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CAPACITOR SENSOR IMPEDANCE PARAMETER MEASUREMENT METHOD FOR THE DEGRADATION DEGREE EVALUATION OF HYDRAULIC OIL IN THE PROCESS OF THERMAL OXIDATION

Key words

Oil degradation, capacitive sensor, capacitor impedance, quality factor, dissipation factor, equivalent series resistance, microprocessor LCR meter.

Abstract

The paper describes a diagnostic method for the evaluation of the condition of hydraulic oil with the use of the dependence between oil degradation and changes in capacitor sensor impedance components. A series of new capacitive sensors has been developed, and impedance components measurements of hydraulic oil HL-46 laboratory oxidative degradation were conducted by means of microprocessor-based LCR meter. Preliminary laboratory measurement results have shown that equivalent series resistance ESR and quality factor Q of a capacitor series circuit model are most suitable for the evaluation of the condition of oil. The measurements indicated the best capacitive sensor sensitivity.

Introduction

In the aspect of electrical properties, hydraulic oils (general lubricating oils) are non-polar dielectric liquids – the best (perfect) electrical insulators. Oil quality as well as its condition are checked not only through the study of its physical and chemical properties, but also through the study of dielectric properties [1–6].

Material dielectric properties are described by means of electrical permittivity ε [7, 8] as follows:

$$\varepsilon = \frac{\mathbf{D}}{\mathbf{E}},$$

where **E** – electric field vector,
D – electric displacement field vector.

A dielectric placed between the two conductive plates (electrical conductors) with any shape creates a capacitor. When a voltage **U** is applied to capacitor plates, an electric field **E** develops across the dielectric. In response to the applied field, **E** dielectric molecules (dipoles) gain electric dipole moment, and it is called the electric polarization of the dielectric. The polarization phenomenon is described by polarization density vector **P,** which can be interpreted as the field induced in the material as the dipoles shift in response to an applied field **E**, while **D** is the field set up by free charges displaced by **E**.

The electrical displacement **D** is related to the polarization density **P** by

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}$$

where $\varepsilon_o = 10^{-9}/36\pi$ [F/m] – is the vacuum permittivity.

Then electrical permittivity ε

$$\varepsilon = \frac{\mathbf{D}}{\mathbf{E}} = \varepsilon_o + \frac{\mathbf{P}}{\mathbf{E}}$$

There are no free electrons in a perfect dielectric. The **E** electric field cannot cause their long-lasting flow; however, it can provoke temporary electrons reallocations, not leaving the atom border but causing its polarization, i.e. directional "tidying up" particles of substance. The alternating voltage applied to capacitor is changing the intensity and direction of the electric field **E** causing polarity changes in dielectric particles. Additionally, at the material which is not a perfect dielectric (perfect insulator), losses appear due to dielectric leakage. As a result, part of the electric energy in the capacitor is exchanged into heat [9, 10].

Two substitute circuit diagrams of a real capacitor are used for depicting these losses. The first one is an ideal capacitor C_s in series with an equivalent series resistance R_s (R_s = ESR) (Fig. 1a), and the second one is an ideal capacitor C_r in parallel with an equivalent parallel resistance R_r (Fig. 1b). The impedance Z of the real capacitor for the series circuit model is

$$Z = R_s - j\frac{1}{\omega C_s}$$

and for the parallel circuit model, it is

$$\frac{1}{Z} = \frac{1}{R_r} + j\omega C_r$$

where ω – is frequency in radians per second.

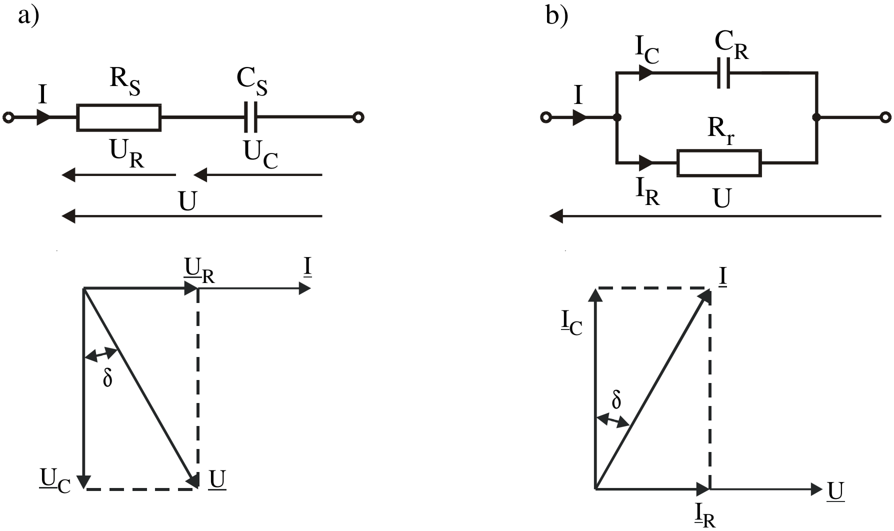


Fig. 1. Two circuit models and its phasor diagrams for real capacitor: a) serial circuit, b) parallel circuit

The parallel circuit model (Fig. 1b) physically more correctly corresponds to the real capacitor than circuit from Fig. 1a. However, because of the problems in the modelling of the resistance R_r on values above, a few hundred megaohms (the clean lubricating oil is an excellent dielectric – $R_r \to \infty$), the serial circuit from Fig. 1a is more often applied in practice. The reactance of a capacitor is

$$\mathrm{Xc} = \frac{1}{2\pi f C}$$

where f – frequency of AC current,
C – capacitor capacitance.

The capacitance of a parallel-plate capacitor is constructed of two parallel plates, both of area *S,* separated by a distance *d* and is approximately equal to the following:

$$\mathrm{C} = \varepsilon\varepsilon_0 \frac{S}{d}$$

Capacitor dielectric losses are expressed as dissipation factor D or the reciprocal of its quality factor Q.

$$\mathrm{Q} = \frac{1}{D}$$

The dissipation factor D is the ratio of the resistive power loss in the ESR to the reactive power oscillating in the capacitor and is expressed by means of the loss tangent tgδ.

For series circuit model

$$\mathrm{D} = tg\delta = \omega R_s C_s \,.$$

For parallel circuit model

$$\mathrm{D} = tg\delta = \frac{1}{\omega R_r C_r} \,.$$

Degradation degree evaluation of the hydraulic oils in the process of the thermal oxidation method uses changes of capacity and the electrical leakage of measuring capacitor made with the examined oil as a dielectric material. Oil conditions change influence its permittivity ε and consequently causes changes in the capacitor's loss tangent.

1. The measurement system

Measuring system shown in Fig. 2 is composed of the measuring capacitor (capacitive sensor) and the LCR microprocessor capacitance meter [11, 12].

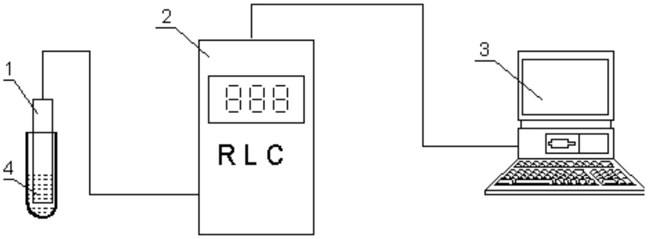
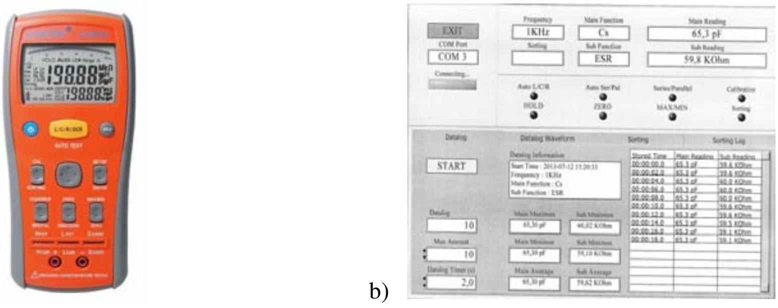


Fig. 2. The measurement set for oil condition evaluation: 1 – capacitive sensor, 2 – LCR meter, 3 – computer, 4 – tested oil

The LCR Meter (Fig. 3a) measures the impedance parameters: capacitance of the capacitor, equivalent resistance, and dissipation factor D (loss tangent tgδ) or quality factor Q for both the serial and the parallel circuit models. The meter can cooperate with a PC, and thanks to dedicated software measurement, the date can be logged to computer text files (Fig. 3b). Measurements can be performed at the selected measuring signal frequency: 100 Hz, 120 Hz, 1 kHz, 10 kHz, and 100 kHz. The capacity measurements accuracy in terms of 2000.0 pF is +/- (0.5% + 5) for measuring signal frequencies 100 Hz–10 kHz.



Frequency: 1KHz
Main Function: Cs
Main Reading: 65,3 pF
COM Port: COM 3
Sub Function: ESR
Sub Reading: 59,8 KOhm
Datalog: 10
Max Amount: 10
Datalog Timer (s): 2,0

a) b)

Fig. 3. LCR meter for measuring capacitor impedance parameters: a) view of the meter, b) the software window for date registration in computer's memory

Capacitive sensor was made in the form of a double-sided printed circuit board with dimensions of 25 mm x 120 mm with parallel traces (plates of the capacitor) on the surface of the rectangle with dimensions of 25 mm x 30 mm. It was assumed that, if a measuring capacitor will be characterized by its own high capacity, than changes in its impedance parameters, because of changes in dielectric properties, it is possible to measure it with the LCR meter.

Table 1 provides a summary of the two types of sensors: capacitive sensors made with gold plated traces and sensors whose traces are covered with a solder mask (a thin lacquer-like layer of polymer).

Table 1. Summary of capacitive sensor types

	S7/S7z	**S3/S3z**	**S4/S4z**	**S5/S5z**	**S1/S1z**	**S2/S2z**	**S8/S8z**	**S6/S6z**
d [mils]	8	8	8	9	10	10	10	12
w [mils]	10	12	22	26	10	20	30	18

For each of the two types, it was manufactured with 8 types of sensors varying the width “w” of the traces (area of the capacitor’s plates) and distance "d" between the traces (distance between capacitor’s plates. Sensors were marked S1z-S8z symbols for gold plated traces (Fig. 4a) and S1 – S8 for traces covered with solder mask (Fig. 4b).

Sensors covered with solder mask will be resistant to short circuits that can occur between the capacitor (traces) during measurements of oils containing metallic contaminants.

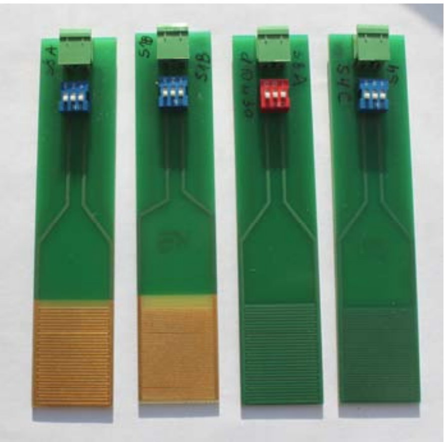

a) b)

Fig. 4. Capacitance sensors: a) S8z and S1z – gold plated traces, b) S8 and S4 – traces covered with solder mask

2. Initial investigations

The research subjects were capacitive sensors (measuring capacitors) specified in Table 1. Conducted preliminary studies aimed to achieve the following:

- Check the impact of hydraulic oil condition changes on capacitance sensor impedance parameters changes in both the parallel and serial capacitor circuit model;
- Check the impact of the measuring signal frequency on the ability to distinguish between changes in oil conditions; and,
- To obtain which of the capacitive sensor design, in the aspect of the width of the traces and the distance between them, has the best sensitivity.

Hydraulic oil HL-46 was used for testing. The fresh oil condition was changed during a 14-week laboratory thermo oxidative process under controlled conditions, with a temperature of 120 °C and an airflow of 15 dcm^3/h.

The oil thermal oxidation results in a change in its physical and chemical properties. In 2, with intervals established as a week's time, a sample of oil was being taken. For every sample, the measurement of the impedance parameters of the capacity sensor that was plunged into the examined oil was made.

In order to get clear changes of impedance parameters, absolute measurements were related to appropriate values of the impedance parameters of capacity sensor plunged in fresh oil. For the serial circuit model, relative serial resistance $r_s = R_s/R_{so}$ and relative quality factor $q_s = Q_s/Q_{so}$ for the capacity sensor covered with solder mask and $r_{zs} = R_{zs}/R_{zso}$ and $q_{zs}= Q_{sz}/Q_{zso}$ for the sensor with gold plated traces were determined. By analogy, for the parallel circuit model of both capacitance sensors types, relative parallel resistances $r_r= R_r/R_{ro}$ and $r_{zr} = R_{zr}/R_{zro}$ and the relative quality factors $q_r = Q_r/Q_{ro}$ and $q_{zr} = Q_{zr}/Q_{zro}$ were determined.

The measurements were done at a temperature of 21 °C for the following measuring signal frequencies: 1 kHz, 10 kHz and 100 kHz. Capacitance change of the series circuit models of capacitive sensors S3 and S3z with elapsed oil thermal oxidation time is shown in Fig. 5.

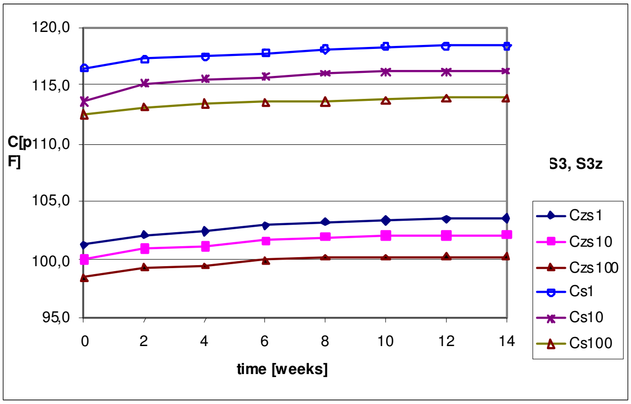


Fig. 5. The effect of laboratory thermal oxidation time of hydraulic oil HL-46 on the capacitance change in capacitor sensors S3 and S3z at measuring frequencies 1 kHz, 10 kHz, and 100 kHz

Analysis of the data in Fig. 5 indicates that a change in oil condition as a result of the 14 weekly thermo-oxidation causes about 2% change in the capacitance of capacitors. This result and the ± 0.5% accuracy capacitance measurement by means of a LCR meter do not guarantee sufficient sensitivity and resolution of measurement and its use to evaluate changes in the hydraulic oil.

Similar results were obtained for the others types of capacitive sensors.

The measurement results and the relative changes in the impedance parameters of capacitive sensors with solder mask (S1,.., S8) at a measuring signal frequency 1 kHz are shown in Fig. 6.

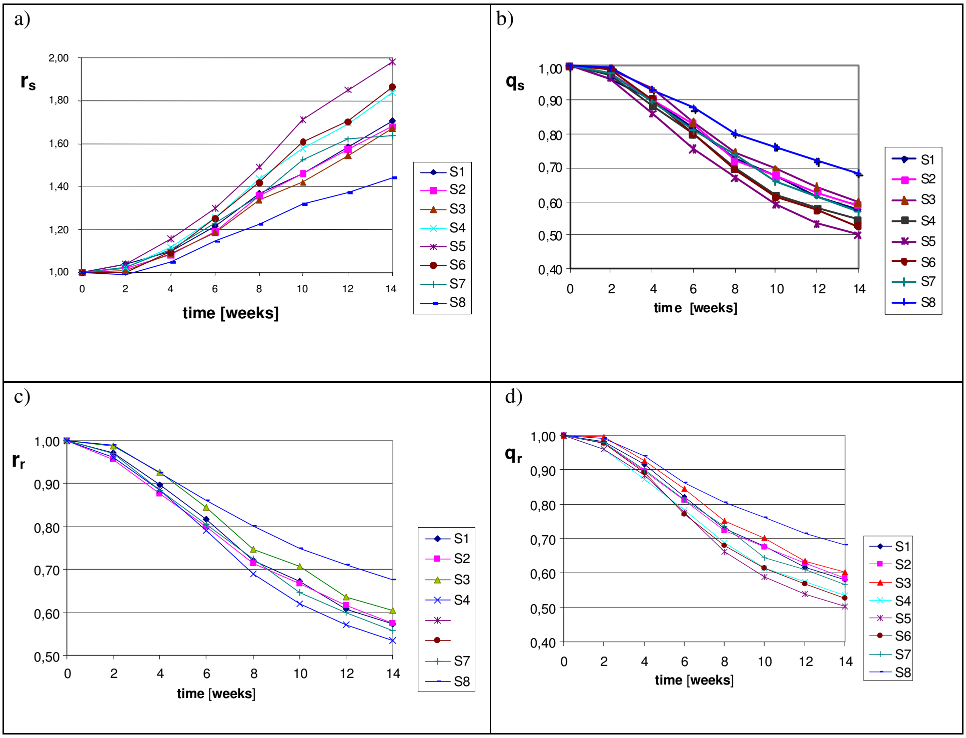


Fig. 6. The effect of laboratory thermal oxidation time (growth of aging products) of oil HL-46 on measuring relative changes in capacitors S1-S8 impedance parameters: a) and b) for series circuit model, c) and d) for parallel circuit model

The data analysis in Fig. 6 indicates that the continuous high growth of relative resistance r_s has occurred during oil thermal oxidation for each capacitive sensor type. For sensor S8, the r_s growth is the smallest, and its value is 1.4 after 14 weeks. For S1-S8 sensors, the value of r_s is within the limits of the 1.7 – 1.98. High R_s changes along with C_s changes cause a significant decrease in the relative quality factor q_s. After 14 weeks for sensor S8, the q_s value is the smallest and is almost 0.7, while for the other capacitors, it is within 0.5 – 0.6. Very similar results were obtained in the measurement of the relative quality factor q_r.

Figure 6c presents relative parallel resistances r_r changes for sensors S1-S4, S7, and S8. During the oil oxidative degradation process, the oil leakage current strongly increases, so the resistance R_r decreases up to the level of 55% R_{so} in the final stage of process. In the figure, there are no r_r changes for sensors S5 and S6, because, for fresh oil, the value of equivalent parallel resistance R_r was greater than the LCR meter upper resistance measuring range, which is 200 MΩ. Additionally, for the samples after 2 and 4 weeks of laboratory thermal oxidation, the value of R_s was greater than 200 MΩ.

Analogous measurements were carried out for the sensor with gold plated traces (S1z, ..., S8z), and the results of relative impedance parameter changes are shown in Fig. 7.

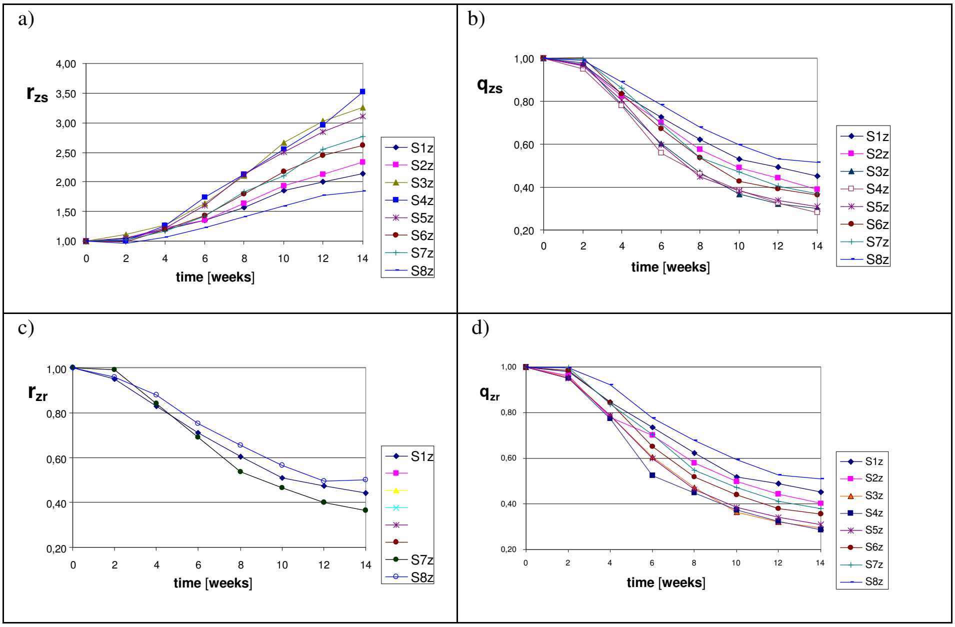


Fig. 7. The effect of laboratory thermal oxidation time (growth of aging products) of oil HL-46 on measuring the relative changes in the impedance parameters of capacitors S1z+S8z: a) and b) for the series circuit model, c) and d) for parallel circuit model

The oil property changes caused by the appearance of aging products as a result of oil oxidative degradation strongly influence the fall in value of relative quality factors q_{zr} and q_{zs} in each of the tested capacitive sensors. After 14 weeks of thermal oxidation, there are 70% declines in the value of quality factors Q in capacitors S1z-S7z for both serial and parallel capacitor circuit models. For capacitor S8z, the result is a bit worse and these declines are about 50%.

Additionally, the r_{zs} changes are characterized by a high (about 3x) increase for capacitive sensors S3z, S4z, S5z, S7z and a somewhat weaker (about 2x) increase for the other sensors.

In Fig. 7c, changes in relative parallel resistance r_{zr} for S1z sensors, S7z and S8z are shown. Decrease R_r resistance for these sensors after 14 weeks of thermal oxidation is about 40 – 50%. As in the case of sensors with the solder mask, capacitors S2z – S6z were characterized by a very high value of parallel resistances Rr > 200MΩ, higher than the upper measuring range of the LCR meter. This leads to a lack of measurement data and indicates the limited usefulness of this parameter for the evaluation of oil condition changes.

Conclusions

Based on initial investigations, it was found that impedance parameter changes in measuring capacitors immersed in hydraulic oil depend on oil degradation occurring during laboratory thermo oxidation. Analysis of the measuring data showed that equivalent series resistance R_s of the capacitor series circuit model and its quality factor Q_s, at a measuring signal frequency of 1 kHz, are parameters that show the largest changes under the influence of thermal degradation of oil. Based on measurements of changes in parameters R_s and Q_s, capacitive sensors that characterize the best sensitivity were chosen. These are capacitive sensors S4 and S5 coated with solder mask and sensors S3 and S4 with gold plated traces. The results of the preliminary laboratory tests introduce the testing of oils derived from the operation of the hydraulic installations. Positive results of these tests and the determination of limit values for parameters will allow for the implementation of the method and measuring system for continuous monitoring of the conditions of hydraulic oils in industrial installations.

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Metoda pomiaru parametrów impedancyjnych czujnika pojemnościowego do oszacowania stopnia degradacji oleju hydraulicznego w procesie termoutleniania

Słowa kluczowe

Stan oleju, czujnik pojemnościowy, impedancja kondensatora, współczynnik stratności, rezystancja strat kondensatora, mikroprocesorowy miernik pojemności.

Streszczenie

W artykule przedstawiono metodę badawczą umożliwiającą ocenę zmian stanu oleju hydraulicznego w procesie termoutleniania poprzez pomiar za pomocą mikroprocesorowego miernika LCR, zmian parametrów impedancyjnych zastępczego układu szeregowego lub równoległego czujnika pojemnościowego (określanego również jako kondensator pomiarowy) zanurzonego w oleju. Opi-

sano konstrukcję czujnika oraz zaprezentowano wybrane wyniki wstępnych pomiarów parametrów impedancyjnych dla różnych typów i rodzajów czujników dla próbek oleju hydraulicznego HL-46 poddanych laboratoryjnemu termoutlenianiu. Wyniki pomiarów pozwoliły wytypować zarówno parametry impedancyjne, jak i wykonanie czujnika w aspekcie najlepszej detekcji zmian stanu oleju.