Is Fault Location Killing Our Cable Systems?

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Abstract— *Power outages caused by faults in underground cable systems can be difficult to locate, however it is always advantageous for a utility to restore power within a short time-frame in order to maintain a high level of customer satisfaction, system performance, and profitability. Although there are different ways to determine the location of a fault within a length of underground cable, a common methodology used by electric utilities involves the use of a voltage pulse unit known to many in the industry as a 'thumper.' As a derivative of a system wide cable reliability program, based on a condition assessment comparable to cable and accessory manufactures' quality control standards, one of the largest utilities in North America set forth a field experiment to help quantify the damage to cable insulation caused by fault location thumping. This paper provides insight into the harmful effects of field applied 'thumping' and offers recommendations on how utility operations managers can minimize their risk of repeat outages, increase customer satisfaction while maximizing safety, efficiency and reliability.*

Keywords—*Cable system, failure, fault location, distribution reliability, assessment, partial discharge, location, asset management*

I. INTRODUCTION

Electric utilities are under immense pressure to reduce downtime, provide estimated time of restoration (ETR) and restore power after a system fault. If the outage is caused by an underground cable system failure, the location of the fault must be determined in order to restore power. Once the cable system is isolated (following IEEE recommended safety practices), a common method used to verify fault location is 'thumping.' The most rudimentary variation of thumping applies high voltage pulses to the faulty cable, resulting in a current arc at the fault location that makes a noise that is often loud enough to hear above ground. This resulting sound wave enables maintenance crews to locate the general area of the location of the fault within the length of cable. Utilities have reported that the risk of subsequent power failures in the same circuit increase substantially after the first fault and thumping process is performed [1]. Some utilities have made procedural changes to the fault location process in order to reduce the risk of repeat failures, but until now, the foot-by-foot impact on the insulation caused by thumping has not been well documented or understood. Over the past five years, a large utility in the southeastern United States has been using an assessment technology comparable to cable and accessory manufactures' quality control standards [Table I] to determine the performance of their underground residential distribution (URD) cable systems. While the primary role of the technology is to assess cable system integrity and future viability to direct the utility's capital reliability program, there have been a number of derivative benefits associated with having a profile assessment of over one thousand miles of underground cable systems. Using this profiling technology, this utility has been able to objectively document the deterioration of cable insulation by comparing the assessment results before and after fault location activities. This paper provides a brief review of the program to provide context, describes the fault location experiment, results, and procedural recommendations. The results of the experiment provide valuable information to assist asset and operations managers to minimize the damage caused by the fault location process and make informed decisions to manage asset return on investment while reducing downtime.

II. BACKGROUND

Concerned with the age and failure rate of its URD cable system the subject utility developed a program to maximize system reliability while limiting asset management costs using a factory comparable offline PD (Partial Discharge) measurement to assess the condition of its cable systems. At the start of the program the utility had over 16,000 miles of in-service underground medium voltage power cable systems. A subset of this population (approximately 1,000 miles or 7% of the total), comprised of cable systems primarily installed before 1986 that were failing at a significantly elevated rate of 23 failures per 100 miles per year. For many years, the utility replaced these cable systems based on traditional metrics of vintage, frequency of failure, age, and construction type. The utility noted that over a three year period that the cost per avoided failure had increased by over 250% and the reliability program was projected to exceed $20 million per year. Reportedly, these increases were incurred because of rising labor and material costs and the inherent inefficiencies of wholesale cable system replacement.

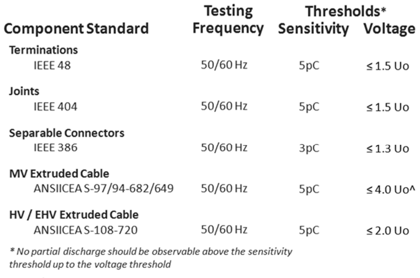
A. Program Results

The 5-year program at this utility assessed over 1,000 miles of 15 kV and 25 kV single-phase URD circuits using off-line 50/60 Hz PD measurement technology. At an estimated cost to replace of $17.50 per conductor foot, this represents roughly $185 million in cable assets. The non-destructive diagnostic assessment with defect location capability demonstrated that, of the cable systems originally flagged for replacement per the traditional criteria, approximately 97% of the population, could remain in service and were eligible for at least an additional 10-year life extension following recommended repairs. The results of the program are that 81% of the cable systems assessed were recommended for defer (no) action, 13% were recommended for repair and 6% were recommended for complete replacement. The program has been a success by all accounts but perhaps the most telling metric is the dramatic drop in system wide failures. After assessing over 19,000 cable systems and taking the appropriate repair and replacement actions, the failure rate has decreased by over 90%. To further compound this success the all-capital program decreased overall costs by 76% and the rehabilitation budget has been stabilized at a much lower level for the foreseeable future.

B. Derivative Benefits

A derivative benefit from the utility's underground cable reliability program is dramatic increase in awareness of issues that impact the life-cycle health of distribution assets. One such benefit came from the analysis of unexpected deterioration after repair. Upon studying this deterioration it became clear that a number of failures were associated with voltage transient activity that manifested after performing a fault location procedure using a voltage pulse technique commonly called 'thumping'. A few anecdotal cases surfaced suggesting that the cable system integrity significantly deteriorated after thumping. This experience coupled with reports of less than optimal fault location results provided the utility with enough information to approve a study to better understand the negative effects of common fault location procedures.

Table I. Manufacturers' Standards



Component Standard	Testing Frequency	Thresholds* Sensitivity	Voltage
Terminations			
IEEE 48	50/60 Hz	5pC	≤ 1.5 Uo
Joints			
IEEE 404	50/60 Hz	5pC	≤ 1.5 Uo
Separable Connectors			
IEEE 386	50/60 Hz	3pC	≤ 1.3 Uo
MV Extruded Cable			
ANSIICEA S-97/94-682/649	50/60 Hz	5pC	≤ 4.0 Uo^
HV / EHV Extruded Cable			
ANSIICEA S-108-720	50/60 Hz	5pC	≤ 2.0 Uo

** No partial discharge should be observable above the sensitivity threshold up to the voltage threshold*

^200 V/mil

U_0 = Operating Voltage

III. HOW CABLE SYSTEMS FAIL

Solid dielectric cable system insulation fails due to an erosion process associated with phenomena called partial discharge (PD). It is well known that the vast majority of extruded insulation cable system failures are associated with partial discharge activity. PD is an electrical discharge or 'micro arcing' that does not completely bridge the insulation [2]. PD can arise from an extreme focus of electric stress, a lack of the appropriate solid insulation, or a combination of both [3]. A focus of electric stress, or stress enhancement, can be caused by issues such as accessory interface contamination, a foreign object, a protrusion of a semiconducting layer, or a water tree. A lack of appropriate solid insulation filled by a gas, or a void, can be caused by such issues as a damaged semiconducting layer, overheating of the cable or accessory insulation, an insulation cut, a lack of accessory void filler or an incorrect accessory/cable interface dimension. PD, and its associated erosion process at a defect site, is rarely active at steady state operating voltage unless the failure is imminent. PD is initiated when localized electric stress overcomes the local dielectric strength. The voltage at which PD initiates is called the inception voltage (PDIV). PD activity extinguishes when the localized stress is sufficiently lowered. The voltage at which the PD extinguishes is called the extinction voltage (PDEV). Voltage transients; fast, short duration electrical transients, are the primary driver of PDIV and insulation failure. The sources of transients include circuit switching, restoration activities (breaker operations and fuse reclosures), fault location and withstand tests, momentary flashovers and grounds (momentary contacts with air insulated components), complete faults elsewhere in the system, sectionalizers, capacitor banks switching, transformer tap changes, and especially, lightning. Transients reflect and resonate within the power system and can increase in magnitude exponentially. [5] Voltage transients, typically occur in the microsecond to millisecond time-frame. This is more than enough time for PD to turn on, erode the insulation, and turn off. Successive transients can cause intermittent growth of an electrical tree (fault channel) [4, 5]. As the electrical tree grows, the PDIV/PDEV drops and eventually, the PDEV is at or less than operating voltage. Once the PDEV is at or less than operating voltage, the next transient greater than the PDIV can initiate PD and the associated erosion process until the cable system fails.

IV. FAULT LOCATION EXPERIMENT

An experiment was designed to provide complete system profiles of cables before and after the fault location procedure was performed. The methodology was modeled after a common 'thump and walk' fault location procedure described during interviews with numerous field staff. It was noted that the procedure reported by field personnel differs considerably from the utility's standard operating procedure; however it represents a reported common practice throughout the utility industry.

A. Common Fault Location Procedure

On the basis of interviews with fault location crews, it is a common practice to use a capacitive discharge unit, or 'thumper', to introduce high voltage pulses to the cable system. The pulses travel through the cable until they reach the breach in the insulation. If the voltage of the pulse is sufficient to bridge the gap in the fault from conductor to ground, the resulting high-current arc will create a sound pressure wave. A technician walking the path of the cable can detect the failure location by listening for the intensity of the audible sound or the 'thump'.

B. Experimental Procedure

The design of the experiment was simple: measure the performance of the cable system as compared to the cable and accessory manufacturers' quality control standards (Table I) before and after the fault location procedure .The preliminary cable assessment provided a foot-by-foot profile of the cable system. 25kV cable systems were chosen with a mixture of mostly 'good' cable (meeting standards – Table I) with at least one substandard (defective) location. A control of three consecutive assessments were performed to demonstrate the pre-fault locate procedure did not adversely affect the condition of the cable system. The fault location procedure consisted of turning on the thumper to 15kV and 'pulsing' the cable system for twenty minutes, allowing plenty of time to simulate a technician walking the round trip length of the cable while listening for the thump. The cable system was then profiled again. The profile results from before and after the fault location procedure were then compared.

C. Data

The original experiment called for twenty aged cross-linked polyethylene (XLPE) cable systems. Very quickly the authors found that accessing this number of cable systems was taxing to operational resources so the goal was lowered to ten samples. The final available case count was eight due some additional unforeseen operational challenges. The total footage of cable systems included in the experiment was an estimated 4,871ft. Three of the eight systems selected turned out to be tree-retardant XLPE cable (TRXLPE), one of which did not have any sub-standard components. This was undesirable from the original experiment design standpoint but the diversity of subject cables ended up providing a useful performance comparison between similar vintage XLPE and TRXLPE insulation systems.

Table II Experiment Results

Sample No.	Year	Insulation Type	Post Thumping Results	Apparent Change
1	1992	TRXLPE	No Degradation	
2	1990	TRXLPE	Degraded	Joint performance degrades
3	1990	TRXLPE	No Degradation	
4	1989	XLPE	No Degradation	
5	1987	XLPE	Degraded	Joint performance degrades
6	1985	XLPE	Degraded	2 Cable locations degrade
7	1985	XLPE	Degraded	7 new cable issues appear
8	1983	XLPE	Degraded	Cable location degrades

D. General Observations

Five of the eight sample cables consisted of pre 1987 XLPE insulation. In general, these cable systems were considerably more sensitive to the fault location procedure. Eighty percent, or four out of the five, of the pre 1987 cable systems showed signs of degradation after the fault location procedure was performed. While the TRXLPE systems performed much better than the XLPE cable systems, still one out of three demonstrated degradation in the PD performance. The only substandard PD sites identified in these cable systems were in accessories. The following are two case studies from the XLPE samples, Sample 6 and Sample 7. Both of these cases demonstrated dramatic deterioration after fault location.

Case 1: Two insulation defect sites show signs of degradation

Sample 6 originally had two substandard PD locations in the cable insulation with an apparent PDIV at 2.25Uo (Figure 1). After the fault location procedure, the apparent PDIV of the two locations dropped to 1.3Uo and Uo. This means that the defect at 383ft would likely be under continuous PD and erosion conditions and probably would have deteriorated rapidly under operating conditions. The other defect at 256ft would likely turn on during voltage transient activity slightly exceeding Uo. Both PD site locations are clearly worse off after the fault location procedure.

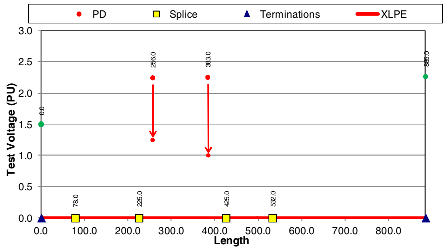


Figure 1: Sample 6 Assessment Results. The arrows indicate the drop in apparent PDIV after the fault location procedure.

Case 2: Seven new degraded insulation sites appear

Sample 7 originally had one substandard PD location in the cable insulation with an apparent PDIV at 1.5Uo as shown on Figure 2. After fault location, seven new sites of insulation degradation appeared with apparent inception voltages between 1.3Uo and 2.25Uo. An interesting observation is that all of the new PD sites appeared between the joints at 62ft and 148ft, which may have been part of a repair. In this case to rehabilitation using two relatively short pieces of cable from approximately 62ft to 148ft and from 556ft to the end could be used to remove the substandard PD activity in the cable system. A reasonable explanation for the appearance of these new PD sites is that the inception voltage (PDIV) may have been above the highest assessment voltage 2.25Uo (30kV) and were not observed during the PD assessment. This is not of consequence since the utility's arresters are configured to prevent transients exceeding voltages on the order of 2.25Uo during service conditions. The apparent drop in PDIV appearance of these new sites after the 15kV fault location procedure suggest that the localized stress at these PD sites during thumping exceeded the stress of the 30kV PD assessment. One possible explanation for higher voltage stresses during thumping is a voltage doubling phenomena discussed in the next section.

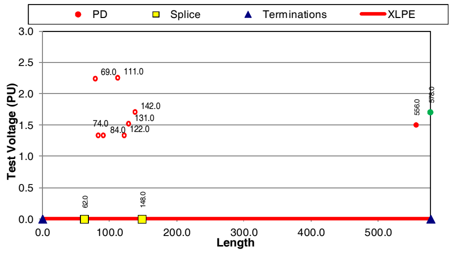


Figure 2: Sample 7 Assessment Results. The original PD site is a solid dot whereas the circles are the 7 new PD sites in the cable insulation after the fault location procedure.

V. DISCUSSION AND RECOMMENDATIONS

The data indicates that degradation after thumping is likely with newer solid dielectric cable and accessories and is very likely with older systems. On the basis of this conclusion and the knowledge of how cable systems fail, the authors recommend that fault location voltage magnitude and duration should be minimized as much as possible. After numerous conversations with utility technicians across North America, the authors have concluded that the value of minimizing thumping exposure is not universally understood. Several additional observations were made during this experiment and while interviewing technicians from numerous other utilities. With each observed issue there is an opportunity to educate the technicians and minimize the risk to excessive thumping practices.

A. General Observations and Recommendations

Turning up the thump volume

A louder thump is easier to locate. Technicians are likely to raise the DC set voltage on the thumper or even gravitate to larger, higher voltage thumper equipment to create a louder thump which sometimes can make the fault easier to locate. This may seem a good practice if the only concern is to get the power back on quickly, but is short sighted since higher voltage pulses or thumps will likely lead to more cable degradation.

Setting the thump voltage

Due to the primitive nature of common thumper equipment, it is quite likely that the voltage pulse as seen by the cable system is much larger than the thumper indicates. The high frequency components of the thumper voltage pulse in the presence of highly inductive test leads and connections to the cable can produce ringing with large overshoots and undershoots that cause the pulse to actually be much larger than the setting displayed on the thumper unit. To counter excessively high voltage thump pulses, technicians should consider the use of voltage pulse settings that are just high enough to yield a fault arc reflection.

Removing surge protection

Removing arresters from a cable system during thumping leaves the cable system insulation vulnerable to thump pulse doubling (i.e., wave reflection). According to well-know transmission line theory characteristics, the sudden impedance at the end of the cable will cause the high frequency elements of the thump pulse to double in height. This transient doubling will not only affect the end of the line but can also affect dielectric systems up to a mile or more away, depending on the thump pulse duration. Once again, in order to minimize cable damage, the thump voltage should be minimized as much as possible.

Concluding the TDR doesn't work

During several interviews with technicians, the authors' have identified misunderstandings about when and how to use time domain reflectometry (TDR) to estimate a fault location. Some technicians interviewed believed that TDR did not work on unjacketed cable. Another did not understand the fundamentals of pulse speed and time delay and its relationship to distance concluding the TDR did not work. Regardless of the reason, the TDR is often seen as an unnecessary additional step and is not used. This is unfortunate because the TDR is a tool that can provide a fault location estimate with just one or two thumps, even if when the thump is not audible. Thus the TDR allows the thump voltage and the thump application duration to be minimized.

B. Recommended Practice Fault Location Procedure

The following description is not an exhaustive fault location approach for all applications and is not a substitute for a comprehensive step-by-step procedure. It is intended to highlight concepts that will likely reduce dielectric system damage and accelerate the location of faults for typical point-to-point URD applications. IEEE guides state that special attention must be paid to ensure the safety of personnel during all tests involving hazardous voltage levels, Clause 6, Safety Procedures in the Field, IEEE Std 510-1983, fault location equipment instructions, and all applicable regulations.

1. *Review maps* –to identify cable system features such as insulation type, length, joint locations, and branches. Complexities such as branches will require isolation or other fault location techniques.
2. *Isolate cable system* – using an appropriate method such as fault indicators, an insulation resistance test and bisection, or TDR method to identify and isolate the failed section of cable. Only re-energize faulted underground cable systems in documented emergency situations or where management has approved the destructive practice.
3. *Install arresters* – at new open points as necessary. This will protect the serviceable cable systems from operational transients during the fault location and repair effort.
4. *Perform a route locate* – to trace and mark the cable route to aide in distance and location measurements.
5. *Perform low voltage TDR* – to identify cable features such as length, joint locations, or an obvious short or open of the shield or conductor.
6. *Characterize fault* – with an insulation resistance test, (if not performed already) to help determine if the fault is high or low impedance provide guidance as to the over voltage necessary to produce an arc in the fault.
7. *Perform a single thump or use a PD assessment.* –to produce a fault location TDR signature. The test voltage should be minimized to the lowest setting to initiate an arc or PD at the fault site.

8. *Measure to physical fault location* – using the distance estimated with the single thump or estimated fault site. Measure from both ends cable to provide a better location estimate.
9. *Use acoustic or electromagnetic sensor or a non-destructive location match technique* -to confirm the physical location of the estimate. Additional ‘thumps’ should only be applied after personal are located at the estimated fault site. Non-destructive techniques require the access to the cable system to identify footage markers, create and identifiable impedance or apply a transmitter to the cable system. Continuous thumping and thumping at voltages over the operating voltage should only be applied in documented emergency situations or where management has approved the destructive practice.

VI. CONCLUSION

This field investigation effort provides a small but clear set of data reinforcing the industry best practice of minimizing the voltage and duration of capacitive discharge or ‘thumping’ techniques used in locating faults in cable systems. The data answers “Yes” to the question posed by the paper’s title “Is Fault Location Killing Our Cable Systems? The ability to profile the cable system with an assessment technique that is comparable to cable and accessory manufacturers’ quality control standards before and after fault location leaves no doubt that fault location is deteriorating (killing) the industry’s cable systems. The authors recommend minimizing the effects of thumping and, where possible, eliminate the thumping practice with the use of non-destructive techniques such as an offline PD assessment which has been successfully used to identify various cable faults in a variety of scenarios. Ideally a factory comparable PD assessment could be used to locate defects before damaging fault location activity occurs. Looking to the future the authors see possibilities that PD assessment may take the place of the capacitive discharge techniques for many fault location applications.

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VIII. BIOGRAPHIES

Benjamin Lanz received a BSEE degree from the University of Connecticut in 1999. Since 1997, his career focus has been power cable system reliability. His experience includes field assessment, assessment technology R&D, reliability consulting, reliability program and client network development and the creation of industry guides and standards. He currently holds the position of Director of Applications Engineering at IMCORP (www.imcorp.com). He is a voting member of the IEEE Power & Energy and Standards Societies and he has served as Chairman of the Insulated Conductors Committee (ICC) workgroups responsible for cable testing and cable reliability. He has published over 50 papers, technical reports, and presentations on the subjects of power system reliability, asset management, and assessment.

Eugene Sanchez Eugene Sanchez received a BSEE degree from the University of Florida in 1976. He is a Lead Engineer in the Distribution Protection/Coordination Automation & Controls and Distributed Generation (DPAC & DG) at Duke Energy Progress. He formerly was a Senior Engineer in the Power Quality Reliability and Integrity (PQR&I) group responsible for analysis and resolution of Power Quality and Reliability issues related to the performance of Distribution Facilities. Also, he performed feeder analysis and protective coordination studies for Distribution Feeders including Smart Grid studies for Duke Energy Progress’ Distribution System Demand Response Project (DSDR). Previously, he also was the East Zone Program Manager for the Preventative Maintenance Program along with point of contact for the design of D-D Substation for large customers. Eugene transferred to the field from Distribution Standards where he conducted studies of transformer and capacitor overcurrent protection, overvoltage protection for all equipment along with other responsibilities including primary underground cable accessories (i.e., terminators, splices, elbows, etc…). He started his career with the Carolina Power & Light (now Duke Energy Progress) company applying/coordinating relay systems and controls for Power Plants, Transmission and Distribution Substations. He is a Registered Professional Engineer in North Carolina and South Carolina.