Life Time Estimation Method for the Feeder Transformers

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In order to prevent damage and to extend the lifespan of equipment in railway power systems, it is necessary to detect early on any deterioration and to assess the residual lifespan of feeder transformers. As such a database containing information about the three main conditions affecting feeder transformers was constructed. First, load characteristics were researched to evaluate thermal deterioration. Second, analytical data of dissolved gas-in-oil was examined to evaluate damage from partial electric discharge. Third, the amount of furfural was investigated to evaluate the deterioration characteristics of insulating paper for feeder transformers. Based on the results of these investigations a lifespan estimation method for feeder transformers was developed. The validity of the estimation method was verified comparing experimental values with estimated values.

Keywords: feeder transformer, insulating paper, dissolved gas analysis, furfural analysis

1. Introduction

Periodical inspection is the typical method for identifying feeder transformer deterioration in railway power supply systems. Usually the heavier the load becomes on a transformer, the larger the increase in temperature of the oil-immersed transformer. Consequently, various materials generated by the deterioration of insulating papers and oils, and from partial damage discharge due to faults during operation [1, 2]. This is why a periodic analysis is performed of any materials resulting from deterioration and dissolved in the insulating oil. Otherwise, overhaul and replace of ageing transformers is determined on the basis of criteria, in the form of values, and the maintenance guidelines. In Japan, maintenance guidelines are usually set in accordance with ministerial ordinances, international standards, or manufacturer recommendations.

It is known that manufacturers and technology organizations usually consider the serviceable life of a transformer to be 25 to 30 years, following which replacing the transformer is recommended [3]. Unfortunately, the downtime available for replacing or maintaining this type of equipment is usually only a few hours in the middle of the night for substations on a commercial railway. Previous studies report that replacement of equipment is expensive and construction is often delayed because securing a work slot is difficult [4]. As such, there is demand for a new evaluation method to determine whether an old transformer needs to be replaced, or whether its serviceable life can be prolonged through further maintenance.

Methods for analyzing deterioration based on dissolved gas analysis (DGA) or furfural (2-FAL) analysis were developed after the 1980s [1, 2, 5, 6]. In 1999 a detailed report on research into transformers on Japan’s power grid was published by the Electric Technology Research Association (ETRA) [5]. However, few reports mention life assessment of feeder transformers on railways [7]. Equally, there are not many reports on the soundness of insulating paper used on feeder transformer windings because the insulation paper can only be analyzed during an overhaul or if the transformer is being rebuilt. In addition, the load characteristics of transformers used on railways differ between rush hour and off-peak hours. Compared to daytime loads on power grids, railway loads fluctuate intensely. Taking this into consideration databases were built to gather these variable feeder transformer conditions, such as the temperature of isolating oils and data from dissolved gas-in-oil analyses. Subsequently, based on the processed data, a correlation was found between the age of the transformer and the number of specimens exceeding the gas value criteria. Then investigations were carried out to ascertain whether the database could be applied to evaluate the residual life of the transformer. Finally several specimens of winding insulation paper were extracted from feeder transformers when being disassembled, and measured soundness was compared with soundness estimated from analyses of the amount of furfural dissolved in the oils. The results of this research were applied to develop a method for estimating the serviceable life of feeder transformers.

2. Feeder transformer condition databases

2.1 Deterioration model of a transformer and inspection periods

A transformer mainly consists of an iron core, a winding (made from a copper conductor) and insulators for relevant components (including the insulating paper, insulating oil, insulating compounds and so on). As mentioned above, the soundness of the transformer is generally evaluated by analyzing the material generated through deterioration and dissolved process in the insulating oil. Figure 1 shows a typical model of a deteriorated transformer.

Usually each railway company establishes its own internal regulations, detailed method and intervals for...
In the aged transformers, the degradation of the insulation may occur.

If internal faults occur, various gases may be generated.

Analysis of the insulating oils

Fig. 1 Typical deterioration model of a transformer

Table 1 The researched interval cycle of the DGA researched in Japan

(a) Railway company maintenance sites

| Item                          | Site A                          | Site B                          | Site C                          |
|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Inspection interval of insulating oil | Every five years (after 10 years use) | Every five years (if the deterioration of oil is detected, every one year) |

(b) Power grid company maintenance sites [8]

| Item                          | For transmission lines | For distribution lines |
|-------------------------------|------------------------|------------------------|
| Inspection interval of insulating oil | Every year            | Every three years      |

Table 2 Data collected for feeder transformers

| Item                          | Max temperature of the oil | Gas-in-oil analysis (DGA) | Furfral analysis (2-FAL) |
|-------------------------------|-----------------------------|---------------------------|--------------------------|
| Transformers for rectifiers   | 239                         | 182                       | 42                       |
| Transformers for distribution lines | 73                         | 60                        | 21                       |
| Transformers for AC feeding circuits | 13                         | 20                        | 6                        |
| Transformers for operation    | -                           | 6                         | -                        |
| Oil-immersed rectifiers       | -                           | 16                       | -                        |
| Total amounts                 | 325                         | 284                       | 69                       |
| Purpose of the survey         | To grasp the deterioration due to temperature rise | To grasp the deterioration due to partial discharge | To grasp the soundness of the insulating papers |

Every year - 284
60 - Site C
69 - (1)
182 - Site B
325 - (2)
73 - Site A
325 - Site A
325 - Total amounts
182 - Site B
182 - Site B
182 - Gas-in-oil analysis (DGA)
21 - Furfral analysis (2-FAL)
239 - Transformers for rectifiers
239 - Transformers for rectifiers
239 - Transformers for rectifiers
73 - Transformers for distribution lines
73 - Transformers for distribution lines
73 - Transformers for distribution lines
69 - Furfral analysis (2-FAL)
20 - Transformers for AC feeding circuits
20 - Transformers for AC feeding circuits
20 - Transformers for AC feeding circuits
6 - Furfral analysis (2-FAL)
16 - Oil-immersed rectifiers
16 - Oil-immersed rectifiers
16 - Oil-immersed rectifiers
- - Furfral analysis (2-FAL)
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2.2 Construction feeder transformer condition databases

Evaluating the residual life of transformers requires various kinds of maintenance data. There is often little difference in the structure of transformers made by different manufacturers, and many facilities are managed according to the same maintenance procedures.

As described earlier, it was mentioned that the deterioration of the insulation is affected by the temperature of the feeder transformer. The temperatures and load data are therefore collected regularly for load management, which means that statistical processing can be used on the data. In addition, various types of data obtained from feeder transformers in operation were collected, including temperature and DGA data from cooperating railway companies. Using the collected data, a database was built for the three types condition affecting the feeder transformers. The collected data is shown in Table 2.

2.3 Research into deterioration with a focus on the relationship between the temperature of the insulating oil and load characteristics

2.3.1 Survey of the Correlation between each item

Generally, the higher the load factor and demand factor, the higher the temperature of the transformer, which leads to insulation deterioration. However, it is expected that, although this may be true for power grids, this may not be suitable for the railways because of load fluctuation. Investigations were therefore carried out of the relationship between summer maximum temperatures of the transformer and load factor, between summer maximum temperatures of the transformer and the demand factor, and between summer maximum temperatures of the transformer versus nominal capacity. A coefficients of the correlation was also derived in order to understand the relation between these items of data. An examination of the null hypothesis was performed using t-tests at the preset significance level (5 %). The equations used for this examination were as follows: (1), (2).

\[
C_{xy} = \frac{s_{xy}}{s_x s_y}
\]

where \(C_{xy}\) : correlation coefficient ; and \(S_{xy}\) : covariance ; and \(S_x, S_y\) : variance ;

\[
T = \frac{(n-2)C_{xy}^2}{1-C_{xy}^2}
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\[
T = \frac{(n-2)C_{xy}^2}{1-C_{xy}^2}
\]
where $T$ = test statistic; 
n = number of participants;

If the coefficient of the correlation is close to 1, it means that the equilateral relationship is strong. In addition, the hypothesis that "there is no correlation" is dismissed when the statistic $T$ is bigger than the significance level.

The results are shown in Table 3 and Table 4. The relationship represented in a scatter diagram is shown in Fig. 2. No notable correlation appears to exist between each item. According to the relationship between the demand factor and the characteristics regarding maximum temperature, the max coefficient of the correlation was only 0.331. In addition, no clear relationship appears between items in the scatter diagram analysis either. The next section, discusses the cause from the viewpoint of daytime load characteristics.

It was mentioned that the average values of the demand factor of transformers for rectifiers was 41 %, 31 % for the load factor, 4250 kVA for nominal capacity, and that the maximum temperature was 47°C. It was also mentioned that the average values of the demand factor of the transformers for distribution lines was 38 %, 31 % for the load factor, 2530 kVA for nominal capacity, and that the maximum temperature was 50°C.

The bar graph of the maximum summer temperatures of the transformer are shown in Fig. 3. The peak temperature in many transformers was less than 60°C. This is within the permissible temperature rise stipulated by the JEC 2200 standard (i.e. an ambient temperature of 25°C : 55 K + 25°C = 80°C). The temperatures found for transformers for distribution lines were slightly higher than those for transformers for rectifiers.

### Table 3  Relationship between items (transformers for rectifiers)

| Items                        | Correlation coefficient | T-test | Results (significance level : 5 \%, n = 239, judgment value = 1.970)                          |
|------------------------------|-------------------------|--------|-------------------------------------------------------------------------------------|
| Max temperature vs. demand factor characteristics | 0.142                   | 2.213  | There was a little correlation between those (the null hypothesis was discarded)      |
| Max temperature vs. load factor characteristics          | 0.124                   | 1.920  | The null hypothesis could not be discarded                                           |
| Max temperature vs. typical capacity characteristics      | 0.052                   | 0.798  | The null hypothesis could not be discarded                                           |

### Table 4  Relationship between items (transformers for distribution lines)

| Items                        | Correlation coefficient | T-test | Results (significance level : 5 \%, n = 73, judgment value = 1.994)                     |
|------------------------------|-------------------------|--------|-------------------------------------------------------------------------------------|
| Max temperature vs. demand factor characteristics | 0.331                   | 2.957  | There was a little correlation between those (the null hypothesis was discarded)      |
| Max temperature vs. load factor characteristics          | -0.028                  | 0.236  | The null hypothesis could not be discarded                                           |
| Max temperature vs. typical capacity characteristics      | -0.070                  | 0.588  | The null hypothesis could not be discarded                                           |
2.3.2 Observations regarding daytime load characteristics

No clear correlation was found between maximum temperatures and load factors. Therefore, the detailed characteristics of the transformers were examined using the data provided at the substation where the temperature was recorded hourly. Transformers installed along the same route were chosen as the subjects for the survey which was located near an urban area and had ten-car trains passing every ten minutes. Observations were carried out on a Wednesday in August, 2015. It was a fine day, and the max outside temperature was 31°C.

An example is shown in Fig. 4. Usually transformers for rectifiers are shut down at night. Therefore, the measured temperature was lower in the early morning. The temperature began to rise gradually during the rush hour later in the day, and reached its peak in the afternoon to evening period. The maximum temperatures of the other twelve transformers along the route were recorded from the afternoon through to the middle of the night. The peak temperature for some transformers for distribution lines reached their peak between the afternoon and the middle of the night, while others maintained the same temperature through the day.

The results shown above indicate that the temperatures of most transformers for rectifiers did not reach their maximum during rush hours. This suggests that there is no clear correlation between the maximum temperature and the load factor. A weak correlation was observed between the demand factor and the temperatures of transformers for distribution lines. The reason for this is that transformers for distribution lines are not stopped at night, and their temperatures were therefore maintained by load losses such as illumination and no-load loss in their iron core.

2.4 Survey of transformer DGA data

As mentioned in section 2.1, various gases are produced by insulating material and dissolve in the oil when insulating papers and oils in the transformer deteriorate. The soundness of a transformer can be assessed during inspection based on values obtained from an analysis of this phenomenon.

An analysis was therefore carried out to perform an age assessment of the transformer. Analytical data from the transformer insulator was also examined to see if it could be used to estimate the transformer’s serviceable life. It is noticeable that inspections are repeated for each transformer. The analysis was therefore conducted using a number of specimens. For reference, an oil-immersed type rectifier was also analyzed. Table 5 summarizes data by type of equipment. The criterion values recommended by references [5] and [6] are shown in Table 6. In Fig. 5, the ratios between the well-conditioned transformers and the ill-conditioned transformers which are in minor failure are also shown by five-year-aging range.

| Item of equipment                              | Number of inspected instruments | Number of specimens | Number of specimens (exceeding the criterion value based upon the reference No.5) | Average of the deteriorated instruments | Average aging |
|-----------------------------------------------|---------------------------------|---------------------|---------------------------------------------------------------------------------|----------------------------------------|--------------|
| Oil-immersed rectifiers                       | 16                              | 31                  | 10                                                                              | 32 %                                    | 22.7 years   |
| Transformers for rectifiers                   | 182                             | 350                 | 40                                                                              | 11 %                                    | 18.5         |
| Transformers for distribution lines           | 60                              | 114                 | 48                                                                              | 42 %                                    | 17.6         |
| Transformers for AC feeding circuits          | 20                              | 33                  | 6                                                                               | 18 %                                    | 24.0         |
| Transformers for operation                    | 6                               | 6                   | 1                                                                               | 17 %                                    | 28.5         |
| Total amounts                                 | 284                             | 534                 | 105                                                                             | —                                       | 18.3         |
Table 6  Criterion values [5, 6]

|                     | H₂ | CH₄ | C₂H₆ | C₂H₄ | C₂H₂ | CO  | TDCG |
|---------------------|----|-----|------|------|------|-----|------|
| ※ Criterion value   |    |     |      |      |      |     |      |
| (based upon         |    |     |      |      |      |     |      |
| the reference No.5  |    |     |      |      |      |     |      |
| (ppm)               | 400| 100 | 150  | 10   | 0.5  | 300 | 500  |
| ※ Criterion value   |    |     |      |      |      |     |      |
| at condition 1      |    |     |      |      |      |     |      |
| (based upon the     |    |     |      |      |      |     |      |
| reference No.6      |    |     |      |      |      |     |      |
| (ppm)               | 100| 120 | 65   | 50   | 35   | 350 | 720  |

The study revealed that one or more gas indicators exceeded the criterion value in approximately 20% of all specimens. Transformers for distribution lines were characterized by deterioration starting at a relatively young age (sometimes 10-15 years old). References [5] suggests a technique for assessing deterioration from the ratio of three kinds of gases (C₂H₆, C₂H₄, C₂H₂). However, there were only 2 specimens in which three kinds of gases were detected at the same time. In many specimens, only one or two kinds of gases were detected.

The relationship between total dissolved combustible gas levels (TDCG; TDCG consists of H₂, CH₄, C₂H₆, C₂H₄, C₂H₂, and CO) and the age of the transformer is shown in Fig. 6 to assess the validity of the techniques sued for understanding deterioration based on TDCG tendencies. The tendency for TDCG to increase suddenly because of aging was not seen. In addition, the coefficient of correlation between TDCG data and aging was only 0.259. Therefore, though the TDCG data is suitable for determining soundness when conducting specimen analysis, it is difficult to use tendencies in TDCG data to estimate the lifespan of a transformer.

3. Development of a method to estimate the lifespan of feeder transformers

3.1 Evaluation of soundness of winding insulating paper based on specimens retrieved during disassembling work and a survey of existing literature

The degree of polymerization (DP) of cellulose in the insulating paper is one of the properties greatly influencing the mechanical strength of transformer windings [2, 9, 10]. A decrease in the mechanical strength of the transformer winding induces risk of a serious accident occurring in the case of an overcurrent. In addition, extracting the insulating paper directly from a transformer during operation and replacing the transformer winding is very expensive. Therefore, the lifespan of a transformer is deemed to end with the decreases of the transformer winding strength. It is generally accepted that DP can be estimated by analyzing the furfural concentration in the oil which is an indication of deterioration in the cellulose molecules.

The quantity of furfural formed by the insulating paper may change with the load characteristics of the transformer. For example, the temperature of insulating oil rises mainly near the upper winding where the transformer load is heaviest. This means that insulating paper in the upper area of the winding deteriorates more easily, and as the load rises, furfural generation becomes more concentrated in the upper windings. Insulating papers were therefore extracted from feeder transformers (along a High Speed...
line) being disassembled according to manufacturer recommendations (over 30 years), and their soundness measured. In order to compare the characteristics of deterioration, measured DP examples of feeder transformers and power grid transformers were collected through a survey of available literature. The method used for extracting the insulating papers is shown in Fig. 7, while survey data of the soundness of the papers obtained with a base reference soundness value of 100 % is shown in Table 7 [7, 9].

Table 7  Data from survey of measured soundness [reference 7, 9]

| Age of the instrument | Soundness of the paper (measured) | Transformer Type |
|-----------------------|----------------------------------|-----------------|
|                       | (Initial value = 100 %, Criterion value = under 45 %) |                  |
| Upper area of the transformer | Lower area of the transformer |                  |
| 34 years              | 56 %   | 65 %   | For power grid (according to the reference No.9) |
| 37 years              | 50 %   | 68 %   | For power grid (according to the reference No.9) |
| 36 years              | 65 %   | 64 %   | For AC feeding (High speed railways-1) |
| 41 years              | 65 %   | 66 %   | For AC feeding (High speed railways-2) |
| 38 years              | 63 %   | 65 %   | For rectifiers (rural area railways) (according to the reference No.7) |

Table 7 indicates that the soundness of windings in electric power company transformers differs between the upper and lower areas, and that deterioration in the upper area progressed faster than in the lower area. Progress of deterioration in the railway feeder transformers however was slower, considering the age of the feeder transformers. Deterioration of feeder transformer windings therefore need to be considered under light load conditions, and a model in which the windings deteriorate gradually and continuously could represent the deterioration of a normal feeder transformer.

3.2 Comparison of actual and estimated soundness values derived from the quantity of furfural

 Given the expense of assessing insulating paper soundness only through demolition of the transformer, this type of evaluation is usually difficult. It is therefore necessary to determine soundness from the quantity of furfural which can be extracted easily during operation.

A correct estimate result however is hard to be obtained unless the various influencing factors, related to the detailed specifications of the transformers etc., are taken into account. The measured values shown in Table 7 were compared with values estimated from the quantity of furfural. The amount of furfural per unit mass of paper can be calculated using the following equation (3).

$$F = (f_1/d) \times O \times S / P_a$$  \hspace{1cm} (3)

Where parameter $F$ is the amount of furfural per unit mass of the paper (mg/g), parameter $f_1$ is the amount of furfural per unit mass of insulating oil (mg/g), parameter $d$ is the dissolution ratio of furfural to the insulating oil, parameter $O$ is the amount of insulating oil (L), parameter $S$ is the density of the insulating oil (kg/L, $S = 0.89$), and parameter $P_a$ is the mass of the paper relating to the formation of furfural. From equation (3), it is understood that the definition of the correct mass of paper is necessary to evaluate the soundness of the insulating paper. According to railway companies, both the load factor and demand factor of the transformers were under 20 %, and the max temperature of the transformers was also lower than the criterion value. The parameter $P_a$ was therefore defined as the whole mass of paper including both insulating paper of the winding and press board. Parameter $d$ was consequently defined as 100 % (i.e. absorption of furfural was ignored).

Several characteristics have been proposed for estimating the soundness of insulating paper from the quantity of furfural [5]. However, the characteristics suitable for esti-
mations in a railways in context have not been so far clarified. This study opted to use two characteristic expressions and compared the actual value of the soundness with the estimated values derived from the quantity of furfural. The characteristics are shown in Fig. 8.

In technique A, the soundness was calculated in consideration of the low temperature of the transformer. When using technique A, the actual value and the estimated value were in relative agreement. In technique B, the characteristic expression was obtained by taking into account electric power grid transformers which are operated in a high temperature environment. Technique B however produced a large disparity between the actual and estimated value.

In technique A, the estimated value was the same as or lower than the actual value. It is thought that applying technique A avoids over estimating the residual lifespan.

### 3.3 Evaluation of the soundness of the paper using the amount of furfural

This section discusses the soundness and the residual life of the insulating paper. The deterioration of the insulation paper progresses at a constant rate of decline relative to the length of time the transformers are operated. As such, the residual life of the insulating paper is expressed generally through the regression equation (4) and the conversion equation (5).

\[
PR / PR_e = (1 - r)^N \tag{4}
\]

\[
Y = \ln(PR_e / PR) / \ln(1 - r) \tag{5}
\]

where parameter \(PR_e\) is the initial soundness of the insulating paper (= 100 %), parameter \(PR\) is the estimated soundness of the insulating paper, parameter \(PR_e\) is the criterion value of the soundness (ETRA recommends 45 %), parameter \(r\) is the constant annual rate of decline, parameter \(N\) is the duration of the operation of the transformers and parameter \(Y\) is the estimated residual life.

For example, the following equation was applied to the specimens mentioned in section 3.1. According to the result, \(1 - r = 0.9895\) was obtained from a calculation based on \(n = 41\) years and \(PR = 65\ %\), and the residual life was estimated at 35 years. The characteristics of the estimated soundness converted from the amount of furfural measured in railway company transformers are shown in Fig. 9. The curve shows the characteristics of the progression in deterioration obtained on the assumption that the insulating paper reached the end of its lifespan at 30 years based on the manufacturer’s recommendation. As the insulating paper reached the end of its lifespan at 30 years based on the consideration of the insulator reached the end of its lifespan at 30 years.

4. Conclusions

In order to prevent equipment damage and to extend the lifespan of equipment, databases were compiled to grasp the conditions affecting feeder transformers. Several specimens of winding insulating paper were extracted from feeder transformers during disassembling, and measured soundness values were compared with estimated values.

Based on the results of these investigations, a new estimation method for the lifespan of feeder transformers was developed. The results of this research can be summarized as follows:

1. Databases containing conditions affecting feeder transformers were compiled and a study was conducted to ascertain whether the data obtained through analysis of a transformer’s insulator could be applied to estimate the lifespan of transformers. Results showed that there was no clear correlation between the maximum temperature and load factor. In addition, the coefficient of correlation between TDCG and aging was low. Therefore, it is difficult to apply this data to evaluate transformer lifespan.

2. Using the measured soundness of the insulating papers extracted from feeder transformers during disassembling, the validity of techniques to determine deterioration by the amount of furfural was investigated. Results showed that the estimated soundness which was calculated in consideration of the low temperature of the transformer and the actual soundness, were in relative agreement. In addition, there was no specimen whose deterioration exceeded the criterion value.

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Fig. 9 Estimated soundness of railway transformers
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