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Life estimation of distribution transformers using thermography: A case study

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ABSTRACT

In the present study, a new method is offered for estimating the life of distribution transformers. So, it was attempted to determine the remaining lifetime of distribution transformers through using thermography from the body of 193 transformers used in Yazd Electric Distribution Company. To this end, environmental temperature, environmental humidity, and the transformers load capacity were calculated in tandem with thermography. Moreover, to test the offered method, oil samples of 49 transformers were collected, and their lifetime was estimated through conducting oil tests. The offered method determined the range of temperature changes of the transformers body for a three-year timespan using Bonferroni's confidence interval estimation algorithm. These ranges were determined for 144 transformers and for the remaining 49 transformers, the estimated lifetime was measured through using the suggested algorithm and comparing them with the findings obtained from the oil test. This indicated the estimating accuracy of the suggested algorithm.

1. Introduction

Transformers are one of the most crucial devices in distribution networks. Their unexpected failure will impose heavy and irreparable costs, reduced proper servicing, and even network outage [1–3]. Given the importance of transformers in distribution networks, estimating their remaining lifetime can be a proper strategy for increasing the useful lifetime of transformers. Moreover, life estimation of transformers can be of great significance for creating and conducting periodic and preventive visits, proper loading for each transformer, determining proper points for network maneuvering, and optimal distribution corresponding to the loads of feeders for network users [4,5].

Currently, electric power distribution companies are always attempting to take numerous measures in different areas to provide appropriate services, saving, and quality servicing (without any outage) to subscribers. Therefore, investigating the remaining lifetime of this device is of great significance for fulfilling the aims of electric power distribution companies. Many researchers have investigated this significant issue. For example, to determine the status of transformers and estimate their lifetime, the paper-oil system of this device has been investigated [6]. In another study, the remaining lifetime of transformers was investigated and estimated through using the analysis of insoluble gases in oil and gas chromatography [7–11]. Another study investigated the insulation system and the remaining lifetime of transformers by analyzing the two factors of load and environmental temperature. In another study, the researcher used thermovision cameras to investigate the relationship between body temperature and the hot spot of the oil used in the transformer, a factor closely related to the lifetime of transformers [12–14]. Not only transformers but also other electrical equipment such as capacitors in power electronic systems [15], need to be tested for lifetime. Also we can illustrate, the criteria useful to identify simple and quick operations through which "the why and the when" a scheduled maintenance can be performed in order to avoid excessive checks and controls [16]. Recently thermography has had a wide range on condition monitoring. In [17], thermography is used to access landslide risk, also, in industrial systems, thermograph camera can be easily used for monitoring and alerting the supervisor about over temperature or current dissipation cases [18].

In the present study, it was attempted to estimate the remaining lifetime of transformers by using thermography of the body of transformers without conducting oil tests. In the following sections, it is attempted to discuss estimating the lifetime of transformers by using the findings of oil test (part2), data collection (part3), implementation of the suggested method (part4), and results (part 5).

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2. Estimating the lifetime of transformers by using the findings of oil test

Previous studies indicated that the lifetime of transformers can be estimated in different ways, one of which is using DP[1] parameter, which is determined by using the oil test [19]. Table 1 shows an example of this relationship.

In the present study, it is attempted to estimate the lifetime of transformers by conducting the oil test for some of the transformers, determining DP parameters, and using Table 1.

3. Data collection

The data used in the present study are divided into two categories. The first group includes the data available in the electric power distribution company, and the second group refers to the information that needs to be measured. Information such as the number of transformers, year of production, application type of the transformers, installation address, transformers' codes, and transformers' capacity were obtained from the transformers' records in electric power distribution companies and from a piece of GIS software. Moreover, the information, including the transformers' loads, environmental temperature, environmental humidity, and thermal images of the body of the transformers, were obtained and recorded using relevant equipment.

Since around 13,000 transformers with different size are used in the distribution network and given the statistical issues and applying Equation (1) for covering the statistical population, it was necessary to test around 200 transformers. For this purpose, 200 transformers with size of 100–2000 kVA were selected, after conducting the required investigations. 75% of the transformers were used to extract the proposed algorithm. Moreover, the remaining 25% of the transformers were used to test the suggested method.

$$n = (z^2pq/d^2)/(1 + (1/N)((z^2pq/d^2) - 1)) \quad (1)$$

In which n is the sample size, N is the statistical population size, z is the normal value of the standard unit, p is the proportion of the population with a certain attribute, q is the proportion of the population lacking a certain attribute, d is the allowed error value or error percentage, z is the normal value of the standard unit, and d is the allowed error value, which is usually equal to 0.01 or 0.05.

P: If p and q values are not available, they can be considered 0.5; the variance will reach its maximum value.

For this purpose, 144 transformers were used to extract the algorithm. These transformers had not experienced any accidents or overloads, and their production years were equal to their lifetime. Moreover, 49 transformers were randomly selected for testing the proposed method, and by conducting the oil test, the real lifetime was determined. Given the limitations occurring throughout the study, the information for 7 transformers were not usable and was excluded from the calculations.

To access the field data, four photos were taken with the right angle of sunlight from four sides of the transformer. Fig. 1 shows how to take a photo. The distance between camera and transformers is almost 13 m. Simultaneously with the thermography of 193 transformers, the oil samples of 49 transformers were collected as well. Fig. 2 shows the thermography conducted simultaneously with the oil sampling of one of the transformers. Also, simultaneously with the thermography, the environmental temperature and humidity were measured and recorded as well. Furthermore, as Fig. 3 indicates, voltage, current, and three-phase power of each transformer were recorded using a power analyzer.

[1] Degree of polymerization

Table 1
Lifetime estimation according to DP parameter [19].

Estimated Degree of Polymerization (DP)	Estimated Percentage of Remaining Life	Interpretation
800	100	Normal
700	90	Aging
600	79	Rate
500	66	Accelerated
400	50	Aging
380	46	Rate
360	42	
340	38	Excessive
320	33	Aging
300	29	Danger zone
280	24	High Rick
260	19	of Failure
240	13	End of Expected Life
220	7	of Paper
200	0	Insulation and of the Transformer

Fig. 1. An example of transformer body thermography.

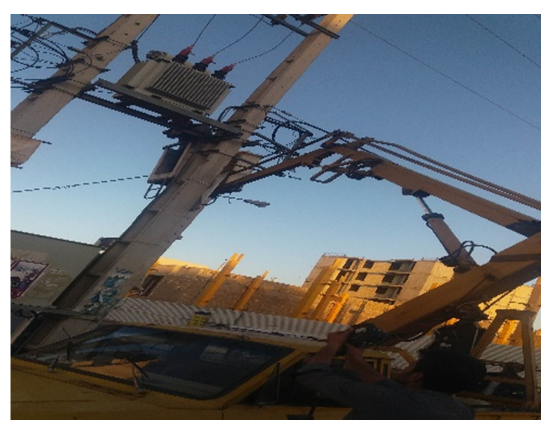

Fig. 2. Oil sampling conducted simultaneously with thermography.

There is no limitation for environmental conditions and recording other data. Just we need them for using in camera software for receiving the accurate of the transformers body temperature.

4. Implementation of the proposed method

To acquire a proper algorithm of estimating the lifetime of transformers using the temperature of their body, the initial tests were conducted in the transformer laboratory of Yazd Electrical Distribution Company (YEDC). As can be seen in Fig. 4,

Fig. 3. Acquiring transformer's load information conducted simultaneously with thermography.

Fig. 4. Simultaneous short-circuit test of new and used transformers.

two 200 kVA transformers underwent a simultaneous short circuit test; one of them had been used in the network for 30 years, and the other one was completely new.

Then, thermal images were taken from the body of the two transformers. As shown in Fig. 5, the difference between the body temperatures of the two transformers is quite evident.

Thus, given the direct thermal relationship between the body with the oil and electromagnetic coil, the hypothesis of the relationship between the lifetime of the transformer and its body temperature was supported. The relationship between the

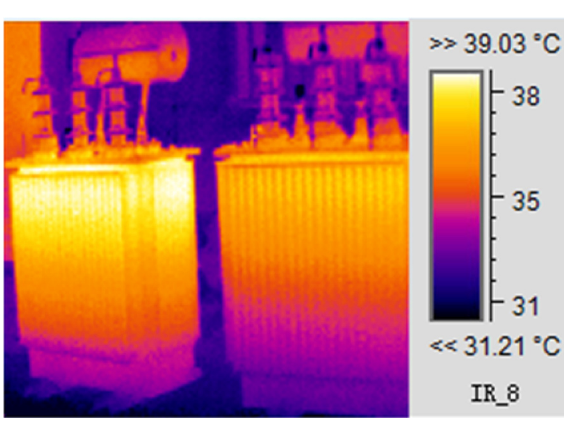

Fig. 5. Thermography of two transformers undergoing the short-circuit test.

transformer's lifetime and its body temperature was then investigated. In the following sections, we discuss the steps involved in conducting the present research.

All of the data introduced in part 3 (except for the thermal images) were in the form of numerical quantities that can easily be used. However, thermal images call for conducting an analysis using thermovision camera software. In the investigation of each thermal image, considering some of the measured parameters will result in higher accuracy of the temperature obtained from the thermal images taken. The information needed for the software of the camera includes radiation coefficient, humidity percentage, and environmental temperature, simultaneously with thermography and the distance between the thermograph and the

Table 2
The grouping of the transformers according to their production years.

Age of transformer (years)	Year of manufacture	Group Num.
1–3	2011–2013	1
4–6	2008–2010	2
7–9	2005–2007	3
10–12	2002–2004	4
13–15	1999–2001	5
16–18	1996–1998	6
19–21	1993–1995	7
20–24	1990–1992	8
25–27	1987–1989	8
28–30	1984–1986	10
31–33	1981–1983	11
34–36	1978–1980	12

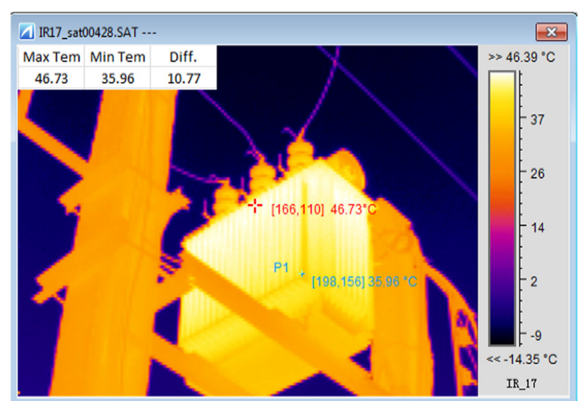

Fig. 6. The measurement of temperature difference after considering the parameters required for thermal imaging camera software.

Table 3
The transformer's lifetime group based on the temperature difference of the body.

Age of Transformer (year)	Calculated Temperature Difference (°C)	
	Upper Bound	Lower Bound
1–3	6.64	6.19
4–6	7.55	7.20
7–9	7.74	7.55
10–12	8.00	7.80
13–15	8.45	8.21
16–18	8.71	8.57
19–21	9.17	8.95
22–24	10.41	10.19
25–27	10.78	10.61
28–30	11.55	11.42
31–33	12.03	11.74
34–36	12.62	12.11

Table 4
The comparison of the findings of both methods.

	Results of Oil Test		Results of Thermography			
Row	DP*	Remaining Lifetime(year)	Temperature Difference (°C)	Age of Transformers (year)	Remaining Lifetime(year)	ERROR%**
1	23.94	0	14.3	>36	2.74	6.9
2	187.3	0	12.6	34--36	4.08	10.2
3	193.8	0	10.1	21--22	18.09	45.2
4	230.6	4.12	12.5	34-36	4.47	0.9
5	415.9	21.67	9	19--21	20.54	2.8
6	439.9	22.86	8.7	16--18	22.14	1.8
7	449.6	23.34	8.7	16--18	22.14	3.0
8	460.5	23.88	8.6	16--18	23.57	0.8
9	522.2	26.94	8.2	12--13	27.04	0.2
10	613.3	31.46	7.6	7--9	32.47	2.5
11	619.3	31.76	9.7	21--22	18.48	33.2
12	636.2	32.59	7.6	7--9	32.45	0.4
13	658.8	33.72	7.6	7--9	32.45	3.2
14	717.1	36.60	7.5	4--6	34.29	5.8
15	734.4	37.46	8.5	15--16	24.58	32.2
16	744.8	37.98	8	10--12	28	25.0
17	778.5	39.65	8.1	12--13	27.52	30.3
18	782.6	39.86	6.7	3--4	36.89	7.4
19	843.9	40	6.4	1--3	38.07	4.8
20	854.7	40	6.4	1--3	38.07	4.8
21	870.7	40	6.6	1--3	37.18	7.1
22	875.1	40	6	1--3	39.84	0.4
23	884.3	40	6.8	3--4	36.71	8.2
24	929.9	40	5.4	1--3	40	0.0

(*continued on next page*)

Table 4 (*continued*)

	Results of Oil Test		Results of Thermography			
Row	DP*	Remaining Lifetime(year)	Temperature Difference (°C)	Age of Transformers (year)	Remaining Lifetime(year)	ERROR%**
25	929.9	40	6.9	3--4	36.53	8.7
26	937	40	5.2	1--3	40	0.0
27	970.3	40	6.2	1--3	38.96	2.6
28	980.2	40	6.2	1--3	38.96	2.6
29	991	40	5.7	1--3	40	0.0
30	>1000	40	6.4	1--3	38.07	4.8
31	>1000	40	5.6	1--3	40	0.0
32	>1000	40	5.4	1--3	40	0.0
33	>1000	40	6	1--3	39.84	0.4
34	>1000	40	6.5	1--3	37.6	6.0
35	>1000	40	4.8	1--3	40	0.0
36	>1000	40	4	1--3	40	0.0
37	>1000	40	5.3	1--3	40	0.0
38	>1000	40	6.6	1--3	37.18	7.1
39	>1000	40	6	1--3	39.84	0.4
40	>1000	40	5.3	1--3	40	0.0
41	>1000	40	6.2	1--3	38.96	2.6
42	>1000	40	5.2	1--3	40	0.0
43	>1000	40	5.5	1--3	40	0.0
44	>1000	40	5.2	1--3	40	0.0
45	>1000	40	5.4	1--3	40	0.0
46	>1000	40	5.5	1--3	40	0.0
47	>1000	40	5.6	1--3	40	0.0
48	>1000	40	6.7	3-4	36.89	7.8
49	>1000	40	9.1	19-21	19.64	50.9
Average of ERROR% =						**6.8**

* Degree of polymerization **((column 3 – column 6)*100)/40.

transformer, which is adjustable for acquiring a more accurate temperature.

From the above-mentioned parameters, the radiation coefficient depends on the material and color of the body. The material and color of the body are commonly provided in tables, and they cannot not accurately be measured; different colors and materials as well as the dirt of the body prevent the accurate measurement of the radiation coefficient of each transformer. Thus, to reduce the effect of this parameter, some studies have taken the maximum and minimum temperature differences of the body of transformers into account [20,21].

In addition to reducing the effect of radiation coefficient, this temperature difference significantly reduces the transformer's loading effect on the results. The studies conducted in this area indicate that momentary load changes of the transformers have no effect on their lifetimes. However, the loading record of the transformer will certainly affect its lifetime.

After preparing the data, the difference criterion of the hot spot temperature as well as the cold spot temperature of the transformer's body were evaluated to estimate the lifetime of the distribution transformers. In doing so, depending on their production years provided in Table 2, as many as 144 transformers were categorized into 12 lifetime groups and each group has 12 transformers. These transformers had not experienced any accidents or overloads and their production years were equal to their lifetime.

As can be seen in Table 2, the lifetime range of each group is three years. This was determined based on the 1 to 36 year lifetime range of the transformers and the maximum and minimum temperature difference of the body of the transformers.

The measurement indicated that the maximum and minimum temperature difference of the body of transformers for the 36 years of their lifetime ranged from 6 to 13 degrees centigrade. This limits reduction of the lifetime range of each group to less than 3 years.

Fig. 6 shows an example of measuring the temperature difference of a transformer's body after considering the environmental conditions.

After measuring the temperature difference and grouping the transformers, the mean and standard deviation of each group were measured, and the confidence interval of each group was determined using Bonferroni's confidence interval estimation method. The findings indicate that for each lifetime group, the range related to the temperature difference does not interfere with the other lifetime groups. Thus, through using this method, the transformer's lifetime is estimated by using the temperature difference under the aforementioned conditions. Then the transformer is placed in one of the suggested lifetime groups.

It is also worth noting that in Bonferroni's confidence interval estimation method, given the error level of 0.02. The details of the findings will be presented in the following section.

5. Results

Given the temperature difference in choosing 12 transformers for each lifetime group using Bonferroni's method, the confidence interval of the temperature difference appropriate for each group was determined and the results are shown in Table 3.

As was discussed in part 3, to test the proposed method of the present study, the oil samples of 49 transformers were collected simultaneously with thermal imaging. The remaining lifetime of the aforementioned 49 transformers was estimated through using the oil test and the proposed algorithm methods, and the findings were provided in Tables 1 and 3, respectively. The comparison of the findings of the two methods is provided in Table 4.

As can be seen in Table 4, the findings of the oil test as well as those of the proposed algorithm were comparable in 43 cases with error percentage[2] less than 10%. Also average of percentage of errors is 6.8%. This indicate that, the proposed method can estimate remaining lifetime of transformers similar to oil test finding.

6. Conclusion

In the present study, a new method was provided for estimating the lifetime of distribution transformers. In this method, the remaining lifetime of distribution transformers is estimated through applying thermal imaging from the body of the transformers, without conducting the common tests.

For this purpose, as many as 193 transformers were tested. The selected transformers underwent thermal imaging of these transformers, as many as 144 undamaged and intact transformers were selected; these transformers had not experienced any accidents or overloads. Moreover, their production years were equal to their lifetime. These transformers were used for providing the proposed algorithm. As many as 49 transformers underwent the oil test, and their lifetime was measured through applying the frequently used methods. Simultaneously with thermal imaging, other required field information, including environmental temperature and humidity as well as the loading of the transformers, was measured.

The proposed algorithm indicates the relationship between the temperature difference of hot spot as well as cold point with the real lifetime of the transformers. For the 144 investigated transformers, as many as 12 three-year lifetime ranges were determined using Bonferroni's method.

The results obtained from the lifetime estimation of the transformers using the proposed algorithm were similar to the findings obtained from the lifetime estimation of the transformers by using the oil test. Of the 49 transformers tested, as many as 43 transformers had similar finding with error percentage less than 10%. Total average of error percentage is 6.8%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. (A)

In statistics, multiple testing problem occurs when one considers a set of statistical inferences simultaneously or infers a subset of parameters selected based on the observed values. Two of them are Bonferroni test and *t*-test.

A Bonferroni test is a type of multiple comparison test used in statistical analysis. When an experimenter performs enough hypothesis tests, he or she will eventually end up with a result that shows statistical significance of the dependent variable, even if there is none. The *t*-test can be used to determine if the means of sets of data are significantly different from each other and variables are independent.

So in this research, Bonferroni confidence interval is used and explained as in the following.

Confidence Interval

In any n-dimensional space, one can determine the upper and lower bounds for the data that fall into the same category, so that a set of data whose entire aspects are within the same interval can be categorized as the same category. For a one-dimensional space,

[2] Error percentage is difference the remaining lifetime of two method divided by total lifetime(40 year) in percent

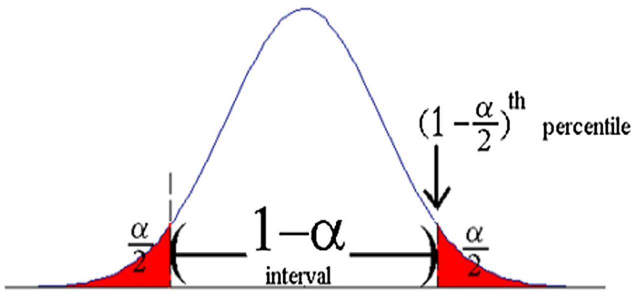

Fig. A-1. A schema of determining the confidence interval in each space dimension.

which is the topic of discussion in the present study, as can be seen in Fig. A-1, one can define the upper and lower bounds for each category that have the same characteristics by using the interval of each set of data from the origin of the coordinates [22]. In fact, the center of each category is the mean interval of the data and the origin of the coordinates. The intervals of the upper and lower bounds from the mean of each category is equal, and it is measured through using Equation 1.The confidence interval determined for the center of each category is reliable when: 1. it does not interfere with the confidence interval of the other categories; and 2. the information of the new set of data is exactly at the confidence interval of a category corresponding to it [23].

To achieve the confidence interval, it should first be made clear what level of confidence interval is acceptable. The confidence intervals considered in most of the study are 90%, 95%, and 99%. This means that if the study is repeated 100 times, in 90, 95, and 99 percent of the cases the same range will be achieved. The farther the interval confidence is from 100, the less accurate the study will be.

By using the existing data, one is able to determine a range with upper and lower bounds around the mean of the data, so that the new data and information are within that range with a significant confidence. This confidence interval will be measured using Eq. (1) [24].

$$CI = \mu \pm Z_{(1-\alpha/2)}(\sigma/\sqrt{n}) \tag{A-1}$$

In which n is the number of samples, μ is the mean of the samples, σ is the variance of the samples, Z is the confidence coefficient (from the confidence coefficients table), α is the estimated error level, or error level for short, and 1- α is the confidence level. The confidence level needs to be at a level that satisfies the researcher, and it is considered to be within 90% to 99%.

For example, if the error level is α = 0.05, the confidence interval will therefore be 1-α = 0.095. Thus, a confidence interval of 95% for the mean of the population will have an upper bound as well as a lower bound.

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