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Analysis of Sag Caused by Stresses on Electrical Transmission Lines

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Abstract: The majority of design failures are attributed to a confluence of different stresses operating on the material both internally and outside. If the stress levels are controlled within the system's design parameters, early failure won't happen. The longevity of the material can be significantly shortened and failure may occur if the sum of the stresses exceeds the design capacity. The stress value utilized in the design of a structure or machine should be significantly less than the material's tensile strength to account for subpar material workmanship and potential overloading. Research has been done on improving the mechanical, electrical, and thermal properties of materials by reinforcing them with nano- or micro-particles. The stresses associated with overhead transmission lines are reviewed in this work in order to provide design and manufacturing guidelines for overhead power line conductors. It takes into account the pressures on the conductors as well as the forces that cause such stresses.

Keywords: Sag; Conductors; Stress; Transmission line; Aluminum alloy.

INTRODUCTION

Stress is a material's internal resistance to a force or pressure that would otherwise cause it to deform [Nabhani, F. *et al*., 2011]. These counterforces tend to return the atoms in the materials to their normal positions if the elastic limit or yield point is not exceeded. The total resistance developed is equal to the external load or force [Nabhani, F. *et al*., 2011]. If the elastic limit or yield point is not surpassed, these counterforces tend to bring the atoms back to their original places in the materials. The total amount of resistance created is equal to the external force or load. Stress is the name for this resistance [Levitt, J. 2015]. Materials mechanics, also referred to as the strength of materials, focuses on examining stresses and deflections in materials under load [He, M. *et al*., 2014; Steinmann, P. and Maugin, G.A. 2006]. The ability to safely design structures that can hold their intended loads is made possible by an understanding of stresses and bending moments [Ngo, T. *et al*., 2007].

However, if a force is applied to a structural member, the force will cause that member to experience both stress and strain [Abe, M. *et al*., 2000]. In contrast to strain, which measures the deformation brought on by the force, stress measures the force per unit of cross-sectional area. The two main categories of stress are shear stress and normal stress. Since the force's direction is parallel to the region resisting it, axial stress and bending stress are examples of normal stress [Irvine, M. 1992].

Since the force's direction is parallel to the region resisting it, shear stress comes in the forms of torsional stress and transverse shear stress [Roberts, T.M. and Al-Ubaidi, H. 2001]. A transmission line conductor may be loaded by an axial force, which produces an axial stress, tensile stress, or compressive stress; a shear force, which produces a transverse shear stress; a bending moment, which produces a bending stress; or a torsion, which produces a torsional stress [Ugural, A.C. and Fenster, S.K. 2003; Carvill, J. 1994; Ross, C.T. and Chilver, A. 1999; Costello, G.A. 1997]. Shear strain results from shear stress, bending strain results from bending tension, and torsional strain results from torsional stress [Knapp, R.H. 1988; McDiarmid, D.L. 1991; McDiarmid, D.L. 1987; Lobontiu, N. and Garcia, E. 2004]. Pressure-generated stresses, forces supplied gradually, temperature-induced stresses, friction-driven vibration stresses, torque- or twisting-moment-induced shear stresses, and stresses brought on by cyclic loading are examples of induced stresses [Predki, W. *et al*., 2006; Atherton, D.L. and Jiles, D.C. 1986; Varotsos, P. *et al*., 1998; Ibrahim, R.A. 1994; Collins, J.A. *et al*., 2009; Hetnarski, R. B. *et al*., 2009; Weissmüller, J. *et al*., 2003]. Transmission line stresses include longitudinal stresses brought on by lateral deflection, vibrational stresses, residual stresses, and stresses originating from direct lateral attractive and repulsive forces between conductors [Farzaneh, M. and Teisseyre, Y. 1988; Abd-El-Aziz, M. *et al*., 2011; Alfredsson, K.S. and Josefson, B.L. 1992].

To achieve product excellence at the lowest feasible overall cost, design is regarded as a quality

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technique. Strength, rigidity, dependability, safety, cost, weight, ergonomics, aesthetics, manufacturing considerations, assembly considerations, conformance to standards, friction and wear, life, vibrations, thermal considerations, lubrication, maintenance, flexibility, size and shape, stiffness, corrosion, noise, and environmental considerations are all factors that need to be taken into account during the design process [Chitale, A.K. and Gupta, R.C. 2011; Bhandari, V.B. 2013; Shim, J. 2004]. Numerous design factors are functions of stress [Chen, G. *et al*., 2004]. Designing with ergonomics in mind involves thinking about how people (users) interact with machines and their environments in order to reduce the user's physical and mental strain [Kahya, E. 2018; Khan, I. A. 2012]. The mechanical characteristics of materials, which are influenced by stress, include strength, stiffness/rigidity, elasticity, plasticity, ductility, brittleness, malleability, toughness, machinability, resilience, creep, fatigue, and hardness [Singh, U.K. 2009].

Engineering materials go through heat treatment, which is a series of procedures involving heating and cooling a metal or alloy in its natural state to achieve specific desired conditions or properties without changing its chemical composition [DeGarmo, E.P. *et al*., 1997]. Heat is a type of stress, and it is applied to engineering materials to achieve certain desirable conditions or properties [DeGarmo, E.P. *et al*., 1997]. Tempering, spheroidizing, annealing, hardening, normalizing, and surface or case hardening are some of the several heat treatment procedures [Jutz, H. 2006]. The objectives of heat treatment are to increase the hardness of metals, reduce stresses created in the material after hot or cold working, improve machinability, soften the metal, alter the structure of the material, enhance its electrical and magnetic properties, alter the grain size, and increase the qualities of metal to provide better resistance to heat, corrosion, and wear [Bhateja, A. *et al*., 2012].

Analyzing desired material qualities, screening potential materials, and choosing the best material are the many processes in the material selection process for design. The minimum total number of parts in a product, the least amount of variety of parts, the use of standard parts, the use of modular design, the design of parts to be multifunctional, the design of parts for multiple uses, the choice of the least expensive material, the design of parts to facilitate manufacture, and the shaping of the parts to minimize operations are all manufacturing considerations in design [Jahan, A. *et al*., 2016]. Direct current (DC) produces a single-directional force or stress, whereas alternating current (AC) produces a vibrating force or stress [Lloyd, J.R. 1999; Radley, I. *et al*., 2006]. Heat is another type of stress in addition to pressure. Strain results from the stress that is introduced into a conductor. Mechanical stress is the name given to this kind of stress. Because the conductors are tensed as a result of the temperature-induced stress in it through voltage and current, a transmission line is referred to as a high-tension or tensional stress line [Karetta, F. and Lindmayer, M. 1996; Chuan, L *et al*., 2014].

The main means of transporting electricity are conductors and cables, which are essential for the consistent, effective, and economical supply of power [Amin, M. and Stringer, J. 2008]. Except at lower voltage levels, conductors are typically not insulated and are suspended overhead from poles and towers. In contrast, cables are always insulated and are typically utilized in underground applications, such as in densely populated urban areas, where the usage of overhead lines is constrained by real estate costs, safety issues, and aesthetic considerations [Buijs, P. *et al*., 2011].

Underground cables are also used in applications where overhead lines are hard to locate, e.g., water crossings, and they are increasingly considered advantageous for their resilience to wind and ice storms [Dunn, S. *et al*., 2018]. Metrics that can be used to gauge advancements in the capabilities of cables and conductors include reduced space requirements, less electromagnetic frequency exposure, no contribution to visual pollution, and low life cycle costs. [Bi, Z. *et al*., 2016].

Long mechanical structures with an electrical purpose, such as overhead power lines or bare conductors, link substations together [Kopsidas, K. *et al*., 2012]. In order to transmit power over great distances, each line in the power system can be treated as a single device. These can include a variety of parts, including foundations, conductors, towers, and fittings [Mensah, A.F. and Dueñas-Osorio, L. 2016]. Phase spacing, bundle configuration, number of sub-conductors in the bundle, and design temperature of the line are a few of the factors that work together to determine the values of the electrical parameters resistance, inductance, and capacitance (expressed as R, X, and B when computed using system frequency), which establish the power flow capability [Adam, J.F. *et al*., 1984]. Additionally, they have an

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impact on the design of the structure, the conductor's mechanical characteristics, the cost of the line, and the expected operating performance [Kiessling, F. *et al*., 2014].

A conductor carries a current, which generates a magnetic field that interacts with other nearby magnetic fields to produce a force [Ramadan, Q. *et al*., 2004]. Electromagnetic stress is the name for the force created by two conductors that is proportionate to the current and tension involved. Large mechanical forces are produced in the supporting system and the conductor by the high transient current. Additionally, as current flows through a conductor, electrons migrate from one end to the other, imparting some of their momentum onto the metal atoms, which then begin to move gradually [Roy, K. 2014]. Additionally, high mechanical strains and extreme localized heating or "hot spots" are produced by the current [Ciappa, M. 2002]. When stressed, all metals go through a mechanical deformation process known as creep, which is more noticeable at high temperatures [Collins, J.A. 1993]. The cross-sectional area of the wire has an inverse relationship with electrical resistance or stress [Ruschau, G.R. *et al*., 1992]. The resistance or stress to the movement of electrons is known as electric resistance or stress [Butt, A.M. *et al*., 1990]. Low electrical resistance or stress characterizes effective electrical conductors [Chen, Z. *et al*., 2011].

According to studies, copper wire in a transmission line can withstand mechanical deformation or creep [Li, J., and Dasgupta, A. 1993]. Silver is regarded as the best electrical conductor, with gold, silver, copper, and aluminum also being considered to be good conductors [Fassler, A. and Majidi, C. 2013]. Precious metals like gold and silver typically have more expensive applications, which tends to restrict their use on a big scale [Corti, C.W. and Holliday, R.J. 2004]. Copper or aluminum are often the most widely used materials for electrical conductors. In addition to being a good conductor, copper has little electrical stress [Li, Y. and Wong, C.P. 2006]. Aluminum and its alloys are excellent choices for all bare overhead transmission lines due to copper theft and cost. In order to recommend improvements in quality and dependability, this study will examine frequent stresses in conductors while highlighting the benefits and demerits that were employed in their evaluation.

Conductor Geometric Model Establishment

Included in mechanical stresses are: loss of clearance, misalignment of the dynamic and static load, overhung load and bending, and conductor movement objects in flight, the wrong core fit poorly shaped structures, vibration, exhaustion or component failure persistent tensions. Then, voltage, vibration, current, electromigration, tracking, corona, transients, electromigration, and electrostatic coupling are examples of electrical stressors. Temperature gradients, thermal overload, friction, loading, thermal unbalance, and voltage variations are all examples of thermal stresses. Corrosion, temperature, erosion, and wear are examples of environmental stressors [Ciappa, M. 2002; Bonnett, A.H. and Soukup, G.C. 1992; Offline, S. 2013; Mazzanti, G. 2009; David, E., Parpal, J.L. and Crine, J.P. 1996; Cygan, P. and Laghari, J.R. 1990].

Forces and stresses can pass through a material, but when the geometry of the material changes, the flow lines shift in order to accommodate the loads, either moving closer together or farther apart. If there is a hole or notch in the material, for example, the flow lines will congregate close to the hole or notch and the stress will have to flow around it. A stress concentration is a term used to describe the peak stress that results from the flow lines' rapid grouping together. A stress riser is a term for the feature that results in the concentration of stress [Madrazo, V. *et al*., 2012]. A transmission cable sags due to stress [Muhr, M. *et al*., 2005]. Strain or distortion brought on by stress acting on the conductor results in sag [Papailiou, K.O. 1997].

The following are the elements that contribute to transmission lines sagging [Slegers, J. 2011]:

1. Temperature: The conductor's current, the surrounding temperature, the intensity of the sun's rays, and the wind speed.
2. Age: Over time, strand settling in and metallurgical creep may cause conductor sag to worsen.
3. Conductor weight: The conductor's droop is directly inversely proportionate to its weight.
4. Span length: Sag is inversely correlated with the square of the span length.
5. Wind: The conductor will appear heavier when there is a wind load on it, which will increase tension.
6. Material kind and material type.

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Force analysis for a conductor with a single-span

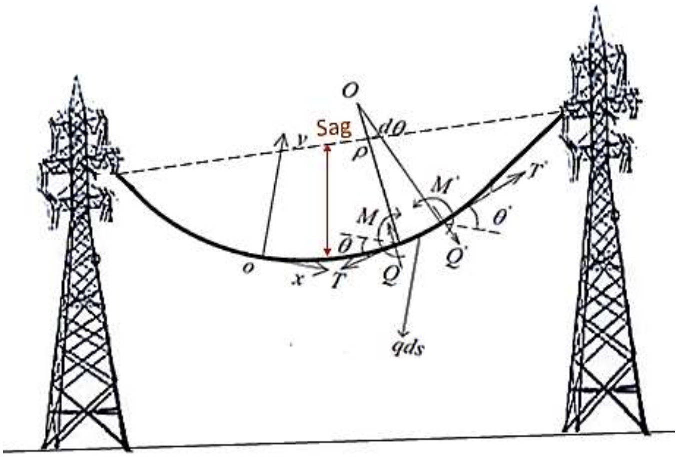

Fig.1: Schematic diagram of force analysis of conductor in single-span [Oluwajobi, F. I. 2012]

The internal force of an overhead line is, calculated as follows (See **Fig 1**):

(a) The bending moment and the curvature have the following relations [Li, Y. *et al*., 2016].

$$1/\rho = M/EI \quad (1)$$

The internal force can be, obtained under the assumption of elasticity by using the radius of curvature ρ [Li, Y. *et al*., 2016].

(b) Moment, $M = EI/\rho$ (2)

(c) Shear,
$Q = (2EI\rho q \sin\theta)/(EI-q\rho\text{^}3 \cos\theta)$ (3)

(d) Axial force,
$T=\rho dQ/ds+\rho q\cos\theta=dQ/d\theta+\rho q\cos\theta$ (4)

Where:
ρ = radius of curvature; E = elasticity; q = internal force; I = inertia; M = moment; Q = shear; T = axial force
The axial force can be influenced by the bending moment and shear. Researches show that the true axial force of a non-flexible wire is lower than that of a flexible wire.

Generic Thermal Stress Behavior on Conductor

Temperature and stress do not depend on where they are applied to a structure or material. However, if the stress is maintained, the temperature will rise, which will result in a reduction in the material's elongation. The stress temperature coefficient will be zero if there is no elongation. The heat balance equation for an overhead conductor, as depicted in Figure 2, is equation 5. Temperature and stress do not depend on where they are applied to a structure or material. However, if the stress is maintained, the temperature will rise, which will result in a reduction in the material's elongation. The stress temperature coefficient will be zero if there is no elongation. The heat balance equation for an object is Equation 5.

$$Q_j+Q_m+Q_s+Q_f=Q_c+Q_r+Q_w+mCp(dT_c)/dt \quad (5)$$

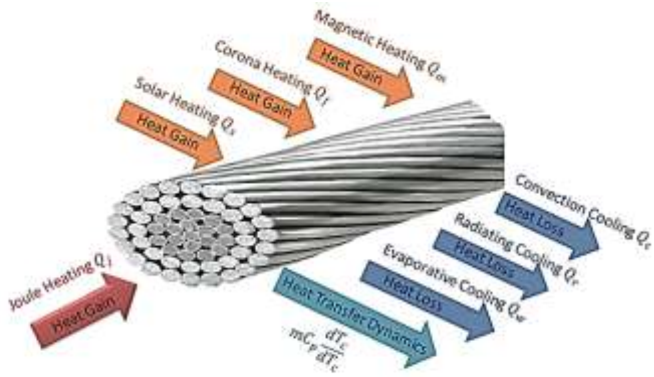

Fig.2 Thermal characteristics of a generic overhead conductor represented [Li, Y. *et al*., 2016]

The dynamic heat balance equation is written out in the IEEE Standard. [Dong, X. *et al*., 2014]:

$$Q_j(T_c)+Q_s=Q_c(T_c)+Q_r(T_c)+mC_p(dT_c)/dt \quad (6)$$

According to Fig. 3 below, the conductor system's net heat input (Q) determines the long-term thermal-mechanical fatigue and creep damages. This net heat contribution is determined by:

$$Q_{(netinput)}=Q_{(jouleheating)}+Q_{solar}-Q_{radiation}-Q_{conduction} \text{ --(7)}$$

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Fig. 3. Thermal behavior of overhead conductors [Li, Y. *et al*., 2016]

Where:

Q = Heat capacity; Q_j = Joule heating; Q_m = Magnetic heating; Q_s = Solar heating; Q_f = Corona heating; Q_c = Conventional cooling; Q_r = Radiation cooling; Q_w= Evaporation cooling; $mCp(dT_c)/dt$ = Heat transfer dynamics, T_c = Temperature of convention, m = mass; Cp = Specific heat capacity

FINDINGS AND DISCUSSION

Table -1 demonstrates various conductor kinds, code names, the impact of stress on conductors, and references

Code name	Conductor description	Effect of stress on the conductors	Reference
AAAC	All Aluminum Alloy Conductor	At temperatures exceeding 90–100 °C, annealing occurs and strength is lost. Sags	[Kavanagh, T. and Armstrong, O. 2010]
ACAR	Aluminum Conductor Aluminum Alloy Reinforced	It suffers from corrosion stress.	[Bobić, B. *et al*., 2010]
ACSR	Aluminum Conductor Steel Reinforced	High temperatures cause annealing and a loss of strength. It experiences galvanic corrosion as a result of the presence of aluminum and steel, which are dissimilar metals, in marine environments or in industrial environments..	[Hardy, C. *et al*., 2005; Azevedo, C.R. and Cescon, T. 2002]
ACSS	Aluminum Conductor Steel Supported	Has a relatively low strength and modulus, which might restrict its use in areas with heavy ice loads.	[Mateescu, E. *et al*., 2011]
ACIR	Aluminum Conductor Invar Reinforced	When the conductor temperature rises, the sag grows more gradually.	[Sato, K.I. *et al*., 2011]
ACCR	Aluminum Conductor Composite Reinforced	The ceramic fibers break when the conductor is bent.	[Dobránszky, J. and Bitay, E. 2018]
ACCC	Aluminum Conductor Composite Core	The surface of the conductor is observed to have a higher roughness coefficient. At temperatures above 170°C, the core weakens and loses strength permanently. when the temperature is raised, sags	[Elmehdi, B.A. 2018]
G(Z)TACSR	Gap Type Super Thermal Resistant Aluminum Alloy Steel Reinforced	The use of running blocks causes friction or tension to build between the aluminum layers and the steel core.	[Galant, S. *et al*., 2012]
Z(S)TACIR	Super Thermal Resistant Aluminum Alloy Conductor Invar Reinforced	The tensile strength is lower. Since ductility is not provided by solid solution hardening alone, conventional invar alloy wire lacks the necessary torsion properties to be employed as electrical cables.	[Özkurt, Z. *et al*., 2010]

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CONCLUSIONS

Any conductor should take stress into consideration while designing it because it is a crucial aspect. Transmission lines are primarily constructed economically, but additional conductive material with high strength and poor heat conductivity is needed because of sag. It will be easier to resist heat as stress, which results in the thermal expansion that causes sag on the transmission line, by using refractory metals from the transition elements as reinforcement in the microstructure of the Aluminum-based alloy conductor. Heat-resistant or refractory components should be included in the alloy to improve All Aluminum Alloy Conductors (AAAC). In order to improve the corrosion resistance of Aluminum Conductor Aluminum Alloy Reinforced (ACAR), corrosion-resistant materials should be added. Heat- and corrosion-resistant components should be added to the alloy of aluminum conductor steel reinforced (ACSR) to improve it. The Aluminum Conductor Steel Supported (ACSS) should be engineered so that the steel, and not the aluminum, will support the weight. The alloy of Aluminum Conductor Invar Reinforced (ACIR) needs to have elements with high melting temperatures. High strength and strain fibers or elements should be added to aluminum conductor composite reinforced (ACCR) for improvement. Enhancing Aluminum Conductor Composite Core (ACCC) properties using materials that are heat-resistant and high strength. By using a friction-resistant lubricant, Gap Type Super Thermal Resistant Aluminum Alloy Steel Reinforced (G(Z)TACSR) should be enhanced. High tensile strength, high torsion, and ductile materials should be used to improve Super Thermal Resistant Aluminum Alloy Conductor Invar Reinforced (Z(S)TACIR). The conductor's strength shouldn't be impaired in the meantime. Zinc and chromium are two metals that can be utilized to combat corrosion stress. Niobium and molybdenum can improve durability, corrosion resistance, and strength of Aluminum based alloy.

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