

Technology Selection for Optimal Power Distribution Efficiency in a Turboelectric Propulsion System

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ABSTRACT

Turboelectric propulsion is a technology that can potentially reduce aircraft noise, increase fuel efficiency, and decrease harmful emissions. In a turbo-electric system, the propulsor (fans) is no longer connected to the turbine through a mechanical connection. Instead, a superconducting generator connected to a gas turbine produces electrical power which is delivered to distributed fans. This configuration can potentially decrease fuel burn by 10% [1]. One of the primary challenges in implementing turboelectric electric propulsion is designing the power distribution system to transmit power from the generator to the fans. The power distribution system is required to transmit 40 MW of power from the generator to the electrical loads on the aircraft. A conventional aircraft distribution cannot efficiently or reliably transmit this large amount of power; therefore, new power distribution technologies must be considered. Two critical components in the power distribution system that must be redesigned are the cables and power converters.

Sizing algorithms for a conventional copper cable and a superconducting cable have been developed to determine the best method of power transmission. In order to create the sizing models, cable structure and materials were selected for both cable types. The sizing models determine the dimensions and weight of the cables as a function of system nominal voltage and cable length. A range of values were used for the design variables to produce sizing data; then, the data was regressed to create simple equations that can be used to estimate cable size. A turboelectric propulsion system required the use of inverters and rectifiers. Converter structures and control schemes will be explored and the optimal alternatives for this application will be modeled. The final goal of this research is to estimate the weight of the cables and performance of the converters to determine the optimal combination of power distribution technologies for a turboelectric propulsion system.

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INTRODUCTION

The environmental impact of aircraft is one of the primary concerns in the design of commercial aircraft. Many organizations around the world have set aggressive goals to reduce aircraft fuel burn, emissions, and noise. An example of these goals is the NASA subsonic fixed wing aircraft performance goals. The NASA third generation goals (N+3) expect at least a 75% reduction in NOx emissions, a 70% reduction in fuel burn, and a 71 dB reduction in noise compared to current aircraft performance by 2025 [2]. Improvement to propulsion technology will be a key in reaching these goals. A technology that can potentially assist in achievement of the NASA N+3 goals is turboelectric propulsion.

Turboelectric propulsion is a revolutionary system in which the propulsor (fans) is no longer connected to the turbine through a mechanical connection; therefore, both

components can be set at their individual optimum speeds. Furthermore, turbo-electric propulsion makes use of distributed fans. This concept uses several small fans in the place of the traditional large propulsors on the wings or sides of the fuselage. The distributed fans are usually placed on the top side of the fuselage of a blended wing body aircraft in order to take advantage of boundary layer ingestion which increases fan performance. Also, the smaller fans can run at faster speeds than their larger counterpart in a turbofan engine.

By using this new propulsion system, NASA has estimated that fuel burn could be reduced by 10% [1]. The reduced fuel burn will also help contribute to reduced harmful emissions. In addition, this architecture can be modified to allow for the use of alternative fuels such as hydrogen. The system can also aid in the reduction of noise by using the fuselage to shield the noise from the ground.

In order to implement this system, many challenges must be overcome. New technologies will have to be implemented into the architecture to create this system. Most of these technologies are still in the experimental stages; consequently, data is limited. Since these technologies are not completely developed, there is uncertainty in their weights and performance. The increased number of components adds complexity to the system, and the interactions between components are not yet understood. One of the primary components of the turboelectric architecture that needs to be designed is the electrical distribution system. The performance of this system will affect the power in the system and the interactions between components. This study focuses on the design of the two primary components of the power distribution system - the power distribution cables and power converters. Recommendations for technologies to be used in the design of these technologies will be made. The performance of the cables and their size will be estimated for selected architectures and materials. Furthermore, power converter types and control schemes will be explored to determine the best selection for this application.

SYSTEM ARCHITECTURE

The size and performance of the electrical distribution is dependent on the entire turboelectric propulsion architecture since it will be responsible for power flow between components. The power output and power requirements of each element will be important factors in the design of the electrical distribution system. The placement of the components will also be important because it will determine the length of the cables in the system.

The aircraft selected for this study is the NASA concept vehicle N3-X. The N3-X is a blended wing body aircraft that can carry approximately 300 passengers and has a range of 7,500 nautical miles. The cruise speed will be Mach 0.84, and the cruise altitude will be 30,000 feet [1]. This aircraft has a distributed propulsion system consisting of 14 fans driven by electric motors which span the upper body of the aircraft. The gas turbines and generators are located at the wing tips so that they receive undisturbed air and supply a bending moment for the wings. This aircraft was selected since some preliminary design has been conducted for the turboelectric propulsion system. Components such as the generators and motors have been sized for this particular aircraft and preliminary weight and performance values have been published. Sizing the electrical distribution system will further contribute to the preliminary sizing information for the N3-X propulsion system.

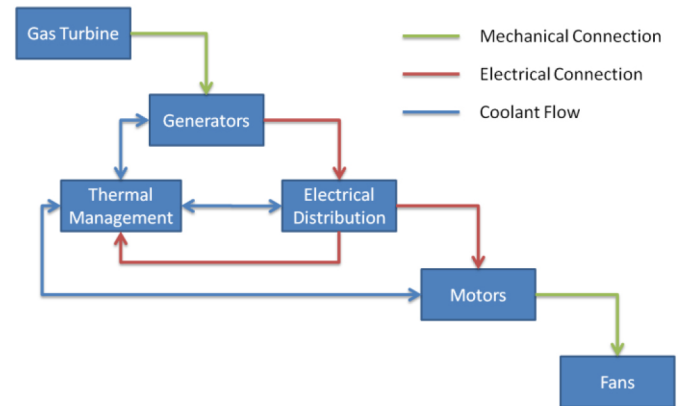


Figure 1. Turboelectric Propulsion System Architecture

A turboelectric propulsion system consists of six primary components: gas turbine, superconducting generator, distribution system, thermal management system, superconducting motors, and fans. An overview of the system architecture is shown in [Figure 1](#). The connections are color coded based on the connection type. The green lines show a mechanical connection. The direction of the arrow shows which component is the source of energy and which component receives it (at the arrow head). The red lines represent an electrical connection. The direction of the arrow shows the direction of current flow. The blue lines show the flow of coolant. The arrows are in both directions for each line because the coolant will circulate through the system.

As shown by [Figure 1](#), the primary task of the electric distribution system is to deliver power from the generator to the motors for the fans. Also, the electrical distribution system must be cooled. Therefore, coolant will be delivered from a thermal management system. In turn, the electrical distribution system must deliver power to the thermal management system. In this study the focus is going to be on delivering power from the generator to the loads. The cables and power converters will be designed for the maximum power draw by the system. For the NASA N3-X, the expected value for the maximum power load is 40 MW [1].

POWER DISTRIBUTION CABLE DESIGN

The power distribution cables are responsible for delivering power between components. A number of design choices must be made in order to determine the size and performance of the cables. The hierarchy of these choices is laid out in [Table 1](#). One of the first decisions that must be made in the design of the power distribution cables is whether the power will be distributed in AC or DC. Although AC power is traditionally used, in high power applications such as turboelectric propulsion, DC has the potential to outperform AC for several reasons. The first reason is that the bus may require the use of superconducting cables. Superconducting cables have virtually no losses when

operating with DC power [3]. AC superconducting cables have losses and will force a fixed ratio between the generator and motor. This inhibits being able to operate the generator and motor independently in order to achieve the best efficiency. The second reason is that batteries and other storage devices can easily be added to the bus to provide additional back-up power. Lastly, if any load is capable of producing regenerated power, the power can easily be returned to the bus [4]. Although many advantages for DC distribution exist, some issues have to be addressed; the main two are system stability and power quality. The system must be able to remain stable under transient loads. One way to address these concerns is through converter design. With the proper design, converters can help stabilize the bus by properly mitigating power while maintaining high power quality. The next decision to be made is whether to use conventional cables or superconducting cables. Both options will be sized in order to determine the appropriate selection. The structure of the cables and appropriate materials were selected based upon the choices presented in [Table 1](#).

Table 1. Cable Design Choices

Transmission	AC			DC		
Type	Conventional			Superconducting		
Material	Copper	Aluminum		YBCO	BSCCO	
Structure	Single Core	2-Core	3-Core	Single Core	2-Core	3-Core
Coolant	Water	Air	Oil	Hydrogen	Nitrogen	

Conventional Cable Design

The first decision that must be made in the design of the conventional cable is determining its structure. Most conventional cables have a cylindrical core which acts as a conductor. The conductor material is an important design choice as well. The material must have a sufficient current density to transmit and accommodate the power load while maintaining a reasonable weight and cost. The most popular choices for this type of cable are copper and aluminum. Copper is the most widely used because of its good current density, good conductivity, and relatively low cost.

In addition to the conductor, protective layers must be added to the structure complete the cable. There are three layers that must be added to the cable: a dielectric layer, a magnetic shield, and a cooling sleeve. The purpose of the dielectric layer is to resist the potential between the wire and the magnetic shield. Its thickness is selected based on the system nominal voltage. Many standards for the selection of the dielectric thickness have been created by organizations such as the International Electrotechnical Commission (IEC) and the Association of Edison Illuminating Companies (AEIC). The AEIC standards are the most widely used in

North America and were used to determine dielectric thickness in this study [5]. XLPE was selected for the insulation for the cable do to its long term reliability [6]. The purpose of the magnetic shield is to protect the wire from the magnetic field induced by the current flow, so the thickness of this layer is dependent on the maximum current flow through the wire. This layer is often made out of aluminum. For this architecture, a cooling sleeve will be necessary in order to maintain a safe temperature for the wire. The maximum allowable temperature is an important constraint to include into the design so that excess heat does not damage the cable or any surrounding electronics such as the power converters. Also in situations where the cable may be in close proximity to fuel lines, the designer must ensure that the heat expelled by the cable will not ignite the fuel.

Conventional cable modeling

The primary purpose of the cables is to transmit power from a source to the loads. The source for this system will be the generators located at the wing tips. The primary loads are the electric motors that drive the fans. The first step in the design of the cables is determining how much power must be delivered by the generator. The motors will consume 40 MW, but there will be losses along the way that must be calculated and added to the total amount of power supplied by the generator (P_{dem}).

$$P_{dem} = P_{load} + P_{loss} \quad (1)$$

The amount of power lost per meter in transmission can be calculated as

$$P_{loss} = I \times V_{wire} = \frac{\phi \times L \times P_{load}^2}{A \times V_{nom}^2} = \frac{4 \times \phi \times I^2 \times L}{\pi \times d^2} \quad (2)$$

In order to solve [Equation 2](#), either the system nominal voltage or the current must be known. System nominal voltage can be set through the use of an actively controlled power converter. So, system nominal voltage was selected to be a design variable in this design problem. In a commercial aircraft today, the nominal voltage of the network is 28 Volts DC. However, in this new architecture, the power transmitted by the distribution system is almost 40 MW. In order to reach that power demand, the current in the wires would have to reach 1.43 MA. Therefore, a range of the values for system nominal voltage will be explored. Using these values current can be determined since the power load is known.

Once the amount of power that must be supplied by the generator is known, the cables are sized in order to carry the maximum power load. One method of sizing the wire is to set a maximum allowable power loss or heat rejection. For an aircraft this value can be taken as 0.2% of the maximum power load [7]. In this case the diameter of the wire would be

$$d = 2 * I_{max} \sqrt{\frac{\varphi}{\pi \times q_{max}}} \quad (3)$$

Even if only 0.2% of the power is rejected as heat, this still creates a significant heat load due to the high power level. The heat load can cause a significant temperature rise in the cable. If the temperature rise is too large, the cable and surrounding power electronics could be damaged. Therefore, a cooling sleeve needs to be added to the design to ensure that the temperature of the cable does not exceed an acceptable value. Most electronic components start to fail at temperatures of 125 degrees Celsius. The amount of heat generated will be determined by the amount of losses in the cable. The temperature will vary throughout the wire due to a temperature gradient caused by heat losses in the wire, so the cable design must ensure that the maximum temperature is not exceeded anywhere along the wire.

Superconducting Cable Design

In order for a material to be considered “superconducting”, it must distribute two properties - zero electrical resistance and perfect diamagnetism, when cooled below a critical temperature. This critical temperature is usually cryogenic (below 123 K). The zero resistance means that there are losses when transmitting direct current. The perfect diamagnetism means that the material does not permit an externally applied magnetic field to penetrate into its interior [8].

In this application DC transmission was chosen since there are some losses in superconducting cables when transmitting AC power [9]. Also, HTS DC cables only carry real power; there is no reactive power, so there will be no significant derating of the cables [10] - meaning that the cables will not lose their ability to transmit their full power rating.

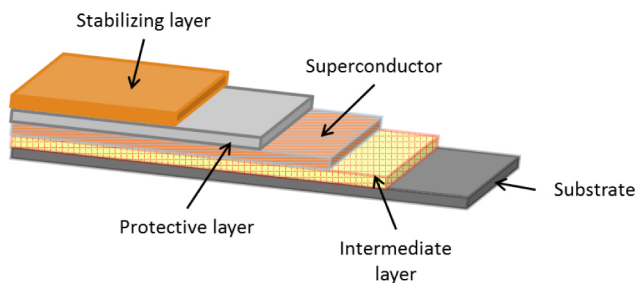


Figure 2. YBCO Tape Structure

The structure of a superconducting cable is quite different from a conventional cable. First of all, there is no cylindrical wire that carries the current; instead, superconducting wires are made in “tapes”. The structure of the tape is shown in Figure 2. In order to make the cable in a cylindrical shape, these tapes are wrapped around a former. The liquid coolant can flow through the center of the former, adjacent tubes, or in an outer layer surrounding the HTS tape. On the outer side

of the superconducting tape, there is electrical and magnetic shielding as in the case of the convectional cable. Two examples of the different configurations for HTS cables are shown in Figure 3.

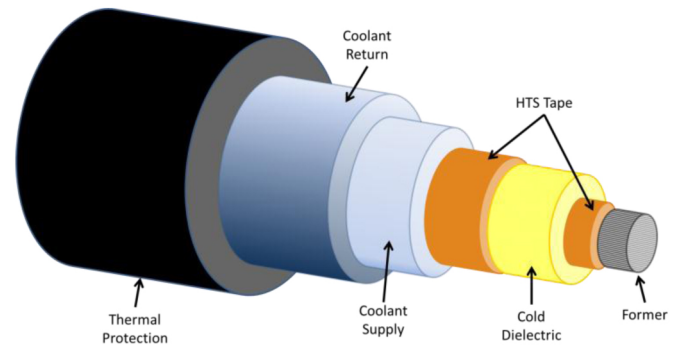


Figure 3. Simple HTS cable configuration

In order to determine the size of the wire, the following parameters must be determined: HTS tape material, HTS tape thickness, HTS tape winding pitch, dielectric thickness, coolant type, former diameter, and outer cable diameter. Based on current research, the best superconducting material for this application is yttrium barium copper oxide (YBCO). It is the most cost effective option for the current carrying capacity required for this application. Studies have shown that YBCO tapes have been created that have a critical current density of 1.4-1.5 MA/cm². The current carrying capacity of these wires is about 400 A per cm of wire width [11]. When the wires are transmitting direct current, the amount of power that the wire can carry is proportional to the volume of the wire.

As in the case of the conventional cable, electrical insulation will be needed. The amount of shielding need will be dependent on the cable dimension of the former and HTS tape, the system nominal voltage, and the design stress of the insulation. Along with the electrical tape and insulation, the cable will also include a thermal management system. The purpose of the thermal management in the wire is to keep the superconducting tape under the critical temperature. There is no heat generation in a continuous DC superconducting tape; however, in the actual system there will be joints and imperfections in the cable which will cause a small amount of heat production which is estimated to be around 5 W/m [1]. There will also be heat invasion from the cable's surrounding. Hirose estimates this to be about 0.7 W/m/Cable [3]. The insulation is sized in a similar manner as insulation in current cables. The thickness is directly proportional to the voltage and amperage in the wire.

Cryogenic temperatures in the cable will be maintained using a cooling sleeve as the outer layers. The cooling sleeve will consist of a supply channel and a return channel. Some HTS cable designs place the coolant supply channel within the former. This design was not chosen because if supply stream is within the former, it will be at high voltage. The high voltage of the supply stream will require the use of high