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High performance overhead power lines with carbon nanostructures for transmission and distribution of electricity from renewable sources

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A B S T R A C T

Integration of information, communication and materials technologies into the electricity Smart Grids is the key to sustainable clean energy future. This study focuses on materials innovation and design of power transmission lines. Conventional bi-material power transmission lines consist of aluminum conductors with steel reinforcement. Increase in temperature of transmission lines due to Joule heating limits their current carrying capacity and the efficiency of power transmission. New design of transmission wires proposed in this study consists of carbon nanostructure (CNS)-epoxy composites in a multilayered architecture to enable multifunctional capabilities. Excellent thermal transport properties of CNS-epoxy composites are utilized to optimally dissipate heat from the outer surface of transmission wire in order to maximize its performance. A coupled electrical-thermal finite element (FE) analysis of Aluminum Conductor Steel Reinforced (ACSR) wires is performed and the results are benchmarked with those obtained from relevant IEEE standards. The validated model is then extended to new transmission line composed of aluminum conductor - composite core with CNS-epoxy composite coating (ACCC-CNS). Steady-state coupled FE analyses of ACSR and ACCC-CNS wires indicate that the proposed design of ACCC-CNS wire enables transmission of larger currents than an equivalent ACSR wire for the same amount of conductor material due to reduced operating temperature. The proposed design of power lines would enable development of Smart Grids for more efficient utilization of electricity from renewable sources.

1. Introduction

1.1. Smart grids and electric transmission

Increasing urbanization, developing digital economy and business environment requiring electronic transmission of data are the major factors contributing to the growth in electricity demand. Electrical power research institute (EPRI) report on electricity technology roadmap shows that electrification has promoted a drop in energy usage intensity while promoting the economic and societal development (Fig. 1). According to International Atomic Energy Agency (IAEA) report, by 2030 electricity would constitute 22% of the total energy consumed worldwide as compared to 18% in 2000 (International Atomic Energy Agency (2004)). Since most of the high growth economies of 21st century are located in developing part of the world, it is projected that by 2030 these developing countries will utilize 43% of global electricity production compared to 27% in 2000 (International Atomic Energy Agency (2004)). This high demand for electric power is met by numerous power generation plants, supported by strong transmission systems, supplying safe, reliable and economic electricity to its commercial, residential and industrial clients.

Three major technologies namely generation, transmission, and distribution have been growing under the umbrella of Smart Grids (Cardenas et al. (2014); Nejadfard-Jahromi et al. (2015); Zahurul et al. (2016); Santo et al. (2015); Selvam et al. (2016)). Efficient and reliable transmission of electricity is intricately connected to living standards. Integration of information and communication technology into the electricity smart grids is the key for meeting the future electricity demands and efficiency requirements (Bouhafs et al. (2012); Gungor et al. (2011); O'Driscoll and O'Donnell (2013); Battaglini et al. (2009); Electrical Power Research Institute

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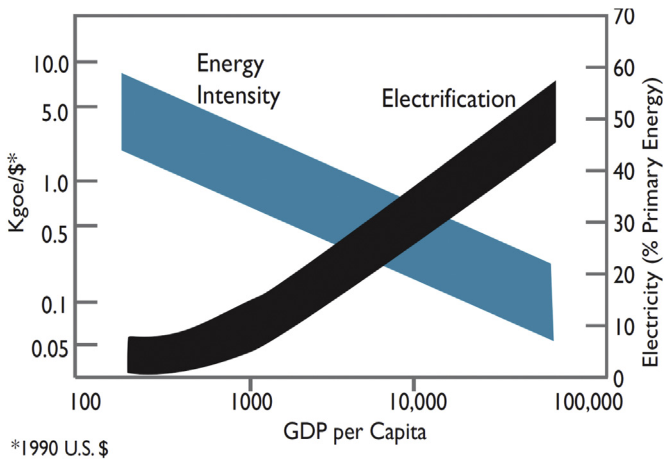

Fig. 1. Energy intensity and economic development as a function of electrification (Electrical Power Research Institute (2003)).

(2003)). The ever increasing electric power demand and stringent environmental regulations necessitate the integration of renewable energy power plants with new electric transmission lines and replacement of aging transmission lines to improve the grid stability and reliability (Edison Electric Institute (2013); World Bank (2011); StatPlan Energy Limited (2012)). Lund et al. (2015) has recently emphasized the importance of Smart energy system design for large clean power schemes in urban areas and predicted that increasing the renewable electricity share beyond a limit without a smart design adds only limited benefit. Governments and private entities all over the world are addressing the issue by providing strategic funding and stimulus to the industrial enterprises interested in developing efficient electricity transmission and distribution (T&D) systems. Responding to this trend, the power transmission industry is searching for high performance alternatives to conventional transmission lines in order to meet the projected demand for the bulk transmission of electricity.

1.2. Materials technology

From the technology development point of view the European Union in 2010 established an energy technology policy for Europe to support the 2020 energy and climate change targets. One of its key initiatives was to address materials technology that will be needed in order to achieve the 2020 targets (European Commission (2010); Giordano et al. (2013)). A recent review on materials used for generators in wind turbines by Lacal-Arántegui (2015) indicates that the improvement in materials specifications is challenging but achievable in most areas. However, the cost reduction has been identified as a crucial aspect of renewable energy production. Overhead electricity transmission wires are the primary carrier of bulk electricity from generation facilities to the distribution sub-stations (over 90% of total market). Most of the existing transmission lines use aluminum conductor - steel reinforced (ACSR) wires developed in 1920s. The increased demand for electricity constrains the existing transmission and distribution (T&D) systems to operate at higher efficiency and reliability levels. However, with the current state of electricity transmission technology, approximately 9% of the total electricity generated (1.8 trillion kilowatt-hours out of 20.3 trillion kilowatt-hours) is lost in the form of line losses during transmission of electricity globally (World Bank (2014)). Therefore, the electric utility companies are searching for high performance alternatives to construct new transmission lines and replace existing transmission lines. This warrants improved design of transmission wires with innovative materials capable of offering higher transmission efficiency. The current carrying capacity and efficiency of transmission lines are primarily limited by their elevated operating temperature owing to Joule heating (Kovač et al. (2006); Banerjee (2014); Chen et al. (2012)). The amount of energy lost due to Joule heating depends upon the resistivity of the conductor, conductor temperature and the amount of current. Steady-state temperature of the transmission lines is resultant of energy balance between heat generation due to Joule heating and heat loss from the wire to the surrounding (IEEE (2013)) via radiation and convection. Higher conductor temperature promotes thermal deterioration of wires and increases the wire sag. These two have often been cited as the reasons for physical failure of transmission lines causing brownouts and blackouts (Harvey (1972); Burks et al. (2010); Bhuiyan (2011)). The life-cycle analysis of 11 kV electrical overhead lines and underground cables concluded that the system with lowest conductor resistance should be selected to minimize the deteriorating life-cycle impacts (Jones and McManus (2010)). Nevertheless, the choice of conductor material is limited by the materials technology.

Several electrical equipment manufacturers attempted to develop high capacity solutions to reduce power transmission bottlenecks. For instance, 3M offered high ampacity Aluminum Conductor – Aluminum Composite Reinforced (ACCR) transmission wires with aluminum-zirconium (Al-Zr) alloy as primary conductor (3M Publication (2003)). However, these transmission lines cost 3–6 times more than the conventional ACSR transmission lines (Iowa State University (2011)). In 2005, CTC Global introduced a high temperature - low sag Aluminum Conductor – Composite Core (ACCC) transmission wire with Al-1350-O alloy as the conductor in place of conventional Al-1350-H19 alloy (CTC Global Corporation (2011)). Both of these wires received limited enthusiasm from highly conservative power transmission industry because introduction of new conductor material for the design of transmission lines would require capacity re-evaluation of all the accessories of transmission lines. These issues are alleviated in the new design of transmission lines proposed in this study.

This study examines the new transmission line architecture as a high performance alternative to conventional ACSR transmission wires. Superior electrical, thermal and mechanical properties of CNS materials (Pal and Kumar (2016a,b); Arif et al. (2016); Kundalwal and Kumar (2016)) are utilized to design such a high performance wire. The new transmission line (ACCC-CNS) proposed in this study consists of conventional Al-1350-H19 alloy as conductor and glass fiber reinforced epoxy composite core to sustain thermo-mechanical load with CNS-epoxy composite outer layer. The inner-CNS layer protects the composite core from stray radio frequency (RF) generated by the electromagnetic pulse (EMP) emanating from high electric current carrying aluminum conductor. The outer CNS-epoxy layer with increased thermal conductivity and high emissivity is expected to facilitate optimal dissipation of the heat generated in the conductor. Incorporation of outer CNS composite layer in the transmission wires may also enable in-built deicing capability and protection from lightning strike and foreign object damage (Al-Saleh and Sundararaj (2009); Chu et al. (2014)). In this study, the performance of the new ACCC-CNS and ACSR transmission lines is investigated in terms of line loss due to Joule heating using both transient and steady-state coupled thermal-electrical finite element (FE) analyses. For both wires (ACCC-CNS and ACSR), conductor surface temperature is considered as the measure of energy loss due to Joule heating.