Robust Composite Materials for Transmission Conductors

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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. 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. There is a need to develop more robust conductor materials that can withstand these challenges.

aluminum conductor transmission network thermal expansion

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]. Corruption in energy sector, equipment misuse, unlawful connections and disconnections, inadequate power zoning distribution, and overloading of power transmission lines all exacerbate power crisis [9]. Scholars such as Alawar et al. [10] 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 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 [11]. Ma et al. [12] 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.

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. [13] 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 [14], 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 [15][16][17]. 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 [17][18][19][20]. Some authors believed that 3D printing is one of the best ways of consolidating composites for better performance [21]. In their opinion, Giordano and Nicolais [18] remarked that the quality of pultruded products can be improved by guiding the polymerization and rheological kinetics of the resin. Krasnovskii and Kazakov [16] 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. [19] 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. [22] 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 [23][24][25]. 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 [13], 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 [26] 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 [26]. 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.

2. 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 [27][28]. 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.

2.1. 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} [29], 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. [30] 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 [31]. 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 [32]. 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 [33]. 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% [34]. Al-CNTs are therefore a potential conductor material capable of performing creditably in increasing power in the grid.

2.2. 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 [35]. It has been found that this ceramic is also a good reinforcing material for Al alloy. Firestein et al. [36] 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% [37]. There were 90% [38] and 130% [39] improvements in ultimate tensile strength of Al-5 wt.%BN prepared through powder metallurgy, but this was reduced to 50% [36] 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.

2.3. 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. [40] 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. [41] 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 % [42]. Wang et al. [43] 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.

2.4. 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 [44], SiC has good thermal stability, excellent electrical conductivity, and high thermal conductivity. Yaghobizadeh et al. [45] 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 [46]. In another study, the addition of 5 wt % of SiC improved the hardness by 32%, wear resistance by 40%, and COF by 6% [47]. Kamrani et al. [48] 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.

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