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Numerical Investigation on Thermal and Electrical Stress in Electric Vehicle Cabling Network

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ABSTRACT

Global warming and an impending energy problem have compelled nations to become greener and cleaner. Worldwide, interest in electric vehicles (EVs) is growing as a result of rising gasoline prices and environmental concerns. The need for electrical components and cabling networks is expanding along with the demand for electrified vehicles. The complexity of vehicle electrical, electronics, and control circuits is also rising. There are many wire and cable performance issues in modern e-mobility, including limited space, vibration, high-temperature variation, unfriendly fluids, and rising data transmission requirements. Thus, it is important to study and evaluate the thermal and electrical stresses in the electric vehicles cabling network to avoid insulation failure, which causes fire accidents in the electric components of EVs. An EV's entire electrical system gets hotter, and insulation strength is affected by both temperature and the electrical field. The insulation system is one of the most important components in any electrified vehicle. From a design and protection perspective, the computation of electric potential distribution and electric field within and around the cables of electric vehicles is very important. The strong non-linear dependency of the electrical conductivity of the insulation material on prevailing electrical stress and temperature makes the field problem not only coupled but also non-linear. Finite Difference Numerical (FDM) is used for non-linear field computation. In this paper, different electric vehicle cabling network layouts were studied and listed the challenges. Chosen the high voltage cables of electric vehicles from the cabling network and numerically computed the conductivity, temperature, and electrical fields of cable.

1. Introduction

The automobile industry contributes significantly to global environmental pollution and plays a significant role in climate change. As we all know, the transition from conventional to electric vehicles is increasing drastically worldwide, primarily because of environmental pollution [1,2]. Electric vehicles are gradually becoming popular worldwide, considering environmental concerns and rising

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fuel prices. The number of electric vehicles in the market is rapidly increasing, as is the use of lithium batteries, but in order to sustain the rapid growth of the electric vehicle market for a long time, safety must always be the top priority. Overcharging, single battery failure, and short electrical circuits are the root causes of electric vehicle fire accidents [3]. Advanced and large electric vehicles use voltage levels much greater than individuals can tolerate. Accordingly, the battery voltages of electric vehicles, which vary from 120 V to 1500 V DC, are much higher than protective extra low voltage [4]. In an electric vehicle, high voltage is defined as voltages exceeding 60V. One of the biggest problems with high-voltage cars is safety because of the high voltages. The majority of gadgets are still connected by physical wires, despite the fact that some of them use wireless connectivity.

In modern automobiles, there are numerous wire and cable performance issues, such as limited space, vibration, temperature variation, unfriendly fluids, and rising data transmission requirements. As a result, it is critical to developing a method to prevent fires caused by insulation failures in EV electric components [5-7]. Due to the increasing number of connections, the complexities in electrical power vehicles increases, and insulation is extremely important for providing the electrical safety of members traveling in vehicles, batteries, high voltage cables, motors, and other electrical and electronic systems associated with various forces in EV. Overheating or over-stressed electrical devices in heavy electric vehicles may experience arcing faults causes for fire accidents in vehicles. The insulation failure of the battery and high voltage cables and its consequences can impair its normal operation. Due to insulation failure of the battery, high voltage cables, and/or other electrical components information, which is not visible from the outside often, the initial damage remains undetected since the EV continues to perform its normal operation, although with the reduced short circuit withstanding capability. But several such occurrences/consequences may lead to catastrophic failure of the EV electrical system, which is highly undesirable. Most of the literature is missing a detailed study of EV cabling networks and insulation problems due to external heat generation as well as heat generation in the dielectric medium of the cable. Therefore, evaluation of the insulation strength of the cabling network is important to prevent it from developing a major failure [3,6-9].

The accurate design of insulation is undoubtedly a challenging task. It requires a comprehensive understanding of the electro-mechanical forces and their impact on the life of the insulation of electric vehicles' battery systems and wiring harnesses [10,11]. The field evaluation is not as straightforward as it might appear at first glance since the coupling nature between the electrical and the thermal conductivity of the insulation are very complex to understand [12-14]. The primary objective of this research work is to pursue a systematic and comprehensive study to understand how the health of insulation and evaluation of insulation strength by the influence of temperature generated by other electric circuits on the cabling networks in electric vehicles. The task mainly comprises the numerical approach and theoretical assessment of the influence of temperature, electrical stress, heat generated by the battery, and cables.

2. EV Cabling Network

The design of wire harness systems for automobiles has grown in importance and value within the automotive sector. For autonomous self-driving cars and electric vehicles, it is much more important. The wiring harness is currently the third most expensive and third-heaviest component in electric vehicles. From literature reviews, different automotive cabling is explored and listed below.

2.1 Optical Fiber (Glass/Plastic)

Optical fibers are finding use in automotive applications for communication between the various sensors and the infotainment system. The optical fibers are as follows.

2.2 Plastic Optic Fiber

They are based on the MOST (Media Oriented System Transport) standard. One of the biggest advantages of these cables is that they are electromagnetic interference-free; They are used in vehicle monitoring and safety systems to check the deformation in case of a collision, and POF exhibits high attenuation for long-distance communication, and this is where Glass Optic fiber comes into play.

2.3 PVC Wire

Poly Vinyl Chloride is used for the insulation of the wires. PVC is a thermoplastic polymer with high dielectric strength; PVC is created by using an extrusion process; PVC is used for applications subject to temperature fluctuations, and the selection of these wires is made on the basis of the insulation and the working temperature range they offer.

2.4 Heat Resistant Wires

These wires are useful for connections where the temperature is quite high and are especially needed for charging connectors. The heat-resistant wires have a rating of a minimum of 600V, and the working temperature can be as high as 260c.

2.5 Shielded Wires

Basically, foiled shielding and foiled and braided shielding are used in shielded cables. These cables are used to avoid electromagnetic interference and help in reflecting the energy and transferring the noise to the ground by picking it up. The foiled shielding is also known as tape shielding, and the commonly used materials are either copper or aluminum. The wires are simply wrappers around this thin sheet below the jacket. Braided shielding makes the use of braids, i.e., a mesh of thin copper wires, and is comparatively easier to work on and more effective even though coverage is not 100%. The foiled and braided shielding method is used to provide EMI protection for high-duty applications. All these wires consist of a drain terminal which is used to ground the shielding in its entirety. By considering the above different types of cabling networks, it is very important to list out the different wiring layouts and major challenges that arise in the cabling network [15-20]. The major challenges in the automotive cabling networks are shown in the Figure 1.

When the cable is affected by the temperature of the environment and the current flowing through it, as well as when the cables are routed in close proximity with little room for airflow, thermal performance is even more important. A comprehensive examination is needed of the thermal specifications for EV/HEV cable systems, in Figure 2 shows the generalized solution to major challenges in the electric vehicle's network.

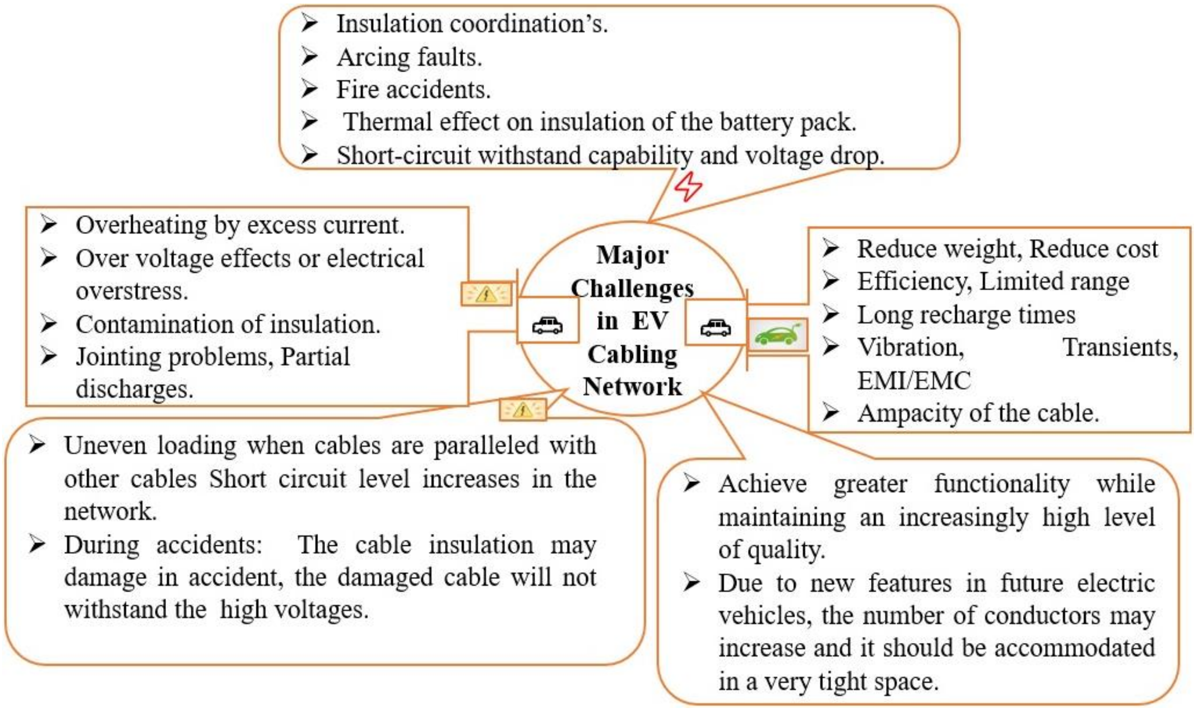


Fig. 1. Major Challenges in EV Cabling Network

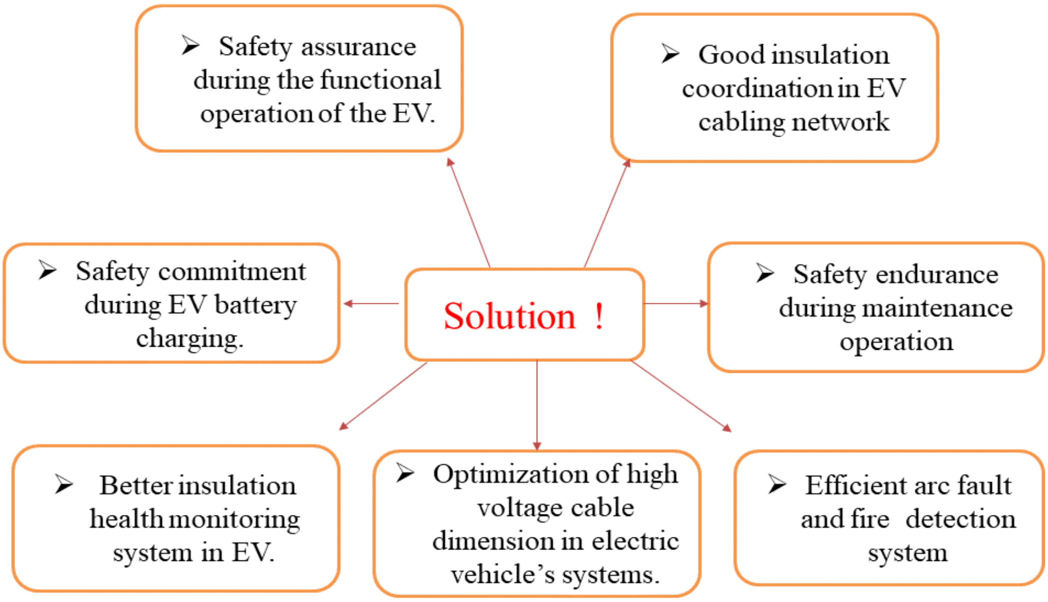


Fig. 2. Generalized solution for major challenges in EVs

3. Theoretical Modeling

In general, current density is defined as the flow of current across the cross-section of a conductor. It is the quantity of charge transmitted per unit of time. So, using Ohm's law, the following equation can represent this relationship

$$j = \rho . v = \rho . \mu . E \tag{1}$$

where ρ - charge density, v- velocity, J - current density, the velocity of the charge depends on the electric field (E) through a proportional coefficient known as charge mobility (μ1) and relation with conductivity (σ) is as given below

$$\sigma = \sum n_i q_i \mu_i \tag{2}$$

There are a few presumptions regarding the relationship between conductivity and temperature [11,12]. The concentration of charge carriers and their mobility is affected by temperature; the transport of the carriers is thermally activated, and the carriers are located in potential that restrict their mobility.

The equation for high-field ionic conduction, a crucial process in HVDC polymeric-insulated cables, was considered to provide an analytical model of conduction as a function of electric field and temperature. The current density J is created by the interaction of conductivity(σ) and the electric field E.

$$J(E,T) = \sigma(E,T).E \tag{3}$$

The local electric field and temperature impact the carrier density and movement. Dielectric materials often exhibit (Arrhenius relation), or an exponential increase in conductivity with temperature, field, or the square root of the field. An empirical model for direct current conductivity, the empirical equation for temperature and field-dependent conductivity, which is widely found in the researches by Boggs *et al.,* [21], Prasad *et al.,* [22], Zulkifli *et al.,* [23], Wang *et al.,* [24], and Illias *et al.,* [25], is as follows:

$$\sigma(E,T) = A.exp^{\left(\frac{-\phi.q}{k_b.T}.\frac{sinh(B.|E|)}{|E|}\right)} \tag{4}$$

where,
A and B constants
φ = Thermal activation energy in eV
q = Elementary charge
T = Temperature
E = Electric Field in V/m

These equations can be used to write the governing differential equations for electric field distributions. However, their validity becomes highly questionable for larger and practical values of temperature and stresses.

The following gives an empirical equation with appropriate validity over a wider range of temperatures and stresses [24].

$$\sigma(E,T) = A.exp^{\left(a|E| - \frac{b}{T}\right)} \tag{5}$$

Here A is a measure of the conductivity, a is coefficients of stress, and b is coefficients of temperature. Electrical and thermal continuity in the insulation serves as the foundation for the development of the governing equations of stress and temperature distribution in a DC cable. The boundary conditions of a loaded cable consider for field evaluation.

3.1 Current and Thermal Continuity Equations

The modeling of the electric field in the voltage of the cable will use the mathematical equations of electric field distribution as shown below. Electric field strength (E) and electric potential (V) are related in Eq. (1).

$$E = -\nabla V \tag{6}$$

For a single source, the divergence of J must be zero according to the current continuity equation and the continuity of the current density. The current continuity formula is

$$\nabla . J = 0 \tag{7}$$

$$J = \sigma E \tag{8}$$

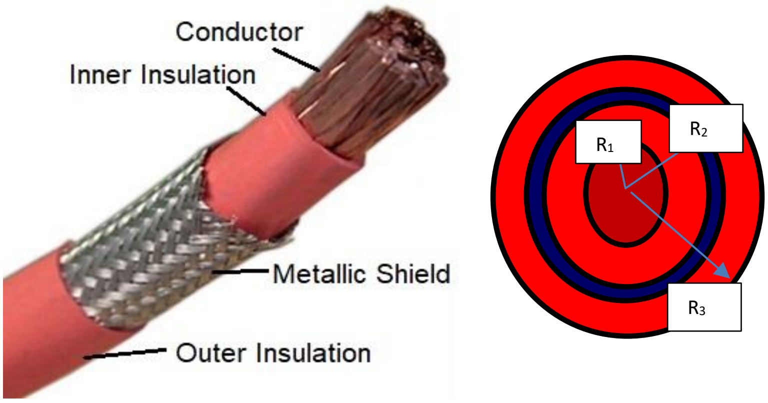
$$\nabla . (-\sigma \nabla V) = 0 \tag{9}$$

$$\nabla \sigma . \nabla V + \sigma \nabla^2 V = 0 \tag{10}$$

Similarly, the integral of the heat flux is heat flowing into volume, that is the vector k(dT/dn), which runs across the surface of the volume element and equals the scalar divergence (or accumulation) of k(dT/dn) per volume element. The formula for the continuation of heat is

$$\nabla . \left(k \nabla (T)\right) + \sigma |\nabla (\mathrm{V})|^2 = 0 \tag{11}$$

These two continuity equations' real and continuous solutions are used to determine the study state distribution of temperature and electric stress in the dielectric. In Figure 3(a) shown the EV cable for evaluation of thermal and electrical fields and cable geometrical view shown in the Figure 3(b) for discretizing the domain.



(a) (b)

Fig. 3. Generalized solution for major challenges in EVs; (a) A typical layout of EV cable [19], (b) Geometrical Structure of cable

4. Numerical Modelling

Numerical methods are extremely effective tools for problem-solving. They can handle large systems of equations, non-linearities, and complicated geometries that are common in engineering practice and are frequently impossible to solve analytically. As a result, they greatly improve your problem-solving abilities. In the numerical method, partial derivatives are approximated by infinitesimally small quantities to obtain a differential equation which is solved iteratively and the solution is obtained as a numerical value. Numerical methods can be used to obtain solutions for any arbitrary geometry where solutions employing analytical methods become difficult to obtain. Numerical methods can be used to solve problems having linear as well as non-linear constraints. Since all of the input parameters are represented by algebraic variables, the analytical solution is given in terms of simple functions that are clearly defined and further examined. However, they are unable to deal with non-linearity and non-conforming geometries. Nothing that all practical measurements and fabrication are subjected to tolerance, a 100% accurate answer loses its significance [26].

4.1 Different Numerical Methods in Brief

4.1.1 Finite difference method

The finite difference method (FDM) is a unique numerical technique for solving partial differential equations since it may be used to solve inhomogeneous, linear, and even non-linear problems. The iterative approach is always recommended for requiring the least amount of computational work because it produces sparse matrices. The domain is discretized using this technique. The programming will be significantly easier due to local approximation.

4.1.2 Finite element method

It is applicable to both anisotropic and inhomogeneous systems. A grid's size can be readily adjusted to the gradient of potentials, allowing small elements to be placed in areas with high gradients and vice versa. The shapes and sizes of the pieces can be set to match arbitrary boundaries. It is a domain-based method, it will not satisfy the governing equation exactly. However, an attempt is made to satisfy the boundary condition more or less exactly. Accuracy may also be improved using higher order elements without complicating boundary conditions.

4.1.3 Charge simulation method

In the charge simulation method for a given charge distribution, field distribution is uniquely defined. In all electrical engineering applications, charge resides only on the surface of the conductor. If the conductor is removed and replaced by dielectric outside but with surface charge distribution unperturbed, then field distribution remains the same. It is a simple method to discretize the problem involving unknown surface charge distribution fictitiously dividing the charge holding surface into small areas and then assuming unknown charge densities to be constant with the area.

4.1.4 Surface charge simulation method

It is a boundary discretized method, in which the charge distribution over the surface of the boundary is piece-wise approximated.

4.1.5 Boundary element method

Laplace's and Poisson's equations, as well as other partial differential equations, can be solved using the boundary element approach, which is a relatively novel method [25-28].

4.2 Discretization and Difference Equation Formulation

The finite-difference method is distinguished by the ability to obtain discrete equations by replacing derivatives with appropriate finite-divided differences. For solving PDEs in finite difference and finite element analysis, domain discretization is a key process with elements and nodes. Among all the numerical methods, the finite difference method is used to discretize the domain of the cable. In Figure 4 shown the domain discretization process.

Governing Eq. (10) for electrical stress distribution in cylindrical coordinate system is

$$\frac{\partial \sigma_r}{\partial r}.\frac{\partial V_r}{\partial r}+\sigma.\frac{1}{r}\frac{\partial V}{\partial r}+\sigma\frac{\partial^2 V}{\partial r^2}=0 \tag{12}$$

The following algebraic equation is created by approximating the partial derivatives using first-order differences.

$$\frac{\sigma_{n+1}-\sigma_{n-1}}{r_{n+1}-r_{n-1}}.\frac{V_{n+1}-V_{n-1}}{r_{n+1}-r_{n-1}}+\frac{\sigma_n}{r_n}\frac{V_{n+1}-V_{n-1}}{r_{n+1}-r_{n-1}}+\sigma_n\frac{V_{n+1}-V_{n-1}}{\Delta r^2}=0 \tag{13}$$

Governing Eq. (11) for thermal stress distribution in cylindrical coordinate system is

$$\frac{T_{n+1}-2T_n+T_{n-1}}{\Delta r^2}+\frac{1}{r_n}\frac{T_{n+1}-T_{n-1}}{2\Delta r}=\frac{\sigma_n}{k}E_n^2 \tag{14}$$

The stress distribution in the aforementioned equation is computed numerically. By resolving the above equation, determined the temperature distribution. The third term (E_n^2) on the right-hand side of the analytical solution was overlooked; however, included it in the numerical solution.

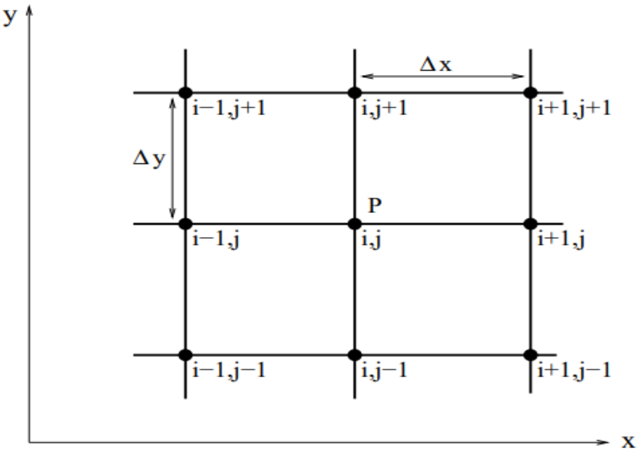
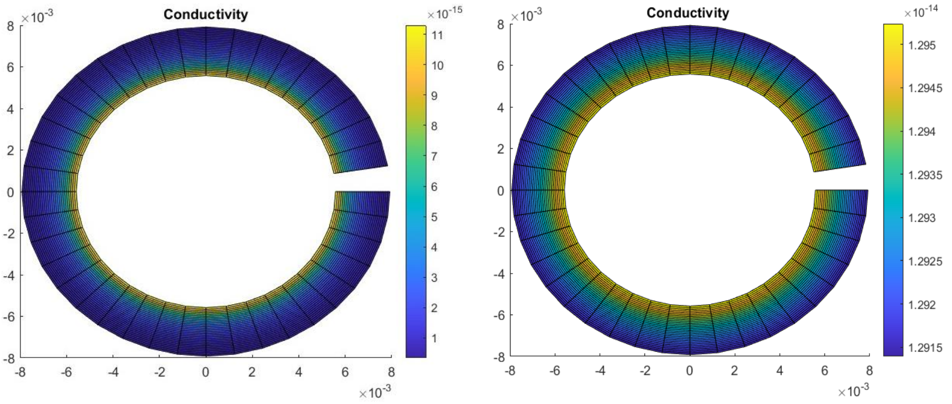


Fig. 4. EV Cable Insulation discretization

5. Results and Discussion

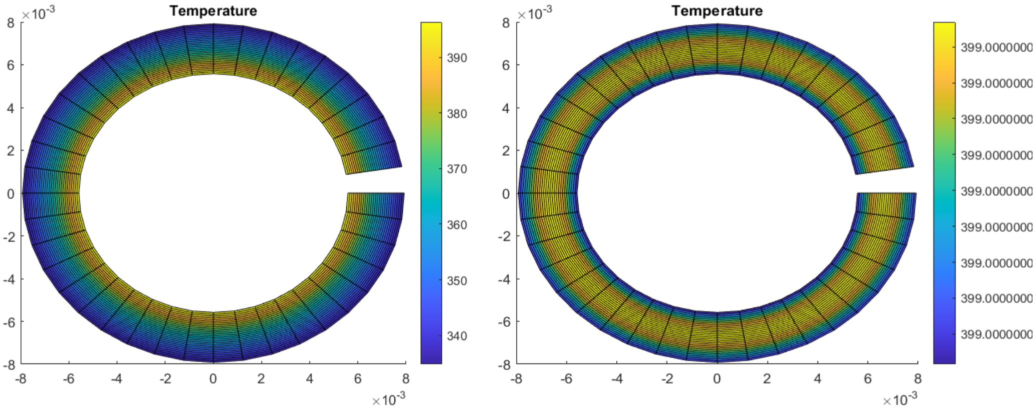
The cables insulation depends on conductivity, radial distances, temperatures and electrical field. The conductivity in DC cable is traced to a thermal origin, being the consequence of thermal runaway. The causative principles of a runway under direct electric stress are somewhat more complex than that under AC. As the electric field is increased, the dielectric conductivity increases and hence the temperature. A cumulative compound effect makes it reach asymptotic proportions implying the violation of Ohm's law hence an imminent breakdown.

The numerical results plots for stress, temperature, and conductivity are presented and clearly show variation with radial distances at 1500V DC in Figure 5 to Figure 7, the whiter portion is a conductor in all the plots. In Figure 5, the conductivity is more on the surface and near the conductor. In Figure 6(a) shows the temperature variation with radial distances and less loaded cable. In Figure 6(b) shows, the temperature variation, and the temperature is maximum in insulation between conductor and sheath of the cable. In Figure 7(a) shows the stress variation with radial distances, the stress is maximum on the surface of the conductor. In Figure 7(b) shows the stress variation with full load current in the cable, the stress is maximum near the sheath of the cable. From all the simulated plots, wherever temperature and stress are maximum, need to provide good insulation to avoid the failure of the insulation.



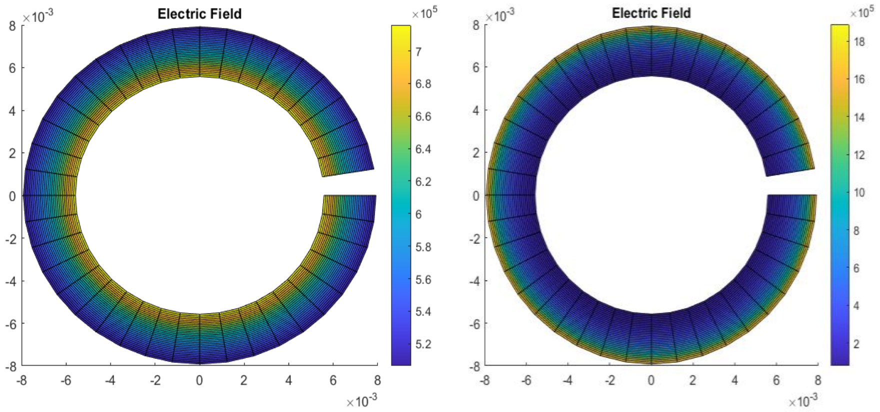
(a)
(b)

Fig. 5. (a) Conductivity of the insulation with low current, (b) Conductivity of the insulation with high current



(a)
(b)

Fig. 6. (a) Temperature distribution with low current, (b) Temperature distribution with high current



(a) (b)

Fig. 7. Electrical field distribution with low current, (b) Electric field distribution with high current

6. Conclusions

In electric vehicles, the battery is the most expensive component after the motor and transmission system, and the cabling network is also a valuable part of the automotive industry. The wiring system is the third highest cost and heaviest component in a car. The finite difference method has been considered to solve coupled non-linear Poisson's equation among all the numerical techniques. The FDM has the advantage of the least amount of computational work because it produces sparse matrices. This work aims to develop a suitable numerical scheme for evaluating electric and thermal stress distribution in DC cabling networks in EVs. A numerical scheme is developed for the iterative solution of the resulting coupled non-linear FDM equation. The coupled non-linear electrical and thermal (Poissons) equations are solved using an iterative approach in a cylindrical coordinate system. Numerical results are shown to exhibit very good matching with the analytical results, thereby providing a strong validation of the work. Simulation results provide deeper insight into the thermal and electric field distribution and their dependency on the load current. The internal heat generation within the dielectric volume is included in the FDM simulation. This work has to be extended for different types of EV cabling networks to the 2D case, which is more general and practical.

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