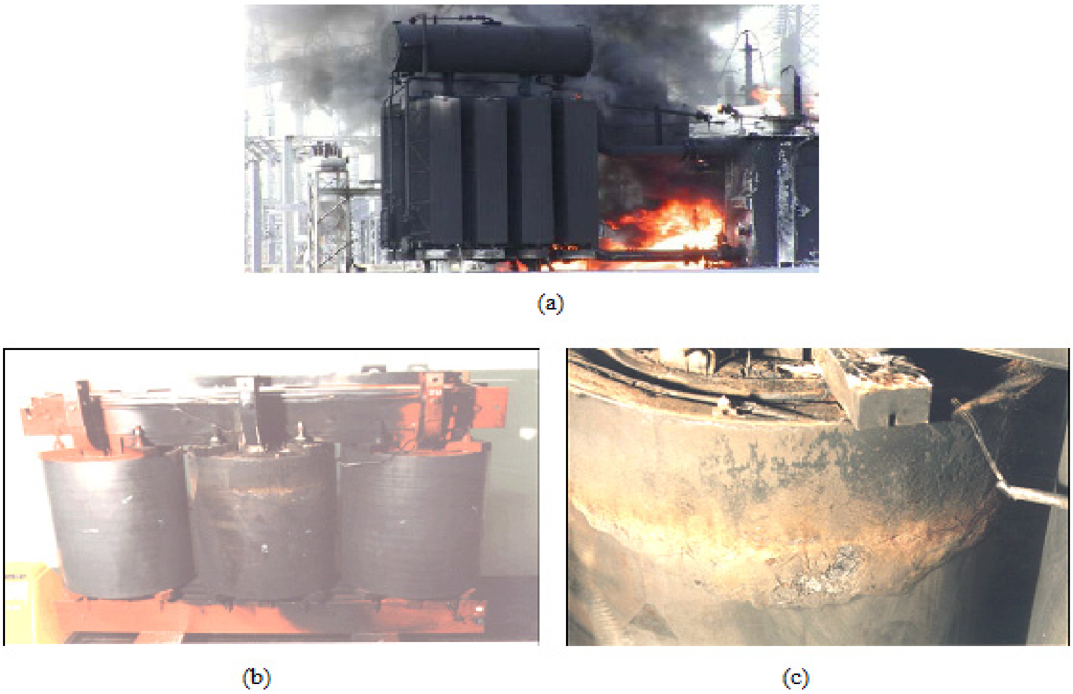
Partial discharge activity in transformers will cause inter turn short circuits, which subsequently lead to a local overheating by induced currents. This will increase the partial discharge activity due to the rising local temperature and related material deterioration. Once this chain reaction is initiated, the breakdown of the complete system is unavoidable. This breakdown may be accompanied by fire hazards (Figures) which can entail dreadful damages, often more expensive than the purchase costs of the transformer itself. Due to the absence of self healing effects, as they exist in liquid or gaseous insulating systems, partial discharges in dry-type transformers lead to irreversible damage and disintegration of the inter turn insulation.

In order to prevent failure it is mandatory to monitor transformers during operation by an appropriate monitoring system. Although many dry-type transformer failures were encountered where there was no commercial protection system available until to date.

The main reason is that partial discharge monitoring systems are generally too costly, because their price can exceed the price of the transformer to be monitored. Therefore a new modular system has been developed, which protects transformers on-line against overheating. In case of an overheating alarm, e.g. an off-line analysis of the transfer function will verify the winding shorts. A specific replacement of the faulty coil or the improvement of the defective insulation is then possible.

2. Prototype for Direct Monitoring of Transformer Temperature

Local overheating caused by inter-turn short circuits is a pre-stage of breakdown. The result is fire and fume development as shown in Fig. 2. A shut-down of a transformer in time avoids consequential damages.



(a)

(b) (c)

Fig. 2. (a) Explosion in transformer, (b) Burnt transformer bearing secondary damage and(c) Burnt coil of a dry-type, epoxy insulated transformer due to inter-turn short circuit.

The new overheating protection system, the high and the low voltage coil as well as the core can be guarded against overheating. The principle of operation as shown in Fig. 3. Is based on a temperature dependant shift of the optical transmission properties of a fiber optical cable. An optical sensor does not cause any electromagnetic interference or influences the operation of the transformer in any other way. If a light signal is injected into one side of the fiber optic sensor it can be detected at the opposite end with an optical receiver as shown in Fig. 4. (b). If the surface temperature of the optical fiber raises the light transmission is attenuated by the deteriorated reflectivity characteristics. At still higher temperatures the light transmission is interrupted, and, no signal can be received any more. This state is used for providing an overheat alarm.

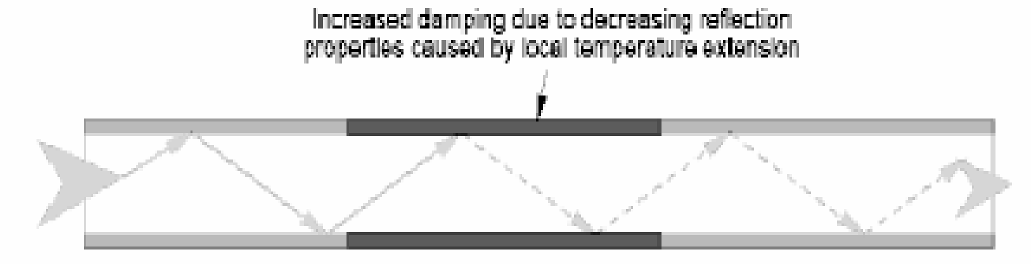


Fig. 3. Principle of Operation of Fiber Optical Sensor.

This fiber optic sensor is mounted on the surface of all coils and the core of the transformer which allows overheat protection of the whole device. A temperature increase caused by winding shorts will spread out annular. This leads to the typical ring shaped changes of the resin colour. Therefore it is not necessary to place a sensor directly on a hot spot but on any position on the overheated winding package. A special mounting technique as shown in Fig. 4. is used.

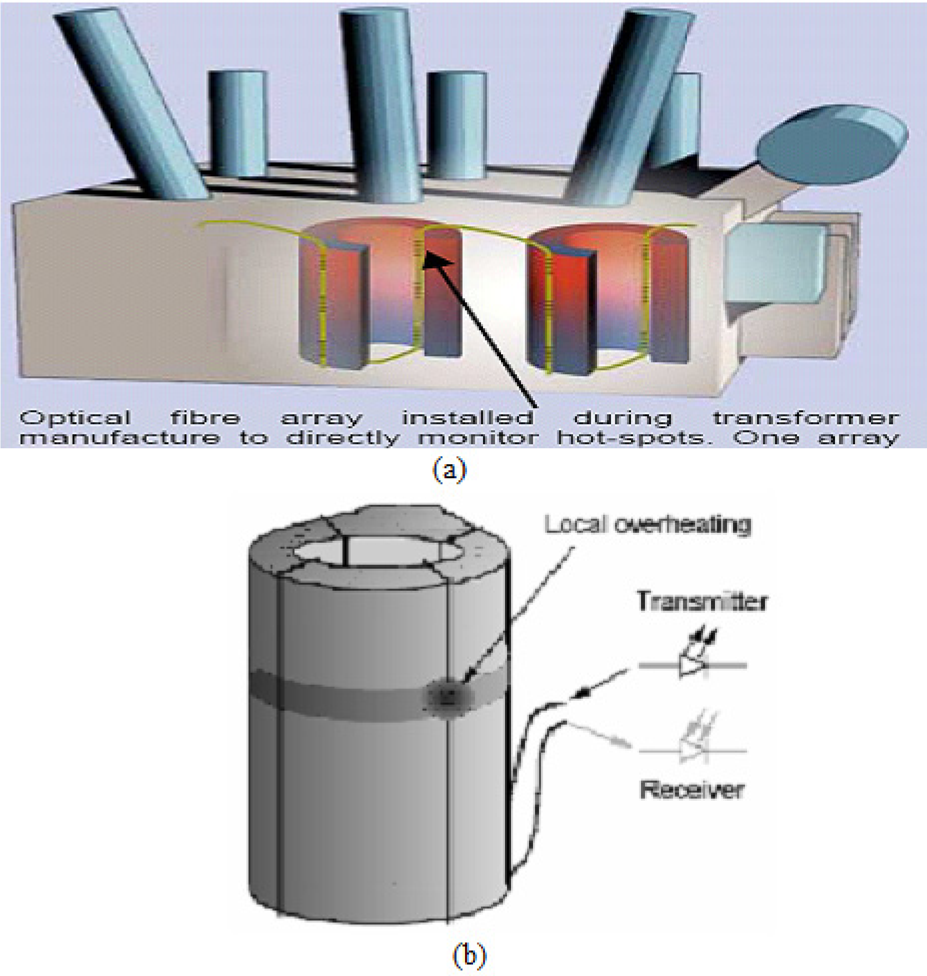


Fig. 4. Prototype for Overheating Protection System by using FOS.

In this technique [10], only one single optical fiber sensor and only one control unit is required for the protection of a transformer in operation.

3. Mathematical Model of Generic Fiber Microbend Sensor

Intensity modulation induced by microbending in multimode fiber is considered as a transduction mechanism for detecting environmental changes such as pressure, temperature, acceleration, magnetic and electric fields. An idealized generic microbend sensor as depicted in Fig. 5.

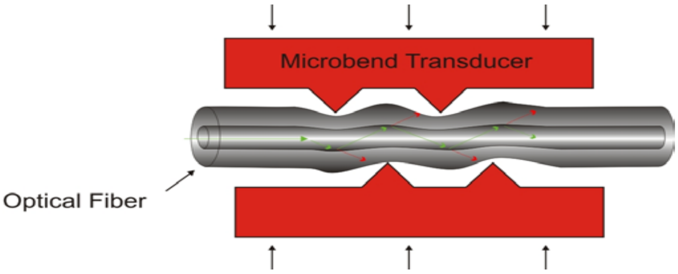


Fig. 5. Microbend Sensor.

The sensing fiber which is sandwiched between a pair of deformer plates is somehow constrained to bend in a regular pattern with periodicity Λ. The deformer in response to an appropriate environmental ΔE, applies a force ΔF to the bent fiber causing the amplitude of the fiber deformation X to change by an amount ΔX. The transmission coefficient for light propagating through the bent fiber T is in turn changed by an amount ΔT so that

$$\Delta T= (\Delta T/\Delta X)D\Delta E\ , \tag{1}$$

where,

$$D\Delta E=\Delta X \tag{2}$$

In terms of the applied temperature ΔT, Equation (1) becomes

$$\Delta T=(\Delta T/\Delta X).A_S\ \acute{\alpha}_s\ Y_S\ (K_f+A_sY_s/L_s)^{-1}\Delta\theta\ , \tag{3}$$

where $\Delta\theta$ is the temperature change. For sensitive temperature sensor equation (3) implies that one should have $L_s\ K_f << A_sY_s$. In this condition equation (4) becomes simply

$$\Delta T \cong (\Delta T/\Delta X).\ \acute{\alpha}_s\ L_s\ \Delta\theta \tag{4}$$

Various Parameters Analysis for Different Perturbation is shown in Table 3.

Table 3. Parameters Analysis for Different Perturbation.

Environment	**D**	**Minimum Detectability**	**Remarks**
Pressure	$A_PK_f^{-1}$	N.3 * 10^{-4}dyne/cm^2	$A_{P=1cm}{}^2\ K_f^{-1}$ =33*10^{-8}/dyne /cm for silica fiber
Temperature	$\acute{\alpha}_s\ L_s$	4*10^{-6}°C	L_s = 1 cm $\acute{\alpha}_s$ =24*10^{-6}/°C for aluminium1
Acceleration	$m_p\ K_f^{-1}$	N.3 * 10^{-4} cm/sec^2	1cm^2 and 1mm thick lead plate
Magnetic Field	$d_{33}^{H,E}l_s$	9.6*10^{-5} Oe	Ls= 1cm and $d_{33}^{H,}$= 10.4*10^{-7}/G(for perm alloy)
Electric Field	$d_{33}^{H,E}l_s$	1.7* 10^{-1}V/m	Ls= 1cm and $d_{33}^{E,}$= 593*10^{-12}m/V (forPZT-5Hpiezoceramic)

Under an environmental perturbation ΔE, the photo detector signal output i_s is given as

$$i_s= qew_o/hv\ (\Delta T/\Delta X)\ D\Delta E\ , \tag{5}$$

where h is Planck's constant, v is the optical frequency, q is detector quantum efficiency, e is the electron charge, and W_o is the input optical power. Assuming a shot-noise –limited detection system, the mean square photo detector noise is given as

$$i_n^2= (qew_o/hv)\ \Delta f\ , \tag{6}$$

where Δf is the detection bandwidth**.** The S/N power ratio is thus

$$i_s / i_n^2 = (qw_o/hv)(\Delta T/\Delta X)^2 D^2 (\Delta E)^2 (2T\Delta f)^{-1} \quad (7)$$

The smallest signal that can be detected is given for the condition S/N =1, which yields

$$\Delta E_{min} = D^{-1}(\Delta T/\Delta X)\sqrt{2Thv\Delta f /qwo} \quad (8)$$

The first factor is specified to the particular design of the environmental sensor; the second two factor, however are general and apply to all environmental microbend sensors. We can define a generic microbend sensor as one which measure ΔX as defined by Equation (2). Then from Equation (2) and (8) we have

$$\Delta X_{min} = (\Delta T/\Delta X)^{-1}\sqrt{2Thv\Delta f /qwo} \quad (9)$$

If we know the performance of our generic sensor, we can predict the response of our specific sensor by separately determining D.

The microbending sensitivity was also found to depend linearly on the length of the bent fiber having highly absorbing coatings, while for fibers with less absorbing coatings the dependence is weaker. Then the macro bend effect was studied experimentally in several multimode fibers and it was found that bends with a radius of less than 2 cm cause significant losses which can dramatically minimize microbending sensitivity. In addition to the sensing fiber, the other components of the microbend sensor have been also considered. Various light sources were examined, and it was found that LED gives much better performance, especially at low frequencies than lasers by minimizing speckle, which can introduce significant lead noise, which is minimum with LED, can be further reduced by using high N. A. sensing fibers. Such a combination automatically rejects any light from the higher modes which carry most of the lead noise. Then various detection schemes, which can be utilized to detect displacement. The sensor was found to have good detectability, wide dynamic range, and high stability to lead environment. Finally, based on this generic sensor performance, the predicted minimum detectable environmental changes in detecting pressure, temperature, acceleration, magnetic and electric fields were found to be very promising for most of the cases.

4. Results and Discussions

Based on the expression for the change in transmission coefficient of optical fiber for generic configuration of microbend temperature sensor, the simulation on MATLAB 7.5 is as shown below.

Subsequently a model was constructed for application of the sensor at higher temperature range from 0 to 100 degree C. It was found that the results were linear but the slope was too steep for the instrumentation signals to capture the data.

The results are as shown in the graph given below in Fig. 6. (b) The graph of the measured values for the transmission constant is as given below which shows that the results are quite linear.

In order to correct the slope iterations were performed to arrive at suitable gain for the amplifier and the desired response is reproduced. This can be practically implemented by simply adjusting the feedback network of the instrumentation operational amplifiers in the transducer stage. Similarly for other temperature ranges the gain can be suitably changed so as to get the plots in the measurable range. This model constructed can thus help in designing the temperature sensors effectively for different types of applications to work at different temperature ranges.

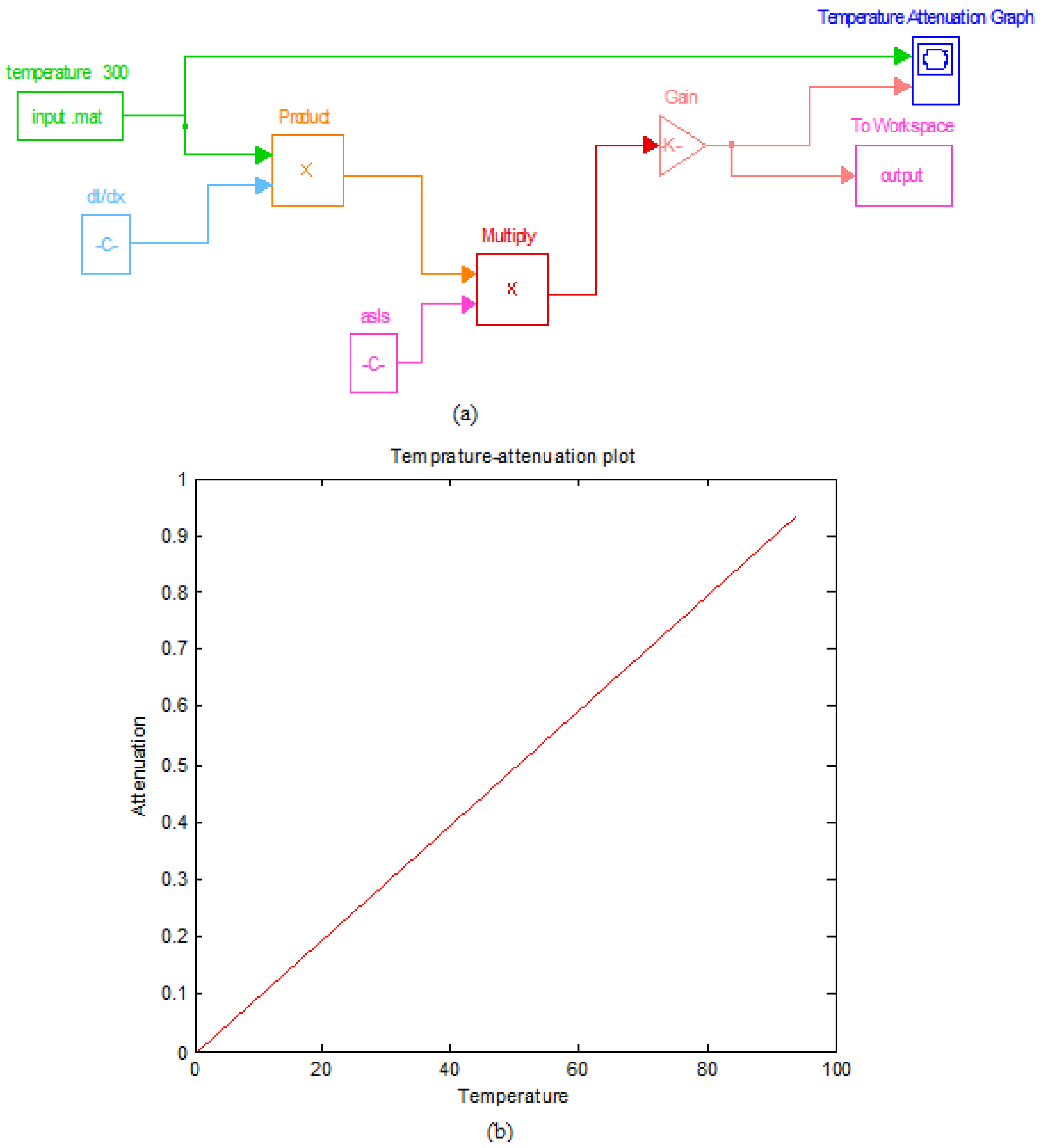


Fig. 6. (a) MATLAB-SIMULINK Model for Microbend Sensor**. (b)** Temperature-Attenuation Plot.

5. Conclusions and Scope for Future Work

In this manuscript modelling in Fig. 6. (a) of microbend configuration of fiber optic sensor has been simulated on MATLAB 7.5 and results discussed to arrive at an optimal design for temperature sensor for transformer. It has been found that graph of the measured values for the transmission constant is quite linear.

Present applications of instruments do not provide consistency no accuracy in their indications of winding temperature. Indirect measurement that includes, Thermo well simulating system are slow to respond to step load changes Aging of power transformers is mainly driven by winding temperature, More frequent loading to full capacity has shown need for better control of winding temperature.

By making use of Indestructible fiber optic sensors we can avoid catastrophic failure and emergency shutdowns by monitoring long-term, gradual transformer deterioration. By now, this is quite for sure that Fiber optic sensor has reached a level of dependability that makes them a natural choice for this important function for direct monitoring of temperature of transformer.

The most important advantages of this overheating protection system are summarized as follows:

- Overheating of both insulation and core can be detected online.
- In case of a local temperature extension an alarm reduces the risk of fume, fire or damage of the insulation.
- No electromagnetic interference, surface discharges or any other impairment of the environmental conditions.
- Safe overheating detection in a range of 80 °C up to 170 °C which is well tried in practical operation.(various other ranges are possible depending on applications).
- Cost efficient and easy to install.
- Processing unit enables due to an intelligent design self control and supports several interfaces as well as remote access.

Scope for Future Work

From this point in the research, there are several other areas for possible future work. The major areas of study are given below:

- This work focused on the implementation of the diagnostic module on three single-phase transformers of the same age and type. However, in order for the neural network to provide more accurate identification for many different types of transformers, a larger database with data from many different models and years of operation is required. For this reason, one area of possible future research is to implement the system described in this thesis on many more transformers. Through this, it is hoped that the system will actually witness different failures and be able to train itself to different types of behaviour, normal and abnormal.
- The work of this thesis focused on transformer diagnostics. However, the diagnostic module and fault detection system can easily be expanded to include circuit breakers and other substation equipment. This research could focus on using the diagnostic system presented in this thesis for fault diagnosis of all substation equipment. This would ultimately lead to the final goal of an intelligent substation.
- Research has focused on diagnostics at the individual substation level. Work can be done to integrate the diagnostics and health information of several substations together into one network. By doing so in combination with neuro-fuzzy system could see more types of failures and train itself to different health conditions. In addition, the network would be able to provide information to the utility about the health of the grid and what areas may be aging and need replacement. The network could send out warnings when one substation is having problems so that other substations could compensate.

Transformer and substation diagnostics is an expanding field of study. The diagnostic module and fault detection system presented in this thesis can be altered and expanded to provide more and more valuable information on the health of substation equipment. The potential of this system is vast and with further investigation, the concept of an Intelligent Substation can be realized.

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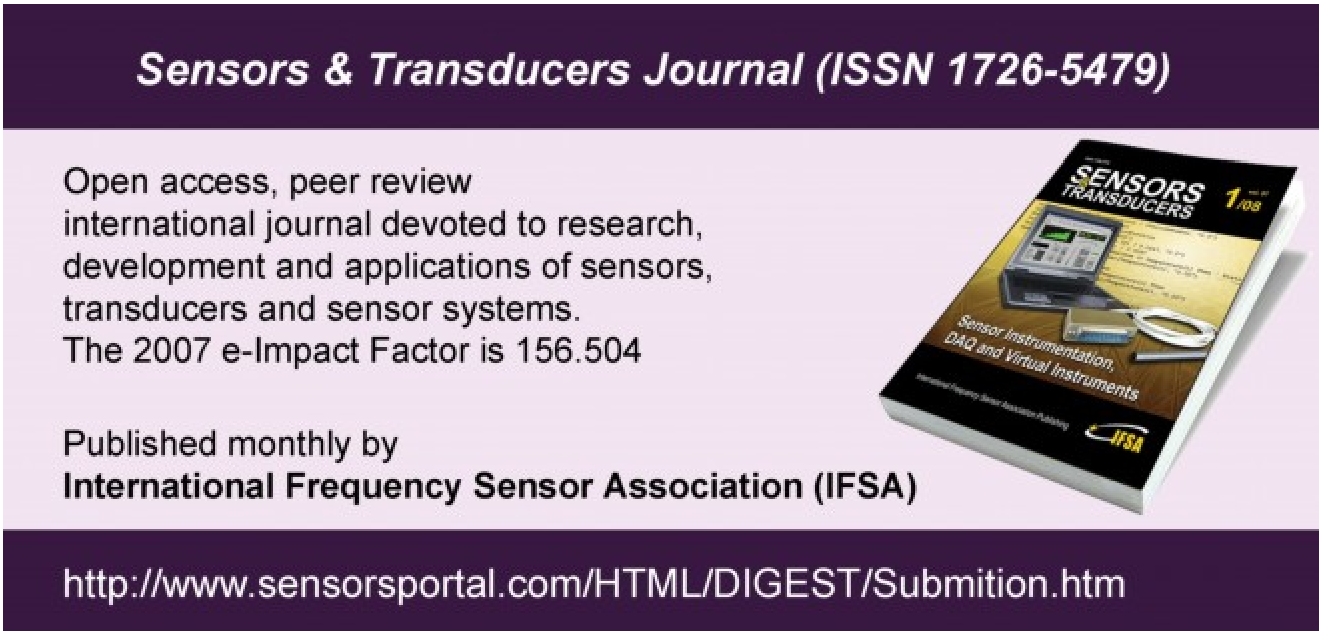

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