Analysis of Knee Point Temperature (KPT) determination on High Capacity Low Sag (HCLS) conductors for optimizing the ampacity load and sag on the overhead transmission lines system

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Abstract. The modern overhead lines with High Capacity Low Sag (HCLS) conductors can be operated at higher current carrying capacity. The main advantage of HCLS conductors is the special design of operating conditions, which cause the transformation of the mechanical pull load from the conductors to the reinforcing core. This transformation is called "knee point temperature". This study aims to determine the knee point temperature and the effect on sag HCLS conductors. The simulation will be conducted on the HCLS conductors, namely ACCC/TW LISBON (310), which stretches between a span of 100meters. The electrical loading of conductors is gradually giving until a temperature of 180°C is reached. From the simulation results, we can determine the knee point temperature of the ACCC/TW LISBON (310) conductor is around 60-62°C. The value of the sag after the knee point temperature tends to be stable even though the ampacity loading is increased.

1. Introduction
The problem facing the energy supply currently is not only generating capacity, but also the ability to distribute and transmit power to meet the increasing demand. The limited capacity of transmitting power through the existing transmission line is the limitation of heat that is allowed through the conductor. The conventional transmission line consists of aluminium conductors stranded in high-strength steel- reinforced (ACSR). When the current is increased to meet the demand, the lines will heat up and elongated due to the coefficient of thermal expansion in the steel material and aluminium wire, which is causing sag. As the value of the sag increases, the risk of earthing or mechanical failure will also increase. One way to overcome the problem of sag and capacity limitations is to replace conductors from the conventional types to high capacity low sag (HCLS) conductors’ types. In this study, a simulation will be conducted to determine the knee point temperature in the HCLS conductor of type ACCC (Aluminium Conductor Composite Core). From the simulation results will be compared with the results of calculations to predict optimal ampacity loading on the overhead lines transmission system.

1.1. High Capacity Low Sag (HCLS) conductors
The ACCC/TW (Aluminium Conductor Composite Core) and ACCR (Aluminium Conductor Composite Reinforced) are the new generation transmission lines that are designed primarily to
overcome the problem of high temperatures sag. The core of ACCR uses high strength ceramic fibres embedded in the aluminium matrix [1]. This ceramic fibre is intended to replace the existing steel wire with a more conductive core and has a lower coefficient of thermal expansion. Whereas the core of ACCC/TW conductor is made with lightweight carbon fibres and boron-free e-glass fibres which are bonded using a thermosetting epoxy matrix at high temperatures. Both of these conductors offer higher capacities and lower sag and can be operated at higher temperatures continuously than ACSR. The design of the ACCC/TW is very different from conventional ACSR conductors. The ACCC/TW consists of Al grade 1350-O wire, which is softened in the form of a trapezoidal (trap) wires stranded around the composite core. The trap aluminium wires are softer (yield strength of 59 to 76 MPa) compared to aluminium wire (160 to 200 MPa) used by ACSR conductors and Al-Zr alloys used by ACCR [2,3]. Al grade 1350-O wire is softened because in the ACCC/TW conductor, the mechanical loads will be borne by the composite core, which is not the case for the ACSR and ACCR conductors. This conductor has an operating temperature range of up to 200 °C, which is much higher than ACSR conductors, which have an emergency temperature of 100 °C to 120 °C. This condition increases the ability to deliver higher ampacity. To achieve the same ampacity load, ACCC/TW can operate at cooler temperatures [1,4].

1.2. Calculation of current carrying capacity

The current carrying capacity of a conductor is the maximum current value under steady-state which is affected by the rise in conductor temperature at given ambient temperature conditions. The current carrying capacity calculation in the conductor can use the heat transfer equation which is defined as a functional relationship between the conductor current temperature and surrounding conditions [5]. The value of the current carrying capacity is influenced by the conductor resistance (Rdc), the maximum permissible conductor temperature, the conductor surface conditions, the intensity of sunlight, solar radiation, wind speed, ambient temperature, and other factors [6-8].

As the conductor temperature increases, a steady-state can be achieved when the heat generated by several variations of the heat source is the same as the heat loss. This condition is expressed in the heat equilibrium equation as follows [9-17]:

\[ P_j + P_{sol} = P_{rad} + P_{conv} \]  

Where:
- \( P_j \): heat caused by the Joule effect.
- \( P_{sol} \): the sun's heat generated by the surface of a conductor.
- \( P_{rad} \): heat loss through conductor radiation.
- \( P_{conv} \): heat loss due to convection.

Whereas the equation of current carrying capacity:

\[ I_{max} = \sqrt{\frac{P_{rad} + P_{conv} - P_{sol}}{RT}} \]  

Where:
- \( I_{max} \): the current carrying capacity (Amp)
- \( RT \): the electrical resistance of the conductor at temperature \( T \) (ohm/m)

1.3. Sag and tension of conductor

The conductors of electrical transmission and distribution lines must be in a safe position, eliminating all possibilities that can injure humans. But along with increasing time, the conductor may experience elongation, and change in tension, so that it can change from the original position after installation.
Despite being affected by weather and loading on a line, the conductors must be kept at a safe distance from buildings, objects and people or vehicles that are adjacent to the line. The overhead transmission line or conductor is usually has a uniform weight along their length. Because of these characteristics, we can use the catenary form between support points [18]. The shape of the catenary changes with the conductor temperature or the addition of ice and wind loads. To ensure adequate vertical and horizontal distances under all weather conditions and electrical loads, and to ensure that the mechanical strength of the conductor is not exceeded, the conductor behaviour of the catenary under all conditions should be known before the line is designed. The conductor's behaviour in the future is determined through calculations, commonly called sag-tension calculations. Sag-tension calculation predicts conductor behaviour based on suggested tension limits under various load conditions. This tension limit determines the percentage value of rated strength conductor which must not be exceeded at the time of installation or while the line is operating [18]. General formulation used for sag calculations:

\[
D = \frac{H}{w} \left( \cosh \left( \frac{wS}{2H} \right) - 1 \right) = \frac{w \left( S^2 \right)}{8H}
\]  

Where:
- \( D \) : maximum sag of the conductor.
- \( H \) : the horizontal component of tension.
- \( w \) : the conductor weight per unit length.
- \( S \) : span length.

1.4. Knee point temperature

In a non-homogeneous conductor design, where the core material has a different material, this has two purposes. First, to increase the overall mechanical strength of the conductor. Second, to reduce the coefficient of thermal expansion (CTE) of the whole conductor by offering a CTE of the core that is much lower than the CTE of aluminium material. As its function, the conductor will get various electrical loads that cause the conductor's temperature to heat up. The dissimilar of CTE between the core and the aluminium wire strands will cause a changes in tensile load sharing. The aluminium strands will expand longer in length than the core at a higher temperature. When the temperature rises, the aluminium strands will relax and shift the tensile load to the core. At a certain temperature, the tension on aluminium strands is displaced by the thermal expansion of aluminium and all tensile loads is transferred to the core, so there is no tensile load on the aluminium strands. The point of this transition is called the knee point temperature. For accuracy in determining the value of thermal knee points, especially in ACCC/TW conductors can use methods developed in programs such as PLS-CADD™ or Sag10®. But when programs such as PLS-CADD™ or Sag10® are not available, and knee point temperatures need to be determined, there are numerical methods that can be used to produce the thermal knee points. One numerical method that can be used is the Sag Hybrid Method [19]. This method performs two calculations simultaneously, using the composite property of the conductor, and the core property.

Mathematical equations for sag-tension calculations are used repeatedly and iteratively to calculate changes in conductor and core length as a function of temperature. From this repeated calculation, the knee point temperature can be determined when the tension in the conductor is the same as the tension in the core. This equation can be programmed into Microsoft Excel, and the iterative calculations can be carried out [20].
2. Research methods

![Figure 1. Sag testing configuration.](image1)

![Figure 2. Sag testing schemes.](image2)

The method used to determine the knee point temperature is carried out on the ACCC/TW LISBON (310) conductor where this conductor will be performed on the simulation of overhead transmission line system. The test configuration, as shown in Figure 1, shows the installation position of the conductors between 2 towers, with a level length of 100 meters. At both ends of the conductor are installed accessories in the form of dead ends and insulators. At one end of the conductor, a load cell is installed, as a tool to determine the tension or mechanical tensile load experienced by the conductor attached. In this test, data on the sag and tension in the conductor will always be recorded. The measurement of the sag will begin from the ambient temperature to the maximum operating temperature. The configuration and schematic of the sag test can be seen in Figure 1 and Figure 2. The sag test is carried out using an initial tension of around 25% RTS of the conductor. The electrical loading is gradually giving until the temperature 180 oC is reached. From the results of this measurement, a graph of sag will be made. From this graph, we will be able to know that at certain temperature conditions, the sag pattern will change along with the increase in conductor temperature. The increasing of the sag will tend to be smaller and more stable which is known as knee point temperature.

3. Result and discussion

In this study, a series of tests has been carried out three times. The first test, the objects of conductors are consist of ACCC/TW LISBON (310) and ACSR HAWK (240/40). This test is carried out in parallel to make a direct comparison between the two conductors with the same environmental conditions. The second and third tests only use ACCC/TW LISBON (310) as the test. The 1st, 2nd, and 3rd tests are carried out on different days so that the environmental conditions received by the test conductor object are always different. From the ACCC/TW LISBON (310) test carried out repeatedly, it is expected to obtain sufficient data representing the actual sag value.
The data from the results of this test will be compared with the sag value based on calculations. Sag value calculation is done mathematically according to the formulation discussed in the previous section. By using a calculation program, analysis, and prediction of sag and knee point temperatures can be performed in a variety of environmental conditions. The characteristics of sag and temperature of the test results is shown in figure 3.

Based on figure 3, it can be shown that with an increase in conductor temperature, the sag value also increased, but in at a certain point the sag rising trend changes significantly, the sag increases relatively small and tends to be stable, this condition persists to the maximum permissible operating temperature for the ACCC/TW conductor which is 180°C - 200°C. To carry out the next discussion will be compared the graph of the sag to the temperature characteristics between the test results of the ACCC/TW LISBON (310) conductor and the calculation results of the ACCC/TW LISBON (310) conductor.

Figure 4 shows that the temperature increases causes the increases of sag value. At a certain point, the sag rising trend changes significantly. The sag value increases relatively small and tends to be stable, sag pattern changes, at this point called the knee point temperature. The pattern of sag increase can occur so because of the displacement of the mechanical tensile load that was previously charged to the conductor as a whole shifted to be charged only by the core.

The following graph shows the sag shift pattern, based on the conductor sag and the core sag.

**Figure 3.** Graphs of sag to temperature characteristic at ACSR HAWK and ACCC/TW LISBON conductors based on the results of the 1st, 2nd and 3rd test.
Figure 4. Graph of the knee point temperature in ACCC/TW LISBON (310) conductor based on the test results of the 1st, 2nd, 3rd and the calculation.

Figure 5. Graphs of sag and tension characteristics of temperature at the core and ACCC/TW LISBON conductor.

Figure 5 shows the final sag pattern, where at condition before the knee point temperature, the final sag will follow the conductor sag pattern, but after the knee point temperature, the final sag will follow the core sag pattern. This can occur because in the condition before the knee point temperature, the conductor tension is greater than the core tension, but after the knee point temperature, the tension condition starts to reverse, the tension position at the core is greater than the tension of the conductor. At the knee point temperature, the final sag begins to shift from the sag that is borne by the conductor tension to borne by only the core tension. The final sag after the knee point temperature will tend to be stable according to the condition of the core tension.

From the calculation analysis, to reach the knee point temperature, a higher ampacity load is required for a longer span length. The loading capacity for a span of 100m - 500m with an initial tension of 1800kg - 2400kg can be seen in the table 1 below:
Table 1. The knee point temperature and loading capacity in various span length.

| Span (m) | Knee Point Temperature (KPT) (°C) | Loading Capacity (%) |
|---------|----------------------------------|-----------------------|
| 100     | 61.03 - 63.84                    | 39.97 - 43.03         |
| 200     | 74.69 - 74.91                    | 52.85 - 53.02         |
| 300     | 86.57 - 86.80                    | 61.32 - 61.47         |
| 400     | 95.83 - 97.60                    | 67.85 - 67.90         |
| 500     | 102.84 - 106.89                  | 70.66 - 72.69         |

4. Conclusion
The study clearly shows the knee point temperature characteristic of the high capacity low sag (HCLS) type of ACCC/TW conductor, where the sag becomes stable at the temperature point of 61.03 °C. The value of knee point temperature in ACCC/TW conductor is influenced by span length, initial tension, sag, and ambient temperature.

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References
[1] Deve H and Anderson T 2003 3M Aluminum Conductor Composite Reinforced Technical Notebook (795 kcmil Family): Conductor and Accessory Testing 3M, St. Paul, MN
[2] Thrash F R 2001 ACSS/TW-An improved high temperature conductor for upgrading existing lines or new construction 2001 Power Engineering Society Summer Meeting, Conference Proceedings (Cat. No. 01CH37262) I 182–5
[3] Thrash F R 1999 ACSS/TW-an improved high temperature conductor for upgrading existing line or new construction [C] Transmission and Distribution Conference
[4] Pon C 2004 High temperature–sag characterization test on 1020 kcmil ACCC/TW conductor for composite technology corporation Kenectrics North Am. Inc. Rep. No. K-422024-RC-0003-R00
[5] Anders G J 1997 Rating of electric power cables: ampacity computations for transmission, distribution, and industrial applications (IEEE)
[6] Conductors O E 1995 Calculation Methods for Stranded Bare Conductors IEC Stand. 61597
[7] Xia Z, Xia Y, Xu Z and Wu J 2015 Study on the calculation model of maximum allowable time and ampacity for overload operation of overhead transmission line in a short time 2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT) 1458–61
[8] Alberdi R, Albizu I, Fernandez E, Bedialauneta M T, Fernandez R and Mazón A J 2019 Wind Speed Effect on the Conductor Temperature of a Distribution Line 2019 International Conference on Clean Electrical Power (ICCEP) 669–73
[9] Kanálik M, Margitová A, Urbanský J and Beňa L 2019 Temperature calculation of overhead power line conductors according to the CIGRE Technical Brochure 207 2019 20th International Scientific Conference on Electric Power Engineering (EPE) 1–5
[10] Davis M W 1977 A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines--Part I: General description and justification of the real time thermal rating system IEEE Trans. Power Appar. Syst. 96 803–9
[11] Foss S D, Lin S H, Stillwell H R and Fernandes R A 1983 Dynamic thermal line ratings part ii conductor temperature sensor and laboratory field test evaluation IEEE Trans. power Appar. Syst. 1865–76
[12] Koval D O and Billinton R 1970 Determination of transmission line ampacities by probability and numerical methods IEEE Trans. Power Appar. Syst. 1485–92
[13] Davis M W 1977 A new thermal rating approach: The real time thermal rating system for strategic overhead conductor transmission lines--Part II: Steady state thermal rating program IEEE Trans. Power Appar. Syst. 96 810–25
[14] Black W Z and Byrd W R 1983 Real-time ampacity model for overhead lines IEEE Trans. Power Appar. Syst. 2289–93
[15] Foss S D, Lin S H and Fernandes R A 1983 Dynamic thermal line ratings part I dynamic ampacity rating algorithm IEEE Trans. Power Appar. Syst. 1858–64
[16] Vakili F, Viles M R, Reding J L and Sherry N G 1986 Dynamic thermal line loading monitor IEEE Trans. Power Syst. 1 62–6
[17] Uski S 2015 Estimation method for dynamic line rating potential and economic benefits Int. J. Electr. Power Energy Syst. 65 76–82
[18] Douglass D A and Thrash R 2006 Sag and tension of conductor Electr. power Gener. Transm. Distrib. Press. Florida, 2007).
[19] Alawar A, Bosze E J and Nutt S R 2006 A hybrid numerical method to calculate the sag of composite conductors Electr. power Syst. Res. 76 389–94
[20] Global C T C 2011 Engineering Transmission Lines with High Capacity Low Sag ACCC® Conductors First Ed. Ed.