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ELECTRICAL CONNECTORS FOR OVERHEAD LINES

Evaluating assessment and test methodologies to improve quality

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Utility distribution systems utilize a variety of connectors to join and attach overhead conductors. These components are simple and relatively inexpensive; however, due to their critical function and the large number of components utilized in the electrical system, they deserve some consideration from the maintenance perspective.

Factors such as corrosion, improper installation, and manufacturing defects can cause in-service failure of connectors leading to safety risks to lineman crews and the public, and compromising the reliability of the power supply.

Many utilities have experienced this problem and some have made efforts to mitigate the risk. Due to the nature of the connector design, the defects are typically hidden and cannot be detected easily. As a result, blanket replacement sometimes is the only option, which can be inefficient due to the large number of connectors replaced prematurely.

Thus, a need exists for an effective inspection tool that electric utilities can use to provide information on the condition of the connectors currently in service. This tool would allow utilities to plan for the timely replacement of deteriorating connectors, thereby reducing risks and costs in system operation.

In order to identify the most effective inspection tools, a study titled, *"Assessment/Test Methodology of In-service Electrical Connectors for Overhead Lines"* was conducted by Powertech Labs Inc., under contract from the CEATI Distribution Assets Life Cycle Management (DALCM) Interest Group, to review the electrical connector assessment practices currently employed by utilities, as well as other potentially applicable methods described in the technical literature. Researchers tested the identified methods using connector samples collected in the field and samples created in the lab to simulate corrosion. Subsequently, researchers compared the collected measurements to the actual condition of the connector samples.

STUDY APPROACH

The utility overhead distribution system uses numerous connectors. These connectors vary in design and coupling methods (that is, compression splices, automatic splices, and clamps). Carl Tamm, a consultant with Classic Connectors, considers connectors the weakest point of the overhead line.

The main objective of this study was to review and evaluate the best practices for in-situ condition assessment and testing of overhead electrical connectors. The study provides evaluation, ranking, and recommendation of inspection techniques that utilities can use to assess the condition of in-service electrical connectors, giving quantitative information on their present condition. These assessment methods would allow maintenance personnel to plan prompt replacement times for deteriorating connectors, thereby reducing the risks and cost of in-service failures and premature replacements.

The scope of the project, established with the support of the Distribution Assets program representing 37 North American electric utilities, included a number of tasks (refer to *"Tasks for Connector Project"* sidebar).

TASKS FOR CONNECTOR PROJECT

- Identify most common connector types and features
- Identify connector failure modes and causes
- Review state-of-the-art connector condition assessment methods through a technical literature review
- Survey participating utilities' practices and testing methodologies currently used for connector inspection
- Evaluate the most promising inspection methods through laboratory tests
- Summarize findings and provide recommendations, including the most effective assessment approach, equipment, and procedures as supported by verification results, and suggestions for further research

"Even though some connectors fail due to mechanical stress, electrical failures appear to be more commonly reported."

CONNECTOR TYPES

Before considering the various connector assessment and test methodologies, connector types, their features and failure mechanisms should be understood. Researchers identified the four most common connector types: wedge, compression, bolted, and automatic. These connector types differ in materials, design, and service applications; however, the failure mechanisms appear to be common for all types. Another major distinction in connector types is whether they are current carrying or not (for example, dead-end connectors).

The connector type will indicate what possible stress and conditions the connector will be exposed to and thus it can be used to assign a risk factor to the connector for the purpose of asset management.

FAILURE MECHANISMS

Even though some connectors fail due to mechanical stress, electrical failures appear to be more commonly reported. In these situations, the connector resistance increases over time to a high enough value that a rapid deterioration of the connector occurs, resulting in destruction due to electric overheating.

The cause of an increase in electrical resistance is usually a combination of several factors:
- High initial resistance due to improper assembly/installation or defective materials
- Degradation of electrical interfaces in the connector through thermal cycling
- Oxidation of electrical interfaces due to contaminants and environmental effects

For current-carrying connectors, electrical resistance appears to be the main factor in determining the service life of a connector, provided it is appropriately designed and installed to withstand electrical and mechanical stress loads normally seen in service.

Over time, the contact resistance of the connector will increase from its initial nominal value at the time of assembly. Steffen Grossmann, Helmet Lobl, and Helmut
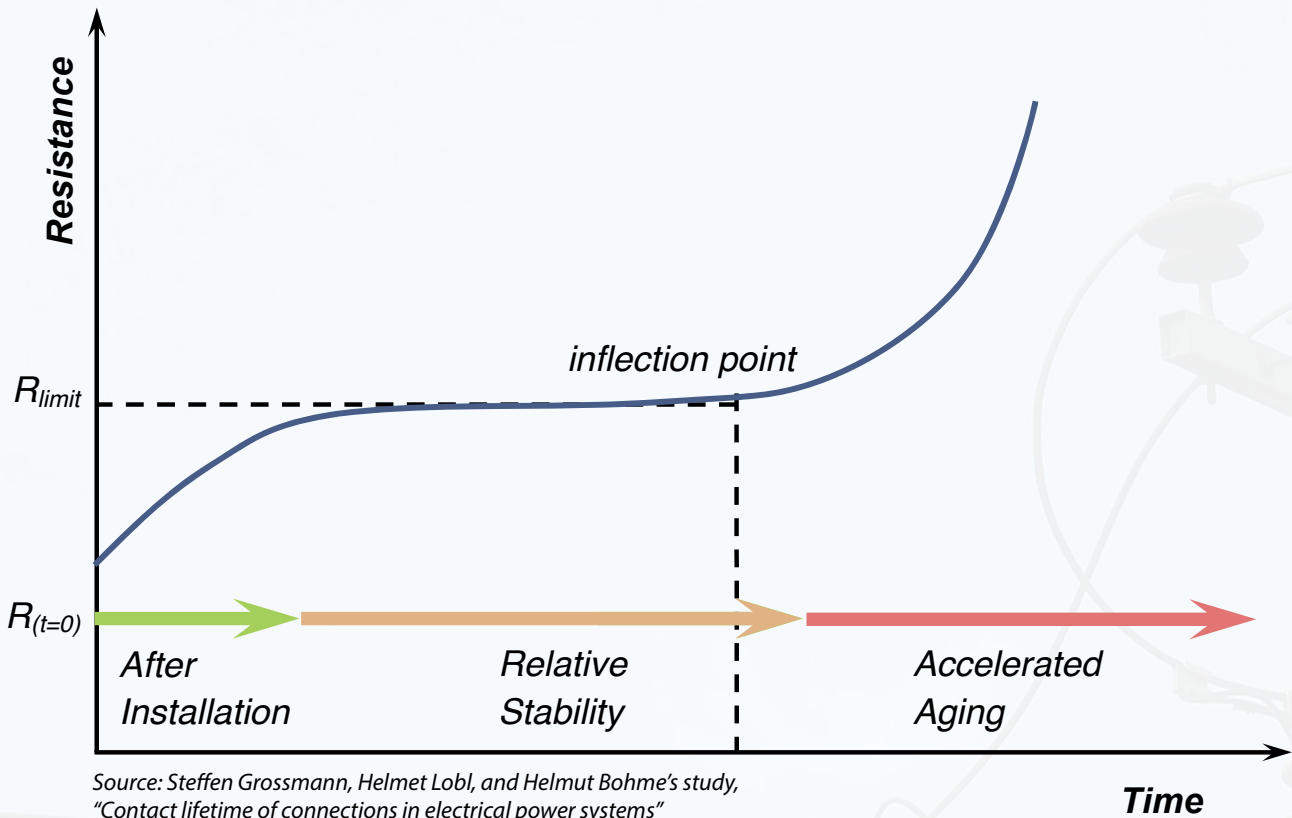
Figure 1

Principle of connector resistance vs. time

Resistance

R(t=0)

R_{limit}

inflection point

After Installation

Relative Stability

Accelerated Aging

Time

Source: Steffen Grossmann, Helmet Lobl, and Helmut Bohme's study, "Contact lifetime of connections in electrical power systems"

Bohme identify in their study, *"Contact Lifetime of Connections in Electrical Power Systems"* three factors that influence the rate of change of contact resistance (refer to *"Contact Resistance Changers"* sidebar). Figure 1 shows the increase of connector resistance with time and the three phases of the connector service life as proposed by this theory.

Once the electrical resistance of the connector reaches a critical value, progression to failure is quite rapid. Either a thermal runaway process or arcing will occur. The material at the connector to conductor interface will eventually soften or melt, destroying the connection. Softening of the conductor will also affect its mechanical strength. For connectors under tensile load, the end failure mode might cause a mechanical separation of the connector and the conductor.

The relationship between connector temperature and resistance is interdependent. The connector temperature is a result of a balance between the heat generated by the passage of current through the connector, and the heat dissipated from the connector. Since the resistivity of the connector material is temperature dependent, as the temperature of the connector increases, more heat will generate at a given current level.

However, since dead-end connectors do not carry current, the resistance of the connector joint is not applicable as an indicator of its condition. For these types of connectors, mechanical fatigue is the primary failure mechanism associated with long-term aging. Failures due to mechanical fatigue occur in connectors, including dead-end varieties, subjected to mechanical loads. The cause of this failure mechanism is typically attributed to problems with design, installation, manufacturing, or in-service damage.

Additionally, mechanical failures can be caused by overloading. Overloading occurs due to improper installation (for example, over tensioning the line), using incorrectly rated connectors or due to accidents or natural events such as windstorms and icing events. In general, there appears to be fewer reports of connector failures due to mechanical fatigue and overloading compared to electrical failures.

CONTACT RESISTANCE CHANGERS

Factors that influence rate of change in contact resistance

- Rate of connector joint expansion/contraction due to thermal and mechanical stress
- Rate of conductor and connector oxidation/corrosion
- Temperature of the connector

Source: *Grossmann, Lobl, and Bohme study, "Contact Lifetime of Connections in Electrical Power Systems"*

Although connectors vary in the way they are connected to the conductor, the failure mechanisms appear to be common for all types. The most common failure mechanism appears to be the long-term increase in electrical resistance; however, due to the long-time scales of this process, most connectors are replaced before they fail.

CONNECTOR INSPECTION METHODS

In reviewing the current technologies and the technical literature, four established and widely used inspection methods are prevalent: visual inspection, infrared (IR) temperature measurements, resistance measurements, and radiographic inspection. Each method has its own benefits and shortcomings.

A utility survey has found that some utilities have used the aforementioned inspection methods with various degrees of success. Based on responses, participating utilities considered the in-situ resistance measurement technique as the most accurate

inspection method. However, only a few utilities have used this technique due to its higher cost of implementation. In addition, most utilities that experienced success in identifying degraded connectors used several different inspection methods. The most commonly used included resistance measurement, infrared thermography, and visual or radiographic inspection.

LAB TESTS

Based on the results of the technical literature review and utility survey, researchers chose several condition assessment methods, including alternating current resistance measurements, infrared thermography, direct temperature measurements, and radiographic inspection, for further evaluation in the lab. The purpose was to, first, confirm the findings described in the previous sections and, second, obtain more data on the practical application of the aforementioned assessment methods.

Researchers selected connector test samples from a number of aged field samples based on visual and radiographic inspection. In order to supplement the quantity of connectors in poor condition, additional samples were prepared in the lab to simulate connector corrosion and improper installation. Figure 2 shows a connector sample having several anodized conductor strands in order to simulate deterioration due to oxidation/corrosion.

Researchers evaluated the samples using the aforementioned condition assessment methods and then subjected the samples to fault current tests. Subsequently, the researchers dissected the samples to determine their exact condition and to decide if any correlation existed between the condition assessment results. Researchers made some notable observations during the lab tests.

For example, a considerable challenge in evaluating connector assessment methods lies in obtaining connector test samples that have a range of conditions, from excellent to poor. This process is necessary to properly judge the resolution and effectiveness of a particular test method.

It is also important to have a sufficiently large population size of samples so that the test results will have some statistical significance. A large number of samples will also naturally provide variation in connector parameters that researchers might not have considered during initial planning.

Given that connector failures are a statistically rare occurrence, the main problem of sample collection is finding field samples in worse than average and poor condition (refer to Figure 3 on page 26). These types of samples are crucial to benchmarking the condition assessment methods identified in the study.

RESISTANCE MEASUREMENTS

AC resistance measurements compared well with sample conditions; however, when making measurements on connectors that join conductors of different size, the results had to be interpreted with that fact in mind.

In addition, the placement of the measurement tool should be such that the length of conductor and connector included in the measurement are consistent. Maintenance engineers should choose test procedures and pass/fail criteria carefully, in conjunction with a thorough calibration and validation process using aged field samples or fabricated lab samples of known condition.

DIRECT TEMPERATURE MEASUREMENTS

Direct temperature measurements appear to provide a satisfactory correlation with connector condition. However, this test method did not appear to detect deterioration or resistance measurements. From a practical perspective, this method has the same limitations as resistance measurement as it also requires direct access to

Figure 2

the conductor, making it expensive and time consuming. In addition, environmental conditions, line loading conditions, and connector geometry will influence the temperature difference of measurements and will increase inconsistency of the test results.

INFRARED THERMOGRAPHY

Infrared thermography (IR) inspection appears to be the least expensive and most practical method. However, this technique appears to be only effective for detecting severely deteriorated connectors under favorable environmental conditions, with appropriate line loading, adequate equipment, and properly trained and experienced personnel.

Due to the difficulty in managing the number of variables influencing infrared inspection, this method is unlikely to be 100-percent effective and, therefore, would not be reliable on its own. Researchers observed both false positive and false negative inspection results—even in lab conditions. In addition, this method is less reliable for new connectors and/or conductors because of their low emissivity.

RADIOGRAPHIC INSPECTION

Radiographic inspection is useful in identifying problems associated with improper installation, and since this is one of the more common causes of connector failure, radiographic inspection may have some potential. Additionally, utility personnel can use this method to identify heavy corrosion in automatic splices (refer to Figure 4 on page 28).

However, at this point, utility personnel cannot use radiographic inspection to identify improper crimping of compression connectors or bolted joints not fully tightened. As a result, the technique's application is limited to detecting certain defects such as misalignment or incomplete connector insertion. In other words, utility personnel should consider radiographic inspection only for specific applications.

STUDY CONCLUSIONS

Based on the information gathered in the technical literature, the results of the utility survey and the observations from the tests performed in the lab, AC resistance measurement appears

Cross-section of an automatic splice with heavy corrosion

Figure 3

to be the most reliable connector inspection method currently available. However, the major drawback is the significant cost and time associated with this method. Other assessment techniques can be effective for specific applications. An approach that combines several assessment methods such as AC resistance, direct temperature measurements, and infrared temperature measurement would be the most successful.

Given the large number of connectors in the distribution system, it would be cost prohibitive to perform resistance measurements on all connectors or even a significant portion. An inspection approach that combines several of the discussed methods to sample the population and provide statistical input for analysis based on a reliability criteria and lifecycle cost analysis would likely be the most successful. An appropriately structured program that uses documented guidelines and procedures together with a data management system will provide a clearer picture of connector condition in the power grid. Based on the results of the utility survey, it appears that several utilities are achieving success with this approach.
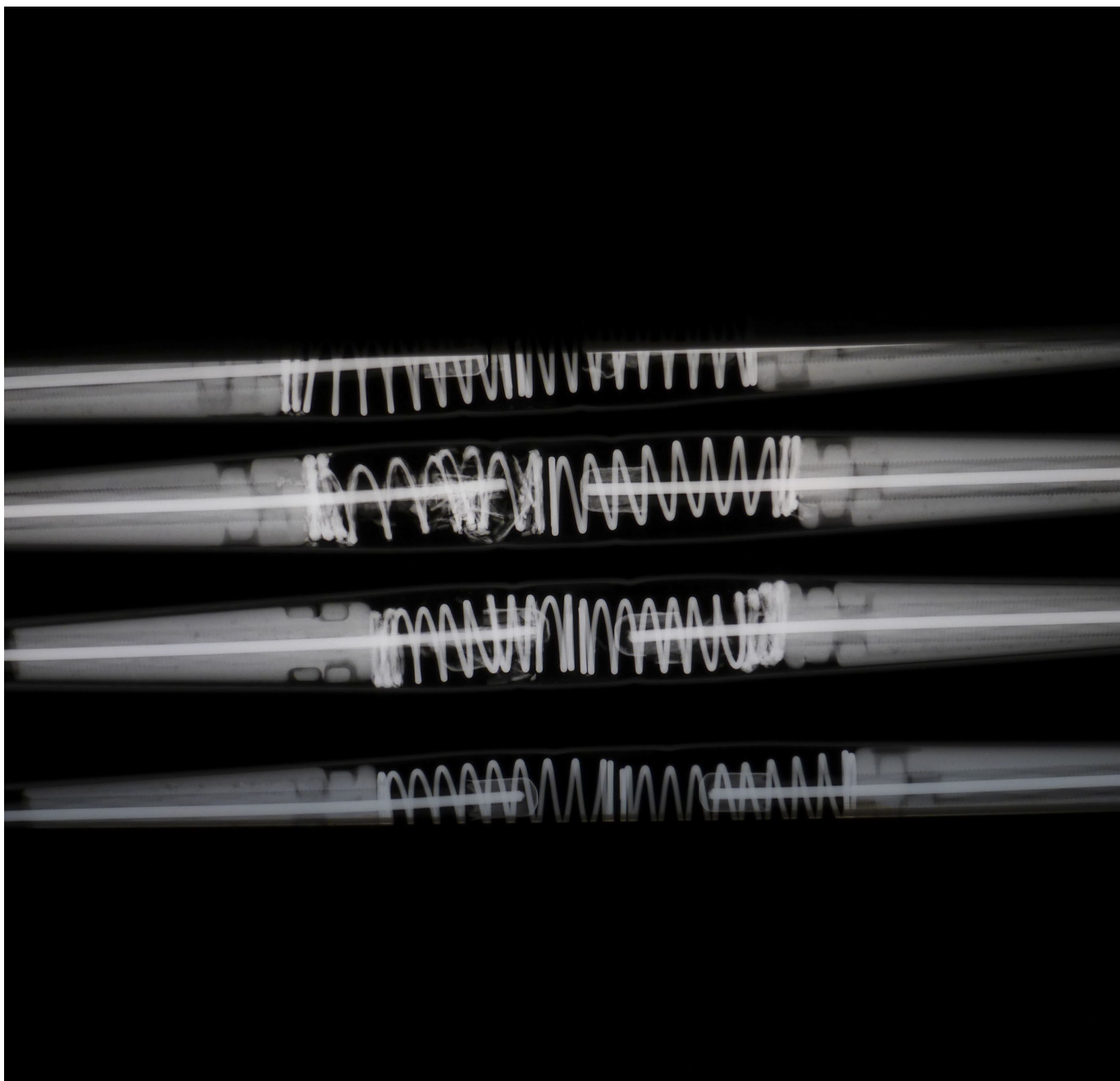
A more commprehensive investigation evaluating the effects of resistance measurements on different connector types is necessary.

Researchers provided the following additional conclusions and recommendations based on the results of the laboratory tests, utility survey, and technology review.

1 A need exists for a comprehensive field study of the AC resistance test method, supported by statistically significant field data to give utilities confidence to utilize this assessment method.

2 An inspection using infrared thermography is only effective in detecting severely deteriorated connectors under favourable environmental conditions, with appropriate line loading, adequate equipment, and properly trained and experienced personnel.

3 A more comprehensive investigation evaluating the effects of resistance measurements on different connector types is necessary.

4 The condition assessment methodologies evaluated in this study are applicable to connectors used in both the distribution system as well as the transmission system. Electric utilities can further develop their condition assessment methods more effectively by pooling resources from both systems together. **ET**

Alex Babakov, Chris Morton, and Hong Li, are electrical engineers working with Powertech Labs. Alex works on projects and research activities specializing in testing and condition assessment of T&D utility equipment. Chris specializes in laboratory testing and failure analysis work on electrical equipment. Hong Li has extensive experience and knowledge in asset management of T&D structures and components. Robyn Pascal is the Program Manager for Distribution programs at CEATI International.