Transformer Condition Monitoring using Fiber Optic Sensors: A Review

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Abstract: ***Review for research in a specific field plays an important role to find out the future scope of research work in that direction. This paper gives an extensive review about the application of optical sensors for condition monitoring of transformers. Monitoring of different parameters of transformer oil using optical sensors as a part of transformer condition monitoring has been discussed. In addition, classification and sensing principle of different optical sensors is also described. This paper also attempts to present few methodologies adopting for condition monitoring of power transformer.***

Keywords: Transformer, Optical fiber, Condition monitoring
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1. Introduction

Power transformer is one of the most expensive and important static device in a power system network. Any failure of this device will lead to serious consequential losses. This costly electrical device has to function for long periods without any problem. Condition monitoring for preventive maintenance of these equipments is important and essential to have reliable and uninterrupted power supply [1]. Condition assessment and condition monitoring of power transformer can be done by monitoring the various properties of transformer oil [2-5]. Optical sensor based instrumentation system can be used as diagnostic tool in predictive, preventive and corrective maintenance of transformer. This enables utility engineers to have in-depth understanding of transformer oil as a part of condition monitoring of transformer.

2. General concept and need of condition monitoring

Condition monitoring means the continuous evaluation of the health of equipments throughout its serviceable life. It is the continuous study of the operating parameters of any device so that changes of any monitored parameters can be used to forecast the need for maintenance before breakdown or unwanted situation occurs. It can also be used to estimate the life-span of the machine. Though condition monitoring can be extended to provide primary protection, but its real function must always be to attempt to recognize the development of faults at an early stage. Such advanced warning is obviously desirable since it allows maintenance staff greater freedom to schedule outage in the most convenient manner, resulting in lower down time and lower capitalized losses. Transformer condition monitoring can be divided into following six main categories.

- Condition monitoring by thermal analysis
- Condition monitoring by winding vibration analysis
- Condition monitoring by dissolve gas analysis
- Condition monitoring by winding movement and deformation
- Condition monitoring by partial discharge analysis (PD)
- Condition monitoring by on load tap changer

3. Optical fiber basics

Optical fiber have mainly three parts; core, cladding and jacket. Core and cladding generally made of glass or plastic. Jacket is a layer of material used to protect the fiber from physical damage. Cores have the refractive index more than that of cladding. Light propagates mainly through the core following the light guiding principle "total internal reflection". The structure of an optical fiber is shown in fig.1.

Figure1: Structure of optical fiber.

Optical fibers are classified mainly in to two groups called single mode and multimode. Multimode fiber again classified based on the refraction profile in to two groups; step index fiber and graded index fiber. Step index fibers have a constant index profile over the whole cross section and graded index fibers have a nonlinear but rotationally symmetric index profile falls from center to outwards. The refractive index profiles of single mode and multimode fibers are shown in fig.2.

4. Fiber-Optic sensor based instrumentation system

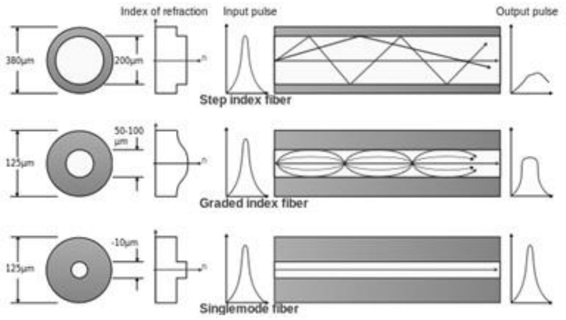

Figure2: The refractive index profiles of fibers

Generally, a fiber-optic sensor system consists of an optical source (laser, LED, laser diode, etc.), optical fiber, sensing or modulator element transducing the measurand to an optical signal, an optical detector and processing electronics (optical spectrum analyzer, oscilloscope, etc.) [6]. Schematic of optical sensor based instrumentation system is shown in fig.3.

5. Fiber-Optic Sensor Classifications

Fiber-optic sensors are categorized in to two groups referred to intrinsic and extrinsic sensors. The intrinsic fiber-optic sensor has a sensing region within the fiber and light never goes out of the fiber. In extrinsic sensors, light leaves the fiber and reach the sensing region outside, and then comes back to the fiber [7]. Fiber-optic sensors can also be classified under three categories [6]: the sensing location, the operating principle and the application, as shown in Table 1.

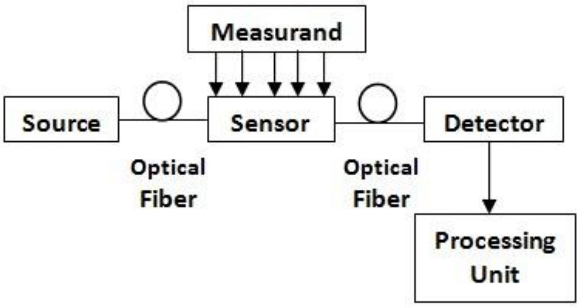

Figure3: Basic components of the system

6. Advantages of fiber-optic sensors

Fiber optic sensor technology has drawn attentions worldwide because of its indispensable application in almost all industries [1-23]. The optical fiber sensors provide off line and online measurements of various parameters like temperature, pressure, vibration, strain, current, pH, rotation, toxic gas, humidity liquid level, liquid flow and many others that are based on the different sensing principles [1-8].

Optical fiber sensors have several advantages over conventional sensors which includes light weight, high sensitivity, simple structure, compact size, less signal loss, low cost, high stability and longevity, high corrosive resistance, high repeatability, immunity to electromagnetic interference, low power consumption, easy multiplexing and integration with other conditioning units [1- 23]. These types of sensors are also well suited for real time monitoring of transformer oil level [2, 3], where electromagnetic induction resistance and electrical isolation are strictly required.

TABLE 1: FIBER-OPTIC SENSOR CLASSIFICATIONS

Category	Class
sensing location	point sensors
	distributed sensors
	quasi-distributed sensors
operating principle	intensity sensors
	phase sensors
	frequency sensors
	polarization sensors
application	physical sensors
	chemical sensors
	bio-medical sensors

7. Transformer oil analysis

Condition monitoring is a part of predictive maintenance. It allows maintenance to be scheduled; helps to predict the possible time of failure measuring the deterioration level and find out the action to be taken to avoid the consequences of major failure. The monitoring technique may be either online or offline depending on the type of the used technique. In the last twenty years different methods and tools have been developed and many papers have been published for condition monitoring of power transformers. The complexity in design, construction, operation and environment factors on power transformer have made the proper condition assessment process very difficult. It has been found from the literature that the health of power transformer and its lifespan during the service period mainly depends on the insulation level of the transformer oil. The mineral insulating oil in the transformer gives dielectric strength, efficient cooling, protect the transformer core and coil assembly from chemical attack and prevent the buildup of sludge in the transformer[8]. When the properties of the oil have changed enough that the oil can no longer satisfactorily perform any of these functions, the oil is said to be bad oil and significantly reduces the transformer's life expectancy. The limits of transformer oil properties as per BIS 335-1993 is given in Table2. While the transformer oil in operation, transformer oil is subjected to electrical, thermal and mechanical stresses [9, 10]. In addition there are contaminations caused due to chemical interactions with windings and other materials of solid insulation, catalyzed by high temperature. As a result, the original properties of the transformer oil changes gradually, rendering it ineffective for its intended purpose after many years. Hence this oil is periodically tested to ascertain its basic properties, and to make sure it is suitable for further use or any action has to be done. The tests which are considered sufficient to ascertain the quality of oil before acceptance and to determine whether the condition of the oil is adequate for continued use in the transformer and to suggest the type of corrective action needed, if required, are as given in table 3.

8. Optical Sensor Applications

Paper [2, 3] deals with optical sensors to measure transformer oil level in the tank using the evanescent principle. In paper [4], author describes a microprocessor based temperature monitoring instrumentation system based on optical phase modulation principle using interferometric optical sensor. Paper [10] explain about the application of fiber-optic sensor to measure hot-spot temperature of transformer oil using microcontroller based signal

TABLE 2: LIMITS OF THE OIL PROPERTIES AS PER BIS 335-1993

Property	*Method*	*Limits*
Appearance	IS 335	Clean transparent
Density at 29^0 C	IS 1448 P:16	Max 0.89 gm/cm3
Viscosity at 27^0C	IS 1448 P: 25	Max 27 cSt
Interfacial Tension	IS 6104	Min 0.040 N/m
Flash Point	IS 1448 P:21	Min 140 ^{0}C
Pour Point	IS 1448 P:10	Max – 6 ^{0}C
N Value (acidity)	IS 1448 P:2	Min 0.03 mg KOH/gm
N Value (Inorganic)	IS 1448 P:2	Nil
Corrosive Sulphur	IS 335	Non-corrosive
BDV (unfiltered)	IS6792	Min 30 kV (rms)
BDV (filtered)	IS6792	Min 60 kV (rms)
DBF	IS 6262	At 90 ^{0}C, Max 0.002
Resistivity	IS 6103	At 27 ^{0}C, Min 1500 X 10^{12}
Resistivity	IS 6103	At 90 ^{0}C, Min 35 X 10^{12}
N value after oxidation	IS 335/1222	Max 0.4 mg KOH/gm
Sludge after oxidation	IS 335/1222	Max 0.1
oxidation inhibitor	IS 13631	not additives
Water content	IS 13567	Max 50 ppm
SK Value	IS 335	Limits under consideration

processing system for which experimental tests has carried out on a 25kVA transformer. In paper [11] three common principles; fiber Bragg gratings, Raman scattering and interferometric point sensors are exemplarily examined for temperature measurement using fiber optic sensor.

TABLE 3: TEST OF TRANSFORMER OIL

Physical test	**Chemical test**	**Electrical Test**
Appearance	Neutralizations number	Electric strength
Density	Water content	Dielectric Dissipation Fact.
Viscosity	Sediment & sludge	Resistivity
Pour point	Corrosive Sulphur	
Flash point	Oxidation stability	
Interfacial tension	Inhibit content	

Their working principles along with recent findings and applications of the sensing concepts are also presented. In paper [12], basic investigations of the partial discharge behaviour of a test arrangement with implementation of fiber optic cables is presented. In this work transformer board or plastics under air or oil test setup is examined with different types of fiber optical sensor. A fiber optic sensor based instrumentation system is used in paper [13] to monitor the moisture level in transformer oil where a bare bent multimode fiber is used as optical sensor. The author describes about the change of output light intensity due to the change of refractive index proximity to the sensor. Paper [14] proposes the combine use of optical and gas sensing technology for the testing of transformer oil where optical sensor provides the absorption properties of transformer oil. In paper [15] use of interfeerometric intrinsic sensor is explain to measure the vibration of magnetic cores of power transformer. Apart from vibration, thermal magnitude of the transformer is also discussed in the same paper. In papers [16, 17], interferometric fiber optic sensors with intrinsic transducer is used to measure ultrasound of acoustic emission from partial discharge inside power apparatus. Intensity based partial discharge measurement using optical sensor has also been discussed in paper [18]. In paper [19, 20], transformer oil condition has been analyzed studying the change of light at output due to absorptive of gases by optical sensor. An approach to power transformer asset management using health index and based on condition monitoring and standard diagnosis has been discussed in papers [21-23]. All these literature has been given as tabular form in table 4.

TABLE 4: LITERATURE IN TABULAR FORM

Monitoring parameter	Principle used	Reference
Transformer oil level	Intensity based on evanescent effect	[2], [3]
Temperature	Phase modulation	[4]
Hot-spot temperature	Intensity based	[10]
Temperature	fiber Bragg gratings, Raman scattering	[11]
Partial Discharge	Raman scattering, Rayleigh,	[12]
Moisture	Intensity based	[13]
Gas	Intensity	[14]
Vibration	Phase, intensity	[15]
Partial discharge	Phase change	[16, 17]
Partial discharge	Intensity based	[18,19]

9. Conclusion

Optical sensor basics, different principles and their applications for transformer condition monitoring have been reviewed extensively. It is found from the literature that optical fiber sensing technology and the instrumentation system is an ideal tool to measure various parameters of transformer oil to estimate the health condition of different transformer. Recent research clearly shows that optical sensors are the most sensitive, light, reliable and cost effective sensors for condition monitoring of transformers.

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