New Bare Conductor for Transmission and Distribution Overhead Lines of the Future

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Abstract – **In this paper a short historical overview of bare conductor types is given. Usually applied types of conductors for transmission and distribution overhead lines are described. The basic conductor physical, mechanical and electrical parameters important for selection of the optimal conductor type and size for a given line are explained. A new type of conductor, called Aluminum Conductor Composite Core (ACCC), with better properties than other types of conductors, is shown. The construction of ACCC type of conductor, its properties and comparison with the properties of the usually used ACSR conductor are presented.**

Keywords – **Conductors for overhead lines, composite core, conductor capacity (ampacity).**

I. Introduction

Remarkable changes have occurred in the transmission and distribution of electrical energy from the time of the first commercial sale of electricity. From that time till now, extensive change has been made in the area of types of conductors available to transmit and distribute electricity. The first three-phase power transmission on long distance was presented on the Frankfurt Exposition in 1891, when power of 230 kVA from a hydroelectric plant at Lauffen was transmitted to Frankfurt, 175 km away, by three bare-wires operating at 15 kV. In the past years, the demand for electrical power has increased significantly. Growing energy demand and ageing electricity infrastructure underline the urgent need for new and upgraded transmission lines. For example, in the power system of the Republic of Macedonia US $52 million should be invested for reconstruction of 30 existing and construction of 30 new 110 kV transmission lines till 2020 [1]. This is necessary to meet the utility requirements for quality electrical energy, delivered without interruptions. Also, the transmission lines should be able to accommodate the peak loads, especially now, when the market of electrical power is deregulated. Nowadays utilities have been looking for ways to increase the capacity of existing transmission lines with minimal capital investments. An efficient way is to replace the existing (usually ACSR) line conductors with new types. The new conductors should have better current-carrying capacity (ampacity) and smaller sag on higher operating temperature. Recently, in 2005, after long research period, two USA companies, conductor developers Composite Technology Corporation (CTC) [2] and 3M Co. [3] have introduced new conductor types in which the steel core was replaced with a composite, providing several significant advantages. In CTC's Aluminum Conductor Composite Core (ACCC) conductor, the steel core is replaced with a pultruated carbon/glass hybrid composite. 3M's Aluminum Conductor Composite Reinforced (ACCR) conductor features a core of thousands ultra-high strength aluminum oxide fibers, wrapped with aluminum-zirconium conducting wires.

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II. Historical Development of Different Conductor Types

At the beginning of 1880's copper was the first metal used to transmit electricity.

Before the end of 19'th century, aluminum began to replace copper as the metal for transmission and distribution conductors. The first transmission line using aluminum conductors was constructed in California in 1895 [4]. Four years latter, transmission line using a stranded aluminum conductor was constructed and remained in operation for more than 50 years. Aluminum possesses a conductivity-to-weight ratio twice that of copper and its strength-to-weight ratio is 30% greater than copper. Also, taking into account that the price of aluminum is lower than the copper, in the early 1900's, aluminum conductors became widely used and completely replaced the copper for overhead applications.

But, during the time, experience indicated the need for a conductor with a greater strength-to-weight ratio. In 1907 a new type of conductor was introduced. This conductor was constructed of aluminum round wires helically wrapped around a core of steel wire(s) and combined the light weight and high ampacity of aluminum with the strength of a galvanized steel core. The excellent physical, mechanical and electrical properties of this conductor, well known as Aluminum Conductor Steel Reinforced (ACSR) were the reason for rapid acceptance by the transmission line design engineers, almost exclusively throughout the world until 1939.

After this period, a new all aluminum-magnesium-silicon alloy conductor was introduced. This conductor retained similar mechanical and electrical properties of ACSR, with reduced weight and better corrosion resistance.

In 1974 annealed (soft) aluminum was used in a new high temperature operated conductor called Aluminum Conductor Steel Supported (ACSS). This conductor, with better conductivity was designed for use as a replacement conductor in upgrading existing transmission and distribution lines with minimum investments.

Applying new materials (as zirconium and invar) in last decades several types of conductors were constructed. The Super Thermal Resistant Aluminum Alloy Conductor with

Invar Reinforcement (STACIR) is designed to operate up to 210 ^{0}C during normal conditions.

Few years ago, 3M Company have designed new conductor type called Aluminum Conductor Composite Reinforced (ACCR). This conductor has much better properties then usually used ACSR conductor. The high cost of the aluminum oxide fibers for conductor core and expensive zirconium in the aluminum alloys for the wires, doesn’t make this conductor competitive on the market, yet. The cost estimates of ACCR are 7-10 times that of conventional ACSR [5].

After several years of research work, in 2005, application of the General Cable’s technology for trapezoidal aluminum wires (TW) wrapping [6] and CTC’s pultrueded composite core technology together have created the new Aluminum Conductor Composite Core (ACCC/TW). The excellent mechanical and electrical properties and acceptable price of this conductor promise that ACCC/TW will be transmission and distribution conductor of the future.

III. Usually Applied Bare Conductors

Transmission and distribution bare conductors are generally made from two different metals - aluminum and steel, but there are conductors made only from aluminum alloys. The last designed conductors are constructed from aluminum and high strength composite core. Aluminum part provides electrical conductivity and has small influence on the conductor strength. The conductor core accepts almost all mechanical tensions. Aluminum wires shape can be round or trapezoidal. Application of trapezoidal shaped aluminum wires yields compact conductors with less void area then round wires. Aluminum wires are made from hard drawn aluminum or soft aluminum (i.e. annealed or “0” temper). These types of aluminum have very different electrical and mechanical properties. Electrically, hard drawn aluminum possesses 61,2% IACS conductivity (International Annealed Copper Standard) whereas, soft aluminum has a conductivity of 63% IACS [4], [7]. Mechanically, the tensile strength (resistance to breaking) of hard drawn aluminum is approximately three times that of soft aluminum. Conductors manufactured with hard drawn aluminum can be operated at temperatures which don’t exceed 93 ^{0}C when aluminum starts to anneal. The annealing can cause breaking of the conductor under high wind or ice conditions. In opposite, higher temperatures have no effects on the soft aluminum tensile strength. Because of this reason, operating temperatures for conductors manufactured with soft aluminum can theoretically reach 250 ^{0}C. In practice, temperature limit of 200 ^{0}C has been in existence for 30 years [7].

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

1. AAC – All Aluminum Conductor is made up of one or more strands of hard drawn aluminum. Because of its relatively poor strength-to-weight ratio, AAC has limited use in transmission lines and rural distribution where the long spans are applied. However, AAC has 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 very suitable conductor in coastal areas.

2. ACSR – Aluminum Conductor Steel Reinforced is widely used conductor more then hundred years. It consists of a solid or stranded steel core surrounded by one or more layers of hard drawn helically wrapped aluminum wires. The amount of steel is used to obtain higher conductor strength and amount of aluminum to obtain proper ampacity. To meet varying requirements ACSR is available in a wide range of aluminum-steel cross-section ratios. The steel core wires are galvanized to prevent from corrosion. If aluminum wires are made of hard drawn aluminum the ACSR operating temperatures are 75 to 80 ^{0}C. Application of soft (annealed) aluminum wires enables high operating temperatures between 200 and 250 ^{0}C. This conductor with conventional or extra high strength steel core wire(s) and soft aluminum wires is called Aluminum Conductor Steel Supported (ACSS).

3. AAAC – All Aluminum Alloy Conductor is high strength Aluminum-Magnesium-Silicon Alloy conductor. It was developed to replace the high strength 6/1 ACSR conductors. 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. Service life of AAAC is around 60 years, twice as durable as ACSR. It is superior to ACSR conductors when used in distribution lines.

4. ACAR – Aluminum Conductor Aluminum-Alloy Reinforced is combination of one or more layers of hard drawn aluminum strands helically wrapped over a core of one or more aluminum alloy wires which have high tensile strength. This is a conductor with an optimal balance between mechanical and electrical properties.

Conventional conductor’s designs have traditionally used round wires, but the trapezoidal aluminum shaped wires-TW are also available. Applying trapezoidal wires new types of conductors AAC/TW, AAAC/TW, ACSR/TW and ACSS/TW with less void area then round wires are constructed.

Usually applied conductors for transmission and distribution lines in Republic of Macedonia are AAC, ACSR and AAAC.

IV. Selection of Optimal Conductor Type

High voltage overhead transmission and distribution lines must satisfy many simultaneous requirements, as: minimum electrical resistance, safe clearance above the ground, sufficient strength for applied loads, lowest present net worth cost spread over the life of the line, etc. As it was shown in section III, a wide variety of conductor types are available to meet the demands for different ampacity in many different climates and types of terrain. It is clear that all the major cost components of an overhead line depend upon conductor physical, mechanical and electrical parameters.

The basic conductor parameters are: a) conductor diameter, b) weight per unit length, c) conductivity of material(s), d) cross-sectional area(s), e) modulus of elasticity, f) rated breaking strength, g) coefficient(s) of thermal expansion, h) cost of material(s), i) maximum unloaded design tension, j) resistance to vibration and/or galloping, k) surface shape/drag coefficient, l) fatigue resistance and m) corrosion resistance, [4]. To meet the utility demand for power which grows every year, it is necessary to provide sufficient transmission capacity of the grid. This problem can be solved on two ways. The first one is to construct new lines with the present overhead conductor types and constructing technology. Because of the high cost and difficulties in obtaining new rights-of-way for corridors and environmental restrictions, utilities usually avoid constructing new transmission lines. The second, very efficient and optimal cost solution is reconductoring of existing lines. If there is a type of conductor which has greater ampacity and at least the same or better physical, mechanical and electrical parameters than existing line conductor, it can be used without additional reconstructions or modifications of existing line towers. Such type of high capacity conductor, called Aluminum Conductor Composite Core (ACCC) [9], recently was offered on the market.

V. NEW TYPE ACCC CONDUCTOR

The ACCC/TW conductor shown in Fig. 1 (left), was developed as a conductor with improved several key properties in comparison with conventional widely used ACSR conductor with the same outer diameter.

The primary design objectives included increasing the strength of the conductor (by replacing the stranded steel with stronger material), increasing the rated ampacity, and the resistance to sag at high temperatures. To meet these objectives, a pultruated carbon- and glass-reinforced fiber polymer matrix composite core was developed to replace the stranded steel core used in ACSR.

During the pultrusion process, continuous unidirectional (0^0-axis) carbon fibers form a cylindrically shaped solid core while a layer of similarly oriented E-glass fibers, is placed as a shield. The bundled fibers are wet out with a high-temperature toughened epoxy. The fiberglass layer serves two purposes: first, it separates the carbon from the conductive aluminum wires to prevent galvanic corrosion. Second, it counterbalances the more brittle carbon and improves the flexibility and toughness of the core. The one-piece rod composite core lead to a core with a greater cross-sectional area, but a smaller diameter which implies larger loading with reduced tensile stresses over that of the steel core subjected to the same loads.

Fully annealed (soft), H0 (O’) tempered 1350 aluminum trapezoidal wires with conductivity of 63% IACS are helically wrapped in one ore more layers around the composite core. The use of trapezoidal wires yields compact conductor with less void area than ACSR. The compact trapezoidal wires, coupled with a smaller composite core, result in an ACCC/TW conductor that has approximately 28% more aluminum cross-sectional area than ACSR and ACSS with round wires and same outer diameter. Thermal properties of composite core and soft aluminum wires enable high operating temperatures of ACCC/TW, continuously up to 180 ^{0}C. The greater aluminum content in ACCC/TW with high electrical conductivity, combined with the capability to work at high operating temperatures, can double the ampacity of an existing transmission line with ACSR conductors. The current capacity I in A can be calculated using steady-state thermal rating method based on Eq. 1, [9]:

$$I = \sqrt{\frac{q_c + q_r - q_s}{R_{Tc}}}\ , \qquad (1)$$

where q_c is the convection heat loss in W/km, q_r is radiated heat loss in W/km, q_s is the solar heat gain in W/km, and R_{Tc} is the 50 Hz (or 60 Hz) ac resistance of the conductor in Ω/km, at operating temperature Tc.

Because the annealed aluminum is not strong, the composite core of ACCC/TW carries the entire load of line. The coefficient of thermal expansion (CTE) of the ACCC/TW core is $2{,}77 \cdot 10^{-6}$ per ^{0}C, more then four times smaller then the CTE of galvanized steel core [8], [9]. The initial sag D is proportional to the span length S, and calculated by Eq. 2 [10]:

$$D \cong \frac{w \cdot S^2}{8 \cdot H} \text{ or } \cong \sqrt{\frac{3 \cdot S \cdot (L - S)}{8}}\ , \qquad (2)$$

where w is the linear weight, L is the actual length of the conductor, and H is the horizontal component of the applied load. The very small CTE of ACCC conductors, results with small sags and safe clearance in high operating temperatures.

VI. COMPARISON OF ACCC/TW AND ACSR

ACCC/TW conductors are similar in weight and size to typical conventional ACSR conductors, but they have a much higher ampacity. These properties allowing them to replace ACSR conductors on existing overhead lines without structural modifications of supporting tower systems while allowing far more power to be transmitted. A new ACCS/TW and conventional ACSR conductors with same outer diameters are shown on Fig. 1.

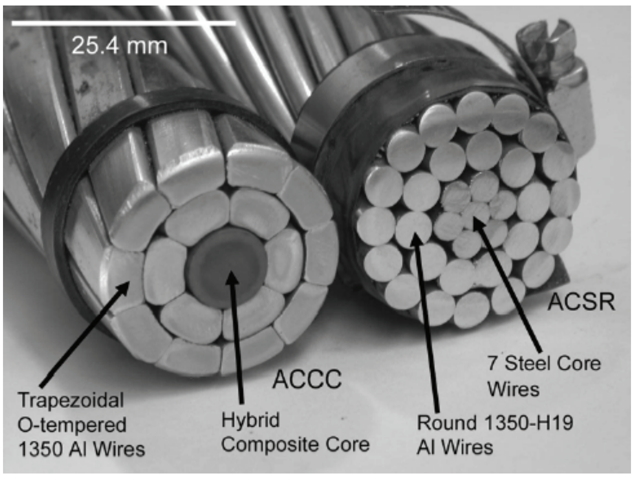

Fig. 1. Comparison between ACCC/TW (left) and ACSR (right) conductors with same diameter [8], [9].

The data for mechanical and electrical properties for ACCC/TW and ACSR conductors taken from [2], [5], [6], [8] and [9] are given in Table I.

TABLE I
COMPARISON OF ACCC AND ACSR PROPERTIES

Conductor properties/type	**ACCC/TW**	**ACSR**
Outer diameter (mm)	28,15	28,15
Aluminum area (mm^2)	517,00	402,97
Fill factor (%)	93,80	75,00
Linear weight (kg/km)	1556,60	1626,60
Rated strength (kN)	182,80	140,10
Core diameter (mm)	9,50	10,36
Core rated strength (kN)	169,03	74,90
Core tensile strength (kN/mm^2)	2,38	0,89
Core thermal coefficient ($1/^0C$)	$2,77\cdot10^{-6}$	$11,5\cdot10^{-6}$
Core elastic modulus (kN/mm^2)	110,30	199,96
DC resistance at 20 ^0C (Ω/km)	0,0541	0,0702
AC resistance at 75 ^0C (Ω/km)	0.0676	0,0863
AC resistance at 200 ^0C (Ω/km)	0,0955	0,1211
Ampacity at 75 ^0C (A)	1025	908
Ampacity at 100 ^0C (A)	1265	1123
Ampacity at 180 ^0C (A)	1760	no oper.
Max. operating temperature (^0C)	180	75
Price (Euro/m) (year 2005)	11,37	3,80

An experiment for conductor sagging with increasing operating temperatures is presented in [9]. The measured sag behavior versus temperature is shown in Fig. 2. When the current was increased to 1500 A, the sag for Drake ACSR increased to 1,9 m, while the sag in ACCC/TW increased 0,34 m. The temperature of ACSR increased to 240 ^0C, while that of ACCC/TW increased to 180 ^0C, despite carrying the same current. At equivalent temperature of 180 ^0C, the ACSR sag was 1,57 m, while the ACCC/TW sag was 0,34 m. It is obvious that the ACCC/TW conductor showed markedly lower sag over the entire temperature range.

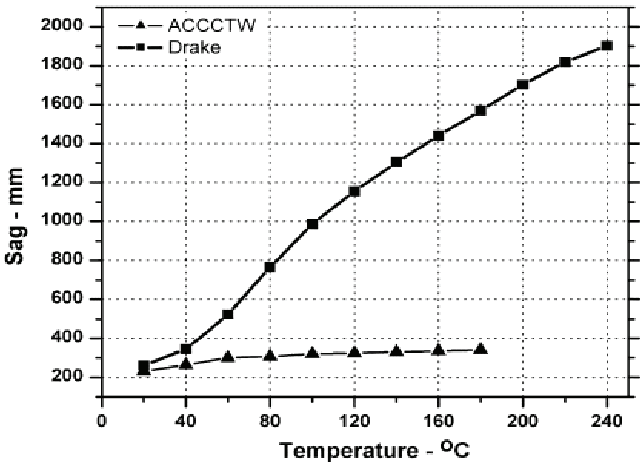

Fig. 2. Comparison between measured sag data for ACCC/TW and ACSR-Drake sonductors with same outer diameter 28,15 mm [9].

The properties comparison shows that ACCC/TW conductor is superior to ACSR conductor of the same diameter in several important performance areas, because of the following reasons: a) it has 28% more aluminum area (with high purity aluminum of 63% IACS) and higher operating temperatures up to 180 ^0C, which provides twice the ampacity of conventional ACSR and lower line losses, b) it has smaller or similar weight as ACSR, which allows to replace existing line conventional conductors without structural modifications of supporting towers, c) its composite core has very low thermal expansion coefficient which results with small sag and safe clearance of the conductor on high temperatures, d) the high rated strength enable construction of new lines with greater spans and reduced number of line towers by up to 16% (reducing total line costs), without problematic high temperature sags, e) a composite core material will not rust or corrode during the period of conductor exploitation, f) the annealed aluminum stranded wires in the conductor have self-damping properties which may eliminate the need for dampers and other anti-vibration devices, g) nonmagnetic and nonconductive core decrease the inductive heating and intensity of electromagnetic fields, i) installation procedures are the same as the conventional ACSR conductors with little instructions and easy technique for core splicing, etc.

VII. CONCLUSION

In this paper a short review for historical development of different conductor types is given with purpose to show the materials and properties of usually used conductors in the past 100 years. Four major types of bare conductors usually used till now for overhead lines are shortly described. Recently a new type bare conductor for transmission and distribution lines with excellent properties, ideal for upgrading and double increasing the ampacity of existing lines was offered on the market. The key properties of this conductor are explained and compared with usually used ACSR conductors. Taking into account all advantages of new ACCC/TW conductor and 3 years experiences in its application, make utilities to believe that this is the conductor of the future.

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