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Predicting the Ageing Time of Thin Film Sacrificial Copper Strip Sensors Over a Wide Range of DBDS Concentrations

Nur Izyan Husnina Zulkefli[1], Mohd Shahril Ahmad Khiar[1,*], Sharin Ab Ghani[1], Imran Sutan Chairul[1], Nor Hidayah Rahim[1], Asimi Ana Ahmad[2]

[1] High Voltage Engineering Research Laboratory, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Melaka, Malaysia
[2] Chemical Engineering Technology, Malaysian Institute of Chemical and Bioengineering Technology, Melaka, Malaysia

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ABSTRACT

Catastrophic transformer failures are often attributed to corrosive sulphur-related faults. However, the existing challenge lies in the absence of practical, real-time monitoring techniques for sulphur corrosion, especially on-site. Previous studies have proposed the use of thin film sacrificial copper strip sensors as a promising solution to address this issue. Yet, their effectiveness in detecting corrosive by-products resulting from varying concentrations of DBDS breakdown remains unexplored. To bridge this knowledge gap, this study introduces an alternative technique that utilizes MATLAB software for linear interpolation and extrapolation. The findings demonstrate the capability of this technique to predict the ageing time of thin film sacrificial copper strip sensors when exposed to corrosive by-products derived from DBDS breakdown across a broad concentration range. This research aims to provide a valuable contribution towards enabling effective monitoring of sulphur corrosion and enhancing transformer maintenance practices.

1. Introduction

Insulation systems play an important role in determining the lifespan of power transformers. In oil-filled power transformers, insulating oils and paper perform a dual function as an electrical insulator and as a coolant to dissipate heat from transformer windings. It is essential to track the deterioration of the insulation system in order to prevent unexpected transformer failures, which can be very costly. Various condition monitoring tools have been developed to detect the causes of transformer failures. Since the beginning of the 21st century, various techniques have been proposed to monitor copper sulphide-related failures in oil-filled power transformers [1-6]. According to Yang *et al.,* [7], this type of failure is caused by the high operating temperature of transformers and the presence of corrosive sulphur compounds (i.e., corrosive by-products resulting from the breakdown of dibenzyl disulphide (DBDS)). However, it takes time for corrosive sulphur to form and show

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[*] *Corresponding author.*
E-mail address: mohd.shahril@utem.edu.my (Mohd Shahril Ahmad Khiar)

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appreciable changes in the insulation system, and this contributes to the increasing number of transformer failures worldwide.

Sulphur corrosion results in the dissolution of semi-conductive copper sulphide in insulating oils [3]. Sulphur corrosion continues with the deposition of copper sulphide on the insulating paper and this compound can penetrate through the insulating paper (Figure 1). This leads to internal discharges and creates a low resistance path through the insulating paper, culminating in catastrophic power transformer failures [8]. In general, there are two approaches used to monitor the progression of sulphur corrosion in transformer insulating oils. Qualitative analysis is commonly used by the industry. The corrosivity level of insulating oils is determined by comparing the discolouration of the copper surface with the ASTM copper strip corrosion standard (Figure 2). In addition, a fresh metal strip is aged according to the procedure detailed in Table 1.

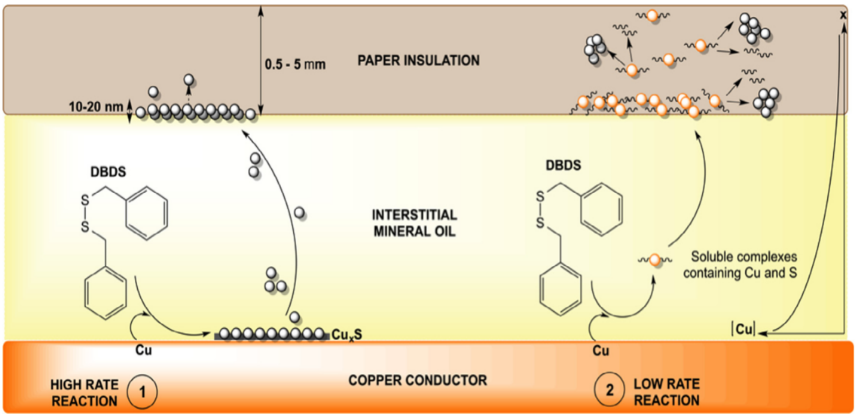

Fig. 1. Formation of copper sulphide on insulating paper proposed by Facciotti [9]

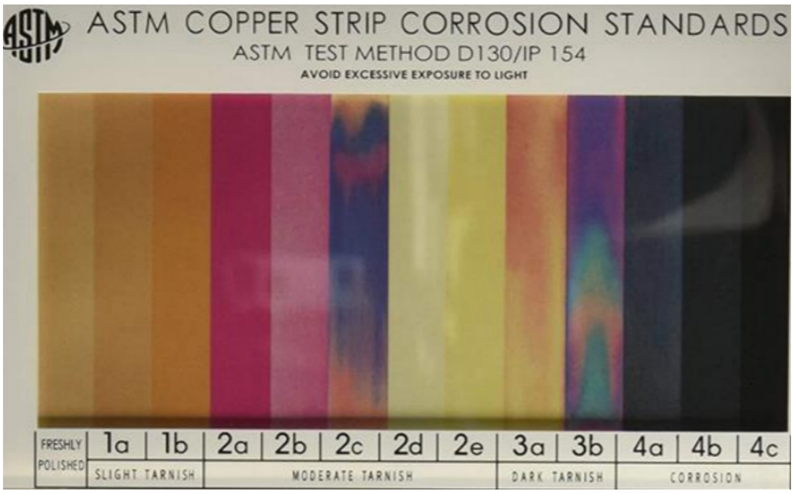

Fig. 2. ASTM copper strip corrosion standard [10]

Table 1
Standard oil corrosivity test [11]

Method	Material	Description (Oil/Metal/Paper)	Temperature (°C)	Ageing Time (h)	Remarks
DIN 51353	Silver	100 mL/1600 mm^2/-	100	18	Silver plate corrosion
ASTM D1275A	Copper	250 mL/300 mm^2/-	140	19	Copper corrosion
ASTM D1275B	Copper	250 mL/300 mm^2/-	150	48	Copper corrosion
BS EN 62535	Copper	15 mL/540 mm^2/ 540 mm^2	150	72	Corrosion of paper-wrapped conductors

The procedure outlined in the ASTM D1275B standard is more sensitive in detecting the corrosivity of the insulating oil. Compared with the ASTM D1275A standard, the procedure stipulated in the ASTM D1275B standard is more time-consuming owing to higher ageing time. However, both of these standard test methods are not really accurate to determine the deposition of copper sulphide on the insulating paper. For this reason, the BS EN 62535 standard test method was introduced by the International Council on Large Electric Systems (CIGRE), which involves immersing a copper strip (length: 30 mm) in 15 mL of insulating oil. The copper strip is immersed inside a vial filled with the insulating oil and the copper strip is then aged for 72 h at 150 °C. Two types of tests are performed: (1) bare copper strip and (2) paper-wrapped copper strip. The paper-wrapped copper strip test (also known as coated conductor deposition (CCD)) is carried out to assess the formation of copper sulphide deposits by the insulating oil. However, this technique is disadvantageous for the following reasons. First, the presence of oxygen can contribute to changes in the oxidation level. Second, the air above the oil in the enclosed vial will be pressurised with an increase in temperature, leading to undesirable chemical reactions.

Several quantitative approaches have been developed to quantify the amount of corrosive sulphur compounds present in transformer insulating oils. One of these is X-ray fluorescence (XRF) spectroscopy, which measures the amount of copper and sulphur in percent by weight (wt %) [6,12]. XRF spectroscopy involves directing a high-energy X-ray beam (primary radiation) onto a sample. The atoms in the sample become excited and begin emitting lower-energy radiation. This secondary radiation is known as fluorescent radiation. The elemental composition of the sample can be determined based on the principle that each atom emits radiation at a characteristic wavelength (energy), which varies depending on the atom's unique electron configuration [13]. However, this technique is relatively expensive, requires well-trained operators, and this technique cannot be conducted instantaneously. Furthermore, the aforementioned techniques only require a small sample volume compared to the overall transformer oil volume, and therefore, these techniques do not evaluate the corrosivity level of transformer insulating oils in bulk. The aforementioned techniques are all offline conditioning monitoring tools. Hence, it is imperative to develop a simple, reliable, and effective online conditioning monitoring tool, which will enable the operator to continuously monitor the progression of sulphur corrosion in transformer insulating oils in real time.

Interestingly, a new technique was proposed in 2019 to monitor the progression of sulphur corrosion in transformer oils using thin film technology [14,15]. This technique enables one to monitor the progression of sulphur corrosion in transformer insulating oils by correlating the change in resistance (ΔR) of thin film copper strip sensor with the concentration of corrosive sulphur compounds (i.e., DBDS and elemental sulphur). However, the range of DBDS concentrations used to evaluate the capability of the thin film copper strip sensors is very limited. In this research, a feasible technique is proposed to assess the capability of thin film copper strip sensors in monitoring the progression of sulphur corrosion in transformer insulating oils. Codes were developed in MATLAB software based on the interpolation-extrapolation concept. The proposed technique enables one to predict the ageing time for a fixed value of ΔR over a wide range of DBDS concentrations.

2. Methodology

The methodology adopted in this research is shown in Figure 3. The data used in this research were obtained from Khiar *et al.,* [16]. The methodology involved the development of codes using MATLAB software in order to obtain the interpolation and extrapolation datasets. The results were divided into three categories: (1) low DBDS concentrations ($x \leq 100$ ppm), (2) medium DBDS concentrations ($100 < x < 750$ ppm), and (3) high DBDS concentrations ($750 \leq x \leq 1200$ ppm). The predicted values were obtained using MATLAB software.

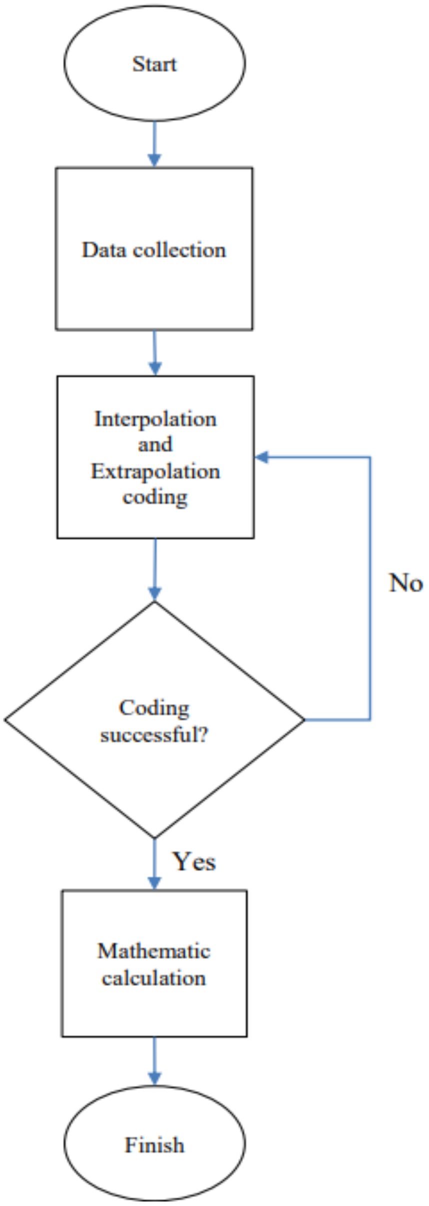

Fig. 3. Flow chart of the research methodology

2.1 Data Collection

Table 2 shows the changes in the resistance of the thin film sacrificial copper strip sensors (Δ*R*) aged at different DBDS concentrations obtained from Khiar *et al.,* [16]. Theoretically, increasing the DBDS concentration will increase the rate of sulphur corrosion on copper. This is certainly true in the case of the sensors proposed by Khiar *et al.,* [16], who found that there is a positive correlation between the Δ*R* and the DBDS concentration.

Table 2
Change in resistance (Δ*R*) of the thin film copper strip sensors used to monitor the progression of sulphur corrosion the insulating oils with different DBDS concentrations [16]

130 °C			
DBDS Concentration (ppm)	Ageing Time (h)	Δ*R* (mΩ)	Standard Deviation
100	5	1.19	0.36
	10	7.61	0.05
	15	15.58	0.03
	20	25.81	0.01
	25	32.20	0.03
250	5	8.66	0.03
	10	25.31	0.02
	15	44.22	0.03
	20	60.96	0.13
	25	75.91	0.04
1000	5	10.84	0.04
	10	44.17	0.38
	15	88.96	0.2
	20	129.60	0.14
	25	173.31	0.24

Based on the data in Table 2, a new algorithm was developed based on the interpolation-extrapolation concept using MATLAB software. Interpolation is the process of estimating values from two known values whereas extrapolation is the process of estimating values beyond these two known values [17]. The main idea is to formulate an analytical function that passes through the given points in order to interpolate or extrapolate the points [18]. At present, there are no analytical functions for the thin film copper strip sensors. Therefore, MATLAB software was used to develop the correlations between the Δ*R*, ageing temperature, ageing period, and DBDS concentration.

2.2 Interpolation and Extrapolation using MATLAB Software

Figure 4 shows the MATLAB code for the initial dataset provided in Table 2. Here, *'xt'* denotes the ageing time (in hours) while *'y_'* denotes the change in resistance at a particular DBDS concentration. The syntax *'yst=[30 100 180]'* in Figure 5 represents the standard resistance for each DBDS concentration. The data were interpolated and extrapolated to determine the new ageing time at a DBDS concentration of 100, 250, and 1000 ppm. The syntax *'xnew_100 = interp1(y_100ppm,xt,yst,'linear','extrap')'* was used for the interpolation. The function *interp1* gives interpolated values of a one-dimensional function at specific query points using linear interpolation. The vectors *y_100ppm* and *yst* contain the sample points, and the vector *xt* contains the corresponding values, *x(y)*. The attributes *'linear'* and *'extrap'* specify the methods used to evaluate the points outside the domain of *x*. It is crucial to set the attribute in the algorithm to *'extrap'* for extrapolation. Alternatively, one also can define a scalar value, and the function *interp1* returns the values for all points outside the domain of *x*.

```
%% data collection for 130 °C %%
xt=[5 10 15 20 25]; %% ageing time %%
y_100ppm=[1.19 7.61 15.58 25.81 32.2];%% 100 ppm %%
y_250ppm= [8.66 25.31 44.22 60.96 75.91]; %% 250 ppm %%
y_1000ppm=[10.84 44.17 88.96 129.6 173.31];%% 1000 ppm %%
```

Fig. 4. MATLAB code for the initial dataset

```
%% standardize the resistance %%
yst=[1 100 180];
xnew_100 = interp1(y_100ppm,xt,yst,'linear','extrap')
xnew_250 = interp1(y_250ppm,xt,yst,'linear','extrap')
xnew_1000 = interp1(y_1000ppm,xt,yst,'linear','extrap')
```

Fig. 5. MATLAB code used to standardize the resistance

Next, MATLAB code was written to transpose the values into a 3×3 matrix (Figure 6). The syntax *'yppm=[100 250 1000]'* was used to set the values of the DBDS concentrations for the y-axis. Next, the row vector was specified by setting the fixed resistance values (1, 100, and 180 mΩ). Next, the interpolation-extrapolation process was executed for the new DBDS concentrations. The new predicted concentrations were set at 25, 50, 175, 500 ,750, and 1200 ppm. The syntax *'xnew1_'*, *'xnew2_'*, and *'xnew3_'* were used to define column 1, column 2, and column 3, respectively. Next, the interpolation-extrapolation process was carried out using the code in Figure 7. Finally, the last part of the coding process involved using the *'plot'* function to plot the graph for each DBDS concentration (Figure 8).

```
%transpose the array
xt = reshape([xnew_100 xnew_250 xnew_1000],[3,3])
%change y-axis to concentration
yppm = [100 250 1000];
%call to first row (30mΩ)
row1 = xt(1,:)
y_30 = row1
%call to first row (100mΩ)
row2 = xt(2,:)
y_100 = row2
%call to first row (180mΩ)
row3 = xt(3,:)
y_180 = row3
```

Fig. 6. MATLAB code used to transpose the data into a 3×3 matrix

```
%I/E coding for 25 ppm, 50 ppm, 175 ppm, 500 ppm, 750 ppm and 1200 ppm
xnew1_50 = interp1(yppm,y_30,50,'linear','extrap')
xnew1_25 = interp1(yppm,y_30,25,'linear','extrap')
xnew1_175 = interp1(yppm,y_30,175,'linear','extrap')
xnew1_500 = interp1(yppm,y_30,500,'linear','extrap')
xnew1_750 = interp1(yppm,y_30,750,'linear','extrap')
xnew1_1200 =interp1(yppm,y_30,1200,'linear','extrap')

xnew2_25 = interp1(yppm,y_100,25,'linear','extrap')
xnew2_50 = interp1(yppm,y_100,50,'linear','extrap')
xnew2_175= interp1(yppm,y_100,175,'linear','extrap')
xnew2_500 = interp1(yppm,y_100,500,'linear','extrap')
xnew2_750 =interp1(yppm,y_100,750,'linear','extrap')
xnew2_1200=interp1(yppm,y_100,1200,'linear','extrap')
xnew3_25=interp1(yppm,y_180,25,'linear','extrap')
xnew3_50= interp1(yppm,y_180,50,'linear','extrap')
xnew3_175= interp1(yppm,y_180,175,'linear','extrap')
```

```
xnew3_500= interp1(yppm,y_180,500,'linear','extrap')
xnew3_750=interp1(yppm,y_180,750,'linear','extrap')
xnew3_1200=interp1(yppm,y_180,1200,'linear','extrap')
%cumulative data for 25 ppm, 50 ppm, 175 ppm, 500 ppm, 750 ppm and 1200 ppm
xppm_50= [xnew1_50 xnew2_50 xnew3_50]
xppm_25= [xnew1_25 xnew2_25 xnew3_25]
xppm_175= [xnew1_175 xnew2_175 xnew3_175]
xppm_500= [xnew1_500 xnew2_500 xnew3_500]
xppm_750=[xnew1_750 xnew2_750 xnew3_750]
xppm_1200= [xnew1_1200 xnew2_1200 xnew3_1200]
```

Fig. 7. MATLAB code used to interpolate and extrapolate the data

```
%plot graph original concentrations
plot(xnew_100,yst,'r*-')
hold on
plot(xnew_250,yst,'g*-')
hold on
plot(xnew_1000,yst,'y*-')
hold off
legend('100 ppm','250 ppm','1000 ppm')

%plot graph low DBDS concentrations
plot(xppm_25,yst,'r*-')
hold on
plot(xppm_50,yst,'g*-')
hold on
plot(xnew_100,yst,'y*-')
hold off
legend('25ppm','50 ppm','100 ppm')

%plot graph medium DBDS concentrations
plot(xppm_175,yst,'c*-')
hold on
plot(xnew_250,yst,'y*-')
hold on
plot(xppm_500,yst,'b*-')
hold off
legend('175 ppm','250 ppm','500 ppm')

%plot graph high DBDS concentrations
plot(xppm_750,yst,'k*-')
hold on
plot(xnew_1000,yst,'y*-')
hold on
plot(xppm_1200,yst,'m*-')
hold off
legend('750 ppm','1000 ppm','1200 ppm')

grid on
ylim([10 180])
xlabel('Time (h)')
ylabel('ΔR (mΩ)')
```

Fig. 8. MATLAB code used to plot the graph according to the DBDS concentrations

2.3 Interpolation-extrapolation using Mathematical Equation

Linear interpolation is a mathematical method used to create a new dataset from known data points. Linear extrapolation is identical to linear interpolation; the primary difference being that in the latter, the new data points are beyond the range of the existing data points. Simply put, new data points are created from linear interpolation and extrapolation of the existing data points. Two-point coordinates are necessary for both linear interpolation and extrapolation. The collection of data points was used to create the equation, which was then used to locate new data points along the line. Linear interpolation and extrapolation were performed using the following equation:

$$y = y_1 + (x - x_1)\frac{(y_2 - y_1)}{(x_2 - x_1)} \tag{1}$$

In order to evaluate the feasibility of the proposed technique, the predicted values obtained from MATLAB software were compared with the calculated values obtained from Eq. (1). The percentage error between the predicted and calculated values was determined using the following equation:

$$\text{Percentage error} = \left|\frac{\text{Ageing time}_{\text{MATLAB}} - \text{Ageing time}_{\text{Mathematical}}}{\text{Ageing Time}_{\text{Mathematical}}}\right| \times 100 \tag{2}$$

3. Results

Table 3 shows the ranges of DBDS concentrations used in this research. It shall be noted that these ranges are based on the data tabulated in Table 2.

Table 3
Ranges of DBDS concentrations in parts per million (ppm)

Category	DBDS Concentrations (ppm)
Low concentrations	$x < 100$
Medium concentrations	$100 < x < 750$
High concentrations	$750 < x < 1200$

The ΔR of the thin film sacrificial copper strip sensors show a significant change when the sensors are aged at various DBDS concentrations, as illustrated in Figure 9 to Figure 11. In general, there is a positive linear relationship between ΔR of the sensors and DBDS concentration in the presence of oxygen. The results indicate that the corrosive by-products of DBDS have a pronounced effect on the corrosivity of the insulating oil, regardless of the ageing temperature. Interestingly, the results shown in Figure 9 to Figure 11 indicate that sulphur corrosion is a time-dependent process. It is worth noting that the presence of oxygen in the insulating oil may have a significant effect on sulphur corrosion [19]. As the oxygen level increases, the interaction between an unstable sulphur compound (such as DBDS) and the copper strip decreases.

3.1 Characteristics of the Thin Film Copper Strip Sensors at Low DBDS Concentrations

Figure 9 shows the results of the interpolation-extrapolation process using MATLAB software at low DBDS concentrations. In general, the ΔR values increase with an increase in the DBDS concentration. This is similar to the results of Rehman *et al.,* [20], where the rate of sulphur corrosion increases in a linear fashion with respect to the presence of DBDS corrosive by-products [19,21,22]. Interestingly, the presence of a small concentration of DBDS (25 ppm) is sufficient create a corrosive environment in the insulating oil. In general, the ΔR value increases slowly at the lowest DBDS concentration (25 ppm) compared with those at a medium concentration (50 ppm) and high concentration (100 ppm). This is evident from Figure 9, where it takes a longer ageing time (181 hours) for the ΔR of the thin film copper strip sensor to reach 180 mΩ compared with those at a DBDS concentration of 50 and 100 ppm.

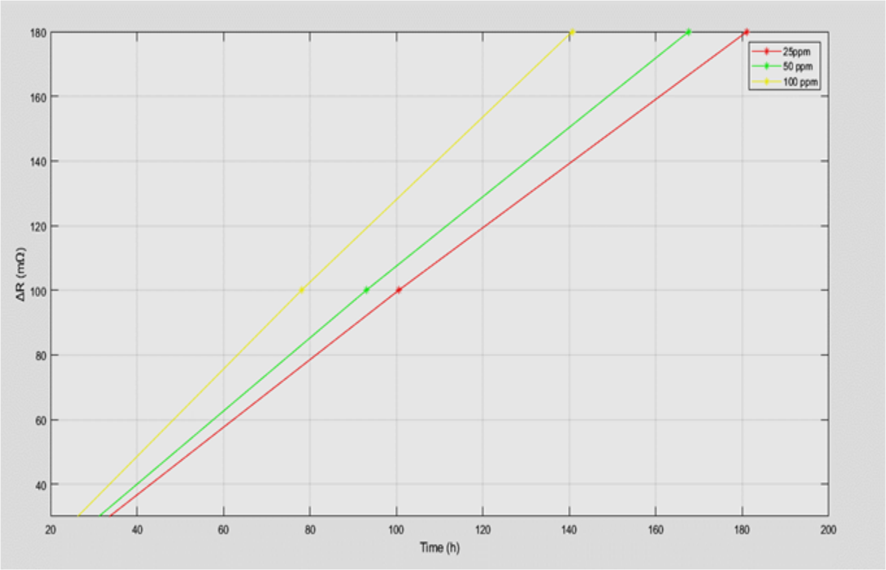

Fig. 9. Variation of the Δ*R* of the thin film sacrificial copper strip sensors aged in the insulating oils with low DBDS concentrations at 130 °C obtained from interpolation and extrapolation

3.2 Characteristics of the Thin Film Copper Strip Sensors at Medium DBDS Concentrations

Figure 10 shows the results of interpolation-extrapolation process using MATLAB software for medium DBDS concentrations. A significant increase in the Δ*R* can be observed within the shortest ageing time for the highest DBDS concentration (500 ppm). It takes 48 hours for the Δ*R* to reach 180 mΩ for a DBDS concentration of 500 ppm compared with those for a DBDS concentration of 175 and 250 ppm. The slope of the graph between 1 and 100 mΩ is steeper with a value of 4.03 ppm/h for a DBDS concentration of 500 ppm. In contrast, the slope is flatter for a DBDS concentration of 175 and 250 ppm, with a value of 1.9 and 3.2 ppm/h, respectively. This indicates that the rate of corrosive sulphur compounds generated is closely related to the DBDS concentration. The steeper the slope of the graph, the faster the progression of sulphur corrosion.

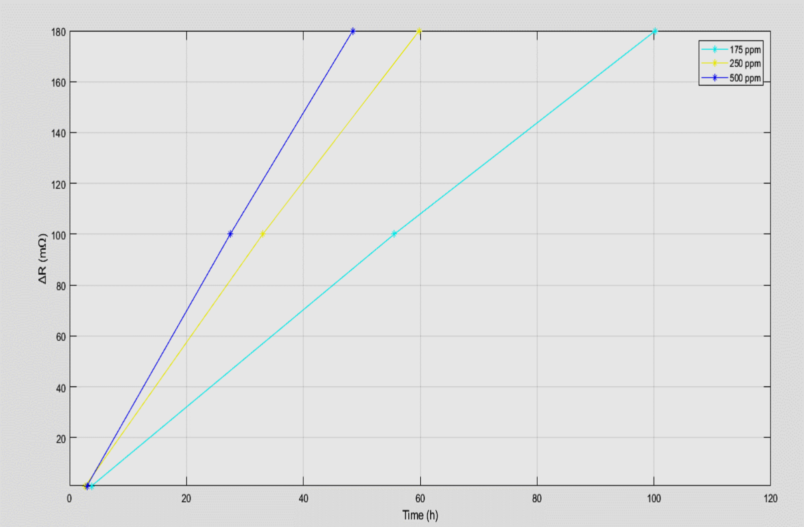

Fig. 10. Variation of the Δ*R* of the thin film sacrificial copper strip sensors aged in the insulating oils for medium DBDS concentrations at 130 °C obtained from interpolation and extrapolation

3.3 Characteristics of the Sensor at High DBDS Concentrations

Figure 11 shows the variation of Δ*R* with respect to the ageing time for high DBDS concentrations. In general, the Δ*R* increases with an increase in the DBDS concentration. The corrosive by-products of DBDS begin to attack the copper surface as early as 3 h. The most substantial reduction in ageing time can be observed for the highest DBDS concentration (1200 ppm), where it takes only 16.69 h for the Δ*R* to reach 180 mΩ. It is apparent that even though the ageing temperature remains constant at 130 °C, the effect of the DBDS corrosive by-products on the Δ*R* of the thin film sacrificial copper strip sensors is visible over a shorter ageing period.

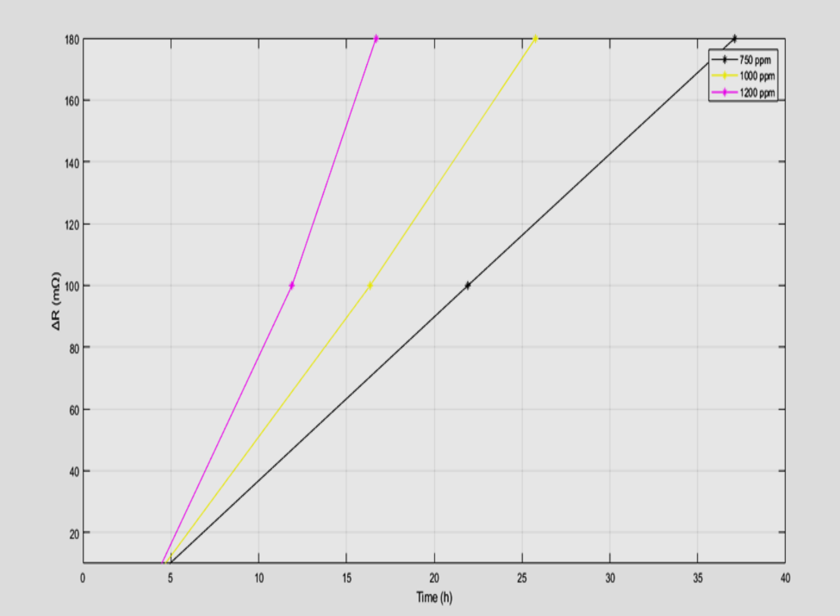

Fig. 11. Variation of the Δ*R* of the thin film sacrificial copper strip sensors aged in the insulating oils for high DBDS concentrations at 130 °C obtained from interpolation and extrapolation

3.4 Evaluation of the Proposed Technique

The data obtained from linear interpolation-extrapolation using MATLAB software and the data obtained from mathematical calculations using Eq. (1) are presented in Table 4. The percentage error denotes the difference between the predicted and calculated ageing time. In general, the percentage error values are relatively low within a range of 0.00–0.10 %. In addition, the maximum error is only 0.37 % and only six values exceed 0.1 %. This indicates that the proposed technique is feasible to predict the ageing time of the thin film copper strip sensors based on a known value of Δ*R* of the sensors.

Table 4
Comparison of the ageing time obtained from MATLAB and mathematical equation

Categories	DBDS Concentration (ppm)	Δ*R* (mΩ)	Ageing Time in MATLAB (h)	Ageing Time using Mathematical Equation (h)	Percentage Error (%)
Low	25	1	5.92	5.93	0.17
		100	100.55	100.54	0.01
		180	181.07	181.07	0.00
	50	1	5.56	5.55	0.18
		100	93.04	93.03	0.01
		180	167.60	167.61	0.01
	100	1	4.80	4.81	0.21
		100	78.00	78.01	0.01
		180	140.65	140.65	0.00
Medium	175	1	3.77	3.77	0.00
		100	55.55	55.54	0.02
		180	100.23	100.23	0.00
	250	1	2.70	2.69	0.37
		100	33.06	33.06	0.00
		180	59.81	59.81	0.00
	500	1	2.97	2.97	0.00
		100	27.49	27.50	0.04
		180	48.46	48.46	0.00
High	750	1	3.25	3.25	0.00
		100	21.92	21.92	0.00
		180	37.11	37.12	0.03
	1000	1	3.52	3.53	0.20
		100	16.35	16.34	0.06
		180	25.76	25.76	0.00
	1200	1	3.74	3.75	0.27
		100	11.90	11.91	0.08
		180	16.69	16.70	0.06

4. Conclusions

In this study, MATLAB codes were developed based on linear interpolation and extrapolation to predict the ageing time for a particular change in resistance (Δ*R*) of thin film sacrificial copper strip sensors. Based on the low percentage errors between the predicted and calculated values (less than 0.4%), it can be deduced that the proposed technique is capable of predicting the ageing time of the sensors over a wide range of DBDS concentrations. The results reveal that the rate of corrosive sulphur generated is proportional to the DBDS concentration of the insulating oil. The Δ*R* increases slowly at low DBDS concentrations compared with those at medium and high DBDS concentrations. The results indicate that the DBDS concentration is the main contributor towards the sulphur corrosion process, where the reaction between copper and DBDS corrosive by-products will increase the Δ*R* of the sensors.

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