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Review of the Effectiveness of Impulse Testing for the Evaluation of Cable Insulation Quality and Recommendations for Quality Testing

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Abstract— This project investigates impulse breakdown testing as a means of determining the as constructed standard of MV power cable. A literature survey is undertaken to elucidate the place of this test in an overall cable test regime and to determine the factors that impact on the performance of the test method. Testing was undertaken on ESB Networks cables to establish if a merit order ranking was feasible based on this test and to determine if the test could detect defects in the inner semiconducting layer. Based on this, conclusions and recommendations are made regarding the overall applicability and usefulness of this test.

I. INTRODUCTION

The life expectancy and reliability of operation of an XLPE cable depends greatly on the “as manufactured” extrusion standard of the insulation and semi-conductive layers. The probability of cable faults due to insulation breakdown increases as the number of defects in these layers increases. To ensure that MV cables supplied to ESB Networks meets its reliability and lifetime expectations, the cables undergo a number of test stages. These are shown below:

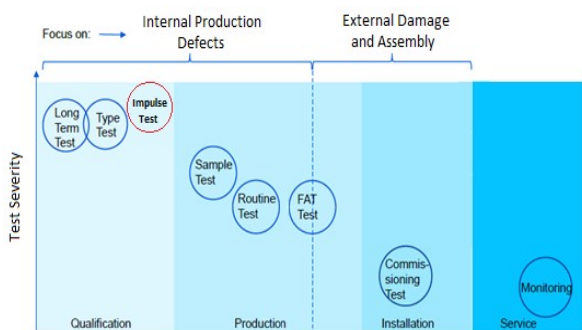


Fig. 1. Test Philosophy

The first test stage is the qualification stage which is carried out on prototype cable samples to confirm that the cable design

proposed meets lifetime endurance requirements set out in the cable specification. During this stage samples of proposed cable designs are subject to long term ageing, under thermal cycling and elevated voltage stresses, to ensure that the design of the cable meets the required long-term performance requirements. ESB Networks specifies long term testing for its medium voltage cables using the CENELEC Accelerated Ageing procedure whereby cables are subjected to 3U₀ at 50 Hz for two years or at 500 Hz for 3 months.

In addition, Type Test tests are undertaken at the qualification stage by ESB to ensure that the cable design meets detailed IEC and ESB Networks electrical and material requirements Specification requirements. The electrical type tests based on IEC 60840 for 52 kV cables and IEC 60502 for 20kv cables consist of the following sequence of tests:

- Partial discharge measurement
- Bend test
- Partial discharge test
- Impulse withstand test
- Heat cycle voltage test
- Tan delta measurement
- AC Power frequency test.

The qualification stage is followed by Routine AC and PD tests on production lengths, additionally in the case of 20kv cables a four-hour AC voltage test on a sample cable length. The commissioning test stage now generally consists of AC testing, performed at frequencies between 0.1 HZ and 50 Hz with PD monitoring for long circuits, for relatively short circuit lengths, a soak test is normal.

When cables pass standard Type and Sample and Routine tests outlined by the IEC, the margin by which the cables have passed these tests is unknown to ESB Networks.

For this reason, impulse breakdown step testing and elevated voltage Type testing was investigated in this project to determine the usefulness of impulse breakdown step testing in relation to;

- Providing a useful merit ranking of different suppliers cables
- Providing insight into the expected performance of cables in long term ageing tests and Type tests
- Indicating the degree of ageing of cables aged in service.
- Detecting manufacturing defects such as gaps in the inner semicon layer
- Indicating a least cost way by which the impulse breakdown performance can be increased

Before discussing each of the above applications of impulse breakdown testing, it is useful to review the factors which affect impulse breakdown strength factors.

II. LITERATURE REVIEW OF XLPE IMPULSE BREAKDOWN STRENGTH FACTORS

Influence of Repetitive Impulse Shots

Fig. 2. below shows the relationship between impulse level and number of impulses.

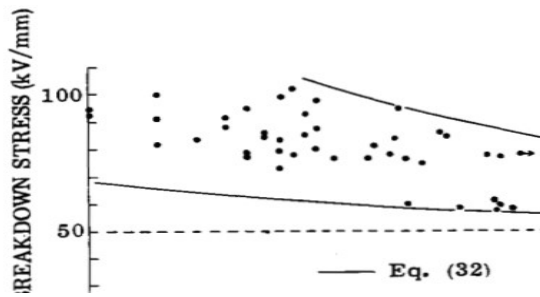


Fig. 2. Minimum Breakdown Voltage

There is a threshold impulse voltage level (approximately 60% of breakdown voltage). below which the cable insulation will withstand repeated impulses indefinitely. Fig. 2 also shows that there is an aging effect during the test process if the magnitude of the impulse level is close to breakdown level –see the top curve in the diagram.

Apart from this reference, most other references state that there is no ageing effect arising from repeated impulses at breakdown level; however, uncovering specific research which underpins this assumption was not found to be possible.

Influence of Cable Test Temperature

A temperature of 95°C - 100°C is specified for impulse testing within the IEC 60540 and 60840 Type test standards. In T.U. Graz impulse breakdown tests, the cable samples are tested at room temperature. This reduces both the costs and complexities

of testing. A temperature compensation factor can be used for 20kV and 52 kV cable to roughly convert results at room temperature to those at 95°C - 100°C. The temperature conversion factor, based on experimental evidence, is 1.25 for negative polarity impulses and 37% for positive polarity impulses. [5] The 1.25 factor is used extensively in Japanese cable qualification tests and cable insulation thickness design.

Influence of Steepness of Impulse Wave Front

The rise time, or the steepness of the front of the impulse wave is another factor that impacts on the impulse testing breakdown level. The time for the impulse wave to reach its peak and the impulse wave tail off time are controlled by a pair of resistors. The basic arrangement per Marx impulse generator stage is modelled as follows:

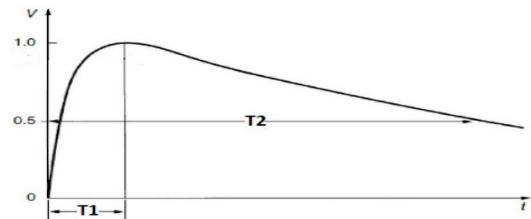


Fig. 3. Impulse Generator Setup and Resultant Waveform [1]

The steepness of the front of the wave (T1) and (T2) are determined by the value of resistors used in the test circuit. As impulse breakdown strength can vary with wave front steepness as well as equipment tolerances and human operator factors, the waveshape should accompany breakdown test results and also be considered when comparing one set of test breakdown results with another.

Effect of Increased Volume on Breakdown Strength

The probability of defects in insulation increases in line with the increase in cable insulation volume as shown in the graph below. As a result, the impulse breakdown strength decreases significantly as insulation volume increases. Japanese research indicates that average insulation stress per mm can be used to describe impulse breakdown performance levels.

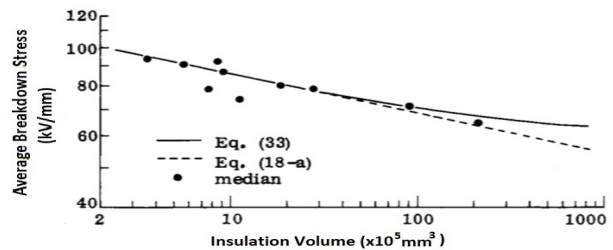


Fig. 4. Relationship of Impulse Breakdown Stress and Volume [1]

Location of Impulse Breakdowns in the Cable Core

As can be seen in Fig. 5, the proportion by volume of breakdowns originating in the inner semi con layer (conductor shield) is fewer than in the XLPE insulating layer. The majority of the breakdowns originated at contaminants within the insulation layer.

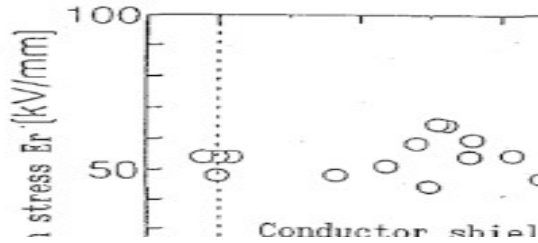


Fig. 5. Cable Failure Position Within Cable Core [3]

From the plot above, the proportion by volume of breakdowns originating in the inner semi con layer (Conductor shield) is fewer than in the XLPE insulating layer. The majority of the breakdowns originated at contaminants within the insulation layer. [4]

Effect of Impulse Polarity on Breakdown Strength

In accordance with the T.U. Graz specifications for extended impulse testing, all impulses applied to the cable are of negative polarity. The IEC standard for Impulse testing involves application of usage of ten positive impulses and ten negative impulses. The dual polarity approach of IEC is more severe than single polarity testing and a severity factor of 14% is quoted in the literature to account for this factor. [5]

Effect of Relaxation of XLPE Mechanical Extrusion Stresses on Impulse Withstand Voltage

After XLPE cable extrusion residual mechanical stress can be produced within the insulation volume as a result of the heated XLPE cooling unevenly after the extrusion process. Online relaxation can relieve this stress by reheating the outer insulation, Based on 14 samples, 7 relaxed and 7 unrelaxed, the Weibull distributed impulse breakdown results showed an increased impulse breakdown strength of 22% in the stress relaxed cables relative to the unrelaxed cables i.e. the impulse breakdown value increased from 1100kV to 1346kV [3].

Background to Step Impulse Breakdown Testing

A step Impulse breakdown test method and protocol for MV cables was developed by the University of Graz in the early 2000's. This test protocol is used by utilities in Austria, Hungary and Germany as a Specification conformance check. One of the chief advantages of this method, relative to AC endurance step

testing, is that it avoids the use of de ionized water terminations. Such terminations are significantly more demanding in terms of equipment and installation resources than the simple and fast cable sheath stripping employed by the TU Graz method.

In the TU Graz method, the voltage grading is controlled via the outer semi-conductive layer which forms a lattice network with the capacitance of the cable. The stress grading is shown in Fig. 8 below; the peak voltage is plotted as a function of the distance from the grounded shield. The voltage stress in the insulation is almost reduced to a linear form.

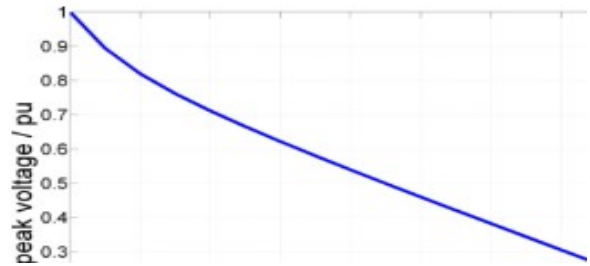


Fig. 6. Voltage Stress in the Area of Voltage Grading

The risk of damaging de ionized water terminations is also eliminated. In addition, the TU Graz test is performed at room temperature, thereby requiring no heating and heating control circuits, which adds to the simplicity of the method.

The other advantage of impulse testing is that the damage at the failure point is limited relative to AC step breakdown as shown by the insulation breakdown in the silicone oil below permitting examination of the failure point and its location.

III. TEST PROCEDURE

In the TU Graz testing protocol, five impulses of negative polarity are applied to the cable samples, starting with an impulse magnitude of 350 kV. The voltage is then increased in 50 kV steps and five more impulses delivered. This test cycle is then repeated until there has been a breakdown in cable insulation or flashover at the termination ends. When a termination flashover occurs, the end termination flashover resistance can be improved to allow the testing to continue. If these attempts at avoiding flashover are unsuccessful, the test on that sample is terminated. [4] Five samples of ten meters effective test length are tested in each test session.

Cable Preparation

The step impulse voltage test is carried out on minimum five samples of XLPE insulated cables. The cables tested in this project are all single core aluminium cables with stranded copper

screen wires and PE over sheath. Each sample was prepared to the following specification.

Test Frequency

The impulse voltage magnitude and wave front time and the tail off time must be calibrated in the impulse generator by delivering a series of voltage impulses and recording the voltage level and waveform.

IV. TEST PROCEDURE

The step impulse test is implemented using a suitably rated impulse generator connected via a bare conductor to the test cable length which is suspended from a gantry crane using a polymeric rope and earthed at one or both sides to the test hall earth grid as shown below.

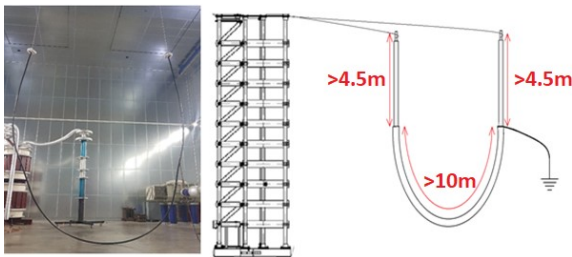


Fig. 7. Test Setup

ESBN Threshold for Passing Impulse Breakdown Tests

The pass threshold for 20kV cable is set at 900kV and 1200kV for 38kV cable, using a 50kV impulse step regime. The 20kV pass level was based on the average value of TU Graz 63% Weibull values obtained from a population of 60 cable tests the 52kV cable impulse breakdown pass level was determined based on ESB Networks results to date. Due to the insulation volume effect, the probability of defects increases with insulation volume. As result the threshold pass voltage for 52kV cable is less than what the insulation thickness ratio between 52kV and 20kV (10 mm : 5.5 mm) i.e. approx. factor of 2 would imply.

Test Frequency

For ESB Networks cable term contracts which typically have a duration of five years, the impulse to breakdown test samples are taken at six-month intervals from standard production. This ensures even distribution of impulse test samples over the contract period and facilitates trend analysis of the results over time.

The IEC 60502 and 60840 standards require that cable be subjected to 20 impulses (10 positive and 10 negative) at 125kV for 20kV and 20 impulses 250kV for 52kV at 95-100°C. By aggregating the 20 impulse steps associated with each of the

above impulse breakdown pass levels and adjusting them to compensate for testing at room temperature (1.25) [1] and for testing using negative polarity only (14%) [2], the above step impulse breakdown pass levels of 900 kV and 1200kV can be compared with equivalent impulse voltage levels specified in IEC Type tests for 110kV and 170kV cables respectively. See severity diagram below. It can therefore be seen that the above pass levels for impulse step test breakdown are onerous and are a stringent test of the cable core as manufactured.

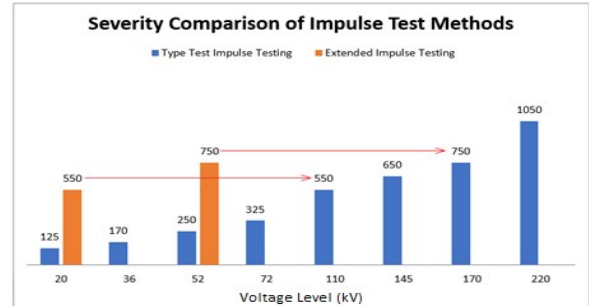


Fig. 8. Severity Comparison

Merit Ordering of Cables

Order	Cable Breakdown Results (20kV)		
	Cable No.	63% Value	Pass Mark (900kV)
1	Cable 6	1020kV	Pass
2	Cable 7	955kV	Pass
3	Cable 4	942kV	Pass
4	Cable 8	775kV	Fail
5	Cable 5	701kV	Fail

Table 1. 20kV Cable Breakdown Results

Order	Cable Breakdown Results (38kV)		
	Cable No.	63% Value	Pass Mark (1250kV)
1	Cable 1	1545 kV	Pass
2	Cable 2	1386 kV	Pass
3	Cable 3	1318 kV	Pass
4	Cable 4	1136 kV	Fail

Table 2. 38kV Cable Breakdown Results

From Tables 1 and Table 2 above, it can be seen that comparisons can readily be drawn between the cable breakdown voltages for each voltage level. This allows for a simple merit ordering system to be established. Not only does this table show the order by which the cables are ranked, but also shows the reserve on the cable above the pass value. It is expected that a larger reserve should correspond to a longer life expectancy in the cable. Testing on 20kV cables shows a range from 701kV to 1020kV, the highest result having a reserve of 120kV above pass

level. Similarly, for the 38kV test set, there is a range from 1136kV to 1545V with the highest having a reserve of 345kV above the required pass levels.

V. ANALYSIS OF RESULTS

Indicator of Performance in Accelerated Ageing and Type Tests

To provide an insight into whether good performance in the Impulse Breakdown Test would translate into good performance in AC ageing tests, an elevated voltage type test was conducted on a 52kV cable (30kV U₀) tested to IEC 110kV Voltage level.

The list of tests performed per IEC 60840 were:

- Bend Test.
- PD test at 1.5 U₀ (96kV)
- Heat Cycle at 2 U₀ (128KV at 95 °C)
- Impulse Voltage Test 10+ & 10- (550KV at 95 °C)
- PD Test
- AC Power Frequency Test at 2.5 U₀ (128 kV)

The cable passed the full suite of elevated voltage type tests for the same design of XLPE cable as had passed the Impulse Breakdown step test. This indicates that good performance in the impulse breakdown herald's good performance in long term ageing tests as well as in type tests.

Determining Method of Achieving Higher Breakdown Strength Cable Core

The results for impulse tests can be used to determine the most economical way to improve the impulse breakdown strength. For example, the results can be examined for breakdown location using a silicone oil bath or other investigation method. From that analysis one can determine if it is better overall, in terms of cost and standardization to replace the cable with a higher specification grade of XLPE insulation or alternatively replace the inner semiconducting layer or layers. This is clearly shown by Wald and Woschitz in the paper "Influence on the Impulse Strength of XLPE-insulated Medium Voltage Cables for Different Composites". [4]

Usefulness of Indication of the Degree of Ageing of Cables Aged in Service on the Network

This method was used to evaluate the effect of rejuvenation fluid on samples of 20kV cable extracted from an Austrian network before and after the treatment. The withstand voltage increased from approximately 300kV to 475 kV (+55%) for one cable circuit and from 412kV to roughly 512 kV. The withstand voltage of the treated cable was very close to the withstand voltage of new 20 kV XLPE insulated cables in the TU Graz

impulse breakdown strength database which are in the range of 600 - 700 kV.

In 2010 ESB Networks impulse tested 52kV cable samples which had experienced 17 years of operation. The breakdown results obtained using the TU Graz procedure averaged 713kV. When this result is processed and translated into equivalent IEC Type test impulse pass values, it exceeds the 250kV BIL requirement by a significant margin.

Detecting Defects Such as Gaps in the Inner Semicon Layer

For the purpose of determining the effectiveness of impulse breakdown testing in detecting the presence of serious cable core defects such as missing sections of inner semicon, ESB Networks arranged to manufacture a 200m length of 52kV cable with stranded 630 AL conductor and 10mm XLPE insulation. The cable was routine and heat cycled tested at 52kV level (2xU₀) and passed all the IEC tests satisfactorily. The test also included a HV (4xU₀) test for 4 hours which was passed successfully.

However, the cable failed the Impulse breakdown test at 450 kV which was well below the 1300kV level expected for this cable type. This clearly shows the effectiveness of the step impulse test in detecting such defects.

VI. CONCLUSIONS

It was concluded that overall impulse breakdown step testing is a, quick useful and economic testing tool for investigating the "as built" standard of MV cable insulation and semiconducting layers, when used in conjunction with other testing and evaluation strategies by both cable engineers and suppliers.

It can be seen from the results outlined in Table 1 and 2 – Merit Order of Results, that impulse testing to breakdown provides a clear distinction between impulse performance of cables supplied to ESB Networks by various suppliers. Taken in conjunction with CENELEC long-term ageing results and, it should therefore prove to be a useful test measure to enable merit ordering of MV cables, provided that due consideration is given to the fact that only a small proportion of all cable production is being tested and to the fact that impulse test results should be carefully compared based on the factors mentioned in the literature review above.

It is also concluded that if a cable performs well on impulse breakdown tests, then this performance will be replicated in AC long-term ageing tests such as CENELEC two-year tests at 50 Hz for water treeing.

It is also concluded that this test can provide useful information when creating a balanced cable design including as to whether to upgrade insulation grade or spend money on upgraded semiconducting layers or both.

Taken on the basis of ESB Networks tests on a 52kV cable deliberately constructed without an inner semicon on a stranded 630 sq mm conductor that Impulse breakdown tests were effective in identifying this defect when PD tests and IEC type tests were successfully passed. This success was based on having access to a database of results made up of test results from ESB Networks own test programme and very useful TU Graz published impulse breakdown limit guidelines against which we could compare results with, namely 600kV cut off for 20kV cables

Based on the literature survey on impulse testing, it is concluded that the factors that affect insulation breakdown levels in impulse testing to breakdown are as follows;

- Steepness of the front wave
- Average stress on the insulation and volume of insulation
- Temperature of test cable
- Polarity of the impulse waveform
- Mechanical stresses resulting from the extrusion process
- Presence of extrusion by product gases in the insulation

VII. FURTHER RECOMMENDATION

Standardising the procedure taking into account factors which can impact on the results is considered desirable. These recommendations were broken down into two main categories: standardising test procedures and reducing flashovers. The recommendations are as follows:

Standardising the Wave Front Time

It is recommended that as far as practically possible, that identical values of rise time are used to enable meaningful comparison of test results.

Published Database of Results and Inclusion of the Impulse Breakdown Test in CENELEC Standards

It is recommended that a database of typical results be published to guide cable utilities in relation to typical breakdown ranges for different cable voltages. It is felt this would be helpful to utilities especially if typical values for aged cables were also included. It is also felt that the TU Graz test could usefully be included in the CENELEC test compendium for MV cables.

The main issue that occurs during impulse breakdown testing is the risk of termination flashovers. The following recommendations are made in relation to avoidance of this issue.

Final Value Focused Testing

This is proposed in an effort to reduce the step range of impulse testing. This could be done by following the standard University of Graz procedure for the first cable i.e. starting at the normal voltage and incrementing at 50kV intervals until breakdown. Then, when the breakdown level for the first sample is found, the tests for the remaining four cores could start at approximately 20% lower than the breakdown voltage for the first sample.

Use of Corona Rings

To use aluminium flexi ducting formed into a donut shape and place around the conductor connected to the impulse generator. This mitigates the effects of sharp corners in the bare impulse generator conductor and in the cable end connector.

Use of Semi-con Tape

Wrap semi-con tape around on areas of bare impulse generator conductor and shield wire. This again reduces the probability of concentrated localised charges flashing over during testing.

Use of Water Tubes

Use of water tubes to provide a more even charge at the cable screen earth interface. The water tubes are taped to the cable above the grounded shield.

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