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Intelligent Transformer Monitoring System Utilizing Neuro-Fuzzy Technique Approach

Intelligent Substation Final Project Report

Power Systems Engineering Research Center

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Optical Sensor for Transformer Monitoring

Final Project Report

Smart Sensor Project

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Executive Summary

Transformers are a vital part of the transmission and distribution system. Monitoring transformers for problems before they occur can prevent faults that are costly to repair and result in a loss of service. Current systems can provide information about the state of a transformer, but are either offline or very expensive to implement. This report outlines a new approach that is based on using light absorbance to monitor the state of a transformer. Given that the most critical components of a transformer are immersed in its oil, by monitoring and identifying the condition of the oil, the state of the transformer can be diagnosed. Based on the developed monitoring system, oil is continually sampled from the transformer through a closed circuit, and light is passed through the oil and tested for absorbance. Preliminary experiments have demonstrated that a system based on certain wavelengths could determine the difference between an acceptable or unacceptable sample of oil. Samples of failed transformers showed a general increase in absorbance of the light by oil during the experiment. Additional wavelengths can be identified, which provide more information about the state of the transformer and make the system more versatile in determining fault types. Basic principles of operation, experimental data, and a prototype of this monitoring system are developed under this project, and are presented in this report.

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1. Introduction

This introductory section describes the importance of this research, its impact, and the goals and objectives of the project.

1.1 Motivation

In recent years, increased emphasis has been placed on power reliability and economy. In particular, major changes in the utility industry, primarily caused by restructuring and re-regulation, have caused increased interest in more economical and reliable methods to generate and transmit power. The health of equipment constituting the substation is critical to assure that the supply of power can meet the demand. As has been seen recently in California and more dramatically in the recent blackout in the northeast, the United States is already beginning to reach a point where the transmission and distribution system cannot handle the instantaneous demanded power load.

Transformers, which either raise a voltage to decrease losses, or decrease voltage to a safe level, are among the most expensive piece equipment of the transmission and distribution system. Without transformers, electric power would be uneconomical to transmit over large distances, or would be at a voltage too high to use safely. Transformers are expensive, as is the cost of power interruptions. The savings that would be accrued from the prevention of failures in transformers would be in the millions of dollars. In the past, maintenance of large high voltage transformers was done based on a pre-determined schedule. Maintenance crews would inspect a transformer at set intervals based on its past age and performance history. As can be expected, this leads to many catastrophic failures of improperly diagnosed transformers and the over inspection of other healthy transformers. Because of the cost of scheduled and unscheduled maintenance, especially at remote sites, the utility industry has begun investing in instrumentation and monitoring of transformer. On-line transformer diagnostics is the key to greatly reduce the cost and increase the reliability of providing the needed electrical energy to a growing society. Therefore, preventing in-service transformer failures has a profound economical impact, as well as the ability to deliver a reliable power.

1.2 Research Objective

Since transformers are vital elements of the electric power transmission and distribution infrastructure, they need to be monitored to prevent any potential faults. A failure in a transformer can easily cost several million dollars to either repair or replace, and will also cause a loss of service to customers and revenue until the symptom is found and repaired.

Currently, there are several monitoring systems available, including Dissolved Gas Analysis (DGA) and Particle Discharge. However these monitors are very expensive. The objective of this research is to develop an online, inexpensive monitoring system for the health assessment of high voltage transformers, using the principle of light absorption. A new monitoring system, based on absorbance of light, has the potential to be an online diagnostic tool that can provide early detection of potential abnormalities without going through the expense of DGA. Furthermore, given that light absorption at different wavelength may correspond to different failure modes, this new monitor has the potential for detection of multiple failure modes simultaneously. Finally, given its operational principles and the required hardware and software, this monitoring system will provide an inexpensive approach to transformer diagnostics. Through this online monitoring system, light is passed through the oil of the transformer and tested for absorbance. Experimental results have demonstrated that by using different wavelength, one could determine the difference between an acceptable or unacceptable sample of oil. Based on apriori determined absorbance levels of sampled oil, associated with different transformer failure modes, a database can be created that would be used with this monitoring system. In our experiments, samples of failed transformer oils have shown a trend of increasing absorbance levels. Additional wavelengths can be identified, which provide more information about the state of the transformer and make the system more versatile in simultaneously determining the cause of different faults.

2. Basics of Light Absorbance

Absorption spectroscopy is a method that can be used to measure the concentration and composition of chemicals. The theory of absorption describes changes to a molecular state due to a change in energy. Such a change occurs when a form of energy such as light excites the molecules. Since the energy levels of molecules are discrete, certain chemicals absorb light at specific wavelengths, corresponding to the light absorption properties of the chemical, e.g. transformer oil [2].

There are also other benefits to using light as an acquisition method. First, light is almost immune to pressure effects and the effect of pressure can be neglected even as high as 275 atmospheres. Also, temperature has little effect on the measuring system, although it does shift the wavelength slightly.

Optical-based sensors have been developed and used extensively. Most such sensors are based on optical modulation techniques. There are five types of modulation commonly used with fiber optics and most of them are applicable to liquid light guides. These are intensity, wavelength, phases, polarization, and time modulation.

Intensity Modulation (I): Modulation of number of photons transmitted after absorption or emitted by luminescence, scattering or refractive index changes. Limitations: Aging causes drifting and intensity is temperature sensitive.

Wavelength Modulation (λ): Provides additional spectral information over simple intensity measurements. Wavelength varies due to absorption and fluorescence. Limitations: Line losses, needs suitable spectrometers, and crosstalk.

Phase Modulation (θ): Two coherent light beams in different optical sensors or different paths interfere with one another and one beam is modulated by the chemical environment. Limitations: Bending effects of fiber, noise, and optical components. (These sensors are typically not used)

Polarization Modulation (P): A polarizer produces a controlled state of polarization (linear, circular, elliptical) before the light enters the optode. A change in polarization occurs depending on the chemical interaction and is measured by an analyzer, which can take many forms. Limitations: Random polarization and stress-induced birefringence.

Time Modulation (t): In time domain fluorometry, a pulsed light source generates a short pulse that excites fluorescence in the optode. The decay is measured as a function of time. Limitations: Signal to noise ratio, modal dispersion at long distances. With the use of these modulation techniques, many sensing technologies have been developed.

Mineral oils have been extensively used in high-voltage electrical apparatuses since the beginning of the 20th century, and constitute the dielectric fluid for most liquid-filled transformers currently in service. The oil covers the core and windings and any connections and fittings that require oil for insulation. It flows through the windings and cellulose insulation to not only remove heat from power losses, but also provide insulation between windings, as shown in Figure 1.

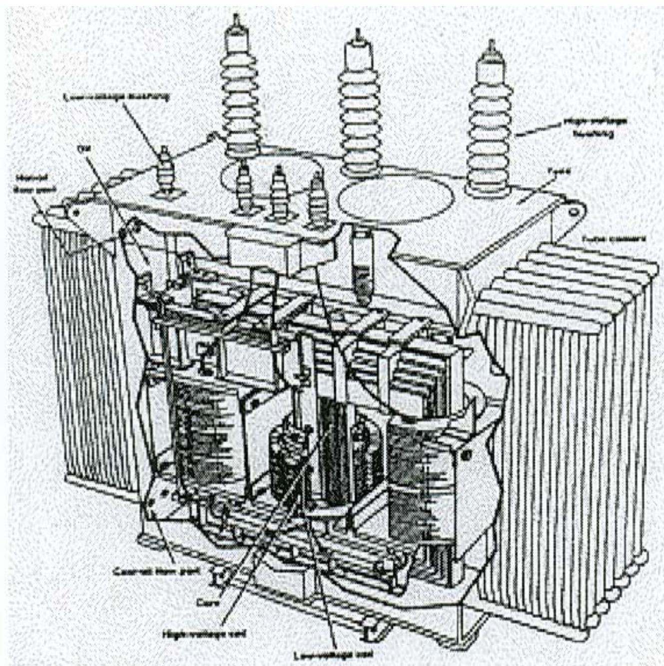

Figure 1: Internal Details of a Transformer

Transformer oil undergoes varying degrees of aging or deterioration under normal operating conditions. The rate of aging will be contingent upon the magnitude of the electrical, thermal, and mechanical stresses. Insulation breakdown in the windings, from coil-to-coil or coil-to-ground, will result in arcing. Under arcing stress, the oil will generate solid carbon, which will form sediment, decreasing the heat dissipation capability. Furthermore, arcing stress will cause a decrease in the dielectric strength of the oil. Therefore, a sensor that can provide an assessment about the condition of oil inside transformers or breakers would be an excellent means for relative diagnostics of the equipment.

Current research indicates that it is the change in dielectric properties of the oil that leads to transformer failure. Thus, oil failure is closely related to changes in the dielectric properties of the material. Various measures are available to detect these changes: particulate generation, fault gas generation, and oil appearance. For example, present preventive maintenance procedures include an analysis of the oil "color" as part of the health evaluation of the transformer. These changes can be observed as a change in the light reflecting characteristics of the oil because the index of refraction is closely related to dielectric properties. Specifically, the index of refraction is a complex number, the imaginary part being related to absorption of light and the real part being related to scattering. Indeed, the absorption line strength for molecules can be expressed in terms of the molecular dipole moment. The oil changes color because it acts as an absorbing spectral filter, and the spectrum shifts with changes in dielectric properties. These same changes can be observed, therefore, as a change in index, or a change in absorption within certain discrete bands.

It has been determined that absorption measurements demonstrate there are both molecular changes in the fuel composition and a marked increase in the particulate present in the fuel as a result of thermal stress. Scattering measurements indicate that while room temperature oil contains particulate with average diameters greater than 0.1 μm, thermally stressed oil contains much larger concentrations of particulate with sizes of

0.06 μm and below. Therefore, light absorption spectroscopy for condition monitoring of the oil inside industrial equipment is applied.

The increase in the intensity of the absorbance in the equipment oil is basically the result of increased concentration of chromophores that exist or can be generated in the chemical compounds of oil [22]. This is further represented in the increase of these chromophores in the individual compound in the machinery oil. These chromophoric groups are shown in Table 1.

Table 1. Chromophoric Groups

≥C=N-	≥C=O	-C=C-	-CHO	≥C=S	-COOR
-COOH	≥S-O	-NO2	-ONO	-N=N-	-N=O
-ONO2	-(C=C)2-	-(C=C)3-	-(C=C)4-	-(C=C)5-	-(C=C)2- acyclic
C=C-C=O	C=C-NO2	C=C-C=N			

Machinery oils are refined from petroleum. They are very complex mixtures and may consist of as many as 2900 paraffinic, naphthenic and aromatic hydrocarbon molecule types, 25% of these being aromatic [23]. These hydrocarbons contribute more than 95% of the mineral oil. In addition, there are no hydrocarbons and impurities in the mineral oil. Thus the properties of machinery, e.g. transformer oils, may vary significantly from one batch to another, even from the same brand. Although the oil manufacturers have analyzed the final products and users, up to 90% of the compounds still remain unidentified, as the high cost of analyses make their full implementation practically impossible.

Despite these complications, for many of these hydrocarbons, their absorption does not occur in the readily accessible portion of the UV region (near or quartz UV). The reason for this is the absorption of energy in the UV region is quantified; the electronic structures of these hydrocarbons determined the wavelength of their absorption. Therefore, we are able to recognize characteristic groups in molecules of widely varying complexities.

In fact, the paraffinic and naphthenic compounds don't absorb in the near UV region. It is the aromatic compounds in the transformer oil that absorb at near UV. The general molecular formula of a paraffinic compound is C_nH_{2n+2}, C-H bond absorb at about 135 nm in the vacuum UV region. Naphthenic compounds have a universal molecular formula of C_nH_{2n}, and absorb at about 165 nm in the vacuum UV.

Aromatic compounds contain at least one aromatic ring. Transformer oil has a high boiling point, generally between 220-250°C, therefore both mononuclear and polynuclear aromatics possibly exist in transformer oil. The conjugated C=C double bonds move the absorption region to the near UV (quartz) region. For example benzene (C_6H_6), which has only one aromatic ring absorbs up to 280 nm. In practice, UV spectrophotometry is normally limited to conjugated systems.

In addition, as the ring becomes more complex the peak of absorption shifts to longer wavelengths. For example, when there is alky substitution (an atom or group of bonded atoms that can be considered to have replaced a hydrogen atom or two hydrogen atoms in the special case of bivalent groups in a parent molecular entity), the energy of absorption decreases and the absorption occurs at longer wavelength. Furthermore, the bathochromic effect is progressive as the number of alkyl groups increases. Actually, when any of the chromophoric groups is attached to an aromatic ring, the absorption is observed at longer wavelengths. Especially, when the number of aromatic rings increases, the absorption tends to move to longer wavelength.

3. Absorbance of Transformer Oil

Ultraviolet/Visible Spectrophotometry is based on the fact that electrons in certain types of chemical bonds are excited from the ground state when exposed to radiation in the wavelength range of 200-800 nanometers (UV: 200-380 nm; Vis: 380-800 nm). The sample will absorb energy at wavelengths whose energies correspond to that required for the electronic transition. UV/Visible Spectrophotometer is used with a range of 200-900 nm. Quartz cell does not absorb above 195 nm, and is selected as the sample cell.

Because the machinery oil is a highly absorptive material, the experiment with 100% oil exceeds the range of the spectrophotometer in the wave region 200-400 nm and there is essentially no absorption in the visible range 400-900 nm. Therefore, we only need to test the UV absorption with this UV/Visible Spectrophotometer. Energy absorbed in the UV region produces changes in the electronic energy of the molecule resulting from the transitions of valence electrons in the molecule.

Tests were performed on acceptable and unacceptable samples of transformer oil to determine if there was a wavelength of light that could differentiate between acceptable and unacceptable oils. Shown in Figures 2 and 3 are absorbance spectra from acceptable and unacceptable samples of transformer oil. A sample of this process is shown in Table 2.

Table 2. Some sample oils and their absorbance and acceptability

Acceptable Oil	Oil sample	Absorbance
Yes	Arc nonsealed 42 min	3.7
Yes	Arc sealed 60 min	3.4
Yes	Arc nonsealed 75 min	3.9
Yes	Arc nonsealed 155 min	4.3
No	Arc sealed 5 h	6.2
Yes	Thermal nonsealed 24hr	3.7
No	Thermal nonsealed 48hr	6.4
Yes	Thermal sealed 10 days	5.2
No	Oxidation nonsealed 24hr	7.3
Yes	Oxidation sealed 3 days	4.8
Yes	Oil # 1	5.4
Yes	Oil # 2	5
No	Oil # 3	6.2
No	Oil # 4	6.1
No	Oil # 5	6.6
No	Oil # 6	6.5
No	Oil # 7	6.2
No	Oil # 8	8.4

Figure 2 shows the complete absorption for ultraviolet (UV) light, while Figure 3 shows the absorption spectrum for the range that showed the greatest difference between acceptable and unacceptable oils.

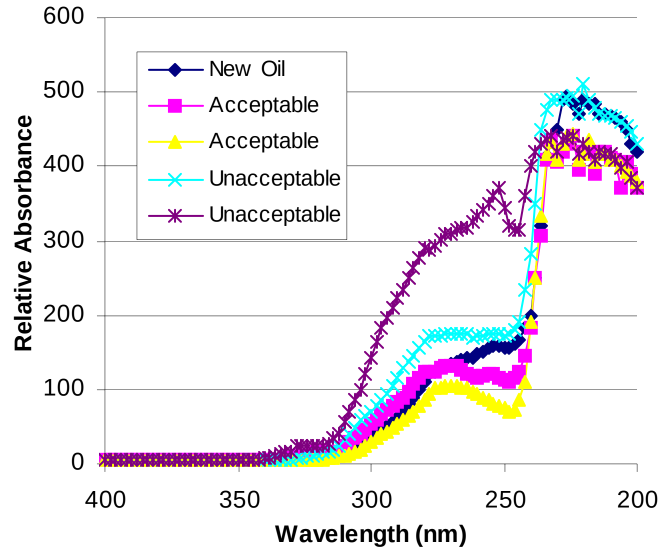

Figure 2. UV Absorption Spectrum

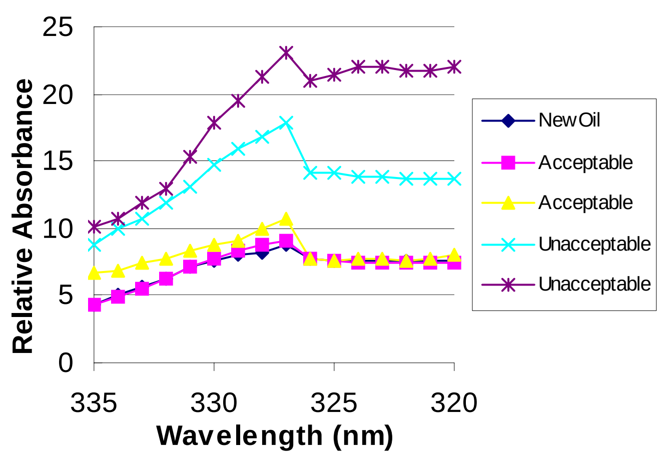

Figure 3. Absorption spectrum at highest correlation

After a certain wavelength was chosen, a preliminary prototype was built, and failures were performed on the transformer oil to show the repeatability of the measurements. To show this repeatability in the absorbance, oil samples were made to fail using three different failure methods: arcing, thermal degradation, and oxidation.

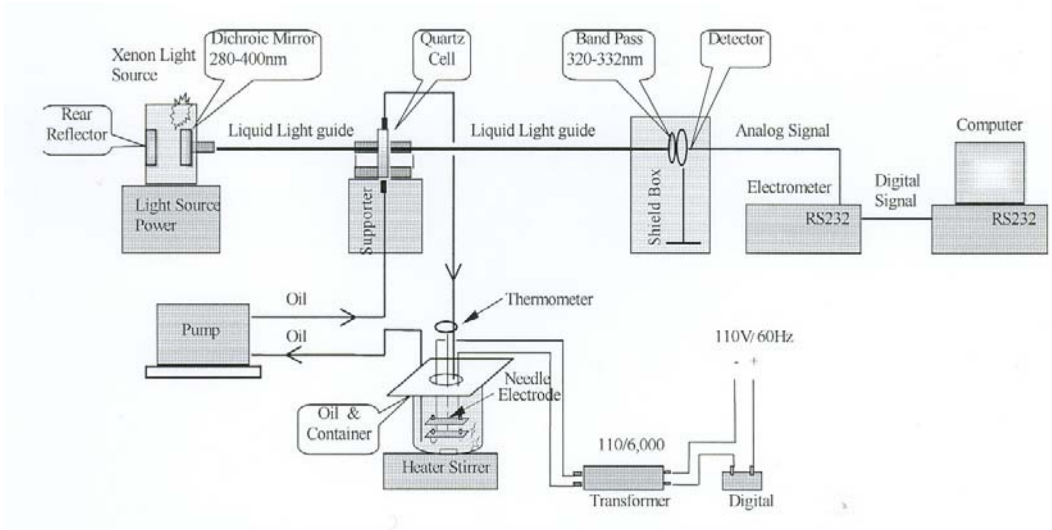

Figure 4: Arcing Degradation Tested with Prototype System

Figure 4 shows a schematic of experimental set up that is used to assess the change in oil light absorptivity after an arcing (an electric transformer failure) takes place in the oil container. A Xenon light source will be used that provides appropriate wavelength. A pump is used to circulate the oil through the quartz cell. By using an optical band pass filter and a light detector, an analog signal is generated that, after calibration, will indicate light absorbance after passing through the oil. The arcing experiment was performed using a transformer and two electrodes to create arcs in the transformer oil. The container was sealed with nitrogen gas to prevent any contact with the oxygen present in the air. The absorbance was continually sampled and the results are shown in Figure 5.

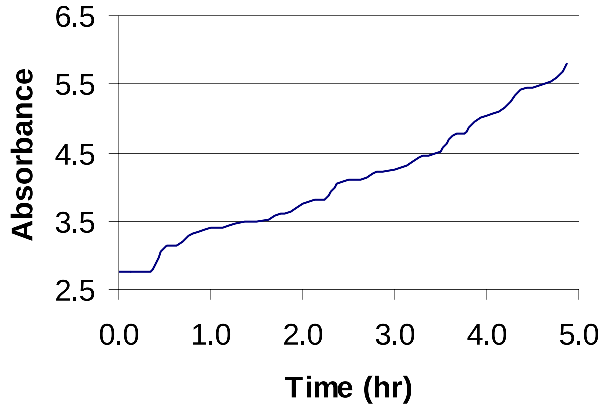

Figure 5: Absorbance in time for arcing experiment

The next experiment was thermal degradation. This experiment was carried out in sealed conditions with nitrogen gas and consists of heating the oil. The results of this experiment are shown in Figure 6.

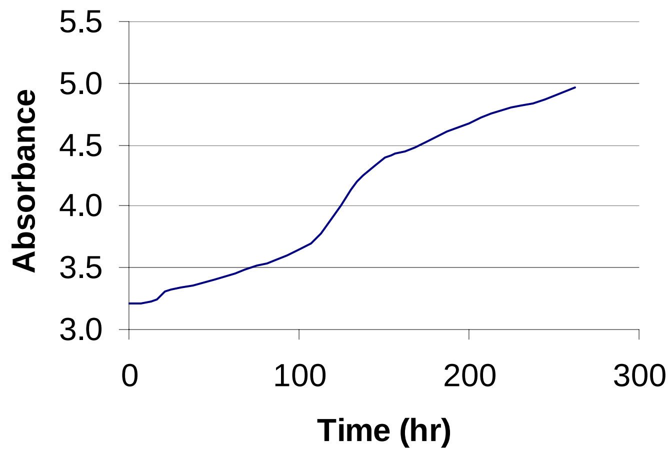

Figure 6: Absorbance in time for thermal experiment

The last experiment was oxidation. This experiment was also performed in a sealed container and consisted of bubbling oxygen through the oil to oxidize the oil.

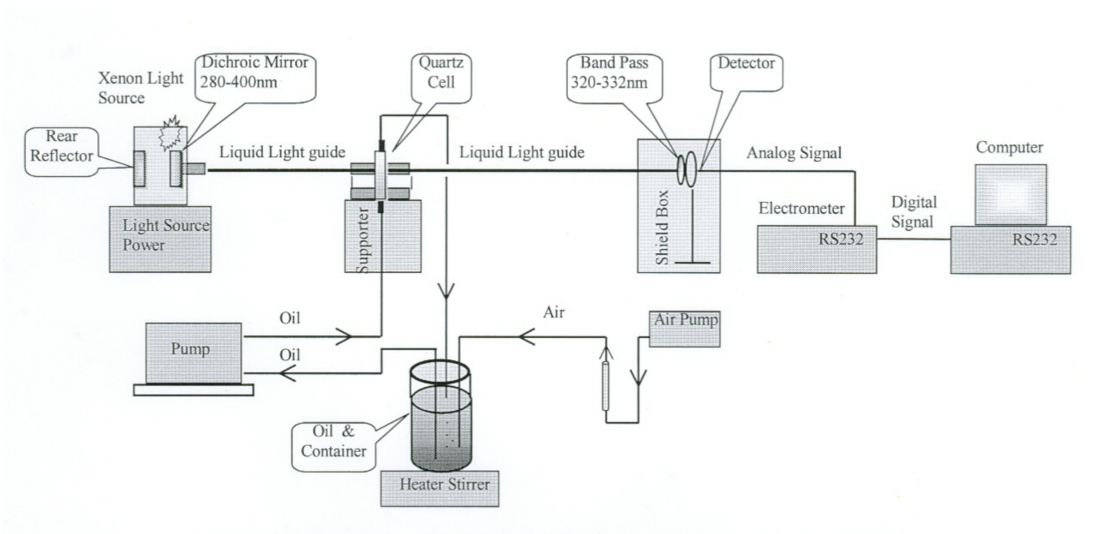

Figure 7: Oxidation Degradation Tested with Prototype System

As illustrated in Figure 7, by adding airflow, using an air pump, oxygen is introduced and oxidation degradation testing is performed to represent common failure in an electric transformer. The results of this experiment are shown in Figure 8.

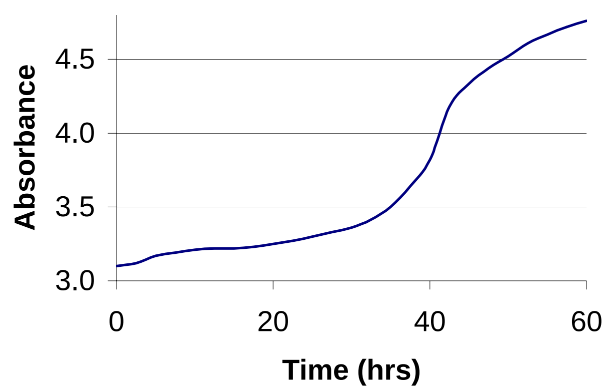

Figure 8: Absorbance in time for oxidation experiment

As can be seen from the above experimental results there is a direct correlation between the absorbance level and the state of the oil. As tests were performed and the oil sample was degraded, the absorbance property increased.

4. Database Information

Although using only one wavelength can differentiate between acceptable and unacceptable oil, additional wavelengths were investigated to access the extend of knowledge and information that can be extracted from this online optical-based monitoring system. To determine what type of fault is present in the system, sample oils are scanned at multiple wavelengths, and information about the samples is correlated with the absorbance level. The extend of this experimentally devised database includes such failures associated with gas concentrations, water content, arcing, etc.

As part of these experiments, it was determined that at a wavelength of 380nm the approximate concentration level of Oxygen can be estimated, and at a wavelength of 390nm the concentration of Nitrogen can be identified. Therefore, a direct correlation between these concentrations and the light absorption level can potentially be used as means of diagnosing the transformer.

To further create this database for the monitoring system, light absorbance was correlated to different faults. Samples of oil from transformers that had failed were tested for absorbance in the UV spectrum to determine if there is a relationship between the absorbance and the type of fault. Seven oil samples were used, five of which were obtained from transformers that exhibited a thermal fault, as well as two samples of oil from transformers that had failed by arcing.

Shown in Figure 9 is the absorption spectrum in the range of wavelengths that provided the most pronounced difference between the thermal and arcing faults. Figure 9 illustrates that by measuring light absorption level at the wavelength of 390nm, it is possible to differentiate between a transformer that is failing from either a thermal or an arcing fault.

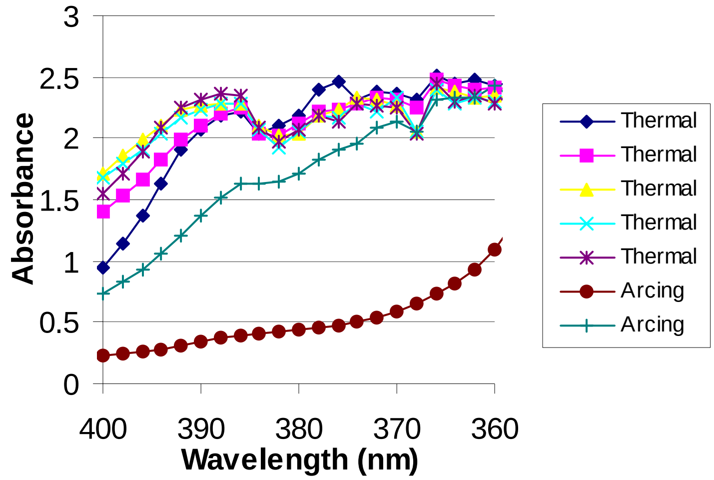

Figure 9: Absorption spectrum for thermal and arcing faults

Once the database of failure modes and light absorbance has been created, then a failure classification scheme needs to be devised. Several techniques are available for this classification, including: a Bayesian classifier, which can be used to determine the probability of possible failures; and a neural network that learns and classifies patters.

5. Bayesian Classifier

Stated simply, a Bayesian classifier uses probabilities of events to determine the probabilities of each event [4]. For example, consider different transformer oil conditions described in Table 1. From this table two states can be determined. The oil is either acceptable or unacceptable. A Gaussian distribution can be used to describe each state.

By the application of a Gaussian distribution, probabilities of each event can be calculated, and a Bayesian classifier would use these probabilities to determine the possibility of each state. A sweep for the probabilities is shown in Figure 10, where the solid trace is the probability of an acceptable oil, and the dashed trace is the probability of an unacceptable oil.

This figure illustrates that at a given wavelength, lower absorbance show that the oil has a higher probability of being acceptable, while at higher absorption levels, the oil has a higher probability of being unacceptable. The cutoff point is at an absorbance level of 5.5. It should be noted that an absorbance level of 6.0 should not be interpreted as having an unacceptable oil, rather the monitoring system would be detecting an oil that has a higher probability of being unacceptable.

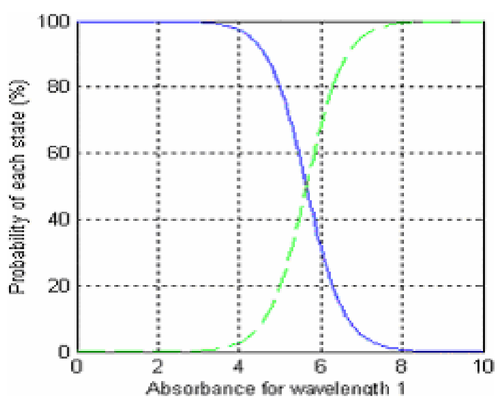

Figure 10: Two-State Resultant probability distribution at a given wavelength

In the previous example, only one wavelength and two states were used. To provide more information about the health of the transformer, more wavelengths can be used and also as a result more states can be determined. If the conditions of the oil samples were known and certain wavelengths have been measured, then a set of observed wavelengths would be used to determine the probability of each condition. Then a rule-based fuzzy interface system can be built to automate the overall diagnostic process.

For example, consider if there are three states (normal, arcing, and thermal), and two wavelengths are sampled. A database of the four samples of oil at two different wavelengths can be derived from running absorbance spectrum by the prototype system. Now, if new sample oil is tested at the same two wavelengths, the probability of each state can be derived. The highest probability is the most likely state that is present in the transformer oil at that operating condition.

6. Monitoring System Prototype

The complete setup of the monitoring system prototype is shown in Figure 11. The power supply provides the input energy to the light source, which sends light at the correct wavelength through a spectrometer cell. A filter is used to isolate a specific wavelength before the light passes to the sensor. The sensor is a phototransistor that responds to the light by creating current. This current is very small (micro amps), which is amplified and changed into a voltage to be read by the on board computer. To supply a current sample of oil from the transformer, a pump is used to cycle the transformer oil from the transformer, through the spectrometer cell and back to the transformer.

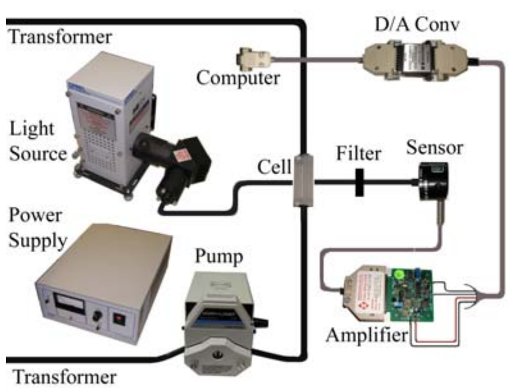

Figure 11: Diagram of prototype system

The filter can be changed so that multiple wavelengths can be measured as long as the wavelength to be measured is in the range that the sensor will respond to. This prototype shows much versatility considering that the only connections needed to the transformer are two oil-taps.

7. Conclusion

7.1 Summary

Much important advancement was reached from the research described in this report. A transformer diagnostic system that could be implemented on large scale, field-level equipment was developed. Through this development, valuable information was gained about the state of the transformer oil for diagnostic. The major contributions of this research are summarized as follows:

- An optical sensor module was designed. This sensor included the non-invasive sensors that have been found to indicate developing faults in transformers, which is the spectrometer. The system also included its own power supply, light source, mini fluid pump and quartz cell to sample the oil continuously. The absorbance of the oil sample is measured and the data is sent to the computer to be diagnosed.
- The data that was sent from the spectrometer is matched up against the collection of unacceptable oil in the database using Bayessian classifier. This classifier that would determine the state of the transformer oil and notify the operator in field online.

- A set of unacceptable oil characteristic has been obtained. This type of data was obtained to represent three types of transformer failure due to arcing, thermal degradation and oxidation. The experiment results have shown that there are significant differences in its absorptive level between the oil condition that has been degraded due to these failures and the oil in good condition.

7.2 Future Work

The result presented in this research focused on validation and implementation of the optical based sensor to detect the state of the transformer oil, which could be used to prevent failure to the transformer overall. This validation was accomplished through the design of a diagnostic module, which could non-invasively collect data that has been shown to provide diagnostic information about the health of transformers through the oil condition. From this point in the research, there are several areas for possible future work. The major areas of study are given below.

- This research focused on the feasibility and implementation of the diagnostic module on transformers of the same age and type. However, in order for sensors 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 report 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 behavior, normal and abnormal.

- The experimental results obtained in this research only used a limited amount of oil sample. Future work could utilize more samples that represent any common failure to the transformer. By collecting more samples, it is possible to achieve more robust and accurate diagnostic capability.
- The diagnostic module designed in this research still require a USB connection to main computer in order to transfer the data. This limits the portability and increases the work needed for installation. An area of future research could focus on the development of a hardware and signal-processing module that would utilize wireless communication.
- Finally, there is also a great amount of work that can be done in the area of pattern recognition of faults and life expectancy. Once a large database of data has been collected from several different transformers and different types of faults have been witnessed, it will be possible to try to classify behaviors and how they relate to impending failures. In the long term, the pattern classification could lead to life expectancy predictions for the transformer.

Transformer diagnostics is an expanding field of study. The diagnostic module and fault detection system presented in this report can be altered and expanded to provide more and more valuable information on the health of a transformer. The potential of this system is vast and with further investigation, the concept of an intelligent diagnostic for transformer or even substation level can be realized. The result in this report, which is a design for an online optical sensor based on absorbance of light, shows great promise on being a successful monitoring system for high voltage transformers.

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