Connectors — The Weak Link

Increased operating temperatures are cause for concern

By Carl R. Tamm

When considering increased conductor temperatures, numerous issues are of concern, particularly with the dynamic effects on electrical connectors when suspended overhead aluminum conductors are operated at high temperatures, specifically above 93˚C (200˚F).

The majority of line hardware associated with suspension and support of bare aluminum overhead conductors has been designed for a maximum operating temperature for conductor of 70–75˚C. However, due to load growth and demand, as many utilities approach conductor operating temperatures of 90–95˚C and beyond on standard conductors such as aluminum conductor steel-reinforced (ACSR) and all aluminum conductor (AAC), serious questions must be answered.

Mother Nature has conveniently drawn a line in the sand for us, and the magic number is 93˚C (200˚F). This is the temperature associated with the onset of long-term annealing of the tempered aluminum alloys used in the manufacture of most connectors in this industry. Increasing demand for electrical power, coupled with deregulation in the electric utility industry, has nearly exceeded the capacity of the transmission and distribution infrastructure in the United States today. In some areas, critical limits are repeatedly exceeded, resulting in rolling brownouts. The time and expense of developing new rights-of-way for more transmission lines is forcing a review of the present system. In the interim period, many utilities have increased their current load on existing lines, thereby increasing operating temperatures beyond the 90˚C range.

As this trend continues, numerous questions arise as to what the "real" limits are. The following points are a few of the issues of concern.

Conductor

The predominant conductor in use, and consequently in question, is ACSR. In a properly sagged conductor at normal operating temperatures in the range of 40–60˚C, the aluminum stranding of ACSR conductor carries approximately 40–60 percent of the tensile load, depending on conductor size and construction. The balance is carried by the steel core. Connectors designed for use with ACSR are designed with this stress distribution in mind, where the steel and aluminum components are sized accordingly.

It is well known that hard drawn or tempered aluminum alloys, whose mechanical properties have been enhanced by those processes, begin to anneal at 93˚C producing a cumulative effect on the material properties. The difference in tensile strength from a tempered or hard drawn condition to a fully annealed condition is typically on the order of 50 percent to as little as 30 percent of the original design. Thus, an aluminum component originally designed and manufactured to endure something on the order of 27,000 lbs will only support approximately 8,500 lbs in its annealed condition.

Obviously, AAC, aluminum conductor alloy reinforced (ACAR), and all aluminum alloy conductor (AAAC), not having the steel member to assist their support, are even more prone to sag effected by thermal stress than is ACSR.

Connectors

With the exception of automatic splices, most electrical connectors rated for full tension applications on ACSR conductor utilize a separate gripping means to provide a purchase of the steel core member. These are known as conventional or 2-die compression connectors, and single-die compression connectors.

The conventional or 2-die compression connector design for full tension consists of an aluminum body component and a separate field-installed steel eye component, which is compressed directly onto the steel core of the conductor.

This design does not rely on any aluminum component to carry the tension load supported by the steel core of the conductor. Normal sag tensions will rarely exceed the breaking strength of the steel core in normal conditions. Therefore, one may speculate that loss of strength of the aluminum is less likely to result in a catastrophic failure of this type of connector.

Installing ClampStar® rigid type shunt over 795kcmil splice, live, HotSticks, 34.5 kV.

The gripping unit serves as a filler component, and is designed to grip the steel core of an ACSR type conductor. This is an aluminum component, which is placed over/on the exposed core of the conductor, and then, along with the conductor, inserted into the body. The body is then crimped onto the gripping unit with a "circular die" resulting in an elliptical shaped crimp section. The crimping is continued to the end of the connector, completing the process.

There exists an uncrimped section of aluminum between the factory crimp that secures the steel eye component of this connector and the field-installed crimps. This portion of the aluminum tubing supports the entire tensile load. Operating the connector at temperatures above 93˚C will result in annealing the aluminum components of this style connector, thus risking mechanical failure. The tempered alloys used in most connectors have a strength 2.5 to 3 times greater than the annealed alloy. When 66 percent of the strength is lost from a connector, you may confidently expect it to fail.

Bolted connectors or strain clamps provide a range of conductor sizes they will accommodate. These are rarely, if ever, rated for full tension. While most will provide full tension or (95 percent of the conductors' rated breaking strength [RBS]) on the smaller conductors in their size range, it is rare that they will support full tension on the larger conductors in their respective size range.

Bolted connectors or "strain clamps" along with "automatic splices" do not have separate gripping means for purchase of the steel core of a non-homogenous conductor. They rely entirely upon compression of the aluminum strands onto the steel core to create sufficient purchase or frictional engagement with the steel core to support the tensile load of the steel core in combination with the tensile load of the aluminum stranding.

Obviously, operating the conductor above annealing temperatures, thereby softening the aluminum stranding, will affect the ability of bolted connectors and automatic splices to effectively maintain secure purchase of the steel core.

The Electrical Interface

Electrical connections, other than welds, have a finite life, and will eventually fail. The interface of an electrical connection is a dynamic structure. Interaction on the atomic level is quite dramatic. Thermal gradients in microscopic asperities continuously approach and occasionally exceed the melting point of the base materials. This results in rupture, extinction, and subsequent re-establishment of these microscopic asperities (the actual points of electrical current transfer), intermetallic diffusion, and continual change (increase) in the resistance of the connection. Increasing current, thus increasing thermal energy in the connection, serves to aggravate the condition, thereby accelerating the eventual failure of the connection.

Aged connections are particularly susceptible to premature failure when subjected to substantially elevated temperatures. As previously mentioned, electrical connections, other than welds, have a finite life and will eventually fail. Properly applied and properly installed, electrical connectors are typically designed to serve several decades. The overwhelming majority of connectors in the utility industry today were designed to operate on 70–75˚C conductors (30˚C rise over a 40˚C ambient). The connectors, because of their greater mass and greater surface area, will exhibit surface temperatures below that of the conductor; however, the temperature at the electrical interface will be substantially higher. (Once a connector exhibits surface temperatures that equal or exceed the conductor temperature on which it is installed, it is considered to have failed).

Lack of care in preparation is the predominant cause of premature failure of electrical connectors, particularly aluminum connectors. The cleaning of both the conductor and the connector is particular and imperative, and unfortunately, often is not performed to reasonable expectations. Failed connectors have been found with dirt and soil in them! Any foreign material will further degrade the connection. Connectors that are properly cleaned and installed may operate successfully at temperatures above their design limits, but lack of proper preparation and poor construction methodology greatly diminishes their prospect to do so.

Inhibitors

Traditional mineral oil-based inhibitor compounds will not tolerate extreme temperatures. The base mineral oil of such inhibitors begins to breakdown at 162˚C. While the connector may appear to be operating far below that threshold, the electrical interface is operating at much higher temperatures than may be detected on the surface of the connector. The design parameters assigned engineers in the early part of the 20th century was to design a connector for a 30-year life expectancy, operating at a maximum conductor temperature of 70–75˚C. Empirical data has supported life expectancies of 40–70 years for electrical connectors applied to conductors operating at maximum temperatures of 70–75˚C. The vast majority of the North American power grid was built between the end of World War II and the 1970s. Doing that math is easy — most of our grid is now 40-70 years old!

A single die compression deadend failure due to excessive heat on conductor.

The increase of current density resulting in conductor operating temperatures in the range of 90˚C and higher, presently adopted by most utilities, has resulted in an ever-increasing number of reported connector failures. Most of these prove to be related to the inevitable breakdown of inhibitor compounds under extreme thermal conditions, and a lack of inhibitor having been used (poor installation practice).

Great concern exists for connectors that were installed prior to year 2000, as the inhibitor used was almost certainly mineral oil-based; operating beyond their design parameters of 75˚C conductor temperature will accelerate the deterioration of these inhibitors.

Synthetic inhibitors that operate with much greater success in extreme thermal environments have been developed. Such inhibitors are required for applications on high temperature/low sag (HTLS) connector systems and are typically recommended for all applications because of their superior stability.

Liability

Overhead electrical conductors have a potential to fail. Because they are suspended overhead, their failure commonly results in their coming to rest on the ground. Apart from the mechanical impact, the propensity for these energized components to cause severe damage, serious injury, or death is unmistakable.

It is important to understand that present industry standards do not subject connectors that have been through heat cycle testing to post mechanical stress requirements. The mechanical requirements are tested on new connectors, which have not been subjected to thermal cycling. The test temperatures to which connectors are subjected during these tests, such as ANSI C119.4 - Class A or Class AA, do not qualify the connectors for operation above 93˚C.

While many lines exist today which have been subjected to exceedingly high temperatures and have not yet failed, the propensity for them to fail has been substantially increased due to the thermal stress to which the conductor and connectors and suspension systems have been subjected.

Special conductors such as HTLS have been developed, along with the associated connectors and suspension supports appropriate for use at conductor temperatures up to 250˚C. Prudent design practice for increasing line capacity is to utilize these materials when building new lines, rather than subject traditional materials to thermal stress beyond their design limits.

While the question may be repeated over and over, and study after study may be conducted to determine at what thermal limits aluminum conductors, both homogenous and non-homogenous, and aluminum-bodied structural connectors may be operated, the true answer is provided by the material properties. For those still seeking this answer, Mother Nature has conveniently drawn that line in the sand, and that mark is 93˚C, particularly for connectors older than the turn of the century. **UP**

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