MVDC Bipolar Power Cables with Rectangular Geometry Design for Envisaged All-Electric Wide-Body Aircraft

Anoy Saha
Zero Emission, Realization of Optimized Energy Systems (ZEROES) Laboratory, Department of Electrical and Computer Engineering
The University of Texas at Dallas
Richardson, TX, USA
email: anoy.saha@utdallas.edu

Mona Ghassemi
Zero Emission, Realization of Optimized Energy Systems (ZEROES) Laboratory, Department of Electrical and Computer Engineering
The University of Texas at Dallas
Richardson, TX, USA
email: mona.ghassemi@utdallas.edu

***Abstract*— Designing power cables that provide high power and low system mass is one of the major goals in achieving the future all-electric wide-body aircraft. Radiative and convective heat transfers from a cable's surface to the surrounding air determine how much current is permitted to flow through it. At a cruising altitude of 12.2 km (18.8 kPa) for wide-body aircraft, the limited heat transfer by convection poses thermal issues for the design of aircraft cables. These thermal challenges are exacerbated for bipolar electric power systems (EPS), which are usually made up of two power lines next to each other. The cable's surface area affects both convective and radiative heat transfers. Changing the shape of the cable is one technique to improve heat transfers and compensate for the reduced convective heat transfer caused by low air pressure. In comparison to cylindrical and cuboid cables, the rectangular geometry design gives a bigger contact area with the surrounding atmosphere for the same cross-section area, hence it is anticipated that the heat transfer would rise and as a result, the cable's maximum power-carrying capability will be higher. The purpose of this paper is to design ±5 kV bipolar MVDC power cables with rectangular geometry to raise the maximum current carrying capacity of the cable and analyze its performance with bipolar cylindrical and cuboid geometries.**

Keywords—all-electric aircraft (AEA), low pressure, MVDC power cables, rectangular geometry, thermal analysis.

I. Introduction

To achieve net-zero emissions, a primary focus must be on the electrification of transportation systems. In 2021, transportation contributed the most to U.S. greenhouse gas emissions, representing 29% of the total [1]. The U.S. Environmental Protection Agency (EPA) states that commercial airplanes and large business jets are responsible for 10% of U.S. transportation emissions and 3% of the country's overall greenhouse gas output [2]. To achieve net-zero aviation, several recent studies have focused on using electrical systems in commercial aircraft to replace traditional mechanical, hydraulic, and pneumatic systems [3]. In future generations of electrified aircraft like more electric aircraft (MEA) and all-electric aircraft (AEA), electric power systems (EPS) will need to be able to deliver a high amount of power while keeping the overall system mass to a minimum. Power cables, as one of the EPS's primary components, have a lot of room for improvement in terms of reducing the system mass. Implementing higher voltage operations is one potential approach for reducing the weight of cables and, as a result, the overall mass of the aircraft's EPS [4]. Previous work of ours discussed three bipolar ±5 kVDC EPS designs for a large-scale AEA [5], where a high ampacity of 1 kA is needed for some cables in the system to distribute the enormous thrust power under both normal condition and all single contingencies.

Power cables in aviation have to deal with problems like partial discharge (PD), surface charges, arc and arc tracking, and thermal management. Among these problems, the heat transfer management of a cable is very important because they have significant impacts on its weight, size, and maximum current capacity [6, 7]. Heat transfer by convection is drastically reduced at an altitude of 12.2 km (18.8 kPa), which is the cruising altitude for wide-body aircraft. Because of this, the maximum current that can flow through the conductor is also decreased at this altitude [8-13]. Due to the typical configuration of bipolar MVDC power cables, which consists of two adjacent power cables, the associated challenges are considerably greater. The effective management of heat transfer is of the utmost concern in cable design. Cable heat dissipation occurs primarily in two ways: radiation and convection. The surface area of the cable is a key part of this process. To put it simply, a larger surface area allows the cable to radiate more heat. The majority of cables have traditionally possessed a cylindrical form. However, using a rectangular shape might provide us with a larger area for heat to dissipate. Rectangular cables may improve heat transfer management, particularly in locations with restricted airflow. This innovative way of thinking might result in cables that function well without overheating or requiring additional materials. In our previous work, coaxial bipolar cable is compared with conventional cylindrical form [9]. In [10], a cuboid geometry single cable/pole is compared with a cylindrical one, but their performance under bipolar configuration is not evaluated.

In this study, an integrated electrical, thermal, and computational fluid dynamics (CFD) model is developed using COMSOL Multiphysics to analyze the rectangular geometry for bipolar cable design and compare its maximum permissible current to that of a cylindrical bipolar cable and a cuboid bipolar cable. Using this model, the temperature and electric fields are also calculated for three types of bipolar cable systems. This study provides valuable insights for designing rectangular

This work was supported in part by the U.S. Advanced Research Projects Agency-Energy (ARPA-E) under Award DE-AR0001677, in part by the U.S. National Science Foundation (NSF) under Award 2306093, and in part by the U.S. Air Force Office of Scientific Research under Award FA9550-20-1-033.

MVDC power cables that operate at 18.8 kPa pressure and carry more current and power than cylindrical bipolar and cuboid bipolar cables.

II. Model

A coupled electrical, thermal, and CFD model is necessary to assess the necessary properties of MVDC bipolar power cables operating at 18.8 kPa. In a previous study of ours, such a complex model was developed [8]. In this study, a 5 kV MVDC cable with NL-EPR insulation is used for designing the three types of bipolar cables. The geometrical characteristics of the cylindrical and cuboid cableables are shown in Tables I and II, respectively. Figs. 1 and 2 show the geometry of the cylindrical bipolar cables and cuboid bipolar cables. The cables can withstand temperatures of up to 105°C in typical uses without suffering damage [14]. This temperature was used to calculate the maximum permissible current for the cable.

TABLE I. Geometrical Properties of Cylindrical Cable [14]

Parameters	Value
Diameter of Core Conductor (mm)	28.372
Diameter over Semiconductor Layer 1 (mm)	29.769
Diameter over Insulator (NL-EPR) (mm)	34.341
Diameter over Semiconductor Layer 2 (mm)	35.865
Diameter over Copper Layer (mm)	36.119
Overall Diameter of the cable (mm)	40.437
Weight Per Unit Length of two cables (kg/m)	12.983

TABLE II. Geometrical Properties of Cuboid Cable [10]

Parameters	Value
Conductor Length of one side (mm)	25.270
Semiconductor Layer 1 Length of one side (mm)	26.514
Insulator (NL-EPR) Length of one side (mm)	31.310
Semiconductor Layer 2 Length of one side (mm)	32.667
Copper Layer Length of one side (mm)	32.893
Cable's Overall Length of one side (mm)	36.015
Weight Per Unit Length of two cables (kg/m)	12.953

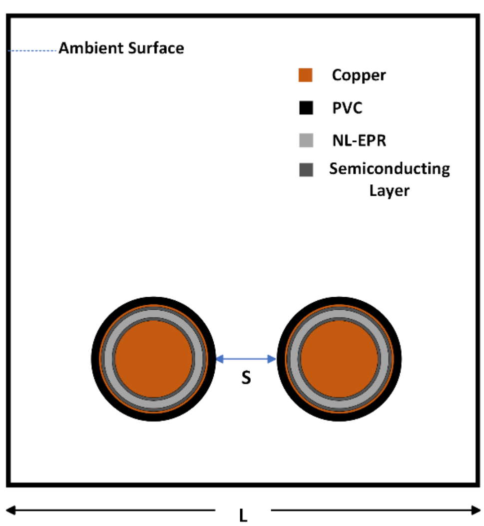

Fig. 1. Geometry of cylindrical bipolar cables used for simulation.

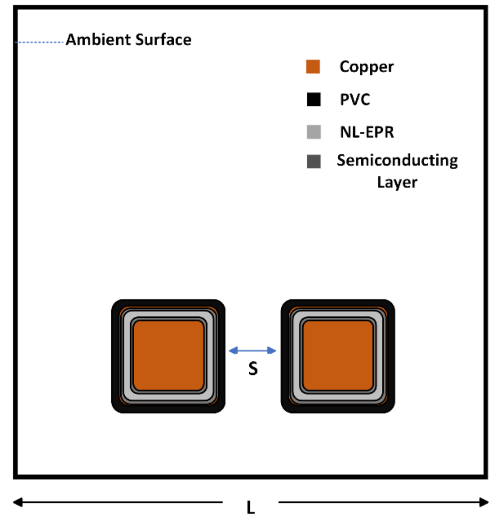

Fig. 2. Geometry of cuboid bipolar cables used for simulation.

Since the electric field is infinite at the sharp corners of a rectangle, that's why rounded corners are used in designing rectangular geometry cables like cuboid cables. To have the same cross-section area of a core conductor in rectangular and cylindrical cables, one can demonstrate that:

$$L_c \times W_c = \pi \left(\frac{D}{2}\right)^2 \times K \tag{1}$$

$$r^2 = \frac{(L_c \times W_c) - \pi \left(\frac{D}{2}\right)^2}{4 - \pi} \tag{2}$$

where L_C is the length (m) of the rectangular cable, W_C is the width (m) of the rectangular cable, D is the diameter (m) of the cylindrical cable, r is the corner radius (m) of the rounded rectangle and K is the coefficient for the rounded corners. In this study, for rectangular cable design K value is considered 1.01. Details about choosing K value were discussed in [10]. Also, the length-by-width ratio of the core conductor is considered 5. The main purpose of this study is to design a rectangular cable, whose weight per unit length and electric field norm are the same as cylindrical and cuboid cables. To maintain the same values for those parameters, other layer thicknesses are modified and analyzed. Tables III and IV illustrate the geometrical properties of the designed rectangular cable and the material properties of the cables, respectively. Fig. 3 shows the geometry of the rectangular bipolar cables.

TABLE III. Geometrical Properties of Rectangular Cable

Parameters	Value
Length of the Core Conductor (mm)	56.504
Width of the Core Conductor (mm)	11.301
Semiconductor Layer 1 Thickness (mil)	20
Insulator (NL-EPR) Thickness (mil)	93.5
Semiconductor Layer 2 Thickness (mil)	20
Copper Layer Thickness (mil)	5
PVC Jacket Thickness (mil)	40
Weight Per Unit Length of two cables (kg/m)	12.981

TABLE IV. MATERIAL PROPERTIES OF THREE TYPES OF CABLES

Parameters	NL-EPR	PVC	Semiconductor
Thermal Conductivity (W.(m.K)$^{-1}$)	0.3	0.19	10
Heat Capacity (J.(Kg.K)$^{-1}$)	1800	1050	2405
Density (Kg.m^{-3})	860	1350	1055
Surface Emissivity	-	0.91	-

A square-shaped aluminum duct with a length (L) of 250 mm and an emissivity of 0.18 is used in this study for all simulations. The duct is full of air, and the pressure inside is 18.8 kPa. The temperature on the outside of the duct is 40ºC. The "S" in Figs. 1, 2 and 3 represents the separation between the negative and positive poles. The voltage of the positive and negative poles are +5 kV and -5 kV, respectively. To ensure electrical safety, the cable is positioned at a distance of 1 inch from the floor side of the duct.

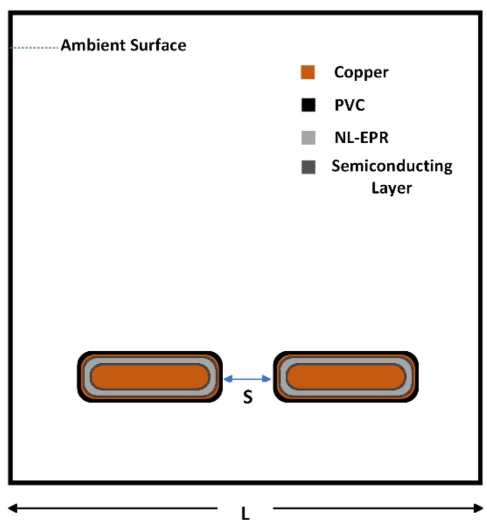

Fig. 3. Geometry of rectangular bipolar cables used for simulation.

The conductive, convective, and radiative heat transfers as well as the electric field distribution throughout the insulation of a DC power cable are described by a set of equations and expressions. The heat is transmitted to the surrounding medium through conductors, insulators, and PVC jackets. The equation for the transfer of heat from the cable's core conductor to its sheathing can be written as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = Q + q_o \quad (3)$$

where k is thermal conductivity (W.(K.m)$^{-1}$), T is the temperature (K), C_P is the specific heat capacity at constant pressure (J.(kg.K)$^{-1}$), ρ is the density (kg.m^{-3}), and q_o is the heat flux (W.m^{-3}). The formula for the total amount of radiation emitted by the cable and absorbed by the surrounding duct is,

$$q_{12} = \varepsilon_{eq}\sigma_S(T_S^4 - T_{amb}^4) \quad (4)$$

where T_s and T_{amb} are respectively the temperature (K) of the cable's surface and the ambient temperature, σ_S is the Stefan's constant (W/(m^{2}K^4), and ε_{eq} is the equal emissivity and is denoted as:

$$\varepsilon_{eq} = \frac{A_1}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2\left(\frac{A_2}{A_1}\right)}} \quad (5)$$

where A_1 and A_2 are the surface area of the cable and surrounding object, respectively, ε_1 and ε_2 are their surface emissivity, and F_{12} is the view factor described as

$$F_{12} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{cos\theta_1 cos\theta_2}{\pi R^2} dA_1 dA_2 \quad (6)$$

where dA_1 and dA_2 are elemental areas, R is the connecting line between the surfaces, θ_1 and θ_2 are polar angles made by R and the surface normal.

In addition, natural heat convection transfers heat within the air domain. Details about the natural heat convection are found in [8].

The DC conductivity of polymers can be expressed by using empirical formulas such as:

$$\sigma(E,T) = Aexp\left(\frac{-\varphi q_e}{k_b T}\right)\frac{\sinh(B(T)\ln(E))}{E^\gamma} \quad (7)$$

where E is the electric field (V.m^{-1}), q_e is the electron charge, k_b is Boltzmann's constant, φ is the thermal activation energy, σ_0, A and γ are constants, and $B(T)$ is a parameter that depends on the temperature. The distribution of the electric field can be calculated by using,

$$E = -\nabla V \quad (8)$$

$$J_e = \sigma E \quad (9)$$

where V is the voltage (V), J_e is the current density (A.m^{-2}), and σ is the conductivity (S.m^{-1}). The temperature, velocity, and electric fields are coupled, as shown by Eqs. (3)–(9). To reach the steady case, the study time is set to be 30 hours.

III. SIMULATION RESULTS

The main purpose of this research is to design the rectangular bipolar cable systems for future wide-body AEA and analyze its effectiveness compared to cylindrical bipolar cable systems and cuboid bipolar cable systems. The rectangular bipolar cables are designed in such a way that it is maintained the same weight per unit length and the same maximum electric field norm as those for cylindrical and cuboid bipolar cables. For all the cables, the maximum permissible temperature is 105°C. This temperature is used for calculating the maximum permissible current for three types of cable systems. The voltage of one pole is -5 kV and the other one is +5 kV. The temperature of the duct is 40°C and air pressure is 18.8 kPa.

Fig.4 shows the maximum permissible current of the rectangular bipolar cable system, cylindrical bipolar cable system, and cuboid bipolar cable system. The maximum permissible current of the rectangular bipolar cable systems is higher at all distances between the cables compared to the cylindrical and cuboid bipolar cable systems. When the distance between the poles is 2 inches, the maximum permissible current of the rectangular bipolar cable systems is 1230 A, which is about 8.3 % and 5.6% higher than the cylindrical bipolar cable system and cuboid bipolar cable systems, respectively. At S=0 inches distance between the cables/poles, the current carrying capacity of all types of cables are lower than other distances. The main reason is that the radiative and convective heat fluxes are lower at 0 inches distance between the cables. Figs. 5 and 6 show the radiative and convective heat fluxes of three types of cables.

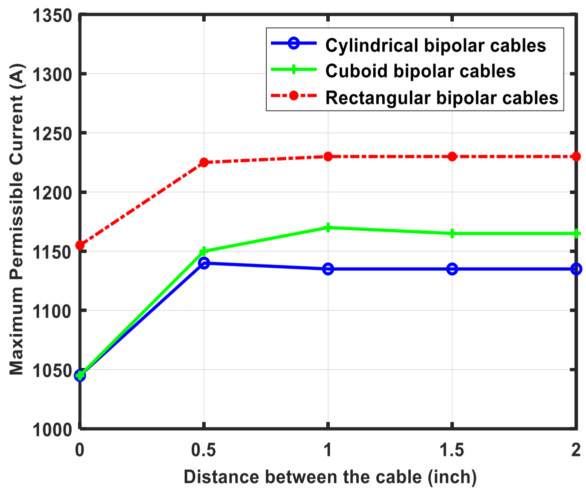

Fig. 4. The maximum permissible current of rectangular, cylindrical, and cuboid bipolar cable systems.

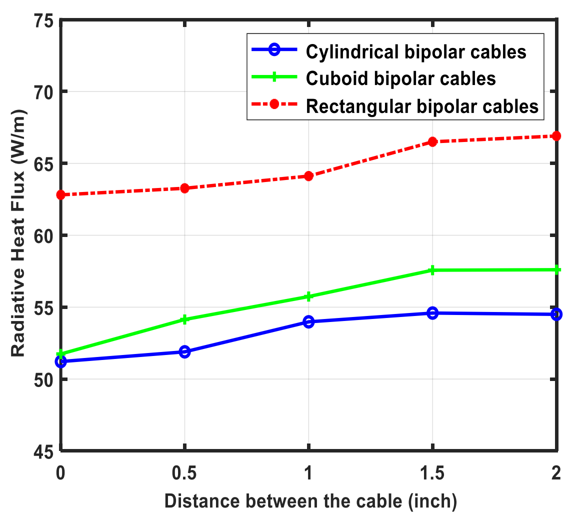

Fig. 5. The radiative heat fluxes of rectangular, cylindrical, and cuboid bipolar cable systems.

By extending the distance between the poles, the radiative heat flux of all three types of cables increases; however, the growth is noticeably greater for rectangular-shaped cables than for cylindrical and cuboid-shaped cables. The rectangular bipolar cable's outer surface area is greater than that of the cylindrical bipolar cables and cuboid bipolar cables, resulting in a greater radiative heat transfer. Fig. 6 shows the convective heat fluxes of three types of cables. Convective heat fluxes are much lower at a distance of 0 inches between the cables than at any other distance between the cables. The reason for this is that because the cables are so close together, there is a lack of convection on one side of the cable. When S=0.5 inches, the convective heat fluxes suddenly increase to a higher value, then by increasing distance between the cables it decreases slightly for all the cables. As the radiative heat transfer increases by increasing distance between the cables and convective heat transfer reduces for higher distences, in turn, the maximum permissible current as shown in Fig. 4 dose not change for example after S=1 inches.

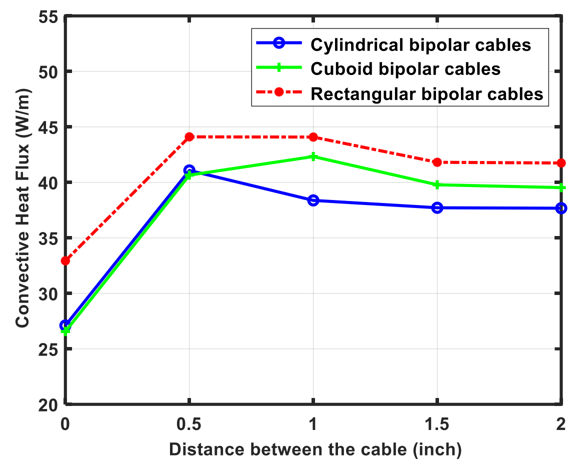

Fig. 6. The convective heat fluxes of rectangular, cylindrical, and cuboid bipolar cable systems.

The electric field distribution across the cylindrical bipolar cables, cuboid bipolar cables, and rectangular bipolar cables at 0 inches distance between the cables are depicted in Figs. 7, 8 and 9, respectively. The maximum electric field is identical for all three types of cables. Furthermore, the electric field norm at the rounded edges of the cuboid bipolar cables and rectangular bipolar cables are not intensified, as it should be. So, the designed cables are electrically safe for operating in low pressure conditions.

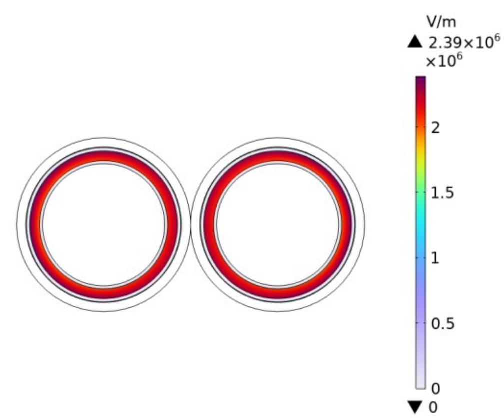

Fig. 7. The electric field distribution across cylindrical bipolar cable systems

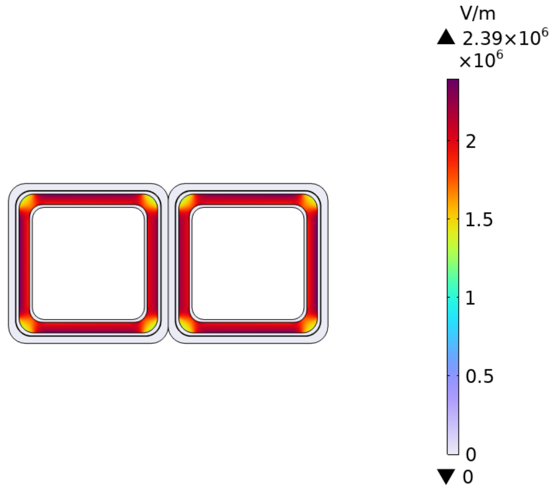

Fig. 8. The electric field distribution across cuboid bipolar cable systems.

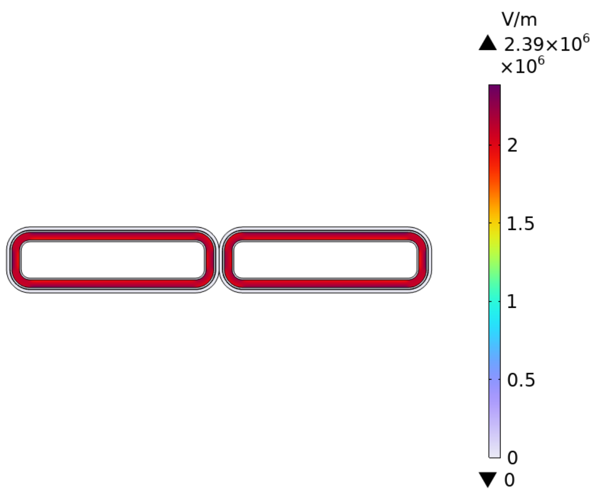

Fig. 9. The electric field distribution across cylindrical bipolar cable systems

IV. Conclusion

In this paper, a rectangular bipolar MVDC cable system for future wide-body AEA is designed and analyzed by using a comprehensive coupled thermal, electrical, and CFD model. A rectangular bipolar cable is designed to increase maximum permissible current while maintaining the same weight and maximum electric stress as cylindrical and cuboid bipolar cables. For the bipolar rectangular cables, the maximum current carrying capacity is increased by about 8.3% and 5.6% compared to the cylindrical bipolar cable system and cuboid bipolar cable system, respectively. It was also demonstrated that the higher radiative and convective heat transfers for the rectangular cable systems are the cause of the increased maximum permissible current. The electric field norm of this cable system is also examined, and it is determined that it is electrically safe to operate in low pressure conditions for wide-body AEA.

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