North American Performance Experience of HV and EHV Extruded Cable Systems

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ABSTRACT

Utilities and specification bodies are very interested in understanding industry wide performance of underground transmission system. The most recent document considered by utilities is CIGRE TB 379 from WGB1.10, issued in 2009. Unfortunately, some issues limit the usefulness of this document in the North American context. This work provided users with a current assessment of the risk associated with HV & EHV cable systems, by expanding on the information in the CIGRE document by surveying both manufacturers and utilities and focusing on cable systems installed since 2000. The disbursement of component failures was then obtained and the most likely failure rate and most likely failure range were estimated. A partial "bathtub curve" for HV & EHV cable systems was developed. This work found that North American HV & EHV Service Performance data for modern extruded systems differ from the reported CIGRE data.

KEYWORDS

Reliability, HV, EHV, Extruded Cable Systems, Cable, Accessories

INTRODUCTION

Underground transmission systems are viewed by some utilities as "New Technologies" and by others as "Established Technologies". Independent of which perspective is considered, utilities and specification preparation bodies are very interested in understanding the true meaning of industry wide performance surveys conducted to date. This interest is driven by the improved reliability index ratios for underground / overhead transmission systems (1) {SAIDI 350 / <30 & SAIFI 1.2 / <0.1}. The most recent document considered by utilities at the start of this work was CIGRE TB 379 from WGB1.10, issued in 2009 (2). Unfortunately, some issues limit the usefulness of this document in the North American context.

The work reported here sought to provide users with a current assessment of the risk associated with HV & EHV cable systems, by expanding on the information in the CIGRE document by surveying both manufacturers and utilities and focusing on cable systems installed since 2000, including components that failed in service and excluding third party damage. The authors simultaneously collected data on failures, installed lengths, and then identified components that failed, considering both HV (69 - 150 kV) and EHV (230 – 400 kV) cable systems. The disbursement of component failures was then obtained and the most likely failure rate and most likely failure range were estimated.

Finally, a perspective on a partial "Bathtub Curve" for HV & EHV cable systems was developed. This work found that North American HV & EHV Service Performance data for modern extruded systems differ from the CIGRE data. This could be due to differing data sets, larger North American participation, reduced confirmation bias, and/or increased data verification.

APPROACH

North American engineers reported a need to place extruded systems in perspective (1, 3) and had experienced difficulty in using the global survey results due to,

- Unfamiliar voltage ranges ,
- Inclusion of results from older cable technologies (pipe type, steam cure, etc.),
- Disbursement of failures at odds with experience.

Thus, there was interest in refining the CIGRE study (2) for the use in a US context by

- Limiting the period to cable systems installed during the years 2000 to 2014,
- Limiting the study to extruded cable systems only,
- Expanding the sources of information.

Sources of Data

To address the concerns that were raised when the project was launched, the following steps were included in the methodology. The procedure included the following,

- Inclusion of both manufacturers and utilities,
- A large Contact Group ,
- A clear request for information on cable systems installed since 2000;
- Consideration of only components that failed in service excluding third party damage (did not consider commissioning test failures, fires, dig-ins, etc.),
- Simultaneous collection of data on failures and installed lengths for the responding manufacturer and utility ie failure/length pairs,
- Collection of failures that were not provided with a corresponding length, termed here "orphan" failures,
- Wherever possible identification of components that failed,
- Voltage class groupings based on IEC standards HV (69 kV – 150 kV) and EHV (230 kV – 400 kV) were used for high level analyses,
- In most cases, duplicate data were identified and "double counting" of failures was avoided.

Analysis

Data

In total, 40 entities provided information. Cable system lengths were described in terms of conductor length. In this study, the convention of each failure encompassing 1 mile was adopted – the selection of 1 mile or 1,000 ft. as the basic length unit has approximately a 3% impact on the failure rates.

This work identified 68 failures associated with 9,503 conductor miles of cable. The failures include 53 with known lengths and 15 “orphans” where the lengths were not provided or were unknown. Lengths were assigned to the “orphans” by either comparison with similar installations (e.g. switch yard connections were assumed to be similar in length) or through using the median length of that voltage class. ‘Patching’ the lengths of the ‘orphan’ failures to provide failure/length pairs gave a total of 114 pairs for analysis.

Failure Rates

There is not a clear single method to analyze the data with and without ‘orphans’, each method has its own merits; thus, it was decided to use both and report as a meta study.

The data were treated as “count” data (i.e. a discrete number of failures occurring in a variety of cable system lengths within a time period at different utilities/manufacturers). Moreover, in most cases the number of failures in the pair is not only discrete, but also much smaller than the length. As such, it was decided to use the “Poisson Distribution” (4) in the analysis. The “Poisson Mean and Confidence Interval” were calculated and used for the analyses.

Sources of Bias

In any study of this type, there is the issue of “Confirmation Bias” to consider, namely that utilities that have not experienced failures are much less likely to provide data on their good experience than those that have experienced failures. Furthermore, the fidelity of record keeping / institutional knowledge is much better for EHV systems than HV. A 69 kV failure might be unreported, whereas this is highly unlikely for a 345 kV failure to be unreported.

Utilities with experience of failures readily reported. The Confirmation Bias associated with the good performers was minimized by repeated outreach to the relevant utilities to confirm good performance and the relevant lengths.

Interactions with participants confirmed that under reporting at lower voltages does exist. This work also produced estimates that were considered reasonable for the magnitude of the under reporting. However to maintain the clarity of the computed results, it was agreed that these unreporting factors would not be applied to the data. This reature is responsible for the large asymmetric bounds on the HV failure rate estimates.

Time to Failure

Although not requested, some (but not all) of the failure data were provided with specific times in service before failure or a range of times before failure. Consequently, it was realized that enough data were available to,

- Identify if there were different failure modes: Early / Infant, Middle, Late / End of Life (5, 6, 7, 8),
- Estimate when these modes become apparent,
- Assess the relative differences in modal failure rate.

The analysis was undertaken for about 50% of the failures. No length information was used in this analysis, thus only relative failure rates could be inferred.

RESULTS

Sources of Failures

Figure 1 shows the disbursement of failures per component class over the whole time period. In this work, we include GIS within the termination grouping.

We estimate that the Margin of Error for this portion of the study (Figure 1) is between 7 and 14%.

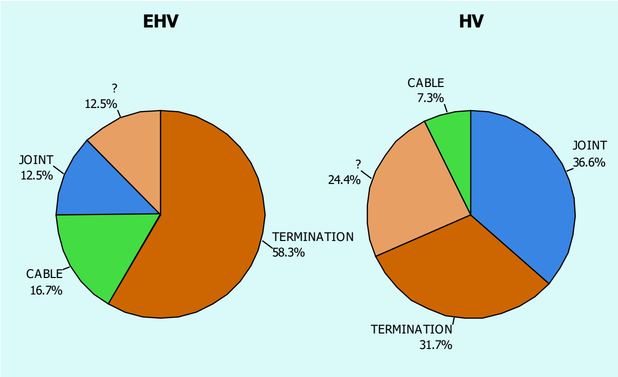

Figure 1: Disbursement of cable system failures by component failing segregated for HV and EHV classes

Failure Rates

Failure Rates were estimated using the Poisson Distribution for a number of assumptions that were considered reasonable. These results enabled the “most likely” distribution of Failure Rates to be produced - Figure 2. This shows that it is unlikely for failure rates to be above 0.003 or below 0.0002. The location of the peaks indicate the most likely rates.

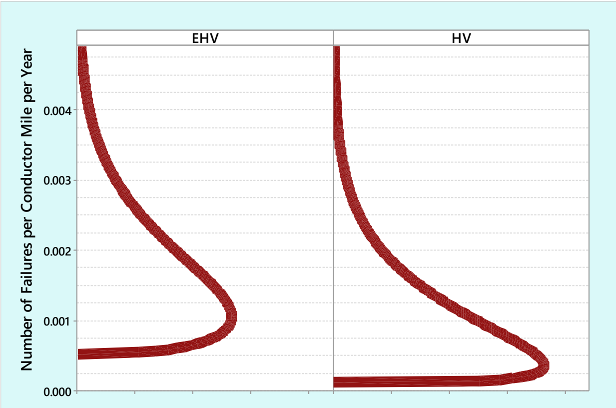

Figure 2: Distribution of the Annualized Failure Rate Estimates segregated by Voltage Class – no allowance for under reporting

Consequently, based on the reported data, it is more likely that the HV failure rates are lower than rates at EHV.

Using the same approach, the Failure Rates for the different components were established from Figure 1 and Figure 2. Figure 3 provides the most likely rates in columnar format.

Close and Return

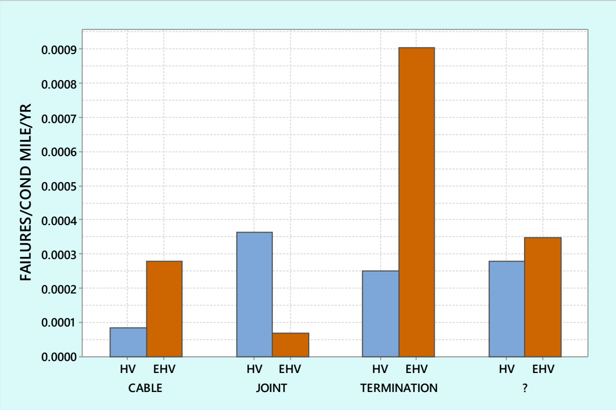

Figure 3: Component failure rates computed from disbursement and failure rate data – no allowance for under reporting

Life Cycle – Bathtub Curve

An initial Weibull Curve was constructed assuming a single mode of failure for all the data (5, 6, 8),. It was found through inspection of the curve and the goodness of fit statistic that this single mode did not provide an optimal fit to the data. There were indications that two lines (hence two modes) would be a better fit to the data. Using an iterative process for segmentation, it was determined that the most appropriate, data driven, grouping for the failure data was,

- Mode 1 – Time <1.5 years,
- Mode 2 – Time >1.5 years.

The Hazard Plot / Failure Rate from the fitting of these two modes is provided in Figure 4.

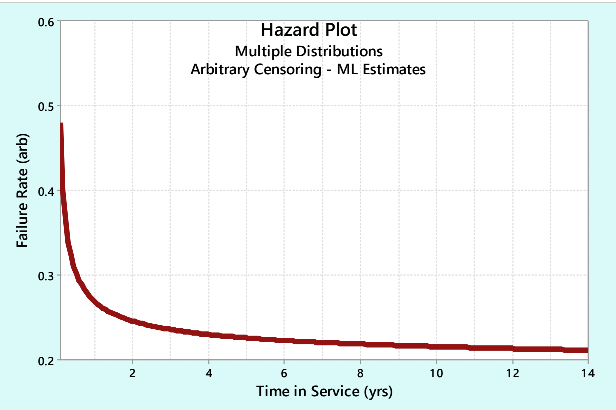

Figure 4: Composite (two mode) Hazard Plot (derived from the Weibull Analysis of time to failure data

Inspection of the Hazard Plot reveals a striking similarity to the left hand and middle sections of the classic "Bathtub Curve", which underpins most discussions of Reliability / Asset Management. This is confirmed by inspection of the Shape Parameters estimated in the separate Weibull Analyses.

Mode 1 has a Shape / gradient of approximately 0.3, if a Shape/gradient is <1 then this is characteristic of "Early or Infant Mortality" failure modes. Infant Mortality is characterized by a decreasing failure rate (i.e. operation causes the weak units to fail leaving the good performers, thus reliability improves with time; proactive replacement is not beneficial).

Mode 2 has a Shape / gradient of 0.97, if a Shape/gradient is approximately 1, then this is characteristic of middle or random mortality failure modes. "Random" failure mode is characterized by an equal likelihood of old units failing as new units as middle-aged units. "Proactive Replacement" is not beneficial as there is no way to select the ones likeliest to fail from the age data alone.

It would be <u>incorrect to interpret</u> the data in Figure 4 in terms of a "Life Statement" (9) for the HV / EHV population (for example *for technologies used since 2000 50% will experience a failure within 2 years*). This is because this analysis only includes the failures and not the associated survivors. Such a population "Life Statement" could be constructed (most likely using a modified "Dauser Shift" technique (5)) but it was outside the scope of the work reported here.

It is also important to recognize that these data do not include the failures / events that occur during commissioning tests. The meta data accompanying failure incidents suggests that circuits that experienced commissioning test failures and then were rehabilitated, did not go on to experience failures within the timeframe studied.

Interpretation of the Hazard Plot (Figure 4) supports,

- The "End of Life" mode will start to initiate at some time >14 years and most likely >18 years (based on the time elapsed since the data were collected),
- The "Infant Mortality" mode no longer becomes apparent in the 2 to 4 year range,
- The relative "Infant Mortality" failure rate is on the order of 2.5 times larger than the "Random" failure rate.

CONCLUSIONS

On the basis of this work we conclude that

1. The improved fidelity of the reliability estimates has been a benefit for US users.
2. North American HV and EHV service performance data for modern extruded systems differ from the CIGRE data available in 2014. Lower overall and component failure rates were found in this North American study,
    - EHV – 1.2 to 1.8 failures per 1,000 conductor miles per year { we estimate an error of +/- 25%};
    - HV – 0.75 to 1.2 failures per 1,000 conductor miles per year {we estimate an error of + 100% /- 25%, including the likely impact of under reporting of HV failures}.
3. The disbursement of the components failing in service differs (lower cable component) between the CIGRE and this work.

4. The sources of the differences (to CIGRE) described above were not established explicitely, but could plausibly be due to,
    a. Reduced timescale 2000 – 2014,
    b. Larger North American participation 40 entities,
    c. Reduced "Confirmation Bias" – input was included from entities that did not have failures,
    d. Increased data verification – reduced double counting, resolution of conflicting inputs, and clarification of data received.
5. The sequence / age of the failures follows the "Bathtub Curve", but it is possible to only discern the early and middle portions of the curve.
    a. "Infant Mortality" failure mode is expected to be complete within 2 to 4 years in service.
    b. "Infant Mortality" rate is approximately 2.5 times higher than the middle failure rate (Random).
6. It has not been possible, within the scope of this work, to develop a Population Life Statement for the time based Failure Analysis.

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