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A Multidiscipline 35 kV Cable Failure Investigation

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Abstract - Cable failure investigations must evaluate all facets of cable technology to reach a complete understanding of why and how an underground power cable failed. This paper presents the salient points of a recent investigation into an in-service failure after only several weeks of operation.

Keywords: XLPE cable failure, multidiscipline investigation, in-service failure

1. Introduction

Several 35 kV, 500 mm^2 (1000 kcmil) cross-linked polyethylene, copper tape shield, PVC sheathed power cables feeding a new dc arc furnace at a Mexican industrial plant failed shortly after energization. The investigation followed a preliminary work plan and schedule that included a detailed analysis of cable manufacturing, installation, operation methods, failure events, power system topography, operation and power system protection. The work plan provided laboratory analysis to support all studies and conclusions. On site evaluations at both the cable manufacture facility and the industrial plant were carried out.

2. Electrical System Study

As part of the investigation into the cable failures, a system study was carried out to determine if overvoltages in the industrial distribution network could have been a contributory factor to the failure of the cables.

An EMTP (Electro Magnetic Transient Program) study was performed simulating the 35 kV distribution network in detail, including harmonic filters and the step down transformers at the converters. Circuit breaker operations were simulated, and the effect of filters and possible harmonic resonance in the distribution network was examined. The results did not show any overvoltages that would endanger the insulation of the cables. Maximum overvoltages occurred during line-to-ground faults, which caused the sound phase voltages to increase to about the phase-to-phase voltage. This is normal and to be expected in similar systems and should not result in insulation failure. A maximum transient overvoltage found from the simulation was 65 kV peak which compares with the cable power frequency voltage withstand capability of 98 kV peak. The 35 kV system exhibited a natural resonant frequency between 120 and 180 Hz. Due the type of filters installed this is not likely to cause linear or ferro resonance. It is believed that dielectric stresses across the cable insulation did not contribute to the cable failures.

Fig. 1 shows the fault current for a single line to ground fault. The current shown is about 1100 A r.m.s. close to the 1200 A recorded during the actual incidence. Fig. 2 shows the voltages on phases B and C during the SLG fault on phase A. The voltage rise on the sound phases is 47 kVp, approximately the normal phase-to-phase voltage, 34.5 kV r.m.s.

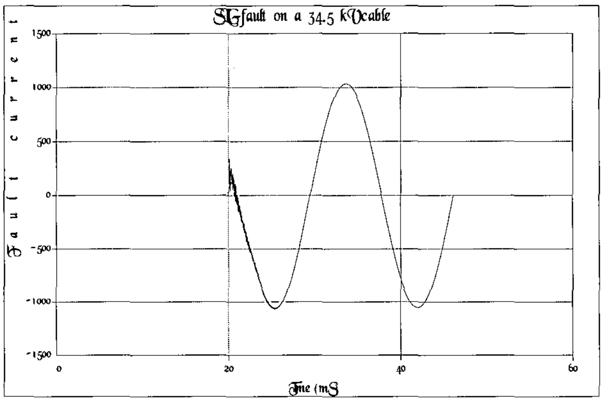

Fig. 1 Closing onto a SLG fault. Fault current in phase A r.m.s.

Fig. 3 shows the voltage stress across a discontinuity in the cable sheath (copper tape). This stress reaches the value of the phase-to-ground voltage across the gap in the tape. Depending on the length of the gap this would lead to arcing or tracking across the insulation and result eventually in insulation failure and a fault to ground.

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A review of protective relay operations as part of the failure investigation verified that during the cable failure all protective relays correctly operated. Lower magnitude cable faults (restricted by the transformer grounding resistor between 911 amp to 1,250 amp) were each time selectively detected and cleared by appropriate protective relay operations. A high magnitude fault (14,700 amp after destructions of the transformer grounding resistor) was (also appropriately) seen by several (cleared by) instantaneous relays. The fault was cleared by instantaneous relay operations, but in this case selective clearing was not possible. Therefore it can be concluded that protection operation during the cable faults was satisfactory.

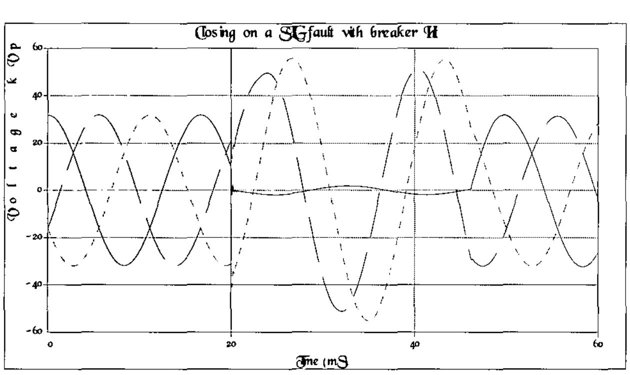


Fig. **2** Closing onto a SLG fault. Voltage rise on sound phases kVp ph-g.

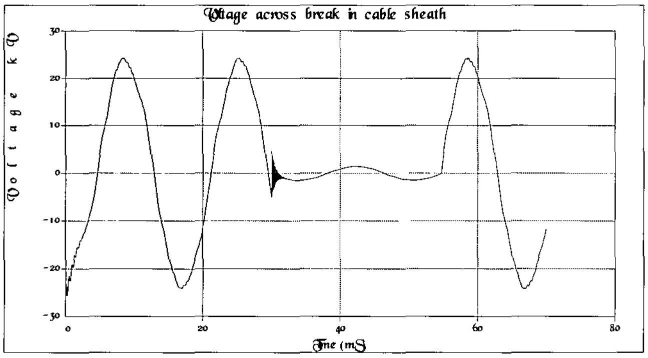


Fig. **3** Voltage across gap in the shielding copper tape Sparkover followed by recovery

3. Simulation of Cable Installation

A section of the cable about 25 cms long was cut from the spare cable sample and the copper tape was carefully removed by peeling off its PVC jacket. The copper tape was used to evaluate the effect of edge defect on its tensile properties.

3.1 Tensile Tests (on tape with a sound edge)

Three tensile dumbbell test specimens 5 cm gauge long and 1.9 cm wide were machined from the copper tape to evaluate the tensile properties of the copper tape that has a sound edge. The test parameters, specimen dimensions and results of the tensile tests are shown in Table 1.

3.2 Tensile Tests (on tape with a damaged edge)

Three tensile test specimens 5 cm gauge long and 1.9 cm wide were machined from the copper tape. The edges of these specimens were superficially scratched at the middle of the gauge length to form a shallow defect. This edge defect was required to simulate the segregation of inclusions on the edge of the tape. The test parameters, specimen dimensions and results of the tensile tests are given in Table 2.

The results of the tensile tests with and without edge damage clearly indicate that the condition of the edge of the copper tape has a significant effect on its tensile properties. The superficial scratch on the edge of the copper tape dramatically reduced the elongation. The tensile strength of edge-damaged copper tape is lower than that of copper tape that has a sound edge. These observations suggest that if tramp elements and oxides are segregated at the edge of the copper tape, its elongation and tensile strength are reduced.

Two 2.44 m long samples were removed from the 10 m long spare cable. One sample was used to simulate the bending operation of the cable during installation and other sample was used to simulate the pulling operation.

3.3 Bending Operation

The middle section of the sample was bent manually around a 71 cm diameter sheave. The ends of the sample were clamped using hose clamps to ensure that the copper tape at the ends remained in place. One end of the sample was anchored near the sheave while the free end was bent around the sheave in a 'U' shape. The sample was bent six times in one direction, and then the bend area was examined for cracks using an eddy current inspection technique. Subsequently the sample was reverse bent six times and the bend area was examined for cracks.

No cracks were found on the bend areas. Instead, the copper tape at the bend area had slipped to accommodate the bending stress. The PVC jacket at the bend area was carefully removed to expose the copper tape, but no damage was found.

3.4 Cable Pulling Operation

The second 2.44 m long sample was used to simulate the cable being pulled around a 15 cm diameter sheave. The ends of the sample were clamped with self-tightening grips

Table 1 Tensile Test Results on New Copper Tape.

Sample ID	Width (inches)	Thickness (inches)	Area (sq. in.)	Cross-head speed (in./min.)	Peak load (lbs)	Tensile stress, (psi)	Elongation (%)
1	0.749	0.005	0.003745	0.2	132.8	35,460	62.5
2	0.750	0.005	0.00375	0.5	131.2	34,986	47.8
3	0.751	0.005	0.003755	1.0	134.8	35,898	61.1

Table 2 Tensile Test Results on Damaged Copper Tape.

Sample ID	Width (inches)	Thickness (inches)	Area (sq. in.)	Cross-head speed (in./min.)	Peak load (lbs)	Tensile stress, (psi)	Elongation (%)
4	0.750	0.005	0.00375	1.0	102	25,546	12.9
5	0.750	0.005	0.00375	0.5	94.2	25,120	10.7
6	0.750	0.005	0.00375	0.2	95.8	27.200	14.8

(cable pulling sock) and hose clamps. One of the grips was anchored to a post through a rope and other end was attached to the crane. The middle section of the cable was allowed to bend through a 15 cm diameter pulley. The sample was pulled through at 90° bend using various loads. A load cell (dynamometer) was attached to the crane to monitor the load during the pulling.

After six pulling operations, the middle section of the cable was non-destructively inspected using the eddy current examination technique. The cable was then straightened and pulled six times in the reverse direction. The middle section of the cable was examined using the X-ray radiographic and eddy current examination techniques. Wrinkles were observed on the copper tape. Further pulling of the cable was carried out using different configurations to see whether a crack would initiate at the edge of the copper tape. Although the extent of wrinkling was increased, the tape did not show any signs of cracking.

After the completion of the test, the section of the sample containing wrinkles was dissected and the PVC jacket was peeled off to expose the copper tape. The copper tape in the middle section of the cable showed wrinkles. A section of the wrinkled tape was cut for more examination. There were no signs of cracking. Instead, the upper half of the tape was uniformly deformed.

4. Metallurgical Investigation

The first part of the metallurgical investigation assessed the copper tapes taken from a new cable (unused) from the manufacturer's plant (see Fig. 4). The second part assessed the integrity of the copper tapes taken from a failed cable (see Fig. 5).

The micrographs in each Fig. show a marked difference in the material properties of the copper tapes. Fig. 5 shows the presence of tramp elements and oxide inclusions, while Fig. 4 is free of these contaminants.

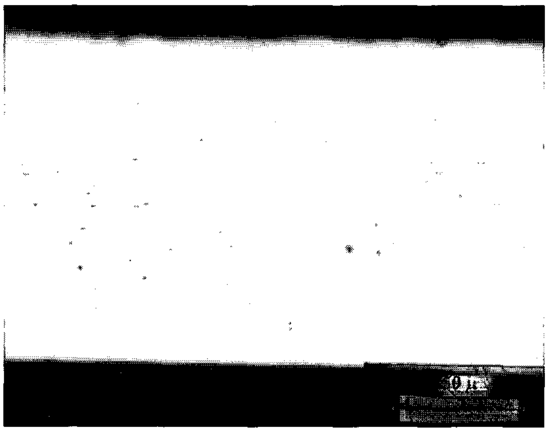


Fig. 4 Microstructure of the edge of the copper tape taken from a new and unused cable.(Mag. 500X)

Fig. 5 Microstructure of the edge of copper tape sample showing tramp elements and oxide inclusions.(Mag. 500X)

5. Discussion

The cable failure investigation examined all possible causes of failure. As a result of electrical system studies, protection and control evaluation and numerous laboratory testing programs the following comments can be made.

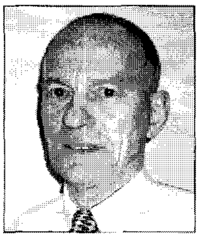
1. The electrical system study did not show any overvoltages of sufficient magnitude to damage the cable insulation.
2. Review of the protective relay operations verified that during the cable failure all protective relays operated correctly.
3. The cable failure was probably caused by a combination of two problems. The first and most damaging, was the over-tensioning and mishandling of the cables during the installation. And the second problem was the presence of tramp elements in the copper tapes left during manufacture of the tapes.
4. Once the copper tape shield separated into sections during installation, each ungrounded portion experienced a voltage through capacitive coupling leading to sparking across the resultant gap in the copper tape, rapidly eroding the semiconductive insulation shield and finally the cable insulation.

6. Conclusions

Based on the findings of this investigation, the following conclusions were drawn:

- Tramp elements and oxide inclusions appeared at localized areas along the edge of the copper tape of the failed cable. These defects reduced the tape's tensile strength and elongation.
- Bending and pulling the cable through a sharp radius can easily wrinkle the copper tape of the failed cable. Certain parts of the cable can be exposed to an excess of 3000 lbs of load when the cable catches around the sharp bend. When the edge of the copper tape that contains the defect is caught in this way, the copper tape will fracture due to mechanical overload.

Hence, it is concluded that the fracture of the copper tape of the cable took place due to a combination of the defect on its edge and an abnormal bending operation. It appears that these two factors individually would not fracture the copper tape.



Harry Orton

Harry Orton graduated from the University of New South Wales (Australia) with a Bachelor of Engineering (Honors) in Electrical Engineering in 1966 and a Masters of Applied Science from the University of British Columbia (Canada) in 1969. He graduated from the BCIT Venture Program in May, 1995. He is currently working on a Ph.D. at the University of New South Wales.

After graduation in 1969, Mr. Orton worked at BC Hydro as an Electrical Research Engineer where he helped build one of the largest utility based research centers in North America. For over twenty years he worked as a specialist in the field of underground power transmission and distribution cables and accessories. He progressed to the level of section supervisor in charge of Insulation Studies and then to Manager of Technical Activities. He has been a project manager on CEA and EPRI underground cable research projects since 1977 and was Chairman of the CEA Cable Failure Task Force from 1987 until 1993.

In 1994 he went into his own consulting engineering business as an underground power cable specialist. He is now Principal and owner of Orton Consulting Engineers International Ltd. based in Vancouver and affiliated with the International Consulting Engineers. Contract work takes him to the US, Asia and to Europe.

Harry is very active in the IEEE, Insulated Conductors Committee (ICC) as Chairman of Task Group A2D on the Characteristics of Semiconductive Shields and Task Group B15D on Cable Accessory Diagnostics and is Chairman of the Transnational Subcommittee on Underground Power Cables. He has published over 40 papers on the applications of underground transmission and distribution power cables and has given many presentations to the IEEE, ICC, research institutes, universities, manufacturers and utilities Worldwide. He has given invited presentations and seminars in Japan, Brunei China, Singapore, Malaysia, Hong Kong, Korea, Australia, Indonesia, Canada and the US.

Mr. Orton has organized, run and lectured in the UBC Power Cable Seminars since their inception in 1990. He is on the Board of Governors for the EIC, a member of the Vancouver Board of Trade, the Canadian Council of the Americas, American Society for Testing Materials (ASTM) and the Hong Kong Canada Business Association and is a Registered Professional Engineer in the Province of British Columbia, Canada. Mr. Orton holds Canadian, US and International patents on cable diagnostics.

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