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# Development and Applications of Advanced Systems for Real Time Condition Monitoring of Electric Power Apparatus – An Overview

M. M. Mohsin and Shabana Khatoon

***Abstract* – Most of the advanced communication systems based on fibre optics have been developed during last 3 to 4 decades. In addition to telecommunication applications, the optical fibres are also used in the field of transmission of data regarding various electric as well as non-electric parameters in different operating systems ranging from measurement of current, voltage, temperature, pressure and pH values of the fluid used in electrical power apparatus to measurement of strain in civil engineering structures.**

**Insulation condition monitoring of high voltage electric power equipments is of significant importance in maintaining a safe and reliable electricity supply system. New developments in the area of the signal measuring and its conditioning, data processing and analyzing as well as environmental aspects make a more precise and detailed condition evaluation possible. By detecting faults in power apparatus at an early stage, it is possible to locate and repair defects before they cause an unexpected damage to equipment and over all break-down to the system.**

**In recent years, Fibre Optic Sensors (FOS) have been deployed successfully in electrical equipments for their monitoring. Mainly due to their small size, they are enable to be widely used in structural elements. In fact, advances in production of optical fibre made it possible the recent development of innovative sensing systems for the health monitoring of electrical insulation in electric power apparatus operating at high and extra high voltages. FOSs show high sensitivity and accuracy in temperature, pressure, stress and partial discharge measurement in these equipments. In this paper an overview of development of FOSs and their applications in power equipments such as transformer, switch gear, power cable, over head transmission line, rotating machine and also substations for accurate measurement of temperature, pressure, moisture and other parameters as well as faithful and reliable communication of the measured data has been presented.**

***Key Words: Advance Communication System; Fibre Optic Sensor; High Voltage; Condition Monitoring; Partial Discharge;***

## I. Introduction

In high voltage networks, reliability and economical operation of the equipment is so important that unexpected fault and shutdown may result in a great accident and get a high penalty in lost output cost, particularly under an even-increasing competition environment. Electrical, thermal and mechanical aging and high voltage field strengths may affect the insulation medium of the equipment. Depending upon the individual equipment, different monitoring and diagnostic systems are in use. With these systems, significant parameters will be received and based on these recorded data (for example; temperature, optical signals and electrical quantities etc.) prediction for the future behavior of the device can be made. With advances in testing techniques and the employment of the more appropriate monitoring systems the detection of the early sign of deterioration in the insulation system is become possible to extend the life of certain units.

Beside advantages; recent advances, and cost reductions has stimulated interest in fibre optical sensing. So, researchers combined the product outgrowths of fibre optic telecommunications with optoelectronic devices to emerge FOS.

M.M.Mohsin and Shabana Khatoon, Department of Electrical Engineering.
ZHCET, Aligarh Muslim University
India.

Numerous researches [1], [2] have been conducted in p 35 decades using FOS with different techniques. Intensity, phase, and wavelength based fibre optic sensors are the most widely used sensors. By using fibre optic sensors, it must be guaranteed that the installation of fibre cables causes no addition disturbance inside the insulation system.

## II. Optical Fibre Basics

Optical fibres are transparent fibres, usually made of glass or plastic, for transmitting light. They are flexible strands roughly of the diameter of a human hair. With the use of this latest technology, large amounts of data can be transmitted over long distances. Optical fiber communication systems transmit information at wavelengths that are in the near infrared portion of the spectrum, just above the visible light spectrum, and therefore undetectable by the naked eye. Typical optical transmission wavelengths are 850 n m, 1310 n m, and 1550 n m. During last several years the optical fibres are used to broadcast light signals and audio signals, producing distortion-free sound. In addition, fibre optics is useful in medical procedures (for internal inspection of the body), automobiles, and aircraft.

Though fibre optics was first invented in the 1930s, the use of this technology barely started in the late 1960s. A serious momentum occurred in the 1980s when the phone companies started to replace their long distance copper cables with fibre cables. Gradually, all transmission systems and networks started using fibre cables. Although, fibres can be made out of either transparent plastic or glass, the fibres used in long-distance telecommunications applications are always glass, because of the lower optical attenuation. Both multi-mode and single-mode fibres are used in communications, with multi-mode fibre used mostly for short distances (up to 500 m), and single-mode fibre used for longer distance links [3].

A fibre-optic communication sensing system contains a transmitter that produces and encodes the signals, an optical fibre that transmits the signals over a distance, an optical regenerator that is essential to boost the signal for long distances, and an optical receiver, which receives and decodes the signals [4]. Optical fibres are generally arranged in bundles known as optical fibre cables. Each bundle is protected by a jacket, the cable's outer covering. A single optical fibre consists of core (the central part where the light travels), cladding (special additives surrounding the core), and buffer coating (plastic coating that protect the fibre from break and moisture).The index of refraction of the cladding material is less than that of the core material, so that the light is internally reflected and propagates through the fiber instead of leaking out [3]. The basic structure is shown in figure 1.

Optical fibres are classified into two types, single- mode fibres and multi- mode fibres. Single-mode fibres feature small cores (around 5 to 10 microns in diameter) and broadcast infrared laser light of wavelength 1,300 to 1,550 n m. Multi-mode fibers have larger cores (50 to 62.5 microns in diameter), transmitting infrared light (wavelength ranges from 850 to 1,300 n m) from LEDs.

Compared to the copper wires, optical fibres are less expensive, thinner, have higher carrying capacity, less signal degradation, carry digital signals, high sensitivity, and are non-flammable, light weight, and flexible. Since signals degrade less, lower-power transmitters are used instead of the high -voltage electrical transmitters required for copper wires. The signal coming out of a fibre wire possesses the same quality and intensity as when it was first entered into the cable [5]. An optical cable is resistant to electromagnetic interference, as well as to crosstalk from adjoining wires.

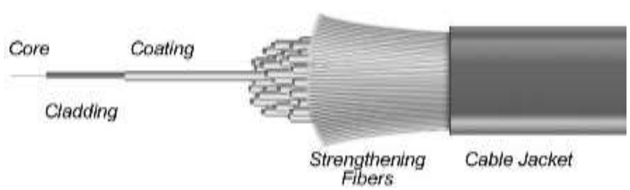


Figure 1 Basic structure of an optical fiber

# III. Fibre Optic Sensor

FOS is a sensor that uses optical fibre either as the sensing element, which is known as intrinsic sensors, or as a means of relaying signals from a remote sensor to the electronic equipment that process the signals is called as extrinsic sensors. Because of their telecommunication origins, fiber optic-based sensors can be easily integrated into large scale optical networks and communications systems. Electrical power is not needed in optical fibre sensors therefore they may be used at the remote location [6].

FOS are excellent for monitoring environmental changes. FOS technology has been under development for the past 40 years and has resulted in the production of various devices, including fiber optic gyroscopes i.e. sensors based on temperature, pressure, and vibration; and pH values measurement. Because FOSs are dielectric devices that are generally chemically inert, they can be used in high voltage, high temperature, or corrosive environments. In addition, these sensors are compatible with communications systems and have the capacity to carry out remote sensing. FOSs are devices that can perform in harsh environments where conventional electrical and electronic sensors have difficulties. They do not require electric cables for their performance and are technically ideal for working in hostile media or corrosive environments for applications in remote sensing.

To date, fibre optic sensors have been widely used to monitor a wide range of environmental parameters such as position, vibration, strain, temperature, humidity, pressure, current, electric field and several other environmental factors. Therefore, fibre optic sensors can be designed to withstand high temperatures as well [4].

# IV. Types of Fibre Optical Sensors

FOS can be classified into two major categories: intension-metric and interfero-metric. The working of an intension-metric sensor depends on variations of the radiant power transmitted through an optical fibre. They are made by using an apparatus to convert what is being measured into a force that bends the fiber and causes attenuation of the signal. Whereas an interfero-metric sensor relies on measured induced phase change in light propagating through the optical fibre. External forces (such as compressive stress) can introduce small bends in an optical fibre which couples light out of the fibre, thereby varying the intensity of light transmitted through the fibre. A micro-bend sensor is a common intension-metric sensor. Two interfero-metric type sensors are Fabry-Perot and Fibre Bragg grating (FBG). The Fabry-Perot sensor consists of two mirrors placed in line with the optical fibre. Strain induced changes in the longitudinal mirror spacing produces a measurable phase change in the light frequency [7].

FBG sensors are the most widely used wavelength based fibre optic sensors. FBGs are formed by constructing periodic changes in index of refraction in the core of a single mode optical fibre. This periodic change in refractive index is normally created by exposing the fibre core to an intense interference pattern of ultra violet energy. The variation in refractive index so produced, forms an interference pattern which act as a grating. FBGs perform direct transformation of the sensed parameter to optical wavelengths – independent of light levels, connector, or fibre losses – or other FBGs at different wavelengths [7].

# V. Applications of Fibre Optic Sensors

Over the past decades, a variety of fibre optic sensor configurations have been developed for measurement of several parameters in structures. FOS can be embedded in various kinds of equipments such as transformers, cables, transmission lines, substation equipments or rotating machines. The optical fibre itself can be divided into two basic types: single mode and multimode fibres. Usually, the former can be used as localized or mechanical sensors, such as strain or force sensors, while the latter can be used as sensors in a more wide range such as single point, multipoint, distributed and thermal and other sensors. Several applications of FOSs for condition monitoring of various electric power equipments are described in the following sections.

## A. Power Transformer Monitoring

The main components that ensure the normal operations of transformers are the windings, core, main tank, cooler, oil, and On Load Tap Changer (OLTC). The key parameters that have to be monitored are the fault of OLTC, ageing of the oil/paper insulation (in both windings and the main transformer), and the load and operating condition. Winding and main insulation is one of the biggest problems that affect the life of transformer. It can be indicated by temperature, gas-in-oil, partial discharge and moisture analysis [8].

Hot-spot temperature is always caused by overloading or local overheating. It is the limiting factor for the load capability of the transformer and has a big effect on transformer life via thermal aging behavior of insulation. The problem is that it is difficult to measure because of insulation problems. Using fibre optic temperature sensors seems the only way to get hot-spot temperature directly. However, it always costs a lot [8].

Giovanni Betta et al. [9] in 2001 developed an enhanced fibre optic temperature sensor system for point measurement and distributed measurement along the winding for temperature monitoring within 25 kVA, ONAN type cooled transformer. The fibre of 200 μm plastic silica was used. The optical characteristics of that fibre were: Refractive index of core $n_1 = 1.457$, refractive index of cladding $n_2 = 1.376$ and Numerical aperture = 0.39. They made comparative hot-spot temperature measurements using fibre optic temperature sensor system and with a traditional k-type thermocouple based monitoring system during a cooling test. Both sensors were positioned in the transformer oil tank where the hot-spot temperature was expected, positioning of the sensors is shown in figure 2. The test was carried out at 100 % nominal load conditions for 12 hours and then the transformer is switched off. The temperature of oil was then measured by both the sensors. From the results it was concluded that the proposed optical fibre sensor response time was enough low to allow the hot-spot temperature to be accurately monitored in a range of 0 to 130 °C in comparison to thermocouple based sensors.

## B. Power Cable Monitoring

S. Jones et al. [10] reported a condition monitoring system for 330 kV Power Cable. This monitoring system was designed and installed as part of a new 330 kV power cable circuit in Sydney, Australia by Trans Grid and J-Power Systems Corp. The monitoring system used distributed temperature sensing system (DTS) for temperature monitoring of the power cable and prediction functions based on a DTS and fluid pressure monitoring. The optical fibre cable used as communication channel, which provides means to exchange the data.

The 28 Km cable is connected between an existing 330 / 132 kV Sydney South substation and a new 330 / 132 kV indoor substation built at Haymarket in the Sydney central business district (CBD) and consists of four independent and phase separated hydraulic sections. The cable circuit is predominately installed direct buried in-ground apart from a 3.6 Km tunnel section in the Sydney CBD.

The two substations are interconnected via an optical fiber cable network dedicated to the condition monitoring system. A DTS unit is located at the end of the cable to monitor the temperature of the cable and environment along the route. The DTS used Raman back scattering. A local controller is located at the end of each hydraulic section to transmit the local oil pressure and valve status to the graphic user interface (GUI) host server in Haymarket substation. The optical fiber network for the five local controllers is double looped for redundancy. The GUI host server in Haymarket substation acquires, processes and records data from the DTS units and local controllers and is directly connected to the Haymarket substation SCADA to exchange key operational information.

A DTS unit, used in this monitoring system can measure up to 15.5 Km route length using a Multi Mode Graded Index (GI) optical fiber. Therefore, two DTS units were installed at the ends of the Cable 42 to cover the entire 28 Km cable route.

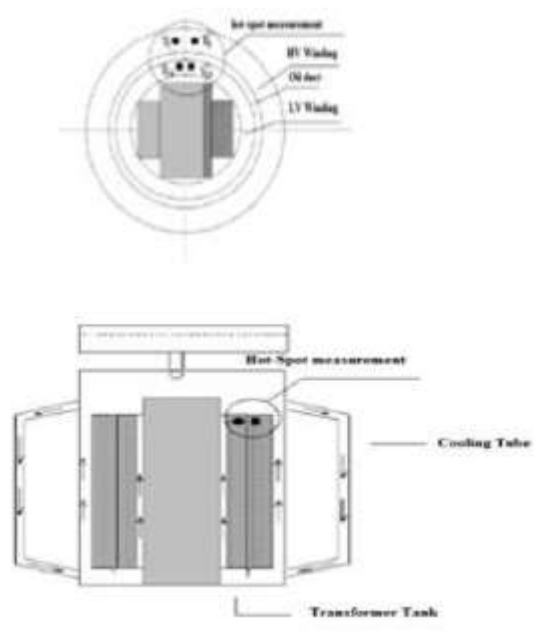


Figure 2 - Positioning of the two sensors for hot-spot temperature measurement.

## C. Over Head Transmission Line Monitoring

Not only foreign researchers but Indians also worked on the development of optical fibre sensing technologies and put efforts to make them suitable for different applications.

Tarun. K. Gangopadhyay et al. [11] developed and reported a complete temperature measurement system on the 400 kV power transmission line at Subhash gram substation of Power grid Corporation of India using FBG optical sensors in 2009. Each FBG sensor has wave length range of 1545 and 1550 nm. A device using FBG sensor was fabricated with aluminum mount connected via FO Cable and installed on aluminum conductor steel reinforced power conductor for continuous two years measurement. They used the probe with different placing, in the first set the FBG was mounted inside the aluminum probe and was placed in a temperature chamber. In the second set, aluminum probe with the FBG is placed inside the egg-shaped aluminum housing and then the assembly is placed on rod heater, where measurement was done and compared with the results with thermocouple temperature measurement sensor. In both the cases they experienced that FBG sensor behaves perfectly with 0.2°C accuracy.

After calibrating the sensor system, they installed the temperature set up on HV (400 kV) power transmission line conductor of Power Grid network. A fibre-optic insulator was used to take the fiber-optic connection from high voltage (400 kV) to ground potential (zero volts) without risk of damage to creep currents. Figure 3 shows the installation activity with control room in the background. The FBG interrogation system and PC are placed for temperature monitoring in a remote control room at a distance about 200 meters as shown in figure 3. From the field experience they noticed and showed that the temperature of HV power conductor can be recorded during the different time of a day at the substation using fibre optic FBG sensors. From this sensor system sagging of the conductor can be calculated using further software. Better monitoring of the thermal and mechanical loads on power lines can be possible using this sensor system to a more efficient utilization of the transmission capacity, enhance the reliability and provide better knowledge of the condition of the power lines and their remaining lifetime.

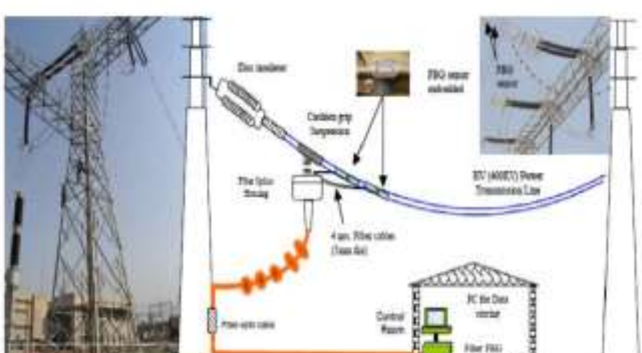

Figure 4Temperature measurement set-up installed on high Voltage (400KV) power transmission line conductor

## *D. Monitoring of rotating machines*

The electric rotating machines are totally enclosed and their insulation is very much prone for thermal failure due to poor cooling conditions. Therefore, it is necessary to use condition monitoring techniques to avoid heavy financial loss due to pre-mature failure of such machines. Nowadays, many monitoring techniques and tools are available to ensure a highly reliable operation of a generator / motor. However, many of these tools are expensive when used for low power motors. New, cost-effective systems based on sensor arrays and smart software algorithms are needed.

As discussed in earlier sections, fibre optic technology has many advantages including small size and high dynamic range and resolution. They are also used in rotating machines to monitor temperature, pressure as well as to measure the vibrations [12].

For reliable operation, the minimum requirements for a FOS should be:

- Sensitivity: 100 mV/g
- Frequency: 5-1000 Hz
- Dynamic Range: 0-50 g
- Resolution: smaller than 0.1 μm at 100 Hz
- Resonance Frequency: higher than 2500 Hz
- Temperature range: -20°C to +135

The number of sensors installed in a machine varies, and could be from 6 on one end winding, up to 13 or more, if both end windings and core are fitted with sensors. The sensors are installed in locations of minimum vibration, making one believe there is no vibration problem. Different methods are used in the selection of sensor locations, and they could be driven by operational experience or design. In some cases, six sensors on one end winding will be installed 60 degrees apart. If stator winding has two parallel paths per phase, 6 sensors could be located on the first line end bars of each phase. However, in both cases if modal testing was not conducted the sensors could be installed in locations of minimum vibration, making one believe there is no vibration problem.

Model testing is sometimes used to determine the optimum location of the sensors. However, since this test can only be performed at ambient temperature, not at winding operating temperature, it is possible that with a temperature increase, the optimum location positions could be changed. Also, since stiffness of the end-winding will decrease as the temperature increases, it is expected that natural frequencies in operation will be lower than during the off-line test, performed at ambient temperature [12].

## *E. Substation Monitoring*

Condition monitoring of power substations is a significant issue for the national utilities. Current methods for monitoring the condition of high voltage equipment are time consuming and often inaccurate, therefore causing catastrophic damage to the substation equipment.

FOS, though, a relatively new technology in India has been gaining much attention. Optical sensors are particularly well suited for conditioning and monitoring applications in that they are light weight, durable, and can be incorporated within equipment without being intrusive. The potential uses of FOSs in substations are monitoring of electrical parameters as current and voltage and other parameters such as temperature, vibration etc. Wear and degradation analysis would also be possible using optical fibers to determine viscosity, acidity, degradation by-products, and wear or by using the fibers to collect near-infrared spectra.

A **400 kV / 220 kV** substation situated at Maharanibagh, New Delhi, India uses an extrinsic type of fibre optic sensor (50/125 μ m-UM multimode 6F indoor cable), by using this optical fibre cable, they made a communication system for monitoring and control of electrical equipment. It transmits thermal radiations coming from transformer tank through a transmitter. These signals received by the receiver are then monitored on the system. By analyzing these signals, internal temperature of transformer, humidity and other electrical parameters such as active power, reactive power, current, voltage etc can be measured [13].

The configuration has been shown in figure 4. It shows the optical fibre link for continuous monitoring system at Maharanibagh substation. The relays, intelligent electronic devices and bays are connected to ethernet switch via optical fibre. Ethernet switch is used as transceiver and can support multiple fiber connectors without loss of port density. It can both receive and transmit the light signals from or to optical fibre and could be stored in computer memory.

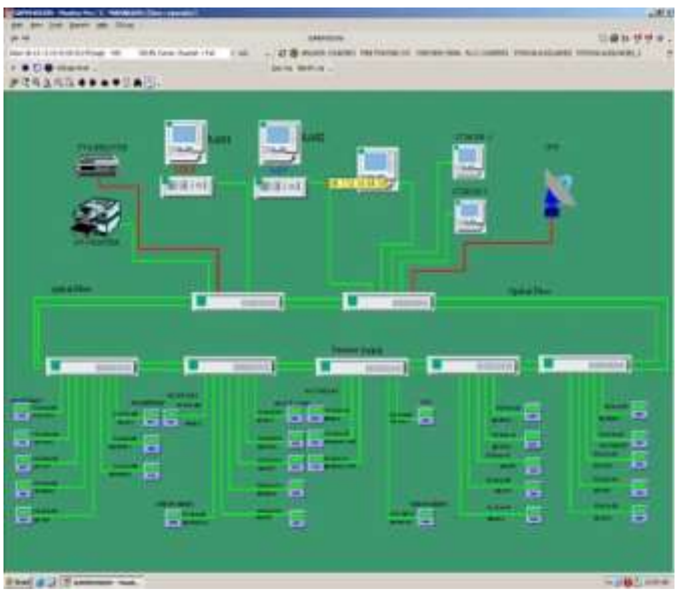

Figure 4 Supervision of GIS using optical fibre cable

# VI. Conclusions

- Monitoring of hot-spot and partial discharges inside H.V Transformers with fibre optic sensors are much effective with respect to other sensors.
- FOSs are flexible and adjustable and can be set to any desired location in power equipment.
- Fibre optic sensing technology can detect easily premature faults such as due to rise in temperature or occurrence of PD.
- Fibre optic technology can allow utilities to manage overload conditions more effectively.
- The use of optical fiber sensing technologies for the monitoring and diagnosis of the condition and performance of heavy power equipment in substations could provide the better results.
- This technology offers a reliable and inexpensive measurement for many sensing applications such as pressure and pH value measurement of fluids in oil industry, strain measurement in civil structures like bridges, dams etc.

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