INNOVATIONS FOR IMPROVED TRANSMISSION SYSTEM RELIABILITY AND ASSET UTILIZATION

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Abstract:

Utilities are facing declining usage and revenues, while competition from non-traditional energy providers increases. To stay competitive, utilities must reduce cost while improving utilization and reliability . To achieve these goals, utilities are embracing the innovative use of materials in the design of conductors.

There has been rapid growth in sensor and communication technologies, sometimes referred to as the "Internet of Things" or "Industrial Internet of Things". This has enabled distributed, wide area monitoring of assets, which, when combined with advanced analytics, enables condition based maintenance to reduce cost. It also gives vision into the actual operation and condition of an asset, thus allowing for higher, more reliable utilization.

Aging transmission lines are being called upon to meet ever higher power transfers. Increased power flow can cause elevated conductor temperatures which can degrade conductors and hardware, or cause operational safety issues. This can lead to load curtailments, system failures and may require extensive line rebuilds. The use of advanced conductor types, including innovative designs using light weight, high tensile carbon fiber, offer lower cost and more flexible operating options for utilities.

This presentation will discuss how these new technologies can be implemented to improve reliability and utilization of the transmission system. It will cover different rating methods used around the world, technologies for monitoring asset health and operation, predictive maintenance usage and best practices for their selection and application.

I. INTRODUCTION

The generation, transmission and distribution of electric power started out as one of the most innovative and dynamic industries of its time. Most power engineers know the historical battle between Thomas Edison's DC (Direct Current) system and George Westinghouse's AC (Alternating Current) system. Over a period of 10 years from 1885 to 1895 the fundamentals of the power system we use today were developed, with the modern AC circuit breaker added in 1924. There have been improvements to these basic devices over the years, and new devices added to improve the system, but the basic structure of the power system remained the same for many decades.

Approximately 100 years later, from 1985 to 1995, the seeds were planted for the next revolution in the power industry with the introduction of the PC (Personal Computer). The PC and the technology it is based on provided the catalyst for the automation of the equipment used in the power delivery system. The use of the PC changed the way society learns, communicates and interacts, both individually and with businesses. It has led to an expectation of faster service delivery, more choices over energy usage and more information – all available when desired. Combined with the desire to reduce our carbon footprint, this has led many to question the fundamental design and operation of the electric grid.

The utility industry has been slow to react to many of the signals that changes were needed. As an industry whose priority is to provide power reliably and affordably, stability requires that any innovations be fully evaluated. This puts the industry in constant conflict with the pace of advancement in technology today. Our challenge today is to determine what new technologies are adopted and how to responsibly integrate these into the grid in a timely manner.

To do this will require a different grid design. New technologies and materials must be integrated. This paper will discuss two areas, monitoring technology and new materials used in overhead conductors, and their application to the grid.

II. USE OF ADVANCED MATERIALS IN OVERHEAD CONDUCTORS

A. History of Conductor Development

Early overhead transmission conductor was made of copper strands because of the high conductivity of copper. However, the conductivity benefits of copper are outweighed, literally, by its weight. Aluminum possesses a conductivity-to-weight ratio twice that of copper and its strength-to-weight ratio is 30% greater than copper. Aluminum 1350-H19, once known as "EC" grade, has been the aluminum of choice for decades. The "H19" designates the tensile, or "Hardness", requirement. For overhead conductors H19, or "Extra-Hard", is used.

The first conductors used were solid conductors. These were relatively stiff, making them difficult to work with, and were limited to smaller sizes. The stranding of several smaller size "wires" into a "stranded conductor" resulted in a product that was more flexible. The first stranded All-Aluminum Conductor (AAC) was a 7-strand "transmission" conductor installed in 1899. AAC is still used today, primarily for short span distribution applications.

As the demand for power and transmission distances increased, higher strength-to-weight designs were needed. In 1907 the first composite conductor, Aluminum Conductor Steel Reinforced (ACSR) was introduced. ACSR is comprised of 1350-H19 aluminum stranded over a stranded, coated steel core that provides strength reinforcement. ACSR quickly became the dominate conductor used in the United States (US).

The next "innovation" in conductor design was the introduction of aluminum magnesium- silicon alloy for stranded conductors in 1939. With the outbreak of WWII, steel was in short supply. All-Aluminum Alloy Conductors (AAAC) designed to be "equivalent" in performance to smaller distribution sizes of ACSR saw widespread adoption. Combining a stranded steel core with aluminum alloy strands, Aluminum Alloy Conductor Steel Reinforced (AACSR), gave a superior design for very long span applications, for example, river crossings. Many different aluminum alloys are in use around the world.

B. Introduction of HTLS Conductors

There were no major innovations in conductor design for over 35 years. In 1973 Reynolds Metals introduced the first high temperature, low sag (HTLS) conductor, Steel Supported Aluminum Conductor (SSAC), which is known today as ACSS (Aluminum Conductor Steel Supported). This conductor was designed for operating temperatures up to 200°C (verses 75°C for ACSR and AL Alloy) to deliver higher power flows on transmission lines for a given structure design.

In the early 1990's, higher performing ACSS and ACSS-TW conductors were introduced. The use of MA (Mischmetal, class A coated) steel core wires allowed for conductor operation up to 250°C without the loss of strength associated with equivalent aluminum clad steel cores. The "TW" denotes an aluminum "Trapezoidal Wire", also known as shaped wire. By shaping the aluminum strands, the void areas from stranded round wire, "interstices", are reduced.

ACSS-TW comes in two configurations: "diameter equivalent" or "area equivalent" to a round wire construction, see Figure 1.

- Area equivalents give approximately equal power transfer in a smaller cross-sectional area, thus reducing wind drag and ice buildup. This reduces structure load in areas prone to these conditions.

- Diameter equivalent designs are favored as they deliver more power for a given conductor size. This reduces loses and provides increased power delivery for a given conductor diameter and structure design.

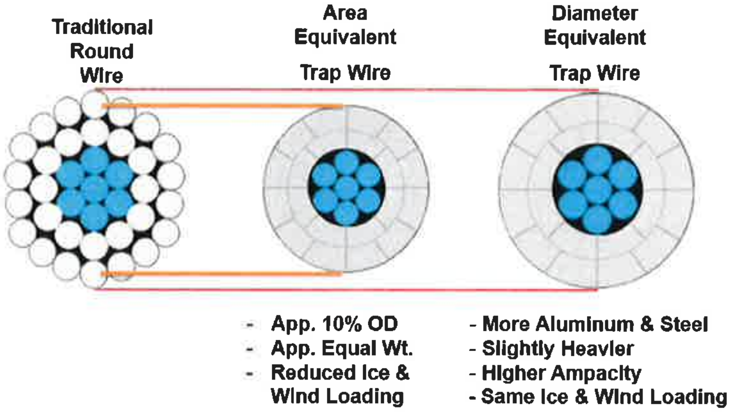

Figure 1. ACSS-TW Configurations

Adoption of ACSS in the US was slow due to a lack of understanding of how to apply the conductor, design requirements which unduly penalized its installation tensions. tThe ease of obtaining rights-of-way's (ROW's) to build new lines discouraged innovation, and financial models favored building bigger lines with less efficient conductors. Today ACSS is the primary, and in some cases the sole, transmission conductor used by the majority of utilities in the US. Tens of millions of feet of ACSS and ACSS-TW have been installed around the world, making it the most widely use HTLS conductor.

In 2005 two new HTLS conductors were introduced: ACCC® (Aluminum Conductor Composite Core) and ACCR (Aluminum Conductor Composite Reinforced). ACCC is comprised of a single, carbon fiber matrix rod with trapezoidal (TW) fully annealed aluminum strands. The ACCR conductor is comprised of a metal matrix (aluminum oxide fibers embedded in high purity aluminum) stranded core with high temperature aluminum-zirconium alloy wires stranded on it. Since their introduction in 2005 several additional stranded carbon-fiber, polymer matrix core (ACPR) conductor designs have been introduced.

C. Mechanics of HTLS Conductor Operation

While HTLS conductors vary in their composition, they all function based on the same principle – the reduction of line sag due to thermal loading using core materials with lower thermal elongation than their conductive aluminum or aluminum alloy strands.

Despite their simple appearance, all composite conductors (ACSR, AACSR, ACSS, etc.) are complex, dynamic systems that respond differently to thermal and mechanical loading. Through the combination of differing materials for the core and conductive strands, along with varying manufacturing techniques, conductor designs can be optimized for differing operating environments. This makes comparing these conductions difficult and confusing at times.

For the purposes of this paper, the conductor mechanics will be simplified to a conceptual level. For a more detailed understanding of these concepts, two resources are The Southwire Overhead Transmission Manual and the CIGRE Green Book on Overhead Transmission.

D. Thermal Response of HTLS Conductors

Overhead transmission conductors experience two types of "loadings", thermal and mechanical.

- Thermal loadings are the result of the power flow imposed on the conductor, under the current environmental conditions and the electrical characteristics of the its composite materials.

- Mechanical loadings are tensions imposed on the conductor due to the conductor's weight, its installation tension and environmental factors such as wind and ice.

All composite conductors, being composed of two dissimilar materials, respond differently to thermal loading. For overhead transmission conductors, the key material property to be considered is the coefficient of linear thermal expansion. Table 1 shows typical linear thermal coefficients for the materials used in HTLS conductors.

Material	Per °C x 10^{-6}
Aluminum & Aluminum-Alloys	23.0
Coated Steel	11.5
Metal Matrix Composite (Typical)	6.3
Carbon Fiber Polymer Composite (Typical)	1.7

Table 1. Typical Linear Thermal Expansion Coefficients of Conductor Materials

This effect has been well documented in ACSR conductors. As the name suggests, typical transmission conductors rely on the extra-hard H19 strands to carry 20% to 50% of the applied mechanical load, with the steel core providing reinforcing strength, over the "normal" operating range of the conductor. Thermal response over this range is calculated as a composite ("blended") linear thermal coefficient proportional to the steel-to-aluminum ratio.

From the table above, aluminum expands at roughly 2 times the rate of steel. Therefore, as the conductor heats, the aluminum strands elongate and eventually a majority of the load tension is transferred to the steel core. This point is commonly referred to as the "Knee-Point" temperature of the conductor. The knee point temperature is affected by steel-to-aluminum ratio of the conductor, but generally occurs between 70°C and 100°C operating temperature. Over time, as the aluminum strands elongate due to the initial tension and conductor weight, a process called "Creep", the knee-point shifts transferring more of the load tension to the steel core, as shown in Figure 2.

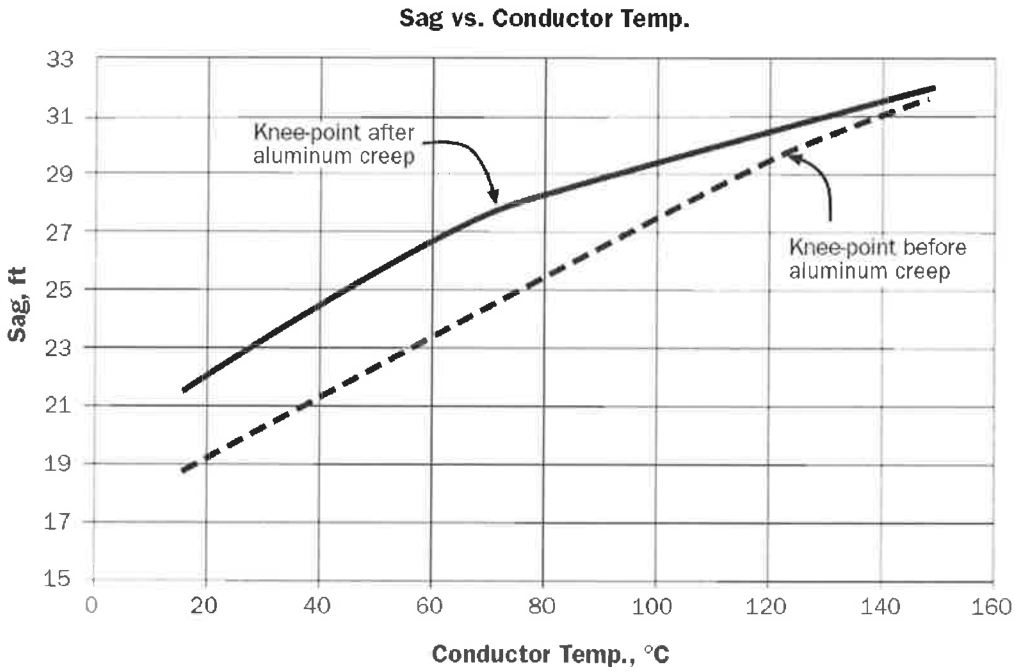

Figure 2. Knee-Point Temperature as Affected by Elongation of Aluminum Strand

Once the load transfers to the steel core, the thermal elongation of the conductor increases at the rate of the steel only. This lower expansion rate results in a slower increase in sag as the conductor temperature increases over the recommended operating range of 75°C operational (also called "every day") to 100°C emergency temperature.

At higher temperatures, above 100°C, the rate of sag resulting from thermal loading increases due to further elongation of the 1350-H19 extra-hard aluminum or aluminum alloys. The high aluminum temper results as the conductors do not yield, thus imparting additional compressive tensile force on the steel core. Designs using fully annealed aluminum do not experience this affect, as this low temper aluminum strands expand radially before applying significant compression to the steel core.

ACSS takes advantage of the lower yield strength of the fully annealed 1350-O aluminum to shift the load to the core much sooner. As the conductor is pulled to sagging tension, depending on the conductor temperature (usually close to ambient), the aluminum readily elongates, transferring the mechanical load to the steel core. This affect is more pronounced at low temperatures and occurs during the first thermal cycles of the conductor. By transferring the load to the steel core early, ACSS has lower thermal sag over its full temperature range, 200°C to 250°C depending on the manufacturer.

The transfer of tension to the steel core early is critical to the performance characteristics of ACSS conductors. Specifications for "O" Temper (1350-O) aluminum allow for a wide variety in performance of ACSS conductors. This is most evidenced by the manufacturing method for the conductor. There are two generally accepted methods for making ACSS:

- Batch Annealing – In this method the conductor is stranded using 1350-H19 then the full reel is heat treated in an oven to the proper temper. This results in a "tighter" stranding that improves the installation characteristics of the conductor, reducing installation time and cost. Batch annealing also allows the manufacturer to deliver a consistent, fully annealed product thus improving its performance. However, it is a more expensive process, resulting in a slightly higher up-front cost.

- Pre-stranding or "bobbin" annealing – In this method the aluminum is annealed (the heat-treating process by which the temper is lowered) prior to stranding. This results in a generally lower performing conductor:
    - The final stranding process is complicated as the fully annealed aluminum tends to elongate ("stretch") in the strander.
    - This results in a looser strand., which can cause installation problems such as "Birdcaging' (the balling of aluminum strands going into stringing blocks) and increases the temper of the aluminum strands.
    - This also increases the aluminum temper to the less ductile end of the "O" temperature range, resulting in less load transfer to the steel core during installation.
    - This increase in temper results in a higher conductor sag compared to batch annealed ACSS, see Figure 3. In fact, batch annealed ACSS with lower strength steel cores can perform as well as bobbin annealed ACSS with more expensive, higher strength steel cores, thus providing lower cost solutions.
    - This process allows the use of lower thermally performing coatings on the steel core wires, so it is important to specify the proper steel coating to ensure long term product life over the rated operating range of the conductor.

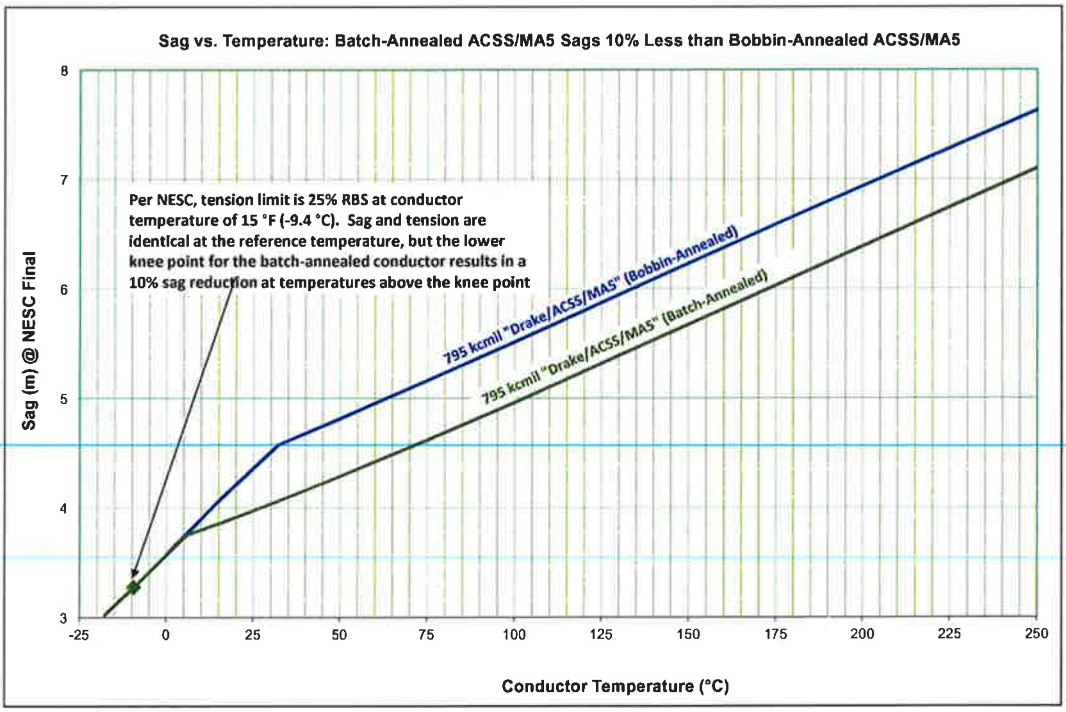

Figure 3. Performance variation between differing manufacturing methods.

Another benefit to the reduction of tension in the aluminum strands in ACSS is the increased self-damping characteristics of the conductor. Testing has proven the superior energy dissipation capabilities of ACSS conductor, see Figure 4. This decrease in the conductor's susceptibility to aeolian vibration can safely allow a slight increase in line tension compared with other conductors. Depending on the line design, this can greatly reduce the final sag of the conductor.

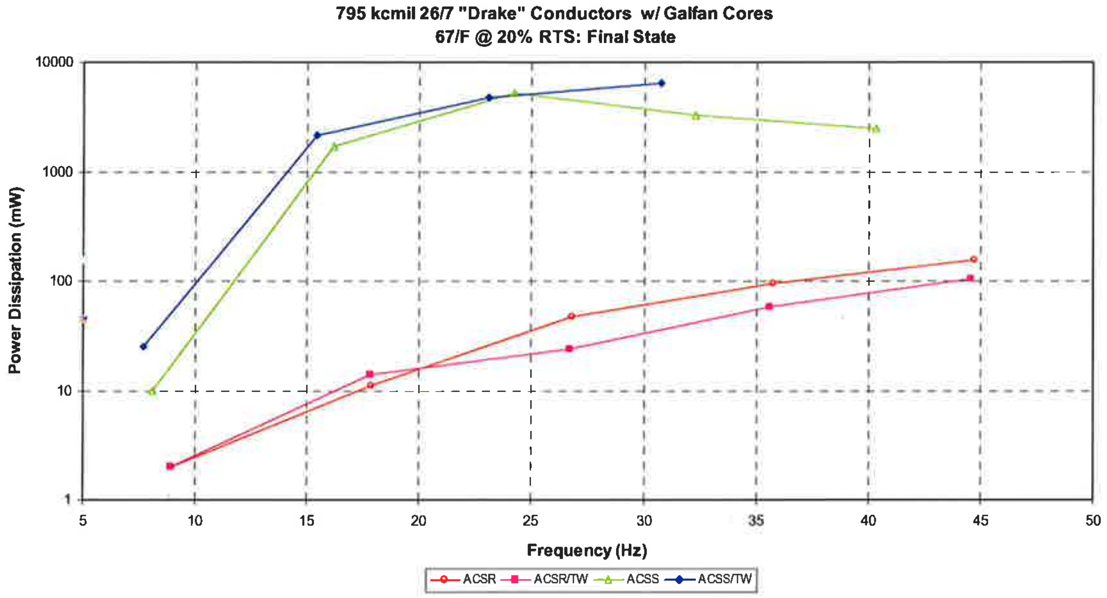

Figure 4. ACSS vibration performance verses ACSR, approximately 10x increase in power dissipation.

Carbon fiber polymer matrix and aluminum metal matrix HTLS conductor work on this same principle of mitigating thermal expansion. From Table 1, the thermal expansion rates of these materials are much less than that of steel. There are many combinations of aluminum tempers and alloys used in HTLS composite core conductors, resulting in even greater differences in the composite thermal expansion rates.

E. Mechanical Response of HTLS Conductors

The mechanical response of the three HTLS conductor types varies greatly based on the conductor design. There are two components to the mechanical response:

- Plastic deformation – the permanent elongation of the material due to mechanical "stress" after the stress is removed.

- Elastic deformation – the recoverable elongation of the material after the mechanical stress is removed.

The mechanical response is generally referred to as the "modulus" of the conductors. A higher modulus means the conductor has less elongation under mechanical load. The modulus for a conductor is highly dependent on the materials and the ratio of core-to-conductive strands.

The topic of mechanical response is beyond the scope of this paper. The reader is encouraged to contact the conductor manufacturer to determine the proper HTLS conductor design for their application.

F. Example Comparison

As mentioned previously, conductor performance varies greatly among differing conductor constructions. In Figure 5 the performance characteristics of several conductors is shown. The assumptions for the underlying calculations are shown in the figure. In this example:

- 795 kcmil ACSR "Drake" is used as the reference conductor.
- Three 795 kcmil ACSS round wire conductors are shown demonstrating the differences in batch annealed and bobbin annealed products.
- Two 795 kcmil 7-strand, carbon fiber, polymer-matrix composite core conductors as denoted by "C7®". The ZTACCR denotes an Aluminum Conductor, Composite Reinforced construction with a high temperature "ZT" aluminum alloy. The ACCS denotes an Aluminum Conductor, Composite Supported construction with fully-annealed 1350-O aluminum.

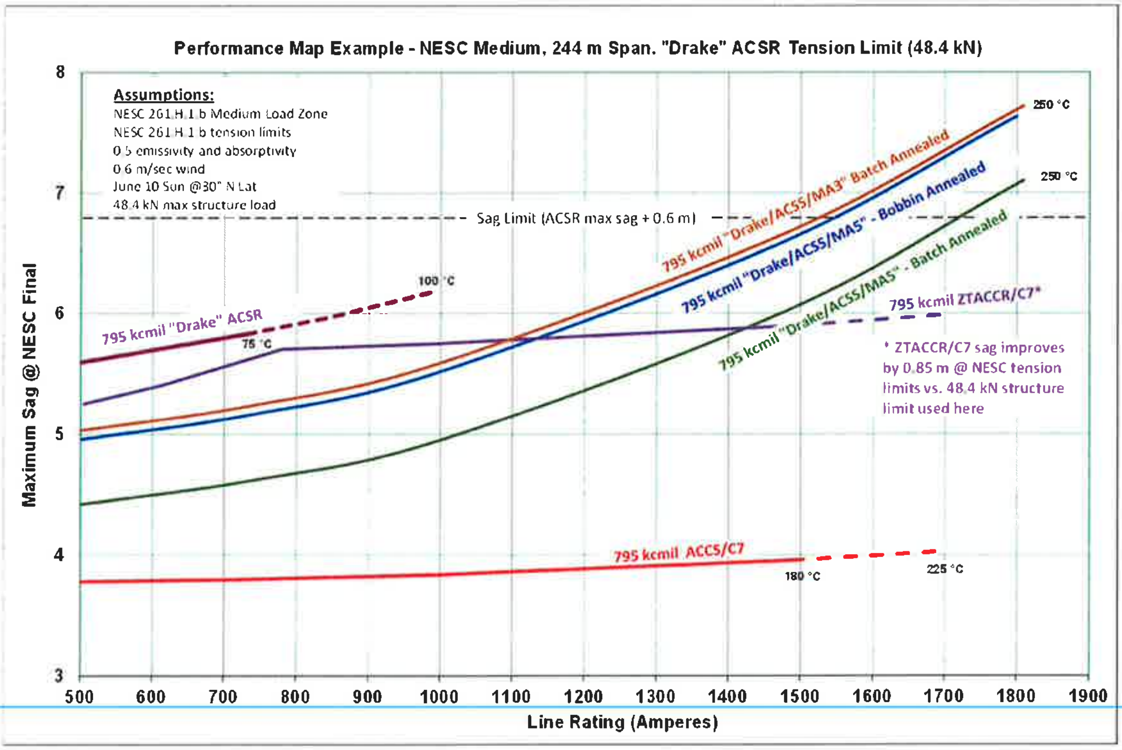

Figure 5: Performance map for several HTLS conductor designs.

In this figure there are obvious performance differences between the differing conductor designs, and significant cost differences in the products. Based on the requirements of the applications, the engineer should select a conductor with the proper balance of cost and performance.

III. APPLICATION CONSIDERATIONS

HTLS conductors were initially designed for reconductoring applications. They were intended to be installed on existing structures to increase power flow. Since their introduction, their benefits have led utilities to incorporate some designs into new construction, even becoming the standard conductor for transmission projects.

HTLS conductors work best on lines with intermittent, heavy power flows. Lines such as inter-grid tie lines and connections to renewable energy sources were some of the first applications on new builds. When properly applied, HTLS conducts can reduce line design cost by carrying everyday power flow requirements at low operating temperature while providing the flexibility to carry higher power flows without violation clearance requirements.

As utilities in the US began using more ACSS, and primarily ACSS/TW, the first HTLS conductors, they realized this flexibility also added robustness to new line builds. Grid design requires lines to be capable of absorbing load when other critical grid elements fail, referred to as N-1 or N-2 contingencies. With conventional conductors, this requires oversizing the conductor for these infrequent events, resulting in larger structures, foundations and costs. Using ACSS/TW, utilities found they could use their standard, or smaller, structures in new line builds which more than offset the incremental up-front conductor cost.

There are several considerations which affect the selection and application of HTLS conductors:

- Up front, purchase price of the conductor verses its overall value.
- Compartmentalization of utility functions and competing departmental goals make valuation of the wide-ranging benefits difficult.
- Lack of understanding of how to design with and apply them.
- Risk aversion to using new technology
- Mechanical loading and environmental conditions
- Economics of line loss

It is critical to involve the conductor manufacturer early in the design process to capture the full benefits of using these conductors. Typical design constraints may not be applicable to these conductors, so small changes in the design parameters can result in large savings in overall line design and life cycle cost of the line.

Because of the varying designs and performance characteristics of these conductors, the designer should always request design information for any conductor being considered. There are generic conductor models available, but these should be used with caution. Even the performance of established products, such as ACSS, can vary significantly among manufactures so it is critical to use verified conductor models from the manufacturer.

IV. CONCLUSION

The use of new technologies in the design, operation and maintenance of transmission assets is increasing. The cost benefits of using information for proactive maintenance is proven to reduce maintenance cost, reduce operational downtime, improve safety and improve customer satisfaction compared to the run to failure approach. However, issues with transmitting the data back to a central system still limit the widespread deployment of these technologies on transmission systems.

New conductor types can be used to increase the flexibility and robustness of system operation for a nominal increase in investment. At a minimum, critical lines connecting that are required to carry high power transfers, albeit infrequently, can be implemented at a lower cost than traditional methods.

As with any asset, conductor selection should be made taking into consideration the utility's operational and maintenance methods. It is critical to bring the conductor manufacturer in early in the design process to capture the full benefit of these new conductor types.