Validating Reliability Improvements of New Cable Designs – A Case Study of 600 V Self Sealing Cables

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ABSTRACT

Utilities and Manufacturers continually deploy new technologies on their systems with the goal of either providing new functionality or improving reliability. Although these devices can be tested in the lab, these results need to be confirmed by field experience. The traditional anonymous Control group approach is often not possible in the Utility context as installations are made when possible and older technologies remain active. This paper describes a technique that the authors have developed for use on Utility systems to validate the performance of a range of technologies (Reclosers, Transformers, Meters, Lighting etc). In this document the process is illustrated using a new design of LV cable.

KEYWORDS

600 V cable, reliability modelling, case study, self-sealing cables, Crow-AMSAA, reliability growth, validation

INTRODUCTION

Manufacturers continue to make and utilities continue to deploy new and innovative cable designs to address important technical and reliability problems. These new solutions are tested in the laboratory through a series of development and approval tests. Although the deployment begins only when all of these tests are completed to the satisfaction of all involved; there is still a need to verify that the solution really does address the problem in the field and does not introduce other unforeseen issues. This need exists because there are some very important differences between laboratory tests and field experience; laboratory tests are designed to deliver consistency and repeatability, service experience increases the scale (generally by length of product) and exposes the solution to the ill-defined rigors of service. Although absolutely essential, monitoring performance in service is a challenging undertaking.

Classically, the service performance challenge would be addressed by selecting an area of known problems and constructing a group with the new solution and a group without the new solution – the control population. The performance would be monitored for a suitable period of time until a clear and verifiable difference could be discerned. Unfortunately for new cable solutions this approach is not feasible for a number of reasons:

- Record keeping is often not robust enough to segregate the inputs from the mixed Control and New populations
- Installation needs to be part of the normal operation of the utility such that stock & training variables do not interfere
- Confirmation Bias (an *ab initio* perception of good or poor performance) can overwhelm the desired signal
- Once the effectiveness of the new solution is confirmed upgrading the control population can prove to be a logistical and philosophical challenge

Thus, often the only practical way forward is to deploy in areas and compare performance with a non-matched, non-intercalated Control Group. Consequently, the analytical strategies used need to be sufficiently robust to provide a clear result. The clarity / certainty of the result is important as large investment decisions on the parts of the Utility and Manufacture will ride on this result.

In these cases, one issue that becomes important is the success of the new solution – if it is effective then there will be fewer problems (i.e. we end up dealing with very small numbers) such that the effects will be quantized and effect of any incorrectly attributed problem will be amplified (the effect of 2 missed failures in 100 is small compared to 2 missed in 15).

Figure 1: Corrosion Failure of Traditional 600 V CAble

Figure 2: Self-Sealing 600 V Cable

A case study was undertaken on the Duke Energy system using their 600 V (LV) cable system and is described here to illustrate the procedure. The final connection between residential customers and the primary underground distribution system is made using low voltage (600 V) unshielded cables (often termed “secondary” cables). These low voltage systems can often be damaged during or soon after installation as builders and landscapers complete their construction work. Sometimes this damage results in an immediate failure (dig in) while other times the insulation is just damaged enough to allow moisture ingress and eventual corrosion of the conductor (Figure

1).

Cable manufacturers have approached this problem in a couple of ways: (1) tougher insulation materials and (2) self-sealing insulation (Figure 2).

The example studied in this paper involves the transition from traditional 600 V insulations to a self-sealing insulation.

This paper discusses an effective analytical solution using the Crow-AMSAA methodology using the secondary cable case study from Duke Energy. In particular the paper describes:

1. Crow-AMSAA technique for Performance Evaluation
2. Overview of Low Voltage (600 V) Cable Designs
3. Why Low Voltage Cable Systems Fail?
4. Results of Duke Energy Case Study
   a. Data from multi-year pilot study
   b. Performance predictions

CROW-AMSAA / RELIABILITY GROWTH MODEL

The Crow-AMSAA technique (or Reliability Growth Model) [1] utilizes log-log representations of cumulative performance and cumulative experience. This method is particularly useful for identifying changes in population performance (i.e. lower or higher failure rates). In the case of cable systems as well as other devices, the performance metric is typically taken to be service failures while the experience could be chosen to be length, number of segments, time in service, or some combination. Figure 3 shows an example of a Crow-AMSAA plot for aircraft engines where the experience variable is taken as flight hours.

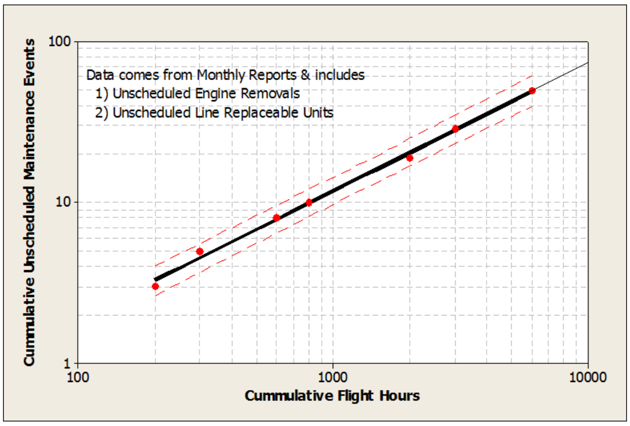

Figure 3: Crow-AMSAA Plot for Aero Engines [1]

A linear regression fit is used to establish the baseline failure rate. Any bends or knees in the data would indicate some change in performance that would subsequently produce a change in gradient or slope. The gradients are correlated to the population failure rates. Thus, any improvement or deterioration in performance causes a bend. Increases in the gradient with respect to the baseline correlate to higher failure rates while decreases in the gradient represent comparatively lower failure rates.

The regression fit may be extended to future experience levels to provide an estimate of the failure performance. This technique is used extensively in the Duke Energy case study.

600 V CABLE DESIGNS AND CAUSES OF FAILURE

Secondary cables are used in the USA to route power from each transformer to 3-8 residential homes. There are three primary types in use today:

1. Standard - single layer of extruded insulation (typically low density XLPE)
2. Abuse Resistant/Ruggedized – single and dual layer medium or high density XLPE
3. Self-Sealing – double layer of insulation with visco-elastic sealant encapsulated within insulation

Low voltage cable systems are somewhat unusual in terms of failure mode in that most failures are attributed to damage resulting from installation, dig-ins, rodents, and other incidental damage caused by homeowners that typically occurs early in the life of the cable system. In each of these cases, the insulation is damaged such that moisture ingress occurs. This leads to corrosion or a fault if sufficient moisture is present. The exact timing of the fault is related to the moisture content of the surrounding soil as dry soil does not provide a low resistance path to ground.

Both the Standard and Abuse Resistant/Ruggedized designs rely on material strength and careful handling to prevent damage to the insulation. However, once damage occurs, the damaged location must either be repaired with a joint or the entire cable run replaced to avoid a failure in the future. Unfortunately, such damage is rarely identified in the field prior to a fault.

In the case of Self-Sealing designs, once the insulation is damaged to the point of being breached, the sealant flows out through the breach and seals it within a short time period thus preventing the moisture ingress that would ultimately cause failure in the future.

It is important to understand that the dielectric failure modes that occur in low voltage secondary cables are quite different to those typically impacting medium and high voltage cable systems.

DUKE ENERGY CASE STUDY

Duke Energy conducted a pilot program to determine the benefits of transitioning their 600 V cable systems from Standard and Abuse Resistant designs to a self-sealing design. One operating region was selected for the pilot program due to its location and past performance. Service performance and installation data were obtained for the 2003 – 2009 period for the pilot region (Anderson, South Carolina) as well as broader regions ("Southern" and "Carolinas"). It is important to note that "Anderson" is a subregion of "Southern" and "Southern" is a subregion of "Carolinas". In total, over 120 million conductor feet of secondary cable was installed in this period. Figure 4 shows the installed lengths for 67 mm^2 (2/0 AWG) cable for each subregion.

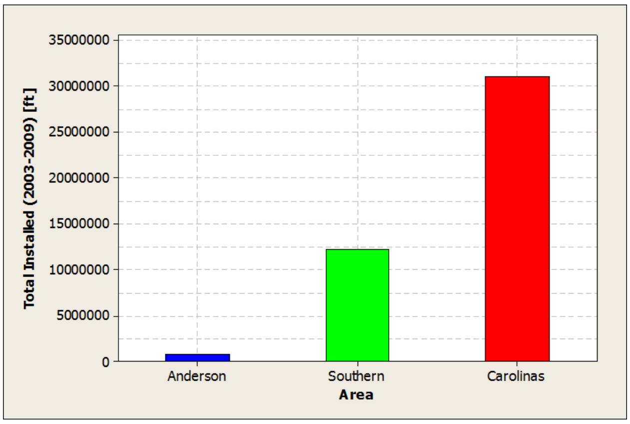

Figure 4: Secondary Cable Installed 2003-2009 by Region (67 mm^2 (2/0 AWG) Cable Only)

The raw performance and installation data were provided as combined annual figures for each of the regions. This limits the available analysis routes as most approaches would have required either a finer time scale or more years of data than the seven data points available. The Crow-AMSAA approach described above is amenable to such data so long as the experience variable is carefully chosen.

Historical Analysis Results

The exact timing of the transition to the Self-Sealing design was not provided *a priori* and so could be used to validate the analysis results. Figure 5 shows the Crow-AMSAA plot for each of the regions utilizing an experience variable consisting of years in service and length. Each data marker corresponds to one of the seven years (i.e. the first data point is 2003, the second 2004, etc.). A number of useful observations are apparent:

1. Anderson shows a knee/bend in the gradient starting in 2006. This corresponds to the time when the Anderson region transitioned to a Self-Sealing one.
2. All regions display a slight increase in cumulative failures in 2009 resulting from cable damage that yielded a fault. This is most likely related to emergence of the regions from drought thus the available water caused the reporting of previously un-detected faults.

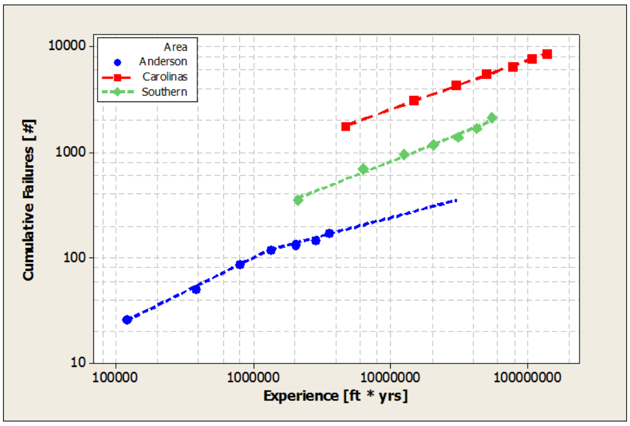

Figure 5: Reported Secondary Cable Failures (Installed 2003-2009) segregated by Region and presented in Crow-AMSAA format.

The change in gradient for Anderson was identified using a moving least-squares regression approach. Once the transition year was identified, the data were split into two groups: 2003-2006 and 2006-2009 (2006 was kept in both sets to allow for continuity). The gradients for both time periods were then estimated again using a least-squares linear regression and the results are shown in Table 1.

Table 1: Crow-AMSAA Gradients by Region and Time Period

Region	2003-2006 Gradient	2006-2009 Gradient	Difference 2003 – 2006 to 2006 - 2009
Anderson	0.634	0.372	-0.262
Southern	0.530	0.595	0.065
Carolinas	0.477	0.459	-0.018

As Table 1 shows, the change in gradient within Anderson after the transition was:

- A reduction, thereby indicating a reduced failure rate
- 4-15 times smaller than the changes in the other (non-Self-Sealing) regions.
- Sufficiently larger than the other regions to be significant

These findings imply that a change occurred within Anderson that was unique to Anderson and not system wide otherwise similar changes in gradients would have been observed for the other regions.

Failure Projections for Pilot Regions

Although very beneficial to show that a definitive improvement was realized; it is also useful to be able to make some reasonable predictions on performance for a few base cases. With the gradients established for the full 2003-2009 period, it is then possible to extrapolate into the future to estimate the potential for avoided failures – assuming that no other changes occur. Figure 6 shows the extrapolations for Anderson considering two scenarios:

1. All cable installations continue to be made using the historic mix of Standard or Abuse Resistant/Ruggedized designs – black curve
2. Cable installations continue with Self-Sealing design – red curve

As Figure 6 shows, with the transition to Self-Sealing cables, the Anderson region potentially avoided 69 service failures (difference between the black and red curves). As time passes, this value grows assuming no as yet unidentified failure modes develop.

The projections are based on the average cable installation lengths installed in the region. The same installed lengths are used for both scenarios.

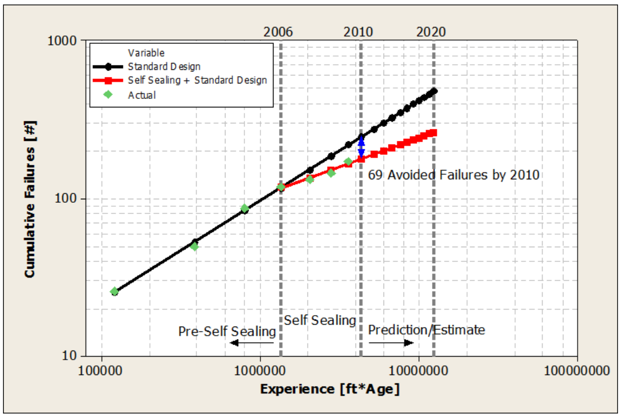

Figure 6: Crow-AMSAA Projections for Anderson Region – Standard and Self-Sealing & Standard Systems

Of course, the Anderson cable system as a whole remains a mixture of Standard, Abuse Resistant, and Self-Sealing; however, the Self-Sealing proportion grows in relation to the others. This analysis does not provide the true performance of the Self-Sealing design precisely because of the population hybridization. It does, on the other hand, provide reasonable assurance that the new cable design provides improved service performance (within the time frame studied) as compared to the alternatives in use. It would, therefore, be useful to estimate the performance of a pure Self-Sealing system.

Towards a ”Complete” Self-Sealing Cable System

The best approach available to us for estimating the performance of a completely Self-Sealing cable system is to estimate the gradient for such a system. As mentioned above, the hybridization of the Anderson system prevents direct calculation from the available data. However, as the pilot program progressed, a larger proportion of the Anderson system transitioned to Self-Sealing cable. In theory, there should be gradual changes in gradients within the pilot study period that would assymmptotically approach the true Self-Sealing gradient. Figure 7 shows the gradient estimates as the pilot study progressed.

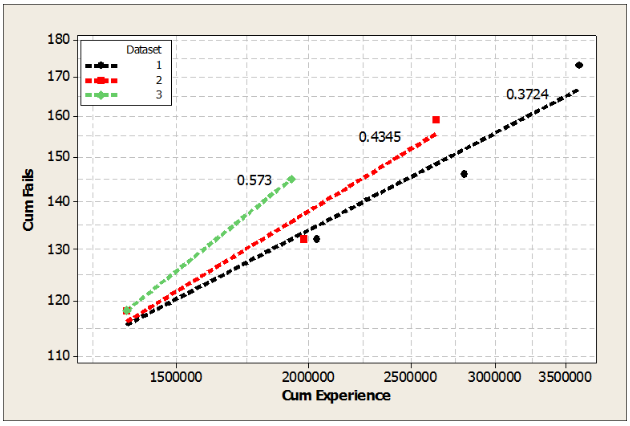

Figure 7: Self-Sealing Gradient Estimation, for selected times (1, 2 & 3 years)

As Figure 7 illustrates, the gradient decreases as a larger portion of the cable population becomes the Self-Sealing design. These gradients can then be used as data for an exponential function of the form shown below:

$$f(x) = Ae^{-Bx} + C \qquad [1]$$

The primary interest is to estimate the value of *C* in Equation 1 as this corresponds to the pure Self-Sealing cable system gradient. While not ideal in terms of the number of parameters to estimate, this model does allow some estimate to be made. The resulting estimated gradient for a Self-Sealing cable system is 0.37.

CONCLUSIONS

Confirming the benefit of new technologies or remedial actions in the field is an important yet difficult proposition for Utilities. Most forgo the confirmation as the data required for the classical approaches are difficult to obtain or cannot be translated into the form needed for the analyses. This paper shows that these issues need not be barriers as the Crow-AMSAA method is simple to use, amenable to different problems and provides robust and accessible solutions.

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