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Review of Thermal Stress and Condition Monitoring Technologies for Overhead Transmission Lines: Issues and Challenges

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ABSTRACT The overhead transmission line system is one of the methods of transmitting electrical energy at a high voltage from one point to another, especially over long distances. The demand for electrical energy is increasing due to the increase in the world population, the evolution of transport technology, and economic expansion, thereby resulting in overloading to the overhead line (OHL) system. In building new infrastructure for transmission lines, several issues need to be addressed. Thus, optimizing existing power by increasing the ampacity of power line is a practical solution to meet energy demand issues. During long-term operation, the temperature of OHL conductors may increase beyond their rated temperature, which is typically 75 °C for conventional conductors such as aluminum-conductor steel-reinforced cable. This condition is defined as thermal stress, which results in lower sag vertical clearance, tensile loss, elongation and creep, and reduced life span of the conductors. This condition must be avoided to ensure that the line is not permanently elongated, which can disrupt the vertical ground clearance, and to expand the conductor's life. Other factors such as lightning, wildfire, aging, and degradation of the conductor can also cause thermal stress on the conductors and have thermal effects on the conductor's performance. Therefore, unwanted thermal stress needs to be examined and identified by monitoring the thermal effect and behavior of the lines. This paper presents the state of the art in monitoring technologies that can be used to identify thermal stress on OHL conductors, including the issues and challenges in monitoring. At the end of this paper, a few suggestions are included to address the occurrence and assessment of thermal stress in lines. Ultimately, this work may provide complete information to researchers and maintenance engineers to enable them to make better decisions on condition monitoring, operation, and maintenance of the system.

INDEX TERMS Overhead transmission line, thermal rating, conductor temperature, thermal stress effect, conditioning monitoring.

I. INTRODUCTION

Overhead transmission lines are divided into short, medium, and long distances, with different voltage levels from 33 kV to more than 500 kV. The transmission lines consist of an overhead line (OHL) conductor, which is suspended by transmission towers and supported by pin-type suspension and air insulators, withstanding both normal operating voltage and over-voltages due to switching and lightning. The most commonly used conductor for transmission lines is aluminum-conductor steel-reinforced (ACSR) cable due to its weight and lower cost. Different types of conductors can

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be used in OHL design according to the terrain and capacity requirements. Thus, OHL conductors need to be improved to enhance their electrical and mechanical properties [1], [2]. The projected electrical energy demand against the world population is shown in Fig. 1 [3]. The growth of the world population is directly linear to the overall energy demand, both increasing significantly since 1940, and the energy demand is predicted to increase exponentially in the future. The increase in energy demand is also related to the increased use of electrical appliances in households, social activities, lifestyle, and climate change. Meanwhile, the global industrial sector energy consumption has increased significantly since 2006, as shown in Fig. 2 [4], because of the Fourth Industrial Revolution. This situation will produce a tremendous impact on energy demand, which is predicted to reach as high as 71961 ZW in 2030.

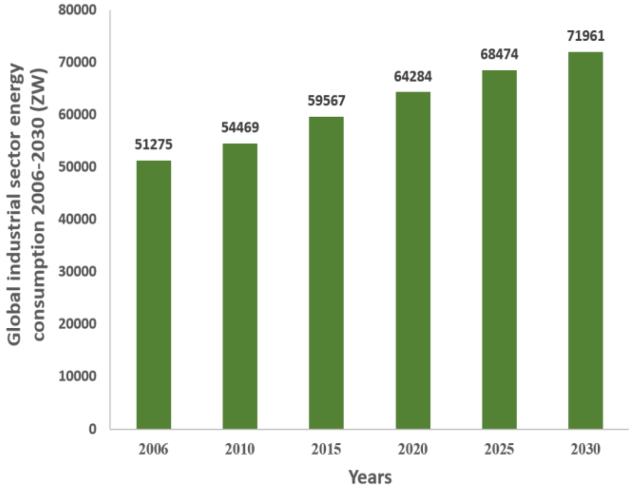


FIGURE 1. Estimation of energy demand in the industrial sector [3].

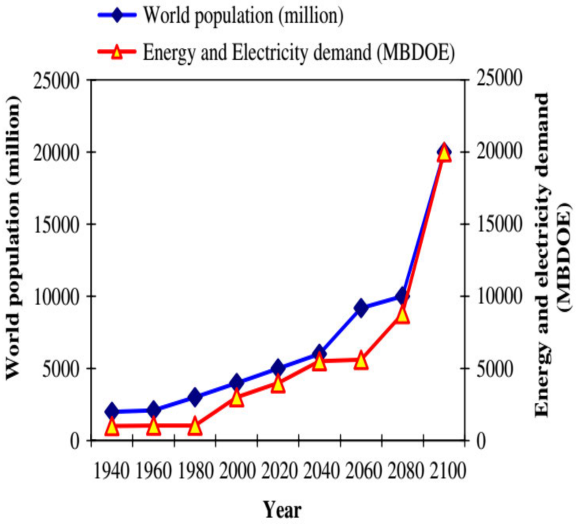


FIGURE 2. Population growth versus energy and electricity demand[4].

Thus, to meet the energy demand, OHLs need to have better capability to transmit higher energy. An important issue that may emerge is how the ampacity of transmission lines can be enhanced to improve the optimization of power lines for accommodating electricity demand. Another option is to build new infrastructure for transmission lines. However, implementing a new transmission line is not a straightforward process because many aspects need to be considered, such as right of way and high cost and time consumption [5]. Therefore, research on increasing line capacity load [6], thermal behavior of conductors [7], [8], dynamic line rating (DLR) by using real-time data [9], upgrading existing line such as reconductoring of lines needs to be strengthened. Many studies address issues such as reconductoring old conductors to improve their performance or increase the line rating [10]–[12].

Reconductoring may help, but this approach has limitation in terms of conductor size selection due to existing capacity and costly installation. Thus, upgrading the line rating is more practical to solve issues. Load carrying capacity can be upgraded by increasing the line rating; however, more current can flow over the thermal limit, causing overload and increased conductor operating temperature. This incidence indicates that conductors must not exceed the maximum allowable conductor temperature in their design to ensure the reliability and safety of transmission line. The maximum allowable conductor temperature is governed by 1) the maximum permissible sag of the conductor and 2) the thermal limit of the conductor or hardware damage [13]. Therefore, conductor temperature limits the transmission line capability.

Thermal rating is an important factor that needs to be taken into account in designing and operating transmission lines. One major blackout was reported in the Northeast United States in 2003 due to the overloading and the failure of the operator to detect the initial contingency state [14]. Wildfire, short-circuit, and lightning may also lead to the increase in temperature and thus cause the conductor to experience thermal stress in lines. The increase in the conductor temperature affects the mechanical properties and deteriorates the durability of conductors, causing sag and reduced ground clearance, tensile loss, accelerated aging of components during long-term operation, and disrupted performance of transmission lines. An overheated conductor might also damage the insulator by causing microcracks [15]. In the long term, accelerated damage may affect the ability of an insulator to protect the system.

The issue of thermal stress along transmission lines has become a topic of interest and priority in current research, which cover the causes and effects of thermal stress, and the methods of improving the reliability of the system and enhancing the transmission line performance [16]–[19] {Formatting Citation}. Various monitoring techniques have been developed to address thermal stress along the transmission lines. The monitoring of OHLs should be able to take place under many conditions, such as normal, transient, and contingency or fault conditions. Normally, monitoring OHLs takes into account real-time data and atmospheric condition to ensure the accuracy. Therefore, monitoring OHLs also involves monitoring weather conditions to determine the line rating of a specified conductor, thus ensuring that conductors are in good condition and perform well, which may reduce losses and risk of faults.

In this paper, contemporary trends and advancements related to overhead conductors and comprehensive studies to identify and monitoring thermal stress on OHLs are reviewed. The following are the main contributions of the paper:

- Conventional OHL and modified conductors are briefly reviewed. The reasons for market availability of replacement conductors along with the advantages of different types of conductors are presented.
- A fundamental review on thermal line rating is presented along with thermal stress and potential risks associated with untreated thermal stress in terms of mechanical and electrical performances.
- A review of the issues and challenges encountered during thermal stress monitoring is presented.
- The available standards for overhead transmission line related with thermal behavior of the lines are given to help engineers in planning, design, and maintenance process scheduling.
- The state-of-the-art equipment and techniques for detecting thermal stress and suggestions for the assessment of thermal stress are given, thus helping ensure that the operation and maintenance process can be performed effectively.

Conventional and modern OHL conductors are highlighted in Section 2. The transmission line thermal ratings are discussed in Section 3. The causes and effects of thermal stress are discussed in Section 4. The effects of thermal stress on OHLs are discussed in Section 5. Thermal monitoring techniques, available standards for OHLs, issues, and challenges are discussed in Section 6. The conclusion of this review and suggestions for future improvement of thermal stress condition monitoring technologies are outlined in Section 7.

II. OHL CONDUCTORS

A transmission line consists of a capacitor and separated by air, which acts as a dielectric between them. The potential difference between conductors in transmission lines causes them to be charged similarly to capacitors, proportional to its length. Capacitance is neglected for short transmission lines but is considered an important parameter in long lines (typically more than 100 km) and in high-voltage lines [20]. As the length of conductor increases, the capacitance also increases in OHLs. When more than one conductor is placed close to each other, a coupling effect from the electric field will occur. This effect is represented by mutual capacitance between the conductors and is associated with the ability to hold an electric charge between two adjacent conductors.

The magnitude of mutual capacitance depends on the distance between spacing conductors. The decrease in the distance between line phases increases the mutual capacitance. A high mutual capacitance corresponds to high losses and power transmitted to the receiving end. In contrast, if the height of the line increases, then the capacitance will also decrease, thereby increasing the tension of lines [21]. In some cases, the conductor may break due to excessive tension. Therefore, sag is allowed to minimize the tension in lines, and both have been compromised towards the safe limits.

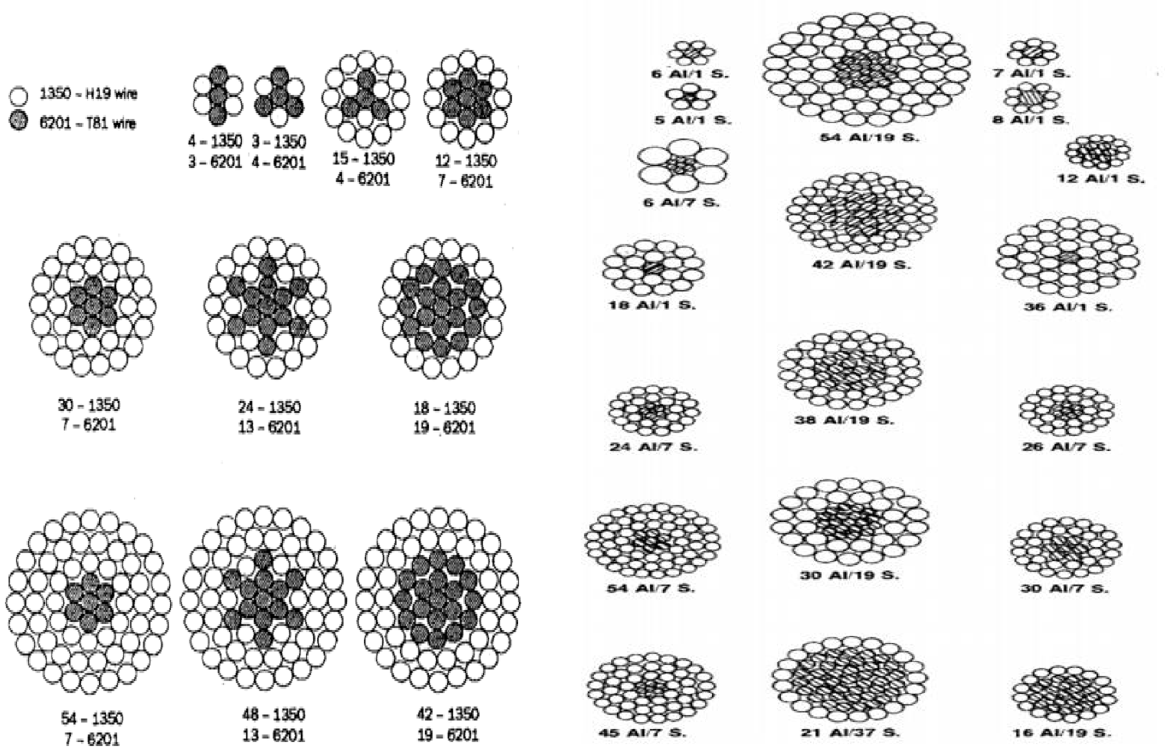
Another practice is by having a line transposition whereby the conductors or phases being moved to the next physical location in a regular sequence in order to reduce the effect of capacitance and the electrostatic unbalanced voltages. This will also help to reduce the system losses and to stabilize the system voltage.

OHL conductors are an important structure in a power transmission network. An OHL is used to transmit the wave of voltage and current from one point to another along transmission lines. The selection of conductor type, dimension, and electrical and mechanical properties has a major impact on transmission line design. The overhead bare conductor can be classified into two types: homogeneous and nonhomogeneous [22]. A homogeneous conductor consists of the same strand material, whereas a nonhomogeneous conductor—also known as a composite conductor—consists of mixed strands of wires from different materials. Usually, two types of materials are combined in a conductor to enhance its the mechanical and electrical properties. Two types of overhead conductors are used in transmission lines: conventional and modified. A modified conductor is designed to cope with specified line applications and requirements. It can also operate in higher temperatures than the conventional conductor. A good conductor should have optimum efficiency in transmit electric power during operation. Aside from implementation and hardware costs, electrical properties need to be considered in selecting the right conductor. A good conductor should have [22]:

- Lower thermal elongation expansion. Material wire with a low thermal coefficient expansion is preferred, thereby ensuring that the conductor can withstand high temperatures with less sag.
- Lower electrical resistance. A conductor with a low electrical resistance experiences less electrical loss and allows for increased ratings.
- High conductivity of material. High conductivity enables the flow of more current through the conductor, thereby allowing more energy to be transmitted.
- High strength of material. This feature ensures that the conductor can withstand high operating temperatures and extreme weather.

A. CONVENTIONAL CONDUCTORS

Conventional conductors have a round wire strand made from different types of materials that comprise several strands united into a bulk conductor. The arrangement of the strands of a conventional conductor is shown in Fig. 3. This figure illustrates a wire stranding that consists of a center wire surrounded by one or more layers depending on the size of the conductor. However, the number of high-strand cores will delay the effect of the elongation of a conductor. Conventional conductors include all-aluminum conductor (AAC),



(a) (b)

FIGURE 3. Strands of (a) ACAR (b) ACSR wires [22].

all-aluminum alloy conductor (AAAC), aluminum-conductor alloy-reinforced (ACAR), ACSR, and aluminum alloy conductor steel-reinforced (AACSR) [22], [23]. Traditionally, a conventional conductor consists of all- aluminum alloy strands, where the aluminum core of the strands is replaced with other core strand materials such as steel or alloy (e.g., ACSR and AACSR) to improve their electrical and mechanical properties because aluminum wire has a high thermal expansion coefficient, resulting in faster expansion of the core strand when exposed to high temperature. Furthermore, it has the potential to creep under high temperatures over their operation times. In contrast, steel strengthens the conductor by bearing the tensile load and having low thermal elongation properties. Alternatively, most transmission lines use the ACSR conductor as bare overhead transmission line due to the following advantages [23]:

- The presence of steel core in ACSR reduces its elongation and thus its tendency to experience low sag during operation.
- ACSR has good conductivity and high-tensile strength, thereby enabling it to be installed in icy and wind loading areas.
- ACSR offers more durability, having five times greater fatigue life than AAAC. Thus, it is at less risk of being broken by falling tree limbs.

With these advantages, ACSR is a common conductor, as mentioned earlier in overhead transmission lines.

The standard operation temperature of conventional conductors ranges between 50 °C and 75 °C depending on the size of the conductor [24], [25]. However, some conductors can operate beyond the normal ranges according to their size due to uprating line issues. For instance, the maximum continuous operating temperature for ACSR DRAKE 795 kcmil (26/7) is 93 °C with emergency rating of 127 °C [19]. Nevertheless, the normal maximum operating temperature of conventional conductors should not exceed 75 °C to prevent annealing. The conventional conductor tends to give permanent losses due to the annealing of aluminum strands at temperatures over 94 °C to 100 °C caused by thermal stress [19], [22].

In the CIGRE technical brochure [26], the maximum allowable conductor temperature is prorated at 95 °C as long as the electrical clearance does not exceed when increase the thermal rating of the conductor. This condition will help increase the thermal rating between 20% and 40% without replacing the conductor for OHL. However, continuous exposure to high temperature may degrade the tensile strength of OHLs. Reference [27] concluded that a nonhomogeneous conductor has better mechanical properties than a homogeneous conductor. These newly obtained properties increased the maximum operating conductor temperature over 80 °C without negative effects on the conductor. The selection of conductor installation is another crucial aspect. A conductor must not only withstand wind and weather loading, but must

TABLE 1. Commonly available conventional conductors in OHL.

	Composite material	Function	Advantages	Disadvantages	References
AAC	Outer: Al Core: Al (extra-hard-drawn 1350-H19)	▪ Most urban areas at short-span lengths	▪ Good corrosion resistance ▪ Better conductivity than AAAC ▪ Lighter than ACSR	▪ Poor strength	[22], [28]
AAAC	Outer: Al 1350-H19 Core: 6201-T81 Al alloy	▪ Seacoast area ▪ More suitable than ACSR in overhead distribution	▪ Excellent corrosion resistance ▪ Higher tensile strength than AAC ▪ Lower resistance than equivalent ACSR	▪ Moderate conductivity ▪ Moderate hardness against bending stress ▪ Prone to fatigue failure problem ▪ Present aluminum alloy makes it expensive	[22], [28]–[30]
ACAR	Outer: Al 1350-H19 Core: 6201 Al alloy	▪ Wide transmission line application	▪ Excellent corrosion resistance ▪ Higher strength ▪ May be consider as a replacement for conventional ACSR	▪ Lower corrosion resistance than AAAC	[22], [31]
ACSR	Outer: Al 1350-H19 Core: Galvanize steel	▪ Wide usage in long-span transmission lines and rural distribution area ▪ Suitable across rivers ▪ Ice and wind loading area	▪ Excellent strength and low sag ▪ Good conductivity ▪ Higher durability compared with AAAC in bending stress	▪ Maximum operating temperature of 93 °C, limited to heavy load operation. ▪ Less conductivity compared with ACAR	[22], [24]

also be suitable to the local terrain. For example, a conductor installed near the coast will be prone to severe corrosion problems. Therefore, AAAC is more suitable because it has superior anticorrosion properties. The AACSR conductor is good for extra-long spans, such as across rivers, because of its combination of high-tensile aluminum alloy and steel, thereby having a higher tensile strength and moderate conductivity for conducting electric current. Table 1 lists a comparison of common conventional conductors and their application in OHL.

B. MODIFIED CONDUCTORS

The improvement of conductor performance was studied in [22], [24], [32]–[40]. The conventional conductor has been upgraded to enhance its power through the transmission line under specific conditions. Modifications such as using different types of coating for corrosion resistance, deformation of strand shape, and changing the geometric configuration of the conductor, were made to optimize the conductor performance. The electrical and mechanical properties of transmission lines were improved to strengthen the conductor's ability to resist strong wind (galloping), low wind speed (aeolian vibration), ice loading, and high temperatures. Table 2 lists the various types of modified conductors according to their respective groups.

The trapezoidal wire (TW) geometry of aluminum wire will reduce 10% of the outer diameter of a conventional round conductor [22]. As a result of the compactness, more aluminum conductors can be added, thereby it is stronger to endure in icy and wind load. This type uses a conventional conductor with a modified geometric configuration but with a lighter weight and improved current carrying capacity. TW conductors are typically used to increase the current carrying capacity and reduce the impact on the conductor to ensure that it can handle high operating temperatures and has a low sag effect [23]. For instance, ACSS/TW not only has a reduced diameter but also an increased operating temperature range from 200 °C to 250 °C without affecting the mechanical properties [39]. The TW conductor is also applied to the self-damping conductors such as ASCR/SD to reduce the conductor size and hence offer better temperature gradient, low resistance, and low drag for better resistance to the aeolian vibration [33].

Another conductor with different geometric arrangements is the motion resistance conductor, which consists of a twisted- pair (TP) conductor and oval conductor to better withstand extreme wind loading. These conductors are used to address aeolian vibration and galloping due to high wind speed. The effect of aeolian vibration and galloping may result in conductor fatigue, damaged structure and flashover when conductor phases make contact with each other. Motion resistance conductors have two sub-conductors according to the thermal and mechanical strength required by the line. The sub-conductors can consist of AAC, AAAC, ACAR, ACSR, ACSR/TW, and AAC/TW conductors [22]. CIGRE WG 22.11.04 recommends a safe design tension at an average

TABLE 2. Types of modified conductor.

Group	Type of conductor	Function	Advantages	Disadvantages	References
TW	ACSR/TW, AAC/TW, AAAC/TW, ACSS/TW	▪ Application reduces wind and ice load problem	▪ Improves mechanical and electrical properties of conventional conductor ▪ Lighter than equivalent diameter with conventional conductor ▪ Geometric configuration increases current carrying capacity ▪ Restricts creep over long-term service	▪ Lines up to 16 kV, small conductors may be prone to the corona effect ▪ Manufacturing the geometric configuration for stranding wire machine needs special equipment, which may be prone to breaking	[22], [37]–[40]
TP	ACSR/TP, AAC/TP, ACAR/TP	▪ Anti-galloping motion and aeolian vibration	▪ Configuration prevents ice formation ▪ Low power losses	▪ Limited use for other applications ▪ Lower operating conductor temperature ▪ Costly installation and hardware	[22], [34], [35]
HTLS	ZTACIR (with INVAR), GZTACSR, TACSR, ACSS, ACCR, ACCC	▪ Use in high load operation ▪ Wind area and aeolian wind ▪ Crossing river or long distance	▪ Higher conductivity ▪ Operates in high temperatures ▪ Low potential sag ▪ Lighter ▪ Suitable in extreme weather ▪ Minimum fatigue issues	▪ Higher installation cost ▪ Higher energy losses	[11], [22], [24], [32]

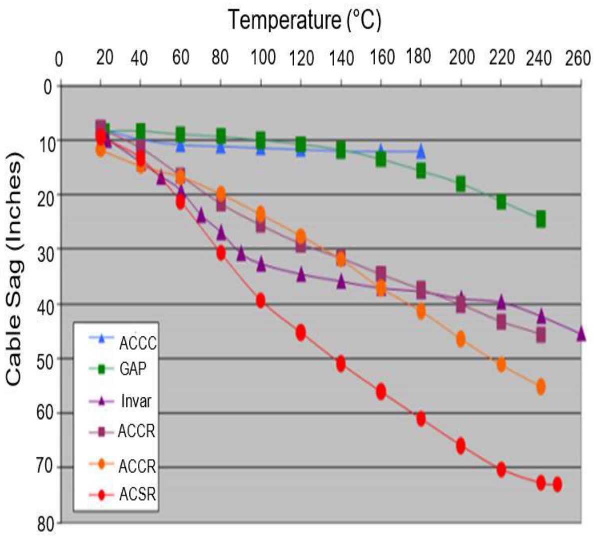
temperature by using a certain conductor according to terrain categories to address the aeolian vibration [41].

The high-temperature low-sag (HTLS) conductors became popular several years ago due to its high performance. Research has covered the performance [42]–[45], durability [32], [46], [47], economic cost [24], [48]–[50], ways to increase the ampacity line [51], [52] and material properties of HTLS conductors [1], [53], [54]. An HTLS conductors is not only able to address the vibration and galloping issues but can also increase the current carrying capacity of transmission lines to meet higher electricity demand. Given space construction and investment issues, the HTLS conductors is also viewed as the best solution to power demand issues. The HTLS conductors can operate at higher temperatures ranging from 150 °C to 250° C [55]. Table 3 lists the operating temperatures of several HTLS conductors, showing that these conductors can better withstand high-temperature operations than the conventional conductor.

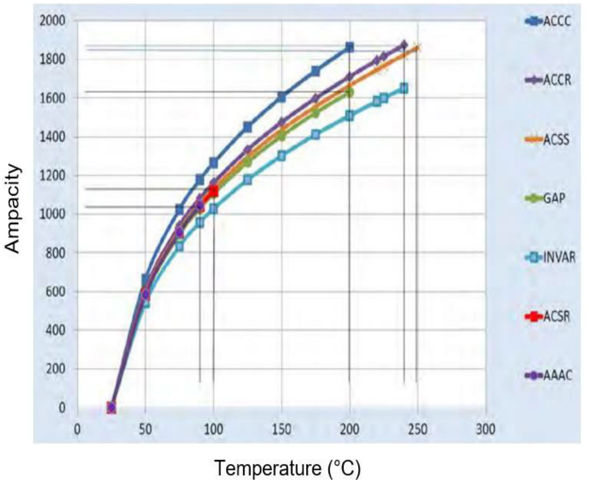
HTLS is an option to reconductor existing transmission lines and deal with power demand. It also has less weight, less sag, and more strength even at the same diameter as ACSR. Moreover, HTLS conductors have the potential to carry more current than conventional conductors. The performance of the composite-core ACCC conductor was recently studied in [44]. The sag of the ACCC conductor was much lower than that of ACSR when they exceed their knee-point temperatures of 90 °C and 70 °C, respectively, because of the mechanical properties of ACCC, which has a lower core tensile strength than ACSR at approximately the same diameter. A detailed comparison between HTLS and ACSR was discussed in [56].

The performance comparison of several HTLS and conventional conductor as reported by manufacturers is shown in Fig. 4 (a) and Fig. 4 (b) [57]. The comparison shows that HTLS can better handle high conductor temperatures with low-sag incidence at elevated temperatures compared with the conventional conductor. However, among the HTLS conductors, ACCC performs best because it has low-sag impact even at elevated temperatures due to the high-tensile strength of carbon hybrid contributed by the core strand compared with most other HTLS core strands. The geometric design of HTLS conductors offers a smaller conductor to address the sagging problem and to maintain a good clearance when the conductors are operated at elevated temperatures, thereby reducing the structural weight and installation cost [22]. HTLS not only offers better geometry configuration but also has good electrical conductivity. Other advantages of HTLS include [58], [60], [61]:

- Good conductivity and low resistivity, which allows more current flow to optimize the carrying capacity.
- A low thermal expansion coefficient, which gives it the ability to withstand high operating temperatures with lower thermal elongation, resulting in minimum sag impact.
- Lower electrical resistance, which offers less electrical loss and allows for increased rating.



(a). **Comparison of sag performance between several conductors [57].**



(b). **Comparison of ampacity between conductor OHLs [57]**

FIGURE 4. (a) Comparison of sag performance between several conductors [57]. (b) Comparison of ampacity between conductor OHLs [57].

TABLE 3. Properties of HTLS conductor [22], [58], [59].

Type	Material configuration	Operating temperature
TACSR	**Outer**: Thermal-resistant aluminium zirconium alloy **Core**: Galvanized steel reinforced	150 °C (continuous) 180 °C (emergency)
(Z)TACSR	**Outer**: Thermal-resistant aluminum zirconium alloy **Core**: Galvanized steel reinforced	210 °C (continuous) 240 °C (emergency)
GZTACSR	**Outer**: Thermal-resistant aluminum zirconium alloy **Core**: Galvanized steel reinforced	210 °C (continuous)
TACIR	**Outer:** Thermal-resistant zirconium aluminum alloy **Core:** Iron–nickel alloy steel	150°C (continues)
(Z)TACIR	**Outer**: Thermal-resistant zirconium aluminum alloy **Core**: Aluminum-clad invar alloy/zinc-coated invar alloy	210 °C (continuous)
ACCC	**Outer**: Annealed aluminum **Core**: Epoxy/fiber glass	180 °C (continuous) 200 °C (emergency)
ACSS	**Outer**: 1350-0 annealed aluminum **Core**: Steel	210 °C (continuous)
ACCR	**Outer**: Aluminum zirconium alloy **Core**: Metal matrix composite wires with alumina fibers	210 °C (continuous) 240 °C (emergency)

Thus, HTLS conductors are the best solution to upgrade the power lines from ACSR and to be used for new high-voltage transmission lines. Alternatively, reconductoring HTLS from existing lines of a conventional conductor is more practical to improve the capacity of power lines. Therefore, the economic cost of reconductoring has driven a new field of studies. Table 4 shows the comparison cost between ACSR and ACCC, taking into account the new construction of power lines by using a different ACSR conductor or replacing an existing ACSR conductor with ACCC to improve the current capacity of the lines.

The new ACSR Hawk conductor is considered because it can improve the current capacity by 13% more than the existing ACSR Ostrich conductor. However, the new ACSR conductor is bigger than the old one. Thus, the weight of the conductor needs to be considered to avoid sagging issues. The ACCC conductor has a 31% higher current carrying capacity than the existing ACSR conductor and a lower weight and size [49]. The cost of reconductoring of HTLS is two times lower than building a new ACSR power line option. In contrast, a study in [50] on uprating a 220 kV double circuit to 1260 A compared a few HTLS conductors for uprating with an equivalent diameter as the existing ACSR conductor. The ACCC offers the lowest power losses because of its low resistance. However, ACSS is preferred because the ACCC conductor has 51% higher installation and maintenance costs than the ACSS conductor, as shown in Fig. 5. However, despite its high installation cost, the ACCC conductor offers

TABLE 4. Comparison cost of applicable solution to improve power line rating [49].

110kV	ACSR (Ostrich) conductor for existing line	ACSR (Hawk) conductor for new construction	ACCC conductor for uprating existing line
Diameter (mm)	17.27	21.79	17.09
Altering current (AC) resistance at 25 °C (Ω/km)	0.190	0.1198	0.1520
Current capacity (A)	490	640	921
Total investment cost Euro (€)	N/A	2440000	1595000

N/A = not available.

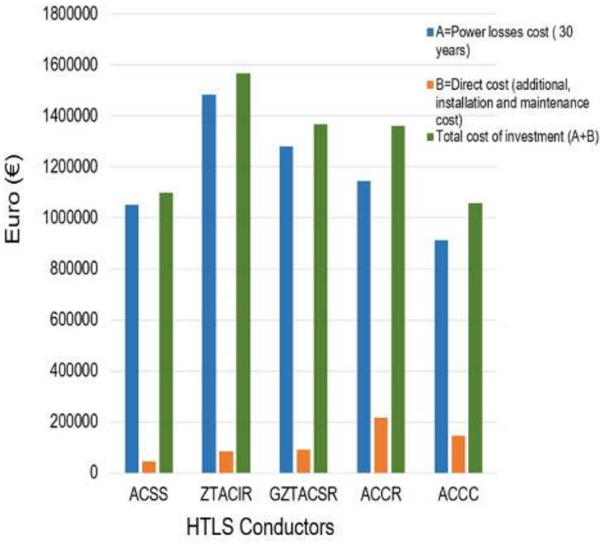


FIGURE 5. Comparison cost of reconductoring HTLS for 220kV [50].

more benefits because it can reduce more line losses than other HTLS conductors, thereby ensuring more profitable long-term returns, as reported in [57]. Another study in [48] used the ACCC conductor for uprating 132 KV power lines because it ensures better profits than other HTLS conductors given its approximately three times higher power transfer capability than the ACSR conductor. Table 5 shows the comparison cost between ACSR and ACCC conductors per foot according to the current capacity and diameter size[45]. The conductor size is represented as the area of the conductor in kcmil unit. The ACCC conductor is smaller than the ACSR conductor and avoids sag issues because of its light weight, and it can also operate at high temperatures.

III. TRANSMISSION LINE THERMAL RATING

Thermal rating is associated with the continuous temperature conductor as it limits transmission line capability. Increasing the thermal rating allows transmission lines to be operated close to their actual ampacity. As a result, line temperature will increase as well. Ultimately, the transmission lines can be fully utilized to transmit higher electrical power throughout the operating time. Ampacity is referred to as the maximum continuous current carrying capacity of the conductors, where the rating needs to comply with the permissible sag and line ground clearance stipulated during the planning and designing of the line according to the size of the conductor of the transmission line.

The line rating cannot be obtained directly from the line. It has to be calculated based on the assumed or measured weather condition, solar heating, convective and radiative cooling, load current, and physical properties of conductors. Two standards are available to determine the transmission line thermal rating, namely, IEEE 738 standard and CIGRE standard [62], [63], which can be used to determine the maximum ampacity of the bare conductor, which is the maximum line rating that refers to continuous current flow along the line in the steady-state thermal rating and transient rating.

In the steady-state thermal rating, these standards provide the same concept of heat balance, where the heat gain to the conductor is balanced by the heat dissipated to the surrounding air. In contrast, the transient rating, the conductor is not in the thermal equilibrium as the heat stored in the conductor. Both standards can be used to determine the conductor temperature and have been studied and reported in [64]. This work applied the same concept and found that both standards have different equations and considerations in determining the ampacity rating in the calculation. Nevertheless, both methods have no significant difference in their results [19], [65], [66]. The temperature and thermal rating may be different in each span due to different atmospheric conditions although the same current loading flows through the lines. The line rating of the conductor was calculated by using available standards and applying real-time data in [67], [68]. The line rating of the conductor is dependent on weather conditions in specific circumstances. This line rating is called dynamic thermal rating, which can assist operators in forecasting the line rating and temperature of lines as well in their planning, designing, and operating process.

A. STEADY-STATE THERMAL RATING

The steady-state thermal rating is defined as the maximum electric continuous current corresponding to the maximum allowable conductor temperature according to weather condition and physical conductor parameters. In this state, the line rating is constant and does not vary with time. Likewise, the conductor temperature and current are constant and uniform; this condition is called equilibrium condition. The IEEE and CIGRE standards are aligned in using the heat balance concept, where the heat obtained from the conductor is balanced with the heat loss (cooling process). Thus, no heat is stored in the conductors. The heating and cooling process of the OHL conductor is illustrated in Fig. 6 [69]. The figure indicates that the heat gain of the conductor is contributed by solar heating (P_s) and ohmic losses (P_j), and heat loss is due to convection (P_c) and radiation (P_r) by the

TABLE 5. Comparison cost between ACCC and ACSR according to current [45].

Current capacity requirement (A)	Size (kcmil)	ACCC		ACSR		
		Number of trapezoidal Al wire	Price/foot ($)	Size (kcmil)	Number (Al/steel)	Price/foot ($)
1000	430	10	3.80	666.6	24/7	3.06
1260	611	16	3.36	954	45/7	2.84
1400	713	18	3.69	1192.5	45/7	3.50
1520	816	19	4.01	1351.05	54/19	4.63
1760	1020	22	4.78	1590	45/7	4.90

All ACCC cores are the same as the composite-core round-shaped geometry at the center conductor.
The price of the conductor varies even under the same group of conductors according to mechanical and electrical properties such as weight, overall diameter, number of strands, size of strands, and coating material for corrosion and DC resistance.

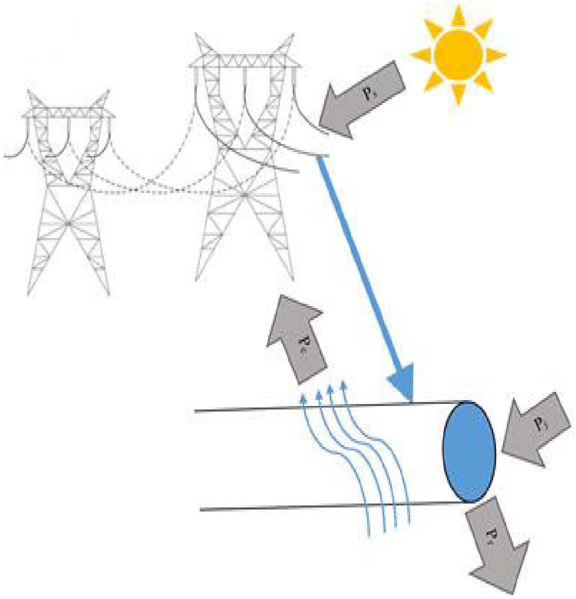


FIGURE 6. Heating and cooling process of overhead conductor [69].

conductor. CIGRE recommends taking into account the skin and magnetic effects in heating calculation especially for an odd number of aluminum layers of the conductor.

The heat produced by conductors as a result of solar radiation and ohmic losses can increase the overall conductor temperature. Solar intensity can be determined through measurement. Normally, the value is obtained from a methodological station near the transmission line or by using an appropriate measurement device located specifically under the measurement area of the transmission line. This method can provide the real-time thermal rating during operation under any circumstance. However, for planning and design purposes, maximum solar radiation may be considered in worst-case conditions. In other hands, solar heat gain can be determined by using the IEEE and CIGRE methods. A detailed calculation of solar heat gain is described in [62], [63]. A comparison between the IEEE and CIGRE standards was discussed in [65], [66], [70]. Basically, in the IEEE, the standard SI calculation unit is in W/ft^2, while in the CIGRE standard, the SI calculation unit is W/m^2.

Conductor heat gained by ohmic or joule losses occur when the current passes through the conductor. It is proportional to the resistance of a conductor (Ω/m) times the square of the total direct current in ampere (I^2R_{TC}). Significantly, it affects the thermal rating calculation compared with solar heat gain. The value of conductor resistance varies according to the size, material, frequency, and length of the conductor. Basically, it is provided by manufacturer or it can be calculated at certain desired temperatures, as described in [22].

The amount of current flow through the conductor produces heat in the conductor. The heat stored in the conductor must be dissipated to the environment. Otherwise, it can cause the temperature of the conductor to continuously increase over the temperature rating and result in the deterioration of the conductor. Thus, to reduce the temperature of the conductors, the unwanted heat must be dissipated to the atmosphere by cooling effect. Cooling is the major factor that contributes to heat loss and consists of radiative and convective heat loss.

Convective heat loss occurs when the wind crosses the surface of the conductor and carries heat to the surrounding area of the conductor.

Complex cooling which consists of natural cooling (no wind speed) and forced cooling (low and high wind speed). The high wind speed will contribute to low conductor temperature because more heat transfer occurs during this situation. The IEEE standards recommend calculating the cooling heat transfer in all wind speed conditions, but a higher result will be considered in convective heat transfer to determine the thermal rating. In contrast, radiative heat losses occur without any physical contact between the heated body and the surroundings. Unlike convective heat loss, the heat leaves the conductor and is transmitted to the surroundings without any physical contact (gas, fluid, solid).

Usually, radiative heat transfer is a small fraction of the total heat transfer. However, the wind velocity can also affect the heat transfer of the conductor by which the radiative heat losses can be as much as 40% of convective cooling at low wind speed, and it becomes less important at higher wind speeds [13]. Cooling heat transfer effect under different case studies by using numerical simulation can be found in [71]. Alternatively, the ACSR conductor temperature can be estimated based on IEEE and CIGRE standards, and wind velocity was found to be the major contributor to the reduced surface temperature of the conductor. Therefore, line rating varies for each span along the lines. To address this issue, the operator needs to identify the critical span and use dynamic thermal rating, which involves the present ambient condition under line examination. Thus, the power delivered to the line can be limited to ensure the continuous safe operation of OHL. The heat balance equation in IEEE is given as

$$q_c + q_r = q_s + I^2 R_{TC}, \tag{1}$$

where q_c = convection heat loss rate, w/ft; q_r = radiation heat loss rate, w/ft; q_s = solar heat gain, w/ft; q_j = joule heating losses, w/ft ($q_j = I^2RT_c$; I = conductor current, A (DC or AC at 50 Hz or 60 Hz); and R_{Tc} = resistance of the conductor at operating temperature T_c, Ω/ft.

With (1) rearranged, the ampacity of the line can be written as

$$I = \sqrt{\frac{q_c + q_r - q_s}{R_{Tc}}} \tag{2}$$

The CIGRE heat balance equation is considered another heat source. Heat losses in the equilibrium equation, such as magnetic heating, corona heating, and evaporative cooling, can be written as [62]

$$P_j + P_s + P_m + P_i = P_c + P_r + P_w \tag{3}$$

where heat gain to the conductor consists of P_j = joule heating; P_s = solar heating; P_m = magnetic heating; P_i = corona heating. Meanwhile, heat dissipated due to the cooling effect consist of P_c = convective cooling; P_r = radiative cooling; and P_w = evaporative cooling. However, P_m, P_i, and P_w can be ignored due to the difficulty of assessment. The conductor's temperature did not rise significantly, and any such increase rarely occurs [25], [72], [73]. However, [74] found that evaporative cooling affects the conductor temperature and ampacity of the line. The temperature of a conductor operating under wet conditions due to heavy rain is lower than that of dry conductor.

The effect of rain and precipitation rate on conductor temperature was also studied in [75]. Water droplets formed on the surface of the conductor in the presence of wind, thereby increasing the evaporation rate and lowering the conductor temperature. The result indicate that the conductor temperature drops during rainfall in summer and affects the ampacity of lines. Nevertheless, assessing all lines under wet conditions is difficult because of uneven terrain and weather conditions. Therefore, conductor temperature will be neglected in the calculation of thermal rating [62]. Hence, the heat balance can be simplified as

$$P_j + P_s = P_c + P_r \tag{4}$$

Similarly, with the use of (2), the current thermal rating in the CIGRE standard can be defined as

$$I = \sqrt{\frac{P_c + P_r - P_s}{R_{Tc}}} \tag{5}$$

In accordance with the research interest and the data obtained by researchers, researchers can determine which standard is more practical and convenient because the two standards have minimal differences.

B. TRANSIENT STEADY STATE

Transient steady state is considered during emergency and fault occurrences, where the operating current exceeds the nominal rating, which is the permissible maximum continuous rating of the current in a short period of time. Excess current suddenly changes due to various factors such as lightning strikes, short-circuit occurrences in lines, overload, and the failure of protection devices, thereby causing power system failure. In this state, the conductor temperature increases gradually from the normal operating temperature and varies with the step change of time. This condition may cause the conductor temperature exceed the designed operating temperature. However, in some cases, a short-term temperature increase is allowed.

Current rating with permitted time periods was studied in [76]. This approach is crucial to ensure that the line does not exceed the vertical clearance and to avoid the aging process. The equation of transient steady state can be written as

$$q_c + q_r + mC_p\left(\frac{dT_C}{dt}\right) = q_s + I^2 R_{TC} \tag{6}$$

Then, rearranging (6) will derive

$$\frac{dT_c}{dt} = \frac{1}{mC_p}\left[I^2 R_{TC} + q_s - q_c - q_r\right] \tag{7}$$

where m = mass of conductor per unit length; C_p = specific heat of conductor material, t = remaining time; I = current of conductor; and R_{Tc} = altering current (AC) resistance of conductor at operating temperature, T_c.

The equation is similar to steady-state heat transfer balance with conductor heat capacity included in the transient state according to transient time. Heat capacity is the amount of heat supplied to a mass of material, and it does not change as the conductor size varies. However, for different types of materials, the total heat capacities need to be determined, as in [77]. Table 6 lists the specified heat for common conductor materials at 25 °C. A detailed sample calculation of transient thermal rating is shown in [62], [63]. Reference [78] calculated transient thermal rating by using the IEEE standard under different conditions of real-time data. The study indicates, a small remaining time (time taken from normal operating temperature to attain the maximum allowable temperature) can contribute to thermal load on the line. Studies in [16], [79] estimated thermal rating and conductor temperature during contingencies. Real-time data were used to

TABLE 6. Specific heat of common conductor wire materials [22].

Material	C_P (W-S/lb-°C)	C_p (W-s/kg-°C)
Copper	173	381
1350 aluminum	408	899
6201 alloy	406	895
Al-Zr	412	908
Steel	227	500
AW	245	540

forecast the transient thermal rating in OHLs. For that purpose, important input parameters such as line rating, material properties of the conductor, dynamic weather condition, and direct measurement of OHLs need to be examined.

IV. CAUSES OF THERMAL STRESS AND THEIR EFFECTS ON OHLs

This section highlights factors that contribute to the thermal stress on OHL, which lead to unwanted effects on conductor OHLs. The relations between thermal stress and the effect are shown in Fig. 7.

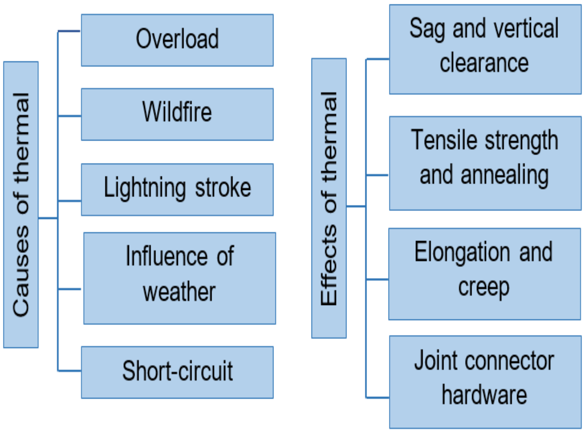


FIGURE 7. Relevance between temperature and effects.

A. CAUSES OF THERMAL STRESS

Temperature is a limitation in overhead transmission lines performance; a predetermined maximum operating temperature cannot be exceeded. Excess thermal stress in conductors may occur due to overloaded operation, short-circuits, and natural causes, such as lightning strikes, wildfire, and weather conditions that can increase the excess heat along OHLs.

1) OVERLOAD

Overload issues are the subject of interest in research on power transmission lines. Overload of the transmission lines occurs when a large amount of current flow and cause power system instability as a result of high load demand, especially during peak hours. Moreover, the limitation of new transmission line construction leads to overloading problems. Heavy load demand has been driven by rapid population growth, economic development over the years, and increased usage of electrical appliances, especially during summer [80]. Thus, the ampacity of existing transmission lines needs to be optimized. However, the CIGRE report recommended that the increase in the conductor temperature should not exceed 20 °C from the maximum continuous operating conductor temperature when the line current is equivalent to the line rating for safety reasons [81] because an excessive current flow will cause the temperature of the conductors to gradually increase from the original design criteria. Eventually, the temperature will exceed the thermal limit of OHL and create excessive thermal stress in lines. In the worst-case scenario, overload may result in power blackouts, which can affect social, economic, industrial, and political activities [82]. A study found that the increasing amounts of current flowing through the lines lead to the temperature rise of conductors, as shown in Fig. 8 [83]. The study also found that, when the current is increased, the allowable overload time of the conductor depends on the conductor size. Study in [84] found that, conductor temperature increase proportionally with the ampacity of the line. Therefore, optimizing the line may pose a risk of temperature rise during operation.

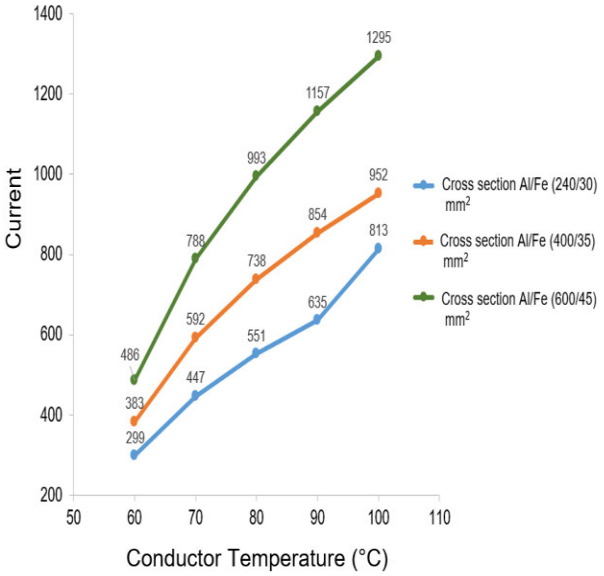


FIGURE 8. Relationship of temperature and current with different diameters [83].

Numerous studies focused on improving the capability of OHL to overcome the overloading issue [40], [85]–[88], [64]–[68]. These studies obtained the maximum allowable operating temperature of the conductor and allowable current through the transmission lines. Therefore, dynamic thermal line rating (DTLR) is applied to the line to calculate the maximum thermal rating by using real-time weather condition data. The actual weather condition on the specified line is used to improve the reliability system of the lines and thus obtain the actual thermal rating.

Alternatively, the dynamic thermal rating system aims to improve the conventional static thermal rating. It is more reliable because it gives an actual conductor temperature according to the current weather conditions. Moreover, it also helps to determine the actual ampacity of the line compared with the static rating [67]. The static thermal rating is not an appropriate method especially during seasonal weather, because it uses constant time data even during a worst-case scenario in the study area. Consequently, static thermal rating has the potential to overestimate the line rating. Apart from the load demand, overloading also occurred due to human errors and protection failures, which cause line tripping. Thus, advanced protection schemes and faulty assessments need to be implemented to avoid unnecessary tripping during operation and prevent thermal overload in transmission lines [64], [86], [89]–[91].

2) WILDFIRE

Wildfire is one of the factors that cause thermal stress along transmission lines. It happens frequently during summer seasons in some countries. Extreme wind velocity and dry wind are the main factors that contribute to explosive fire growth, causing power line failures in California and Australia, as reported in [92]. Wildfire incidences may be induced by natural phenomena or human activities. However, natural phenomena are of particular concern because they are influenced by climate change. Flame temperatures can reach up to 1000 °C to 1200 °C, thereby severely affecting tower structures, conductors, and operations [93], [94]. The conductors can be heated during long-term exposure to fire, as shown in Fig. 9.

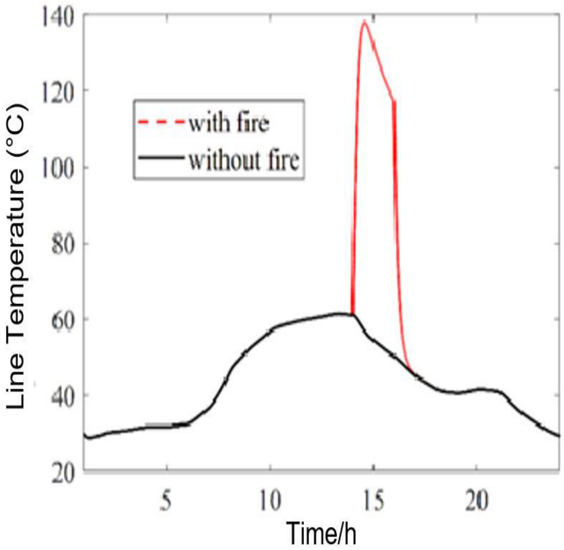


FIGURE 9. Line temperature with or without forest fire [93].

Thermal stress resulting from heat and flame can increase the conductor wire of OHLs. In distribution lines, a wooden pole easily catches fire and melts the conductor. Burned conductors cannot transmit electric currents. Flames from forest fire can increase the overhead conductor temperature in transmission lines and subsequently accelerate mechanical deterioration. This condition may affect the conductor length and increase the ambient temperature. Consequently, the operating temperature of the transmission lines would be approximately higher 5 °C to 15 °C than the ambient temperature. High winds cause the line temperature to rise faster [93]. The interrelationship between the high flame caused by wildfire and the temperature rise from the line conductor is studied by using an ACSR conductor with a wildfire model. The interrelationship was proven, with the overhead conductor temperature increasing as the flame height of wildfire increased under various wind velocities [95]. Thus, a massive fire will more greatly affect the conductor temperature and accelerate the aging of the conductor. The temperature can increase rapidly due to the heat transfer mechanism by convective and radiative heat loss. These two heat transfer methods influence the rise of surface temperature of the overhead conductor [93], [95], [96]. The ambient temperature near the affected area increases due to heat from the fire source, preventing the heat from dissipating from the conductor and accelerating the rise in the conductor temperature. When the temperature exceeds the allowable temperature, emergency condition will be experienced by the conductor and cause the line to age.

3) LIGHTNING STROKES

Lightning is a natural phenomenon that can directly strike shield wires, tower, and phase conductor transmission systems or indirectly strike any object near the line and the ground. The strike may generate transient voltage that exceeds the thermal limit of the struck object, thereby causing supply disruption in a transmission line. Lightning has a peak stroke current with a potential range from 2 kA to 200 kA. Within microseconds at a 40 kA peak strike, it brings a temperature of 30,000 K, and 39.55×10^3 joule/ohm of energy [97], [98]. Therefore, due to that potential, the thermal stress behavior of conductor lines can be affected.

Several studies have been conducted to assess the overhead lightning performance by direct and indirect lightning on the OHLs [99]–[102], [77]–[80]. When lightning strikes overhead phase conductors, it bypasses ground wires in a condition called shielding failure. When lightning strikes the phase conductor, the current will inject into the lines, divide into two parts, then travel toward the line. The upper conductor experiences more frequent strikes than the lower phase conductor. The strike results in a higher amplitude current in upper conductor than in other phase conductors [103]. The CIGRE technical brochure reported that phase conductors were struck by lightning 85 times within five years [104]. [105] reported that flashover induced by lightning strike on the OHL is detrimental to phase conductors and ground wires, as shown in Fig. 10 and Fig. 11. The high current carried by lightning has the potential to burn the outer layer of aluminum wires, which may affect the

FIGURE 10. **Flashover damage [105].**

FIGURE 11. **Lightning damage to conductor [105].**

capability to transmit electricity over OHL. Such damage may not be immediately visible, but it will become more severe during heavy load operation or extreme weather event. Hence, the thermal effect needs to be studied further.

The effect of lightning strike-induced temperature increases on cylinder conductors has been studied. A laboratory test was conducted by using international standard heavy impulse 10/350 μs lightning current impulses [106]. The difference in temperature rise depends on the conductor cross section, where the smallest cross section contributes to a large temperature increase. A small conductor is highly affected, and heavy lightning strike may melt the wire. Hence, a telecommunication conductor is more affected by lightning because of the size of the installed cable. However, research on phase conductor temperature due to lightning strike is limited. Thus, further research on thermal behavior of lines should focus on lightning occurrence because the high peak current and temperature of lightning may lead to thermal stress to the phase conductor and degrade the performance of the conductor. Even short, repetitive strikes can indirectly accelerate the aging process of the line.

4) INFLUENCE OF WEATHER

Thermal stress can also be caused by environmental factors. Weather conditions cause the conductor to contract and expand during temperature changes, and extreme weather affects the thermal behavior of conductors. Fig. 12 shows the various weather parameters that influence thermal stress to the OHL.

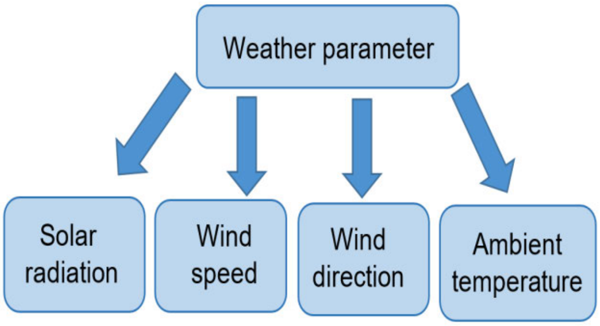


FIGURE 12. **Influence of weather conditions on conductor temperature.**

In the heat balance concept, the heat in the conductor has to dissipate into the air to avoid temperature increase. Therefore, ambient temperatures should be kept low enough to enable heat to move to cooler areas. In contrast, the conductor temperature increases when the ambient temperature increases and worsens without wind or with low wind in the area. The variations in the ambient temperature depending on the vicinity of the transmission line. Regions with extreme changing seasons in summer and winter may have different ambient temperatures, which result in varying conductor temperatures and ampacity of OHLs. The effect of the seasons on the ampacity of the line and conductor temperature during four seasons was studied in [107]. This study aimed to better understand actual line behaviors for optimizing line utilities. During summer peak seasons, electricity demand is higher than that in other seasons due to air conditioner use, thereby decreasing the ampacity of lines [108].

Fig. 13 illustrates the relationship between atmospheric factor and conductor temperature [109]. According to the figure, current load and weather condition parameters such as wind speed, wind direction, solar radiation, and ambient temperature are the crucial factors that contribute to the conductor temperature. The conductor temperature increases when the conductor is exposed to the sun. Higher solar intensity causes the conductor to gain more heat emitted by the sun. The solar heat gain of the conductor relies on solar intensity, exposure of the conductor's surface area to the sun, and the effectiveness of the absorptivity on the conductor's surface. However, the situation worsens without wind, thereby increasing the conductor temperature. A lower cooling effect obstructs the heat transfer process as a result of high conductor temperature. Wind velocity also contributes to determining the conductor temperature. A higher wind speed causes a lower conductor temperature [110] because

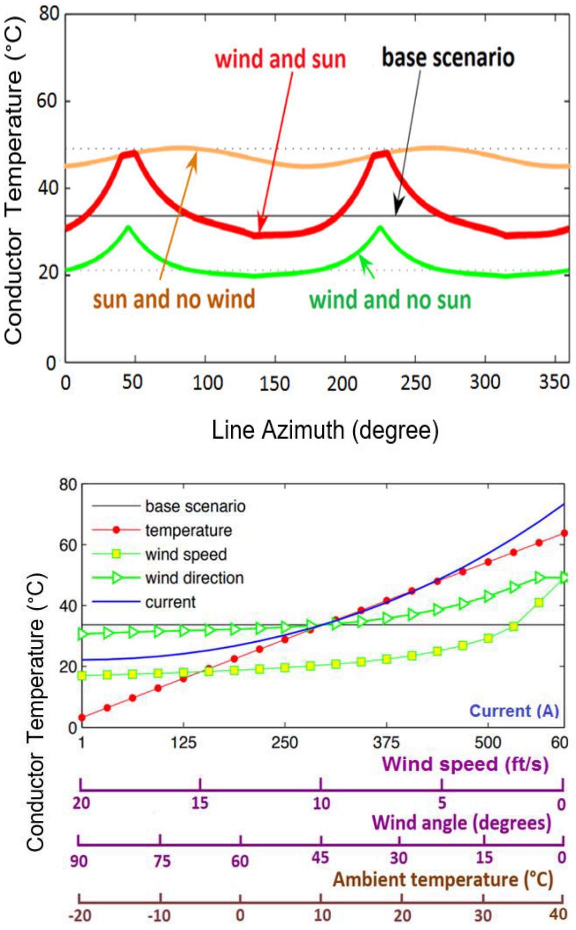


FIGURE 13. Influence of weather conditions on conductor temperature [109].

more heat can dissipate from the conductor under a higher wind speed. Good agreement with a study [74] was found. However, after a certain time, continuous wind speed is less significant on the conductor temperature [111]. The studies also analyze the cooling effect under various wind speeds. The relation between wind effect and the conductor's surface temperature and ampacity was also studied in [112]. Thus, wind is a crucial factor that can influence the line temperature. Studies on wind speed aim to prevent overestimating the conductor temperature and determine how the ampacity can be optimized because the cooling effect is a major factor in changing the conductor temperature along OHLs.

Wind speed and ambient temperature are closely related to each other in influencing the temperature line. Reference [113] shows the correlation of ambient temperature and wind speed on current rating. They reported that the increase in wind speed and lower ambient temperature can increase the line rating. [114] found that the conductor temperature is lower during the day than at night due to higher wind speed during daytime. Hence, the temperature increase may not be solely affected by the current carrying load, but weather plays a role in increasing the temperature during operation. Wind direction also influences the conductor temperature, as found in [115]. The conductor temperature varies along the line according to the angle of the wind blowing on the conductor surface. A parallel wind that blows on the conductor can increase the conductor temperature because the conductor receives low wind speed. The cooling effect is greatest when the wind is perpendicular to the conductor. At this wind angle, higher wind speed against the conductor reduces the temperature, as shown in Fig. 13. Furthermore, the B2 CIGRE working group reported that the conductor temperature and ruling span sag may vary for each span due to different wind directions even though the air temperature, solar heating, and span length of the OHL are constant [116]. Hence, weather affects the conductor temperature as it varies along the lines according to the atmospheric condition. In the worst case, temperature is high when solar intensity and ambient temperature are high, and wind speed is low and the wind direction is parallel to the conductor.

5) SHORT-CIRCUIT

Short-circuit can occur due to excessive current flow of the line during operation, unintentional accident, breakdown of equipment, insulation failure, contact between two conductors due to weather conditions, and environmental natural phenomena. During a short-circuit, a massive electric current flow takes place, which can lead to power outage, broken circuit devices, fire, and explosion. Excess heat is also produced, lead to overcurrent flow through the line conductor. Excessive heating may increase the conductor temperature during a short-circuit and caused the rapid expansion of aluminum wires, which can lead to the bird caging event [105]. Conductor temperatures rose from 120 °C to 180 °C during a short-circuit test [117].

Moreover, short-circuit occurrences in transmission lines are under fault current where the currents may reach or exceed 10000 A. A short-circuit may happen when a higher transformer capacity and larger conductor are installed, thereby producing a high current fault in operating systems [118]. The severe effect of this type of fault has given rise to extensive research in classification, identification, detection, and analysis of short-circuit in power lines [119]–[121].

B. EFFECT OF THERMAL STRESS ON OHLs

OHL conductors experience thermal stress due to high temperature over long-term operations, which will be detrimental to its mechanical properties and ultimately accelerate tensile loss, elongation, annealing, sag and ground clearance, conductor creep, and aging. These characteristics are related to each other and associated with line temperature, and they also affect hardware equipment.

1) SAG AND VERTICAL CLEARANCE

Sagging is the major thermal effect in power lines and occurs when the conductor temperature is elevated over a long period of time during line operation. A high conductor temperature increases the sag value. Sag catenary with different height degrees of various factors contributes to sag incident, as depicted in Fig. 14. The figure shows that sag occurrences increase after the long-term operation of lines due to higher loading imposed to the line and contribute to temperature rise, thereby reducing the electrical clearance of the line from the ground. Sag occurrences need to be monitored to maintain the permissible vertical ground clearance of the line. The relationship between sag and conductor temperature was found in [122]. Studies indicate that sag increase is directly proportional to the line conductor. Sag incidents are most affected by length, span, and weight of the conductor. Long-span OHLs experience more sag incidents than short-span OHLs. Likewise, a conductor with a larger diameter is more exposed to sag incidents than one with a small diameter [123].

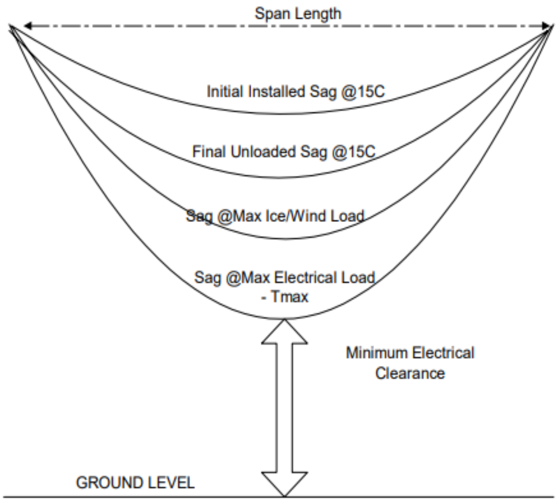


FIGURE 14. Catenary sag caused by different factors [124].

Sag is measured either from the lowest point of the catenary in the vertical axis between two highest levels of the tower (equal level) or between the highest and the lowest level (different level) of the tower in the ruling span. The CIGRE report provides a detailed sag calculation with respect to both catenary levels [124]. Reference [125] calculated the sag of an AAAC conductor with unequal tower spans. However, [126] used the total sag equation error to determine the accuracy of sag data in the calculation. Sag occurrence is of particular concern when it occurs in extreme weather, particularly high winds, thereby leading to galloping. Strong winds will cause phase conductors to swing and make contact with other phases, resulting in a short-circuit that in turn leads to power outages. Hot summer weather emits more solar intensity to the conductor and may increase line temperature [21]. Thus, lines experience sag more than usual during summer. However, sag occurrences are allowed as long as the minimum safety margin from the ground is maintained. Hence, incidents should be monitored to avoid short-circuit, which will cause a fault in line operation such as tripping. Table 7 shows the permissible vertical clearance according to various voltage levels in power lines [127].

TABLE 7. Permissible ground clearance according to different voltage level in power line [127].

Voltage level	Vertical clearance to ground
Less than 66 kV	20 feet (6.1 m)
66 kV to 110 kV	21 feet (6.4 m)
110 kV to 165 kV	22 feet (6.7 m)
Greater than 165 kV	23 feet (7.0 m)

Sag and tension are a topic of interest for most researchers because of their close relationship. Sag is inversely proportional to the tension; a high sag results in low tension of the conductor. The CIGRE technical brochure [124] also takes into account the sag-tension calculation to determine the suitable length or tension of installation cables according to the conductor size. This step is necessary because limiting the tension can determine the breaking strength during operation and installation. When the conductor is being installed, permissible sag is required to prevent the conductor from breaking due to high tension.

2) TENSILE STRENGTH AND ANNEALING

Tensile loss happens when conductors are exposed to high temperatures frequently over a long time. Tension loss can reduce the mechanical strength of a wire conductor especially when the conductor exceeds the permissible allowable operating temperature. Consequently, it will accelerate the conductor length, and the conductor has a great potential to exceed the permissible ground clearance in the design. Moreover, when the conductor temperature increases, the tensile strength is reduced, thereby resulting in lower tension and accelerating sag occurrences of lines. The conductor then expands, thereby decreasing the electrical conductivity and increasing the resistance of the conductor. Consequently, the power losses of the conductor will be higher. Continuous overheating of the conductor result in the annealing process.

Annealing occurs when the conductor is exposed to elevated temperatures over a certain period of time, thereby reducing the hardness and increase ductility of the material. This condition accelerates the aging process and shortens the operational life of the conductor when it operates beyond the allowable temperature. Thus, an aging model was developed to understand the thermal effect on high-temperature operation of the conductor [128]. Furthermore, aging analysis is needed to estimate the life span of the conductor. Analyzing the aging process of the conductor can provide operators with guidelines for maintenance and replacement schedule, planning utilization, and safety margins for system security and reliability [19]. The concept of aging conductors has led to studies on suitable replacements to avoid financial losses caused by failure of aging conductors [129]. Old conductors are also more likely to cause temperature increases in overhead conductors, as supported by [130]. A temperature increase in old conductors is caused by higher heat-radiated power than new lines.

3) ELONGATION AND CREEP

Tensile strength is related to elongation. A higher line temperature will produce uniform thermal stress to the line. Thereby reducing the mechanical strength of the wire conductor and affects the conductor's elongation. This condition will eventually result in permanent elongation called creep, which occurs when the conductor is exposed to high temperature frequently [131]. Creep is caused by tensile loss and increased sag under temperature increase. In this case, the conductor will elongate and stay long even when it operates normally and then continue to elongate when the temperature rises again. Creep is permanent and must be avoided to maintain the minimum vertical ground clearance.

In conductor selection, the coefficient of thermal expansion is an important factor in the accelerated elongation of wires. A nonhomogeneous conductor material has different coefficients of thermal expansion in each wire. Normally, the core of the conductor has a lower coefficient of thermal coefficient expansion as a support function for the conductor. For instance, the thermal coefficient of aluminum (ACSR) is greater than that of steel, as listed in Table 8 [22] because aluminum expands more quickly than steel when exposed to high temperatures and the wire tension reaches zero. All the tension of the conductor load depends on and is supported by steel. This stage is called knee-point temperature. Reference [132] reported that the tensile strength of steel core is not much affected by high-temperature operation under 200 °C. Moreover, [133] found that the deterioration of the conductor during annealing is not significant because steel strand wire does not lose strength at temperatures up to 250 °C even though the zinc coating suffers some damage. This feature is the reason steel is chosen as a support for conductors. However, CIGRE reported that not only external factors such as temperature and mechanical loading of the conductor but also internal factors such as chemical composite and geometrical formation of strand wire contribute to permanent elongation [41]. Moreover, a conductor with a high steel wire-to-aluminum ratio will have a higher strength and can delay the elongation process [134].

TABLE 8. **Thermal linear expansion coefficient of common wire conductor OHL [22], [57].**

Type of wire	Coefficient of linear expansion (x10^{-6}/°C)
Soft-drawn copper	16.92
Hard-drawn copper	16.92
1350-H19 aluminum	23.04
1350-O aluminum	23.04
6201-T81 aluminum alloy wire	23.04
Aluminum zirconium alloy wire	23.04
Galvanized steel core	11.52
Aluminum-clad steel core	12.96
Carbon hybrid epoxy	1.60
Galvanized invar alloy	3.00

4) JOINT CONNECTOR HARDWARE

Elevated temperature will affect the hardware of conductors, such as splice conductor, dead-end clamp, or suspension clamp. High temperature or high current during operation increases the thermal stress of lines, eventually accelerating aging and reducing the service life of the conductor and joint conductor. Temperature distribution is higher when an aluminum slicer connector is used to grip an ACSR conductor. An added aluminum splicer core layer in contact with the aluminum outer conductor layer is expected to increase temperature distribution on the surface conductor [135]. Elevated temperature during operation results in increased resistivity of the splice connector and reduces the clamping strength of the connector [136]. EPRI found that 94.5% of joining connectors failed when a conventional conductor operated at 125 °C. The temperature of the connector is higher than the conductor temperature, which can lead to mechanical losses of the connector [137]. In the long term, this condition may reduce the efficiency and reliability of transmission lines due to connection grip loss or fail, thereby resulting in less efficient electric transfers [132]. Table 9 shows previous research with the reported cause and effect of thermal stress on OHL.

V. MONITORING TECHNIQUES AND AVAILABLE STANDARDS

A. MONITORING DEVICES

The current carrying capacity of conductors is associated with conductor temperature. The amount of current passing through the conductor can be increased either in normal operation or in an unexpected situation during the service life without exceeding the permissible temperature limit. High temperatures may degrade the conductor's performance and deteriorate its service life in various ways, such as annealing, tensile loss, elongation resulting in sag, creep, and eventually exceeding the permissible vertical limit, as discussed in Section 4. Thus, monitoring is required to ensure the security and reliability of the system over a long period of time. It also helps operators understand the thermal behavior of conductors in any circumstance and prevent unwanted thermal stress to maintain the long service life of the conductor. Moreover, failure incidents in the system can be avoided. Monitoring systems aim to ensure that power lines are efficient and capable of transmitting energy for a long time.

TABLE 9. Literature Findings on the Causes of Thermal Stress on OHLs.

Causes of thermal stress	Effects	References
Overload	Conductor aluminium wire becomes longer under operating temperatures up to 93 °C, accelerating the annealing and aging of the conductor.	[19]
	Aging failure of the conductor is more likely at temperatures higher than 90 °C. Weather condition and loading are major contributors to aging.	[128]
	Tensile loss of ASCR of 3% occurs under the normal maximum operating temperature at 100 °C (10,000 hours) and 17% loss at 125 °C in 90 days, but tensile loss of up to 30% occurs during 41 hours operation when the conductor temperature increases to 150 °C.	[152]
	Creeping elongation causes sag depending on the amount of steel in the conductor. The lowest-steel strand wire can lead to faster elongation.	[134]
	When exposed to high temperature (150 °C) for 300 hours, the sag of the ACCC and ACSR increases, and the tension (kN) decreases. Creep increases over 10 years for both conductors. A homogeneous conductor is more susceptible to elongation at twice the rate than steel.	[153]
	Elongation and sag proportionally increase with temperature. Long-distance span and large conductor size experience more sag than short-distance span and small conductor size. Deflection of the insulator affects sag incidence.	[7]
	The aluminum strand wire ruptures when the conductor temperature exceeds 100 °C.	[8]
	A hot spot forms in the splice connector under high temperature, eventually accelerating the aging, reducing connection grip, or failing. Electric transfers are less efficient as a result.	[135], [136]
	ACSR conductor (366 m span) sag is estimated to increase to 1.6 m under high-temperature operation over 20 years.	[154]
	The developed aging conductor model and predicted conductor life ranges from 0 to 45 years. The aging failure is 0 below the maximum normal operating temperature for conductors (90 °C) but increases when the age of the conductor exceeds the permissible temperature in 35 to 40 years.	[128]
	The sag increases proportionally as the Zebra conductor temperature increases (28 °C up to 120 °C). However, the operating temperature of the conductor is limited to 75 °C due to sag incidences.	[122]
Wildfire	The temperature line under forest fire could be 138 °C higher than the operating temperature of a conventional conductor (<100 °C), thereby affecting the tensile strength of aluminum and worsening it because the temperature of forest fires can reach up to 1200 °C.	[93]
	Temperature rises slightly, reducing strength by almost 0.2% for 3 s under a flame	[117]
	Porcelain insulator cracks as the insulator temperature reach up 300 °C.	[15]
	The conductor temperature rises, increasing the sag and reducing the ground clearance.	[96]
Lightning	Lightning flashover breaks the strand wires of phase conductors.	[105]
	The temperature rises when 10/350 µs lightning current impulses strikes the conductor with a cross section less than 16 mm^2, and the conductor may melt due to temperature increase caused by the lightning impulse.	[106]
Influence of weather condition	Low line temperature, high tension and low sag occur during winter, and vice versa during spring.	[21]
	Low wind speed results in high conductor temperature and low line tension.	[155]
	During winter and zero wind, sag increases by 86 cm (temperature of 100 °C) compared with that a line temperature of 80 °C.	[156]
	Conductor temperature proportionally increases with increased on ambient temperature and inversely decreases with high wind speed.	[74]
Short-circuit	The elevated temperature decreases the mechanical strength when a conductor is tested in greater short-circuit current ($I_{sc>}$20kA) with long term exposure, leading to elongation. Tensile strength loss rate depends on material, temperature wire, temperature increment and time duration.	[27]
	High temperature is reported in short-circuit incidences. However, tensile strength is not significant due to short time occurrences.	[76]
	Fly ash from forest fire induces fire between lines, resulting in failure of the operation transmission line system.	[157]
	Conductor sag increases with increased of conductor temperature due to high current.	[118]

Weather is an essential factor in thermal behavior of OHL because it determines the conductor temperature of lines. The thermal behavior of conductors is influenced by weather conditions. A monitoring device needs to be installed either directly on the line or tower, with its locations being on top of the tower, close to the line, or along the line, thereby ensuring that the thermal behavior of the line can be determined and weather data can be provided to treat thermal stress in the OHL. CIGRE [116] provided comprehensive information on the direct real-time monitoring system in OHLs, thereby helping engineers in installations, direct monitoring issues, device, software, and communication that can be used to increase the reliability, accuracy, and economics of operating systems.

Weather parameters along the line are crucial factors that affect the line because they vary from one point to another. Therefore, the conductor temperature and the elongation may differ between each span depending on the span circumstances due to their terrain, wind direction, and shield span to solar radiation. Hence, one or several critical stringing spans have been identified by taking into account the length of the span, shield span, unequal level span, and low wind speed to acquire the lower current carrying capacity, ampacity, or high sag occurrences, which will affect the entire line [123], [138]–[140]. Therefore, a weather station or device measurement is placed on the line or near transmission lines. Weather data can be obtained using either direct or indirect method. The direct method uses a monitoring device or a weather monitoring station near specific towers or lines to obtain the desired weather data. This method also helps ensure that the operating conductor temperature does not exceed the permitted limitation and ensures the maximum utilization of line under a safety margin. A weather monitoring station or sensors are used to determine important parameters, such as solar intensity, wind direction and velocity, humidity air, rate of rainfall and ambient temperature, along with the time and nearby OHLs.

The indirect method can acquire data by using weather forecast through numerical weather prediction [141]–[143] to predict the particular weather condition by using a mathematical model. However, numerical weather prediction models have limited applications, being unable to capture low wind speeds below 3 m/s [144]. Thus, the weather measurement data are more accurate according to particular span circumstances. Table 10 lists all the monitoring devices that are used in monitoring OHLs. These devices have been used in static line rating (SLR) and DTLR methods to prevent overestimating the line rating and to monitor the thermal behavior of the OHL. Table 11 lists a comparison of different monitoring device that have been used for monitoring OHLs. The DTLR system is more practical because it is applied for real-time line rating and uses actual data for a particular line.

In contrast, SLR considers fixed data or assumes data under the worst conditions, such as low wind speed, high air temperature, and full solar heating. SLR also risks either overestimating the line rating or underestimating the ampacity, which results in lower revenue. However, [145] found that the line rating increased by as much as 1.8 times using DLR compared with SLR and varies every month over the year. Therefore, the utility can connect to existing lines without considering newly constructed power lines. The study also found that DLR offers as much as a 8% increase in economic benefit between two network zones in a year compared with SLR. Hence, a monitoring method is needed to obtain weather data and line characteristic data in OHL. Alternatively, monitoring can use indirect calculation of mathematical models for sag estimation and implemented in a computer program. The calculation approach is different according to the level of span [14], [124], [146]. Several studies reported on DTLR techniques that improve protection scheme, line rating, monitoring, power wind integration, and reduce traffic congestion of lines [79], [89], [147]–[151].

TABLE 10. Monitoring techniques applied on overhead transmission lines.

Monitoring	Devices/Method	References
Weather measurement	Thermal rate	[158]–[160]
	Weather sensors	[6], [122], [161]–[164]
	Weather model	[139], [140], [165], [166]
Surface conductor temperature	Power donut	[6], [147], [150], [151], [167], [168]
	SMT	[160], [162], [169]
	Distributed temperature sensor and wide monitoring systems	[110], [170]–[172]
	Surface acoustic wave (SAW) sensor	[173]
	Conductor temperature model (CTM)	[165]
Vertical ground clearance and sag	Laser distance and laser scanning	[122], [174], [175]
Sag and conductor temperature	Current induced in resistive wire	[176]
	Fiber optic-based sensors	[18], [177]
Sag monitoring	Global positioning system (GPS)	[30], [178], [179]
	Ampacimon	[144], [180]–[182]
	Sagometer	[110]
	Magnetic field sensor	[183]–[185]
	Tension ampacity monitoring (TAM)	[165], [186]
Tension monitoring	CAT-1	[140], [166], [171], [187]

B. IMPLEMENTATION OF CONDITION MONITORING IN DIFFERENT COUNTRIES

Monitoring is a crucial aspect of improving the security and reliability of lines during operation. Thermal monitoring is needed because it can prevent undesirable events and helps

TABLE 11. Comparison of different monitoring devices.

Monitor	Devices	Accuracy	Installation location	Cost			Advantages	Disadvantages	References
				Purchase	Installation	Maintenance			
Weather	Thermalrate	N/A	Parallel close to line	Low	Low	Low	No physical contact to line, hence lowering maintenance cost and reducing risk of line outage Flexible installation location	Needs external energy supply Needs numerous sensors for accurate measurement data	[190]–[192]
	Anemometer Air temperature sensor Wind wave Solar sensor	±1–3% 0.03–1 °C ±10.5–3° 2%–5%	Tower structure	Low	Low	Low	Provides present dynamic weather parameter data to estimate line rating Easy installation	Uncertain parameter data due to climate change affecting the actual line rating Some equipment needs scheduled maintenance	[162], [192], [193]
Temperature conductor	SMT (maximum conductor temperature up to 250 °C	N/A	Direct to line	High	Medium	High	Self-supply	Additional weight of line due to number of sensors	[13], [110], [190], [194]
	Power donut (maximum conductor temperature up to 150 °C)	±1 °C	Direct to line	High	Medium	High	Self-power Easy installation	Additional weight of line due to number of sensor	[13], [110], [190], [194], [195]
	Distribution sensor and wide monitoring sensor (maximum conductor temperature up to 300 °C)	±1–10 °C	Direct or close to line	High	High	Medium	Identify hot spot Long-distance monitoring along span	Interruption delay in data communication due to number of sensors	[172], [196]
	SAW (maximum conductor temperature up to 125 °C)	N/A	Direct to line	High	High	High	Measurement not affected by electric and magnetic stress	Data communication needs support from other components	[13], [173], [194]
Vertical ground clearance and sag	Laser scanning	± 0.20% ±1.5 mm	Near conductor line, middle of span	Medium	Low	Low	Does not need calibration and measurement is not affected by extreme weather condition	Height measurement range is limited	[122], [195]
Sag and conductor temperature	Resistive wire	N/A	Under bottom line conductor	Low	Low	Low	Average conductor temperature can be obtained	Unexpected weather condition may affect the accuracy of measurement	[176]
Sag	GPS	±19.6 cm	Direct to line	High	High	Medium	Directly measures sag according to DLR	Comes with package, thus possibly resulting in additional cost Corona incident may interrupt signal frequency	[178], [197]
	Ampacimon	±20 cm	Direct to line	High	High	High	Equipment does not need calibration.	Additional cost as the equipment comes with a package (estimated cost: €90K)	[191], [195]
	Sagometer	±15 m	Tower structure	High	Medium	High	Able to calculate sag in night operation. Simple installation-no outage.	Needs external power Extreme weather may affect the image of the target	[13], [110], [194], [195]
Tension	CAT-1	N/A	Dead-end structure of the power line	High	Medium	High	A low number of sensors is required as tension calculation takes the ruling span and average conductor temperature	Interval time-consuming data transmission	[13], [190], [191], [194], [195]

The rough cost is given because the actual cost varies depending on system configuration and architecture and is not publicly available.
N/A = not available.

identify the thermal behavior of lines. The OHL capability is restricted by high temperature, which results in the risk of thermal stress. Several monitoring systems are available. Table 12 shows the monitoring technologies that have been implemented in several countries.

C. STANDARDS AVAILABLE FOR OHLs

Standards are required in designing, planning, and operating a transmission line to address the safety issues, minimize risks, and sustain the reliability of transmission lines during operation. It also helps transmission engineers with economic planning in terms of cost and dispatch system and ensures efficient maintenance. Table 13 lists the available standards for overhead transmission lines.

VI. ISSUES AND CHALLENGES

Conductor temperature and thermal rating are crucial elements to maintain good operating performance. A good conductor should be operated at a prescribed temperature to prevent the risk of thermal stress to lines. Typically, the maximum allowable conductor temperature is up to 75 °C for ACSR conductors because they are mostly used in OHLs. Thus, a high conductor temperature during operation has a

TABLE 12. **Monitoring technologies used in different countries.**

Countries/ Location	Capacity	Technologies	References
Northeast England	132 kV	Power donut	[147]
India	230 kV	Weather station, SMT sensor	[162]
Northeast of Spain	220 kV	Distributed temperature sensors	[170]
Cedar Grove-Athenia, NY	230 kV	Power donut, weather station	[168]
Malaysia	275 kV	Weather sensor, Laser distance measurement sensor	[122]
New Zealand	220 kV	CAT-1, Power donut, load cell	[187]
Virginia, US	115 kV, 500 kV	CAT-1	[166]
Leiden and Sassenheim Netherlands	150 kV	CAT-1, distributed temperature sensor	[171]

bad effect on the conductor's life span because it may degrade the conductor's tensile strength and vertical clearance [188]. Moreover, the conductor temperature and ampacity of lines vary in each span due to terrain, session, load flow, and variability of weather conditions such as ambient temperature, solar irradiation, wind speed, and direction. Strong winds are among the main challenges in determining the conductor temperature. Therefore, monitoring along the line or tower is needed to address the issues.

At present, dynamic time thermal condition monitoring is the better option than static thermal rating because it helps determine the actual real-time value to obtain accurate thermal line rating and conductor temperature according to the actual situation in the measurement area. Moreover, risk underestimation or overestimation by static thermal rating can be reduced by real-time dynamic thermal rating. Reference [67] found that conductor temperature by dynamic line rating in complex terrain is lower than static thermal rating. In addition, this method is more reliable because of the availability of real weather data during the assessment of the particular area. However, it forecasts short-term conditions, which vary because weather conditions and conductor temperatures change with time. Certain issues emerged during monitoring and forecasting emergency conditions, especially in areas that have a complex terrain and frequently changing weather conditions. For instance, areas with a high rainfall rate and most probability of ice-covered conductors during winter need more attention due to the evaporative effect, which affects the conductor temperature changes and thermal limit.

Furthermore, various studies covered weather data and calculated the errors of uncertain parameter weather data. However, they faced challenges in determining actual real data in the study area due to irregular climate change, thus causing difficulty in the estimation and prediction of conductor temperature during operation.

Hence, operators rely on measurement devices for line monitoring to examine the conductor temperature, hot spot, tension, sag, vertical clearance, ampacity, and weather condition. However, using monitoring devices increases investment and maintenance costs, which may impose extra charges to consumers. Furthermore, it will probably result in heavy load to lines, which can lead to vertical clearance issues. As an indirect monitoring method, numerical calculation can be used to determine the conductor temperature, and its results can be compared with measurement data to obtain accurate results [189]. Weather data are required to perform the calculation. However, better understanding uncertain weather parameters is a challenge in improving the monitoring instrumentation, thereby influencing the conductor temperature of OHL. Moreover, line monitoring is challenging given the varying measurement data for each span, especially for transmission lines in complex terrain. Thus, operators need to find the best data measurement approach They must consider appropriate monitoring devices and suitable placement location according to the terrain to obtain a precise real-time conductor temperature. Either direct or indirect monitoring is faced with the challenge of ensuring accurate data measurement during operation.

Global warming, uncertain seasons, weather, and climate changes cause variations in the conductor temperature. Therefore, accurate estimation of OHL measurement conductor is a major challenge. Hence, the critical span needs to be identified, with either single or several spans being used to ascertain the worst circumstances. The critical span is the line that has the worst or minimum weather condition, ampacity,

TABLE 13. Standards for overhead transmission lines.

Standards	Titles	Description
CIGRE, W.G B2.12 (244) [58]	Conductors for the uprating of overhead lines	Provides information on the thermal effect of conductors under elevated temperature and presents a suitable conductor that can operate at temperatures up to 100°C
CIGRE, W.G B2.43 (601) [62]	Guide for thermal rating calculation of overhead lines.	Thermal rating method on OHLs in steady state, under short circuit, transient
CIGRE, W.G B2.47 (708) [105]	Guide on repair of conductor and conductor-fitting systems	Provides information on system failures in relation to conductor and conductor fitting and actions to overcome it
CIGRE, W.G B2.12 (324) [124]	Sag-tension calculation methods for overhead lines	Calculation is related to permissible installation of sag cable in the design and construction of OHLs. It also provides information on creep tests of conductors
CIGRE, W.G B2.42 (643) [137]	Guide to the operation of conventional conductor system above 100 °C	Provides information on the thermal effect on a conventional conductor and connector operating above 100 °C
CIGRE, W.G B2.51 (638) [201]	Guide to overall line design.	Describes the parameters that affect the electrical aspects of the line, conductor and tower configurations
CIGRE, W.G B2.12 (299) [81]	Guide for selection of weather parameters for bare overhead conductor ratings.	Practical guide for developing conservative thermal rating estimates for OHLs assuming the engineer will recognize the need for usual clearance buffers and safety margins employed in the design and operation of overhead transmission lines
CIGRE, W.G B2.55 (763) [26]	Conductors for the uprating of existing overhead lines.	Guideline for reconductoring the conventional conductors of existing lines with HTLS conductors
CIGRE, W.G B2.12 (353) [202]	Guidelines for increased utilization of existing overhead transmission lines.	Guideline considerations for economic and technical upgrading of existing transmission lines
CIGRE, W.G B2.36 (498) [116]	Guide for application of direct real-time monitoring system.	Guideline for direct monitoring and indirect monitoring to determine the conductor temperature with real-time data and the relationship between temperature, sag, and tension with weather condition
CIGRE, W. G B2.26 (426) [55]	Guide for Qualifying High Temperature Conductors for Use on Overhead Transmission Lines.	Provides information and guideline type of HTLS, thermal effect for design, installation and testing of HTLS
IEEE 738 [63]	Standard for calculating the current-temperature relationship of bare overhead conductors.	Calculation of bare overhead conductor temperature and ampacity under steady-state conditions and transient condition.
CIGRE, W. G C4.410 (633) [104]	Lightning Striking Characteristics to Very High Structures	Provides information on the experience of countries in lightning strike to the tower, phase conductor, and protection
IEEE 524 [203]	Guide to the Installation of Overhead Transmission Line Conductors.	General recommendations for the selection of methods, equipment, and tools that are practical for the stringing and grounding of overhead transmission line conductors and overhead ground wires.
IEC 60909 [204]	Calculation of short-circuit current in three-phase AC system	Calculation of short-circuit currents in low- and high-voltage AC system
IEEE 1283 [132]	Guide for determining the effects of high-temperature operation on conductors, connectors, and accessories	Provides guidelines of for existing and new installation of transmission line to thermal effects during high temperature operation of bare overhead transmission conductors, connectors, and conductor hardware
IEEE 656 [205]	Standard for the Measurement of Audible Noise from Overhead Transmission Lines	Describes the manual and automated procedures for measuring audible noise from overhead power transmission lines

current, low vertical clearance, long span, and high temperature [123], [198]. Monitoring a single span poses difficulty in monitoring hot spots along the line. Therefore, critical span can be determined by using the distribution sensor along the line [199]. In this monitoring method, the operators need to identify an optimal sensor placement and use a number of sensors to obtain the temperature distribution along OHLs. Increasing the number of temperature sensors can also ensure that hot spots can be identified, thereby preventing annealing [170]. A new technique of monitoring critical span by using weather data measurement along the line was presented in [200]. The technique can determine the number of sensors, hot spots, and sensor installation locations along the test line.

This technique has improved the traditional critical span monitoring. However, even the new techniques face challenges in choosing an appropriate type of sensor in terms of size, weight, and accuracy for critical span issues. In contrast, monitoring for a single critical span requires a suitable sensor installation location according to different circumstances to ensure accurate data measurement. Moreover, when sensors are used, the cost of purchasing, installation, and maintenance also need to be considered. Some sensors come packaged with installation, service, and communication, thereby increasing operating costs compared with single critical span monitoring.

Wireless sensor network technology in a smart grid system was introduced into a monitoring system to address maintenance cost and scale coverage. This technology can monitor a wide transmission range which is connected with generation and distribution power. Wireless sensor technology is applied in wide area monitoring systems and Internet of Things, which involves monitoring, protection, and control of systems. Real-time data are used, and different types of sensors are installed on OHL systems. This technology works together with telecommunication technology to improve the transfer signal and information on network data especially over a long distance [196], [206]. However, the technology faces new challenges: 1) data security against cyberattacks, 2) expensive installation costs due to massive sensor application and architecture, and 3) switching interface of data communication between transmitting and receiving, storing, processing, and analyzing data. The whole monitoring system needs to be taken into account. Therefore, a robust system must be developed by transmission engineers to overcome all the issues. Various studies have been conducted to block unauthorized access and avoid time delay in the processing, collecting, and transmitting of data [207]–[209].

Although all monitoring devices can be used, manpower is still needed for inspection and monitoring. Therefore, unmanned aerial vehicles (UAVs) have attracted attention because they are highly capable, reduce the reliance on humans, and help reduce working time. Furthermore, UAVs are practical because they can cover hundreds or thousands of kilometers of transmission lines. UAVs have been used for over 30 years and are increasingly being used for inspection and maintenance of transmission lines. However, UAVs have limited capability in detecting damage such as broken shield wire strands, phase conductors, or towers [210], [211]. Broken wire strands will produce a high conductor temperature, thereby leading to excessive thermal stress [8]. However, these incidents were detected during routine maintenance, inspection, and monitoring. While awaiting maintenance, the incident may harm the conductor and accelerate its aging process. Commonly, a UAV consists of a drone and robotics. However, a drone is more beneficial because it can monitor lines closely. The sensor monitoring device may be installed in accordance with operational necessity. However, the following issues and challenges may emerge and need to be considered [212]: 1) the total weight and appropriate size of a monitoring device with a sensor installed; 2) the ability of a UAV installed with numerous monitoring devices to fly through the air; 3) how far the drone can move close to the line for safety reasons given the high voltage flow through transmission lines; 4) the battery life span during monitoring; 5) the appropriateness and accuracy of the monitoring device in capturing the conductor temperature; and 6) different legislation restrictions for commercial application of UAV for operational safety to avoid public and security risks [213]. All issues need to be further examined before UAVs can be widely used. Moreover, the sources of UAVs are scarce, thus limiting further discussion.

VII. CONCLUSION AND SUGGESTION

The capability of OHL is determined by the conductor temperature during transmission line operation. Usually, the ACSR is used for transmission because it can withstand normal operating temperatures of up to 75 °C and emergency ratings of up to 127 °C. However, it depends on the diameter and type of conductor in terms of electrical and mechanical properties. A higher than normal conductor temperature generates unwanted thermal stress and threatens the thermal behavior of the conductor, thereby reducing the strength of the conductor itself, affecting the vertical ground clearance, and accelerating the annealing process of the conductor. Over long-term operation, the conductor's service life and performance will deteriorate. Thus, thermal stress monitoring must be considered to ensure the line will operate satisfactorily to minimize the contingency state in line operation and expand the life span of the transmission line.

The conductor temperature depends on the length span, the load carried by OHL, weather condition, and electrical properties of the conductor. However, each span varies along OHL due to atmospheric conditions according to the terrain of the area, thereby resulting in uncertain parameters and different lengths of span and in turn presenting the main challenge in determining the thermal behavior of OHL. Moreover, issues and challenges in OHL monitoring need to be considered to ensure accurate measurement data. This issue can be addressed by using an appropriate monitoring device and technique.

The study provides a few suggestions to improve monitoring in transmission lines and data collection on thermal stress of OHLs. In some cases, reconductoring with HTLS conductors is another way to ensure that the conductors can withstand temperatures of up to 250 °C. These conductors can handle increased demand and high temperatures, and they can also address the issues of sag during high-temperature operation. Even though they have higher construction and installation costs compared with existing conductors in OHLs, they offer good benefits for long-term operation.

Thermal stress is greatly influenced by weather condition. Weather is the biggest challenge in monitoring the conductor temperature of OHLs. As a result of climate change, the conductor temperature varies in each span length and is more affected under complex terrain, thus possibly reaching or exceeding their limits. Direct or indirect monitoring can help monitor the thermal behavior of OHL. In indirect monitoring, most calculations according to the IEEE and CIGRE standards ignored evaporation heat transfer. To obtain accurate thermal stress, the evaporative effect needs to be taken into account, especially areas with frequent, prolonged rainfall. Humid weather and the presence of wind after rain also change the conductor temperature and ampacity. Thus, considering the evaporative effect can also improve the estimation and prediction pattern of conductor temperature under specific circumstances. Moreover, indirect monitoring results do not reflect the temperature distribution along the conductor and the formation of hot spots on the defective area of the conductor's surface. Finite element method and finite volume method such as ANSYS mathematical package can be used to simulate the distribution of thermal stress of OHL with additional visualization features and to investigate the impact of the more accurate mixed convective cooling model.

Dust particles deposited on an OHL bare conductor can degrade the performance of the conductor. Therefore, pollution events that may contribute to thermal stress to the conductor need to be studied, such as haze events in Asian countries. The haze event pattern is an annual event that carries dry wind and hot weather together with dust particles. Combustion causes dust particles to deposit on the crevices of conductor wires. Thus, studies on the thermal effect that involve accelerating the aging of the conductor over long-term operation needs to be performed. Thermal stress under DLR in pollution event also needs to be further analyzed given the weak light emittances. The effect of wind speed and ambient temperature of lines during the pollution event needs to be taken into account in the analysis. The ampacity or temperature of the line can be calculated using heat transfer equation provided by the available standards, as mentioned before.

UAV application in line with current technological developments has a high potential in OHL monitoring. Therefore, the application of UAV in monitoring and surveillance techniques is practical because it offers several advantages, such as lower maintenance cost of implementation and manpower; ability to monitor close to lines; efficient maintenance scheduling, which may help quickly detect thermal stress at OHLs; and ability to monitor over long distances. Sensor monitoring devices can be applied via a hybrid detection system of OHLs. Hybrid detection system techniques may help detect and measure the severity of thermal spots at OHLs and monitor the thermal stress of the conductor. Applicable devices are 1) ultrasonic sensor for detecting partial discharge on the cables; 2) infrared camera or thermal camera such as ThermoVision A40M for thermal imaging, which can detect the heat emitted from the surface of the line, identify the formation of hot spots from defective power component, connectors, and splicers; 3) laser scanner for overall conductor detection abnormality; 4) IR sensor for crack detection; 5) monocular camera or digital camera to capture visual images of the conductor; 6) vision camera that can detect dust and smoke incident; and 7) a smart Arduino sensor for weather measurement and detection. These monitoring devices have a light weight and low cost due to their simple circuit.

The use of a wireless portable weather monitoring station by interfacing a smart sensor and weather sensor with a microcontroller can be considered in monitoring transmission lines. This technique ensures accurate weather data measurement of parameters such as temperature and humidity, solar intensity, and wind speed. Examples of a microcontroller that can be used are ATmega or PIC16F887 microcontroller. The data from the monitoring system are transferred to the base station through wireless communication technology, such as the XBee-Pro RF module. This monitoring station can be installed easily in the desired measurement location, is easy to handle, and may help reduce regular maintenance. A suitable location and an appropriate sensor to be integrated with the microcontroller especially at a high voltage and long transmission line distance need to be determined for accurate data measurement. The accuracy of weather reading may help determine the ampacity and the thermal stress of lines, and it can be used by researchers and institutions for weather monitoring research. Monitoring OHLs efficiently can identify thermal stress, which influences the thermal behavior of the line and ultimately enhances the performance, reliability, and capability of OHLs.

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