

Trade Studies for NASA N3-X Turboelectric Distributed Propulsion System Electrical Power System Architecture

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ABSTRACT

This paper outlines power system architecture trades performed on the N3-X hybrid wing body aircraft concept under NASA's Research and Technology for Aerospace Propulsion (RTAPS) study effort. The purpose of the study to enumerate, characterize, and evaluate the critical dynamic and safety issues for the propulsion electric grid of a superconducting Turboelectric Distributed Propulsion (TeDP) system pursuant to NASA N+3 Goals (TRL 4-6: 2025, EIS: 2030-2035). Architecture recommendations focus on solutions which promote electrical stability, electric grid safety, and aircraft safety. Candidate architectures were developed and sized by balancing redundancy and interconnectivity to provide fail safe and reliable, flight critical thrust capability. This paper outlines a process for formal contingency analysis used to identify these off-nominal requirements. Advantageous architecture configurations enabled a reduction in the NASA's assumed sizing requirements for the propulsors. However, significant weight penalties were also identified by including estimates of protection equipment sizing. Following an architecture down-selecting process, first order dynamic models were generated to assess the energy storage requirements for the TeDP system.

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INTRODUCTION

NASA's N3-X hybrid wing body aircraft concept promises dramatic improvements to aircraft performance, pursuant to N+3 targets. A significant portion of these potential improvements are attributed to closely coupled integration of propulsion, power, and vehicle aerodynamic design. This integration is enabled by an advanced turboelectric distributed propulsion (TeDP) system [1][2].

The current iteration of this vehicle's TeDP architecture includes two turboshaft engines positioned at the wingtips and a slotted bank of propulsors positioned at the trailing edge of the lifting body [3][4]. Power is extracted from the turboshaft engine by superconducting electrical machines, converted from AC to DC, and distributed to the centrally located propulsors. Inverters then convert power back to AC to drive superconducting propulsor motors.

Providing propulsive power in this fashion introduces three distinct benefits. First, DC power distribution allows for a decoupling of the fan and engine speeds. There is no need for speed matching on the turbine engines or the propulsor

fans. This, in turn, allows each propulsor to be individually throttled to achieve the optimal pressure ratio. Additionally, higher propulsive efficiency is attained by operating at very large effective bypass ratios. Finally, reductions in fuel burn are also achieved through boundary layer ingestion [5].

While the advantages of this concept are attractive, significant design challenges arise from this dramatic shift in aircraft systems architecture. A wholly superconducting electrical system must meet all steady state and transient thrust requirements, including potential differential yaw control for stability augmentation, under the same reliability requirements as a traditional tube and wing concept with podded propulsion. Reliability and failsafe requirements must be met at minimal weight penalty and acceptable levels of system complexity.

This paper outlines architecture concept trades performed for the N3-X TeDP system. These trades are illustrated in this paper by describing and evaluating four unique architecture concepts. While, each concept includes the same technologies for generation, distribution, protection, and conversion, they

differ in terms of their interconnectivity and redundancy. All architectures employ multiple generators per engine shaft, bipolar grounded distribution with metallic return, and a combination of superconducting fault current limiters and breakers for unit protection. Additionally, all architectures assign propulsors symmetrically to the distribution buses to eliminate asymmetric thrust failure cases. However, architecture differences include the number and interconnection of central distribution buses, generator to distribution system transmission lines, and propulsor feeders. As such, each architecture requires unique strategies for power management during failure conditions.

ARCHITECTURE DESIGN

Baseline Architecture

Figure 1 shows the baseline TeDP architecture for the N3-X concept. The baseline N3-X TeDP Baseline architecture includes two wingtip mounted turboshaft engines which drive cryogenically cooled superconducting electrical generators. Power electronics converts the variable AC voltage of the generators to DC. This dc voltage is further converted to variable frequency and variable voltage AC to power the propulsor motors. Each engine hosts a pair of electrically isolated generators with a dedicated power converter.

It is assumed that marginal weight penalties are associated with one generator rated at 22.4 MVA vs. two generators with a total capability of 22.4 MVA. These generators are coupled to the same shaft and could potentially be housed in the same cryogenic housing. Hence, to reduce the unit maintenance/reliability requirements of the generators, converters, and transmission lines, dual redundancy per power plant is recommended. If these weights become problematic, a single generator could provide sufficient reliability at a potential expense of unit level maintenance costs.

For reasons of additional system reliability, a bipolar grounded superconducting electrical system distributes the generated DC power to the central propulsor distribution buses. Redundancy and spatial isolation are included on the baseline architecture to provide additional reliability. Transmission lines are routed near the leading and trailing edge of the wings to increase redundancy and spatial isolation, thus reducing the risk of zonal common cause failures. Multiple feeder lines then distribute power to the propulsors.

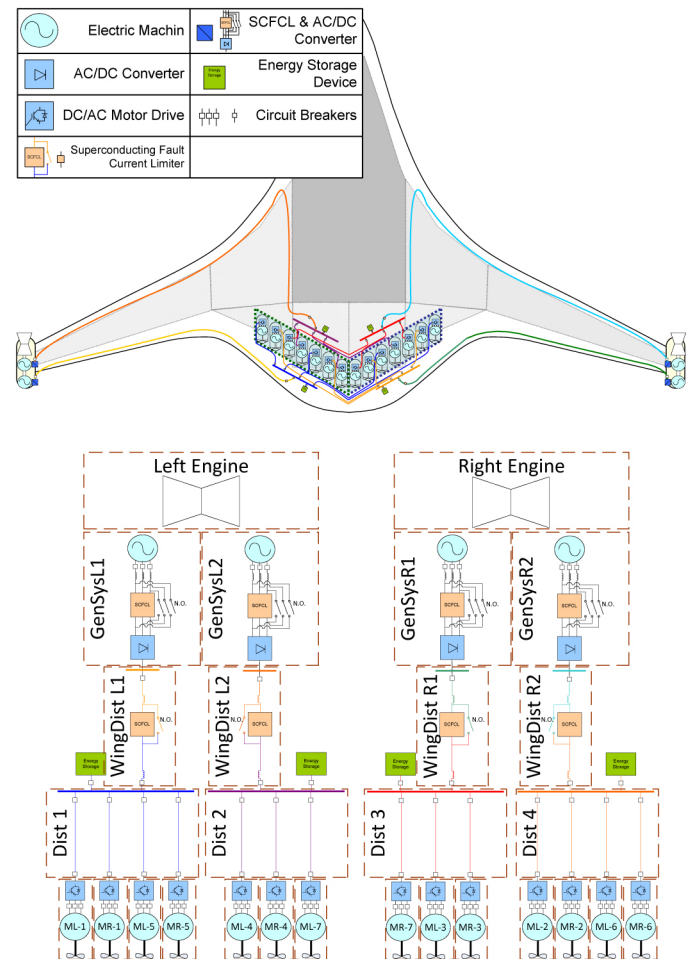


Figure 1. Baseline Architecture Diagram

Propulsor requirements

One benefit to the N3-X concept is the reduction or elimination of single engine out lateral trim requirements. Each engine, generator, and bus provides power to the propulsors symmetrically as illustrated in Figure 2.

A single point failure in the power system will result in a loss in available power for propulsors situated on both the left and right sides of the aircraft. This symmetric loss yields no net yawing moment. Additionally, inboard and outboard propulsors are paired to buses in a fashion which attempts to assign similar yaw provision capability to each distribution bus.

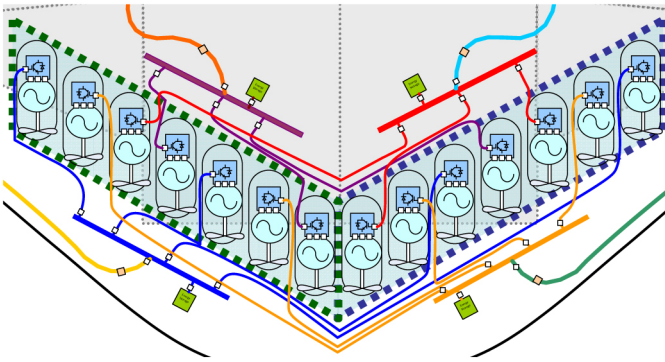


Figure 2. Symmetric Bus Propulsor Assignment

Table 1 outlines the propulsor assignment to each bus. The 14 propulsors in the baseline concept are numbered from outer to inner 1 through 7. The bus colors correspond to the bus colors in Figure 2. Left and Right side propulsors are designated by 'L' and 'R' respectively in the Table.

Table 1. Symmetric Assignment of Propulsors to Distribution Buses

Power Source	Central Bus	Propulsor
Left Engine	Purple Bus	L4, R4 L7
	Blue Bus	L1, R1 L5, R5
Right Engine	Red Bus	L3, R3 R7
	Orange Bus	L2, R2 L6, R6

While the single engine out poses little adverse yaw for this aircraft concept, other exogenous events causes of asymmetric propulsor failure must be considered in architecture sizing. The placement of the propulsors on the top side of the wing near the trailing edge greatly reduces the risk of debris or bird ingestion during takeoff or climb. However, the occurrence of such an event would require increases in propulsor capability requirements to account for a potential simultaneous damage to multiple consecutive propulsors.

FAA regulations require that the ingestion of a large bird (for small inlet area engines/propulsors the bird weight is assumed to be roughly 4 lbm) must not yield a sustained reduction in maximum rated takeoff power or thrust of more than 50% during low altitude operations[6][7]. Traditional turboshaft engines are design to withstand certain level of bird strike without catastrophic failure.

However, bird/debris ingestion at the propulsor presents a non-standard failure condition. Due to the distributed nature of the propulsion system, it may or may not be acceptable that a single propulsor bird strike render it useless (e.g. fan loss or generator quench from sudden torque shock). Allowing failure under bird strike scenarios would allow

propulsor designers to decrease the weight, cost, and complexity of the fan design. However, Allowing a bird strike to yield the loss of a propulsor may be insufficient under some bird strike conditions. When considering flocking bird strike requirements, multiple propulsors may incur damage and yield control and propulsion issues. Assuming that the propulsor is designed so as to prevent fan deflagration due to debris/bird ingestion, a bird strike poses transient electromechanical requirements on the electrical system. This may be characterized by sudden increases in torque, a droop in shaft speed, changes to the fan efficiency, and potential flow path blockages.

Operating voltage

The operating voltage for all architectures considered in this study was arbitrarily assumed to be $\pm 10\text{kV}$. If properly designed for an aircraft type environment, polymeric dielectrics electrical properties tend to greatly benefit from the cryogenic temperatures [8]. Polymer dielectric strength can range from 10-15 kV per millimeter [9]. Epoxy bound nano-particles at cryogenic temperatures can range from 25-40kV per millimeter [10]. The liquid nitrogen refrigerant itself provides some additional electrical insulation and has been shown to assist polymer electrical insulations with mechanical damage as compared to gaseous nitrogen. Typical polymeric insulation materials increase in dielectric strength by 5-10X over room temperature capabilities. Southwire has tested cables to pulsed potentials greater than 100kV [11]. Although evolving, insulation design is progressing towards long term stable and high voltage capability.

In general, increasing the voltage increases the losses associated with alternating current distribution due to dielectric losses and demanding more cooling requirements than that for direct current distribution. Increased voltage in AC or DC distribution system requires a larger dielectric layer, but is generally accepted over increasing the current, which requires increasing the superconducting wire size, the most costly of the cable components. The concern of partial discharge is partially mitigated by the fact that most dielectric voids are compressed to a negligible volume and the metallic cladding of the cryo-cooling fluid and vacuum/insulation layer are grounded and prevent electric field gradients outside of the cable. Additionally, as the current density increases, the quench conductor made of copper will also have to increase which may affect the cable weight.

HyperTech Research estimates that the available engineering current density of MgB2 superconducting cables is 200-400 A/mm², and that by 2035, the available engineering current density will be 2-3 times greater. Current studies have been able to prescribe the optimal voltage for normally conducting distribution equipment [12]. However, to determine the optimal DC system voltage for minimum system weight or maximum power capability for this superconducting system, a system level study should be completed considering the power densities, which are likely to be nonlinear, for each piece of equipment throughout the

electrical system. Such a study requires reasonable voltage sensitivity estimates of power densities for superconducting generators and motors, cable, fault-current limiters, circuit breakers, and cryogenic converters. This fidelity of data is not available today, but as the technology evolves, the data could be collected or could be more accurately estimated in order to complete such a study.

Protection equipment

Four common protection design principles that should be considered are selectivity, sensitivity, reliability, and back up. 13 Selectivity is determined by setting overcurrent protection levels at each protected device and subsequent zones that overlap with the device protection. The device's protection should be most sensitive to a fault within the device. The next overlapping zone should be less sensitive than the device's protection but should activate if the device's protection does not detect a fault within the device. Overlapping zones coordinated properly for selectivity and sensitivity increase the protection system reliability to protect the electrical system from faults. Designing the control scheme with appropriate selectivity and sensitivity allows only the necessary sections of the distribution system to be isolated when necessary to protect the system from damage due to faults while still being able to transmit required power.

Part of protection is the architecture design so that the system has enough redundancy to be able to reconfigure as necessary when one or more generators or one engine cannot provide power to the system. For the baseline architecture, the system is reconfigured by throttling the engines up or down and increasing the load provided to each generator. For more interconnected architectures, the system may use redundant propulsor motor feeder lines, distribution lines, or bus ties to reconfigure the system in order to provide required power to the propulsors. The protection equipment not only protects sections of the equipment from damage during abnormal operating conditions but also allow the system to reconfigure as indicated by a supervisory controller. The protection zones for this architecture are shown in Figure 3.

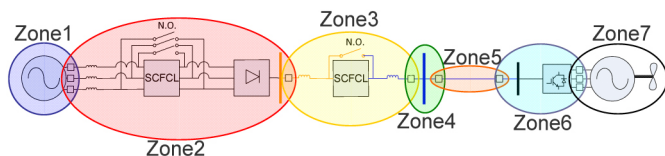


Figure 3. TeDP System Protection Zones

Seven zones of protection were identified between a single generator to propulsor path. Zone 1 protects and isolates the generator. The generator is protected on the engine shaft side through the enforcement of engine limits. Over and under-speed limits are enforced by the engine Full Authority Digital Engine Controller. The generator is also protected on the AC side by breakers. The fault current rating for these breakers is limited by an AC superconducting fault-current limiter (SFCL or SCFCL) placed between the breaker

and the AC/DC converter. Accordingly, each architecture concept requires four AC circuit breakers for Zone 1 protection. Additionally, a total of 4 AC SFCLs are used in all architectures.

Zone 2 isolates the SFCL and AC/DC converter. An AC breaker isolates these components on the AC side and a DC breaker isolates on the DC transmission system side. The DC fault current is limited by a SFCL on the DC transmission line. This transmission line and SFCL are isolated by DC breakers at both the central bus and the generator (Zone 3). Architecture 1, 2, and 3 each use a total of 4 DC SFCL's and 8 DC circuit breakers for the power plant to central bus transmission lines. Architecture 4 requires an additional four DC SFCLs and 8 DC circuit breakers for the secondary transmission lines.

Each device connected to the central bus uses a DC circuit breaker to isolate failures. This constitutes a protection zone (Zone 4) for the bus. Due to a bus tie between the inner buses, Architecture 4 requires an additional DC breaker and DC SFCL. The feeder and bus share one point of protection. Each feeder (Zone 5) is isolated by two DC breakers: one at the bus and one at the propulsor. Therefore, Architectures 1 and 2 require 28 DC breakers in total on 14 feeder lines and architectures 3 and 4 require 56 DC breakers on 28 feeder lines.

The propulsor side protection zones 6 and 7 provide protection in similar fashion to zone 2 and zone 1 respectively. However, due to the limited current rating of the propulsor side components SFCL are not used on these lines. In total, all architectures require 14 AC breakers to isolate faults at the propulsor motor.

Contingency Analysis

While a system may be designed to act most efficiently at nominal conditions, failure scenarios determine the sizing critical requirements for aircraft power systems. The unique role of the TeDP electrical distribution system in supporting flight critical functions requires that failure probabilities be less than 10^{-9} [14][15]. Additionally, fail-safe requirements dictate that no single point failure may result in catastrophic consequences. In the event of a unit level failure, assuming that the fault is appropriately identified and isolated, sufficient capability must be available from the unaffected portions of the architecture. Sizing the architecture components requires a balance between redundancy, unit capacity, and unit reliability. Unit capacity typically refers to the nominal power rating of the unit. All statistically significant failure/contingency scenarios must be considered as a potential source of sizing critical requirements for some unit in the system.

For a commercial aircraft, the takeoff scenario presents the most stringent failure requirements to the architecture propulsion system. For the N3-X aircraft, a minimum of approximately 30,000hp must be available for safe execution of a rolling takeoff according to NASA studies. As such, this