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Review

Advanced Composite Materials: A Panacea for Improved Electricity Transmission

Chika Oliver Ujah [1,2,*], Daramy Vandi Von Kallon [1], Daniel O. Aikhuele [3] and Victor Sunday Aigbodion [1,2,4,5]

1 Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, P.O. Box 524, Johannesburg 2006, South Africa
2 Africa Centre of Excellence for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka 410001, Nigeria
3 Department of Mechanical Engineering, University of Port Harcourt, Port Harcourt 500004, Nigeria
4 Faculty of Engineering and Built Environment, University of Johannesburg, P.O. Box 524, Johannesburg 2006, South Africa
5 Department of Metallurgical and Materials Engineering, University of Nigeria, Nsukka 410001, Nigeria
* Correspondence: omega.ujah@gmail.com

Abstract: The demand for electricity has increased drastically due to population explosion globally. Unfortunately, supply does not meet the demand. Consequently, the transmission grid becomes overloaded, culminating in frequent power outages. Worse still, the transmission grid lacks adequate maintenance, and this has led to energy crisis in Africa and some parts of Asia. In this review, studies on the strength and weaknesses of existing transmission conductors were conducted. Further studied were natural and artificial phenomena that attack the overhead transmission networks. It was observed that besides inherent conductor defects, overloading, bush fire, short-circuit, harsh weather, and lightning were the factors that ravage the transmission grid. Hence, there is the need to develop more robust conductor materials that can withstand these challenges. The conventional conductors such as all aluminum conductor (AAC) and aluminum conductor steel reinforced (ACSR) are challenged by low operating temperatures, among others. High-temperature low-sag (HTLS) conductors that were invented to tackle these shortcomings certainly have higher ampacity and better thermal rating than the conventional conductors. However, some challenges still devastate them. So, from the study conducted, it was discovered that developing advanced nano-based Al-composite conductor would help in ameliorating the challenges prevalent in the transmission grid. Such an Al-nanocomposite conductor would possess higher ampacity and better thermal stability and would be more durable and cost effective.

Keywords: aluminum conductor; transmission network; ampacity; coefficient of thermal expansion; sag

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1. Introduction

For many privately owned and government-controlled power-related businesses throughout the African continent and Asia, the production and delivery of electrical energy has remained a significant burden and concern [1]. This issue, which affects over 60% of people in sub-Saharan Africa and Asia, including women and children who do not have access to regular electricity [2], is thought to be the cause of numerous deaths and health-related issues in the region, owing to constant exposure to fumes from biomass stoves, which are their primary source of power [3]. The scarcity of energy is due to power providers' limited power generation/transmission capability. High power generation and distribution costs, inadequate power infrastructure maintenance, and lack of research and innovation in energy management and power supply are all factors that cause epileptic power supply [4]. These have hampered economic growth and development, the adoption of new energy strategies, improvement in public service delivery, technological advancement, and people's general standard of living [5,6]. Power outages have both direct and indirect effects on the entire functionality of firms/industries, provoking upsurges in economic costs and inflation, declines in produced quantities, and automatic diminishes in sales and productivity [7,8]. Hence, the retardation in economic growth and technological advancement in Asia and sub-Saharan Africa as a result of the incessant power outages as shown in Figures 1 and 2, being a survey by The World Bank's Enterprise Surveys (WBES), 2005–2016 [9]. Although various electrical power specialists and academics have begun research aimed at solving these power issues, their efforts have not been successful in their entirety. Corruption in energy sector, equipment misuse, unlawful connections and disconnections, inadequate power zoning distribution, and overloading of power transmission lines all exacerbate power crisis [10]. Scholars such as Alawar et al. [11] have backed up the aforementioned assertion, stating that although the amount of power produced and required by consumers has risen drastically in recent decades, and the distribution capacity (transmission propensity) and innovations have remained stagnant. Besides high-income countries (Europe, the USA, and Australia), only a small portion of Asia's (east and central) and a miniature portion of Africa's electrical investments go towards maintaining and building of new transmission lines, which has caused serious economic set back and developmental stagnation, as can be seen in Figure 2. As a result of this trend, the available transmission lines are inadvertent or otherwise overloaded in a quest to satisfy the high electrical demand. This invariably culminate into colossal grid failure and malfunctioning [12]. Ma et al. [13] lamented that the electrical conductors utilized in most contemporary transmission lines are over a century old, and hence cannot meet rising demand of electric power.

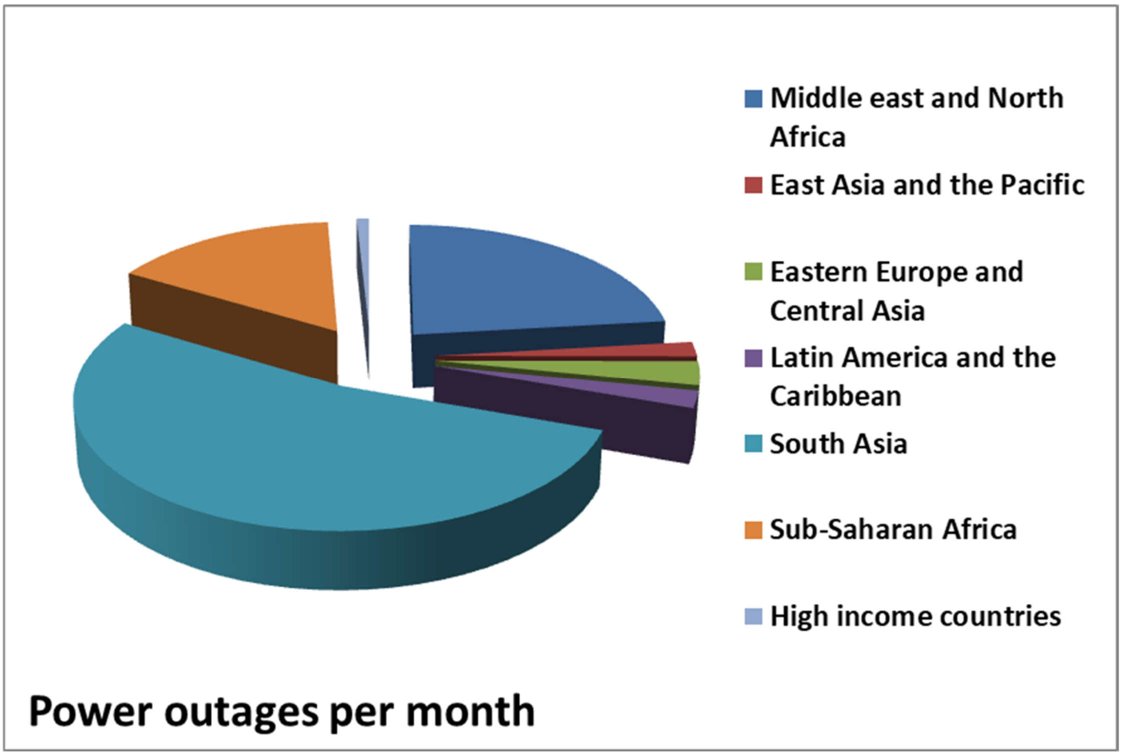


Figure 1. Global power outages per month (The World Bank's Enterprise Surveys (WBES) database 2005–2016) [9].

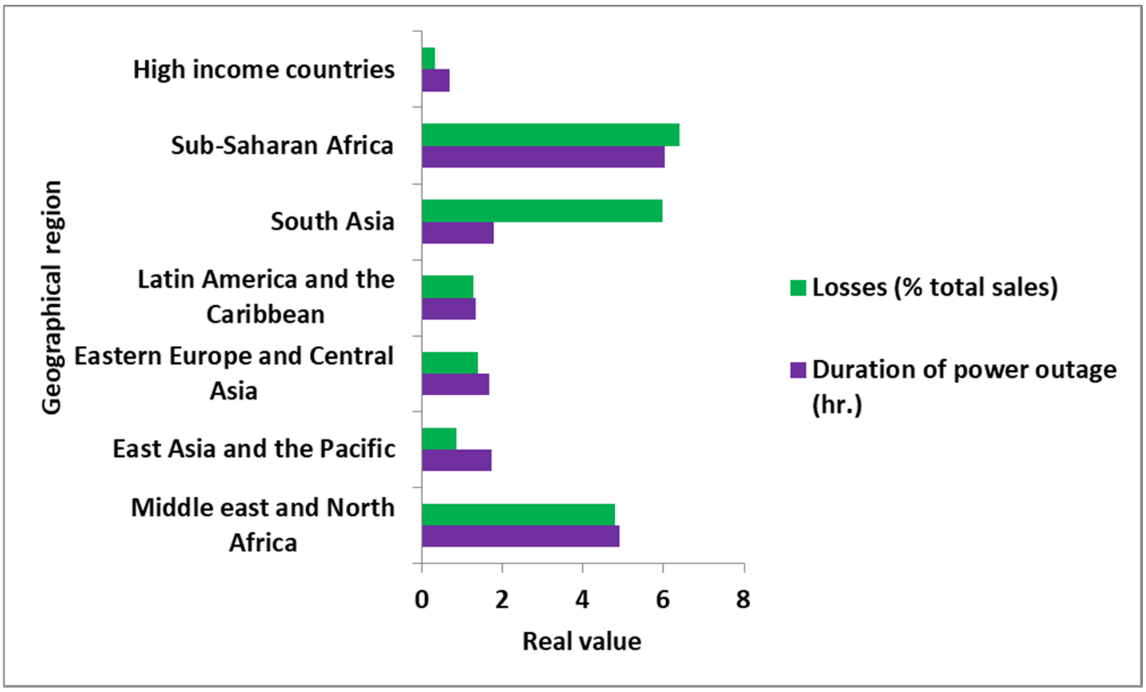


Figure 2. Global losses and power outage durations (The World Bank's Enterprise Surveys (WBES) database 2005–2016) [9].

Moreover, the fretting wear prevalent on the conventional conductors, aluminum conductor steel reinforced (ACSR) was considered to be another serious challenge militating against the power availability in the African and Asian regions of the world. Lending a voice, Ujah et al. [14] opined that poor maintenance, neglect, and lack of research and innovation in the development of power transmission conductors negatively impacts the availability and affordability of electricity in third-world countries. The authors recommended development of more noble and durable transmission cables. They predicted that with smart and robust hybrid nanomaterials, electricity transmission and distribution would improve. This is so because such nanomaterials possess increased electrical conductivity, lower weight, higher thermal conductivity, lower coefficient of thermal expansion, higher wear resistance, and higher corrosion resistance than the existing conductors on the market.

Electrical treeing experienced in transmission grids affects the transmission of electricity. According to Xiaoquan and George [15], electrical treeing breeds inadequate power supply. Electrical treeing manifests as partial discharges on the cables when voltage crosses over an entrapment. This is caused by contaminants trapped inside the conductor. It can also be caused by a mechanical flaw in the transmission line after installation. This manifests as sparks that form tree-like patterns, which may cause serious damage to the transmission network. The source of these entrapments, according to research, is the production techniques of transmission conductors. The techniques that include extrusion, pultrusion, and hot rolling have been adjudged to be prone to producing impure products [16–18]. The authors opined that the panacea to this defect is the use of advanced production technique which produces impurity-free products, or the best when conventional method attains its technological limits and the application of advanced hybrid/nanomaterials with high resistance to abrasion and corrosion [18–21]. Some authors believed that 3D printing is one of the best ways of consolidating composites for better performance [22]. In their opinion, Giordano and Nicolais [19] remarked that the quality of pultruded products can be improved by guiding the polymerization and rheological kinetics of the resin. Krasnovskii and Kazakov [17] advocated for a uniformity and slowness of the pulling speed of pultrusion machine so as to hinder cracks promoted by swift and non-uniform pulling, which breeds fiber breakages or warped products at extreme cases. Khan et al. [20] were of the opinion that the defects associated with extrusion technique can be corrected if adequate precautionary measures were taken. For instance, applying correct additives and maintaining uniform speed of the extruder control the surface roughness of extruded product. Moreover, precision in calculation and addition of resin controls indentation and bubble defects of extruded parts. Lovo et al. [23] opined that infiltrated resin enhances most mechanical properties more than non-infiltrated resin.

The efficiency of the overhead conventional conductor, ACSR, is also challenged by the high density of its steel core, high affinity to corrosion of the steel core, and high coefficient of thermal expansion (CTE) of steel material. These factors limit its current-carrying capacity (ampacity) as well as its cost effectiveness [24–26]. So, research has indicated that replacement of the steel dense core with light weight hybrid nanomaterials would boost its efficiency. This is because the nanomaterials will possess higher corrosion resistance, higher wear resistance, and lower coefficient of thermal expansion (CTE). It will be recalled that coefficient of thermal expansion of composite materials is dependent on the thermal conductivity of the constituent elements [14], which then determines its sag level when current traverses through the material as well as its ampacity. Aluminum conductor composite reinforced (ACCR) is another high-performing transmission conductor in the market that is ravaged with some issues. Banerjee [27] disclosed that the CTE of its metal matrix composite (MMC) core is relatively high, measuring about 6×10^{-6} K^{-1}, which makes it susceptible to moderately high sag [27]. It was also reported that polymer matrix composite (PMC) used in the production of aluminum conductor composite core (ACCC), another improved transmission conductor, can only perform at temperatures below 125 °C. Once this temperature is exceeded, the conductor degrades. The panacea to this is the development of advanced composites, comprising hybrid nanomaterials to replace the polymer core that is susceptible to thermal degradation at elevated temperatures.

Among all the causes of the frequent power outages, poor maintenance of the grid, inadequate replacement of dilapidated conductors, and limitations of the conductor materials, have been the principal issues. Works on transmission conductors abound in the literature. However, no considerable attention has been given to the fact that the type of materials used in developing the conductor could be the source of the grid crisis. So, this review was aimed at identifying all the major problems encountered in overhead transmission grids. It looked into possible solutions to the problems. The bottom line was to increase the ampacity of the transmission grid so as to have a sustainable steady supply of electricity to the poorest nations of the world at affordable rates. This review consists of five sections. Section 1 is the introduction, while in Section 2, the strengths and weaknesses of transmission conductors are analyzed. In Section 3, further challenges of transmission grids are discussed, while prospective conductor materials are discussed in Section 4. Section 5 contains conclusion and recommendation.

2. Strength and Challenges of Transmission Conductors

An electrical conductor is a substance that permits electric current to flow through it, as contrasted by an electrical insulator that obstructs the flow of electric current across it. Good electrical conductors are metals with high conductivity and low resistance. Electrical conductors in the conduction band enable electrons to move freely between atoms of a substance. Metals, metal alloys, electrolytes, and non-metals including graphite and conductive polymers have all been proven to be useful electrical conductors in their raw states [12,28]. However, these materials may be improved and utilized as power transmission conductors for low- and high-voltage transmissions [29]. Aluminum conductor steel reinforced (ACSR) and all aluminum alloy conductor (AAAC) conductors are the most prevalent and widely used conventional transmission conductors on the market [30,31]. They are meant to work at maximum temperatures of 85 and 95 degrees Celsius, respectively, according to Banerjee [27]. The thermal limitations for the conductors are established by the fact that they are annealed as a consequence of subsequent heating [32]. The ACSR conductor is a high-capacity, high-strength conductor that is often used in the construction of overhead power transmission lines. It is made up of layers of aluminum strands wound helically around a galvanized steel core. According to studies, the CTE of steel and aluminum materials are between 11.5×10^{-6} and 23×10^{-6} degrees Celsius, respectively [11,31]. At temperatures above 93 degrees Celsius, the aluminum material in the conventional ACSR conductor anneals and loses its strength, rendering it unsuitable for use [27]. The density of the steel in the ACSR conductor is 7.78 mg/m^3. As a result, the performance of the conductor is restricted by temperature and density. The high coefficient of thermal expansion of ACSR renders the conductor vulnerable to corrosion and excessive sag. So, the high density, thermal limitation, and high cost of galvanized steel are major restrictions in the conductor [33]. However, these issues may be solved by using improved nanotechnology to develop robust and smart conductor materials. The AAAC conductor is made of an aluminum–magnesium–silicon alloy that has a high electrical conductivity, high corrosion resistance, high strength-to-weight ratio, and enhanced mechanical properties, thanks to the presence of magnesium silicide [34]. AAAC conductors are frequently used for power transmission in low voltage transmission lines. The thermal conductivity value is the major problem in this conductor. There is a second phase known as impurities, which ravages these aluminum-based conductors. The impurities can be detected with transmission electron microscope (TEM) [35]. Figure 3 shows pictures of (a) ACSR and (b) AAA conductors, illustrating their various characteristics and designs.

Figure 3. Conventional transmission conductors in the market: (**a**) ACSR and (**b**) AAAC [26].

High-temperature low-sag (HTLS) conductors are another set of conductors that have been improved and proven to be more efficient in transmission networks than the conventional conductors. The HTLS conductors, which were created primarily to increase the ampacity in power transmission grid, exhibit reduced sag and withstand greater temperatures and ice loads. They have numerous significant benefits over the ACSR and AAAC conductors.

The following are some of the advantages: (i) They operate at higher temperatures, typically between 100 and 250 degrees Celsius. (ii) Their installation and operation on existing grids are usually very safe. (iii) They can be easily installed on existing transmission lines without requiring much structural modification, saving time and money. (iv) They are more conductive than the ACSR and AAAC. (v) They have less fatigue-related issues. (vi) They have lower density than the conventional conductors [36–38]. Aluminum conductor steel supported (ACSS), aluminum conductor composite reinforced (ACCR), aluminum conductor composite core (ACCC), and gap-type aluminum conductor steel reinforced (G-TACSR) conductors are examples of the HTLS conductors. When utilized in power transmission grids, their sag performance is one of the most significant attractive properties [39]. Figures 4 and 5 show the essential characteristics of HTLS transmission conductors [14,40,41]. From Figure 4, it can be noticed that all the HTLS conductors possess higher ampacity than ACSR and AAAC conductors.

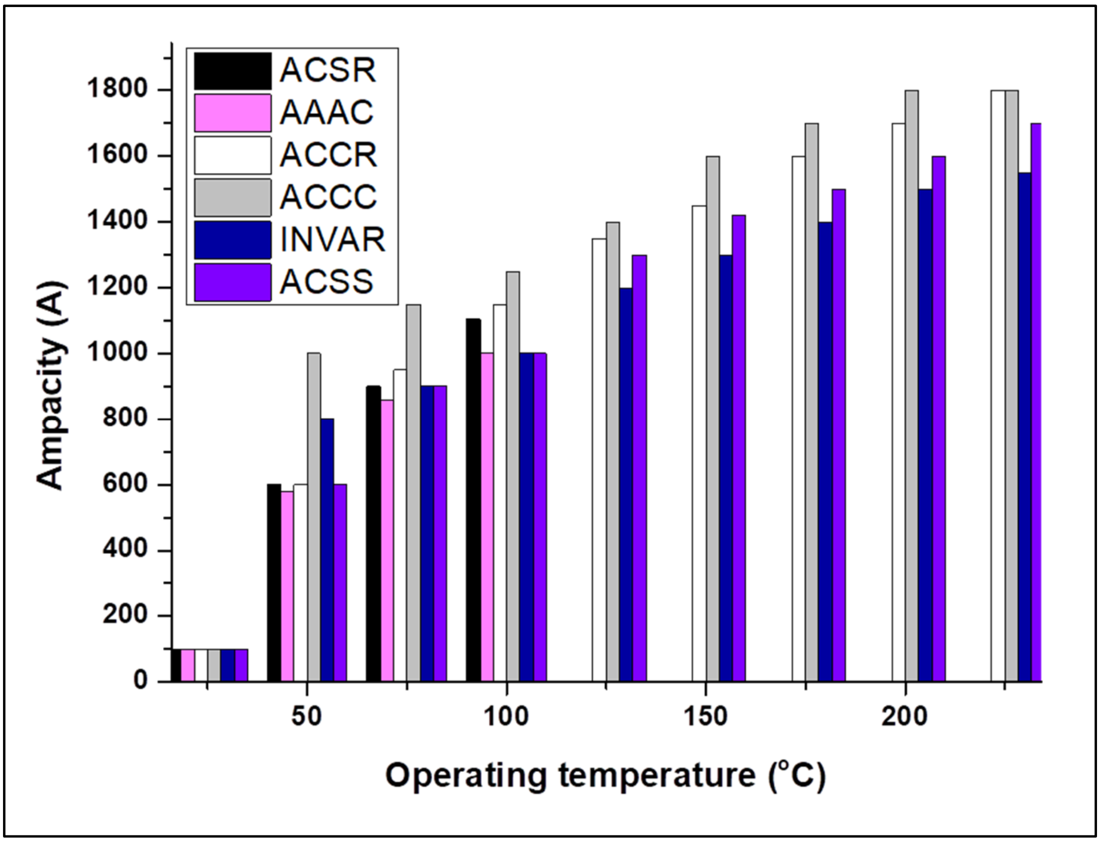


Figure 4. Ampacity versus operating temperature of transmission conductors [39].

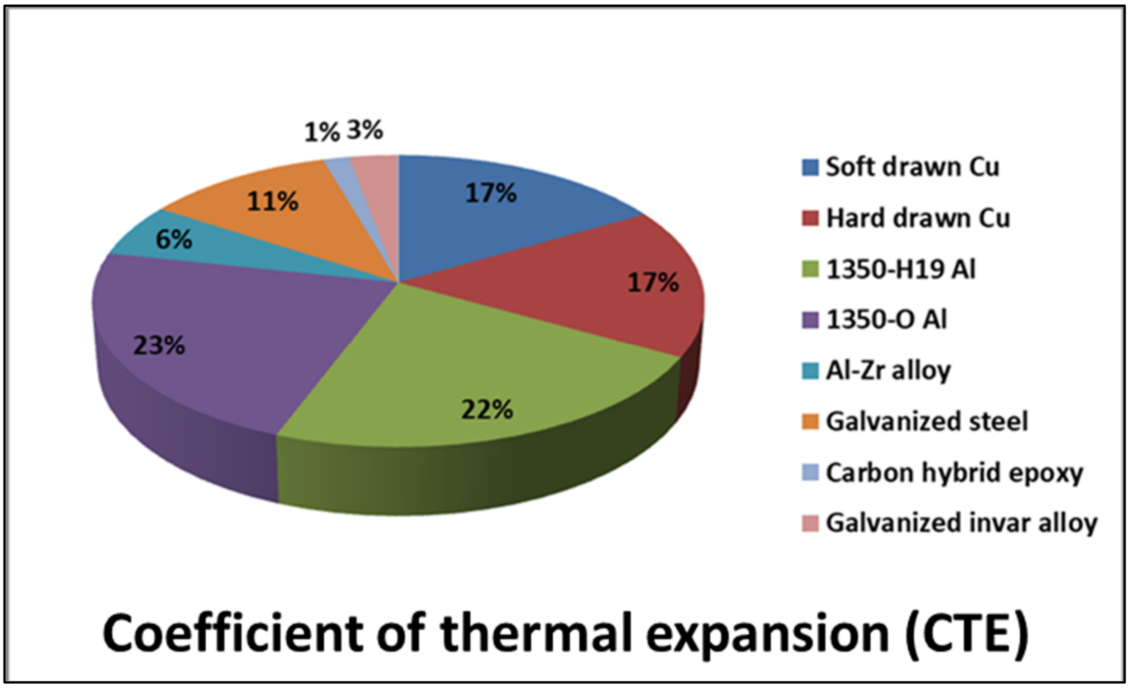
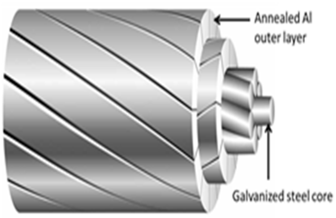
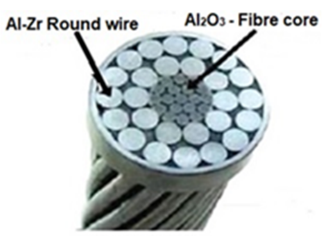
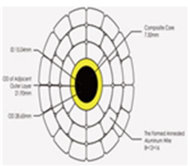
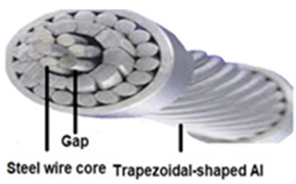


Figure 5. Coefficient of thermal expansion of conductor materials [39].

This is because they can withstand higher temperatures than the conventional conductors, and thus can transmit higher voltage. Higher current produces higher heat as a result of the joule heating (I^2R). It is equally observed in Figure 5 that both Al and steel possess a greater percentage of CTE. Hence, development of transmission conductors with these alloys should be minimized if total discarding is not possible. ACCC and ACCR have the highest ampacity as well as the lowest CTE percentages in the figures. Therefore, they are the most efficient HTLS conductors. Table 1 shows pictures, advantages, and weaknesses of the available HTLS conductors. It is observed that all of them have individual benefits as well as weaknesses. Therefore, it is not yet over for researchers in the development of more robust conductors with optimal functionality. This is because one or more of the issues identified in those conductors precludes their perfect operation, maximum productivity, and efficacy as a power transmission conductor capable of addressing the entire grid crisis.

Table 1. HTLS conductors and their properties.

HTLS Conductors	Conductor Picture	Advantages	Weaknesses	Ref.
(i) ACSS		(i) It can withstand temperatures of up to 250 °C. (ii) It is self-damping and sags lesser than ACSR. (iii) Higher ampacity than ACSR. (iv) Increased fatigue resistance.	(i) The steel core has high density. (ii) The core is prone to corrosion. (iii) Galvanized steel is costly.	[42–45]
(ii) ACCR		(i) Lower CTE than Al or steel. (ii) Higher ampacity. (iii) Lower density than steel. (iv) Higher stiffness and ductility than steel. (v) Can operate at 210 °C.	(i) It has relatively high CTE and, thus, can sag at higher temperatures.	[46–50]
(iii) ACCC		(i) It has very low CTE. (ii) Higher ampacity than ACSR. (iii) It has very low density. (iv) It has very low sag.	(i) It is expensive. (ii) It is weak on mechanical strength, and so cannot carry much ice load.	[11,51–56]
(iv) G-TACSR		(i) Its sag is lower than ACSR. (ii) It operates at higher temperatures than ACSR.	(i) High density. (ii) Difficult to install. (iii) Suffers the same corrosion as ACSR.	[50,57–60]

Some researchers' recent works [33,50,61–63], which focused on the design and development of new HTLS conductors, have demonstrated that those issues ravaging HTLS conductors, as shown in Table 1, could be addressed with innovative design and development of more improved conductors. In their design and development of the robust conductor, an outer layer comprising aluminum–niobium (Al-Nb) alloy and an inner core consists of an aluminum–carbon nanotubes–niobium (Al-CNTs-Nb) composite, as shown in Figure 6. The conductor material's electrical and thermal conductivity, as well as its tribological, corrosion, and mechanical properties, gave it an edge over other HTLS conductors on the market. Table 2 compares the properties of currently available transmission conductors with this new transmission conductor material.

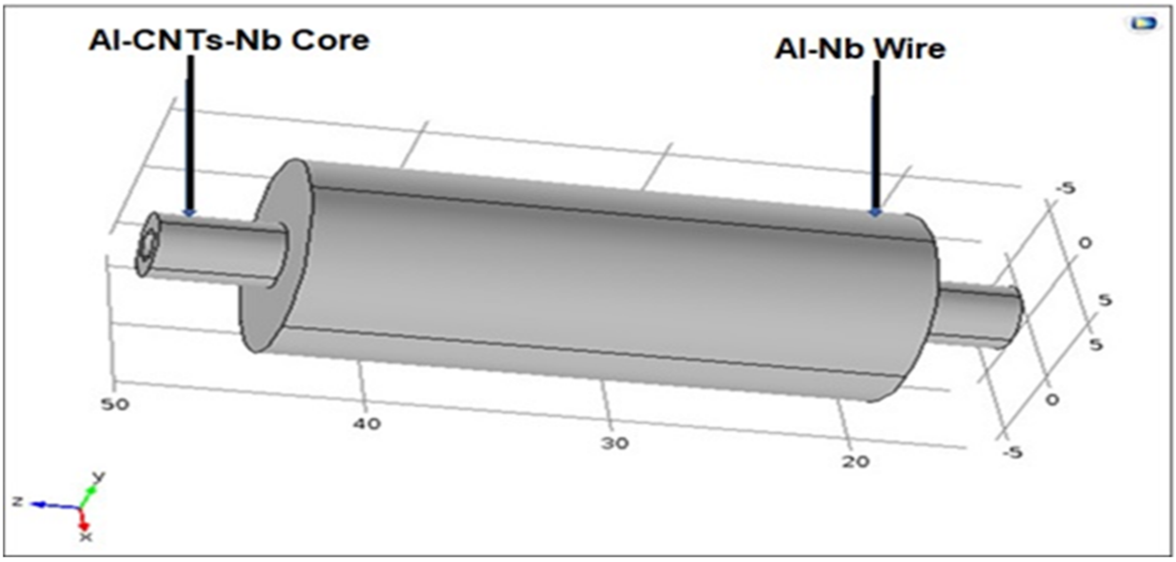


Figure 6. Features of newly developed transmission conductor [50].

Table 2. Comparative properties of transmission conductors [50].

Properties/Types	ACSR	ACCR	ACCC	Al-CNTs-Nb
Thermal conductivity (W/mK)	54	30	1.2	128
Maximum operating temperature (°C)	95	180	125	400
Core density (g/cm^3)	8.05	3.00	1.94	2.72

Meanwhile, critical examination and assessment of the new composite conductor material shows that it is challenged by high density, as Nb is a dense metal. Density is particularly essential in transmission conductors since it dictates how many pole supports are needed to carry the cable [64]. Denser conductors need additional pole supports, which may drastically increase the conductor's cost and installation costs. For this reason, nano-based material with lower density and better properties will be more preferred in the design and development of a smart-composite-based transmission conductor. According to studies, the density of graphene nanosheets (GNs) is a suitable fit for this sort of design since its density is substantially lower than that of carbon nanotubes (CNTs), aluminum oxide (Al_2O_3), niobium (Nb), and steel materials [14,65]. Furthermore, titanium is another element that can be used in place of Nb or steel as the transmission conductor core material. This is because the density of Ti is much lower than that of Al_2O_3, Nb, and steel [66–68].

3. Further Challenges of Electricity Transmission Grids

A number of challenges have been discovered to be militating against the maximum performance of transmission conductors, besides those itemized in the preceding sections. According to [39], overloading of grid, bush fire, lightning, extreme weather conditions, and short circuit are other major challenges that ravage transmission networks.

Overloading of the transmission lines is a situation whereby a gigantic amount of current transverse through a conductor and provokes grid instability resulting in high load demand, especially during peak hours. This can cause power outage and even explosion of the line. This anomaly of excessive load demand has been escalated by rapid population growth and rise in economic development, all culminating into increased electricity demand [69]. Thus, the ampacity of existing transmission lines needs to be optimized. Hence, development of hybrid refractory nanomaterials can ameliorate the effect of overloading. This is because those materials can be stable at a very high temperature. Such materials should have high melting point, high thermal conductivity, low CTE, and low density. Nanomaterials of CNTs, BN, SiC, and TiC [14] are some of the materials that when dispersed on Al alloy will give it good thermal stability to withstand critical temperature rise. That which occurs when there is instantaneous current upsurge which may damage the transmission line if the material has low thermal conductivity and stability.

Bushfire is another factor that inflicts critical damage to transmission conductors. It occurs frequently during summer (dry) seasons in most countries. Excessive wind speed and dry wind cause volatile fire growth, resulting in power line failures in California, Australia, and other fire prone zones such as sub-Saharan Africa [70]. Bushfire occurrences may be caused by natural phenomena or human activities. Unlike human activities, causes by natural phenomena can hardly be controlled as they are ignited by adverse climate change. A report shows that flame temperatures can reach up to 1000 °C to 1200 °C, hence militating against the performance of conductors through causing damage to the tower structures, conductors, and connectors [71,72]. Long exposure of conductors to bushfire can increase the temperature of transmission lines greatly, as shown in Figure 7. It causes the line temperature to rise from 5 °C to 15 °C higher than the normal operating temperature. This leads to premature ageing in transmission lines. Long exposure of conductors to bush flame aggravates mechanical deterioration of conductors. Thus, it reduces its load-carrying capacity, durability, and ampacity. To ameliorate this issue, refractory nanomaterials should be incorporated into the conductor material so that temperature of degradation will be increased. Moreover, human activities that lead to bushfires should be checkmated.

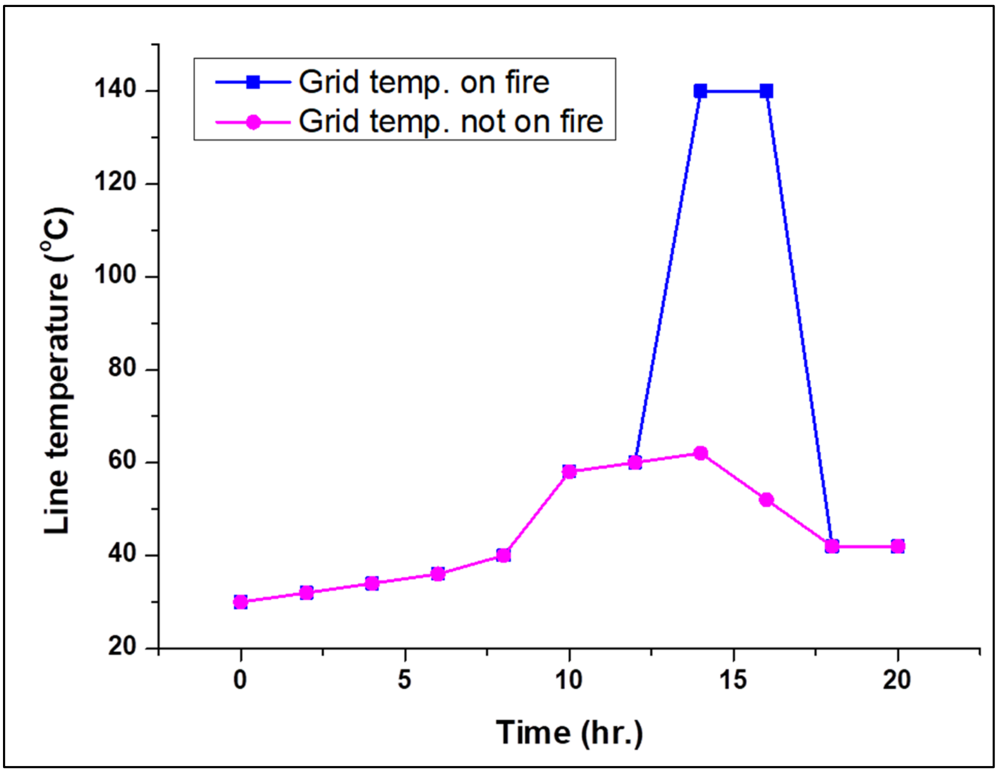


Figure 7. Transmission Line Temperature On/Not On Fire [71].

Lightning is another natural disaster that attacks transmission lines. The strike can produce a momentary current that surpasses the thermal strength of the attacked line, resulting in the disturbance in the flow of current on the transmission grid. Peak stroke current ranging from 2 to 200 kA can be generated by lightning. For a 40 kA peak current strike of lightning, a temperature of 30,000 K and energy of 39,550 J/ohm are generated [73,74]. Imagine this is incident on a transmission conductor—the damage will be great, as can be seen in Figure 8. So, in the event of such attack, the optimal performance of the transmission line will be heavily disturbed, if not destroyed, as is the case of the damage shown in Figure 8. If lightning hits the transmission conductor, its current will be added into the line current. The uppermost conductor witnesses more frequent hits than those beneath it. The lightning attack induces upsurge of devastating current in the upper conductor, which may result in burning down of the outer layer of the upper phase (Figure 8) [75]. Studies have shown that the degree of temperature rise as a result of lightning stroke is a function of the nature of the conductor material as well as the cross-sectional area of the conductor. Materials with higher thermal conductivity are less hit than materials with lower thermal conductivity. Moreover, smaller cross-sections experience higher temperature rise than larger cross sections [76]. This hypothesis can be authenticated by observing that when the same lightning strikes a telecommunication line and an electricity transmission line, the former will be more damaged, because telecommunication lines are smaller in cross-section. Research on ways of ameliorating the devastating effect of lightning on transmission lines is ongoing. Some schools of thought have it that high peak currents provoke quick ageing of transmission cables. It reduces the efficiency of the grid and increases voltage drop on the grid. Materials that have high thermal conductivities are able to conduct heat rapidly away when dispersed on Al alloy. Such materials with their thermal conductivities include CNTs (4000 $Wm^{-1}K^{-1}$), graphene (4000 $Wm^{-1}K^{-1}$), BN (740 $Wm^{-1}K^{-1}$), SiC (490 $Wm^{-1}K^{-1}$), AlN (319 $Wm^{-1}K^{-1}$), and TiC (330 $Wm^{-1}K^{-1}$) [77–80].

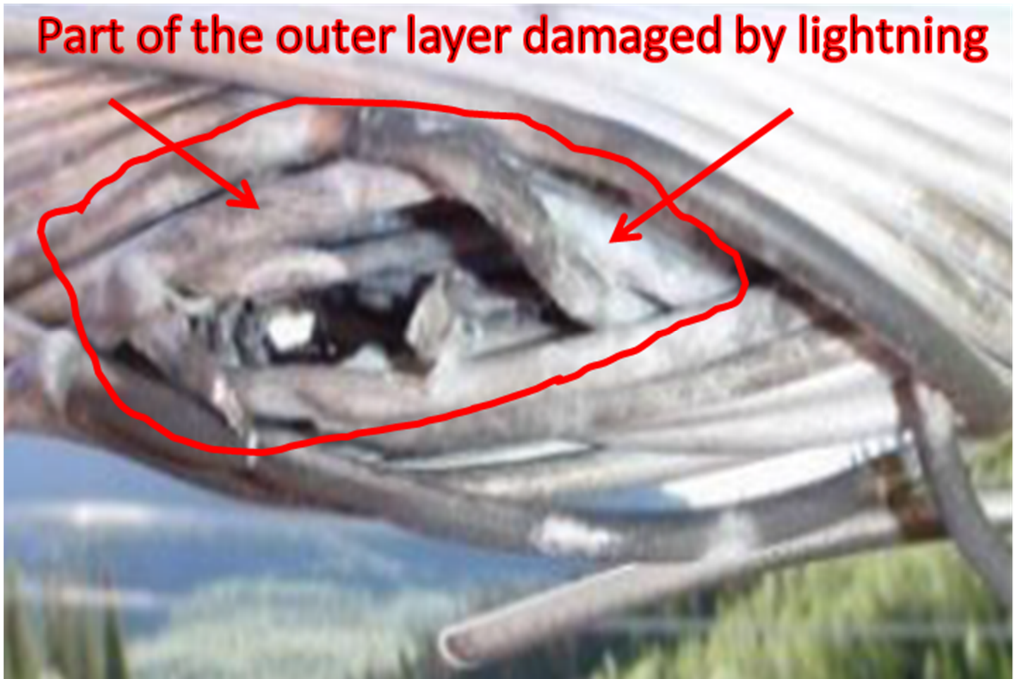


Figure 8. Image of conductor outer layer damaged by lightning [39].

Furthermore, extreme weather conditions provoke destructive contraction and expansion of transmission conductors at the instance of temperature fluctuations. During normal weather conditions, joule heating is dissipated into the environment to avoid undue conductor temperature increase. However, at extreme weather conditions, during summer (dry season) for instance, when the temperature of the ambient is raised by some percentage, the temperature of the conductor will as well be raised by the same factor, resulting in overheating of the conductor and subsequent ageing and creep. Moreover, research shows that during summer or dry season, the use of air conditioners is higher. This elevates the energy demand in the grid and increases thermal stress and expansion of the cable. However, during winter or rainy season, energy demand is reduced but affects the line by inducing line contraction [81,82]. A higher wind velocity stimulates speedy cooling of the conductor temperature [83]. Hence, windy weather is more clement to transmission conductors than humid weather, although the direction of the wind is an essential factor which determines its cooling effect on the conductor [84]. Cooling effect of wind direction that is perpendicular to the surface of the conductor is higher than wind that blows parallel to the surface of the conductor. Generally, the temperature of the conductor is raised when solar radiation and ambient temperatures are high, as well as when the wind velocity is low and the wind direction is parallel to the conductor surface [85].

Research shows that short-circuit is experienced when too large a current flows across the conductor during operation. This could be caused by unexpected accidents, failure of equipment, breakdown of the insulation system, unintentional bridging of two conductors, and other unforeseen mishaps. Short-circuit can lead to collapse of transmission grid, explosion, or fire, since the added current overheats the line. Sometimes, it can cause bird caging (Figure 9) in conductors [86]. In one of the tests to investigate the effect of short-circuit on conductors, it was observed that the conductor temperature was increased from 120 °C to 180 °C [87]. This would explode the conductor if ACSR or AAAC was the conductor installed in that grid. Short-circuit mostly occurs when the transmission lines experience a fault current that is equal to or above 10 kA. Most often, this fault current is produced by connecting large conductors to a high-capacity transformer, which produces a very high current to the connected devices [88,89]. It produces major concerns to researchers on how to ameliorate the effects, causes, and challenges of a short-circuit in electricity transmission grids. However, conductor materials that are able to withstand high temperatures of over 200 °C are recommended in tackling this transmission grid issue. Table 3 summarizes most of the challenges encountered in the transmission grid and the possible ways of ameliorating them.

Figure 9. Bird caging in transmission conductor [90].

Table 3. Summary of transmission grid challenges and control.

Transmission Grid Challenges	Manifestation/Damage	Prevention/Control
Conductor defects	(i) Electrical treeing (ii) Voltage drop (iii) Frequent power outage (iv) Low ampacity	(i) Improved fabrication techniques (ii) Improved and advanced nanomaterials
Overloading	(i) Grid instability (ii) Power outage (iii) Explosion of the line	Reinforcing Al alloy with thermally stable materials such as CNTs, BN, and TiC
Bushfire	(i) Lowers ampacity (ii) Speeds up ageing (iii) Reduces durability (iv) Burns down the wooden tsupports	Fire resistant nanomaterials should be alloyed to Al alloy in order to withstand high temperature of flames
Lightning	(i) Burns down the line (ii) Power outage (iii) Explodes the line (iv) Induces creep	Use of high thermal conductive nanomaterials in alloying of Al to induce speedy heat conduction
Extreme weather	(i) Excessive contraction and expansion of conductors (ii) Creep and ageing (iii) Decline in ampacity	Use of nanomaterials with very low CTE such as CNTs in reinforcing Al alloy as the conductor material
Short circuit	(i) Collapse of grid (ii) Explosion (iii) Fire (iv) Power outage	Use of refractory material that would withstand very high temperatures of over 200 °C

4. Robust Composite Materials for Transmission Conductors

From the available literature, it has been discovered that almost all the challenges militating against the efficiency and optimal performance of transmission lines stimulate a strange increase in the conductor's temperature. The excessive increase in the temperature of conductor provokes one or more instances of creep damage, fatigue stress, or ageing. Therefore, it is logical to state that most of these challenges can better be tackled through the development of robust conductor materials. A conductor material that is robust is able to withstand flame temperatures, for instance. It is able to dissipate speedily the excessive heat generated by lightning. In the period of summer or dry season, the extent of expansion of robust materials will not be too spurious as to initiate damage to the transmission line. It is noteworthy to know why Cu is not the preferred material for overhead transmission conductors, even with its excellent electrical conductivity. It is because of its high density, high cost, poisoning of silicon joints, absence of passivation oxide, and susceptibility to corrosion [50,91]. So, Al and its alloys were the preferred choice since they have most of those properties deficient in Cu. However, monolithic Al alloy lacks adequate strength, creep resistance, fatigue resistance, and thermal stability required to ameliorate the challenges experienced in transmission lines. This is the reason why it must be reinforced with carefully selected nanomaterials in order to boost its properties. Properties of some Al alloys and composites are discussed in this section.

4.1. Al-CNTs

CNTs have a high thermal conductivity of 4000 Wm^{-1} K^{-1}, high modulus of 1 TP, and very low density of 1.7 g cm^{-3}. These excellent properties of CNTs can improve the properties of Al when used as its reinforcement. Reinforcing Al alloy with CNTs improves not only the strength but also the tribological, corrosion, thermal, and electrical properties. If the CTE of the two materials are considered, it will be observed that CNTs have CTE of

10×10^{-6} K^{-1}, while Al has CTE of 23.6×10^{-6} K^{-1} [92], which is a very wide difference. So, during fabrication of Al-CNT composites, a great thermal mismatch occurs. This provokes huge dislocations at the interfaces that give rise to work hardening/strengthening of the composites. This is one of the basis of CNTs strengthening of Al. Kumar et al. [93] investigated the effect of CNTs addition into Al alloy and observed that the corrosion rate was tremendously reduced while the hardness of the composite improved. An increase in tensile strength by 129% was reported when 5 vol % CNTs was dispersed on Al [94]. Another study reported an increase in tensile strength and hardness by 184% and 333%, respectively, when 6.5 vol % CNTs were added to the Al matrix [95]. There was a reduction of corrosion rate by 46% and 47% in NaCl and H2SO4 media, respectively, when 4 wt % CNTs were dispersed on Al [96]. In another study, when 4 wt % of CNTs were added to Al alloy, the coefficient of friction (COF) improved by 52%, the wear volume reduced by 23%, the thermal conductivity improved by 35%, and the electrical conductivity improved marginally by 2% [61]. Al-CNTs are therefore a potential conductor material capable of performing creditably in increasing power in the grid.

4.2. Al-BN

Boron nitride (BN) is a ceramic with excellent thermal and mechanical properties. It has high thermal conductivity, low thermal expansion, noble thermal shock resistance, microwave transparency, non-toxicity, high machinability, non-abrasiveness, is chemically inert, and is non-wetting by most molten metals [97]. It has been found that this ceramic is also a good reinforcing material for Al alloy. Firestein et al. [98] reported that when 4.5 wt % of BN was dispersed on Al matrix, there occurred a 75% increase in tensile strength, a 190% increase in yield strength, and a substantial plastic deformation. In another study of the effect of BN reinforcement on the Al alloy matrix, it was observed that the addition of 4 wt % of BN into Al matrix increased the tensile stress from 212 to 333 MPa (57%) and hardness by 90% [99]. There were 90% [100] and 130% [101] improvements in ultimate tensile strength of Al-5 wt.%BN prepared through powder metallurgy, but this was reduced to 50% [98] when the percentage weight of BN decreased to 4.5 wt %. With these properties of Al-BN, it can be seen that it is another robust composite that can be used in the development of advanced composite conductors.

4.3. Al-TiC

TiC is another excellent ceramic suitable for improving the properties of Al alloy in order to boost its thermal, mechanical, tribological, and corrosion properties. Raviraj et al. [102] studied the effect TiC addition on Al matrix. It was discovered that by addition of 5 wt % of TiC into Al alloy, the yield strength, modulus of elasticity, microhardness, and percentage elongation improved by 88%, 21.6%, 20.3%, and 52.4%, respectively. Bauri et al. [103] recorded a 40% increase in ultimate tensile strength and a 52.6% increase in microhardness of Al-TiC prepared via double pass friction stir processing (FSP). There was tremendous improvement in the tribological properties of Al-TiC composite when the weight percentage of TiC was 7.5 wt % [104]. Wang et al. [105] studied the effect of TiC on the mechanical properties of Al alloy. It was observed that the addition of 0.5 wt % TiC improved the yield strength, ultimate tensile strength, and percentage elongation by 117.3%, 40%, and 81.3%, respectively. It can be seen that Al-TiC has excellent properties and thus can perform creditably in transmission grid.

4.4. Al-SiC

SiC is a good reinforcing phase for Al alloy in electrical application because it has good electrical and thermal properties. According to Porter and Davis [106], SiC has good thermal stability, excellent electrical conductivity, and high thermal conductivity. Yaghobizadeh et al. [107] reinforced Al with SiC and obtained an increase in ultimate tensile strength and hardness by 90% and 31.6%, respectively. Tensile and compressive strengths were improved by 71.4% and 42.9%, respectively, when 18 wt % SiC was added to Al [108]. In another study, the addition of 5 wt % of SiC improved the hardness by 32%, wear resistance by 40%, and COF by 6% [109]. Kamrani et al. [110] reinforced Al with SiC and obtained 64% improvement in yield strength, 48.3% improvement in compressive strength, and 90.4% improvement in hardness with 7 vol % SiC. These excellent properties of Al-SiC indicate that it is equally a potential composite conductor material capable of increasing current in the grid.

5. Future Work

It has been established that the use of Al-nanomaterial composites will be able to ameliorate the challenges being experienced in the grid. Some Al composites have been projected as the possible transmission conductor materials that would perform better than the existing conductors. Therefore, further research work that should be undertaken includes the following:

(i) Production of the suggested Al composites with an improved powder technology technique such as spark plasma sintering. The fabrication would involve optimization of the process parameters and the reinforcement weight fraction. All the composites should be subjected to the same fabrication and testing conditions. Properties to be tested include mechanical, physical, electrochemical, tribological, and thermal properties. These tests would be able to confirm the composite with the best characteristics.
(ii) The best performing composite should be produced and drawn into wire for onward characterization and testing. Properties to be tested on the drawn wire include ampacity, CTE, and tensile strength tests.
(iii) Comparative analysis of the developed transmission conductor and the existing conductors on the basis of their properties and cost must be conducted.

These itemized works are not only timely but very imperative to the advancement of scientific research on electricity transmission.

6. Conclusions and Recommendations

This study was aimed at studying recent publications dedicated to increasing current in the transmission grid; improving the durability of transmission conductors; reducing the overhead cost of transmission networks; and, above all, diminishing frequent power outages. From the literature survey, the following conclusions and recommendations are made:

1. South Asia, Middle East/North Africa, and sub-Saharan Africa are the three major regions mostly hit by frequent power outages.
2. AAAC and ACSR are challenged by a low operating temperature of 95 °C. HTLS conductors can withstand a temperature of 200 °C, above which makes them possess higher ampacity than the conventional conductors. However, ACCC and ACCR, being the best performing, are still challenged by low strength (for ACCC) and relatively high CTE (for ACCR). Hence, this is the imperativeness of this research.
3. Monolithic Al lacks mechanical and tribological properties that are requisite of transmission conductors. So, it is recommended that it should be reinforced with nanoparticles of CNTs, BN, TiC, and SiC in binary and ternary composite systems, produced with SPS, that are characterized and tested. The obtained results should be used to confirm the best composite to be used for further studies.
4. Lightning, bushfire, harsh weather, short circuit, and overloading also contribute to frequent power outages. These are natural environmental hazards that can hardly be avoided. So, to cushion their effects, flame- and heat-resistant nanomaterials are recommended to be used for reinforcing Al alloy that will be used in developing a robust transmission conductor.
5. It is recommended that the best composite should be drawn into a wire and tested. The tests to be conducted should include ampacity, coefficient of thermal expansion (CTE), and tensile strength.

6. Cost and property comparison of the developed conductor and the existing conductors should be conducted. It is expected that the proposed Al nanocomposites would have more ampacity, higher thermal conductivity, lower CTE, and better strength than the existing transmission conductors.

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