

Evaluation of Aviation AC Series Arc Fault Damage to Electrical Wiring Interconnection System Based on MHD Simulation

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Electrical fire hazards due to arc faults are critical to the safety of more-electric aircraft (MEA)/all-electric aircraft (AEA). In this study, the damage behavior to the electrical wiring interconnection system (EWIS) caused by AC series arc fault is carried out. For this purpose, a 2D axis symmetric magnetohydrodynamics (MHD) model is implemented for a single defective insulation cable. The thermal field, flow field, and electromagnetic field are numerically coupled for the computation of the distribution of the temperature. Furthermore, to evaluate the damage effect to a proximal cable, a 3D MHD model is constructed for a typical two-wire bundle system. The influences of central distance and the properties of the insulation materials are taken into account. The results reveal that the high temperature caused by arc fault leads to heavy damage to the faulty cable and an adjacent one.

Index Terms— arc fault damage, aviation applications, electrical wiring interconnection system, magnetohydrodynamics simulation.

I. INTRODUCTION

Arc faults in aircrafts have been received significant concern due to heavy damage to the electrical wiring interconnection system (EWIS) caused by high temperature [1]. Especially, in MEA and AEA, a more compact of the laying of the EWIS has been adopted in a limited space which in general with a harsh electromagnetic environment. As a consequence, the possibilities of cable insulation failure and arc faults have been dramatically increased.

In this paper, the evaluation of the arc damage to EWIS in an AC system is carried out. In specific, a 2D axis symmetric magnetohydrodynamics (MHD) model is implemented for a single wire and then a 3D one is constructed for a typical two-wire bundle. As a result, comprehensive considerations are taken into account to the direct impacts on the faulty cable and the potential cascading impacts on an adjacent one.

II. ARC FAULT DAMAGE SIMULATION BASED ON MHD MODEL

A. MHD Model

An arc phenomenon in typical is dominated by various physical parameters, for instance critical breakdown voltage, maintaining voltage, as well as conductivity of ionized air plasma. In general, the high temperature zone caused by arc fault corresponds to the thermal diffusion, thermal convection and flow field [2]. Basically, an MHD model is constructed by combining the fluid mechanics equations with Maxwell equations, thereby capturing the interaction between the flow field and the electromagnetic fields. Furthermore, to describe the variation of the surrounding temperature, an energy balance equation is coupled to the MHD model [3]. For simplicity, in a 2D axis symmetric model, the continuity equation in time domain can be given by

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} = 0 \quad (1)$$

where, ρ is air density; t represents time; r and z are the radial and axial coordinates, respectively; v_r and v_z are radial velocity and axial velocity, respectively.

Theoretically, the radial and axial momentum conservation equations are respectively governing by

$$\begin{aligned} \frac{\partial (\rho v_r)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r^2)}{\partial r} + \frac{\partial (\rho v_r v_z)}{\partial z} = - \frac{\partial p}{\partial r} - \\ j_z B_\theta \frac{1}{r} \frac{\partial}{\partial r} (2r\eta \frac{\partial v_r}{\partial r}) + \frac{\partial}{\partial z} \left[\eta \left(\frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z} \right) \right] - 2\eta \frac{v_r}{r^2} \end{aligned} \quad (2)$$

and

$$\begin{aligned} \frac{\partial (\rho v_z)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r v_z)}{\partial r} + \frac{\partial (r \rho v_z^2)}{\partial z} = \\ \frac{\partial y}{\partial z} \left(2\eta \frac{\partial v_r}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left[r\eta \left(\frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z} \right) \right] - \frac{\partial p}{\partial z} - j_r B_\theta \end{aligned} \quad (3)$$

where, j_z is current density; B_θ is magnetic field intensity in θ direction; η is viscosity coefficient; p is pressure; j_r is current density in r direction. Furthermore, the energy conservation equation gives

$$\begin{aligned} \frac{\partial (\rho H)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r H)}{\partial r} + \frac{\partial (\rho v_z H)}{\partial z} = \\ \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{rk}{c_p} \frac{\partial H}{\partial r} \right) + \frac{\partial}{\partial z} \left(\frac{k}{c_p} \frac{\partial H}{\partial z} \right) + j_r E_r + j_z E_z - q_r \end{aligned} \quad (4)$$

where, H is the specific enthalpy; k is the thermal conductivity; c_p is specific heat at constant pressure; E_r and E_z are the radial and axial electric field strengths, respectively; q_r is radiation term.

In brief, the governing equation and the conservation equation of the current density can be represented by

$$\frac{1}{r} \frac{\partial (r B_\theta)}{\partial r} = \mu_0 j_z \quad (5)$$

and

$$\frac{1}{r} \frac{\partial (r j_z)}{\partial r} + \frac{\partial (j_z)}{\partial z} = 0, \quad (j_r = -\sigma \frac{\partial \varphi}{\partial r}, j_z = -\sigma \frac{\partial \varphi}{\partial z}) \quad (6)$$

where, μ_0 is vacuum permeability; σ is conductivity; φ is potential.

In fluid dynamics, the Lorentz force $\mathbf{J} \times \mathbf{B}$ drives fluid motion, while Joule heating $\mathbf{J} \cdot \mathbf{E}$ affects the temperature field. The current density $\mathbf{J}$ is determined by the electric field $\mathbf{E}$ and conductivity σ , with $\mathbf{E}$ influenced by fluid motion and electric potential.

B. Arc Fault Simulation for a Single Cable

In this Section, to evaluate the arc fault phenomena for a single cable, a 2D axisymmetric model is implemented, as shown in Fig. 1 [4]. A voltage source with RMS 115V/400Hz is applied. Note that the rated current I_R of the loop circuit associates with the load resistor R_L .

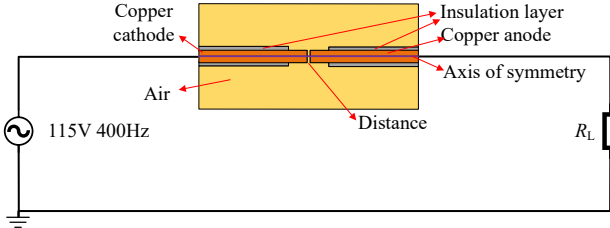


Fig. 1. A 2D axisymmetric model for a single wire.

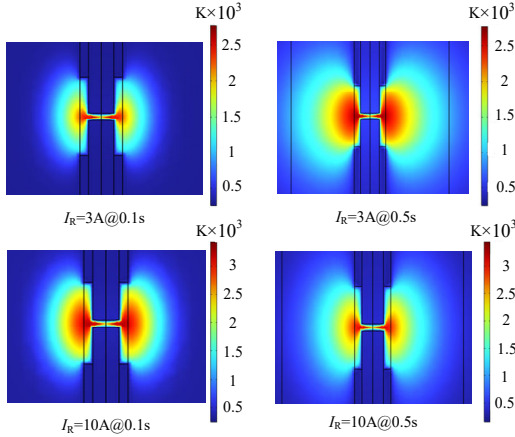


Fig. 2. Temperature distributions for the arc plasma.

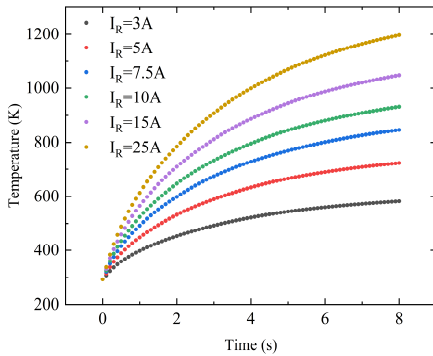


Fig. 3. Temperature distribution of cathode axis at different rated currents.

In specific, the arc fault simulations for the case in Fig. 1 under rated current I_R of 3A, 5A, 7.5A, 10A, 15A, and 25A are carried out. Remark that the distance between the cathode and the anode is supposed to be 2mm. Fig. 2 shows the distributions of the temperature for the rated conditions of 3A and 10A at 0.1s and 0.5s. As can be clearly noted that as the development of the arc fault, the high-temperature zone expands into the surrounding air region. To demonstrate the impact of the value

of the I_R on the thermal field, the variation of the temperature is presented in Fig. 3. Obviously, a positive correlation can be found between the I_R and the arc temperature at a given time instant.

C. Arc Fault Simulation for a Two-wire Bundle

To investigate the impact of arc faults on adjacent cables, a 3D model is established, as shown in Fig. 4. Energy exchange significantly alters the physical and chemical properties of nearby cables [5]. At the high temperatures induced by instantaneous arcs, radiation predominantly drives the ablation of structural components. Fig. 5 presents the temperature distribution of two electrodes under different current levels.

On this basis, an aluminum tube with a radius of 1.1mm is placed 1mm away from the location of the fault arc to study the impact of the fault arc on an adjacent cable.

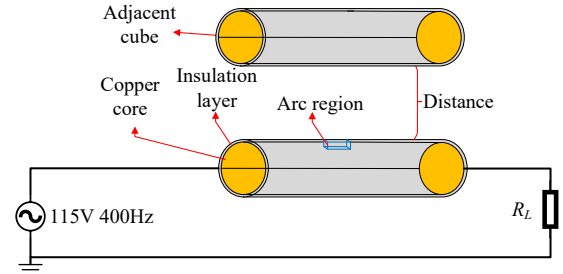


Fig. 4. A 3D model for a two-wire bundle.

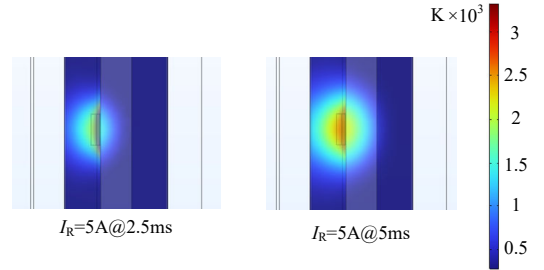


Fig. 5. Distribution of high temperature caused by fault arc.

As illustrated in Fig. 5, the aluminum tube underwent melting due to the elevated temperature induced by the fault arc. In the context of aviation cables, the high temperature exerts detrimental effects on the insulation layer, potentially leading to severe malfunctions.

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