# Breakdown Characteristics of Transformer under Non-Standard Impulse Voltage

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## Abstract

*The optimal and efficient design of any high voltage apparatus depends on reliable design of its insulation, which is tested with the standard lightning impulse voltages of wave shape1.2/50µs. As the insulation strength is not the same for all the wave shapes, a detailed study on the behaviour of insulation under non-standard impulse voltages is essential to make an optimal design .The purpose of this paper is given to create a method of analysis for breakdown characteristics of transformer under non-standard impulse voltages which would be helpful in the reliable design of transformer.*



## 1. Introduction

Recently, there is an increasing demand for further cost reduction of electric power equipment and further reduction of tolerance of insulation designs. For the sake of evaluation of economic insulation designs and insulation reliabilities of oil-immersed transformers[3,4], it is important to evaluate actual overvoltage waveforms generated at substations.

These waveforms having high frequency oscillation components superimposed on impulse waveforms due to reflections in the substations. Furthermore, applying even a standard waveform impulse voltage at a transformer terminal produces an oscillatory voltage with the natural frequency of the winding. For these reasons, .dielectric characteristics of transformer insulation models[2,5] and oil gaps have been investigated under nonstandard-waveform impulse voltages such as high-frequency oscillatory impulse voltages.

Here, we describe the results of the investigations, using oil gap and turn-to-turn and section-to-section insulation models composing the most basic insulation structures of oil-filled transformers, on dielectric characteristics under unidirectional damped oscillation impulse voltages in frequencies ranging up to 1MHz.

## 2. Definitions

### 2.1 Standard Impulse Voltage

As per IEC 60060, a standard lightning impulse[1]is defined to have a front time of 1.2µs with±30%tolerance and a tail time of 50µs with ±20%tolerance and with a peak overshoot of 5%.

$\pm V=V_o\,[\exp(-\alpha t)-\exp(-\beta t)]$

Where,α=0.0146, β=2.467, Vo=1.04. The parameters α and β controls the front timeand tail time of the impulse wave respectively.

### 2.2 Non-Standard Impulse Voltage

**2.2.1 Non oscillatory:**

Impulse wave shapes having different time to front and time to tail beyond the specified tolerance limit and without any super imposed oscillations are grouped as non oscillatory non standard impulse voltages[1].

**2.2.2 Oscillatory:**

Impulse wave shapes having oscillations super imposed in the wave front or the wave tail and with the peak over shoot greater than 5% and peak oscillations above are groped as oscillatory non-standard impulse voltages.

## 3. Test Method

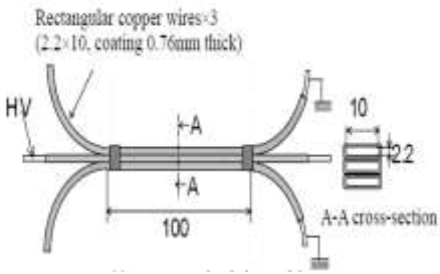
### 3.1 Test Models

Three models were used for the experiments: turn-to-turn insulation and section-to-section insulation models and an oil gapmodel.

#### 3.1.1 Oil Gap Model

The electrode structure is in the form of plane-plane electrodes, which consist of two SUS plane electrodes110 mm in diameter (with a flat plane section 80 mm in diameter) that oppose each other with a gap of 4.0 mm in between. The electrodes are surface-finished according toISO-0.8S. During oil gap tests, an oil mixing pump was installed about 400 mm apart from the electrode surface. After the oil gap broke down, the oil mixing pump was used to mix the oil between the electrodes for one minute and thus driftcarbon, air bubbles, etc. generated at the time of BD away from between the electrodes. Then, the mixer was stopped and the oil was let stand for one minute before proceeding to the next test.

#### 3.1.2 Turn-to-Turn Insulation Model

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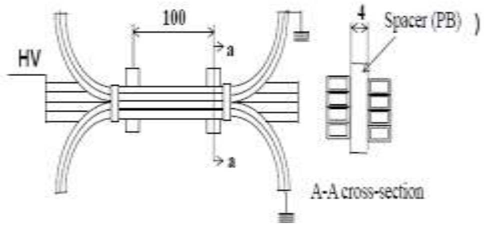
This model simulates the turn-to-turn condition of transformer windings, made by winding a rectangular copper wire 2.2 mm×10 mm with Kraft paper 76µm thick with an airtightness of 800 (seconds per 100 $cm^3$) to a thickness of 0.76 mm on one side to form an insulated rectangular wire and binding three such wires into one bundle.

#### 3.1.3 Section-to-Section Insulation Model

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This model simulates the section-to-section condition of transformer windings, made by using the same insulated rectangular wires as for the turn-to-turn model (with insulating coating 0.76 mm thick) and binding four such wires on one side and having the wires oppose each other via a spacer (pressboard or PB). The 4.0mm thickness of the spacer forms the oil path dimensions between sections.

## 4. Treatment of Models

The turn-to-turn and section-to-section insulation models were dried at 100°C for about 96 h. Each was then set in the test tank, which wasevacuated below 10Pa, then filled With transformer oil. During the test, the water content in the oil was below 10ppm and the withstand voltage of the oil, above 60kv**.**



### 4.1 Testing

Three oscillation frequencies were used for theUnidirectional damped oscillatory voltages[6]: 400 kHz, 700 kHz, and 1MHz.

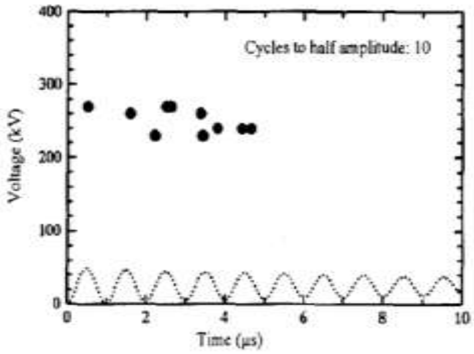
For comparison with the results of tests using oscillatory impulse voltages, other tests were also carried out using standard lightning impulse voltages (+1 .2/50µs) and fast front short duration impulse voltages[7] (actual rise time : 0.5-0.56µs, time to halfvalue:1.11.3µs), which simulate only the first waves of oscillatory impulse voltages of which the frequency is 1MHz.

For the oil gap model, a voltage was applied to one of the electrodes and the other was grounded. For the turn-to-turn insulation model, a voltage was applied to the central copper wire of the bound three wires and the other two were grounded. For the section-to-section insulation model, a voltage was applied at once to the four copper wires on one side and the other four set apart from them by a spacer were grounded.

10 samples each were tested for the turn-to-turn and section-to-section insulation models. The oil gap was tested 15 times under each set of test conditions and only the results of the last 10 tests were accepted, the results of the first *5* being excluded as conditioning.

## 5. Test Results

### 5.1 Oil Gap Model

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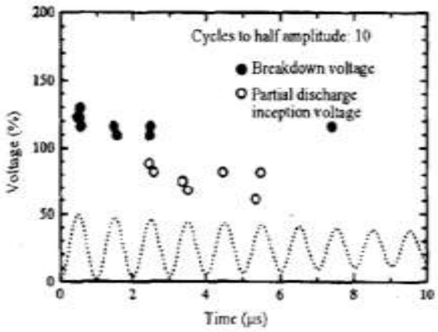
Ŏĕ We found that, mostof the breakdowns occurred at peaks of the oscillations, although some were seen at troughs of oscillation. One breakdown occurred at the first wave of an oscillation. The other breakdowns occurred at the second waveform or thereafter at the fifth wave in the longest time to breakdown case.

With lower cycles to half amplitude for the same oscillation frequency: 1MHz more breakdowns occurred at the first wave of an oscillation. Under the fast front short duration voltages, breakdowns occurred at around or slight beyond the peaks.

### 5.2 Turn-to-Turn Insulation Model

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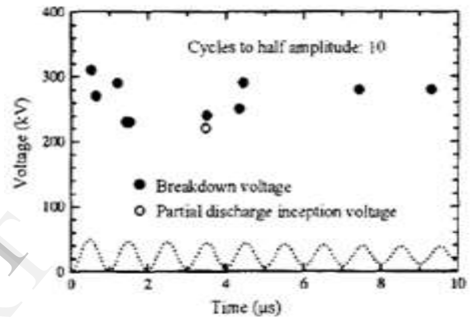
Ŏĕ We found that fiftypercentage of samples broke down at around the peak of the first wave of an oscillation, and the remainder did at the other waves.

Partial discharges occurred at peaks of the third to sixth waves of an oscillation. Asthe voltage was raised, they also occurred at other peaks. Asthe voltage was further raised, they also occurred at troughs of an oscillation.

With the turn-to-turn insulation model, as was the case with the oil gap, with lower cycles to half amplitude, more breakdowns occurred at the first wave of an oscillation.

### 5.3 Section- t-Section Insulation Model

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We found that, breakdowns occurred at waves from first to tenth. In only one sample, a partial discharge wasdetected at the peakof the fourth wave of an oscillation. Its inception voltage was equal to the minimum breakdown voltage. Eighty percentage of the breakdowns occurred at the edges of the spacers between the sections and the remaining 20 percentage occurred at oil gaps between the sections separate from the spacer. With other oscillation frequencies and cycles to half amplitude, more than 50percentage of the breakdownsoccurred at the edges of the spacer.

## 6. Discussion about Results

➢ The breakdown voltages under oscillatory impulse voltages in the present test frequency range (400 kHz-1MHz) were higher than those under standard lightning impulse voltages.

- With the cycles to half amplitude varied at a constant oscillation frequency, for the three models: turn-to-turn insulation, section-to-section insulation, and oil- gap, the partial discharge inception and breakdown voltages increase as the damping factor becomes larger. With the oscillation frequency varied at a constant damping factor, the breakdown and partial discharge inception voltages increase as the oscillation frequency becomes higher.

- The breakdown voltages under the fast front short duration voltage, which simulates the first wave of the oscillatory voltage of which the frequency is l MHz, are comparable to those foroscillation frequency: l MHz and cycles to half amplitude: one cycle.

- The fact that the breakdown voltages increase as the oscillation frequency becomes higher and as the cycles to half amplitude becomes lowerunder the oscillatory impulse voltage can be ascribed to the V-t characteristics: the breakdown voltage decreases with voltage applicationduration.

## 7. Conclusion

To achieve a rational insulation design for transformers, it is important to evaluate dielectric strength against surges actually impinged on equipment on-site. Thus, using turn-to-turn and section-to-section insulation models and an oil gap, an investigation was carried out on the dielectric characteristics of high-frequency oscillatory impulse voltages.

## 8. References

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