Transmission Conductors - A review of the design and selection criteria

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Introduction:

Remarkable changes have occurred in the utility industry since Thomas Edison began the commercial sale of electricity more than 100 years ago. One area that has undergone extensive change has been in the types of conductors available to transmit and distribute electricity. Copper was the first metal used to transmit electricity during the development of the electrical industry in the early 1880's. A review of the selection criteria for transmission and distribution conductors, prior to the extensive use of aluminum, suggests copper conductor sizes were being determined primarily on the basis of mechanical considerations because of the disproportional high conductivity of copper relative to its strength-to-weight ratio. Conductors were, therefore, generally larger than required from the standpoint of efficient electrical conductivity. Because of the weight, span lengths were short, thus increasing the overall cost of the transmission line.

Shortly before the turn of the century, aluminum began to replace copper as the metal of choice for transmission and distribution conductors. The first transmission line using aluminum conductors was constructed in California in 1895, quickly followed by a second line in 1898. The first transmission line using a stranded (7-strand) aluminum cable was constructed by the Connecticut Electric Light Company in 1899 and remained in daily operation for more than 50 years. Starting with these early installations, the use of aluminum electrical conductors has increased steadily until it is the material of choice by transmission line design engineers today. For more than 90 years aluminum has been used by electric utilities for the transmission and distribution of electrical power. Although it's almost completely replacing copper for overhead applications. Of all the known nonprecious metals, aluminum ranks second only to copper in volume conductivity. Aluminum possesses a conductivity-to-weight ratio twice that of copper and its strength-to-weight ratio is 30% greater than copper.

When aluminum conductor came into relatively wide use in the early 1900's, experience indicated the need for a conductor with a greater strength-to-weight ratio. Thus, in 1907 a new aluminum-steel composite cable was introduced. This new conductor combined the light weight and high current carrying capacity of aluminum with the high strength of a galvanized steel core. ACSR, as this aluminum conductor, steel reinforced, cable became known, gained rapid acceptance and was used almost exclusively throughout the world until 1939. The excellent conductivity of ACSR, coupled with its excellent strength-to-weight ratio and ease of handling made it the dominant conductor for rural electrification in the United States that began during the early 1920's.

In 1939 a new all aluminum-magnesium-silicon alloy cable was introduced. The new all-aluminum alloy cable (AAAC) was developed to retain the mechanical and electrical properties of ACSR while improving weight and corrosion resistance characteristics. The introduction of the all-aluminum alloy cable and the subsequent development of the composite aluminum conductor, aluminum-alloy reinforced cable provided new alternatives to ACSR. As with most new products, particularly in applications as critical as electrical transmission and distribution, acceptance of the new alloy conductor was slow. In recent years, however, the recognized electrical improvements of alloy conductors over ACSR has led to an increasing trend of usage in aluminum alloy and composite aluminum-aluminum alloy cables.

More recently, many innovative conductor designs have been developed to address the changing needs of the electrical utility industry. New alloys have been developed to provide thermal stability, increased conductivity, vibration resistance and other specific characteristics. With each change there is a compromise. With each compromise there is a new design opportunity.

Conductor design and/or selection for transmission and distribution lines has become a science. The selection of the optimum conductor type and size for a given transmission or distribution line design requires a complete understanding of the characteristics of all the available conductor types. This understanding must encompass more than just the current carrying capability or thermal performance of a conductor. It must include a systems approach to conductor selection: line stability versus current loading; economic operation versus thermal loading; conductor creep and resultant sag under high temperature and adverse mechanical loading; conductor strength as determined by component metal stress-strain performance and metal fatigue characteristics are just a few of the system design parameters to be evaluated.

Types of Conductors:

There is no unique process by which all transmission and/or distribution lines are designed. It is clear, however, that all major cost components of line design depend upon the conductor electrical and mechanical parameters.

There are four major types of overhead conductors used for electrical transmission and distribution.

- AAC - All Aluminum Conductor
- AAAC - All Aluminum Alloy Conductor
- ACSR - Aluminum Conductor Steel Reinforced
- ACAR - Aluminum Conductor Aluminum-Alloy Reinforced

The various combinations and modifications of these conductor types provide a wide variety of possible conductor designs.

AAC - All Aluminum Conductor, sometimes referred to as ASC, Aluminum Stranded Conductor, is made up of one or more strands of 1350 Alloy Aluminum in the hard drawn H19 temper. 1350 Aluminum Alloy, previously known as EC grade or electrical conductor grade aluminum, has a minimum conductivity of 61.2% IACS. Because of its relatively poor strength-to-weight ratio, AAC has had limited use in transmission lines and rural distribution because of the long spans utilized. However, AAC has seen extensive use in urban areas where spans are usually short but high conductivity is required. The excellent corrosion resistance of aluminum has made AAC a conductor of choice in coastal areas.

ACSR - Aluminum Conductor Steel Reinforced, a standard of the electrical utility industry since the early 1900's, consists of a solid or stranded steel core surrounded by one or more layers of strands of 1350 aluminum. Historically, the amount of steel used to obtain higher strength soon increased to a substantial portion of the cross-section of the ACSR, but more recently, as conductors have become larger, the trend has been to less steel content. To meet varying requirements, ACSR is available in a wide range of steel content - from 7% by weight for the 36/1 stranding to 40% for the 30/7 stranding. Early designs of ACSR such as 6/1, 30/7, 30/19, 54/19 and 54/7 strandings featured high steel content, 26% to 40%, with emphasis on strength perhaps due to fears of vibration fatigue problems. Today, for larger-than-AWG sizes, the most used strandings are 18/1, 45/7, 72/7, and 84/19, comprising a range of steel content from 11% to 18%. For the moderately higher strength 54/19, 54/7, and 26/7 strandings, the steel content is 26%, 26% and 31%, respectively. The high-strength ACSR 8/1, 12/7 and 16/19 strandings, are used mostly for overhead ground wires, extra long spans, river crossings, etc.

The inner-core wires of ACSR may be of zinc coated (galvanized) steel, available in standard weight Class A coating or heavier coatings of Class B or Class C. Class B coatings are about twice the thickness of Class A, and Class C coatings about three times as thick as Class A. The inner cores may also be of aluminum coated (aluminized) steel or aluminum clad steel. The latter produces a conductor designated as ACSR/AW in which the aluminum cladding comprises 25% of the area of the wire, with a minimum coating thickness of 10% of the overall radius. The reinforcing wires may be in a central core or distributed throughout the cable. Galvanized or aluminized coats are thin, and are applied to reduce corrosion of the steel wires. The conductivity of these thin coated core wires is about 8% IACS. The apparent conductivity of ACSR/AW reinforcement wire is 20.3% IACS.

ACSR STRANDINGS

6201 "AAAC" - A high strength Aluminum-Magnesium-Silicon Alloy Cable was developed to replace the high strength 6/1 ACSR conductors. Originally called AAAC, this alloy conductor offers excellent electrical characteristics with a conductivity of 52.5% IACS, excellent sag-tension characteristics and superior corrosion resistance to that of ACSR. The temper of 6201 is normally T81.

6201 aluminum alloy conductors are typically sold as O.D. equivalents for 6/1 and 26/7 ACSR constructions. The O.D. equivalent 6201 conductors have approximately the same ampacity and strength as their ACSR counterparts with a much improved strength-to-weight ratio. 6201 conductors also exhibit substantially better electrical loss characteristics than their equivalent single layer ACSR constructions. However, the thermal coefficient of expansion is greater than that of ACSR. As with AAC conductors, the maximum short circuit temperature of 6201 must be kept below 340°C to prevent dangerous conductor annealing.

As compared to ACSR, AAAC's lighter weight, comparable strength and current carrying capacity, lower electrical losses and superior corrosion resistance have given this conductor wide acceptance as a distribution conductor. It has found limited use, however, as a transmission conductor.

ACAR - (Aluminum Conductor-Aluminum Alloy Reinforced) - ACAR combines 1350 and 6201 aluminum alloy strands to provide a transmission conductor with an excellent balance of electrical and mechanical properties. This conductor consists of one or more layers of 1350-H19 aluminum strands helically wrapped over one or more 6201-T81 aluminum alloy wires. The core may consist of one or more 6201 strands. The primary advantage of the ACAR conductor lies in the fact that all strands are interchangeable between EC and 6201, thereby permitting the design of a conductor with an optimum balance between mechanical and electrical characteristics. In effect, ACAR is a composite aluminum-aluminum alloy conductor which is designed for each application to optimize properties. Inverse ACAR conductors are also available with the harder 6201 aluminum alloy wires being on the outer surface of the conductor and the 1350 aluminum making up the heart of the conductor.

TYPICAL STRANDINGS FOR CONCENTRIC-LAY-STRANDED ACAR CONDUCTORS

AACSR - (6201 Aluminum Alloy Conductor Steel Reinforced) - Is an ACSR with the 1350 aluminum wires replaced by 6201-T81 aluminum alloy wires. The high tensile strength of the 6201-T81 wires combined with the high strength of steel provides an exceptionally high strength conductor with good conductivity. AACSR conductors have approximately 40% to 60% more strength than comparable standard ACSR conductors of equivalent stranding, with only an 8-10% decrease in conductivity. AACSR is available with all core types specified for use with standard ACSR.

SSAC - (Steel Supported Aluminum Cable) - SSAC conductor was designed for use as a replacement conductor in upgrading existing transmission and distribution lines with minimum capital outlay. The premise of design is higher conductor operating temperature without detrimental annealing of the aluminum in standard ACSR causing a loss of strength in the aluminum. SSAC conductor is an aluminum-steel composite conductor resembling standard ACSR in appearance, stranding and overall diameter. This is the extent of their similarities however. SSAC uses 1350-0 (fully annealed) aluminum strands with 63.0% conductivity rather than the traditional 1350-H19 hard drawn aluminum used in standard ACSR which possesses 61.2% IACS conductivity. The steel core may be made of conventional or extra high strength steel core wire. Compared to an equal size ACSR, SSAC has a lower resistance, lower breaking strength, lower creep elongation and lower elastic modulus. SSAC can be operated at temperatures as high as 250°C without loss of strength and can be strung at higher unloaded percentage tensions because of its good self damping characteristics.

SSAC has seen limited use in the United States. Even though SSAC has better conductivity, a higher operating temperature and improved damping characteristics when compared to conventional ACSR, it has a lower breaking strength, typically yielding greater initial and final sags. It is, however, a good conductor to consider for line upgrades if the calculated present worth of electrical losses shows a savings over line conversion cost.

Expanded ACSR - This conductor is designed to be used where large diameter single conductors are required to reduce the electrical stress gradient at the surface of the conductor to provide corona-free operation. Expanded ACSR is used when a single conductor rather than a conductor bundle is used at EHV voltage levels. Expanded ACSR is specially fabricated to have a larger outside diameter than could be achieved using the circular mil area of aluminum required. Expansion is achieved by the use of oversized wires widely spaced in successive wire layers near the core. Expansion has also been achieved by the use of extruded metal shapes and various rope, paper or jute fillers. Expanded conductors can offer improved sag characteristics as well as efficient design. Because of the precise fabrication techniques required to manufacture expanded conductors and a history of installation problems, these conductors have not been widely used.

EXPANDED ACSR

Smooth Body Conductors:

Some cables are designed to produce a smooth outer surface and reduce overall diameter. This smaller diameter reduces the ice and wind loading encountered during severe weather, thereby reducing the pole/tower loading or allowing longer design spans. Smooth body conductors are of two types - compact conductors or trapezoidal shaped wire compact conductors, i.e., TW conductors.

Compact Conductors - Compact overhead conductors are typically available in both AAC and ACSR with diameter reductions ranging from 8% to 11%. AAC conductors are available in a size range of #8 AWG through 1000 kcmil with standard stranding as listed in ASTM. Compact ACSR conductors are available only in sizes #6 AWG through 336.4 kcmil in constructions with a single steel core wire.

Compact conductors are manufactured by passing the stranded cable through powerful compacting rolls or a compacting die. The strands are deformed, to the degree they loose their circularity, partially filling the interstrand voids and the outer surface of the conductor becomes a relatively smooth cylinder. The resulting reduction in overall diameter not only reduces the ice and wind loading characteristics of the conductor but also reduces the stress gradient at the conductor surface.

150% / 200% ACSR - The terms 150% and 200% ACSR refer to a family of single layer (6/1) constructions of ACSR that have 150% and 200% of the strength of the equivalent construction standard ACSR while exhibiting approximately the same overall diameter. The 150% and 200% smooth body ACSR was developed to provide a conductor with a substantial increase in ultimate strength as compared to standard 6/1 ACSR constructions. This is accomplished by using a larger steel core wire and drastically flattening the aluminum strands to create a smooth cylindrical conductor surface.

150% and 200% smooth body ACSR is fabricated by passing the composite stranded cable through a die or rolls so designed to flatten the aluminum strands and fill the interstices which exist in conventional stranded ACSR. This brings about a reduction in overall cable diameter which means a lower ice and wind load and greater strength to loaded weight ratio.

These conductors were primarily designed for use on rural distribution lines. The reduced diameter and extra high strength provide substantial design and operational advantages for the longer spans of a rural distribution line serving sparcely populated areas subject to severe cold weather conditions.

Trapezoidal Shaped Wire Conductors - Shaped wire compact conductors made from trapezoidal (TW) shaped wires is a relatively new conductor design. These conductors can be provided in AAC, AAAC and ACSR constructions and are designated as types AAC/TW, AAAC/TW and ACSR/TW.

Conventional conductor designs have traditionally used round wires. The use of technology to design and produce trapezoidal wires (TW) provides conductor designers with an alternative to conventional round strand conductor designs. The use of trapezoidal wire designs yields compact conductors with less void area and a reduced outside diameter.

With conventional ACSR strandings, the number of aluminum and steel strands uniquely define the ratio of steel area to aluminum area. For example, all 26/7 ACSR constructions have the same ratio of steel area to aluminum area of about 16%. However, with TW strands the number of aluminum and steel strands do not necessarily define a unique steel to aluminum ratio. Therefore the designation of "type" has replaced the stranding designation to more accurately identify TW conductors. For example a 795 kcmil-26/7 ACSR "Drake" has a TW counterpart designated 795 kcmil Type 16, ACSR/TW. The aluminum area and steel area of both conductors are identical. The use of TW shaped aluminum strands will cause the ACSR/TW to have a smaller diameter.

The following table relates ACSR/TW Type Number with standard conventional ACSR stranding.

COMPARISON OF ACSR/TW WITH EQUIVALENT STRANDING OF ACSR

ACSR/TW TYPE Number*	CONVENTIONAL ACSR Stranding

5	42/7
7	45/7
8	84/19
10	22/7
13	54/7
13	54/19
16	26/7

COMPARISON OF ACSR/TW WITH EQUIVALENT STRANDING OF ACSR ACSR/TW TYPE CONVENTIONAL ACSR Number* Stranding 5 42/7 7 45/7 8 84/19 10 22/7 13 54/7 13 54/19 16 26/7

*ACSR/TW type number is the approximate ratio of the steel area to the aluminum area in %.

An alternate design concept is to specify ACSR/TW conductors with equivalent overall diameters to conventional ACSR constructions. In this case, the diameter is matched to that of the standard ACSR while maintaining the same ratio of steel to aluminum by area. Since the aluminum area is increased, the steel area must be increased to maintain the proper area ratio.

If a reduced diameter TW construction is selected, the diameter is reduced by approximately 10% thereby reducing the design ice and wind loading on the conductor. If an equal diameter TW construction is selected, the aluminum area is increased by approximately 20% - 25% providing a decrease in AC resistance of 15% - 20% and increasing the current carrying capacity 8% to 10%.

The use of trapezoidal wires provides a more compact conductor design with mechanical properties at least equal to that of conventional ACSR. Since ACSR/TW designs have the same steel-to-aluminum ratios as their equivalent ACSR constructions, stress-strain and creep data developed for conventional strandings of ACSR can be used to predict sag and tension design data for ACSR/TW conductor constructions.

TW conductor installation requires no special tools, equipment or training.

ACSR TRAPEZOIDAL SHAPED WIRE CONDUCTOR

Vibration Resistant Conductor Designs:

VR Conductor - A wind induced motion resistant conductor, VR conductor is designed for use as a bare overhead conductor in areas subject to aeolian vibration and galloping due to wind and ice. Use of this conductor allows it to be strung to the maximum allowable NESC design tensions without the need for additional vibration protection.

VR conductor is composed of two identical conductors twisted together with a nine-foot left-hand lay, giving the conductor a spiraling "figure 8" shape. This spiraled shaped disrupts the forces created by steady cross winds by presenting a continuously changing projected conductor diameter to the wind. By disrupting the forces created by turbulent wind flow, conductor vibration is prevented. This unique spiral shape, together with less torsional stiffness and varying bending stiffness also reduces or eliminates conductor galloping due to combined ice and wind loads.

VR conductor can be made of component conductors of AAC, AAAC, ACAR, ACSR, AAC/TW or ACSR/TW meeting the appropriate requirements. The type component or subconductor selected should be based on strength and thermal requirements. Constructions are available in all conductor sizes and are suitable for both distribution and transmission requirements.

VR conductor is typically manufactured and sold as an alternate to standard round conductor. The total circular mil area of both component conductors equals the circular mil area of the VR construction. Conductor constructions are normally referred to by the registered code name of the component conductors followed by the VR designation, i.e., "Ibis/VR".

VR CONDUCTOR

ACSR/SD - Sometimes called SDC (Self Damping Conductor), ACSR/SD is a concentric lay stranded, self damping conductor designed to control aeolian type vibration in overhead transmission lines by internal damping. Self damping conductors consists of a central core of one or more round steel wires surrounded by two layers of trapezoidal shaped aluminum wires. One or more layers of round aluminum wires may be added as required.

Self damping conductor differs from conventional ACSR in that the aluminum wires in the first two layers are trapezoidal shaped and sized so that each aluminum layer forms a stranded tube which does not collapse onto the layer beneath when under tension, but maintains a small annular gap between layers. The trapezoidal wire layers are separated from each other and form the steel core by the two smaller annular gaps that permit movement between the layers. The round aluminum wire layers are in tight contact with each other and the underlying trapezoidal wire layer.

ACSR/SD has been very effective in reducing aeolian vibration on transmission lines. However, most contractors charge a premium for installation because of special hardware requirements and specialized stringing methods.

SELF DAMPING CONDUCTOR

Bundled Conductors - A bundled conductor arrangement with two or more conductors in parallel, spaced a short distance apart is frequently used for HV and EHV transmission lines. Many electrical reasons can be cited in favor of bundled conductors. From the stand point of current density per unit area, smaller conductors have higher possible current densities, thus greater metal efficiency. The use of multiple conductors per phase having the same total area as a single conductor will operate at lower temperatures yielding lower resistances and losses for equal loads.

Multiple conductors offer significant improvements in reactance over a single conductor of equal area. The inductive reactance of a two conductor bundle is only about 50% of the reactance for a single conductor having the same circular mil area as the bundled pair. Obviously, the greater the spacing between subconductors, the lower the reactance.

Although important, the electrical advantages of bundled conductors may not be the most important factor influencing their use. The concerns of corona and radio noise may dictate the use of bundled conductors since corona loss of a conductor is a function of the voltage gradient at the conductor surface. The subjects of corona and RIV have been well investigated and will not be further discussed here.

The number and size of conductors per phase have not been standardized. It is dependent upon many factors. Today conductor bundles are a standard design practice for transmission lines designed to operate at 345 kV or higher.

Any of the above discussed conductors including VR Cable, can be used as subconductors for bundle conductor designs. This presents the transmission design engineer with limitless design options.

BUNDLED CONDUCTOR

Surface Finishes:

The surface of a conductor must be relatively clean and smooth to perform satisfactorily as an electrical conductor. However, special surface treatments or finishes may be required to reduce reflectivity or impart other desired special appearance, or in some cases aerodynamic, characteristics to a conductor or conductor assembly. The most common surface treatment and one normally required for conductors used for transmission and distribution lines crossing undeveloped Federal Government park lands is one to reduce the reflectivity of aluminum conductors. This type of surface finish is referred to as non-specular.

NON-SPECULAR CONDUCTOR - The term non-specular is used to infer that the surface of an aluminum conductor, any type aluminum conductor, has been either mechanically or chemically treated to produce reduced reflectivity. The conductor surface must have a smooth matte gray finish which blends naturally and unobtrusively with the environment.

This non-specular finish is typically achieved by passing the finished conductor through a deglaring machine (a type of sandblast machine) in which the conductor surface is blasted with a very fine mild abrasive grit producing a dull matte gray finish. The reflectivity and color of the finished cable is specified by ANSI C7.69 Specifications.

The abrasive action of the blast media is extremely mild and in no way affects the mechanical characteristics of the conductor. The ampacity of current carrying capability of non-specular conductors is slightly increased because the emissivity of the conductor is increased from approximately 0.23, for bright shiny conductors, to approximately 0.42 because of the darker matte gray surface. An increase in current carrying capacity in the range of 5% can be achieved, for the same temperature rise, due to this increase in surface emissivity.

Other surface finishes providing benefits such as improved aerodynamic characteristics have been reported. The merits of such finishes must be evaluated to determine if lasting economic benefits exist.

Conclusion:

The selection of the optimum conductor type and size for a given line consists of finding that conductor which results in the lowest present net worth cost spread over the life of the line. The transmission line design engineer is confronted with choosing a conductor type from among this bewildering assortment. This choice must be based on basic conductor parameters.

It is clear that all the major cost components of a transmission line depend upon conductor physical, mechanical and electrical parameters. A list of these basic parameters are:

- conductor diameter
- weight per unit length
- conductivity of material(s)
- crossectional area(s)
- modulus of elasticity
- rated breaking strength
- coefficient(s) of thermal expansion
- cost of material(s)
- maximum unloaded design tension
- resistance to vibration and/or galloping
- surface shape/drag coefficient
- fatigue resistance

These basic parameters are not necessarily independent of one another. However, certain parameters can be varied independently over a range of design considerations.

It is the hope of this writer that a better understanding of available conductor types and materials will provide a better base for future conductor selections.

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