Voltage-time Characteristics and Reliability Evaluation Method of Oil-filled Transformer for Non-effectively Grounded Voltage Class

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Keywords: oil-filled transformer, V-t characteristics, power frequency withstand voltage test, Weibull distribution, reliability evaluation

JEC-0102-1994 “Standard for Test Voltages” specifies long-term power frequency withstand voltage tests for effectively grounded systems at nominal voltages of 187 kV and above. In these tests, insulation performance with respect to normal voltages over the period of use or one-line ground faults, load rejection, and other temporary overvoltage occurrences are tested. For non-effectively grounded systems of 154 kV and below, there is little advantage to long-term power frequency withstand voltage tests given the magnitude of temporary overvoltage and the economics of testing among other considerations, and so introduction of such testing systems has been deferred.

At present, work has been initiated to revise the JEC-0102-1994 standard for the introduction of power frequency withstand voltage tests with lowered test voltages for non-effectively grounded systems, in light of applications to metal oxide arresters with high protection performance, advances in overvoltage analysis techniques, improvements in the expedience of partial discharge (PD) tests through enhancement of test equipment performance, and other factors.

In determining the testing conditions for long-term power frequency withstand voltage tests, insulation reliability is evaluated using Weibull distributions. However, there have only been several experiments regarding Weibull parameters for such reliability evaluation about oil-filled transformers for use at 500 kV and above, and there are as yet no experiments describing Weibull parameters for 66 to 154 kV oil-filled transformers.

This paper first experiments Voltage-time (V-t) characteristics of 66–154 kV oil-filled transformers, and describes the statistic results of Weibull parameters. Then, the Weibull parameters of this experiment are analyzed in conjunction with existent data. Finally, results of trial calculation of insulation reliability evaluation under various conditions are experimented. The following results were obtained in this paper.

(1) AC short-term part Weibull parameters of main insulation (barrier-oil-duct models) for 66/154 kV class oil-filled transformers were \( n = 40.0, a = 0.20, m = 8.0 \).

(2) Cumulative frequency 50% values of previous Weibull parameters including this experimental results were \( n = 34.9, a = 0.39, m = 13.1 \), equivalent to the parameters of JEC-0102.

(3) Based on the above results, reliability evaluation values were calculated for the short-term part of power frequency withstand voltage tests of 66–154 kV non-effectively grounded systems. In evaluations using the conventional method of the assumed overvoltage, at test voltages of 2.9 pu and below the reliability was less than 98%. In evaluations using the cumulative fault method, at a test voltage of 2.9 pu the reliability was 99% or above.

Table 1. Insulation reliability evaluation results for the short-term (one-minute) part of power frequency withstand voltage tests of 154 kV systems

<table>
<thead>
<tr>
<th>Test voltage</th>
<th>2.4pu</th>
<th>2.9pu</th>
<th>3.4pu (Current value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull parameters (m, a values)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>JEC value</td>
<td>Value in this study</td>
<td>Cumulative 50% value</td>
<td>JEC value</td>
</tr>
<tr>
<td>m=11.75, a=0.39</td>
<td>m=8.0, a=0.20</td>
<td>m=13.1, a=0.39</td>
<td>m=11.75, a=0.39</td>
</tr>
<tr>
<td>Reliability for TOV</td>
<td>Conventional method</td>
<td>58.4%</td>
<td>13.5%</td>
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<tr>
<td></td>
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The power frequency withstand voltage tests are specified on electric power equipment in JEC-0102 by evaluating the lifetime reliability with a Weibull distribution function. It may be applied on 66–154 kV transformer for non-effectively grounded voltage class. The present paper describes the results that measured AC insulation characteristics (Voltage-time characteristics) and Weibull parameters for oil-filled transformer of 66–154 kV class. These measurement parameters were compared with the conventional Weibull parameters, which were applied for oil-filled transformer of voltage class above 154 kV. Furthermore the non-partial discharge test voltage was evaluated by trial calculations, using the parameters obtained this time or typical parameters.

Keywords: oil-filled transformer, V-t characteristics, power frequency withstand voltage test, Weibull distribution, reliability evaluation

1. Introduction

JEC-0102-1994 “Standard for Test Voltages” specifies long-term power frequency withstand voltage tests for effectively grounded systems at nominal voltages of 187 kV and above (1). In these tests, insulation performance with respect to normal voltages over the period of use or one-line ground faults, load rejection, and other temporary overvoltage occurrences are tested. For non-effectively grounded systems of 154 kV or less, there is little advantage to long-term power frequency withstand voltage tests given the magnitude of temporary overvoltage and the economics of testing among other considerations, and so introduction of such testing systems has been deferred.

At present, work has been initiated to revise the JEC-0102-1994 standard for the introduction of power frequency withstand voltage tests with lowered test voltages for non-effectively grounded systems at 154 kV and below, in light of applications to metal oxide arresters with high protection performance, advances in overvoltage analysis techniques, improvements in the expedience of partial discharge (PD) tests through enhancement of test equipment performance, and other factors.

In determining the testing conditions for long-term power frequency withstand voltage tests, insulation reliability is evaluated using Weibull distributions. However, there have only been several experiments regarding Weibull parameters for such reliability evaluation about oil-filled transformers for use at 500 kV and above, and there are as yet no experiments describing Weibull parameters for 66 to 154 kV oil-filled transformers (2–4).

This paper first experiments Voltage-time (V-t) characteristics, which are necessary to evaluate the insulation reliability of 66–154 kV oil-filled transformers, and describes the statistic results of Weibull parameters. Then, the Weibull parameters of this experiment are analyzed in conjunction with existent data. Finally, results of trial calculation of insulation reliability evaluation under various conditions are experimented.

2. Experimental Methods

In recent years, it is generally detecting PD, which is a precursor phenomenon to dielectric breakdown (BD), in power frequency withstand voltage tests. The V-t characteristics for PD were obtained for 66–154 kV oil-filled transformers. At the same time, the V-t characteristics for BD were also obtained. As the time range considered, power frequency/short-term V-t characteristics for up to approximately one hour were obtained. Because there is a high possibility of rational insulation design through lowering of short-term power frequency withstand voltage.

2.1 Determination of Insulation Test Models

The ratio of the lightning impulse withstand voltage to the power frequency withstand voltage (peak value) for oil-filled transformers was 1.8 at 66 kV, and 1.6 at 154 kV (5). On the other hand, the relation of the ratio of the lightning impulse breakdown voltage to the power frequency breakdown voltage (peak value) is held to be greater than 2 between windings and the core, and smaller than 1.8 for breakdown within coils (6). That is, power frequency voltage characteristically determines the insulation between windings and the core, being barrier-oil-duct structures, and the lightning impulse voltage characteristically determines insulation within coils (4). Hence barrier-oil-ducts (main insulation) were considered in studies of power frequency withstand voltage tests in this research.

The insulation test models were represented by 66 kV class
transformer model, because 66 kV transformers and 154 kV transformers are thought not to be significantly different with respect to the insulating oil-duct near the primary windings and sections. The insulation characteristics of the transformer windings are due principally to the higher-voltage windings, and the lower-voltage windings (22 kV, 6.6 kV, etc.) are common regardless of the voltage class. So, the primary-side (higher-voltage side) model was used.

JIS type 1 No. 2 mineral oil, used in oil-filled transformers, was employed as the insulating oil (6).

2.2 Structure of the Insulation Test Model The structure of the barrier-oil-duct models used in this experiment is shown in Fig. 1. This model is the insulation elements in an actual 66 kV oil-filled transformer.

The model structure consists of pressboard 1 assuming as insulation coating wire thickness of 0.5 mm, and pressboard 2 assuming as insulation tube of thickness 3 mm, enclosed between electrodes of diameter 250 mm; a spacer of diameter 100 mm and thickness 6 mm is inserted between the pressboards to form the oil-duct. The edge of the spacer was chamfered in order to avoid electric field concentration. Compared with 500 kV-class models (2) or UHV-class models (3), in this model the oil-duct is made wider from the standpoint of cooling performance and insulation design.

2.3 Experimental Procedure The procedure for assembly and testing of the model was as follows.

1. A test model was assembled as shown in Fig. 1, and was dried by a warm airflow at 105°C for 72 hours.
2. Oil was vacuum-injected through a 0.1 µm filter, and the model was left standing for 24 hours or longer to enable the insulating paper to become impregnated.
3. In order to confirm the state of the insulating oil prior to measurements, insulating oil was sampled and analyzed.
4. Insulation characteristics were measured.
5. The BD locations in test models were studied.

2.4 Experimental Circuit The power supply for tests had adjusted to the measurement voltage when the input circuit breaker was in the open-circuit state. When applying measurement voltage, adjusting the input phase with a switching phase controller so as to suppress the magnetizing inrush current in the tested transformer. PD was measured using the residual charge method with a partial discharge measurement device (ERA). The detection sensitivity of PD was 10 pC.

2.5 Measurement Voltage Setting Measurement voltage settings and partial discharge detection were as follows. Tests were performed using the sudden application method (7). The discontinuation time was one hour. As the applied voltage, three voltage levels (170 kV, 160 kV, and 150 kV) were used, because the value resulting in a cumulative fault probability for PD inception of 50% in one-minute step-up tests was approx. 170 kV. The PD inception time was measured by using a Memory HiCorder to record over short time intervals of approx. 10 minutes, and thereafter using a stopwatch to record times while checking ERA Lissajous’ waveform. Tests were continued after PD inception, and BD characteristics were simultaneously measured.

3. Experimental Results

3.1 Partial Discharge Characteristics V-t characteristics were measured for the short-term part of the power frequency withstand voltage tests of 66 to 154 kV class transformers.

Figure 2 shows the cumulative frequency 50% value of the PD inception time for three voltage levels, from 150 kV to 170 kV. In the figure, “→”, indicates that a single data point exists at which PD began at a time shorter than the displayed time duration. Data points for which PD did not begin by the test discontinuation time are indicated by “→ O”. The
cumulative frequency 50% value assuming the Weibull distribution at each voltage is indicated by a filled square. The regression line is given by the following equation; n-value, representing the slope, was 40.0.

\[ V_{PD} = 184 \times t^{(1/40.0)} \]  \hspace{1cm} (1)

Figure 3 shows Weibull plots for the time (a-value) at the three voltage levels. Data points for which PD did not begin up to the discontinuation time were not plotted, but they were counted in the total number of data points. Regression lines were drawn for the plots in the figure, and the Weibull time shape parameter ‘a’ was determined from the slopes. From an average of the a-value for the three voltage levels, the a-value was found to be 0.20.

With respect to the result for n = 40.0, there is no great difference with the value for oil-filled transformers at 500 kV and above. The PD characteristics for composite insulation containing insulating oil is the same as the BD characteristics for insulating oil, exhibiting an incipient failure type in which the a-value is a small value less than one. The results of this experiment indicated a = 0.20, same as for existing data indicating an incipient failure type.

In this experiment, BD occurs within several seconds from the PD inception for almost all samples, and BD characteristics were similar to the PD characteristics. As results of investigation about the BD locations, in nearly all models it was found that the route of breakdown located in the region from the oil ducts to the chamfered edges.

3.2 Dielectric Breakdown Characteristics

Figure 4 shows the cumulative frequency 50% value of the BD time for the three voltage levels from 150 kV to 170 kV. Data points for which PD did not occur up to the test discontinuation time are indicated by “→⃝”. The cumulative frequency 50% values assuming the Weibull distribution at each voltage are indicated by filled squares. The regression line is expressed as follows; n-value, representing the slope, was 38.9.

\[ V_{BD} = 186 \times t^{(1/38.9)} \]  \hspace{1cm} (2)

Figure 5 similarly shows Weibull plots for the time (a-value) for the three voltage levels. Regression lines of the plots are drawn, and the Weibull shape parameter on time ‘a’ was determined from the slopes. The a-value as determined from an average of the a-values for the three voltage levels was 0.21.

In previous measurements, the BD characteristics of composite insulation containing insulating oil were close to the intrinsic breakdown characteristics for the solid insulation, exhibiting a random failure type with a-value close to 1. In this experiment, BD occurs as soon as the PD inception. The structure of the barrier-oil-duct model in this experiment was such that the oil duct thickness was large relative to the barrier, and it is thought that BD at the oil gap leads immediately to breakdown of experimental models.

4. Discussions of Experimental Results

4.1 Comparison with Previous Data

Table 1 summarizes representative values of existing Weibull parameters, together with the results of this experiment. Data No. 2 was adopted in JEC-0102, which is regarded as the standard value.
in Japan. Data No. 3 is for 500 kV class transformers; the m-value of this result (the average value of 0.2 second and 1 minute) is adopted for study in JEC-0102. Data No. 4 and Data No. 5 were measured for UHV class transformers. The Weibull parameters presented in Table 1 are all incipient failure types for $a < 1$. Data of this experiment, compared with previous data, had n-value, which is equal, and a-value which is the same incipient failure types but which are somewhat small. The models of this experiment are for voltage classes which are lower than for other experimental models, and the proportional thickness of the oil duct in the barrier-oil-duct is high. As explained in section 3.1, in general the insulation characteristics of oil gaps exhibit the incipient failure type with the a-value smaller than one. As explained in section 3.2, the insulation characteristics of the barrier section is close to the intrinsic breakdown, which is a feature of solid insulators, exhibiting the random failure type with the a-value close to one. Hence these experimental results are thought to reflect the incipient failure type, closer to the insulation characteristics of an oil gap.

Next, the five Weibull parameters shown in Table 1 are used to describe cumulative frequency distributions for each of the values n, m, and a, shown in Fig. 6. Result of determining the cumulative frequency 50% value assuming the normal distribution, the n-value is 34.9, the a-value is 0.39, and the m-value is 13.1. The n-value of this experiment is 40.0, a value intermediate between the test data for large transformers in effectively grounded systems (see Fig. 6(a)). With respect to the a-value, evaluation based on the cumulative frequency distribution yields a value of 87%, which is a small value compared to the other results (see Fig. 6(b)).

4.2 Studies Relating to Reliability Evaluation

Table 2 summarizes Weibull parameters used in representative reliability evaluation studies and the data of this experiment.

In JEC-0102 reliability evaluations, the smallest n-value of the previous data at the time was used, and the average of the m-values 0.2 second and 1 minute in reference (2) was used as m-value. In UHV test voltage studies (8)(9), the results of reference (3), providing higher test voltage values, were adopted from two experimental results for the UHV class transformers of Table 2.

As was indicated in subsection 4.1, the results of this experiment indicated a small a-value compared with previous data. Further, with respect to trial calculations of insulation reliability evaluation values in section 5, it was decided to conduct studies using the cumulative reliability 50% values of previous data.
5. Trial Calculations of Insulation Reliability Evaluation

5.1 Reliability Evaluation Formula  In power frequency withstand voltage tests, test voltages are determined through reliability evaluations with a Weibull distribution function. The following equation is used in the short-term part of the insulation reliability evaluation method adopted in JEC-0102 (hereafter in this paper called the independent phenomenon method (conventional method)) \(^{(10)}\).

\[
V_t^{m_1}=\left( N_1 V_{11}^{m_1} T_{s1} + N_2 V_{12}^{m_2} T_{s2} \right) \frac{\ln(1-P_t)}{\ln(1-P_s)} \tag{3}
\]

where \(V_t\) is the test voltage, \(T_t\) is the test time, \(V_{s1}\) and \(V_{s2}\) are overvoltage due to one-line ground fault or load rejection, \(T_{s1}\) and \(T_{s2}\) are overvoltage continuation times, \(N_1\) and \(N_2\) are number of times of the overvoltage \(V_{s1}\) and \(V_{s2}\), \(P_t\) and \(P_s\) are cumulative fault probability during test and life time, ‘\(a\)’ is the shape parameter on time, and ‘\(m\)’ is the shape parameter on voltage.

The independent phenomenon method (conventional method) employs a model which conforms to the fault probability density function from time 0 each time voltage is applied. This model assumes that each phenomenon occurs independently of the history, and that there is no effect of so-called aging, degradation, and other factors.

There has been some deliberation regarding the validity of the evaluation method of Eq. (3) \(^{(11)-(12)}\), and in particular problems have been noted in cases where multiple voltage levels are applied after a voltage application into account, so that evaluation results are low. The details are as follows.

Overvoltage was based on values studied in JEC-217-1984 “Metal Oxide Surge Arresters” \(^{(17)}\). Overvoltage continuation times took into account the operation time of the protective relay. The number of TOV took into account the number of lightning strikes and operation of the protective relay and backup protective relay \(^{(15)}\).

1. Overvoltage occurring for one-line ground faults: 1.73 pu, continuation time 0.2 second, 1500 times/(service lifetime 30 years)
2. Overvoltage occurring for one-line ground fault overvoltage during load rejection: 1.99 pu, continuation time: 10 seconds, 400 times/(service lifetime 30 years)
3. Overvoltage occurring for one-line ground fault overvoltage during rare load rejection: 2.34 pu, continuation time 10 seconds, three times/(service lifetime 30 years)

When the above values are compared with the studies of JEC-0102, strict conditions are applied for one-line ground fault overvoltage values and for overvoltage values and continuation times upon load rejection, because the system is a non-effectively grounded system.

Test voltage values selected 3.4 pu (current value), 2.9 pu, and 2.4 pu from the IEC standard test voltages for 154 kV class equipment \(^{(18)}\). Reliability evaluation values were calculated from the following three Weibull parameters.

1. Values used in JEC-0102 studies (Table 2, No. 1)
2. Weibull parameters obtained in this experiment (Table 2, No. 3)
3. Cumulative fault 50% values of existing data (Table 2, No. 4)

5.3 Reliability Evaluation Trial Calculation Results

Reliability evaluation values were calculated using the conditions of subsection 5.2. The results appear in Table 3. Bold figures in the table are results for which the reliability over the service lifetime is 98% or higher.

When the test voltage was 2.9 pu or lower, a reliability of 98% or higher could not be obtained in the results using the conventional method. Also, in trial calculations using the Weibull parameters obtained in this experiment, when the test voltage was 3.4 pu, the reliability was trial-calculated to be 88.4%.

The \(a\)-value of this experiment is small at 0.20, which strongly influences evaluations. When using the conventional method in particular, there is repetition from 0 to a high incipient failure rate without taking the history of voltage application into account, so that evaluation results are low.

The results of evaluations using the cumulative fault method yielded a reliability of 99.7% or higher for a test object. In trial calculation, insulation reliability evaluation values are calculated for a case in which the history of voltage application has no effect (conventional method), and for a case in which the history has an effect (cumulative fault method).
Comparing the conventional method with the cumulative fault method, in the case of the incipient failure type for which \( a < 1 \), an evaluation using the conventional method yields a more severe result. If the test voltage is lowered when using the conventional method, the reliability drops considerably, and if \( a \)-value becomes small, the rate of decline will increase. On the other hand, when using the cumulative fault method the decline in reliability due to reduced testing voltage is small, and changes in the \( a \)-value have little effect. It is thought that the suitability of the conventional method or the cumulative fault method must be judged based on measured data, considering the physical properties of the insulating material and the process leading to dielectric breakdown.

### 6. Conclusion

V-t characteristics necessary for reliability evaluation of 66 to 154 kV oil-filled transformers were experimented, and Weibull parameters have been obtained by the experimental results. The results were compared with previously obtained Weibull parameters, and the parameter cumulative frequency 50% values were calculated. These results were used in trial calculations of insulation reliability employing two different evaluation methods. The main results obtained are summarized below.

1. AC short-term part Weibull parameters of main insulation (barrier-oil-duct models) for 66/154 kV class oil-filled transformers were \( n = 40.0, a = 0.20, m = 8.0 \).
2. Cumulative frequency 50% values of previous Weibull parameters including the results of this experiment were \( n = 34.9, a = 0.39, m = 13.1 \), equivalent to the parameters of JEC-0102.
3. Based on the above results, reliability evaluation values were calculated for the short-term part of power frequency withstand voltage tests of 66–154 kV non-effectively grounded systems. In evaluations using the conventional method of the assumed overvoltage, at test voltages of 2.9 pu and below the reliability was less than 98%. In evaluations using the cumulative fault method, at a test voltage of 2.9 pu the reliability was 99% or above.
4. Evaluation results using the conventional method and the cumulative fault method were compared. Using the cumulative fault method, the effect of the \( a \)-value on the reliability evaluation was small. Moreover, reliability evaluation results were higher than for the conventional method, and resulted in application of lower test voltages.

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### References

5. Cross-appraisal of the electric power machine and insulation material technology, and systematization of the common technology’, IEEJ Technological Report, No.945 (2003)

Table 3. Insulation reliability evaluation results for the short-term (one-minute) part of power frequency withstand voltage tests of 154 kV systems

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<td>Cumulative fault method</td>
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<td>Value in this study m=8.0 a=0.20</td>
<td>Cumulative 50% value m=13.1 a=0.39</td>
</tr>
<tr>
<td>Independent phenomenon method (conventional method)</td>
<td>58.4%</td>
<td>13.5%</td>
<td>66.2%</td>
</tr>
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<td>Cumulative failure method</td>
<td>98.9%</td>
<td>98.6%</td>
<td>98.9%</td>
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</table>

The voltage of 2.9 pu. This is because in the cumulative fault method, the history of past overvoltage occurrence is taken into account, so a high incipient failure rate is not accumulated in the case of overvoltage repetition.
Jun Takami (Member) was born in Hyogo, Japan on August 8, 1971. He received B.Eng. and M.Eng. degrees in electrical engineering from Doshisha University, Kyoto in 1995 and 1997 respectively. He joined Tokyo Electric Power Company in 1997 and at present a member of High Voltage & Insulation Group at R & D center in Tokyo Electric Power Company. His main research interest is the insulation design of a power system. He is a member of IEE of Japan.

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