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Review of Medium-Voltage Asset Failure Investigations

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Introduction:

Medium voltage cables are an integral part of modern power systems and have existed for over 100 years in various forms. In the past 50 years, extruded cables have largely displaced paper insulated cables. Extruded cables offer many advantages over older designs, but are similarly prone to failure. One of the greatest problems facing the power industry is cable failures. Since cables often are sealed systems, it is hard to do continual assessment, and often failures occur without warning or preparation. In Figure 1, provided by NEETRAC, the costs of testing equipment, replacing all equipment regularly, and running

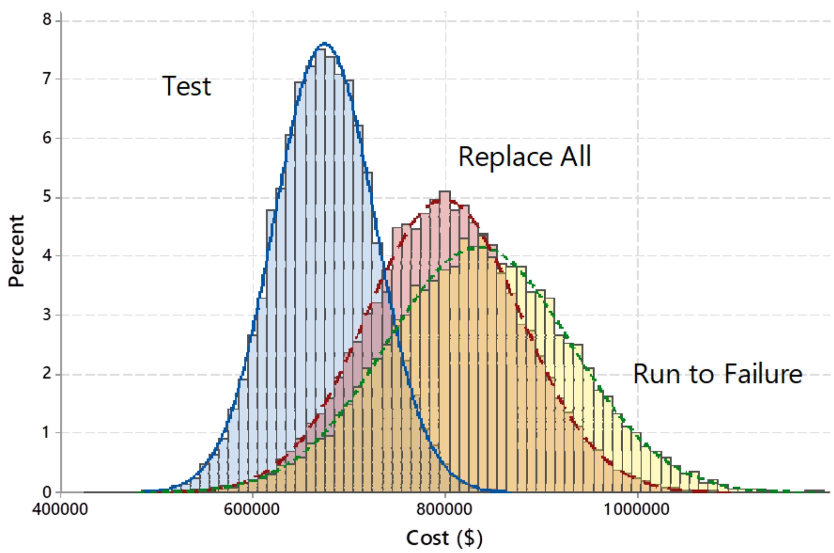

Figure 1: Comparison between Cost Options

equipment to failure is compared. Each cost is shown as a standard distribution to represent the uncertainty associated with failure costs. It is evident from this figure that the costs of testing are significantly lower and have much less uncertainty that the costs associated with running equipment to failure or wholesale replacement prior to failure.

This paper sets out to sample the results of multiple forensic analyses, determine the common causes of cable failures, and identify what users can do to have accurate information on the status of their cables. For the sake of this analysis, cable failures include failures in the termination, splices, connectors, and simply mid-cable failures. By being able to accurately determine potential cable issues before the failure occurs, we will be able to plan better outages, improve system reliability and prevent collateral damage caused by faults. Asset management and a proper testing schedule have been proven to lower costs associated with unplanned outages due to cable failures.

Study Background;

EA Technology LTD is a UK based company specializing in the condition assessment of MV electrical assets. EA Technology's capabilities include manufacturing instruments for field measurements of asset condition through methodologies for investment optimization based on asset condition. In support of this, EA technology has an extensive forensic investigation lab where they have performed countless investigations over the past 50 years. This paper analyzes a subset of the forensic investigations that EA Technology has performed on failed cables and components to determine failure mechanisms and set recommendations for similar system components. This analysis can provide insight into fault mechanism, highlight other at-risk assets, and recommend asset management strategies to reduce future risk of failure. In addition, these reports provide insight into manufacturer quality and jointer workmanship. From these reports, we try to determine two main things: proximate cause and ultimate cause. First is the proximate cause, which is the obvious direct cause of the failure. Examples of this include moisture ingress, and mechanical damage. The next element is the ultimate cause of failure for the system. The ultimate cause is the deeper, systematic reason why the failure occurred. This is often workmanship, training or application errors. To get from the proximate cause to the ultimate cause the authors employed a commonly used management practice called “the 5 Whys”. By asking the question “Why?” and then challenging the answer with “Why?” in a serial fashion the ultimate cause of an event can often be found. The proximate cause of the Titanic sinking is that it hit an iceberg. While addressing that, one would overlook the ultimate cause that White star lines had systematic issues that devalued passenger safety. The hope is that by addressing the ultimate causes of a failure, one can prevent a wider range of proximate causes from developing. Over the course of this paper, major trends developed across both proximate and ultimate causes, as well as across the recommended actions to resolve said actions.

It should be understood that this sturdy involved a small number of samples over short period of time. While the authors believe the results to be representative of actual field conditions, this cannot be guaranteed. Sample size, time period, motivations for investigations, etc. could contribute to variations from a more detailed study. The reader should keep this possibility in mind when considering the findings presented.

Forensic Failure Investigation Process;

EA Technology’s investigations begin with a visual investigation of the samples and an analysis of the fault timeline if provided. This is followed by a review of application parameters and instructions, and a mechanical disassembly. Once disassembled, analytic investigation and specialized mechanical testing is done as needed. Finally, a report is provided to the client detailing the findings and recommendations of the investigation.

Occurring first, a visual investigation can provide vital details on workmanship and manufacturing errors, partial discharge, and moisture ingress into the cables. This step also often includes documentation of the site and failure conditions. If it is possible, an EA Technology representative will be there for the removal of the failed component to ensure no information is lost during the removal process. Being present also allows EA Technology to have a better understanding of the factors leading up to the fault. Next, the team will review the application parameters and instructions provided by the manufacturer at the time of installation. These will be used as a reference for the visual inspection and will be verified to be both accurate and clear. The visual inspection concludes with a mechanical disassembly of the failed element. The cable is deconstructed layer by layer and extensively documented with pictures and measurements. This often speaks volumes about workmanship and cable age/condition.

The next step is the analytical investigation. The details of this vary based on insulation type but in general the analytical investigation dives deeply into suspected issues and determines the severity of underlying issues. For XLPE, the sample is boiled in oil of cloves to make it transparent. This allows the researchers to microscopically examine thin sections the insulation to visualize any inclusion and ambers

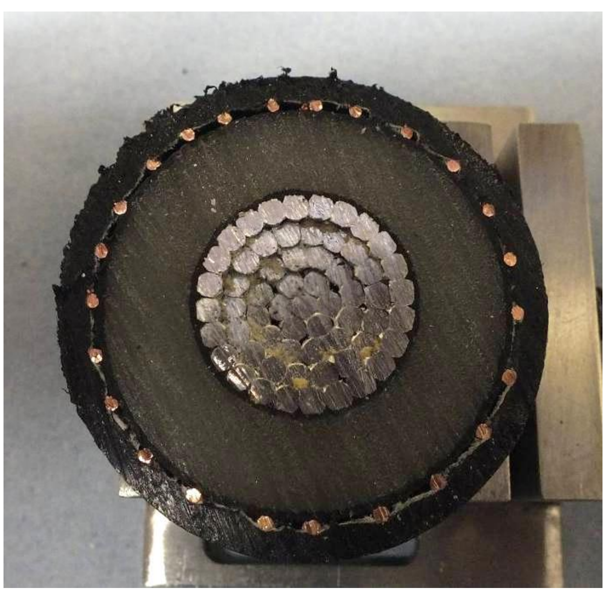

Figure 2: XLPE Insulation

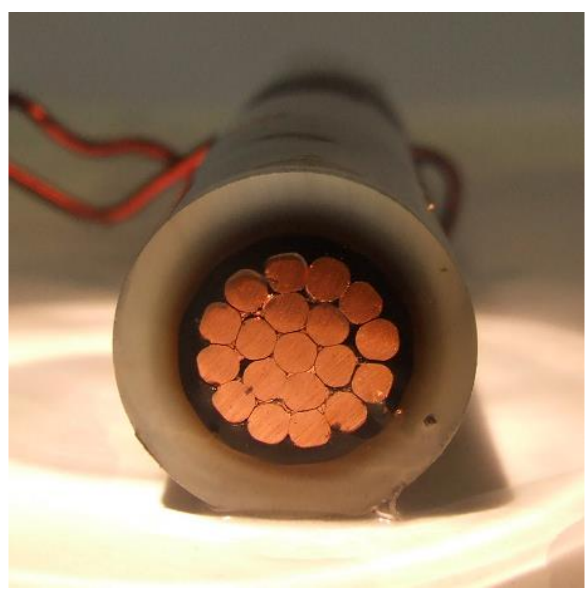

Figure 3: XLPE Insulation made Transparent

from the manufacturing process. Inclusions come from foreign matter that is stuck in the insulation during the extrusion process. Ambers are bits of insulation that weren't fully converted to the final material. Both can affect the dielectric constant of the insulation, but the foreign materials have a more negative effect on insulation quality. Having the insulation transparent also makes it possible to see developing water trees in the insulation. These could have contributed to the fault, or could indicate underlying issues based on size and location. For paper oil insulated cables, the analytical investigation looks into the many mechanical factors that can lead to cable failure. This is done by unraveling the paper and looking for two major things. First, the overlapping of the strands is checked to be even since uneven overlapping can cause concentration of the electric fields and in turn can lead to partial discharge. Second, the strands are checked for waxy patterns located at interstitials of the papers. These waxy residues can indicate partial discharge occurring in the cable and strongly indicates that there are voids or moisture affecting the reliability of the cable.

When necessary, specialized material testing is done to gather more information on the samples. Three major tests that are done are scanning electron microscopy, scanning differential calorimetry, and

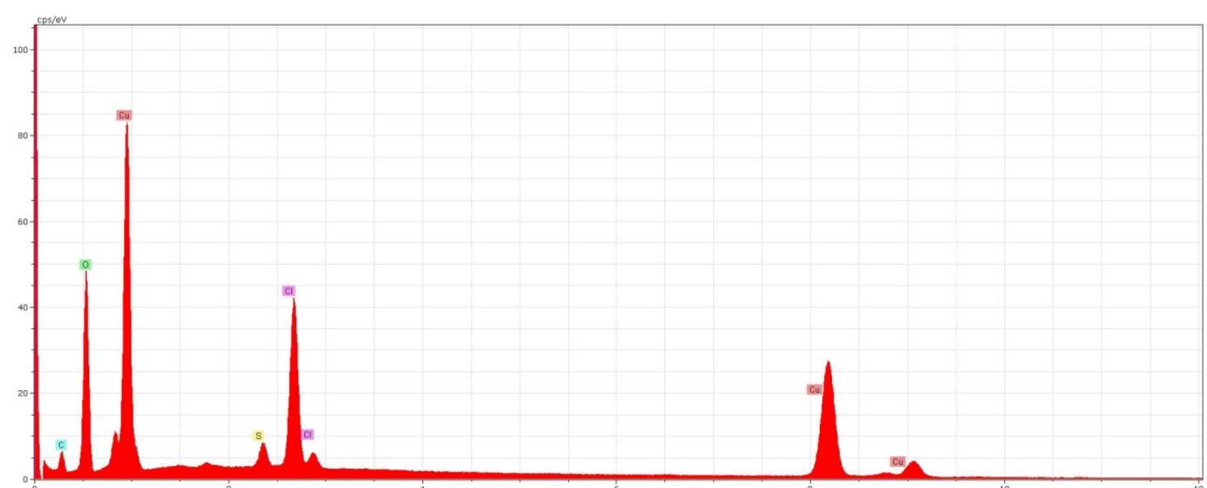

Figure 4: Scanning Electron Microscope based Elemental Spectroscopy

mechanical tests. Scanning electron microscopy, as seen in figure 4, can be used to perform elemental analysis on inclusion to identify foreign compounds. This can be used to compare the materials in the inclusion to the bulk insulation and possibly determine the impacts the inclusion would have on dielectric constants. Scanning Differential Calorimetry can be used to determine that maximum temperature that had been reached by the component prior to failure. This is important information in determining whether the component was used in the wrong application and whether overheating contributed to fault. Finally, mechanical tests can be performed on cable components to determine material characteristic which indicate whether a component was appropriate for the application it was used in. This is commonly done for components expected to perform mechanical tasks.

The findings of all the tests are then compiled into a report and recommendations are drafted based on the findings. Client reports include detailed documentation of the investigation process, conclusions, and recommendations. Conclusions are structured to highlight proximal and ultimate causes of failure based on the data gathered in the report. Finally, recommendations are provided to address the proximal and ultimate causes of the failure. The report often includes a few different types of recommendations. First, there are suggestions aimed at addressing current at-risk assets by lowering the risk of failure. Often cable updates are part of a large program update so a failed cable could indicate larger system concerns. Second, there are suggestions aimed at internal modifications that can prevent these issues in the future. These can be a new training program for jointers, or an asset management program aimed at preventing end of life failures. Finally, there occasionally recommendations aimed at external factors that contributed to the fault. Examples of these are informing a manufacturer of a defect or poor design, or just changing suppliers to use higher quality materials. All recommendations build the foundation for a more reliable system with the aim of reducing failures.

Our study compiles the data drawn from a set of reports to analyze the greater trends indicated by their results and recommendations. We pulled 100 reports generated in 2011-2015 from EA Technology's forensic analysis report database. After the initial review, 27 of the reports were deemed irrelevant and discarded from the study. These often were about lower voltage classes or mechanical failures, or were a condition assessment report, not a failure analysis report. The remaining 73 reports were sorted and analyzed based on the following characteristics: cable age, insulation type, voltage class, installation conditions, failure location, failure causes, and recommendations. These characteristics were graphed and analyzed for evident trends.

Findings:

The first metric that was analyzed was the age of the cable when the failure occurred. It was found that failure occurrence matched the Weibull distribution, the bathtub curve pattern shown in figure 5. Failures can be classified into three main categories: infant mortality, random failures, and end of life failures.

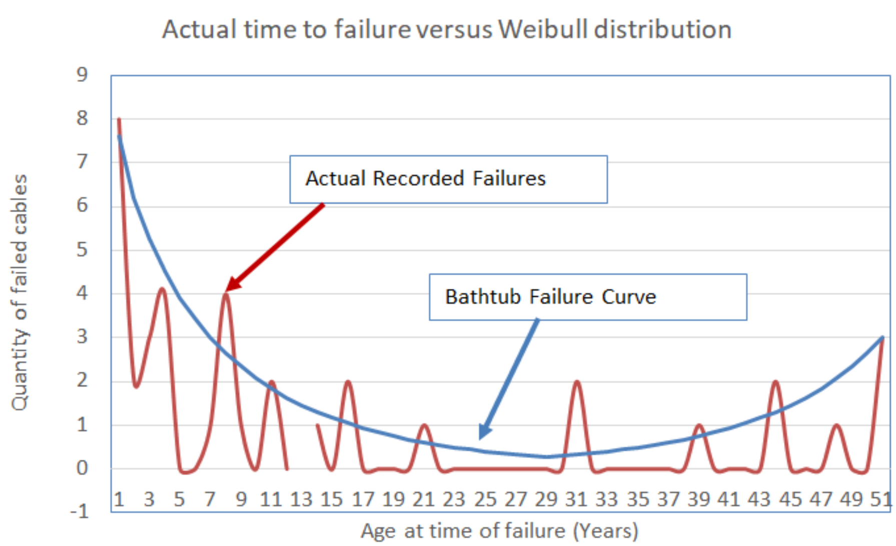

Figure 5: Time to Failure Graph

Infant mortality failures make up the largest segment of the graph and last for approximately 10 years after installation. Following the infant mortality section, random failures occur for the next 30 years or so. There are intermittent and generally uncorrelated. At around 40 years after installation, end of life failures begin to occur and all failures after this point are classified as such. End of life failures are generally only prevented by replacement, but infant mortality and random failures can be prevented by looking deeply into the causes and acting according.

Next, the report samplings were analyzed across insulation type and fault type. Based on the "Historical Overview of Medium and High Voltage Cables" written by the Georgia Tech NEETRAC group, the XLPE and PILC cables show similar ratio of failures per mile of installed cable. EPR shows

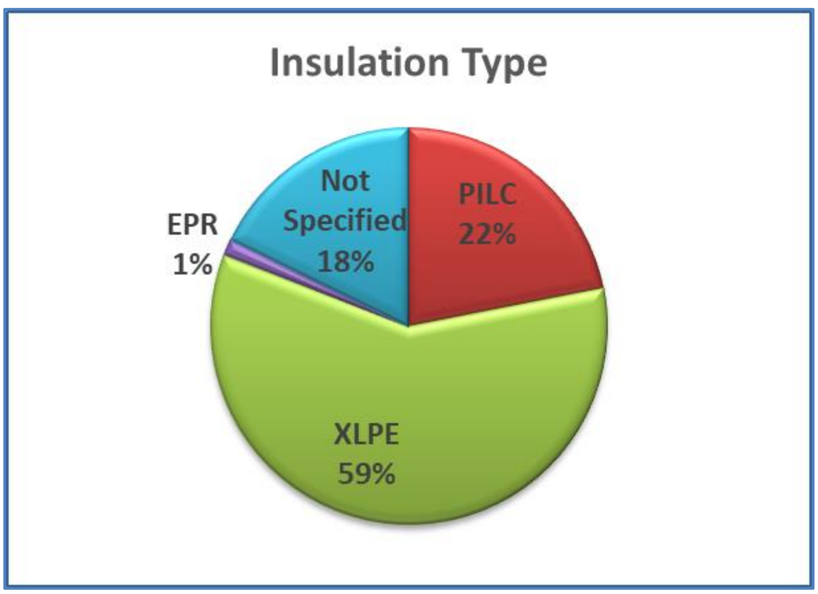

Figure 6: Insulation Type

disproportionally fewer failures per mile. This can be seen in figure 6, which shows only 1% associated with EPR cable.

Next, we analyzed where the failures were taking place. Based on the fault locations seen in the report sampling, 68% of failures occur in places where technicians are working on cables in the field. 25% of failures occur mid-cable where technicians likely haven't been handling the cable much. Clearly, the act of working on the cable in the field may introduce failures. Some explanations for the mid-span failures would include mechanical damage, incorrect application, manufacturing defects, or simply are random failures without a clear reason.

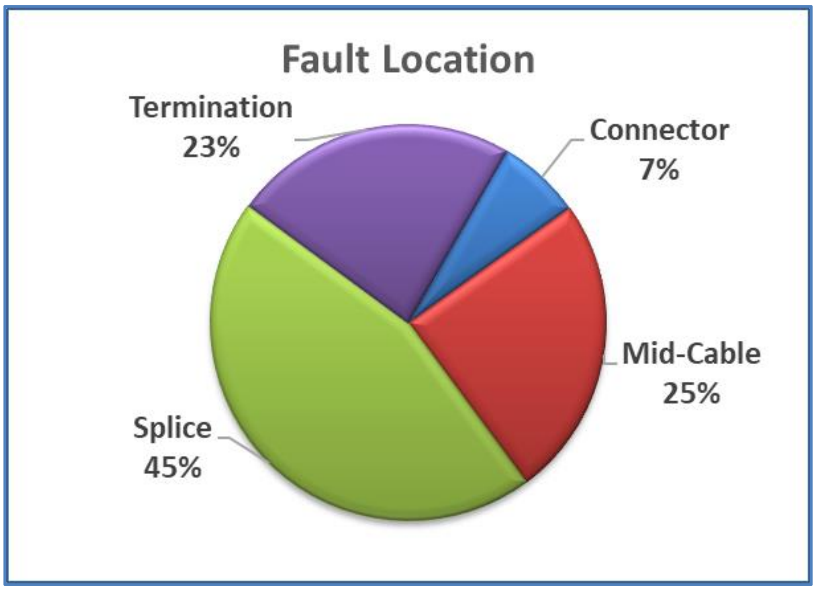

Figure 7: Fault Location

We next characterized and plotted the proximate causes of failure below in figure 8. When reviewing the proximate causes of failure, several interesting trends appear. Assembly mistakes cause 33% of failures commonly found. This indicates a lack of effective communication between manufacturers and installers or in training of jointers. Furthermore, another 40 percent is due to preventable damage to the cable, either from moisture or mechanical damage. Small percentages can be attributed to contaminants, circulating currents, and overheating.

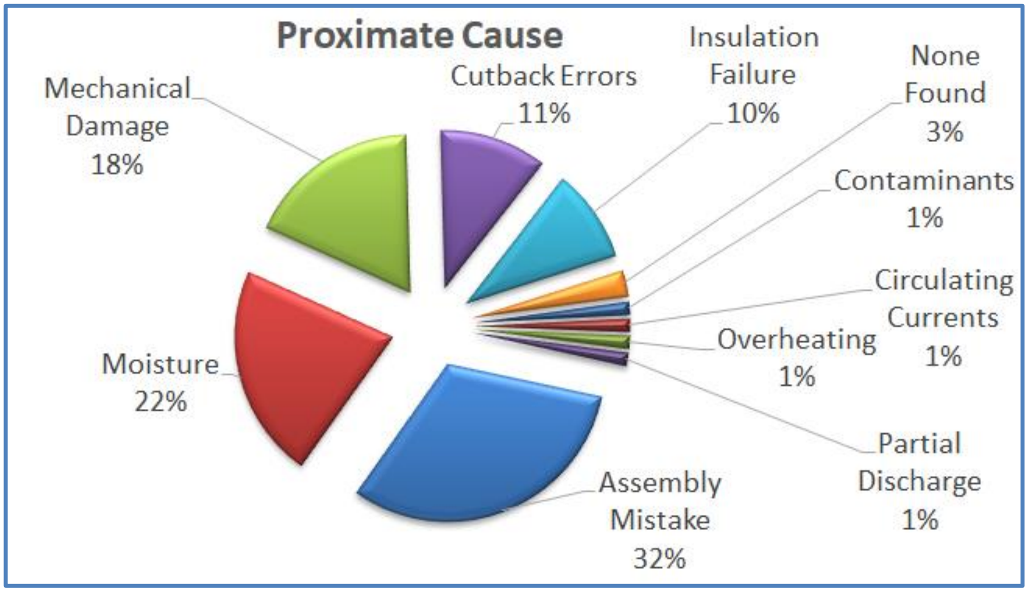

Figure 8: Proximate Causes of Failure

What is missing from this picture is the detail of what is causing these failures. Proximate cause provides insight into what happened but often is lacking the complexity of the full reasoning behind a fault. By looking at the ultimate causes of the sampling, we see that the vast majority of faults can be attributed to workmanship errors. These would include any errors in jointing due to negligence or inexperience, as well as any sloppy work and lack of care. 6% of failures were due to age which is lower than expected based on the correlation to the Weibull distribution discussed earlier. Manufacturing defects presented about 11% of all ultimate causes which is higher than expected. These range from contaminants in the insulation to conductor spacing requirements being violated in the brand new cables. Only in 4% of cases was no ultimate cause found, which suggests steps can be taken to address the vast majority of cable failures.

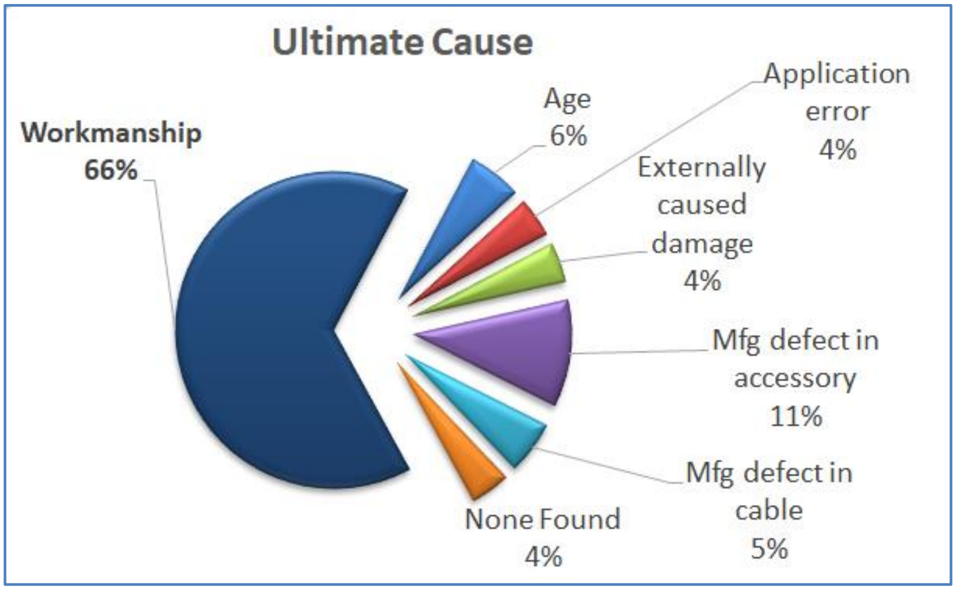

Figure 9: Ultimate Causes of Failure

Based on the ultimate and proximal causes of failure, there are several standard recommendations that would help prevent future failures. The most commonly recommended action was to perform Partial Discharge mapping regularly. Partial discharge is a flashover of part of the insulation system due to a localized electric field greater than the dielectric withstand capability of that part where the overall insulation system remains capable of withstanding the applied electric fields. Partial discharge is commonly found surrounding voids in the insulation and produces a variety of detectable byproducts such as heat, light, sound, scent, electromagnetic waves, and a high frequency electric current. Since the prevalence of partial discharge can indicate issues with insulation quality, a routine of partial discharge mapping can help clients plan for outages to address issues before they escalate. Cable PD testing can provide data about how aging and conditions have affected installed cable, and help prioritize replacement and repair.

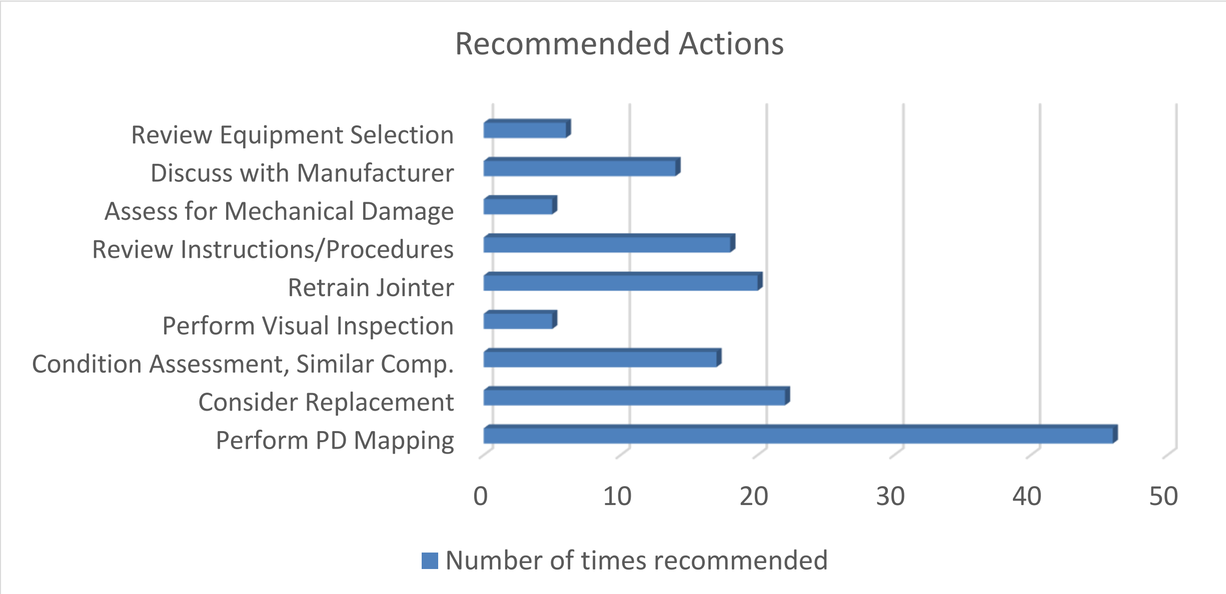

Figure 10: Recommendation Actions for Existing Equipment

Replacement is a commonly recommended action, yet overall it is regarded as only one of many options. The prevalence of PD mapping and condition assessment recommendations suggests that proper asset management techniques can help prevent untimely replacement of working equipment by providing additional information about its operating condition. Discussing the fault with the manufacturer was

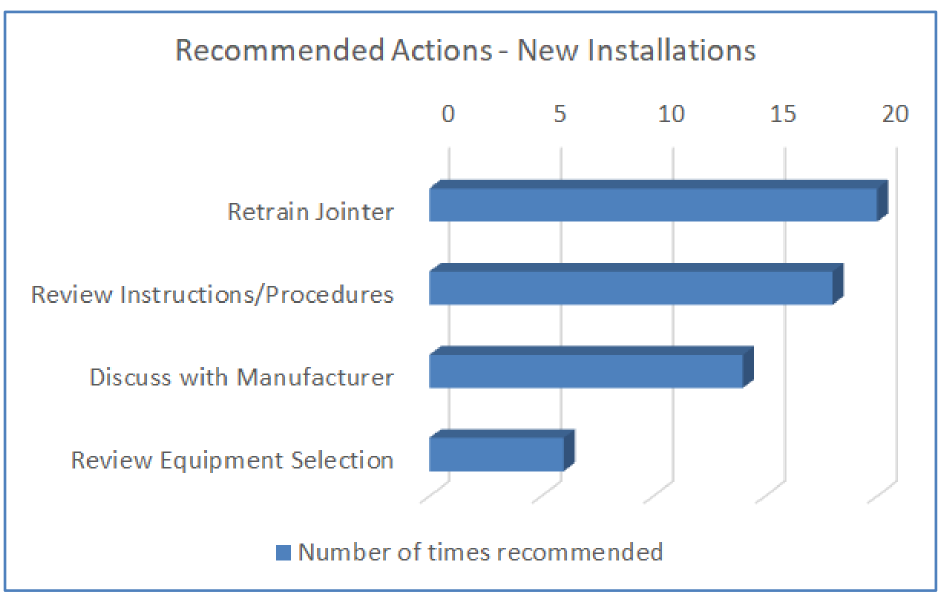

Figure 11: Recommended Actions for New Installations

commonly recommended as well. By having clear and open communication with the manufacturer, there are less likely to be installation errors or application errors. Likewise, with 11% of faults occurring because of manufacturing defects it is important to have clear quality expectations for your manufacturer. Providing them feedback on failed components can prevent future quality issues from costing you so much long term. Visual inspection is relevant for some faults but most often it is felt to be of a limited value since most problems are hidden. This reinforces the value of PD mapping since it provides data that cannot be gathered from visual inspection alone about cable condition and longevity.

Recommendations aimed at preventing failures in future installations are centered around ensuring jointer training is high quality. Having well trained jointers is key to having a reliable system because such a high percentage of faults can be traced to jointing issues. This includes training jointers well and ensuring that instructions and procedures are clear and set your jointers up for success. Talking to the manufacturers throughout the process of a program upgrade can ensure that instructions are being accurately followed. Finally, choosing the correct equipment for the application is frequently recommended since application errors cause about 4% of the failures from this sampling.

Examples

The first example explored is an 11 KV PICAS to XLPE Branch adapter that failed one hour after installation. After investigation, the proximate cause was determined to be an incorrect positioning of the adapter tubes. Alternately, workmanship errors were determined to be the ultimate cause of failure. Throughout the investigation, many quality issues were found. Shear bolts were misaligned, there was no putty in the shear bolts, the tubing was poorly cut and there were gaps in the insulation throughout the sample. Recommendations common for these conclusions include retraining the jointers and assessing the

Figure 12: XLPE/PICAS Joint

components done as a part of this project. This example highlights that finding and fixing the one proximate cause of the failure is not adequate. There were several mistakes that all would have led to failure had the first cause not been present. By addressing the ultimate cause of jointer training, all of the workmanship issues and potential failure points would be addressed.

The next example explored was a 33KV XLPE joint that failed after 18 months in service. The fault hole is visible through the insulation in the figure below. The failure occurred because a connector was not

Figure 13: Failure Location on 33KV XLPE Joint

properly deburred by the jointer. The sharp edge caused mechanical damage and created a concentration of electric fields in the damaged insulation. The takeaway for this failure was that poor understanding of instructions, lack of attention to detail, and lack of training all contributes to the failure of this joint.

The final example explored is a PILC cable that failed after 47 years of service. The 11KV cable experienced a mid-cable failure as seen in figure 14. This failure is a result of age related partial discharge. Although this cable was in service for an appropriate life span, this is an example of how partial discharge mapping could have prevented an unplanned failure. Catching the partial discharge earlier would have allowed the client to plan an outage to address the issues.

Figure 14: Failed PILC cable

Conclusions:

With cable failures costing clients significantly every year, identifying trends in occurrences can help reduce the future failure related costs. Forensic analysis allows for the community to learn from past failures to promote a more reliable and robust system. The following conclusions were drawn from the investigation of 73 forensic analysis reports:

- Cable faults follow a predictable reliability curve and generally can be expected to fail within the first 10 years or after 40 years in service. With about 35% of failures occurring in the first ten years, it is vital that they are installed carefully to prevent the majority infant mortality related faults.
- By ensuring that installations are done following clear and accurate manufacturer's instructions, 2/3 of faults could be prevented.
- Since human error is inevitable in every field, a proper asset management program founded on partial discharge testing can help identify and prioritize issues as they develop.

Furthermore, since faults are inevitable, performing a forensic analysis post-mortem can help diagnose the causes of failure and identify trends in the failures associated with your company and suppliers. Although universal trends have been shown through these reports, these do not necessarily indicate that every company should prioritize the recommendation in the same manner. Company A may have excellent jointers with poor quality cables while company B has the highest quality components and a few subpar practices that are affecting their installations. By receiving custom assessment and recommendations, you may expose problems specific to your company or installations. Forensic analysis provides a much more detailed analysis than a field review can ,and can even help prevent future failures by looking deeper than proximal causes. Even in the cases where there is no evident root cause, every investigation adds to our knowledge base and can help us create more reliable systems in the future.