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DEVELOPMENT OF DIAGNOSTIC PROCEDURES FOR XLPE CABLES WITH WATER TREES

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ABSTRACT

This paper describes the results obtained and work in progress for a research project to develop condition assessment techniques for water treeing in medium voltage XLPE cables. The research was initiated after Ergon Energy experienced failures of 22kV XLPE insulated cables and management sought data and expertise that would allow them to manage a problem that had the potential to cause serious disruptions to the network. The research was carried out in close collaboration with Ergon Energy and with a strong focus to achieve a practical outcome suited to the special requirements of the Authority. It involved long term laboratory ageing experiments, application of dielectric response measuring techniques, field test on suspect cables as well as modelling of the dielectric responses and correlation of the results with the laboratory and field measurements.

KEYWORDS

Water tree, Australia, Forensic Analysis, Non Destructive Diagnostics, Accelerated Ageing, Electric Field Modelling, Field Testing.

INTRODUCTION

Ergon Energy is a power authority responsible for power supply to Queensland except for the more heavily populated south east corner surrounding the capital city of Brisbane. Queensland is a large state in the northern half of eastern Australia and outside its south east corner has a number of smaller but reasonably large cities separated by large sparsely populated regions. This favours the use of equipment that was light, suitable for air transport and could provide results in a short testing period.

Water trees had not been discovered in Australian cables until recent repeated failures of 22 kV cables in North Queensland were attributed to the presence of water trees. Subsequent investigations suggested that the conditions leading to water tree development occurred in a significant proportion of existing cables. There was therefore a requirement to establish procedures for managing degrading cable networks to maintain high reliability whilst at the same time keeping down costs. The first step was to carry out a comprehensive literature search on experience and research on water trees was carried out and documented. This provided the basis for formulation of a program to obtain data and develop techniques that could be used by Ergon in development of their asset management programme. In this paper the programme of research undertaken is described. The primary focus of the research is to develop a better understanding of water treeing and develop techniques that are of practical use to Ergon Energy.

DESCRIPTION OF THE PROJECT

The project originally envisaged four areas of investigation as follows:

- **Ageing experiments**
  In development of these tests the procedures described in IEEE Standard 1407 were used. Accelerated ageing was carried with current circulating in the cables and a voltage of $3U_0$ in water baths of "distilled" water with controlled impurities and held at a temperature of 50^oC. The "time to failure" test option with regular non destructive diagnostic measurements was used.
- **Dielectric response measurements**
  The diagnostic measurements included time and frequency domain tests. These were carried out at regular intervals in order to observe the progressive deterioration of the insulation.
- **Computer modelling**
  The aim of this work was to postulate a model of the conduction as well as the polarisation effects of the insulation together with bow tie and vented water trees of differing densities, distributions and electrical characters. Using this model polarisation and depolarisation current (PDC) would be obtained and compared with data from the field and the laboratory. In this way macroscopic characteristics can be examined for their effect on the PDC. There is also an interest in short testing times to facilitate field testing and these models would assist in obtaining a better understanding of time domain testing.
- **Forensic Analysis**
  Analysis of failed samples and model development requires knowledge of the water tree structure in the cables being studied. To this end a technique to allow slicing of the cable insulation and recording the 3D nature of water treed sample has been developed and is described below. Also knowledge of chemical nature of the water tree sites is valuable input for these studies and these will be carried out as required.
- **Field Tests**
  This provides valuable data on response of field cables and the effect of terminations and joints. Comparison of laboratory results with field data will also enable evaluation of the results from the laboratory tests.

PROJECT IMPLEMENTATION

Close attention was paid to the IEEE Guide to meet the aim

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to “facilitate comparison of data by different laboratories”. An automatic control and monitoring system was implemented to meet the test requirements and to conform with wiring regulation requirements. An added requirement was the need to ensure safety of those who work on the equipment and staff who work in the area near the test bay. Safety procedures, signs and appropriate warning mechanisms were instituted.

For the ageing tests three sets of 10 cables were prepared and placed in 3 HDPE tanks following the procedures given in [1] . The 3 sets comprised:

- new cables
- field aged cables
- rejuvenated field aged cables (rejuvenated using the CableCure process).

Figure 2 is a photograph of two of the tanks in the test bay. One aim of the accelerated ageing tests was research into the application and interpretation of non destructive diagnostic measurements on laboratory aged cables. These results could then be compared with field measurements. Also the tests were carried out to compare the ageing of new cables and rejuvenated cables. The “new” cable group and “rejuvenated” cable group were placed on an accelerated testing program of $3U_0$ and a conductor temperature of 75^oC. The “Time to failure” evaluation technique was used.

Diagnostic tests were carried out with a frequency domain spectrometer and a DC test set measuring polarisation and depolarisation currents. Initially an ambitious test programme also included other tests as well as testing of all cables. However this was changed to a sampling procedure to reduce the time spent testing. These results have shown a gradual deterioration of the cables. The tests are on-going and results are still being analysed. However the time domain results indicate they could provide a practical method for initial assessment of cables on site. This aspect is important for Ergon energy, the partner in the research. They are responsible for a very large and sparsely populated region so that the reduced testing time and portability of the DC test set are important features.

On-site tests have been carried on cables known to be water tree degraded in Cairns, North Queensland. These tests have the added complexity of accounting for the cable joints and terminations in the test data. The analysis of this data is reported in another paper [2].

Interesting results have been obtained from time domain studies of cables before and after energisation. This is discussed under tests on the field aged cables.

The aim of the work on computer modelling has been to obtain a method of representing the cable insulation and water trees in order to derive time domain dielectric responses. These can then be compared with the experimental results obtained from cables in the accelerated ageing test and the field tests. The practical advantages of time domain tests for Ergon Energy have been described above. However the procedures and results from time domain testing of XLPE cables are not as mature as the frequency domain techniques and for which a large amount of literature is available [3] [4] [5]. Thus it was decided to develop a time domain model to assist our research and gain a better understanding of factors affecting time domain measurements in degraded cables. The technique used to develop the model directly applies basic physical concepts rather than conventional mathematical modelling and is relatively easy to implement. More detail about the technique is given below.

TIME DOMAIN DIAGNOSTICS OF FIELD AGED CABLES

In setting up the accelerated ageing test one water bath was dedicated to aged cables recovered from the field. However they were not included in the accelerated ageing test but were left de-energised in the tank. Separate diagnostic tests are being carried out on these cables in order to obtain data and knowledge of cables known to have suffered severe water treeing. When a cable failed in the accelerated ageing test it was decided to replace it with one of the field aged cables which would then be subject to load cycling at about 70 deg C and $3U_o$ voltage. Failure of this cable was expected and measurements of PDC currents were taken prior to inclusion in the accelerated ageing test and at regular intervals during the ageing. The results of this study are reported in another paper [2]. It has been found in tests on field aged cables in the periods just after and before energisation that the measured polarisation and depolarisation curves change. However after thids period they settle down to a stable value. A consequence of this for our test program is that cables must be tested soon after de-energisation in order to obtain reliable data on the cable characteristics.

FORENSIC STUDIES

In all this work it is important to have an understanding of the water tree types and their distribution in the cables being studied. Instead of the normal procedure of microtome slices a technique for cutting a continuous spiral and the ability to magnify the image onto a view scope has been developed. This will enable much quicker evaluation of the water tree distribution in a failed cable and a formulation of the water tree distribution along the cable length as well as over a cross section.

Traditionally, forensic analysis of suspected water treed cable has been done by microscopic analysis. A piece of the specimen is microtomed into slices around .1mm thick, and stained. The slices are then examined optically under a fairly standard microscope (often around 100x power).

Obviously there is a disadvantage in this method in the amount of time expended for each slice – usually time and budget constraints limit researchers to a few dozen slices at the most. This gives an effective sample area of around 1-2mm.

We have developed a system whereby the cable is sectioned into a continuous spring shaped length, and then passed through a device that projects a magnified image onto a screen (see figure 1). In this way, we are able to see an entire ‘cross section’ of insulation at once – at a cost of a slightly reduced magnification (around 50x). While some small detail is lost, and the smallest water trees pass unseen, we are able to examine much greater amounts of sample material. In the initial testing of the device, a sample consisting of 400 ‘slices’ each 0.5mm thick was examined.

By viewing a much greater length of the insulation thickness, we hope to gain a deeper understanding of the nature of the growth patterns of water trees. In addition, a more rigorous statistical analysis becomes possible.

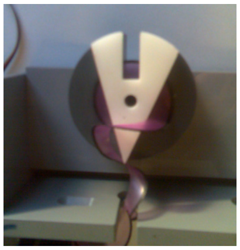

Figure 1: Detail of device used to hold sample for projection.

Figure 2: Water bath tanks in Test bay at the Ergon Energy facility

TIME DOMAIN MODELLING

As described above, part of the research undertaken was to develop a time domain model that would assist in the interpretation of laboratory and field test measurements of polarisation and depolarisation currents.

Rather than using the traditional approach of starting with the partial differential equation (PDE) and using a numerical approximation such as the finite difference or finite element method, a new approach developed at QUT was applied. This starts with the basic physical concepts and implements them directly on the computer, bypassing the conventional formulation of the PDE followed by its numerical approximation. It turns out that this approach gives a simple method that can be implemented relatively easily and has a powerful modelling capability for complex structures such as water trees in XLPE insulated cables. An added advantage is that the model development requires a focus on the basic physical concepts and avoids the need for advanced mathematical knowledge for its implementation. A brief description is given in the following paragraphs.

In essence the approach uses voltage and electric flux to model the electric field in the cable dielectric. The model is being developed to model the polarisation and depolarisation currents for application of a step function voltage followed by a short circuit. It is constructed by dividing a region into small volumes (for a 3D object) or cells of unit depth (for a 2D object). The shape of the volume or cell can be chosen to be any shape. Within each volume or cell a node is chosen to be the reference point at which an unknown voltage is to be calculated. The only restriction is that in the region for which the equation is written the flux flowing over a surface the flux must be uniform – i.e. the flux density vectors must be equal in magnitude and parallel to each other. Fig 3 is an example of a 2D region divided into cells. Location and cell references are shown for the cells with a bold outline. The equation for the flux flowing across the boundaries of the cell with node 1 is:

$$(V_1-V_2)P_{12} + (V_1-V_3)P_{13} + (V_1-V_4)P_{14} + (V_1-V_5)P_{15} = 0$$

Parameters P_{012} etc. are derived from the cell dimensions, node location and material parameters. For a conducting material P is the conductance between two nodes, for the electric field P is the effective capacitance between nodes.

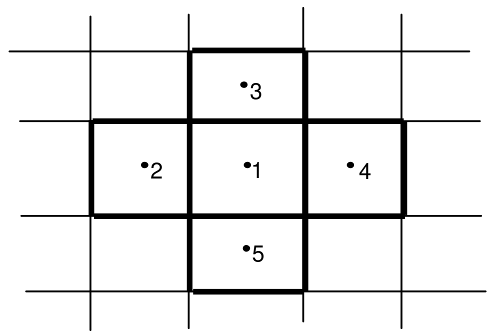

Figure 3: Cells modelling a region of the electric field

The method is being used to model a 22kV single core cable, simulating the insulation properties as well as the structure and electrical characteristics of water trees. It is intended to display the results at the conference.

CONCLUSIONS

The collaboration between the university and the Ergon Energy, the local power authority responsible for supply in regional Queensland has provided the opportunity for using research to obtain a practical outcome in field testing of underground cables. The project has provided the opportunity to combine results from field tests, accelerated ageing and computer modelling with a focus on achieving an outcome that Ergon Energy can use in their asset management program to deal with water tree infected cables.

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