

Propulsion System Component Considerations for NASA N3-X Turboelectric Distributed Propulsion System

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ABSTRACT

NASA's N3-X aircraft design under the Research and Technology for Aerospace Propulsion Systems (RTAPS) study is being designed to meet the N+3 goals, one of which is the reduction of aircraft fuel burn by 70% or better. To achieve this goal, NASA has analyzed a hybrid body wing aircraft with a turboelectric distributed propulsion system. The propulsion system must be designed to operate at the highest possible efficiency in order to meet the reduced fuel burn goal. To achieve maximum efficiency, NASA has proposed to use a superconducting and cryogenic electrical system to connect the electrical output of the generators to the motors. In addition to being more efficient, superconducting electrical system components have higher power density (kW/kg) and torque density (Nm/kg) than components that operate at normal temperature. High density components are required to minimize the weight of the electric propulsion system while meeting the high power demand. Minimizing the electric propulsion system weight helps to reduce the amount of fuel required for propulsion. In this paper, evaluation of the electrical system components such as cryogenic and superconducting generators, motors, power converters, DC and AC cables, energy storage, circuit breakers, and fault-current limiters is presented. A review of the present status of these components and sub-systems is also presented and the progress of technology for future applications is discussed.

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INTRODUCTION

NASA's N3-X aircraft design under the RTAPS study is being designed to meet the reduction of aircraft fuel burn by 70% or better. To achieve reduced fuel burn, the aircraft must be efficient and have minimal weight. As a result, NASA has studied blended-wing body aircraft with distributed propulsion to maximize boundary layer ingestion. This system consists of an array of electric motor-driven propulsors located near the trailing edge of the center wing-body section. The electric power to these motors is provided by two engines each driving top electric generators. The outputs of the generators are connected to multiple propulsors via an electrical distribution system and power converters. Such a system is called a *turboelectric distributed propulsion (TeDP) system*. The propulsion system provides the necessary propulsive power and also assists in aircraft yaw control through differential thrust.

For this aircraft with such a TeDP system, the propulsion system is required to produce 30,000 hp for maximum thrust during takeoff. This requires that the generator or generators connected to each engine be rated at 22.4 MVA. For such a high power electric system, the losses from normal conducting electrical components would be significant. In order to achieve maximum efficiency of the electrical system, an entirely superconducting and cryogenic electrical system with DC distribution is proposed. In addition to eliminating AC losses, a DC distribution system eliminates the need to synchronize multiple AC generators to an AC distribution system and also decouples the fan and engine speeds. The additional weight and power requirements to cool the superconducting electrical system is not considered in this study, although NASA has studied these additional power requirements [1,2]. In addition to being more efficient, superconducting electrical system components have higher power density (kW/kg), torque density (Nm/kg), or current

density ($A/m^2/kg$) than components that operate at normal temperature. These high density components enable the weight of the electric propulsion system to be minimized while meeting the high power demand.

The basic architecture of the superconducting and cryogenic electrical system components that generate, distribute, and consume power are shown with their basic connections in [Figure 1](#). The AC output of the generators is converted from AC to DC using power converters. A superconducting fault current limiter (SCFCL or SFCL) may be necessary between the generator and converter depending on generator or converter fault-current carrying capability. An SFCL limits the fault current flowing through the device so that the fault current rating of components downstream can be reduced. Limiting the fault current rating of components generally reduces the weight of the components at the cost of the added weight of the SFCL. Protection devices (shown as small white squares) are included to protect each component as necessary from a fault. Closer to the load, the transmission line splits among several converters and propulsors motors. Also connected to the bus is the energy storage device which may be used to supply additional power to the system at a faster rate than the engines or generators can respond.

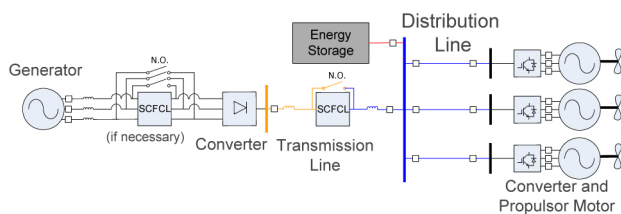


Figure 1. General description of electric power generation, distribution, and consumption.

Applying these fully superconducting and/or cryogenic components to a high power aerospace system is challenging. At this time, none of the components are fully to be implemented in this system, but progress has been made so that such a project may be feasible in the N3-X aircraft timeframe. A review of the present status of these components and sub-systems is presented and the progress of technology for future applications is discussed. The status of the components is characterized in terms of power, torque, or current densities. Additionally, potential control schemes for detecting and isolating faults are discussed. The anticipated component densities and estimated reliability were used to create and assess several electrical system architectures. These architectures show that with proper configuration and control, the electrical system weight can be reduced. Specifically, the propulsor weight can be reduced by 40% by reducing the power rating of the propulsors. In a typical aircraft, the propulsion power is rated to twice the power required for minimum takeoff thrust. For a TeDP system, the power rating of the propulsors can be reduced while still maintaining sufficient reliability and the minimum power required. Additionally, these architecture studies estimate that

that protection equipment weight may be significant and so should be accounted for as the N3-X aircraft design progresses.

BASELINE ARCHITECTURE DESCRIPTION

The Baseline N3-X TeDP architecture is schematically illustrated in [Figure 2](#) and [Figure 3](#). [Figure 2](#) illustrates where each component may be physically located on the aircraft, and [Figure 3](#) shows the electrical system schematic and legend corresponding to [Figure 2](#). The baseline architecture includes two wingtip mounted turboshaft engines which each drive two cryogenically cooled superconducting electrical machines. The power electronics that convert the variable frequency AC power to DC are located close to the generators to minimize the length of the AC superconducting system which incurs greater losses than DC superconducting systems. Each powerplant (engine/generators/converters combination) is sized to provide 30,000 hp (22.4 MVA), the minimum power required at takeoff for the single engine failure scenario as recommended by NASA studies. The transmission lines run across the aircraft with redundant lines physically located in separate areas of the aircraft. The distribution buses split the power from each transmission line and feed power to three or four propulsor converters/motors. The propulsor converters and motors are distributed near the trailing edge of the center wing-body section. The energy storage devices are also placed near the propulsor converters/motors with each distribution bus connected to one energy storage device.

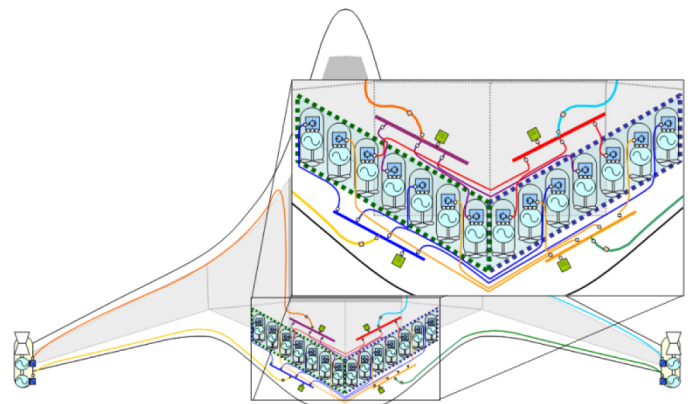


Figure 2. Baseline architecture physical schematic

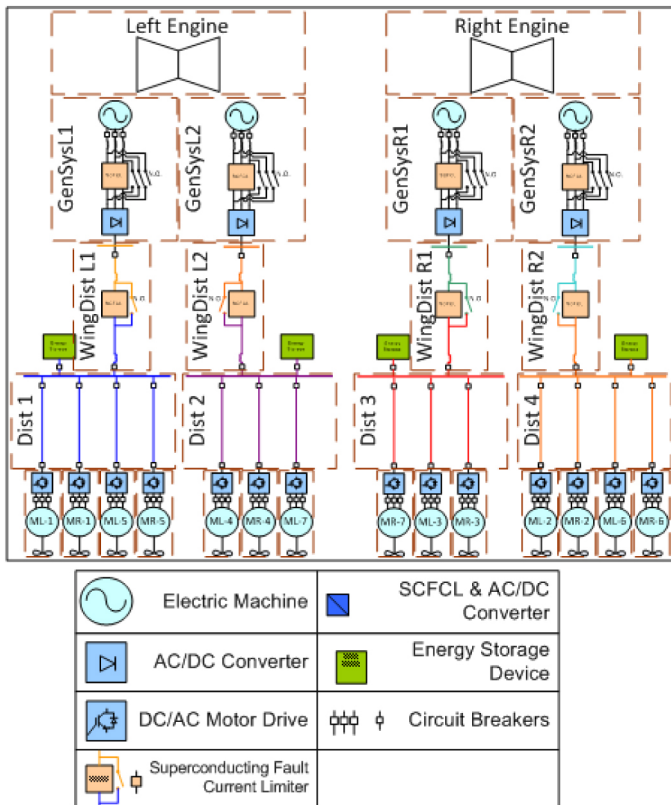


Figure 3. Baseline architecture electrical system schematic and legend

SUPERCONDUCTING COMPONENT TECHNOLOGY EVALUATION

A review of the present status of superconducting systems and sub-systems is presented and the progress of technology for future applications is discussed. The status of the components is characterized in terms of power, torque, or current densities. Additionally, potential control schemes for detecting and isolating faults are discussed.

Superconducting Electric Machine

Presently, there are several superconducting field synchronous machines with room temperature or cryogenic high purity metal armatures [3]. General Electric [4], Westinghouse, Reliance Electric/Rockwell Automation [5], American Superconductor [6], Siemens [7,8], and ALSTOM [9] all have implemented high power generator designs based on superconducting field and conventional armature. Another partially superconducting electric machine was developed for vehicle applications with a torque density of 50 Nm/kg [10]. Literature review shows no fully superconducting machines have been implemented due to alternating current losses in the armature and the expense of superconducting material [11,12]. Both Long Engineering and General Electric have designed fully cryogenic machines for the Air Force Research Laboratory, yet the armatures were cryogenic metal not

superconductor [13]. The field-controlled machines are controlled under a slightly different feedback strategy, current mode instead of voltage mode, due to the negligible resistance of the field coil [14]. These machines would be controlled with a current mode buck power electronic converter and could support large flux density (greater than two Tesla) due to the typical air core design. Contrary to the air core design, there is the homopolar iron core design, which alleviates the need to cool rotating superconducting material [15]. In the homopolar design, the rotor is a variable reluctance structure around which a stationary field coil produces an axially directed magnetic flux in the rotor. The low reluctance paths vary with rotor angle and produce the time varying magnetic flux in the armature coils.

Flux pinned or trapped superconductors use the Meissner effect. When a superconductor transitions from normal to superconducting states under a magnetic field, it will produce an equal and opposite magnetic field when the external field is removed. Thus, the term flux trapped or pinned. By using superconducting electromagnets, bulk superconductor disks have “trapped” magnetic flux as high as 15 Tesla [16]. A flux trapping and flux concentration superconducting rotor machine was designed for aviation. The machine was designed so that in the case of a cooling system failure, the machine could still provide 30% of takeoff power in order to land safely [17]. The field excitation was provided by Bi2223 Helmholtz type coils or NdFe magnets. YBCO plates were used to trap the magnetic flux. A squirrel cage shield was inserted in the air gap to generate asynchronous torque in the case of superconducting winding failure. The superconducting state of the machine provided 150 kW of power at 2700 rpm and weighed 28 kg. This prototype had a torque density of 19 Nm/kg.

Flux “pumping” is a quantum effect, where either a small magnitude thermal transient [18] or small magnitude magnetic field transient [19] is induced in the superconductor in the superconducting state. Repeated induction of either field transient is converted to increased superconductor magnetic flux. This allows in situ magnetization of a superconducting field coil not with extremely large fields but with the repeated application of either a small thermal or magnetic transient. This method could allow for re-magnetization of superconductors after unplanned quench, given sufficient time.

Flux pinned or flux pumped field coils would be controlled as a low inductance permanent magnet machine. The lower inductance requires more detailed control and power electronics drive, such as a multilevel converter [20]. So called “sensorless” control could be used on both the generators and propulsor motors. The generator back electromotive force (EMF) would be used to estimate angle for active rectification at optimal power factor. For propulsor motors, a slow acceleration from a defined electrical angle will allow for synchronization since the propulsor torque will be negligible at start-up speeds.