CHAPTER 3

MONITORING OF MOISTURE IN TRANSFORMER OIL USING A BARE AND BENT MULTIMODE OPTICAL FIBRE REFRACTOMETER

3.1 INTRODUCTION

This chapter presents a bare and bent Optical-Fibre Refractometer for the measurement of moisture content in transformer oil. A mathematical basis of the bare bent optical fibre refractometer has been related to the output voltage which is a function of the refractive index of transformer oil. A microcontroller-based system is used to sample the output voltage and LM35 temperature IC which provides the measure of temperature of transformer oil. Artificial neural network (ANN) has been used for correlating the readings of measurement output and LM35 temperature sensor to the moisture content of the transformer oil.

3.2 EFFECT OF MOISTURE IN TRANSFORMER OIL

Power transformers are one of the most expensive investments in electric power systems [28]. They are fundamental components of an electric power system and their reliability is an important factor in the operation of the system [29]. The transformer oil is a good insulating material. Transformer oil is expected to perform both as an insulating liquid and as heat transfer agent.

All the transformer oil base stocks are mixtures of paraffin, naphthenes and the aromatics, only differing in their proportions. Due to isomerism, thousand structural variations are possible in these three groups. When oil is an integral part of a transformer, its behaviour can be related to its molecular composition and physical properties. Thus it is very difficult to predict the performance of the oil in actual field operations from the fundamental properties of the oil due to complex conditions present in the field transformer which are entirely different from lab test conditions [30].

However, due to some inevitable factors, some unwanted elements like water and dissolved gas can contaminate the oil. As a result, insulation strength gets reduced, that may result in partial discharge of transformer oil [31]. The electrical and heat transfer properties of the transformer oil is severely affected by oxidation. Due to the presence of oxidative components the transformer oil gets heated up and its temperature increases [30]. Moisture in the form of water is found in free states. When moisture in oils exceeds its saturation value then there will be free water precipitation from oil in suspensions or drops. Moisture in oil is measured in parts per million (ppm) using the weight of moisture divided by the weight of oil (µg/g) [32]. Moisture content of a power transformer insulation system is a key parameter for the estimation of its aging condition and operation reliability. Therefore detection of the moisture content is a very essential task within power transformer diagnostics [28].

There are two commonly used off-line methods to measure moisture in transformer oil- the Karl Fischer reaction method and the pressure gauge method [32]. However, other methods are also utilized for the detection and estimation of moisture contents in transformer oil. Hribernik, W., *et al.*[28] proposed a Model-based online detection method which calculates the profiles of water concentration in the cellulosic part of the insulation system, as well as the concentration of water in transformer oil from operational parameters. An advanced model for the moisture diffusion in paper estimates the temperature dependent moisture distributions in the paper for non-uniform temperature distributions along the transformer winding.

Veloso, G.F.C., *et al.* [29] used partial discharge method using acoustic signals which can detect moisture contamination in the insulating oil using acoustic signals of partial discharge. In this work, a piezoelectric sensor is mounted in a reservoir with insulating oils with different levels of moisture.

Chang-Ping, Z., *et al.* [31] used a moisture detection method in transformer oil based on the ultrasonic transit time difference. Wei-Gen, C., et al.[33] used Neural Network method to find the moisture content in transformer oil and made a comparison with methods like chromatography, radiofrequency method, infrared spectroscopy etc. Oommen [34] used thin film capacitive humidity sensor for measuring moisture content in transformer oil. Adris and Kenny, R. B.,[35] used commercially available relative humidity sensors like the Harley moisture sensor, Wood, R., *et al.* [36] used optical Spectroscopy for finding the moisture content n oil.

The dielectric parameter $\varepsilon_{r,}$ (relative permittivity) of a transformer oil indicates the quality of the oil with regard to its insulation property. Again, the square of refractive index is represented as the relative permittivity of a dielectric material. Therefore, the moisture content in transformer oil sample can be related to the change in refractive index of the sample. As temperature affects refractive index, the effect of temperature on the dielectric property of transformer oil (i.e. on its refractive index) should also be taken into consideration. Therefore, it is necessary to relate the change in refractive index of transformer oil with its temperature [37].

This chapter describes a microcontroller-based system using optical fibre and a temperature IC sensor, to measure the moisture content in transformer oil. A bare and bent multimode optical fibre is used as a refractometer to measure the RI of a transformer oil sample. The optical-fibre sensor is prepared by first removing a length of 5 cm of jacket and cladding of a plastic multimode fibre and then the bare portion of the fibre is made into a bend of fixed radius of curvature. The bare and bent portion of the multimode optical fibre is termed as ‘Optical sensor probe’ (OSP). A laser diode is used to launch a laser beam at one end of the fibre. When the laser beam passes through the bare and bent portion of the optical fibre, intensity modulation of the laser beam takes place, depending upon the RI of a transformer oil sample around it that represents the moisture content of the sample.

The laser beam at the other end (output end) of the sensor fibre is detected by a LDR-based potential divider circuit. An ATmega 32 microcontroller based system has been used to sample analog signals from LDR-based potential divider circuit and from the temperature sensor IC LM35. Since the refractive index of transformer oil depends on the temperature, it is imperative that both refractive index and temperature are to be taken into account to determine the moisture content in a transformer oil sample. For this purpose, a trained artificial neural network is used to process and calibrate the input data. The parameters, such as- weightage matrix elements and threshold of the trained ANN are stored in the microcontroller flash memory to determine moisture content of a transformer oil sample using the inputs from the potential divider and temperature sensor IC.

3.3 THEORY OF MACROBENDING

When an Optical fibre is put into a sharp bend then the fibre suffers radiation loss especially towards long wavelengths [38]. The bend curvature creates an angle that is too sharp for the light to be reflected back into the core, and some of it escape into the fibre cladding causing optical loss. This optical power loss increases rapidly as the radius is decreased by an inch or less [39].

Multimode fibres carry a large number (several hundred) of transverse modes, some tightly held, some loosely held, and some are in cladding modes. These different modes have different propagation constants [40].

If a multimode fibre is put into a sharp bend with a radius of curvature less than the critical radius then the optical power loss occurs very rapidly allowing the construction of a relatively sensitive macrobend optical fibre sensor. Macrobend is generally observed when an optical fibre is bent to a radius of several centimetres. The expression for the critical bending radius below which the bent fibre gives substantial radiation loss [41] is given by-

$$r_c = \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_{cl}^2)^{\frac{3}{2}}} \tag{3.1}$$

where n_1 and n_{cl} represent the core and cladding RI of the fibre and λ represent the operating wavelength.

As discussed in Chapter 2 Section 2.3, the attenuation coefficient for a Macrobend multimode fibre (without any special case of flat or graded profile) is approximately given by Gloge [26]-

$$\alpha_B = \frac{2\gamma^2(0)}{n_1 k_0} exp\left[-\frac{2}{3} n_1 k_0 R^{'} \left(\frac{\beta^2 - k_0^2 n_{cl}^2}{n_1^2 k_0^2} - \frac{2a_0}{R^{'}}\right)^{3/2}\right] \tag{3.2}$$

where, $R^{'}$ represents the radius of curvature, a is the core radius, β is the propagation constant and $k_0 = \omega/c$.

The propagation constant β is expressed in normalized form as

$$b = \frac{\left(\frac{\beta^2}{k_0^2} - n_{cl}^2\right)}{n_1^2 - n_{cl}^2} \tag{3.3}$$

where $0 \leq b \leq 1$ for a guided mode

$$\beta^2 - k_0^2 n_{cl}^2 \ = b k_0^2 (n_1^2 - n_{cl}^2)$$

Substituting the expression for $\beta^2 - k_0^2 n_{cl}^2$ in equation (3.2)

$$\alpha_B = \frac{2bk_0(n_1^2 - n_{cl}^2)}{n_1} \exp\left[-\frac{2}{3} n_1 k_0 R' \left(\frac{bk_0^2(n_1^2 - n_{cl}^2)}{n_1^2 k_0^2} - \ \frac{2a_0}{R'}\right)^{3/2}\right] \tag{3.4}$$

If all the parameters in equation (3.4) are made constant except n_{cl} (where n_{cl} is the RI of the cladding), then the attenuation will depend on the cladding material or the surface which will act as a cladding for the fibre.

The loss of optical power (bending, scattering loss, radiation loss etc) in an optical fibre is expressed in terms of attenuation coefficient [42] as

$$\alpha_L = \frac{10}{L} \log_{10} \frac{P(L)}{P(0)} \tag{3.5}$$

where $P(L)$ and $P(0)$ denote the output and input power and L denote the length of the fibre. The attenuation loss for a short section of the fibre does not scale linearly with length [42]. Rearranging equation (3.5),

$$P(L) = P(0)e^{-0.2304\alpha_L L} \tag{3.6}$$

For a multimode fibre with macrobending, the attenuation coefficient in equation (3.6) can be expressed as $\alpha_L = \alpha_B$

$$\therefore P(L) = P(0)e^{-0.2304\alpha_B L} \tag{3.7}$$

Now, expanding the exponential term and neglecting the higher-order terms, equation (3.7) becomes

$$P(L) = P(0)[1 - 0.2304\alpha_B L] \tag{3.8}$$

If, the cladding of the bent portion of the optical fibre is removed and a liquid with refractive index n_l is applied around the bare and bent portion of the optical fibre, equation (3.4) and equation (3.8) is modified as,

$$P(L) = P(0)\left[1 - \frac{0.4608bk_0(n_1^2 - n_l^2)L}{n_1} \times exp\left\{-\frac{2}{3}n_1k_0R'\left(\frac{b(n_1^2 - n_l^2)}{n_1^2} - \frac{2a_0}{R'}\right)^{3/2}\right\}\right] \tag{3.9}$$

Once the bare, bent, optical fibre sensor is prepared with fixed radius of curvature, n_1, R', k_0, b, a_0 and L become constants in equation (3.9). Again, after fixing the LDR and Diode Laser Source across the optical fibre with proper focusing $P(0)$, the input power of the laser ray at the input end of the optical fibre also remains constant. Therefore, power associated with the laser beam at the LDR end will depend on the term$(n_1^2 - n_l^2)$. Equation (3.9) shows that the power associated with the laser beam at the LDR end decreases, if the RI (n_l) of a liquid increases due to change in moisture content in it. Thus, the power associated with the laser beam at the LDR end can be represented as function of RI of a liquid, which is applied around the bare, bent, optical fibre.

$$P(L) \ = f(n_1^2 - \ n_l^2) \tag{3.10}$$

The electrical power loss in the LDR of the potential divider circuit as shown in Figure 3.5 can be expressed as:

$$P_L \ = \frac{(V_{cc} - \ V_x)^2}{R_L} \tag{3.11}$$

where, R_L is the resistance of the LDR and it changes with change in the power associated with the laser beam at the LDR end. V_x is the analog output signal of the potential divider circuit, which provides the measure of change in R_L due to change in RI of the liquid. Thus, electrical power loss in the LDR of the potential divider circuit can be related as the function of equation (3.9), as given below.

$$P(L) \ = f(n_1^2 - n_l^2) \ = \ f\left(\frac{(V_{cc} \ - \ V_x)^2}{R_L}\right) \tag{3.12}$$

Since, V_{cc} and n_1 are constants, the output of the potential divider circuit V_x, would provide the measure of RI of a liquid.

3.4 ARTIFICIAL NEURAL NETWORKS (ANN)

Artificial Neural Networks are neuron-like processing elements which try to mimic simple nervous systems. ANNs have different types of connections. Feed forward neural networks are the most popular model, used in many applications. The fundamental unit or building block of a neural network is the neuron [43]. The general neuron has a set of n numbers of inputs x_i, which represents the source of input signals. Each input x_i is weighted before reaching the main body of the processing element by the connection strength or the weight factor W_{ji}. The input signal is excitatory or inhibitory. In the former case they increase the activation of the neuron whilst in the latter they reduce it. The inputs of a particular type are combined together to give the total input to the j_{th} neuron. A schematic illustration of a processing node (PN) is shown in Figure-3.1.

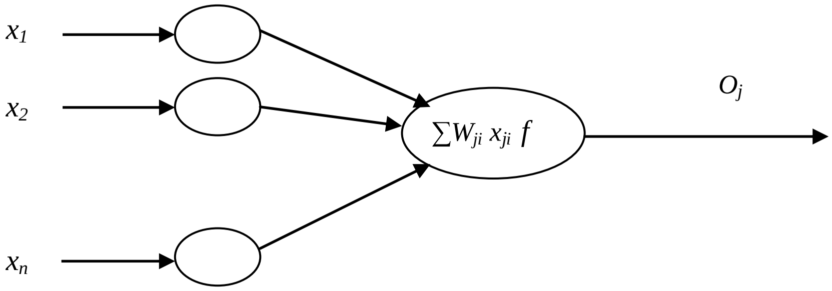

Fig. 3.1: An illustration of a processing node

where, O_j is the output from the processing node and the node activation is determined by an output function, which is considered as

$$f(x) = \frac{1}{1+e^{-x}} \tag{3.13}$$

Among the various ANN architectures available in the literatures, the Multi-layer-Feed-Forward (MLFF) network with error back propagation learning algorithm has been selected for this problem mainly because, (i) it is the most simple and comprehensive neural approach for model base and (ii) it has good generalization capability.

3.5 MULTI LAYER FEED FORWARD (MLFF) NETWORK

In MLFF network the PNs are arranged in layers and only PNs in adjoint layers are connected [43]. It has a minimum of three layers: (i) the input layer (ii) the middle or hidden layer(s) and (iii) the output layer. The information propagation is only in the forward direction and there are no feedback loops. A MLFF network topology is shown in Figure-3.2.

The MLFF network uses separate stages for learning and operation. The learning problem is stated as follows: For a given set of input-output pair(cycle/pattern) (x_1, O_1) ....(x_n,O_n), the connected weightage matrix element W_{ji} for each connected ANN is determined in such a way that the network maps x_i to O_i for i = 1....n, as closely as possible. The error back propagation generalized delta-rule technique is used to train the MLFF network.

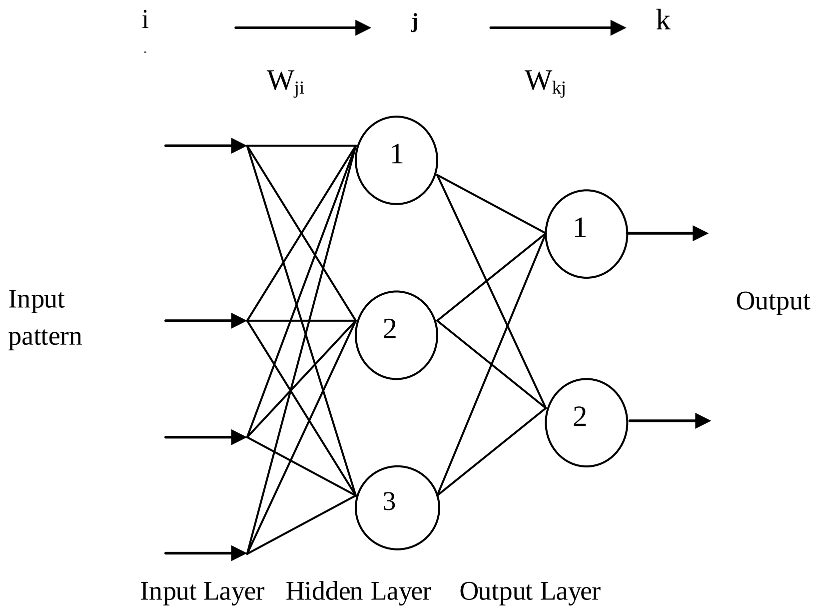

Fig. 3.2: Schematic illustration of Multilayered Feed Forward (MLFF) ANN

Back propagation technique, interconnection weightage matrix element W_{ji} are adjusted such that the error function

$$E = \sum_{p-1}^{P} \sum_{k-1}^{n} \left(d_k^P - O_k^P\right)^2 \tag{3.14}$$

is minimized.

where,

d_k^P =desired output from kth node in Pth training pattern,

O_k^P =actual output from kth node in Pth training pattern,

P = the number of training pattern to input layer,

n = number of nodes in the output layer.

The maximization process is based on gradient descent algorithm. The interconnecting weights between jth layer neurons and ith layer neurons is modified using the following relationship

$$W_{ji}^{new} = W_{ji}^{old} + \eta \delta_j O_i + \alpha\left[\Delta W_{ji}^{old}\right] \tag{3.15}$$

If PN_j is an output layer PN, then

$$\delta^P_{ok=(d^P_k - o^P_k)}\frac{\partial f}{\partial x}$$

if, PN_j is a hidden layer PN, then

$$\delta^P_{hj} = \left(\sum_k \delta^P_{ok} W^P_{kj}\right)\frac{\partial f}{\partial x_i}$$

where k is overall PNs in the layer above the jth layer PN and η and α are the learning rate and momentum factor. The momentum factor and learning rate help in faster convergence of the algorithm. Once network gets trained, the resulting connection weights W_{ji} are stored. In the operation stage the trained network is used to compute outputs from a set of inputs.

3.6 DESCRIPTION OF THE FIBRE-OPTIC REFRACTOMETER

The optical-fibre sensor used for monitoring the refractive index of transformer oil is a plastic clad silica core multimode fibre. The fibre has a dimension of 200/230 with diameter 500µm, the RI of the core of the fibre (n_1) is 1.48 and cladding n_2 is 1.46. The length of the fibre is 60cm from which a length of 5 cm has been unclad by mechanical stripping around the centre. The bare portion of the fibre is then made into a bend of fixed radius of curvature which constitutes the Optical sensor probe (OSP). The geometry of the fibre is shown in Figure-3.3.

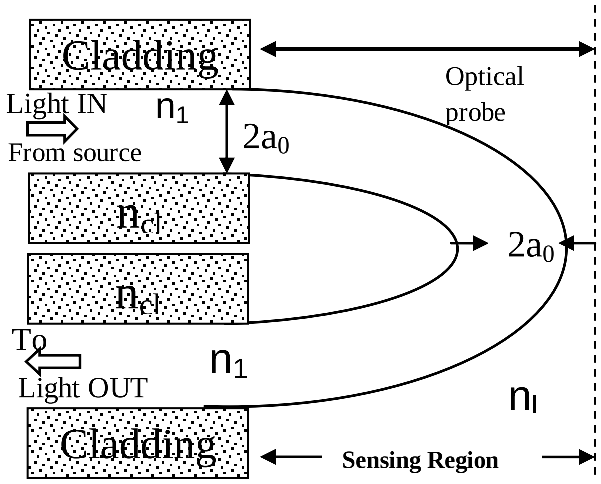

Fig.3.3: Geometry of the bare and bent refractrometer

3.7 EXPERIMENTAL SETUP FOR THE INSTRUMENTATION SYSTEM.

Figure 3.4 shows the configuration of the experimental setup used for the measurement of moisture content of a transformer oil sample. The setup consists of an optical sensor, light source, detector, temperature sensor and a microcontroller system. A Diode Laser Source (Make: Optochem international, power 5mW, wavelength 632nm) is used for launching Laser beam into the input-end of a multimode optical fibre by immersing the bare, bent portion of the fibre into a transformer oil sample. When the laser beam passes through the bare and bent portion of the optical fibre, intensity modulation of the laser beam takes place, depending upon the RI of the transformer oil sample having moisture content around it. The laser beam at the other (output) end of the sensor fibre is detected by a LDR-based potential divider circuit. The output from the potential divider circuit via a Low-Pass-Filter (LPF) is interfaced to an ATmega 32 microcontroller ADC (pin number 40, *ADC0*, analog channel-0) [44]. A LM35 temperature sensor is used to read the temperature of the oil sample at the same time. The LM35 is a three terminal precision centigrade temperature sensor which is used to measure the temperature of the heated transformer oil samples. It is rated for full -55°C to +150°C temperature range and has a scale factor of 10mV/°C [45]. The output of the LM35 temperature sensor is fed to ADC (pin number 39, *ADC1*, analog channel-1) of microcontroller ATmega32 [44]. The display unit of the microcontroller system consists of 16×2 (i.e. two rows having 16 character LCD display) LCD display units. The LCD has been configured as a 5×7 dot matrix 4 bit mode character display. It is interfaced to PORT-B of microcontroller ATmega32 for display control.

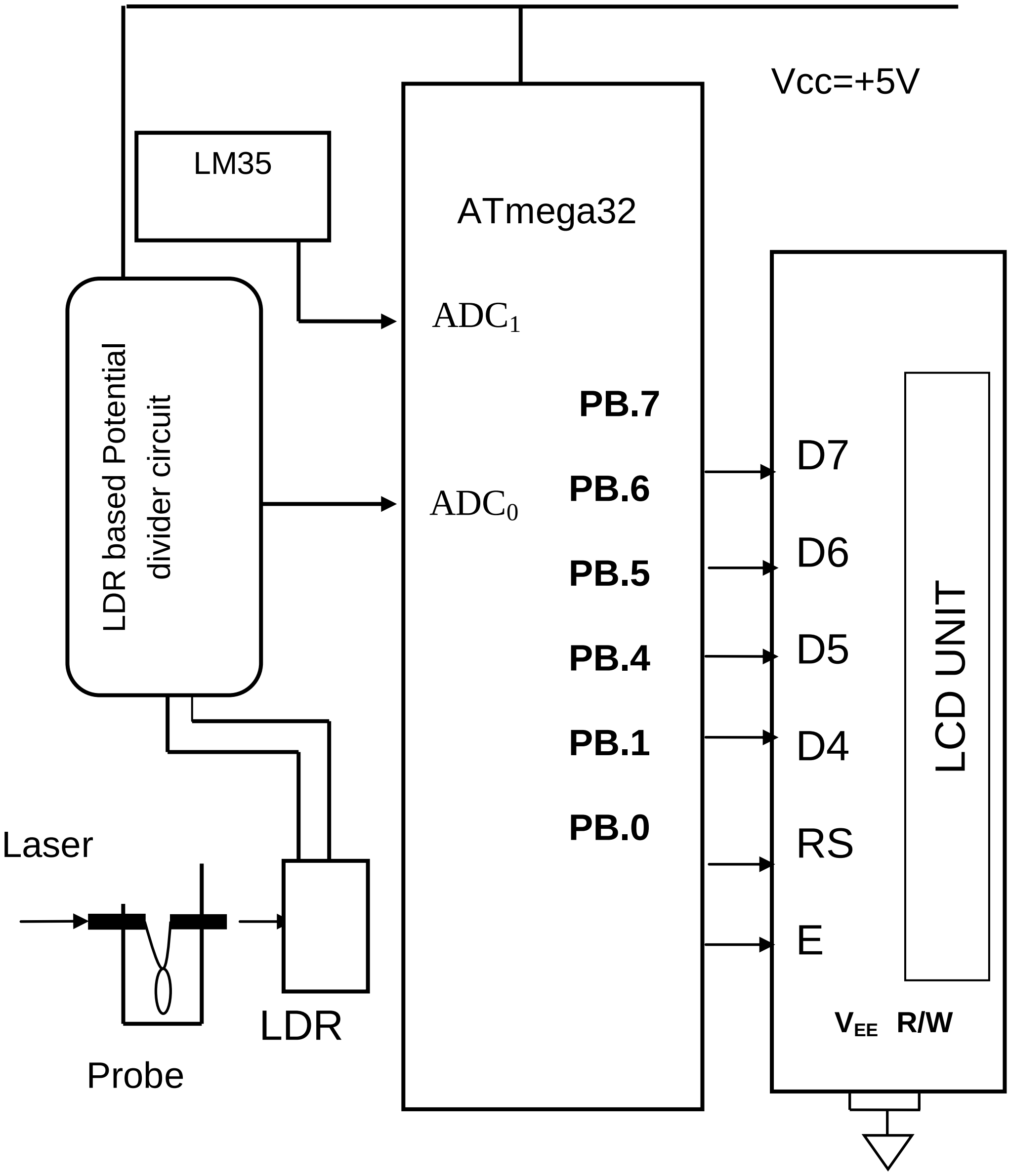

Fig. 3.4: Scheme adopted for the measurement of moisture content in Transformer oil

The potential-divider circuit (Figure 3.5) consists of a LDR in series with a fixed resistance (45kΩ). The output of the circuit is applied to a low-pass filter circuit having a cut- off frequency of 8 Hz to remove the high-frequency noises associated with the measurement circuitry.

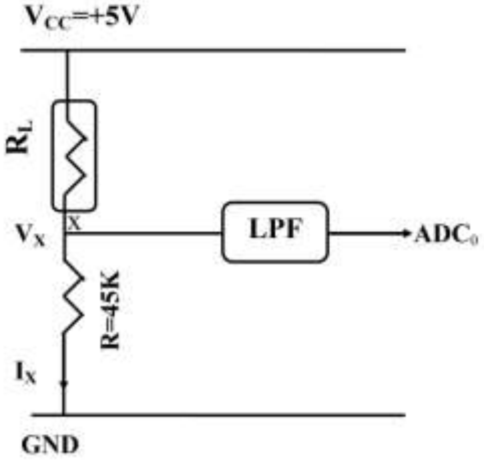

Fig. 3.5: The potential divider circuit

3.8 EXPERIMENTAL PROCEDURE

The experimental procedure adopted for the generation of data sample to train the ANN requires the following steps-

i. The bare and bent fibre is cleaned by dipping it in 100 per cent (v/v) ethanol and allowed it to dry.

ii. The bare and bent portion of the optical fibre is immersed in a transformer oil sample.

iii. The microcontroller-based system samples the values of $V_{test\ liquid}$ and the temperature.

iv. Steps i – iii are repeated with different transformer oil samples having different moisture content and temperature.

v. Using these measurements an ANN is trained. Software has been developed to implement the algorithm of the trained ANN in the microcontroller-based system. To determine the moisture content of a given oil sample the microcontroller-based system samples the RI and temperature of the sample through ADC0 and ADC1 and using algorithm of the trained ANN the moisture content of the sample is displayed in the LCD unit. The flowchart for the microcontroller program is shown in Figure 3.6.

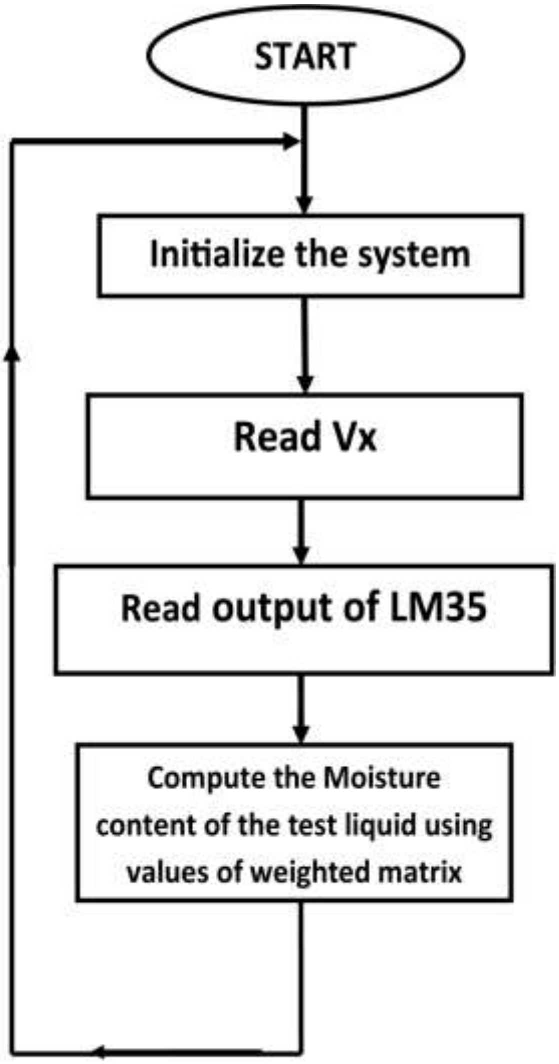

Fig. 3.6: Flowchart for the Microcontroller program

3.9 RESULTS AND DISCUSSION

To generate data cycles to train an ANN for the purpose of correlating the RI and temperature of oil samples to the moisture contents, standard transformer oil samples with known percentages of water content are prepared. These transformer oil samples are then subjected to temperature variation from 30-50 degree Celsius and the microcontroller-based system is used to measure of temperature and RI of the transformer oil samples. The experimental results with different percentages of moisture content and temperatures for different oil samples are presented in Table.3.1.

Temperature of sample		**Digital readings of Microcontroller system with different percentages of oil-water mixture**				
In degree Celsius	Digital value	0 per cent	0.2 per cent	0.8 per cent	2 per cent	3 per cent
50	102	204	312	356	425	438
45	092	141	283	270	368	347
40	081	125	180	194	235	261
35	071	82	128	137	165	188
30	061	60	88	95	104	115

Table 3.1: Measure of output voltage of LDR based potential divider circuit of transformer oil samples with different moisture content and temperature.

The plot for concentration of different transformer oil samples vs. the output voltage (measure of RI with variation of temperature) is shown in Figure 3.7.

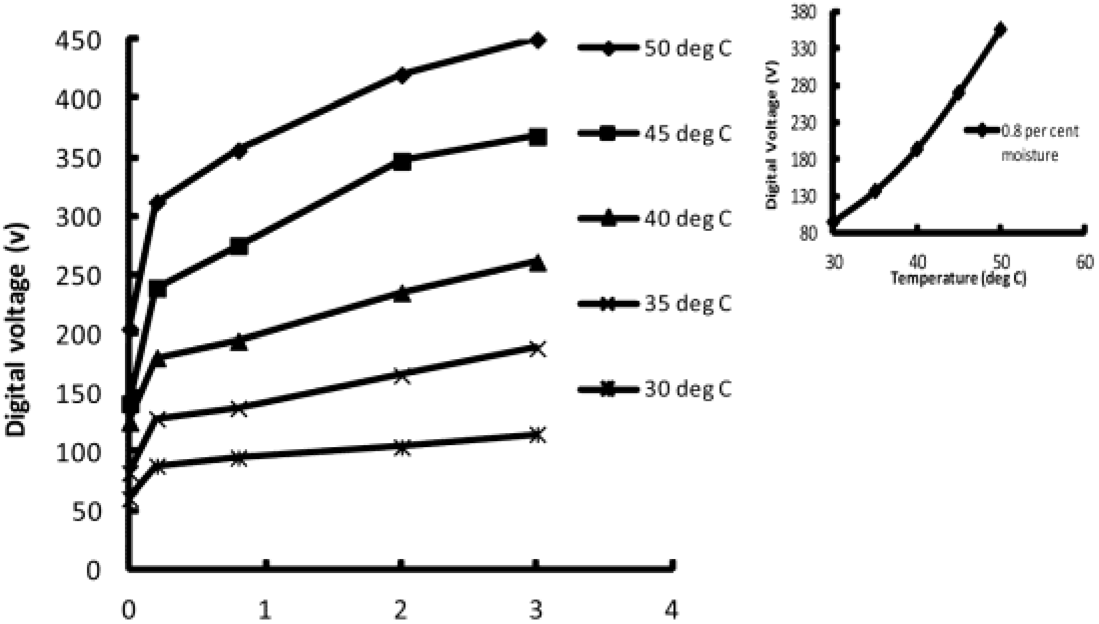

Fig. 3.7: Variation of output voltage with concentration of moisture in oil, Inset: Variation of output voltage with temperature at 0.8 per cent (v/v) moisture concentration

The graph obtained from the experimental observation showed increasing values of output voltages across the fixed resistance of the LDR circuit, for increasing moisture content and temperature. From the different curves, it can be inferred that

i. At moisture content in the range 0-0.2 per cent (v/v), the curves show a significant increase in the output voltage. This implies a low voltage drop across LDR due to low value of resistance in it. The low resistance of the LDR suggest that more light is incident on to the LDR. This could be possible if the RI of the liquid surrounding the bare portion of the fibre is less than the RI of core of the fibre. Thus the presence of moisture and increasing temperature decreases the RI of the oil sample.

ii. As the moisture concentration increases there is a steady rise in the output voltage implying that moisture content in oil decreases the RI of transformer oil less than the RI of the core.

iii. There is a steady increase in the output voltage for moisture concentration in the range 0.2 per cent-3.0 per cent (v/v) in the temperature range 30°C-50°C. This result suggests that the increasing temperature decreases the viscosity of the oil in which the optical fibre sensor has been immersed along with vaporising some quantity of moisture in the oil sample, thereby decreasing the RI of the oil sample further. The graph at the inset shows that at a constant moisture concentration (0.8 per cent) there is a rise in the output voltage. This result suggest that as the temperature increases, the refractive index of the sample decreases, thereby increasing the optical power to the LDR, which decreases its resistance. Thus the voltage drop across the fixed resistance increases.

During experimentation, it was observed that when the temperature was in the range of 40-50 degree Celsius, the moisture was released in the form of gas bubbles. At increasing oil-water concentration, an increase in the release of gas bubbles was observed at elevated temperature. Moreover it was also observed that the presence of water in transformer oil caused the oil to heat up more.

The ANN used for the purpose of correlating the RI and temperature of transformer oil samples to their moisture contents, contains two neurons in at the input layer, four neurons at the hidden layer and one neuron at the output layer as shown in Figure 3.8. The output of LM35 temperature IC and voltage of potential divider circuit represented in Table 3.1 are taken as the input to the ANN input layer. The output layer of the ANN with one neuron provides the moisture content of the transformer oil sample.

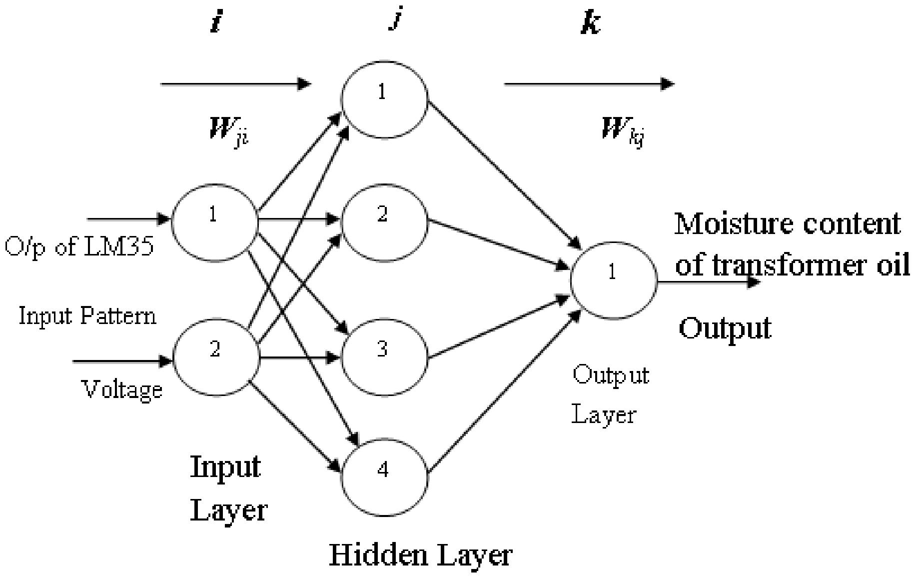

Fig. 3.8: Configuration MLFF ANN used to correlate the RI and temperature of a transformer oil sample to its moisture content.

The experimental results presented in the Table 1 provided 25 training cycles for temperature range 30 – 50 degree Celsius and moisture content range from 0.0 to 3.0 per cent. Back propagation technique is used to train the ANN using these 25 data cycles. The training of the ANN is terminated, when difference between calculated output from the ANN and desired output becomes less than 0.0001. The variation of error at the output neuron with respect to the iteration count is shown in Figure-3.9.

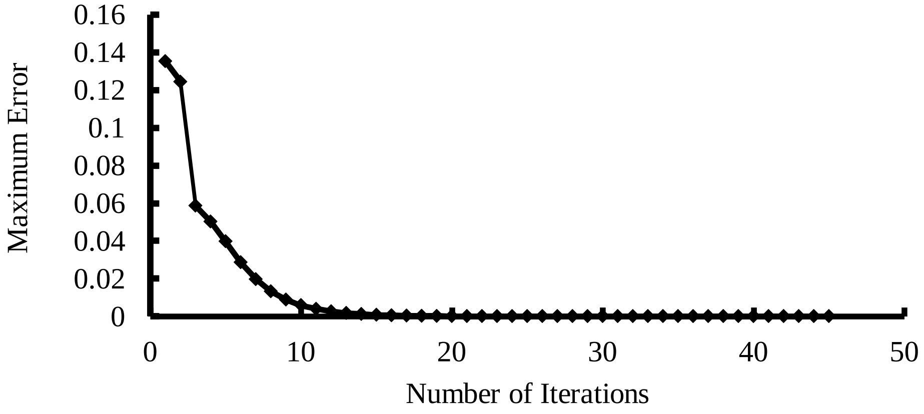

Fig. 3.9: Error curve for the MLFF network

Weightage matrix elements between input and hidden layers and, hidden layers and output layer for the trained ANN are as follows:

i. Between first neuron and the neuron of hidden layer

   W_{11} = -51.237881 W_{12}= 63.035744

   W_{13}= 0.2 W_{14}= 0.2

ii. Between second neuron and the neuron of hidden layer

   W_{21} = -51.237881 W_{22}= 63.035744

   W_{23}= 0.2 W_{24}= 0.2

iii. Between hidden layer neurons and output layer neurons

   W_{11} = 26.923553 W_{21}= 26.923553

   W_{31}= -27.902664 W_{41}= -27.902664

The ANN algorithm with these trained weightage matrix elements is implemented in the microcontroller-based system to determine the percentage moisture content of transformer oil by measuring its refractive index and temperature.

It has been observed that without the LPF, the reading of the LDR-based potential divider circuit keeps fluctuating by -25 to +25 decimal values around the base value. This is due to the noise of the electronic devices and the high-frequency noise of the power supply. The use of a passive LPF circuit (R-C circuit) with cut-off frequency of 8Hz brings down this fluctuation by -2 to +2 only.

3.10 CONCLUSIONS

This chapter describes an instrumentation system to measure moisture content in a transformer oil sample using the measure of refractive index and temperature of the sample. A bare and bent multimode optical sensor is used to measure the refractive index of the sample and LM35 is used as temperature sensor. The noise associated with the measurement (measurement of RI) has been filtered using a passive low pass filter circuit.

To generate data cycles to train an ANN for the purpose of correlating the measure of RI and temperature of transformer oil samples to the moisture contents of the samples, standard transformer oil samples with known percentages of water contents are prepared. These transformer oil samples are then subjected to temperature variation from 30-50 degree Celsius and the microcontroller based system is used to samples the measure of temperature and RI of the transformer oil samples. Software has been developed to implement the algorithm of the trained ANN in the microcontroller based system. Therefore, the microcontroller based system can determine the moisture content of a transformer oil sample at any temperature between temperature range 30 – 50 degree Celsius by sampling the RI and temperature of the sample through ADC0 and ADC1.