Transformer oil degradation detection system based on color scale analysis

Muhammad Fahmi Hakim[1], Rahman Azis Prasojo[1], Rohmanita Duanaputri[1], Bustani Hadi Wijaya[2,3], Hanifiyah Darna Fidya Amaral[1], Zakki Fuadi Emzain[4,5]
[1]Departement of Electrical Engineering, Politeknik Negeri Malang, Malang, Indonesia
[2]UP3 Surabaya Utara, PT. PLN (Persero), Surabaya, Indonesia
[3]Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan
[4]Departement of Mechanical Engineering, Politeknik Negeri Malang, Malang, Indonesia
[5]Departement of Mechanical Engineering, University of Sheffield, Sheffield, United Kingdom

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ABSTRACT

The rise in power transformer load results in degradation of the condition of the transformer oil and ultimately a deficiency in the distribution of electrical energy. This degradation can be slowed down by reconditioning transformer oil based on oil color detection. This research aims to design, test and validate a transformer oil color testing system based on color sensor and microcontroller. To obtain an accurate system, tests were carried out on selecting the types of sensors, the color of the chamber walls, and the shapes of transformer oil sample vessel used. The oil color scale of the samples was determined visually according to the ASTMD1500, 2009 standard as a benchmark. The test results showed that the TCS3200 color sensor was able to detect the color of all transformer oil samples. White chamber wall and test tube as oil sample containers were chosen to increase system accuracy. Overall, the system is able to detect the color of transformer oil, convert to the ASTMD1500, 2009 standard transformer oil color scale, determine the condition of the transformer oil and conclude the level of transformer oil degradation according to CIGRE-761, 2019. Validation results showed the system had an accuracy level of 92.65%.

Corresponding Author:

Muhammad Fahmi Hakim
Department of Electrical Engineering, Politeknik Negeri Malang
65141 Malang, East Java, Indonesia
Email: m.fahmihakim@polinema.ac.id

1. INTRODUCTION

Transformer oil has been widely and long-used as insulation and cooling material for transformers due to its affordability and easy availability [1]-[4]. As consumers increase, the load on the transformer increases which causes the temperature of the oil insulation to also rise and reduce the dielectric strength or also known as degradation [5], [6]. If this continues, it can damage the transformer's insulation strength and impact its performance [7]-[10]. Increasing the temperature of transformer oil can also affect the color of the oil [11]–[13]. However, through proper monitoring of the condition of the insulating oil, the service life of transformer oil can be extended with early reconditioning efforts [14], [15].

One of the current transformer oil degradation testing methods is dissolved gas analysis (DGA) to test the physical condition of transformer oil [16]-[23]. This method utilizes the concentration of various gases dissolved in transformer oil to detect initial damage to the transformer [24], [25]. Another method of testing oil degradation based on the oil color scale shows that color can be an indicator of the age and level of degradation of transformer oil quality [26]-[29] so accurate and practical oil color testing is needed. However, there is no practical and portable oil color testing tool that is capable of displaying the color scale of transformer oil and its degradation level.

Srivastava *et al.* [30] designed real-time transformer oil monitoring using planar frequency-based sensors. In this research, transformer oil conditions were monitored using frequency-based sensors. Physical and chemical changes in an oil sample are related to variations in the sensor's frequency response. Differences in sensor frequency response are related to chemical and physical changes in the oil sample. Mustaffa *et al.* [31] also developed an object color detection system using the TCS3200 color sensor but to differentiate oil palm fruit bunches based on their level of maturity. In order to detect moisture dissolved in transformer insulating oil in real time, Kondalkar *et al.* [32] developed a high-performance planar metal-polyimide-interdigital transducer (IDT) metal-type miniaturized capacitive. The polyimide film modification enhanced the sensor's performance, resulting in increased sensitivity, fast reaction time, and long-term stability in the transformer-oil environment. Hadi *et al.* [33] developed a transformer oil monitoring system using ultraviolet-blue laser. Based on the results, confidence intervals (CI) can be measured reliably, with root mean square errors (RMSEs) of 0.4129 for 450 nm and 0.2229 for 405 nm. This technique demonstrates the feasibility of a low-cost, portable power transformer monitoring device for on-site applications. Leong *et al.* [34] offered a new technique for measuring the color scale of transformer oil, namely using UV light. The color index (CI) of transformer oil may be found using ultraviolet-to-visible (UV-Vis) spectroscopy, as suggested in this paper. The results show a positive correlation between the CI of transformer oil and the absorbance spectrum responses of oils from 300 nm to 700 nm. In accordance with IEC 156, Mahanta and Laskar [35] presented an optical sensor-based transformer oil insulation breakdown monitoring system that makes use of sphere-sphere 2.5 mm electrodes in the test cell. It is discovered that the insulating oil failure modifies its properties, which influences the recommended sensor output voltage that signifies the insulating oil degradation.

As stated in the works [30]-[35], a transformer oil condition monitoring system has actually been developed. However, there has been no research that has designed a tool capable of assessing the level of transformer oil degradation based on a microcontroller-based color scale and utilizing a color sensor as a detector. This research is different from research [30]-[35] because it uses a TCS3200 color sensor as a transformer oil color detector and an Arduino Uno microcontroller as a data processing center. The novelty in this research is a project to design a transformer oil condition detection system based on an oil color scale referring to the ASTM D1500, 2009 [36] standard based on a microcontroller. This device makes it easier for operators to test the level of degradation of the transformer color scale because the color scale value is directly displayed on the LCD screen. Apart from that, the results of oil condition analysis and conclusions on degradation conditions according to CIGRE 761-2019 standards are also displayed [37]. These three parameters are the result of data processing by the microcontroller. In addition, this detection system is portable.

The main objective of this research includes designing, testing, and validating a system for accurately detecting transformer oil degradation levels through microcontroller-based oil color reading. This project focuses on monitoring the level of transformer oil degradation using an Arduino Uno type microcontroller as a data processor, a TCS3200 color sensor, an LCD screen, a test tube, and an acrylic cover. The color of the transformer oil put into the test tube is detected by the TCS3200 color sensor. Data from the RGB color sensor will be processed by Arduino and sent to the LCD screen. Users can find out the color scale of transformer oil tested based on ASTM D1500, 2009 standards and the level of degradation of transformer oil based on the color scale via the LCD screen. Arduino Uno is used in this research because it is easy to program, cheap, and is one of the most widely used microcontrollers so it is easy to obtain [38]. The color range may be found and measured with the TCS3200 color sensor. This color sensor has a broad dynamic response range to light, and its typical output frequency range is 2Hz to 500 kHz [39].

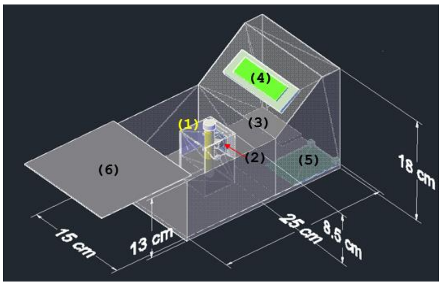
2. METHOD

There are several stages presented in the research method including system design, system work sequence, system testing, and system validation.

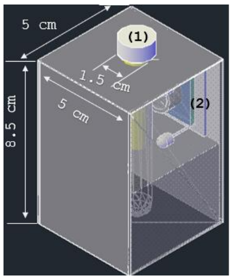
2.1. System design

Figure 1 shows the design of the transformer oil degradation level detection system, based on the color scale, which consists of components such as a transformer oil sample tube chamber (1), color sensor (2), microcontroller (3), LCD (4), power supply (5), and acrylic housing (6). The chamber functions as a place that encloses the test tube and TCS3200 color sensor that is placed against the inside of the transformer oil sample tube container to obtain accurate detection results. According to research [40]-[42] the TCS3200's white light emitting diodes (LEDs) are utilized to illuminate and light up an object's surface to identify color. Then, in order to measure the intensity of the color in terms of the intensity of the red, green, and blue (RGB) components of light, the item reflects light back to the sensor [43]. The sensor supply voltage is 2.7-5.0 VDC and the PCB size is 31.6*24.4 mm. The microcontroller in the form of an Arduino Uno functions to read the detection results of the TCS3200 sensor in the form of RGB data and process that data. Arduino Uno has 14 digital input/output pins that can be used as pulse width modulation (PWM) output and 6 analog input pins. Apart from that, the Arduino Uno is also equipped with a USB connection, electrical terminal, ICSP header, reset button, and operating voltage of 5 V. The LCD functions to display the results of data processing by the microcontroller. The power supply functions as a power supply for the color sensor and microcontroller. The power supply voltage is an input voltage of 220 V and an output voltage of 5-12 VDC.

Figure 1(a) shows the shape and dimension of housing for placing components and Figure 1(b) shows the shape and dimension of test tube chamber inside system. The chamber has length = 5 cm, width = 5 cm, and height = 8.5 cm, equipped with a hole at the top with a diameter of 1.5 cm to insert a reaction tube that can accommodate ± 15 ml of oil sample. The color of the inner wall of the transformer oil sample tube vessel is white.



(a)



(b)

Figure 1. Design of (a) transformer oil degradation level detection system based on a color scale and (b) test tube chamber inside system

2.2. Working sequence of the system

Figure 2 shows the block diagram of the system. The power supply is connected via a DC adapter which produces an output voltage of 5-12 VDC to activate the microcontroller and color sensor (2). The transformer oil sample to be tested is put into a test tube. The color sensor reads the color of the transformer oil. The color reading data in the form of RGB values is sent to the microcontroller input pin. The microcontroller converts it into a number code according to the ASTM D1500, 2009 standard, namely values 0 to 8.5, which is the standard test method for ASTM color of petroleum products [44], using a regression equation with the multi linear regression method. The results of the transformer oil color scale are further interpreted using IEEE C57.152 and CIGRE TB 761. After the data is processed, the data is then sent to the output pin of the microcontroller which connects to the output device in this tool, namely an LCD to display the output in the form of the oil color scale and degradation level. Transformer oil starts from conditions: new, good, service-aged marginal, bad, severe, to extreme.

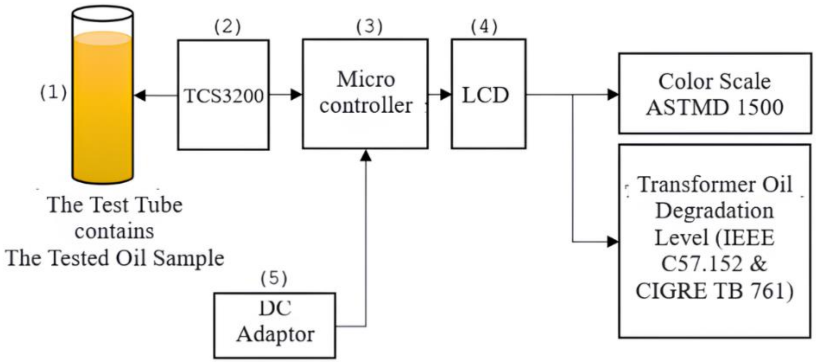


Figure 2. Block diagram of system

2.3. System testing

System testing includes color of transformer oil samples visual assessment or determination, sensor type testing, chamber wall color testing, transformer oil sample vessel testing, and overall system testing in the sequence as shown in Figure 3. Transformer oil samples need to be visually assessed for comparison with the system assessment results. Before deciding to use the TCS3200 color sensor, first compare the performance of it with a UV sensor (GUVA S12SD). This test was carried out to find out the most accurate sensor in detecting transformer oil color for this system. Chamber wall color testing was carried out to determine the wall color that supports the level of accuracy of the system in detecting the color of transformer oil. White and black wall colors were chosen for testing. The transformer oil sample holder also needs to be tested to increase the accuracy of the system because there were options for cuvette and test tube as sample containers. After that, testing was carried out on the system as a whole. The system is said to work well if it is able to detect the color of the transformer oil, convert to the ASTMD1500, 2009 standard transformer oil color scale, determine the condition of the transformer oil and conclude the level of degradation of the transformer oil according to CIGRE-761, 2019. If the system performance test goes well then validation is carried out system output.

Figure 3. Testing stages

2.4. Validation of system test results

The final step in this research is to validate the test results of research products using standard tools for testing the color of transformer oil or other fluids, namely spectrophotometric colorimeters, which are owned by PT. PLN East Java and Bali Transmission Main Unit (UIT JBM). Transformer oil samples that had been tested for their color scale using the research test system were tested again using spectrophotometric colorimeters. From the test results of the two tools, the SMAPE percentage was calculated to determine the accuracy of the research product. The smaller the SMAPE percentage value, the more accurate the color detection of the system.

3. RESULTS AND DISCUSSION

3.1. Determination of the color scale of transformer oil samples based on ASTM D1500, 2009 standards visually

The color scale of the transformer oil test sample was first determined visually according to the ASTM D1500, 2009 standard. Based on this standard it is known that the lightest color has a code number of 0.5 and the darkest color has a code number of 8 with a range of 0.5 on each scale. The darker the color of an oil, the greater the code number. The number of transformer oil samples in this study was eleven oil samples. Visual assessment of the 1^{st} to 11^{th} samples produced a value scale of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 5.5 respectively.

3.2. Selection and testing of sensor types

The first sensor tested was a UV sensor (GUVA S12SD) to detect transformer oil samples inserted into a test tube. Each oil sample scale was tested five times for a total of 55 tests. The results of the transformer oil color scale test using a UV sensor (GUVA S12SD) can be seen in Table 1. It can be seen that the maximum sensor reading results are on a scale of 1.5 and for the next scale (2 – 5.5) the test results are not displayed. This is because the transformer oil color was not readable so the GUVA12SD sensor cannot be applied to this oil color scale test system.

The results of the transformer oil color scale test using the TCS3200 color sensor can be seen in Table 2. The oil sample was put into a test tube. The color sensor and test tube were enclosed in a chamber with white chamber walls. Each oil sample scale was tested five times for a total of 55 tests but shown in Table 2 is only one test value from five tests for each sample, as example. Then the linear regression equation was determined with the independent variables being the parameters R, G, and B and the dependent variable, namely the visual color scale. After obtaining the linear regression equation with the help of Minitab software, the R, G, and B values were converted to color scale values which were considered as the results of the color sensor readings. So that the conversion results match the numbers in the ASTM D1500, 2009 Standard, a tolerance value of 0.25 is applied.

Table 1. Transformer oil color scale test results with UV sensor

No.	Oil color scale	Test	Wavelength (nm)
1	0.5	1	154
2	0.5	2	154
3	0.5	3	153
4	0.5	4	157
5	0.5	5	146
6	1	1	37
7	1	2	40
8	1	3	34
9	1	4	30
10	1	5	33
11	1.5	1	6
12	1.5	2	4
13	1.5	3	7
14	1.5	4	5
15	1.5	5	2
16	2	1	0
17	2	2	0
18	2	3	0
19	2	4	0
20	2	5	0

Table 2. Color scale test results using the TCS3200 color sensor with samples in test tubes and white chamber walls

No.	Scale (by visual)	R	G	B	Regression (y)	Scale (by system)	SMAPEI
1	0.5	122	105	79	0.604516	0.5	0
2	1	123	118	111	0.955874	1	0
3	1.5	124	132	146	1.334572	1.5	0
4	2	133	164	200	2.181504	2	0
5	2.5	140	184	220	2.70356	2.5	0
6	3	147	197	227	3.037516	3	0
7	3.5	151	218	248	3.589668	3.5	0
8	4	155	226	252	3.79542	4	0
9	4.5	161	242	264	4.210948	4	0.1176
10	5	169	267	286	4.863182	5	0
11	5.5	182	303	302	5.794206	5.5	0

Based on Table 2, the regression values were obtained by entering the R, G, and B values into (1).

$$y = 1.253 + 0.02509 * R + 0.00654 * G - 0.01941 * B \quad (1)$$

For example, in experiment number 2, using (1), a regression value of 1.21621 was obtained, while this value was not in the ASTM D1500, 2009 standard color scale value list. To overcome this, a tolerance of 0.25 was applied so that the value became color scale 1. Likewise, in the experiment number 40, color scale value 4 obtained from a regression value of 3.78689 and a tolerance value of 0.25.

The individual SMAPE value (SMAPEI) was obtained from (2).

$$SMAPEI = \frac{|Ft - At|}{(|At| + |Ft|)/2} \quad (2)$$

Where Ft is predicted value, in this case the oil color scale value based on system readings; At is actual value in this case the oil color scale is based on visuals.
The total SMAPEI value from 55 tests is 0.5882, the average SMAPEI value is 0.1070 so, the SMAPE value = 1.07%.

3.3. Chamber wall color testing

Color scale testing of transformer oil samples was carried out in a chamber with light or white and dark or black wall colors to determine the wall color that produces more accurate color scale values. The results of the transformer oil color scale test using the TCS3200 color sensor with samples in test tubes and dark or black chamber walls can be seen in Table 3. Each oil sample scale was tested five times for a total of 55 tests but shown in Table 3 is only one test value from five tests for each sample, as example.

Table 3. Color scale test results using the TCS3200 color sensor with samples in test tubes and black chamber walls

No.	Scale (by visual)	R	G	B	Regression (y)	Scale (by system)	SMAPEI
1	0.5	107	127	147	1.07565	1	0.6667
2	1	125	178	227	0.86999	1	0
3	1.5	128	208	212	1.22384	1	0
4	2	162	314	294	1.6435	1.5	0.2857
5	2.5	175	311	270	2.28509	2.5	0
6	3	217	338	280	3.49287	3.5	0.1538
7	3.5	226	263	300	3.28922	3.5	0
8	4	261	395	310	4.63175	4.5	0.1176
9	4.5	272	399	312	4.94508	5	0.1053
10	5	296	412	330	5.48928	5.5	0.0952
11	5.5	304	392	309	5.89532	6	0.0870

Using Minitab, the linear regression equation obtained is as in (3).

$$y = 0,824 + 0,02935 * R + 0,00324 * G - 0,01124 * B \quad (3)$$

The color scale based on the system was obtained by entering the R, G, B values into (3).

The total SMAPEI value from 55 tests, in the oil color scale test with black chamber walls, is 8.2659, the average individual SMAPE value is 0.1503, and the SMAPE percentage is 15.03%. Meanwhile, testing the oil color scale with white chamber walls, the results of which are also shown in Table 2, has a smaller SMAPE percentage, namely 1.07%, so the white chamber walls produce more accurate measurement.

3.4. Testing of transformer oil sample vessels

The transformer oil sample vessel can be a test tube or cuvette. This test aims to compare the level of accuracy of the instrument reading between an oil sample put into a test tube and an oil sample put into a cuvette. The results of the oil color scale test with the condition of the oil sample being put in a test tube, using a TCS 3200 color sensor, and the chamber walls being white can be seen in Table 2. Meanwhile, the results of the oil color scale test with the condition of the oil sample being put in a cuvette, using a color sensor TCS 3200, and the white chamber walls can be seen in Table 4. Each oil sample scale was tested five times for a total of 55 tests but shown in Table 4 is only one test value from five tests for each sample, as example.

Table 4. Color scale test results using the TCS3200 color sensor with samples inside the cuvette and white chamber walls

No.	Scale (by visual)	R	G	B	Regression (y)	Scale (by system)	SMAPEI
1	0.5	71	64	48	0.55272	0.5	0.0000
2	1	81	78	70	1.00358	1	0.0000
3	1.5	84	90	100	1.5233	1.5	0.0000
4	2	88	108	142	2.2978	2.5	0.1333
5	2.5	83	110	158	2.51598	2.5	0.0000
6	3	93	125	161	2.92241	3	0.0000
7	3.5	97	145	209	3.79549	4	0.0869
8	4	96	146	209	3.8474	4	0.0000
9	4.5	102	162	235	4.44992	4.5	0.0000
10	5	106	178	266	5.10454	5	0.0000
11	5.5	101	185	260	5.41155	5.5	0.0000

Using Minitab, the linear regression equation obtained is as in (4).

$$y = -0,895 - 0,0154 * R + 0,03651 * G + 0,00426 * B \quad (4)$$

The color scale based on the system is obtained by entering the R, G, B sensor values into (4).

The total SMAPEI value from 55 tests, in testing the oil color scale with oil samples inserted into the cuvette, is 2.497. The average individual SMAPE is 0.04541, and the SMAPE percentage is 4.541%. Meanwhile, testing the oil color scale inside tube test, as also shown in Table 2, yields a smaller SMAPE percentage of 1.07%. Therefore, oil transformer inside tube test produces more accurate measurements.

3.5. Performance testing of the device

Before performance testing of the system, components are inserted into the device housing to protect them. Figure 4 shows the appearance of the transformer oil degradation detector system based on the color scale, which Figure 4(a) shows the front view while Figure 4(b) shows the back view of the prototype.

Figure 5 shows that the system can detect the color scale with the detection results displayed on the LCD. Figure 5(a) displays the RGB value of the transformer oil color detection results tested by the TCS3200 color sensor and the transformer oil color scale value according to the ASTMD1500, 2009. If the push button next to the LCD is pressed by the operator, the transformer oil condition analysis results appear according to CIGRE-761, 2019 (Figure 5(b)). Meanwhile, if the push button is pressed again, the transformer oil degradation level appears which is tested according to CIGRE-761, 2019 (Figure 5(c)).

(a) (b)

Figure 4. Transformer oil degradation detector system based on color scale (a) front view and (b) back view

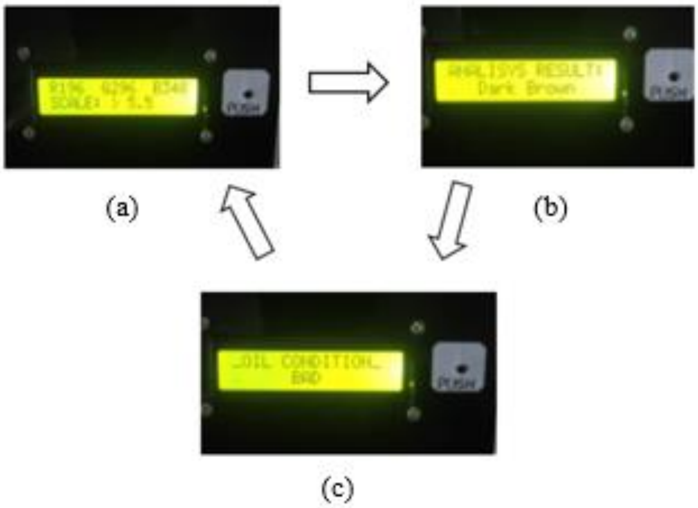


Figure 1. LCD display; (a) oil color scale, (b) oil color classification, and (c) interpretation of transformer oil degradation levels

Based on the performance test results, it can be said that the system can work well because it is able to detect the color of transformer oil, convert to the ASTMD1500, 2009 standard transformer oil color scale, determine the condition of the transformer oil and conclude the level of transformer oil degradation according to CIGRE-761, 2019.

3.6. Validation of the system

After testing the system performance to work well, it is necessary to validate the system test results by testing the oil samples that have been tested using the results of this research using spectrophotometric colorimeters owned by PT. PLN (Persero). Test results from spectrophotometric colorimeters were compared with test results from research tools using the SMAPE method. Validation of these results aims to determine the level of accuracy of the system. In Table 5, the results of testing samples of transformer oil using spectrophotometric colorimeters are displayed along with the comparison results with the system. Each oil sample scale was tested five times for a total of 55 tests but shown in Table 5 is only one test value from five tests for each sample, as example.

Table 5. Color scale reading values by spectrophotometric colorimeters and systems designed by researchers

No.	Scale (by visual)	Spectrophotometric colorimeters		Regression (y)	Scale (by system)	SMAPEI
		Value	Scale			
1	0.5	0.4	0.5	0.604516	0.5	0.0000
2	1	1.2	1	0.955874	1	0.0000
3	1.5	1.7	1.5	1.334572	1.5	0.0000
4	2	2.3	2.5	2.181504	2	0.2222
5	2.5	2.6	3	2.70356	2.5	0.1818
6	3	3	3	2.955275	3	0.0000
7	3.5	3.4	3.5	3.589668	3.5	0.0000
8	4	3.5	3.5	3.79542	4	0.1333
9	4.5	3.9	4	4,210948	4	0.0000
10	5	4.2	4	4.863182	5	0.2222
11	5.5	4.8	5	5.741986	5.5	0.0952

The oil color scale that appears on the spectrophotometric colorimeters was not based on the ASTMD1500, 2009 standard, so a conversion was carried out with a tolerance value of 0.25 with the results listed in the spectrophotometric colorimeters scale column in Table 5Table . This conversion was carried out so that the values can be compared with the system test results. In calculating SMAPEI, the predicted value is the oil color scale value based on instrument readings and the actual value is the oil color scale based on visual spectrophotometric colorimeters. The total SMAPEI value in this test is 4.0403 so the average SMAPEI value is 0.0735 and the SMAPE value = 7.35%. It can be said from the validation results, the accuracy value of this tool reached 92.65%.

This study investigated the effects of transformer oil degradation using a color scale analysis based on a microcontroller and a TCS3200 color sensor. While earlier studies have explored various methods of oil degradation detection, such as frequency-based sensors, Ultraviolet-Blue Laser, and UV-Vis spectroscopy [30], [33], [34], they have not explicitly addressed the practical application of a portable and low-cost system that directly correlates color scale values with oil degradation levels. The absence of such a system in previous research highlights a significant gap that this study aims to fill. The results of this study are actually in line with previous studies on detection systems using sensors, which only differ in the type of sensor or detection purpose. Color sensors have been used in several portable detection systems based on color detection, but are not used to detect the color of transformer oil but rather to detect oil palm fruit bunches, cholesterol levels or pesticide and veterinary drug residues [31]. sterol levels or pesticide and veterinary drug residues [31]. The transformer color detection tool designed by other researchers uses an Ultraviolet-Blue Laser which is capable of detecting the level of confidence intervals [33] and also utilizes ultraviolet-to-visible (UV-Vis) spectroscopy to measure the Color Index [34]. Future research could expand on these findings by employing more advanced sensors or enhancing calibration methods to increase accuracy and sensitivity.

4. CONCLUSION

This research developed and evaluated a system to detect transformer oil degradation based on TCS3200 color sensor and microcontroller. It is important because transformer oil quality is supporting the reliability and efficiency of power transformers, affecting both operational safety and lifespan. The research's findings demonstrate the system's ability to convert RGB values to standard color scale values according to the ASTM D1500 2009. Additionally, the system can assess oil condition and determine degradation levels based on the CIGRE-761 2019. The validation results showed a high accuracy rate of 92.65%. These findings align with the previous studies. The system's performance and accuracy indicate that it is practical and reliable enough for industrial applications. Critics may question the robustness of a color sensor-based system; however, the high accuracy and successful validation against established standards support its credibility and utility. Future research can build upon these findings by using or assembling advanced sensors or refining calibration techniques to improve accuracy and sensitivity. Additionally, enhancing the system's capabilities to assess different types of oil, such as silicone, natural ester, synthetic ester, and others, would further enhance the system's utility. These improvements would enable a more comprehensive assessment of transformer oil. The developed system for detecting transformer oil degradation, using a color sensor and microcontroller, offers a practical, cost-effective, and accurate solution for oil condition monitoring. This system supports preventive maintenance strategies and reduces the risk of transformer failures. It is such an important advancement for industry professionals.

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BIOGRAPHIES OF AUTHORS

Muhammad Fahmi Hakim is Assistant Professor at the Department of Electrical Engineering, Politeknik Negeri Malang. He received B.Eng. and M.Eng. degree both in Electrical Engineering from University of Brawijaya. He has authored or coauthored more than 35 publications especially in area of Electrical Power System Engineering. He has been one of the editors of Elposys: Jurnal Sistem Kelistrikan, Indonesian national journal accredited by Sinta, since 2015. He has written two textbooks that have ISBN in 2017 and 2020, also has filed a number of patents on his innovative ideas. He can be contacted at e-mail: m.fahmihakim@polinema.ac.id.

Rahman Azis Prasojo received the BASc. degree from the Department of Electrical Engineering, Politeknik Negeri Malang, Malang, Indonesia, in 2015, and the M.Sc. and Doctoral degree from the School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Bandung, Indonesia, in 2017 and 2022 respectively. Since 2019, he has been a full time Professor (Assistant) with the Department of Electrical Engineering, Politeknik Negeri Malang. He has published more than 40 conference papers or journal articles in accordance to high voltage power transformer condition monitoring and diagnostics. He is a regular reviewer for various reputable international journals. He received best paper awards in ICPEA 2022, Johor Bahru, Malaysia and ICHVEPS 2023, Bali, Indonesia. He can be contacted at e-mail: rahmanazisp@polinema.ac.id.

Rohmanita Duanaputri received the BASc. degree from the Department of Electrical Engineering, Politeknik Negeri Malang, Malang, Indonesia, in 2014, and masters in Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, in 2017. Since 2019, he has been a full time Professor (Assistant) with the Department of Electrical Engineering, Politeknik Negeri Malang. She has published conference papers or journal articles on the topic of power systems. She can be contacted at e-mail: rohmanitar@polinema.ac.id.

Bustani Hadi Wijaya received B.Eng. degree in electrical engineering from Institut Teknologi Bandung, Bandung, Indonesia, in 2008 and master degree in electrical engineering from National Taiwan University of Science and Technology, Taipei, Taiwan in 2019. He is a practitioner in the electricity sector and has worked at PT PLN (Persero) since 2008. His current position at the company is manager of UP3 Surabaya Utara. He can be contacted at e-mail: bustani@pln.co.id.

Hanifiyah Darna Fidya Amaral received the BASc. degree from the Department of Electrical Engineering, Politeknik Negeri Malang, Malang, Indonesia, in 2012, and masters in Electrical Engineering, Brawijaya University, Malang, Indonesia, in 2019. Since 2020, he has been a full time Professor (Assistant) with the Department of Electrical Engineering, Politeknik Negeri Malang. She has published conference papers or journal articles on the topic of high voltage and signal processing. She can be contacted at e-mail: hanifahdarna@polinema.ac.id.

Zakki Fuadi Emzain obtained the B.A. degree from the Department of Mechanical Engineering at the State University of Malang, Indonesia, in 2013. He then pursued the M.Sc. degree in Mechanical Engineering at the National Kaohsiung University of Science and Technology (NKUST), Taiwan, and completed it in 2018. Since 2019, he has held the position of full-time Assistant Professor in the Department of Mechanical Engineering at Politeknik Negeri Malang. The research areas he focuses on include Additive Manufacturing, Computational Mechanics, and Biomechanical Engineering. He has authored over 25 scholarly publications and conference papers, nationally and internationally, as well as more than 10 patents and books. Currently, he is pursuing a Ph.D. in Mechanical Engineering at the University of Sheffield, UK. He can be contacted at e-mail: zfemzain1@sheffield.ac.uk.