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Total System Reliability Program for Underground Electrical Distribution Networks

W. SHU J. GUO

Novinium

USA

SUMMARY

Electrical Distribution Network includes many components, cables, lightning arrestors, insulators, switchgears, terminations and joints, all of which play a key role on the reliability of the distribution system. As parts of the network age they weaken the entire system so that premature failure can take place anywhere within the electrical distribution system. Because station feeders are the backbone of the power system, the failure of a station feeder can create significant economic repercussion beyond the repair of the cable itself. Therefore, special attention is needed to address the reliability of feeder cables and associated accessories and apparatus. A holistic approach is proposed to look at all components of the system to ensure increased reliability with improved impulse breakdown strength, allowing the asset manager to retrofit an existing system to today's stricter standards. The holistic approach includes enhancement of cable insulation by chemical rejuvenation, reinforcement of cable accessories, non-destructive proof test of the system and lightning surge arrester considerations. This holistic approach looks at everything in the distribution system and once corrective actions are complete, the aged systems are completely updated to comply with the latest standards and thinking regarding reliability issues. The ultimate goal is to eliminate an unscheduled electrical outage.

KEYWORDS

Aged Cable Systems, Cable Rejuvenation, Water Trees, Insulation Assessment, Lightning Protection

ewshu@utilx.com

INTRODUCTION

Station Feeders may appear to be simply larger URD cables; however there are a variety of details that makes feeder cables unique and different from distribution cables in a chemical injection process. These details include physical difference, electrical differences and economic difference. From its geometry, a feeder cable has a larger cable diameter and splice cavity diameters such that special design is necessary to reinforce sealing of fluid inside of the cable conductor and insulation. Usually a feeder cable has increased cable length which would involve multiple construction joints. A way to detect and address those joints cost-effectively is also an important aspect. For electrical differences, feeder cables are normally highly loaded which would bring in a larger temperature swing. Solubility of the injection fluid in the cable insulation at the operating temperature range shall also be taken into consideration. Because a feeder cable has a larger diameter and thicker insulation, the capacitively stored energy is higher than that of a URD cable. When the cable is disconnected from the circuit, the capacitively stored energy needs to dissipate through an appropriate grounding process which limits the transient recovery voltage seen on the cable. All of these differences contribute to the unique challenge of feeder cable injection. Additionally, we understand that a feeder cable failure has significantly greater economic repercussions than a URD cable failure and has great impact on system reliability indices.

A number of years were spent developing specialized solutions to the unique challenges of feeder cable work. A variety of revolutions were made, from injection fluid to termination/joint improvement and more importantly the comprehensive consideration of system reliability. Fluid designed especially for larger diameter and more highly loaded cables are used. Pre and post insulation system assessment in addition to traditional diagnostic testing are performed to ensure that all craftwork was done properly and that no damage occurred to the cable during switching. The condition of connecting transformers, bushings, terminations and splices are also evaluated during the assessment, and importantly aged lightning protection is evaluated for proper protection. When we leave, the circuit owner should feel comfortable that their aged cable systems have been completely updated to comply with the latest standards and thinking regarding reliability issues.

Injection fluid and equipment specially designed for cables with high conductor temperature are discussed in [1-2]. This paper will focus on diagnostic testing, which includes time domain reflectometry, pressure and flow test, pre-screening test and post-screening test, and surge arrester consideration.

DIAGNOSTIC TESTING

When you walk up to a feeder cable, the first thing we want to do is to assess whether the cable is a good candidate for injection. Prior to injection, the injection crew will perform initial testing on the cable segment to determine whether it qualifies for CableCURE® treatment. Such testing includes time domain reflectometry (TDR), pressure and flow test, and pre-screening test in the case of feeder cable injection. If the crew determines that a particular cable cannot be effectively injected, it will be scheduled for replacement. After cable is injected, a post-screening test is also performed to ensure all the craftsman work is performed correctly and that no damage of cable insulation is caused during switching process. The diagnostic testing allows customers to optimize their reliability budget by treating all cables that can be treated, and replacing only those that cannot be effectively treated with the CableCURE® process.

Time Domain Reflectometry (TDR)

A TDR test is employed during injection process to identify the number of joints in the cable run and to evaluate the neutral condition. While a majority of power cables can be treated with the CableCURE® process, cables that have too many blocked splices or too many severe neutral corrosion sites in them may not be cost-effective for rejuvenation. The time and cost of a rejuvenate project, is largely determined by how many splice pits need created. This needs to be known up front.

Pressure and Flow Test

Rejuvenation involves injection of alkoxysilane fluid into the intersticies between the cable conductor strands. The low viscosity monomer flows down the cable strands and diffuses radially through the conductor semicon to reach the water treed region in the cable insulation. A pressure and flow test is to ensure sufficient fluid flow through cable strands as well as the capability of existing joints withstanding the injection pressure.

Pre-screening Test

A pre-screening test utilizing online partial discharge (PD) testing is performed before feeder cable injection. The test includes visual inspection, electrical testing and consultation. This test will catch system components, e.g. cable terminations, switchgears, transformers, cables, that need to be addressed at a high priority that a failure is to occur in a relatively short term. Cables that are aged to a condition so advanced, e.g. with active electrical trees at operating voltage, may not be effectively rejuvenated. These cables will need to be replaced. It is very rare since a cable with active electrical tree at operating voltage usually fails hours to days after the electrical tree is initiated. Twenty plus years field experience had also shown a minimum failure rate that the chance of injecting a cable with active electrical tree at operating voltage is extremely small or the chemical injection can prevent further development of micro sized electrical trees. Nevertheless, the economic impact from a feeder cable failure is significant that it is essential to ensure rejuvenation can help improving its reliability and an unexpected failure can be avoided.

Post-screening Test

After all the termination and splicing craftwork has been performed, PD data will be acquired after re-energizing with conventional CableWISE technology. The assessment is performed without any switching and without the application of overvoltage. The post injection test is to ensure craftwork during injection process is properly performed and make sure that switching process did not damage the cable.

SURGE PROTECTION

Water-trees are slow growing structures which lead to cable failure, but they are not themselves the mechanism of cable failure. Failure occurs when a voltage perturbation of some sort, i.e. a lightning surge, a switching surge, etc., causes the conversion of water trees into electrical trees in the cable's insulation at the sight of reduced strength and increased stress. Authors have seen fully extended shield to shield water trees that did not fail, but that would fail with any system spike. People sometimes wonder why two apparently similar cables operating in similar environments have very different lifespans – don’t look to the history of nominal operations to explain the variations, look to the differences in “shock history”.

Overvoltages are caused by numerous events which could originate from external or internal sources, such as lightning, testing, switching, adjacent system fault, and so on. One of the most commonly experienced external overvoltages is from a highly unpredictable natural phenomenon, lightning. Medium voltage underground cables are often connected to overhead distribution lines, for instance, through riser poles, and are subjected to overvoltages from direct and in-direct lightning strikes. A lightning strike is a fast rise time current pulse, ranging from 0.1 μs to many μs. In common practices, 10 kA of peak current magnitude has been used in analysis for shielded circuits, although peak current magnitude of the first strike was recorded in excess of 100 kA in extreme cases. The induced overvoltage on a cable can often exceed its maximum permissible level. For example, the characteristic impedance of a URD cable is around 35 Ohm, the resulting voltage from a 10 kA lightning pulse could be up to 350 kV without any protection devices.

Lightning arresters are devices that conducts lightning surge current to earth through an internal non-linear elements and limits the resulting voltage imposed on cables. They are often installed in power system to prevent impulse breakdown of equipment and the connecting cables. Arresters degrade and can fail over time. Many times, lightning arresters are missing because they failed. If surge arresters are necessary to be installed in the system to protect the cable when it is new, it is for sure that a surge arrester is essential to ensure sufficient protection to the weakest section of the circuit; the aged cables. So first question to ask is that is the cable protected? In other words, is lightning arrester still in place? And a more important question is, if an arrester is in place, is the surge protection adequate? Does the protective margin still meet the requirement as the cables age?

An important parameter to evaluate the protective level of the lightning protection of the system is the Protective Margin (PM). Eq(1) estimates protective margin as a percentage of the protected system BIL, where BIL is the basic insulation impulse level and TTV is the total impressed transient overvoltage on the system. Depending on the protection scheme applied, the total impressed transient overvoltage will be calculated using different forms. IEEE C62.22 recommends that the minimum protective margin should be at least 20% of the protected system BIL, although the society is raising the discussion whether a higher protective level should be used. One thing to note here is the numerator BIL. In fact, it is the impulse strength of a cable. When a cable is new, BIL is used as the impulse strength of a cable. As cable degrades, the impulse strength of a cable can drop and can be way below its BIL due to water treeing.

$$PM\,(\%) = \left(\frac{BIL}{TTV} - 1\right)\cdot 100 \qquad (1)$$

Research [3] investigated the retained impulse strength for EPR and TR-XLPE model cable as a function of wet electrical aging at 6kV/mm. The data demonstrates that the impulse strength of a water-treed cable can degrade to 60-80% of the impulse strength of new cable for EPR and TR-XLPE insulation. Data in [4] shows approximately a 50% drop of the TR-XLPE cable insulation impulse strength after two years of service aging. Data in [5] presents a continuous reduction of the impulse strength of 35 kV XLPE cable over its service life, and reports the remaining impulse breakdown strength after 7 years of service at 30% of its initial value All the research above demonstrate that the system impulse strength can degrade significantly as the cable ages.

As described in Eq(1), the lower impulse breakdown strength the cable is, the lower the protective margin will be. Therefore, the less protection it is provided to an aged cable. And the further the degradation is, the more fragile the cable will be, but the less the protection is provided by the same arrester. To give a quantitative view, following protective margin calculations are carried out to help us reveal the importance of reconsideration of the traditional protection of aged cables.

Several published work indicated that the remaining impulse strength of the cable insulation can drop from 20% to 75% depending on the degree of aging. It is a reasonable assumption that a 20% reduction in impulse strength can be typical of cables moderately aged, and a reduction in impulse strength greater than 40% represents the cables that are severely aged. Although one cannot predict the exact remaining impulse strength of an aged cable system, the results in these Figures will give a view of how important it is to reconsider the lightning protection installed when the cables were new and what enhanced protection scheme is suitable for the aged cable system. The calculation was carried out with the assumptions that a 10 kA, 8x20 us lightning pulse was imposed to the system. Also, a 5 ft. long lead length with a 0.4uH/ft inductance was assumed. The 5ft. lead length assumption may be excessive in single phase cases, but some lead lengths do get up to 5 ft. or more especially on 3-phase poles. So we use 5 ft. here as an average. The Protective Margin can reduce further if a faster rise-time lightning pulse is used. In the figures, where the PM is less than 20%, it represents in-adequate lightning protection and negative PM means non-effective protection at all.

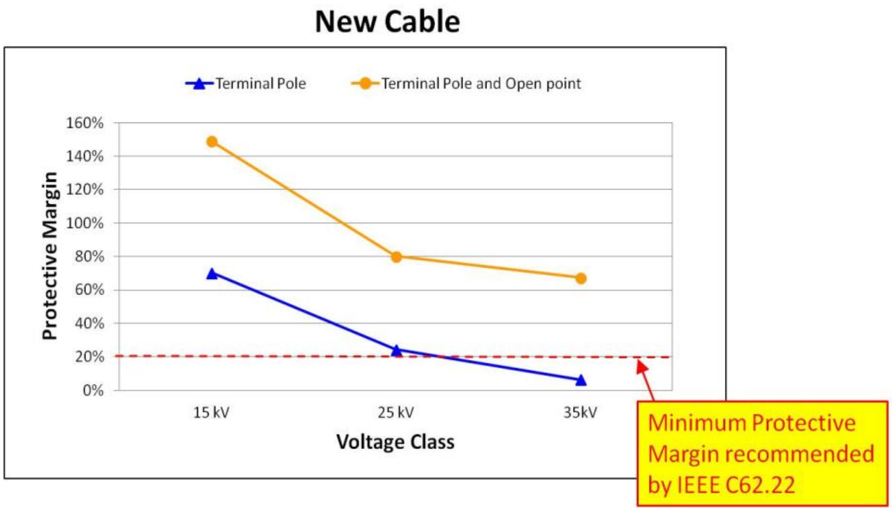

Figure 1. Summary of the protective margin for 15, 25 and 35 kV new cable system under different protection schemes. The calculation was carried out with the assumptions that a 10 kA, 8x20 μs lightning pulse was imposed to the system and a 5 ft. long lead length for the arrester installation with 0.4 μH/ft was used. The Protective Margin can be smaller with the assumption of a faster lightning pulse

Figure 1 shows the summary of calculated protective margin for 15, 25 and 35 kV cable system under different protection scheme when the cable is new. For new cable systems, a terminal pole arrester is sufficient to provide lightning protection to a 15 kV cable although with an additional open-point arrester, extra protection can be provided. The protective margin for 25 kV cables is about 20% (minimum protective margin recommended by IEEE C62.22) with the terminal pole arrester only. The addition of an open point arrester can increase the PM to 80%. For 35 kV cable systems, the PM is 6.4% with the terminal pole arrester only, which is not adequate to protect the system. IEEE recommends a terminal pole arrester for 15 kV cable system and both a terminal pole arrester and an open-point arrester to be installed for 25 kV and 35 kV cable systems.

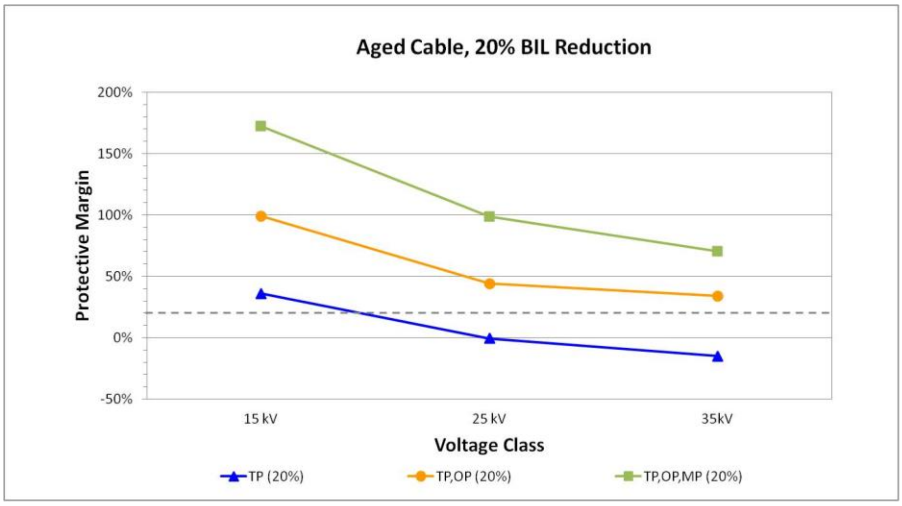

Figure 2. Summary of the protective margin for 15, 25 and 35 kV aged cable system under different protection scheme. The computations were carried out with the assumption that the reduction of insulation impulse strength as a result of water treeing is 20%. The calculated PM was based on 10 kA, 8x20 μs lightning pulse characteristics and a 5 ft. long arrester connection lead length.

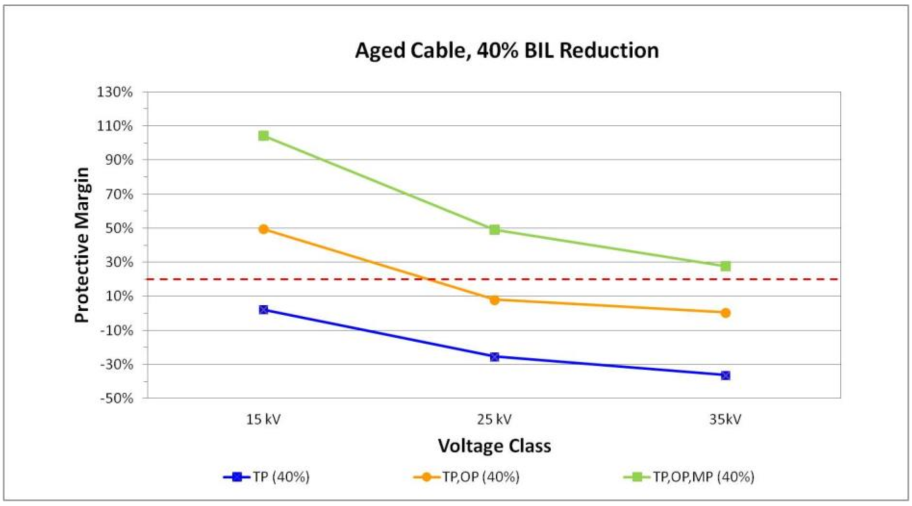

Figure 3. Summary of the protective margin for 15, 25 and 35 kV aged cable system under different protection scheme. The computa-tions were carried out with the assumption that the reduction of insulation impulse strength as a result of water treeing is 40%. The calculated PM was based on 10 kA, 8x20 μs lightning pulse characteristics and a 5 ft. long arrester connection lead length.

From the results in Figure 2 and 3, when a terminal pole arrester is used by itself, the PM is less than 20% in most cases whether the cable is mildly or moderately aged. The only exception is the case of 15 kV cables with 20% impulse strength reduction. Note that the Protective Margins are negative which indicate non-effective protection. Clearly, the terminal pole arrester only is not sufficient to protect even moderately aged cables. There is a great chance that the cable will fail during a lightning event with the protection of a terminal pole arrester only. The calculation indicates that the initial lightning protection designed and implemented when the cable is new may no longer provide sufficient protection as the cable ages to a significant degree. The protection level needs to be re-evaluated and the protection should be designed based on aged cable parameters (reduced impulse strength). When working on an aged cable system, suggested actions are: 1) Check if arresters are in place in aged cable systems; 2) Verify if arrester lead length are optimum; 3) Evaluate whether protective levels are adequate for desired protection.

CONCLUSION

A holistic approach to enhance total system reliability is introduced. The holistic approach includes injection fluid and equipment specially designed to work with feeder cables that operates at higher temperature, pre and post insulation assessment that proofs craftsman work and ensures no damage occurs to the cable during switching, and lightning arrester survey that upgrades surge protection consideration to meet today's restricter standards. The goal of feeder cable program is to provide a holistic service, to review all aspects of the aging portions of a distribution system for enhanced system reliability and to eliminate an unscheduled electrical outage.

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