Connectors – The Weak Link

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°C to 75°C. However, as many utilities approach conductor operating temperatures of 90°- 95°C and beyond, on standard conductors such as ACSR and 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 right-of-ways 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. This conductor is so named, Aluminum Conductor / Steel Reinforced because the steel acts in just that manner, reinforcing the tensile strength of the aluminum. In a properly sagged conductor at normal operating temperatures in the range of 60°C to 75°C, the aluminum stranding of ACSR conductor carries approximately 40% to 60% 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% to as little as 30% 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 8500 lbs. in its annealed condition.
As the conductor increases in temperature, the aluminum, expanding at a faster rate than the steel, will eventually transfer the mechanical tensile load to the steel. This can continue to a point where the aluminum is said to go into compression. As the aluminum expands and the tensile increases on the steel core, the sag of the conductor increases significantly. If it were allowed to heat enough, it would actually transfer all the stress to the steel core, however dangerously low sag clearances occur as we approach that stage, and the current is controlled by design to prevent this occurrence. If such extreme sags, produced by high temperatures do occur, the conductor will not return to the original sag upon cooling. Each subsequent subjection to thermal stress will further aggravate the condition.

Obviously, AAC, ACAR, and AAAC, not having the steel member to assist their support, are even more prone to sag affected by thermal stress than is ACSR.

An additional critical element which must be considered is the effect of current density and high conductor temperatures regarding corrosion of the steel core of ACSR conductors. Such conductors which might normally provide a service life of 75 to 100+ years when operated within their intended design parameters of 50°C to a maximum of 70°C will suffer accelerated deterioration when operated at higher temperatures, especially those exceeding 100°C.

This service life could be reduced to as little as 7-10 years when subjected to operating temperatures in the 125°C to 150°C range.

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.

Single die compression deadends and splices rely on an aluminum component to carry the line tension.
The gripping unit, shown in the plastic bag in the photo above, 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% 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 which they will accommodate. These are rarely, if ever, rated for “full tension.” While most will provide “full tension” or (95% of the conductors 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°C to 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 which 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. Empirical data has supported life expectancies of 30 - 50 years for electrical connectors applied to conductors operating at 70°C to 75°C. The increase of current density resulting in conductor operating temperatures in the range of 90°C, presently adopted by most utilities, has resulted in an 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 which were installed prior to year 2000, as the inhibitor used was almost certainly mineral oil based, and operating beyond their design parameters of 75°C conductor temperature will accelerate the deterioration of these inhibitors.

Synthetic inhibitors have been developed which operate with much greater success in extreme thermal environments. Such inhibitors are required for applications on HTLS connector systems, and typically recommended for all applications because of their superior stability.

**Mitigation Measures**
Understanding that there are multiple reasons that existing lines, built before 2000, have potential risks of connector failures when operated above 90°C, prudence dictates that a means of mitigating this failure potential must be employed. The easiest and fastest, and typically most economical method of protecting the system is to place a shunt over the connectors. It is important to recognize, particularly with single die compression connectors, or automatic style connectors, that the mechanical integrity may be compromised. Therefore, it is recommended that a device be employed which restores both electrical and mechanical integrity to the system.
Installing ClampStar® flexible type shunt over 795kcmil splice, live, barehand, 115kV

Installing ClampStar® flexible type shunt with HotSticks

Installing ClampStar® rigid type shunt with HotSticks

Installing ClampStar® rigid type shunt over 477kcmil automatic splice, live, gloves, 34.5kV

Installing ClampStar® rigid type shunt over 795kcmil splice, live, HotSticks, 34.5kV
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, being energized, the propensity 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, known as “High Temperature – Low Sag” (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 a line in the sand, and that mark is 93°C.

Our employers may have economic and service goals in mind; however, we must not forget that our first responsibility is to the general public and their safety. Unaware of any potential danger, children and adults alike pass underneath suspended conductors, day in and day out – ultimately trusting the professionals in the electrical industry to make the wise and safe decision.