Capacitive Sensor System for Measuring Moisture Content in Transformer Oil

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Abstract: The efficiency and long-term reliability of electrical transformers are highly dependent on the quality of their insulating oil, which serves both as a dielectric medium and a cooling agent. One of the most critical factors affecting transformer oil performance is moisture contamination, which significantly reduces dielectric strength, accelerates aging processes, and increases the probability of insulation breakdown. The purpose of this study is to develop and analyze a reliable method for monitoring the water content in transformer oil. A capacitive sensor system was designed and applied to measure variations in dielectric permittivity caused by different levels of moisture concentration. Experimental measurements were carried out using transformer oil samples with controlled humidity levels, and the obtained results demonstrated a clear correlation between the sensor output and the actual water content. The proposed method provides a simple, accurate, and real-time monitoring approach, which can be effectively used for predictive maintenance and ensuring the safe operation of power transformers.

Keywords Transformer oil, dielectric strength, capacitive sensor, microcontroller, amplifier.

1. Introduction

Transformers are the key elements of the power supply system. Ensuring the stability of the electrical network is a crucial aspect of modern power systems, and transformers play a vital role in maintaining this stability. In essence, network stability refers to the ability of the power system to maintain consistent voltage and frequency values despite fluctuations in power consumption. Transformers contribute to the stability of the network by regulating voltage levels, distributing electrical loads, and providing protection against faults.

Despite their importance for network stability and reliability, transformer power supply systems face a number of challenges that need to be addressed. One of the main challenges is the aging of the infrastructure. Many of the transformers currently in use were installed decades ago and are approaching the end of their service life. As these aging transformers become less efficient and reliable, they pose a threat to network stability. The emergence of problems is often related to the condition and quality of transformer oil. If water particles enter the oil due to changes in weather conditions or external impacts on the transformer, numerous issues can arise (Fingas &Fieldhouse, 2012).

The impact of moisture content in transformer oil is significant, as contamination of the oil with moisture can lead to the following problems:
Loss of dielectric properties of the oil and an increased risk of potential short circuits;
Aging and degradation of insulation materials;
Reduction in the service life of the transformer;
Intensification of electrochemical corrosion in the active parts of the transformer.
The minimum dielectric strength voltage for transformer oil is presented in the following Table 1.

Table 1 The minimum dielectric strength voltage for transformer oil

Operating voltage of oil-filled equipment	Dielectric strength voltage of the oil [kV].
Up to 15 kV.	30
From 15 kV to 35 kV.	35
From 60 kV to 150 kV.	55
From 220 kV to 500 kV.	60

2. Materials And Methods

The dielectric strength of transformer oil (E_m) decreases exponentially with the increase in moisture content (S) in the oil. This relationship is expressed by the following empirical formula:

$$E_m = E_0 \cdot e^{-kS} \tag{1}$$

E_m- transformer oil dielectric strength (kV/mm),E_0– dielectric strength of new (pure) transformer oil (at 0 ppm), S – water content in oil (ppm),
k– empirical coefficient of variation
If the dielectric strength of pure oil is $E_0 = 50\,\text{kV/mm}$ and $k \approx 0.0012$ the change in dielectric strength with increasing water content is shown in Table 2.

Table 2 dielectric strength with increasing water content

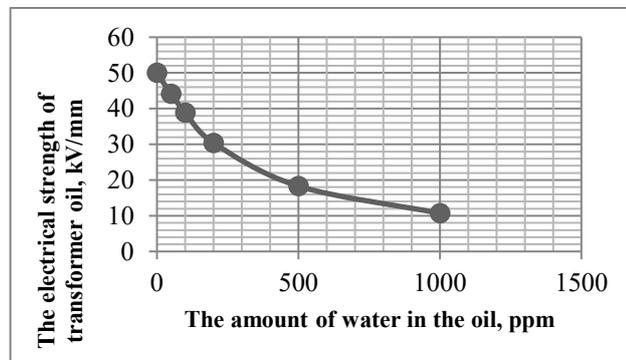| Moisture content (ppm)	Dielectric strength, E_m (kV/mm)
0 ppm	50
50 ppm	44.1
100 ppm	38.9
200 ppm	30.4
500 ppm	18.3
1000 ppm	10.7

Figure 1 Dependence of dielectric strength on the moisture content in transformer oil

From these calculations, it is evident that when the moisture content in transformer oil exceeds 500 ppm, the dielectric strength drops to below 20 kV/mm. This significantly increases the risk of losing

dielectric properties. Therefore, it is crucial to monitor the quality of transformer oil. Traditional methods, although providing accurate results, do not allow for real-time monitoring (Sun et al. 2010). Capacitive sensors, on the other hand, enable continuous and automated monitoring. The sensor consists of two main plates (electrodes) with transformer oil in between. As the concentration of water in the oil increases, the capacitance also increases. These changes are detected by highly sensitive electronic modules and converted into digital values.

The basic structure of the capacitive sensor consists of the following components:

- Measuring electrodes (sensor plates) – Detect changes in the dielectric field.
- Signal amplification module – Amplifies electrical signals.
- ADC (Analog-to-Digital Converter) – Converts analog signals into digital form.
- Microcontroller – Processes the signal and displays the results.
- Display – Shows or transmits the obtained results.

By integrating the system with a microprocessor or IT technologies, it is also possible to monitor the results remotely.

3.1 Capacitive Sensor

The electrodes are mounted on the outer side of a glass tube, allowing for the measurement of the capacitance of the transformer oil sample under test. The tube has a diameter of 15 mm and a length of 150 mm. Each electrode is 100 mm long, and the minimum spacing between the electrodes is 5 mm. When pure oil is used as the dielectric material, the initial capacitance of the sensor is 12.25 pF. We have thoroughly analyzed the sensors in our previous research and in this case, we are characterized by separate characteristics (Baratov et al. 2021; Safarov et al. 2021; Fingas & Fieldhouse 2012)
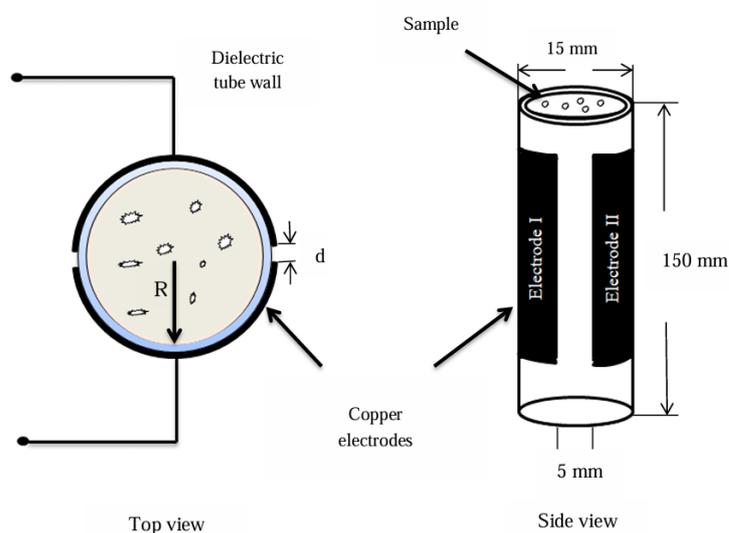

Figure 2 View of the semi-cylindrical capacitive sensor

The capacitance of the sensor primarily depends on the dielectric permittivity of the medium between the pair of electrodes. The actual capacitance (C_a) depends on the transformer oil sample and is in series with the capacitance of the glass tube wall (C_w). Therefore, the total capacitance (C_t) of the sensor can be expressed as:

$$C_t = \frac{C_m C_w}{C_m + C_w} \tag{2}$$

C_t − total capacity, C_m − Capacity of transformer oil, C_w − Capacity of the glass wall.

Determining the dielectric constant

$$\varepsilon_m = \frac{V_s \varepsilon_s + V_m \varepsilon_m}{V_t} \tag{3}$$

V_s, V_m − Volume of water and oil, ε_s, ε_m − Dielectric permittivity of water and oil.

From (2) and (3), the capacitance of the sensor, taking into account the distance between two semi-cylindrical electrodes of the same size, can be expressed as follows (Mustafoqulov et al. 2024):

$$C_a = \sum_{i=0}^{n} 2\varepsilon_0 \varepsilon_a A_e \cdot \left[\frac{1}{d+(i-1)\Delta d}\right] + \frac{\varepsilon_0 \varepsilon_a A_e}{2R} \tag{4}$$

Here: A_e − The surface area of the electrode, ε_0 − is the permittivity of free space, ε_a − is the dielectric permittivity of the sample medium inside the glass tube, d − is the distance between the electrodes, R −is the radius of the tube, Δd − is the step distance between the semi-cylindrical electrodes.

In general, the use of microcontrollers for measuring extremely low capacitances is considered the most effective and accurate method today (Baratov & Mustafoqulov 2023). In measurements of very low physical parameters, microcontrollers primarily rely on measuring the charging or discharging time of capacitors. With the help of microcontrollers or microprocessors, it is possible to capture and process electrical signals in very high-frequency circuits or within very short time intervals (ns).
Temperature of this silence is widely used in measuring the water consumption and level of water in various otherwise, vibrations. In addition, the methods of tanks are also analyzed deeply (Baratov et al. 2022; Baratov et 2021; Leifer & Patro 2002 ; Cudina 2003)
The developed sensor circuit also uses this same principle, with the external circuit consisting of a differentiator. Figure 3 below presents the developed sensor circuit.
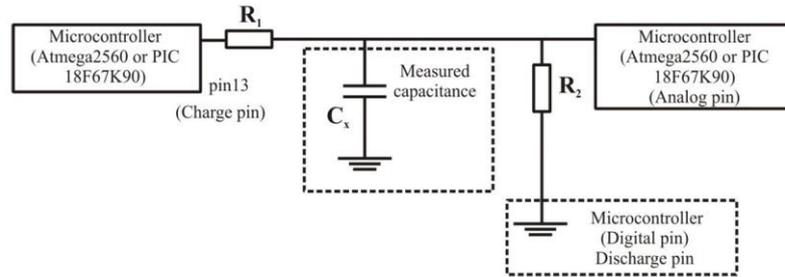

Figure 3 Low capacitance measurement differentiator circuit

In this circuit, the value of the resistor R1 can be about 10 kΩ or higher, and the resistor R_2 can be around 200-220 Ω. The current through the capacitor can be written as:
The current throught the capicator can be written as:

$$i(t) = \frac{dq}{dt} = \frac{d(C_X U_C)}{dt} = C_X \frac{dU_C}{dt} = C_X \frac{dU_{input}}{dt} \tag{5}$$

The output voltage of this circuit can be written as follows:

$$U_{out} = U_{R2} = R_2 \cdot i_{R2} \tag{6}$$

If we take into account the expression (4), then we get the following:

$$U_{out} = U_{R2} = R_2 \cdot i_{R2} = R_2 \cdot C_X \frac{dU_{input}}{dt} \tag{7}$$

So, the input and output signals of this circuit are as follows, they are presented in Figure 4 below.
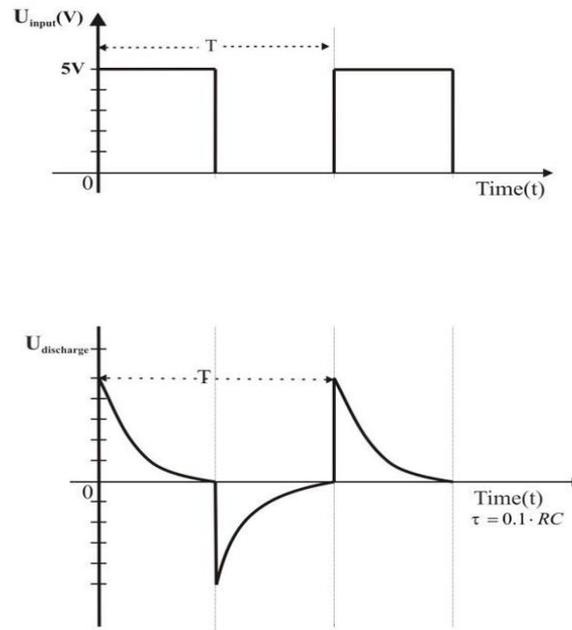

Figure 4 Input and output signals of sensor circuit

The sensor circuit is driven by rectangular pulse with a frequency of 16 MHz. The output signal of the circuit is directly proportional to the values of R_2 and C_X. It's known from the expression (7) or above presented curves. The output signal pulse width is 62.5 ns and it can be adjusted to different frequency according to the measured capacitance value. ATMEGA 328P-UP microcontroller and Arduino Uno platform were used in the experiment. Gauss's law is used to determine the capacitance of the semi-cylindrical capacitor.

$$\varepsilon_a \oint \overline{E} \cdot d\overline{S} = \frac{Q}{\varepsilon_a \cdot S} \tag{8}$$

where E - is electric field(V/m), a ε- absolute permittivity, S - area (m2), Q - electric charge, (C).

When water particles form in transformer oil, they alter the oil-water ratio. Taking the above into account, the capacitance of the sensitive element can be determined as follows:

$$C_a = 2\varepsilon_0 \varepsilon_a A_e \cdot \left[\frac{1}{d+(i-1)\Delta d} \right] + \frac{\varepsilon_0 \varepsilon_a A_e}{2R} \tag{9}$$

Due to their high sensitivity, capacitive sensors are also suitable for measuring the deflection of rotating parts of vibrating manipulators. However, due to their small measurement range, electromagnetic sensors are used for systems that move in a circular motion (Baratov & Mustafoqulov 2023.; Baratov et al. 2023). In addition, capacitive sensors are also widely used to control water levels through sluice gates (Baratov et al. 2019). The sensors are very sensitive and can even accurately measure air bubbles in drinking water and cavitations in various pumping stations (Wu & Gharib, 2002.; Wang et al. 2013).

3. Results and Discussion

The results measured using the capacitive sensor are presented in the following table (Table 3).

Table 3 The results measured using the capacitive sensor

Moisture content (%)	Theoretical Capacitance change (pF)	Measured capacitance (pF)	Error (%)
0.1%	0.095 pF	0.087 pF	8.42%
0.5%	0.472 pF	0.455 pF	3.60%
1%	0.945 pF	0.912 pF	3.49%
5%	4.72 pF	4.15 pF	12.08%
10%	9.45 pF	8.89 pF	5.92%
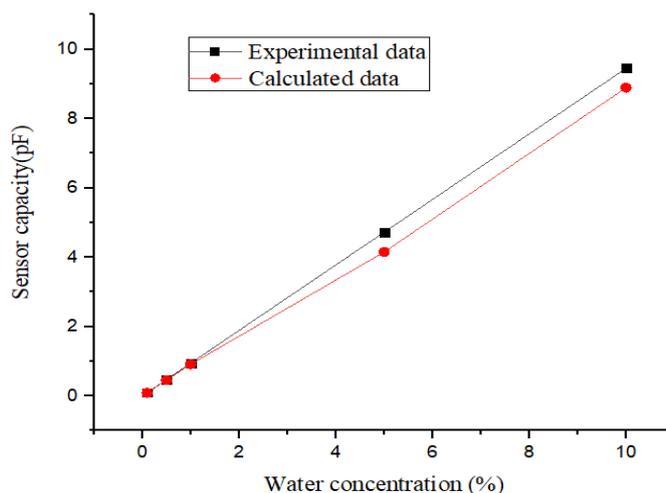
Figure 5 Graph of the dependence of sensor capacitance on the moisture concentration in oil

Both characteristics exhibit high linearity ($R^2 \geq 0.98$), which allows for an accurate estimation of the actual moisture concentration (in percentage) based on capacitance change.

4. Conclusions

Contamination of transformer oil with moisture leads to the degradation of the insulation system and shortens the service life of electrical equipment. Capacitive sensor systems enable real-time monitoring of moisture content, helping to enhance the safety of transformers. This system offers high sensitivity, automation, and rapid response capabilities, making it one of the effective solutions in the energy sector.

Declaration of Ethical Standards

As the authors of this study, we declare that he complies with all ethical standards.

Credit Authorship Contribution Statement

R.J. Baratov: Software, Validation, Formal analysis, Writing -Original Draft, Visualization.
Kh.A. Sattarov and M.Abdullayev: Methodology, Software, Validation, Visualization.
A.M.Mustafoqulov: Investigation, Resources, Writing, Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

Data Availability

No datasets were generated or analyzed during the current study.

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