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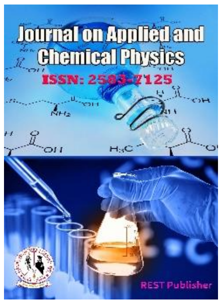

Superconducting Electromagnetic Launch Machine System for Aerospace Applications

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Abstract. *The aerospace industry is constantly experimenting with innovative technologies to improve efficiency, effectiveness and sustainability. The use of superconducting machines emerged as a promising solution to address the growing demands of Aerospace applications. Superconducting machines offer significant advantages such as higher power density, reduced weight and improved efficiency compared to conventional electrical machines. However, efficient cooling methods are critical to maintain superconducting materials at low-temperature operating conditions. This abstract provides a comprehensive overview of superconducting machines and their associated cooling systems designed for space applications. A superconducting machine uses high-temperature superconductors to achieve near-zero electrical resistance, enabling high currents to be transmitted with low energy losses. This feature allows development of lightweight and compact electric propulsion systems contribute to improved fuel efficiency and extended mission capabilities in space vehicles. A cooling system is an important component of a superconducting machine because it ensures that the superconducting materials remain below their critical temperature. Various cooling techniques are being explored, including cryogenic cooling, liquid nitrogen cooling, and cryocoolers. These cooling systems effectively extract the heat generated during engine operation, maintaining the superconducting components in their superconducting state*

1. INTRODUCTION

Superconducting machines are electrical machines that use superconducting materials to achieve higher performance and energy density compared to conventional machines. When cooled below a critical temperature, materials have the ability to carry electrical current without any resistance. The superconducting coil, commonly referred to as a cryogenic field winding, is the main part of superconducting devices. A ceramic material such as niobium-titanium or niobium-tin, is used to make the coil. Large currents may be carried by superconducting devices without any power being lost due to resistance, which is their main benefit. Superconducting devices do, however, face several difficulties. The primary obstacle lies in achieving the necessary temperature reduction for superconducting materials to reach their critical point. Typically, this critical temperature is below the boiling point of LN2, or in the case of certain high-temperature superconducting (HTS) materials, even lower. To accomplish these cooling, cryogenic systems must be employed, thereby introducing intricacy and increased expenses to the entire system. The field of science and technology known as cryogenics studies how extremely low temperatures are created, how they behave, and what effects they have. It entails the analysis and usage of components and systems that operate with cryogenic fluids, like liquefied nitrogen or helium in liquid form, at or below -150°C. Electric propulsion refers to the use of electric power to create propulsion in spacecraft or other vehicles. It uses electrically powered thrusters to accelerate and eject ionized particles or other propellants. Electric propulsion systems are often used in space missions that require low thrust but long duration propulsion, such as maintaining a satellite station, interplanetary travel, and deep space exploration. Computational electromagnetism (CEM) is a branch of electromagnetism that focuses on the use of computational methods and numerical techniques to solve electromagnetic problems. It involves the simulation, analysis and prediction of electromagnetic fields and their interactions with objects and materials. Maxwell's equations, which are a collection of partial differential equations governing electromagnetic phenomena, dictate the behaviour of electric and magnetic fields. Nevertheless, finding analytical solutions to these equations is often restricted to uncomplicated and ideal circumstances. Computational electromagnetism offers a method to numerically solve Maxwell's equations for intricate and practical scenarios. Due to their great power density, efficiency, and small weight, superconductivity machines have the ability to completely change the way we use space. Superconducting machine integration into aeronautical applications is currently in the early phases of research and development, and technical obstacles like the need for cooling superconducting materials must yet be solved.

2. SUPERCONDUCTING MACHINE

Topology of Inductor: The inductor's topology comprises pancake coils and bulk plates. By positioning two coils on the same axis and supplying them with opposite currents, a radial magnetic field is generated within the bulk superconducting plates. These plates are uniformly distributed between the coils around the axis, as depicted in Figure 1. The inductor's magnetic pole count is determined by the overall number of plates. The manufacturing and assembly of each component in the system are straightforward [1].

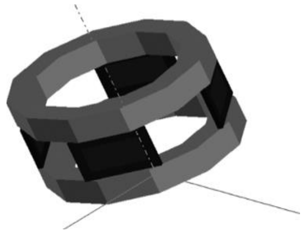

FIGURE 1. Assembly of the inductor composed of pancake coils and bulk plates.

Superconductor generators: Due to the significant acceleration forces placed on the conductors at this size, spinning windings at speeds exceeding 10,000 rpm is more difficult. Only the excited coils are superconducting, while both the stator and the rotor work at cryogenic temperatures. At high operating frequencies, resistivity loses in cryogenic copper are smaller than AC loses in HTS conductors. A power plant with the same specifications is a part of a different development. built on a different framework than the preceding illustration but similar in nature. General Electric employed a magnetic component in the rotor magnetised by a fixed superconductivity coil to handle the high rotational speed. An extremely strong rotor capable of spin at high RPMs is provided by this arrangement [2]. **200 kW HTS Motor Configuration**: the designed synchronous motor makes use of an air-gap magnet inductor that undergoes two steps of cooling to produce an 8-pole excite field. The machine's diagram is shown in Figure 2. Pancake coils and YBCO plates are used to make the inductor. The coils are cooled to 30 K during operation when the YBCO plates are over their critical temperature, increasing current. Generators are set up underneath the YBCO plates to keep them at 90 K while chilling the BSCCO coils. A maximum of one Watt of heat each plate is what is needed to shield it from the other parts of the system. The inductor can be cooled more easily through conduction through an aluminium tool. The G10 rings are used to secure the YBCO plates. When in use, these devices have an inbuilt heater to facilitate the two-step cooling procedure necessary for motor functionality [3].

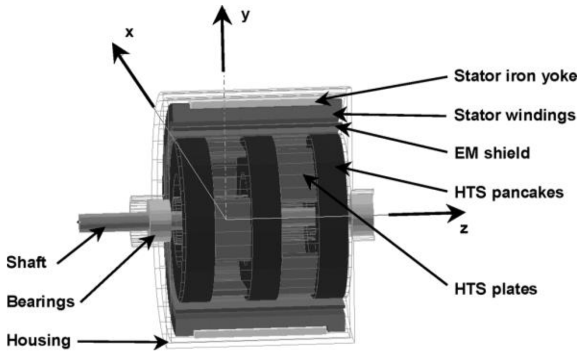

FIGURE 2. 200 kW motor configurations.

The machine's stator functions at room temperature without the need for additional cooling. Aluminium is used to build the mover structure because of its beneficial qualities, including low density, low emissions, and outstanding structural traits. The mover has no iron in it to save weight and avoid saturation of ferromagnetic materials. Instead, a rotating superconductivity field winding is used to create a revolving magnetic field in an armature's stable winding. Magnetic fields produced by superconducting devices are sometimes twice as powerful as those produced by regular machines. Electromagnetic motor have no need for the presence of iron or other magnetic components in the rotating element since they have an air-core [4, 5].

3. ELECTRIC PROPULSION

Electric power has always been too much to be used in aircraft propulsion. Electrical propulsion remains above ground due to big, hefty motors and low density in power storage media. These technologies have matured to the point that they are starting to be taken into consideration for potential application in aviation as a result of advancements in engines, fuel-cell batteries, and capacitors. The benefits of electric propulsion are numerous. Without internal combustion, vehicle emissions can be reduced in terms of noise and contaminants [6]. Design of autonomous power networks before presenting the SEPS strategy, it is important to comment on the architecture of independent (autonomous) networks because it is not a topic that is frequently covered in the literature. Electric (hybrid) ships are a recent application that has gained significant traction [7].All-electric aircraft Transport systems are primarily responsible for the majority of greenhouse gas emissions discharged into the environment. Noise and exhaust pollution from aircraft are common indicators of problems during takeoff. Sadly, airports are situated close to large cities with many of pollution sources. For takeoff, 100% of the engine's power is needed, but for high-altitude cruise, just 60-70%. Reduced environmental harm and little disturbance for those who live close to airports are the primary drivers driving the growth of fully electric aircraft. There are many benefits to using electric power, including removing hydraulic systems, which are responsible for around 70% of aviation downtime, considerably reducing maintenance needs, and distributing generators throughout the aircraft to increase reliability through redundancy in automobiles [8]. A hybrid electric motor. **Losses:** The magnetization loss of the HTS coil may be estimated by monitoring its coil in an open-circuited state, when no transport current is present and only the magnetic loss is assessed. For the purpose of calculating the overall AC loss brought on by a single HTS coil, the 3-phase system stator winds are linked to power resistor with adjustable resistance. By altering the resistors, it is possible to calculate the AC loss across different currents [9].

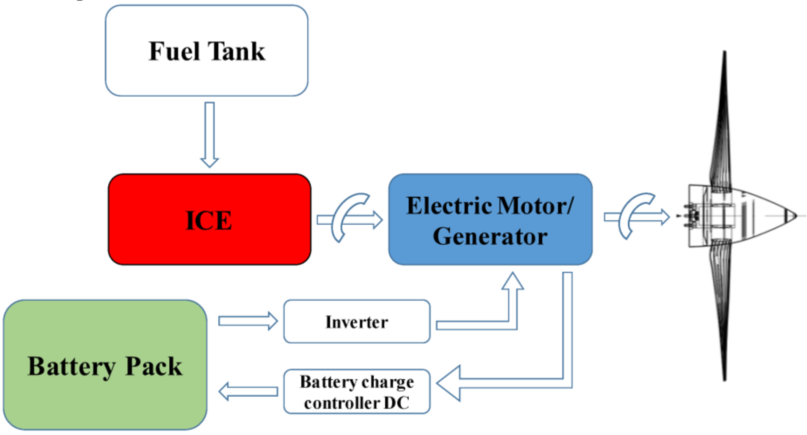

FIGURE 3. Layout of the hybrid propulsion system

4. CRYOGENICS

Cryogenics is a well-established and well-understood field of research, but it has only lately been used to address the specific problem of high-power cryogenic networks. Superconductivity equipment are still in the early phases in regards to practical usage, despite the fact that numerous partly superconductivity machines are already under development [10]. **Cryogenic structures**: There are three basic hypotheses that could be used to cool such a superconducting network are Fully decentralised: Cooling is carried out locally, resulting in an enclosed refrigeration loop with a cryocooler for each device or component subsystem, Partially decentralised: Small cryogenic coolers provide cooling to working temperature, while main coolers supply a medium temperature circuit, Large cryogenic coolers keep a closed loop of cold liquid at cryogenic operating temperatures [11]. **Cryostat:** The Applied Superconductivity and Cryoscience team at the University of Cambridge worked with ICE Oxford Ltd. to design and produce the cryostat used in the system. Figure 4 shows a compressed depiction of the cryostat. There are two unique cooling zones in the system. At the bottom of the first zone is a nitrogen canister that acts as a conductive stator. Additionally, it keeps the tail of the spinning chamber's outer layer at a consistent temperature. It is normally filled with nitrogen gas but is not actively chilled while in operation. The rotor chamber, superconducting stacks, and shafted rotor are all included in the second zone. Helium, a frigid gas, is present here [12].

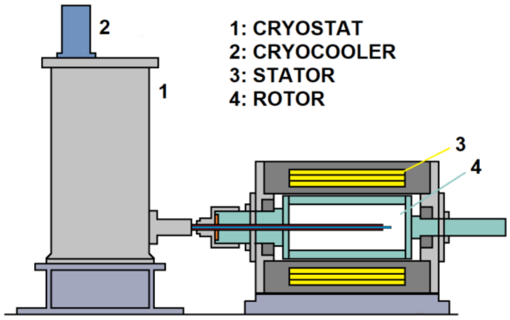

FIGURE 4. Simple diagram of the present system

In the many HTS applications, nitrogen, neon, hydrogen, and helium are frequently the sole options to cryogens. Nitrogen is incompatible with applications requiring temperatures below 60 K, such as HTS motors and turbines used in electric-powered aircraft uses, where a higher current density is required. The bare minimum tank size will be determined by the projected hydrogen fuel consumption as well as the bare minimum hydrogen mass flow rate required for aircraft operation. Furthermore, it is essential to maintain the ambient temperature within the working temperature range when hydrogen is flowing through the HTS devices. [13].The prototype's experimental test setup comprises of a thermal-vacuum chambers with all of the suction and refrigeration components and a sensing system with several types of sensors to monitor various mechanical characteristics. All refrigeration and vacuum systems, as well as the thermal-vacuum chamber, were fixed and ready for operation testing [14].

5. COMPUTATIONAL ELECTROMAGNETISM

Traditional CEM instruments, on the other hand, are low-order (also known as small-domain) techniques, where the structure is modelled by electrically very small surface and/or volume geometry elements, and currents and/or areas within the elements are low-order and are approximated by fundamental functions. They have already shown to be a trustworthy and effective tool for tackling large-scale electromagnetic issues in a number of cutting-edge fields of engineering and science. With a common objective to develop the "ideal" evaluation and design tool for each class of real-world applications and each engineering problem, higher order electromagnetic modelling is unquestionably becoming the mainstream of CEM activity. However, there are still many significant research challenges that must be addressed and resolved. [15].The previous part provided a quick summary of CEM techniques; however the goal of this paper is not to dig more into this subject. Instead, we present a number of challenging EM modelling issues that have significant practical value available CEM instruments. Several of these difficulties will be discussed more in the next section. The MOM for PEC objects has a lower computing cost than the finite approaches, which are able to handle arbitrary objects made up of both PECs and dispersed dielectrics. The number of degrees of freedom that the MOM can manage is frequently lower than what can be handled by the FEM or the FDTD since the MOM forms a dense matrix. Through the application of the Fast Multipole Method (FMM), significant progress has lately been achieved in broadening the scope of the MOM, allowing us to address situations that call for the management of 106 degrees of freedom or more. In order to do this, the Fast Multipole Algorithm forgoes the production of a complete matrix, instead merely storing the employing the multipol approach, using near-field interacting terms, and producing the matrix-vector products necessary for the iterative solution. The parameter of the composites is created by cascading global scattering matrices, which are built in an effective computational method. In the same picture, a comparison between the CBFM findings and the simple fix for this magnitude of issue (which is still doable but costs significantly more when addressed directly) is shown. [16]. in this context, we describe a unique RKDG (Runge-Kutta Discontinuous Galerkin) approach that maintains a time-step proportional to the size of the spatial mesh. To achieve this goal, we create a variant for non-autonomous non-linear systems that retains the restricted capacity Runge-Kutta (SSP-RK) scheme described in and has robust stability at the m^{th}-order and m-levels. We chose to expand the approach because of a variety of positive characteristics it possesses, particularly its SSP property, simplicity in use, and computational effectiveness. The method we provide here, in contrast to that implementation, does not call for the insertion of extra unknowns, which results in a much reduced computing effort and memory demand [17].

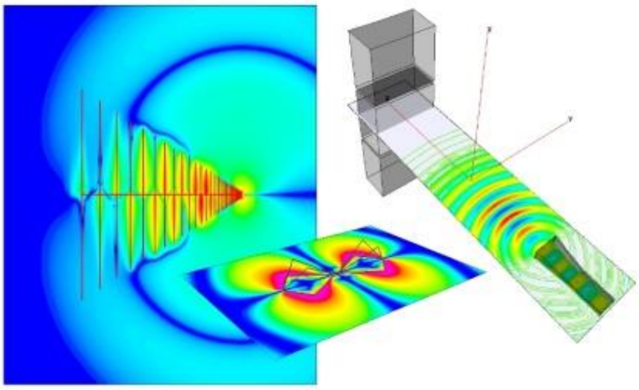

FIGURE 5. Computational Electromagnetic (CEM)

6. APPLICATIONS IN AEROSPACE INDUSTRY

Validation of CFD results and assumptions: The heat transfer coefficient, which is derived from CFD simulations and assumptions about thermal conductivity, accounts for the majority of the uncertainty in thermal management. We conducted an experiment using prefabricated cooling channels between ridge-wire bundles to measure the heat transfer coefficient. For near-term aerospace applications, the AC homopolar synchronous devices are the best option. In the stationary portion of the machine, these machines have both an AC rotor and Direct-Current (DC) excite windings. A solid steel rotor is magnetised by the stationary excitation winding, allowing operating speeds that are only constrained by the fatigue limit of the rotor steel. The operating rates are many times faster than those of traditional 50/60 Hz machines. Only a few kilowatts are the maximum power that machines of this sort using copper excitation windings are capable for aircraft applications, high-speed motors and generators with small size, light weight, and great efficiency are of interest on a global scale. There are several possibilities being thought about. High temperature superconductors (HTS)-based machines, on the other hand, appear to hold promise for allowing machines with the requisite properties. The stress constrain of the rotor teeth and systems for retaining the winding at extremely high speed restrict machines that use excite field winds on the rotor. Both the AC armature windings and the DC field-excited winding are often used in homopolar AC synchronous machines. As a simple iron magnet forging with prominent pole lumps, the rotor can revolve at extremely high rates up to its material's stress limit. [18].This thesis covers two types of engines for MW-class space propulsion applications: non-cryo engines and cryo fully superconducting engines. For the non-cryo option, a slotless topology was chosen with Hallbach array rare earth magnets. A slotless mechanical system can reduce weight and increase electric loading while the Hallbach array design can improve magnetic loading for torque production. The non-cryogenic and cryogenic completely superconducting machines are the two types of machines being looked at in this article for MW-class aircraft propulsion applications. Using halbach array of rare earth magnets, a slot less structure is used for the non-cryogenic alternative. The halbach array design may improve the magnetic loading for torque generation, while the slot less machine construction can save weight and boost electric loading. Superconductors are found in both the stator part and the rotor for the cryogenic FSC option. The stator and rotor have extra room set up for the cryogen system. MgB_2 is used in the stator's AC superconducting coils, whereas YBCO is used in the rotor's DC superconducting coils. [19]. High-speed use Machines using permanent magnets (PM) in the rotor are developed for high-speed applications. However, in such machines, the PM is placed on the rotor with a structural support. The permissible rotor speed is limited by the constraints of the structural support. To describe the design process, a flywheel energy storage application is selected to store 9 MJ of kinetic energy. This electric motor/generator engine coupled to a flywheel produced 500 kW. While the present machine is being constructed for on-ground use to connect with a wheel for energy storage, the equipment stated in this source was created with the purpose of maintaining its size and weight as minimal as possible. For minimising refrigerator cooling power and lowering AC loses in the superconducting coil, an electromagnetic barrier has been added [20].

7. CONCLUSION

Due to the significant acceleration forces placed on the conductors at this size, spinning windings at speeds exceeding 10,000 rpm is more difficult. Only the excited coils are superconducting, while both the stator and the rotor work at cryogenic temperatures. The machine's stator functions at room temperature without the need for additional cooling. Aluminium is used to build the mover structure because of its beneficial qualities, including low density, low emissions, and outstanding structural traits. Electric power has always been too much to be used in aircraft propulsion. Electrical propulsion remains above ground due to big, hefty motors and low density in power storage media. These technologies have matured to the point that they are starting to be taken into consideration for potential application in aviation as a result of advancements in engines, fuel-cell batteries, and capacitors. The benefits of electric propulsion are numerous. Without internal combustion, vehicle emissions can be reduced in terms of noise and contaminants. There are two unique cooling zones in the system. At the bottom of the first zone is a nitrogen canister that acts as a conductive stator. Additionally, it keeps the tail of the spinning chamber's outer layer at a consistent temperature. It is normally filled with nitrogen gas but is not actively chilled while in operation. The rotor chamber, superconducting stacks, and shafted rotor are all included in the second zone. Helium, a frigid gas, is present here. In this context, we describe a unique RKDG (Runge-Kutta Discontinuous Galerkin) approach that maintains a time-step proportional to the size of the spatial mesh. To achieve this goal, we create a variant for non-autonomous non-linear systems that retains the restricted capacity Runge-Kutta (SSP-RK) scheme described in and has robust stability at the m^{th}-order and m-levels. We chose to expand the approach because of a variety of positive characteristics it possesses, particularly its SSP property, simplicity in use, and computational effectiveness. The method we provide here, in contrast to that implementation, does not call for the insertion of extra unknowns, which results in a much reduced computing effort and memory demand/. The heat transfer coefficient, which is derived from CFD simulations and assumptions about thermal conductivity, accounts for the majority of the uncertainty in thermal management. We conducted an experiment using prefabricated cooling channels between ridge-wire bundles to measure the heat transfer coefficient.

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