FEATURE ARTICLE

AC and Impulse Performance of Medium Voltage Ethylene Propylene–Rubber Cables With Over 25 Years of In-Service Aging in a Wet Underground Environment

Key words: distribution cable, EPR insulation, HMWPE insulation, AC and impulse strength, in-service aging

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The article describes shifting from minimizing "initial cost" to minimizing "life cycle cost" by switching from cables insulated with high–molecular weight polyethylene and cross-linked polyethylene to cables insulated with ethylene propylene rubber. This shift reduced the number of failures per year and improved reliability indices.

Introduction

Many electric utilities, including Memphis Light, Gas & Water (MLGW), began installing underground residential electric (URD) facilities in the late 1960s. The earliest URD customers at MLGW were served by paper-insulated lead-covered (PILC) type cable which has a very good service history but was expensive and time-consuming to install. In an effort to install URD facilities at a comparable cost to traditional overhead facilities, direct buried high–molecular weight polyethylene (HMWPE) insulated cables were utilized. These unjacketed cables were constructed with a #2 AWG copper conductor, 6.1 mm (240 mils) of HMWPE insulation, and copper concentric neutrals. Unjacketed feeder cables were constructed with a 380 mm^2 (750 kcmil) aluminum conductor, 6.1 mm (240 mils) of cross-linked polyethylene (XLPE) insulation, and copper concentric neutrals. Initially, feeder cables were direct buried but by the mid-1970s were installed in conduit. All cables were operated at either 12 kV or 23 kV phase-to-phase system voltages.

Failure Rates of Early Polyethylene-Insulated Cables

By 1973, with only 6 years of field service, the HMWPE insulated cables had a failure rate of 4.24 failures per 100 conductor miles per year (4.24 f/100 mi-yr). By 1976, the failure rate had increased to 16 f/100 mi-yr. This high and increasing failure rate resulted in a change to specifying XLPE insulation for all cables. By 1980, the failure rate for the XLPE insulated cable was about 3 f/100 mi-yr. The HMWPE insulated cable yearly failure rate peaked in 1983 at 87 f/100 mi-yr for URD cable, while the XLPE failure rate peaked in 1985 at 11 f/100 mi-yr.

Move to Life Cycle Cost Design Principle

In 1978, the high and accelerating rate of failure of both HMWPE and XLPE cables precipitated a shift from minimizing "initial cost" to minimizing "life cycle cost" of the cable systems. As a result, MLGW attempted to determine the cable designs and materials with established history of in-service reliability. After significant research, MLGW selected an ethylene propylene–rubber (EPR)-based cable design with 16 years of in-service history and nearly flawless reliability. Emphasis was also placed on highly reliable splices, terminations, connectors, transformers, and system design. Because of the unacceptable reliability indices of the "pre-1980" system, the "post-1980" system design and components were used to retrofit the 1967–1979 HMWPE/XLPE based system. Approximately $50 million was spent to improve reliability and bring the URD system to "post-1980" standards. The inflation adjusted retrofit cost was 7 to 8 times the initial installation cost. This effort reduced the number of failures per year, as shown in Figure 1, and improved reliability indices.

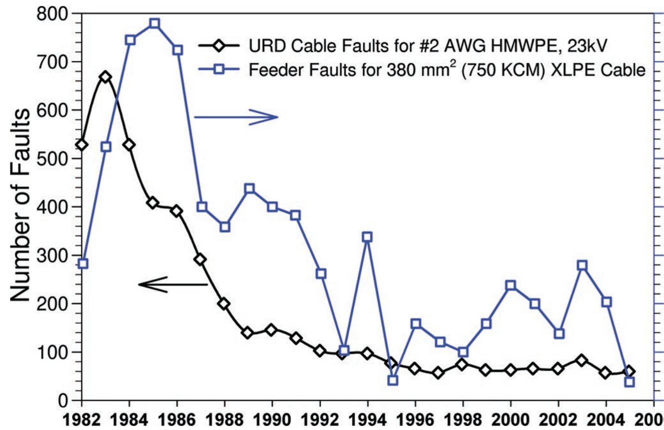

Figure 1. Failure analysis data from Memphis Light, Gas & Water suggested clearly the retrofitting of #2 AWG high–molecular weight polyethylene (HMWPE) and cross-linked polyethylene (XLPE) cables with ethylene propylene–rubber cables reduced the number of service failures. For HMWPE cable, the peak in 1983 represents a failure rate of 87 failures per 100 conductor miles per year. For XLPE cable, the peak in 1985 represents a failure rate of 11 failures per 100 conductor miles per year. The peaks in 1994, 2000, and 2003 were caused by reduction in retrofit funding in the preceding 12 to 24 months. URD = underground residential distribution.

Field Aging Cable Test Program

As a result of this experience, in 1984 MLGW started a long term field aging test project on unjacketed URD cables insulated with various EPR insulations and insulation wall thickness. This field aging test was based on unjacketed URD cables with #2 AWG copper conductor (33.6 mm^2) insulated with 3 types of EPR insulation at 2 insulation wall thicknesses, 6.6 mm (260 mil) for 25 kV rating and 4.45 mm (175 mil) for 15 kV rating, all of which were energized at 23 kV system voltage (13.28 kV phase-to-ground). These cables were installed in a typical URD subdivision during the HMWPE retrofit projects. The retrofit and test cables were installed in a conduit system which, because of field conditions, was partially but continuously filled with water. Initially, the retrofitted cable supplied the subdivision until all of the test cable could be installed, after which the test cables were energized within a 2 week period. Table 1 provides details regarding cable types and quantities installed and stored in this field aging test project. The 6.60 mm wall cable operated at 3.385 kV/mm (86 V/mil) maximum field and 2 kV/mm (51 V/mil) average field, while the 4.45 mm wall cable operated at 4.4 kV/mm (112 V/mil) maximum field and 3 kV/mm (76 V/mil) average field.

Electrical Testing and Data Analysis

Each of the cable types was sampled and AC breakdown tested at their factory to establish initial, i.e., "year zero," breakdown values. After 2, 5, 9, and 24 years of field cable aging, cables were removed from service, cut into roughly 10 m sections, their ends were sealed, and they were packaged in water filled plastic pipes for shipment to the high voltage laboratories

Table 1. Cable types and quantities for the field aging test project[1]

Ethylene propylene–rubber insulation type	4.45 mm/175 Mil	6.6 mm/260 Mil	ICEA [1] classification	Quantity installed (m)	Quantity stored (m)
A		X	III	1,824	942
A	X		III	2,472	954
B		X	IV	2,866	950
B	X		IV	3,018	923
C		X	III	2,778	282
C	X		III	2,831	802
Total				15,788	4,852

[1]According to the Insulated Cable Engineers Association (ICEA) classification for ethylene-propylene-rubber-insulated wire and cable for transmission and distribution [1], type III insulation is for use on shielded cables rated 2,001 V and above with conductor temperature not exceeding 105°C under normal operation and type IV insulation has a specific discharge resistance requirement and is suitable for use on cables rated 2,001 through 35,000 V with conductor temperature not exceeding 90°C under normal operation.

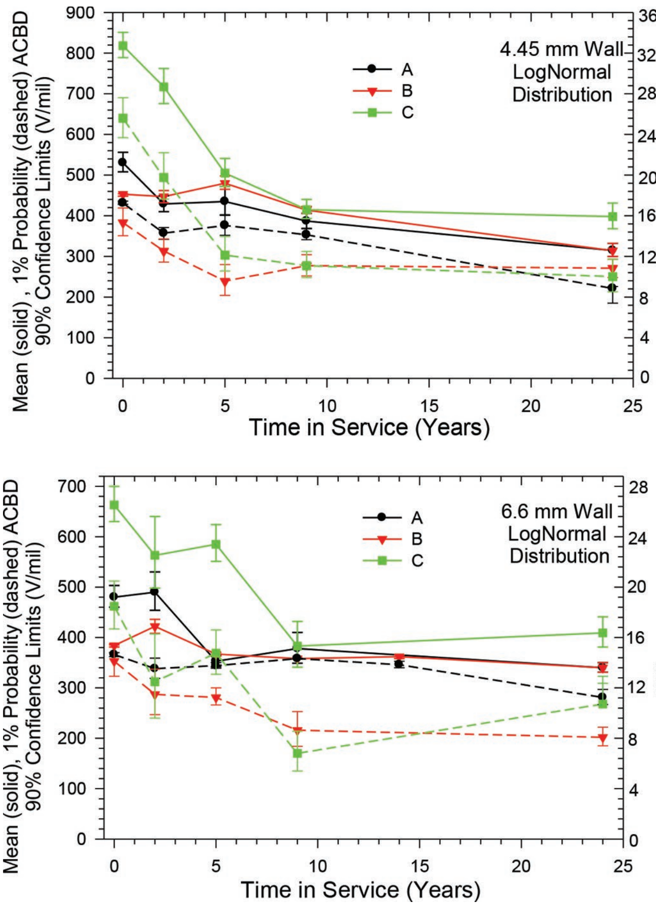

Figure 2. AC breakdown (ACBD) field for the three cable types as a function of years in service at 50% probability and 1% probability with 90% confidence limits, based on a LogNormal distribution and the average field over the insulation wall. The operating field for the 4.45 mm cable was 3 kV/mm, although the normal line-to-ground operating field in a 15 kV system would be only about 1.8 kV/mm average RMS field in the insulation. The operating field for the 6.0 mm cable was 2 kV/mm average RMS field in the insulation.

at which they were tested for AC breakdown strength. Impulse tests were performed on samples field aged for 24 years. Figure 2 shows the AC breakdown field as a function of time in service based at 50% and 1% probability based on a LogNormal distribution of the average field within the insulation wall, with 90% confidence limits, for the 4.45 mm and 6.6 mm wall cables.

The data show some scatter, which is to be expected for any breakdown data, in spite of which, the data for the 4.45 mm and 6.6 mm cables are remarkably similar. At 50% probability, the A and B 4.45 mm cables have an AC breakdown field of about 13 kV/mm (330 V/mil) after 24 years of service, while the C cable type is at 15.7 kV/mm (400 V/mil). The corresponding numbers for the 6.6 mm cable are 13.4 kV/mm (340 V/mil) and 15.7 kV/mm (400 V/mil). All three cable types came to near steady state breakdown field after 9 years, i.e., the breakdown field at 24 years is nearly the same as that at 9 years. As is inevitable, the data at 1% probability have greater confidence limits and scatter than those at 50% probability; however, they suggest that

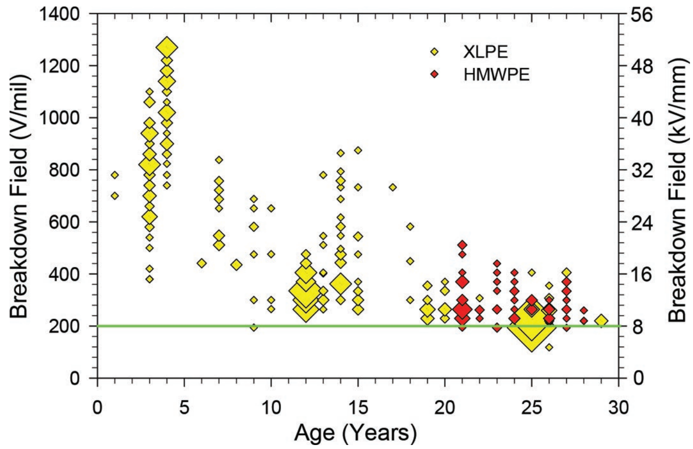

Figure 3. Breakdown data as a function of age for a large number of cross-linked polyethylene (XLPE) and high–molecular weight polyethylene (HMWPE) cables removed from the field as reported in literature [2]. The area of each symbol is proportional to the number of breakdowns at that step, while the center of the symbol indicates the step field. Very few samples have breakdown field below 8 kV/mm, presumably because once the cables reach that field, they tend to fail very rapidly in service.

the field for 1% probability of breakdown is in the range of 8 to 12 kV/mm (200 to 300 V/mil) after 9 and 24 years aging, respectively.

Comparative Data to XLPE and HMWPE Insulation

Figure 3 shows a large number of breakdown data from literature for XLPE and HMWPE of the same vintage as the EPR cables under discussion [2]. The lack of breakdowns below about 8 kV/mm, a well known phenomenon in populations of aged PE cable, suggests that when the AC strength of a cable approaches 8 kV/mm, it fails in service. An AC breakdown field of 8 kV/mm is far more than necessary to withstand normal operating fields (around 2 kV/mm), and the in-service failures of these cables are the result of normal surges on the system, i.e., switching and lightning impulse. This result may be expected based on the fact that the impulse strength of XLPE and HMWPE drops even faster than the AC strength with age.

Figure 4 shows the breakdown field of XLPE cable as a function of years in service at 50% probability and 1% probability of breakdown, along with 90% confidence limits. The 1% probability curve crosses 8 kV/mm at around 8 years, which suggests that the failure rate will be noticeable after about 8 years of aging, which is consistent with the experience described above. By 25 years, the breakdown field at 50% probability has reached about 8 kV/mm, which suggests a very high failure rate for cable of this vintage, although so much of it may have failed by 25 years that it may not have much impact on the failure statistics of the overall system.

The AC breakdown field for the aged EPR cable (Figure 2) is better than for the XLPE cable, but at 1% probability, the breakdown field for some of the EPR cables is in the range of 8 kV/mm, which would suggest an appreciable failure rate. The reason that the EPR cables have negligible failure rate can be seen from

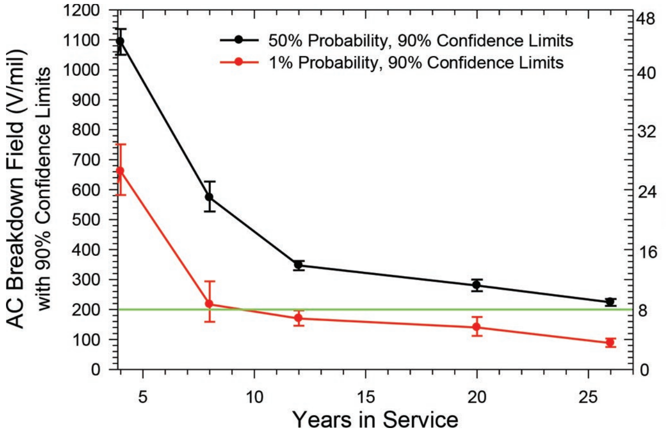

Figure 4. AC breakdown field as a function of years in service for cross-linked polyethylene cable of similar vintage as the ethylene propylene–rubber cable under discussion. The plots are produced based on statistical analysis of data from [2]. The breakdown field at 1% probability crosses 8 kV/mm at about 8 years, which suggests that around this time, the failure rate will become appreciable.

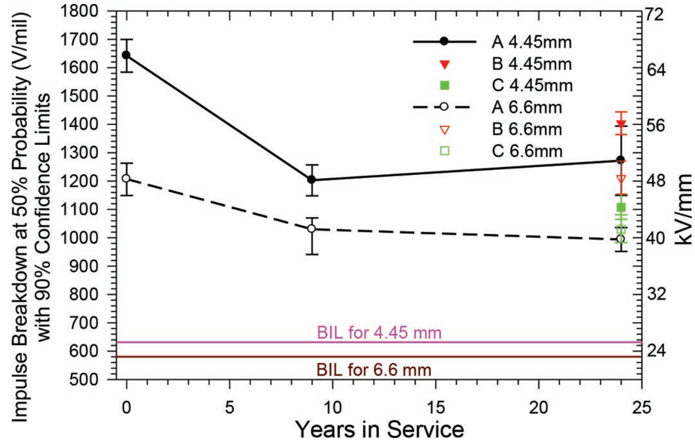

Figure 5. Impulse breakdown field at 50% probability and 90% confidence limits, along with the withstand fields required to meet the cable BIL at 4.45 mm and 6 mm mil insulation wall. After 25 years of field aging, the impulse breakdown field exceeds the impulse strength required of new cable by nearly a factor of two

Figure 5, which shows that after 25 years of service aging at well above normal operating field in the case of the 4.45 mm cable, the impulse breakdown field by far exceeds that required to meet the rated BIL of the cable. The AC voltage strength which far exceeds the requirement for normal power frequency operation, combined with impulse voltage strength which also significantly exceeds that to meet the BIL of the cable, ensures highly reliable operation after 25+ years of in-service aging, and suggests that these EPR cables will operate reliably for the foreseeable future.

MLGW Post-1980 Service Experience With EPR Cable

Since 1980, MLGW has suffered 4 lightning induced cable failures, two of which caused substantial damage to other equipment, such as pad-mounted transformers, arresters, etc. In addition, 4 failures have resulted from squirrel "eat-ins," and 2 failures resulted from severe overloading of the cable, which was subjected to 160% of full load current for several days far exceeding the emergency rating of the cable. Two failures were caused by damage during installation, and 4 failures were caused by damage on the reel before installation. Dig-ins are undocumented. This results in a yearly failure rate of about 0.16 f/100 mi-yr, which does not include failures of splices, terminations, connectors, or failures caused by abuse of the cable (overloading and mechanical damage).

As a result of the high reliability of the EPR cable used by MLGW, commissioning tests are not economically viable as they are unlikely to eliminate service failures. Although the reliability of splices and terminations is not as great as that of the cable, the system reliability is very high. While commissioning tests might detect workmanship errors in splicing and terminating, the cost for such testing would be many times greater than the in-service repairs which result from not conducting the tests.

Conclusion

Field experience at MLGW has justified its decision to install EPR insulated cable. Analysis of AC and impulse breakdown strengths of EPR cables aged on the MLGW system in service since 1983 (for over 30 years) provides confidence that the cable will continue to operate reliably for the foreseeable future. To date, a systematic failure mechanism has not been identified for any of these EPR insulations subjected to normal and moderately (150% overvoltage) "accelerated" operating voltage stress in a wet underground environment.

References

[1] Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy, NEMA Standards, Publication No. WC 8-1992, ICEA Publication no. S-68-516, Dec. 1996.

[2] T. O. Bialek and S. Grzybowski, "Investigation of the performance of field aged HMWPE and XLPE cables," in *2000 IEEE Conf. Electr. Insul. Dielectr. Phenom.*, 2000, p. 760.

Philip Cox was born in Memphis, Tennessee, USA, on July 3, 1958. In 1980, he received a BSEE, with concentration in clinical (biomedical) and power engineering, from Christian Brothers College (University) in Memphis. Other education includes courses in computer programming, law, and pre-med. He is a licensed/registered Professional Engineer in Vermont and Tennessee (USA). He has over 24 years of experience in the electrical power industry and has held various positions at Memphis Light, Gas & Water. Experience includes lighting design, power applications engineering consultation, and his current position as underground electric transmission and distribution systems engineer (MLGW). He has served on various Insulated Conductor Committee (ICC) working groups as standards/guide contributing writer, chair, and vice-chair. He has authored several papers and presentations for the IEEE Power Engineering Society.

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Frank Krajick received a BSEE from Fairleigh Dickenson University in 1972. He joined the Okonite Company in 1973 in their Paterson, New Jersey, High Voltage Laboratory. From 1973 to 1987 he held various electrical engineering positions in the laboratory. In 1987, he became director of Cable Evaluation and Development. He is responsible for the full range of cable testing and qualification of Okonite's solid and laminar dielectrics up to 345 kV. His professional activities include IEEE Power Engineering Society and Insulated Conductors Committee (ICC) and Insulated Cable Engineers Association (ICEA).

Steven Boggs (F '92) was graduated with a BA in physics from Reed College and received his PhD and MBA degrees from the University of Toronto in 1972 and 1987, respectively. He spent 12 years with the Research Division of Ontario Hydro and 6 years as Director of Engineering and Research for Underground Systems, Inc. Steve recently retired from his position as Director of the Electrical Insulation Research Center of the University of Connecticut and Research Professor of Materials Science, Physics, and Electrical Engineering, although he is still working on a number of projects at the University. Until recently, he was also an Adjunct Professor of Electrical Engineering at the University of Toronto. He has published widely in the areas of partial discharge measurement, high frequency phenomena in power apparatus, high field phenomena in solid dielectrics, capacitor technology, and SF_6 insulated systems. He was elected a Fellow of the IEEE for his contributions to the field of SF_6 insulated systems and received the 2010 IEEE Thomas W. Dakin "Distinguished Technical Contributions" award. Presently, Steve spends most of his time doing computational research for a range of companies in the US and Asia through his company, Nonlinear Systems, Inc.

Yang Cao was graduated with BS and MS in physics from Tongji University in Shanghai, China, and received his PhD from the University of Connecticut in 2002, after which he served as a senior electrical engineer at GE Global Research Center. Since 2013, he has been an associate professor at the Electrical and Computer Engineering Department of the University of Connecticut. His research interests are in the physics of materials under extremely high field and the development of new dielectric materials, particularly the polymeric nanostructured materials, for energy efficient power conversion and renewables integrations, as well as for novel medical diagnostic imaging devices. He can be reached at yang.cao@uconn.edu.