Early Detection of Impending Failure in HV Cable Terminations – An Intelligent Asset Management Necessity

S. Chimunda[1] (twangsam@gmail.com), C. Nyamupangedengu[1] (Cuthbert.nyamupangedengu@wits.ac.za) and P. O'Halloran[2] pohalloran@citypower.co.za*

[1]School of Electrical & Information Engineering, University of the Witwatersrand, Johannesburg
[2]City Power, City of Johannesburg

Power cable accessories (joints and terminations) are the weakest link in power cable systems. The higher the voltage the more complex the joints and terminations become in order to effectively control enhanced thermal and electrical stresses. The consequences of a cable accessory failure are catastrophic in supply disruption and replacement costs. Unlike other electrical equipment failures, replacement of a termination or joint often entails installation of one additional joint. In principle, joints and terminations are designed and tested to last the life of the cable itself, typically in excess of 40 years. Experience however has proven that power cable accessories often fail prematurely. It would therefore be naïve to treat the power cable accessories in the same way as the cable itself regarding maintenance and condition monitoring philosophy. In that regard, this paper uses a case study of the root cause analysis on prematurely failing 88 kV XLPE power cable terminations to argue for smart condition monitoring of high voltage cable accessories. The proposition is that in contemporary practice, every high voltage cable accessory design should be accompanied with information on predetermined failure modes. Such knowledge enables utility asset managers to implement appropriate data acquisition (sensors) and processing systems for early detection of impending failures in power cable systems; and this is the essence of intelligent physical asset management systems.

Introduction

In a case study municipal substation, there has been prevalent failures of 88 kV cable terminations after 29 years in operation [1]. All failed terminations were forensically investigated and the failure mechanisms within the cable termination were identified. Furthermore, an online data logging system had been installed in order to record the terminations operating parameters. In the present paper, firstly, the forensically identified degradation mechanisms are presented. A review of the condition monitoring methods in the case study substation is then presented. A possible intelligent solution which allows the identification of impending failure is then discussed.

The power cable termination design

The 88 kV XLPE power cable termination material and geometry and other design aspects are shown in *Figure 1*. Such high voltage power cable termination design is in common use in most South African metropolitan power utilities. In that regard, it can be widely beneficial if problems encountered and solutions associated with the technology are shared among asset managers in the utilities.

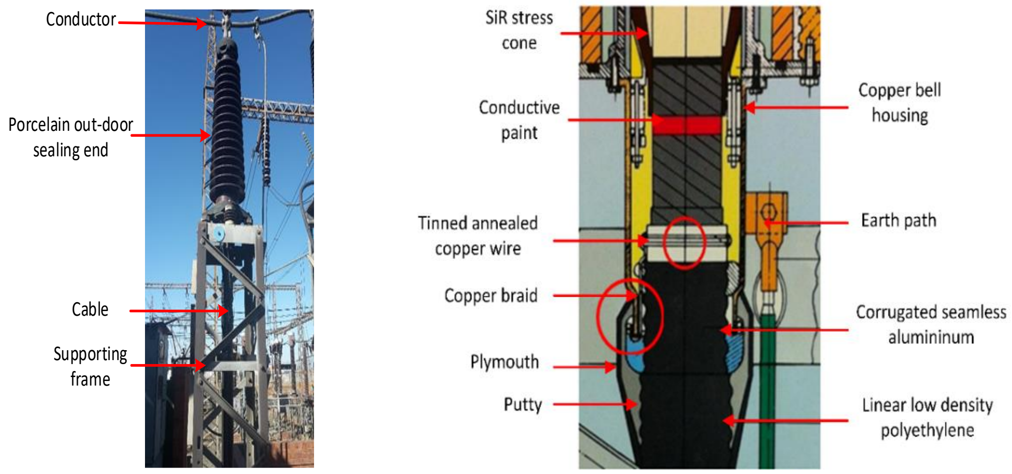

Figure 1. Cross sectional view of an 88 kV XLPE cable termination [1] (source: Patrick O'Holloran)

The identified failure mechanisms

Through forensic analyses of the failed terminations, the predominant modes of failure were identified as corrosion, thermomechanical fatigue and electrothermal degradation [1]. Thermomechanic fatigue and galvanic corrosion occurred at the critical metallic interfaces of the cable termination. *Figure 1* and *Figure 2* show metallic interfaces that are subjected to fatigue fracture and corrosion. The cracked metallic interfaces due to the thermomechanic fatigue may cause current path disruptions and/or establishment of undesired electric potentials. Arcing and corona discharges ensue. In the event of a fault surge, current erode and thermally degrade the underlying semi-conductor material. As an example, the fault current path can be diverted towards the stress cone, which exposes it to accelerated electrothermal degradation. *Figure 3* shows examples of failure at the copper braid and aluminium sheath interface.

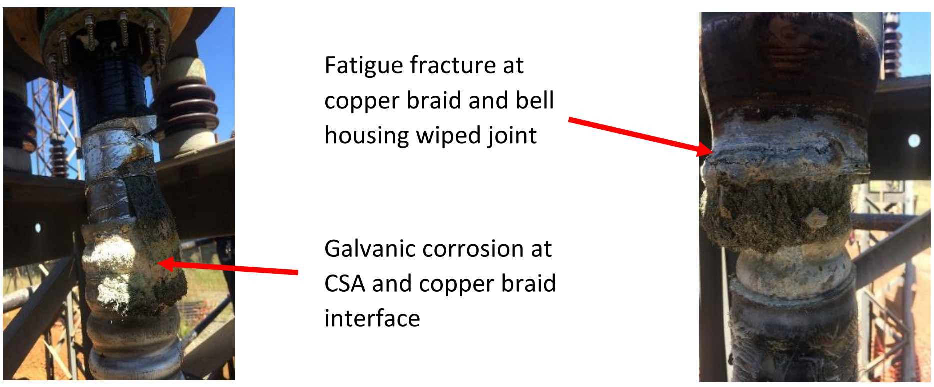

Figure 2.Metallic interfaces subjected to thermomechanic fatigue and galvanic corrosion

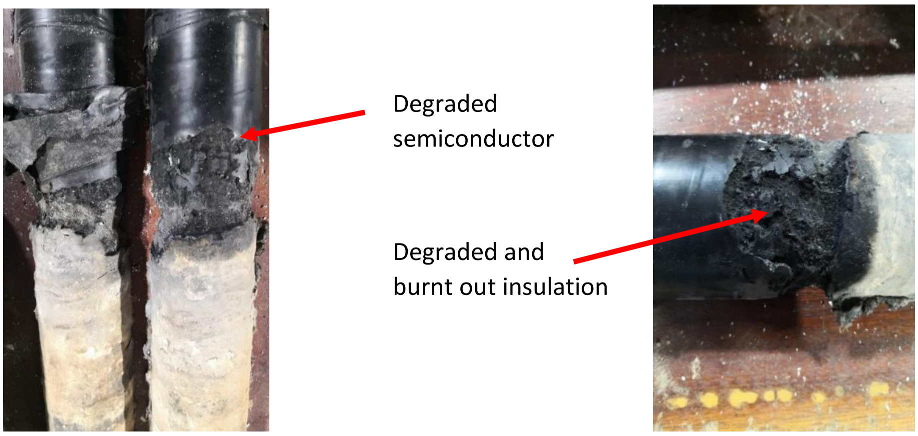

Figure 3. Semiconductor erosion and thermal degradation

The cracked metallic interfaces in the termination also allow water and/or moisture ingress into the termination which in turn initiates corrosion process. The aluminium sheath (shield) can get corroded beginning in the termination and extending for meters along the cable length. An example of such degradation is shown in *Figure 4*. The degraded ground sheath result in discharges between the CSA and the outer semiconducting layer. Such discharges further erode the semiconducting layer and eventually the XLPE insulation leading to complete failure. The partial discharges occurring between conducting surfaces that are at different potentials can easily be misinterpreted as harmless in conventional PD diagnosis methods.

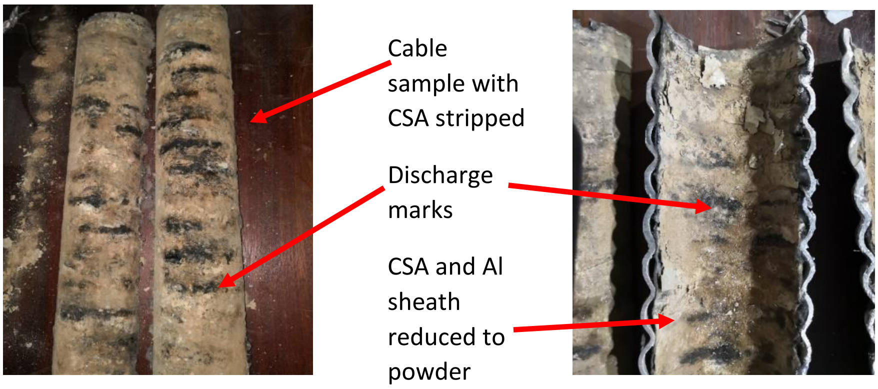

Figure 4. Completely disintegrated and dissolved aluminium foil sheath

Partial discharge condition monitoring

Partial discharge measurements are a common practice in power cable systems diagnosis. In the present case study, the PD diagnosis protocol shown in *Figure 5* is employed. The PD signal acquisition is through a hook-on high frequency current transformer (HFCT) on the connection lead of the termination. The criterion used to differentiate terminations requiring replacement from those that are in good condition (*Figure 5*) is based on the intensity and location of partial discharge activity. Internal partial discharge activity warrants the immediate replacement of the cable termination. Surface partial discharges inside the termination are considered ambiguous and further testing is required, while surface partial discharges outside the termination and corona are discarded as being harmless.

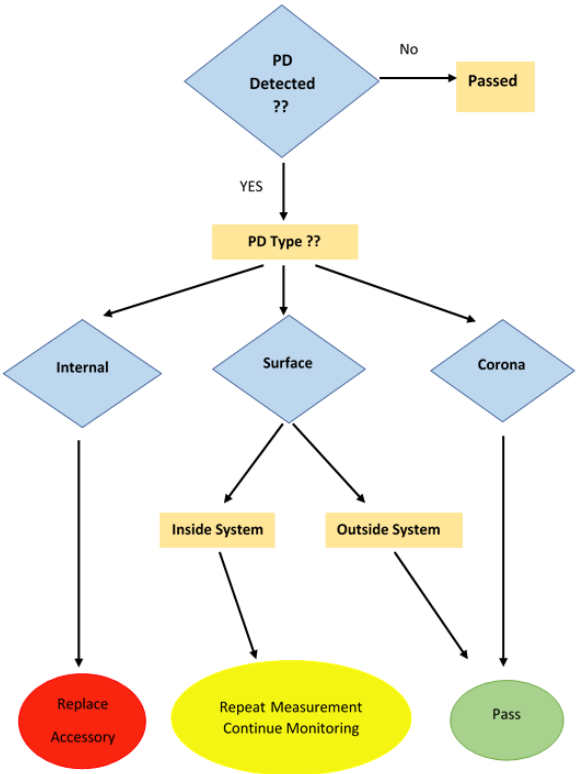

Figure 5.Partial discharge test decision chart

The primary failure of the metallic interfaces will most likely be discarded given the above-outlined partial discharge testing criterion. Sharp edges on the aluminium sheath and fracture solder at the copper braid to copper bell housing wiped connection will cause corona discharges. Subsequently the eroding semiconductor layer will be subjected to surface partial discharges and then finally leading to partial discharges in the XLPE insulation. In the context of the termination under study, PDs only indicate imminent failure and not early warning. There is therefore need for more comprehensive and smart condition monitoring system for the cable termination and indeed other power cable accessories. Use of real-time continuously updated reliability models can be a promising solution in that regard.

Reliability model

In the present work, a weakest link-based reliability model was developed. It is an analytical expression of the remaining life probability as a function of the identified life factors as shown in *equation 1*. Details of the model formulation are in [2]. The model accuracy depends on the ability to accurately determine the various parameters constituting the life factors. In the present work, the data was obtained from onsite measurements combined with the parameters that were obtained from a wide search in the literature. The process inherently entails making some assumptions. The graphical presentation of the reliability is presented in *Figure 6.*

$$R_{E,T,N,C}(t) = exp\left[-\left(\frac{t}{\alpha_0 \cdot \alpha_{E,T}}\right)^{\beta}\right] \cdot exp\left[-\left(\frac{t}{\alpha_0 \cdot \alpha_N}\right)^{\beta}\right] \cdot exp\left[-\left(\frac{t}{\alpha_0 \cdot \alpha_C}\right)^{\beta}\right] \quad \ldots\ldots\ldots\ldots(1)$$

Where $\alpha_{E,T}$ is the Electrothermal life factor, α_N is the Thermomechanical life factor and α_C is the corrosion life factor.

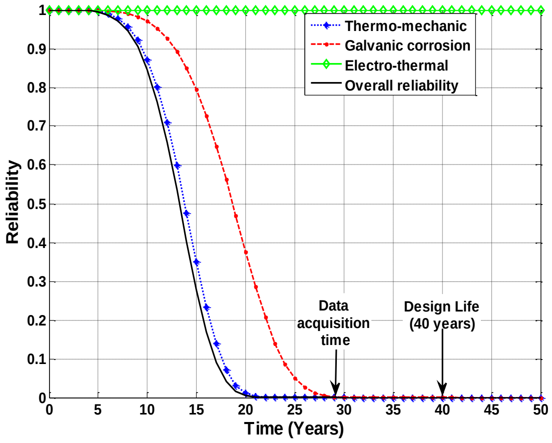

Figure 6: The graphical representation of the reliability probability of the cable termination under thermomechanic, electrothermal and galvanic corrosion life factors [2].

The concept of intelligent asset management

The instrumentation and online data logging systems can be used to obtain real-time operating parameters which together with material specific parameters, make up the mathematical deterministic models. When the degradation models are combined with statistical time to failure data, an estimate of the remaining life of the cable terminations can be made [3]. Furthermore, an intelligent distributed multiphysics 'digital twin' [5] can be developed. This would allow the complex synergistic degradation mechanisms to be observed in real time. The real time operating condition of the cable terminations will assist the maintenance engineer and influence future designs.

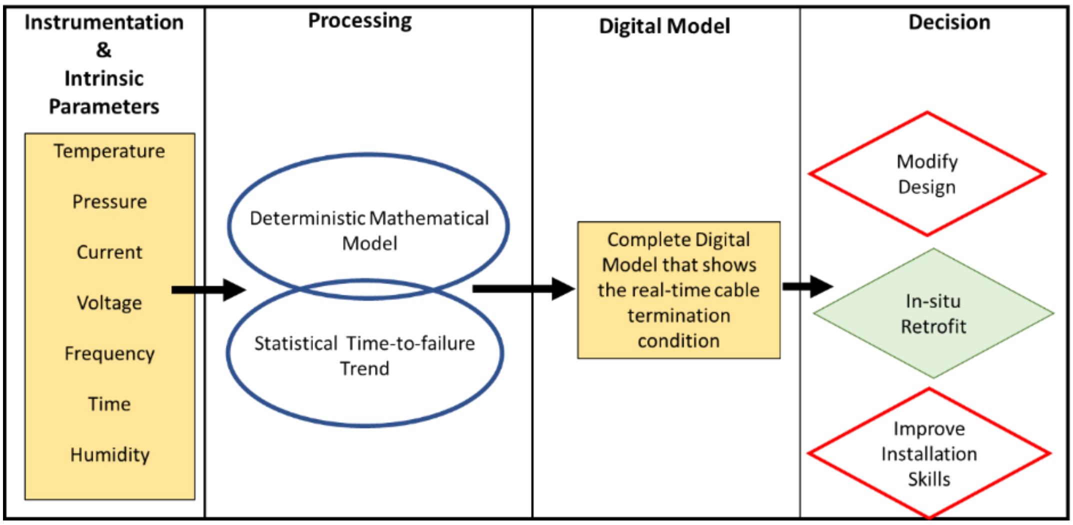

Figure 7. Intelligent cable termination asset management solution

Conclusion

The failure modes of a type of 88 kV XLPE power cable termination have been identified through forensic analyses of failed terminations. The forensic investigations show that not all degradation mechanisms can be identified through partial discharge testing. An intelligent digital twin solution has been proposed. The digital twin solution combines the statistical time-to-failure data, measured operating parameters and real time multiphysics simulations to inform maintenance and design decisions.

References

[1] P. O'Holloran, "Case Study Site Maintenance Engineer," 2017.

[2] S. Chimunda and C. Nyamupangedengu, “A reliability assessment model for an outdoor 88kV XLPE cable termination,” *Electr. Power Syst. Res.*, vol. 177, p. 105979, Dec. 2019.

[3] G. Mazzanti and M. Marzinotto, “Advanced Electro-Thermal Life and Reliability Model for High Voltage Cable Systems Including Accessories,” *DEIS*, vol. 33, no. 3, pp. 17–25, May/June.

[4] M. Grieves, *Origins of the Digital Twin Concept*.2016. 10.13140/RG.2.2.26367.61609

[5] D. Vogeli, S. Grabmaier, M. Juttner, M. Weyrich, P. Gohner, and W. Rucker, “Intelligent and Distributed Solving of Multiphysics Problems Coordinated by Software Agents,” presented at the International Conference on Agents and Artificial Inteliigence (ICAART 2018), 2018, vol. 1, pp. 200–207.