Electrical System Trade Study for SUSAN Electrofan Concept Vehicle

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The SUSAN Electrofan Aircraft concept is a subsonic regional jet transport aircraft that utilizes a single turbofan engine and Electrified Aircraft Propulsion (EAP) to enable propulsive and aerodynamic benefits to reduce fuel usage, emissions, and cost. This paper is a trade space exploration of the electrical system for the concept aircraft, including possible system architectures, and a review of the specific powers and efficiencies required for the electrical components to realize the EAP system.

I. Nomenclature

DCLR: DC Link Regulator
HPS: High Pressure Spool
LPS: Low Pressure Spool
MG: Main Generator
MGC: Main Generator Converter
EEM: Electric Engine Motor
EEMC: Electric Engine Motor Converter
TCC: Turbine Control Motor-Generator Converter

II. Introduction

This paper outlines a trade space exploration of the electrical power system for the SUbsonic Single Aft eNgine (SUSAN) Electrofan aircraft concept. The SUSAN Electrofan is a 180 passenger regional aircraft concept designed with the intent of reducing emissions by 50% while retaining the speed, size, and range typical of large regional jets. Although the SUSAN Electrofan has the size of a large single aisle aircraft, its range is similar to that of the latest regional jets, which is why it is categorized as a regional jet. The emissions per energy unit are reduced by combining alternative fuels with Propulsion Airframe Integration (PAI) with a 10-MW class Electrified Aircraft Propulsion (EAP) system. A trade space exploration of certain key design characteristics of the SUSAN Electrofan is being conducted [1,2]. A high level diagram with the features of the SUSAN Electrofan is shown in Figure 1.

SUSAN Electrofan employs a hybrid EAP system to enable:

1. Single turbofan operation on a large transport category aircraft
2. Increased aerodynamic and propulsive efficiency through placement of electric engines
3. Optimized turbofan sizing and efficiency through control and electric boosting
4. Reduced control surface sizing through thrust augmentation

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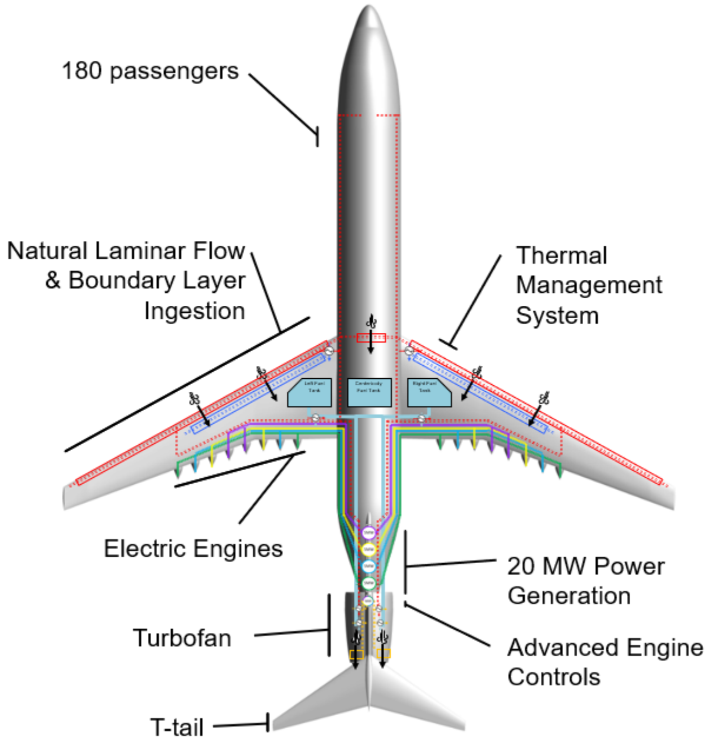

Figure 1 SUSAN Electrofan Features

The Electrical Power System (EPS) required to execute the functions listed and must be capable of on the order of 20MW of power transmission while being extremely light and efficient. If the system is too heavy or inefficient, the penalties of the power system will offset the benefits listed above. The efficiency also has a second impact in that the waste heat from the electrical system impacts the size of the thermal system, which adds additional mass, power, and drag losses.

In order to have a sense of the order of magnitude change in the SUSAN electrical power system size, we look back to the history of aircraft power system sizes. A good review of size and voltage is provided by Avery [3] and augmented by Christou. [4]. The historical trends are shown in Figure 2. The SUSAN electrical power system trade is being conducted at a nominal size of 20MW with a sensitivity exploration between 10 and 30 MW. Power systems of this size on an aircraft necessitate higher voltage operation and thermal management which are significant barriers to overcome in the environmental, flight, and operational conditions of an aircraft application.

This paper provides a status of our trade space exploration. We will touch on power system sizing, voltage selection, bus configuration, and key functions enabled by the system.

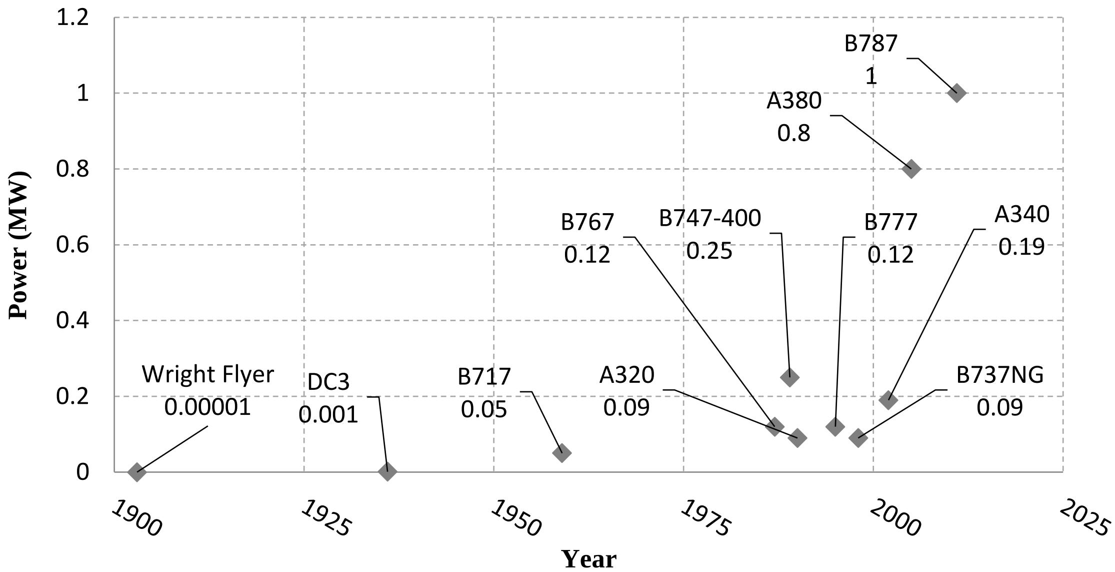

Figure 2: History of Aircraft Electrical Power System Sizes

III. SUSAN Electrical Power System (EPS) Functions

A. Single Turbofan Operation

In order to operate and be certifiable with a single engine, the EAP system must be able to provide propulsion redundancy in the event of a turbine engine failure. In normal operation thrust is provided by a combination of thrust from a rear mounted turbofan and distributed electrical engines on the wings which are powered by a generator driven by the turbofan. In the case of the single turbofan engine failure, the power source for the electrical engines switches from the turbofan driven generator to a single use primary battery to allow flight for approximately thirty minutes. In the failure case, the electric engines provide the thrust.

B. Optimized Aerodynamic and Propulsive Efficiency

The SUSAN power system is used to drive electric engines placed strategically to optimize propulsion aircraft integration benefits. The flexibility of connecting the primary power source on the aircraft, either the generators or the battery, to the electrical engine through a cable enables placement in optimal locations to maximize aerodynamic and propulsive efficiency. This degree of flexibility offers the potential to gain benefits, however the realization of those benefits requires a multidiscipline trade space exploration to understand the interaction of wing, fuselage, and engine placement that previously was relatively decoupled. Those trade space explorations are ongoing with current status being reported by Chau [5], Lynde [6], Machado [7], and May-Fun Liou [8].

C. Optimized Turbofan Sizing and Efficiency

The Turbine Electrified Energy Management (TEEM) concept allows the gas turbine engine to utilize the electric machines that are coupled to the engines in an EAP system as actuators that augment turbine operability. The immediate effect is to improve thrust response and engine stability. However, the goal of TEEM is to trade the now unnecessary design margin in the engine for improved performance, thermal efficiency, weight, and volume.

The engine control system is responsible for maintaining safe, stable, and efficient operation of the engine throughout the mission. Ideally, the turbine engine would always operate on the steady-state operating line of its turbomachinery components; however, during transients (that accelerate or decelerate the engine spools), operation drifts from nominal. This off-nominal condition, caused by a transient mismatch between the engine gas path flow and the turbine blade rotational speeds, can reduce the stability margins of the compressors. Accordingly, additional margin, called the "transient stack", must be included to guarantee safe operation through all transient maneuvers. The need to include additional operability margins constrains the engine design space and sacrifices performance. The TEEM control strategy can be implemented by adding and/or extracting power from the engine spools with electric machines to suppress the dynamic excursions of the operating points away from the steady-state operating line caused by transients. One potential benefit of the TEEM concept would be the reduction or elimination of the transient stall margin stack, providing the opportunity to trade operability in the engine design for improved performance and/or reduced weight [9]. Additionally, the TEEM concept has been studied for improvement during steady-state operation. Potential additional benefits of this steady-state implementation include reduction or elimination of complex actuation schemes for compressor stage matching and stability bleeds; the achievement of more efficient variable cycle operation; and the expansion of the operating range of the engine [10].

The SUSAN Electrofan vehicle will implement the TEEM concept using both the HPS and LPS of the turbofan engine, along with a small amount of re-usable energy storage and an advanced control system, to enable a better performing turbofan. The components utilized in this implementation are the MGCs, the TCCs, the rechargeable batteries, and the EEMCs. A high-level schematic of a representative power bus is provided in Figure 3.

	TEEM: LPS (all 16 circuits)			TEEM: HPS (4 circuits only: 2, 7, 11, 14)		
configuration	nominal	TEEM: +ΔT LPS	TEEM: -ΔT LPS	nominal	TEEM: +ΔT HPS	TEEM: -ΔT HPS
TEEM MainG Action	none	decrease load on MainG	increase load on MainG	none	none	none
TEEM TC M/G Action	none	none	none	none	increase T* on TC M/G	decrease T* on TC M/G
MGC	provide entire PT power	provide partial PT power	provide entire PT power	provide entire PT power	provide entire PT power	provide entire PT power
TCC	none	none	none	none	+ΔT* TC M/G	-ΔT* TC M/G
Rechargable Battery	charge balance maintained via DCLR	discharge & provide partial PT power	charge (storing energy per -ΔT)	charge balance maintained via DCLR	discharge per TCC	charge per TCC
EEMC	drive fans at PT*	drive fans at PT*	drive fans at PT*	drive fans at PT*	drive fans at PT*	drive fans at PT*

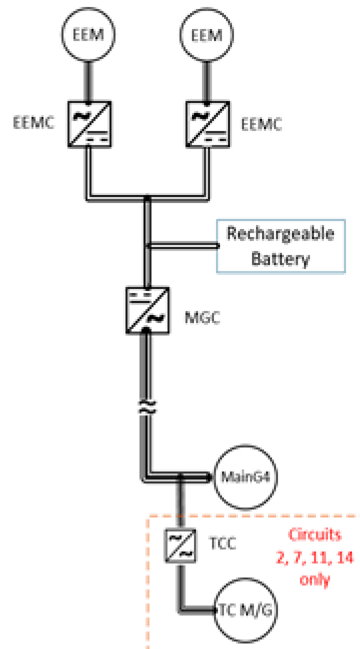

Figure 3: SUSAN EPS TEEM Implementation, with Single Bus Schematic

TEEM implementation in the SUSAN EPS is described in the table in Figure 3. The description is divided into operation on the low pressure spool and the high pressure spool considered separately; although the TEEM controller will act on both spools simultaneously in some instances, it is helpful to consider the implementation on each spool separately for clarification purposes. Each spool can be operated 3 ways: nominal operation, the added torque condition, and the subtracted torque condition. Note that under all conditions, the EEMC is operated at the appropriate propulsion thrust command (PT*), the and the power for this propulsion thrust (PT) generated by the MGC augmented in some instances by the rechargeable battery.

Under nominal LPS operation (note that this action can be taken by all 16 MainG busses), the PT power is provided entirely by the MGC, and the rechargeable battery is not actively involved; appropriate battery state of charge is maintained via the DCLR. Under the LPS increased torque TEEM command, the MainG is unloaded; MGC is only partially responsible for PT power, and the makeup energy is provided by discharging the rechargeable battery. Under the LPS decreased torque TEEM command, the load on the MGC is increased; once again MGC entirely responsible for PT power, and the additional load on the MGC is provided by transferring energy into (charging) the rechargeable battery.

In HPS TEEM operation (this action can be taken by only 4 of the busses: 2, 7, 11, 14), the PT power is provided entirely by the MGC in all modes. Under nominal HPS operation, the rechargeable battery is not actively involved; appropriate battery state of charge is maintained via the DCLR. Under the HPS increased torque TEEM command, the torque command on the TC M/G is increased; the current is provided by discharging the rechargeable battery. Under the HPS decreased torque TEEM command, the torque command on the TC M/G is decreased; the required current reduction is provided by charging the rechargeable battery.

The TEEM control logic will determine how the power system is utilized to influence the HPS and LPS. Ref. [10] describes a potential control strategy, and a similar strategy is expected for SUSAN. There will likely be torque addition on the HPS and potentially the LPS during accelerations. During decelerations, it is likely for torque to be subtracted from the LPS and added to the HPS. Thus, there could be combinations of the operating modes described thus far. In any case, the sum of the power load on the bus will determine if the power demand from the PT power is partially or fully supplied by the MGC, and this will imply if the re-usable batteries are utilized to supply the PT power deficit or to absorb excess power extracted from the engine spools.

D. Reduced Control Surface Sizing

Thrust augmentation to reduce control surface requirements will be explored in future efforts. NASA has completed extensive work including ground and flight testing of Propulsion-controlled aircraft (PCA) aircraft [11]. This concept has potential benefits in both normal operation and failure cases.

IV. SUSAN Electrical System Architecture

The SUSAN electrical architecture concept has features that are meant to help meet the efficiency and emission requirements, while providing the redundancy required for a single turbofan aircraft. An overview of the electrical system architecture is shown in Figure 4.

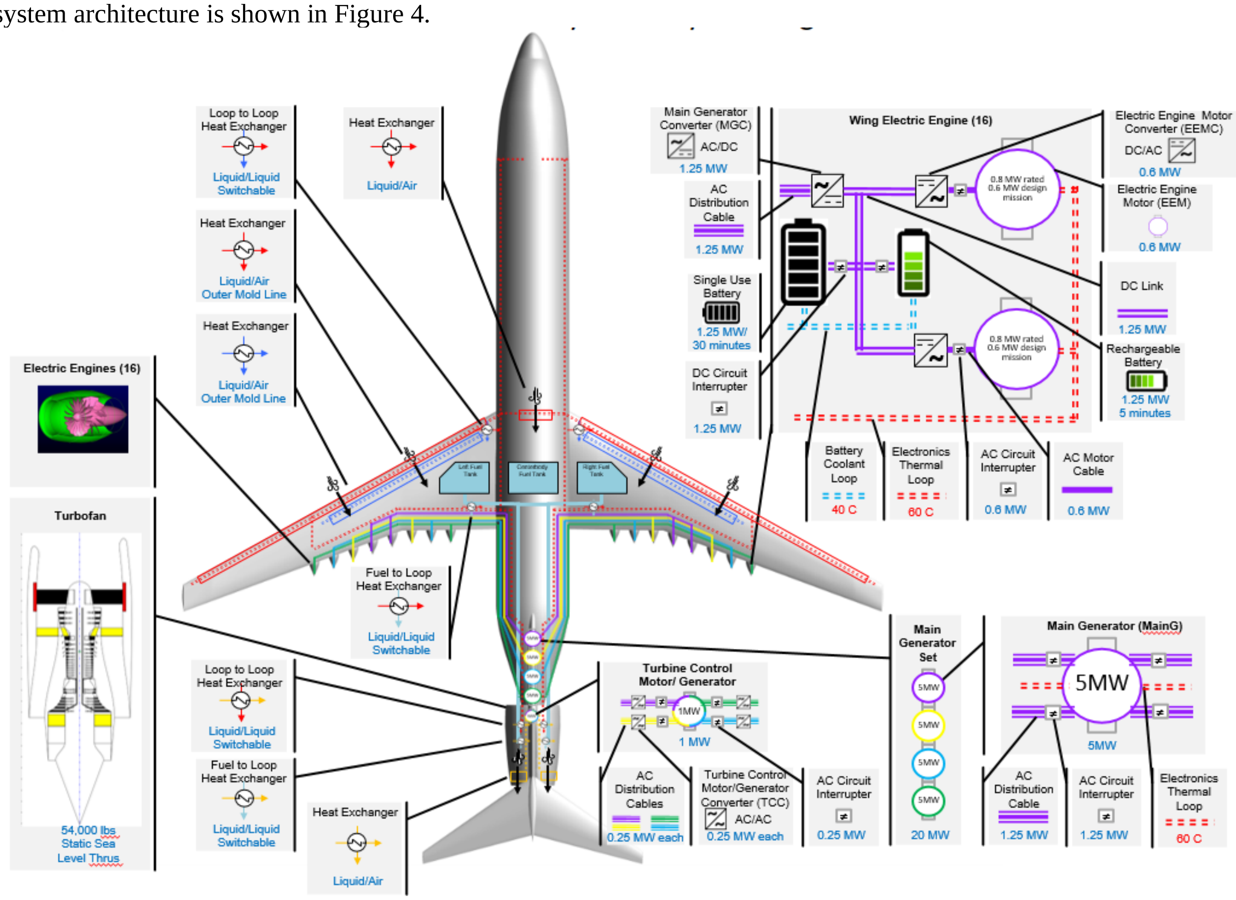

Figure 4: Electrical System Overview

The bottom-right section of Figure 4 shows the generation portions of the electrical system. The main source of electrical power is the Main Generator (MG), driven by the LPS of the turbofan engine. 20MW of electrical power is generated via (4) 5MW machines. In addition to the 20MW generated power on the LPS, a single 1MW generator (the turbine control motor-generator) is driven by the HPS, the output of which is connected to (4) AC/AC converters that enable the outputs of the main and turbine control generators to be electrically connected. The purpose of this generator on the HPS is to achieve the benefits of the TEEM concept discussed above.

The top-right section of Figure 4 shows the battery and wing propulsor portions of the electrical system. There are two sets of batteries that serve two different purposes within the architecture concept. The primary batteries are single-use, non-rechargeable batteries that are to be used in the event of a turbofan engine failure. In the event of such a failure, the primary batteries will provide electric power to the wing propulsors and allow the aircraft to continue flight for approximately thirty minutes. The secondary batteries are rechargeable and will be used during normal flight. These batteries provide both electrical power to the wing propulsors, and the energy storage mechanism to enable the TEEM concept discussed above.

On the wings, an AC/DC-link/AC converter combines the AC power from the generators with the DC power from the rechargeable batteries, and feeds each of the sixteen propulsors, eight on each wing. Each propulsor consists of two counter-rotating electric engine motors (EEM), each driven by an electric engine motor controller (EEMC).

V. **Power System Trade Studies**

A. System Architecture

A trade on the overall electrical system architecture was done, using an approach similar to that used by Armstrong [12]. For this study, a four-bus architecture was initially considered. Other numbers of electrical buses were also traded, and are discussed below. Three configurations of four-bus architectures were traded: direct-distribution, bus-tie, and multifeeder. These configurations are shown in Figures 5-7.

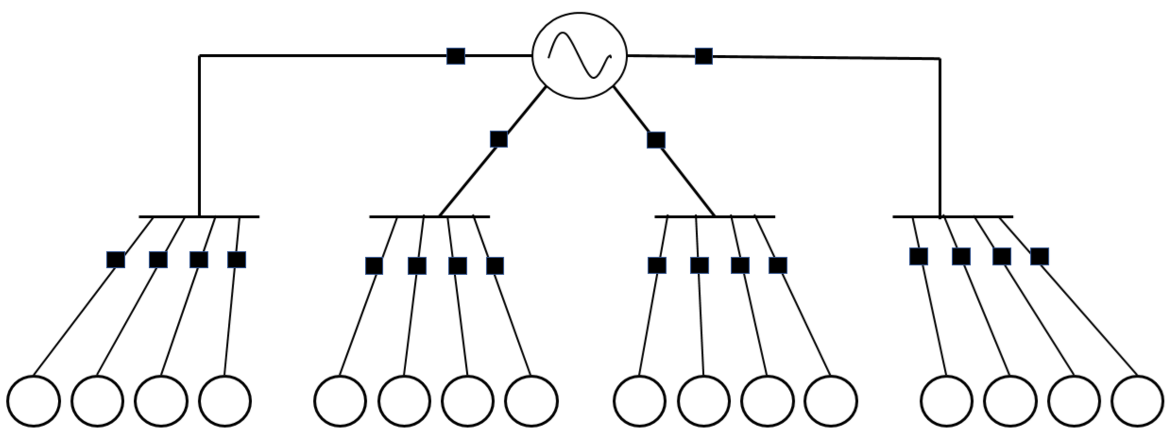

Figure 5: Four Bus Direct Architecture

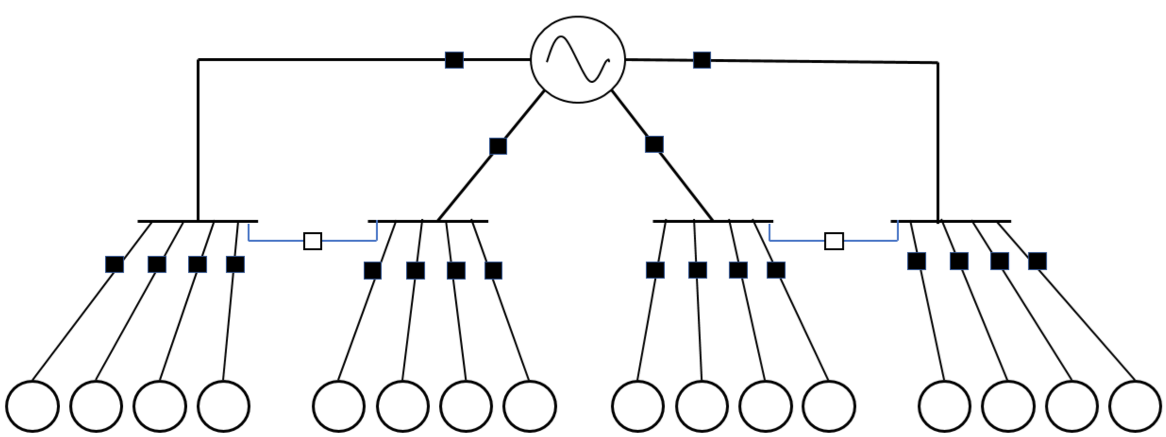

Figure 6: Four Bus Bus-Tie Architecture

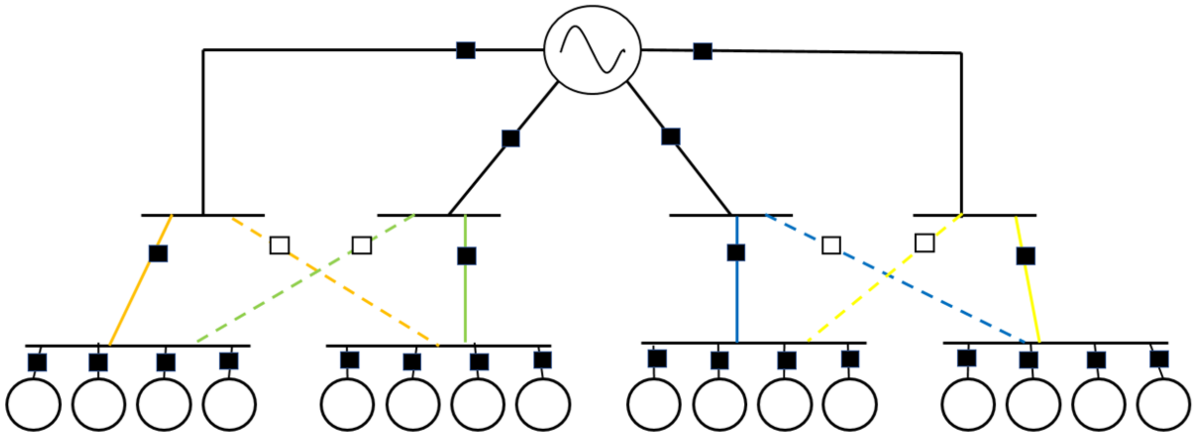

Figure 7: Four Bus Multifeeder Architecture

The direct architecture has some redundancy built in via the four independent buses, however there is no additional redundancy built in. In the event of a bus failure or a generator output failure, four propulsor motors will be lost. The bus tie architecture has additional connections between the buses as shown in Figure 6. In the event of a bus failure, the response from the architecture is the same as the direct architecture: four propulsor motors are lost. However, in the event of a generator output failure, the bus tie can be used to get electrical power from another generator output to the affected motors. In order to keep 100% propulsive power, all conductors need to be oversized in order to carry the additional current. This penalty is discussed further in the following section. If conductors are not oversized, the affected motors can still be powered, but only at 50%, and the motors being shared by the bus tie would also be limited to 50%. The multifeeder architecture adds an additional layer of electrical buses to further expand the redundancy of the system. Each set of motors is fed from two separate buses. In Figure 7, the solid colored lines represent a primary feed to the propulsor motors, and the dotted colored lines represent a secondary feed from a separate bus. In the event of either a generator output failure or a bus failure, the affected motors can be fed from their secondary bus.

The focus points of the trade study were complexity, weight, and redundancy in the event of a bus failure or a generator output failure. A qualitative complexity score was assigned to each of the architectures, based on the increase in conductors and switching events required in a failure condition. The weights are normalized against the direct architecture, and the increase is due to the increase in conductors and connectors required for the other two architectures. The power loss and staggered propulsion percentages assume that conductors are not oversized as described above. The results of the study are shown in Table 1.

Table 1: Electrical Architecture Trade Study Results

4-bus Concept	Complexity	Total Weight (normalized)	Power loss (1 bus or gen failure)	Staggered Propulsion (1 bus failure)	Motors Lost (1 bus failure)	Staggered propulsion (1 gen failure)	Motors Lost (1 gen failure)
Direct	1	1	25%	25%	4	25%	4
Bus Tie	2	1.02	25%	25%	4	12.5%	0
Multifeeder	3	1.44	25%	12.5%	0	12.5%	0

The complexity of the direct architecture is lowest because the motors are fed directly from the generator, and there are no switching events that occur. Complexity increases for the bus tie architecture, and increases further for the multifeeder architecture. The weights of the architectures do not increase drastically with complexity, however as stated above, these results to not include oversizing conductors for failure conditions. This required oversizing is discussed in the following section. Total power loss is the same for all architectures due to the assumption of nonoversized conductors; and a bus or generator output failure results in a total power loss of 25%, even if the affected motors are powered. The staggered propulsion refers to the idea that if the affected motors are operating at a lower propulsive power, then propulsion is not uniform across the wings of the aircraft. These columns are repeated for a bus failure and a generator output failure.

Due to the increase in complexity and little benefit realized by the more complex systems, the direct architecture was chosen for the SUSAN electrical architecture. The problem of a bus failure causing the loss of a large percentage of propulsion is addressed by using more than four electrical buses. That trade study is described in the following section.

B. Number of Electrical Buses

To mitigate the effect of a bus failure on the system, the SUSAN electrical distribution system will use multiple power buses to distribute power from the generators out to the wing propulsors. A trade study of 1, 2, 4, 8, and 16 electrical buses was performed, focusing on system redundancy and weight penalty. A summary of the results of this study are shown in Table 2.

Table 2: Multiple Bus Trade Study Results

Concept	Complexity	Total Weight (normalized)	Power Lost (1 bus failure)	Power Lost (2 bus failure)	Motors Lost (1 bus failure)
1 Bus	1	N/A	100%	N/A	16
2 Bus	1	1	50%	100%	8
4 Bus	1	0.60	25%	50%	4
8 Bus	1	0.53	12.5%	25%	2
16 bus	1	0.51	6.25%	12.5%	1

The normalized weight for each concept is based on parametric component weights plus a penalty factor due to required oversizing of the system to compensate for a failure of an electrical bus. The difference between the concept weights is based on the idea that all components must be oversized to compensate for a failure of one of the electrical buses. For example, in the two-bus configuration, components must be oversized by 100%, because in the event of the failure of one bus, all of the propulsive power must flow through the only remaining bus, so it must be sized to handle 100% power. Since the single bus configuration cannot survive a single bus failure, there is no weight penalty that can be added. Therefore, the 2-bus architecture weight (which is the heaviest due to the oversizing penalty) is normalized to 1, and the weights of the other concepts are shown relative to the 2-bus weight. The 16-bus configuration resulted in the lowest weight, because components must only be oversized by 16/15, or 6.67%. This 16-bus architecture is shown in Figure 8.

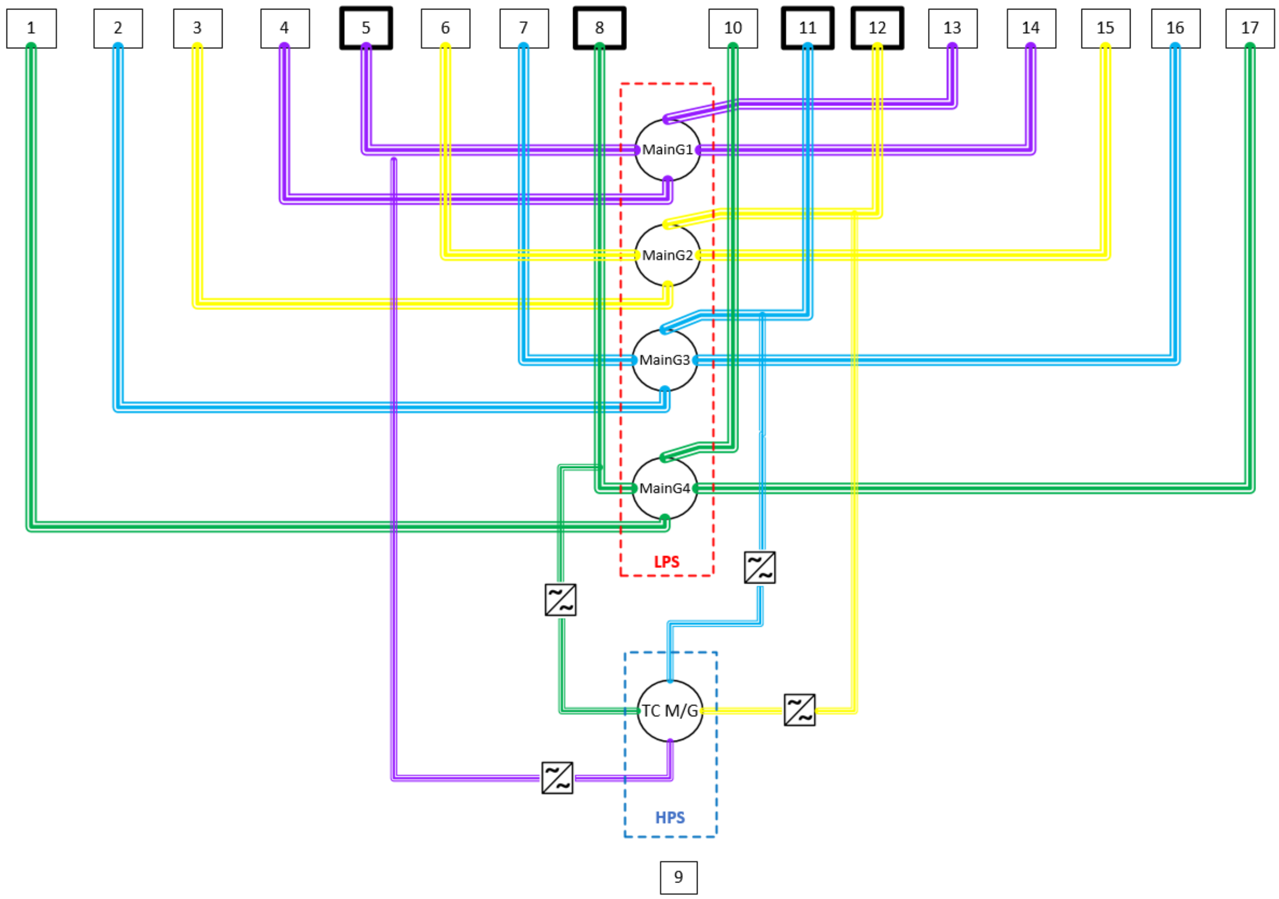

Figure 8: 16-Bus Configuration

This 16-bus configuration is achieved with four individual outputs from each of the (4) 5MW generators discussed above, with each generator output feeding a propulsor. The TC M/G also has four individual outputs, each of which supplements one bus from each of the four main generators. The supplemented buses are chosen so that symmetric propulsion is achieved.

C. Voltage Level

The SUSAN voltage trade is ongoing, with ranges between 1 and 3kV under consideration. Aircraft electrical power system voltages increased from 24V in the 1950s to 540V in the most modern aircraft [13]. Increasing voltages creates challenges related to partial discharge that are exacerbated by the operation at altitude, reducing the breakdown voltage. Benefits of increased voltage are decreased currents for a given power level, which can reduce the weight required for cabling and the resistive losses.

D. Alternating Current vs. Direct Current

Selection between AC and DC distribution is ongoing. Currently the layout mostly uses AC distribution which offers the potential benefits of lower circuit interrupter and cable weights, but may increase the electromagnetic interference (EMI) challenges. DC distribution is still in the trade space. As the system architecture, control, fault management, grounding, and electromagnetic noise management approaches become more refined, the distribution approach will be finalized.

VI. SUSAN Electrical Components

A very high performance power system is required for the SUSAN aircraft in order to allow the overall configuration to close with a benefit. The electrical components that make up the SUSAN electrical system architecture will be required to have very high specific power and efficiency. Table 3 shows a summary of the estimated ranges of required specific power and efficiency for each component that will be evaluated as part of the overall SUSAN trade space exploration.

Table 3: Specific Power and Efficiency Ranges Being Evaluated for SUSAN EPS Components

	Weight				Efficiency			
	Nominal	Min	Max	Unit	Nominal	Min	Max	Unit
Electric Machines								
Main Generator	25	15	50	kW/kg	99%	98%	99.5%	%
Turbine Control Motor/Generator (TCMG)	20	10	30	kW/kg	99%	98%	99.5%	%
Electric Engine Motor (EEM)	20	10	30	kW/kg	98.5%	97%	99.0%	%
Power Conversion								
Main Generator Converter (MGC)AC to DC	30	20	40	kW/kg	99%	97%	99.5%	%
Turbine Control M/G Converter (TCC) AC to AC	15	10	20	kW/kg	98%	94%	99%	%
Electric Engine Motor Converter (EEMC) DC to AC	20	10	40	kW/kg	99%	97%	99.5%	%
Batteries								
Rechargeable Battery	500	200	1000	w-hr/kg	97%	90%	98.0%	%
Single Use Battery	1500	700	3000	w-hr/kg	90%	50%	98.0%	%
Cables								
AC Distribution Cable	2	0.5	10	kg/m/MW	0.040%	0.080%	0.020%	% loss/m
DC Distribution Cable	2	0.5	10	kg/m/MW	0.040%	0.080%	0.020%	% loss/m
Circuit Interrupters								
AC Circuit Interrupters	300	200	600	kW/kg	99.5%	99.7%	99.9%	%
DC Circuit Interrupters	150	100	300	kW/kg	99.5%	99.7%	99.9%	%

Many government and industry efforts are underway worldwide to improve key technologies. An overview of select NASA efforts and industry progress towards performance at the levels needed for the SUSAN aircraft is provided.

Advanced electric machine technology is required for the motors and generators on the SUSAN aircraft. The NASA High Efficiency Megawatt Motor (HEMM) is a point of reference for key performance parameters. The High Efficiency Megawatt Motor (HEMM) is a partially superconducting, synchronous, wound field machine with a superconducting rotor and normal operating temperature stator that can operate as a motor or generator. HEMM is currently between the preliminary design and critical design stage with three key supporting technologies being developed through prototyping efforts [14-16]. Tallerico, Anderson, and Scheidler conducted a sizing study of geared and direct drive version of HEMM that showed performance levels that would be in the range of what is needed for the SUSAN aircraft [17].

The NASA HEATheR converter technology development uses multilevel, interleaving, and other technologies to simultaneously achieve high specific power and high efficiency. Prototype work has been done at the 72kW scale, detailed design of a 250kW version is complete [18], and sizing studies for performance at MW power levels has been conducted. NASA has also developed new magnetic materials for use in electronic filters which can operate at higher temperatures and frequencies than typical inductor core materials [19]. These magnetic materials result in reduced bus and EMI filter mass and losses which can be a significant portion of the overall converter mass and losses. NASA HEATheR converter technology has the potential to reach the performance levels required for SUSAN. Combined analysis of the HEMM and HEATheR converter technologies has been performed, with a goal of understanding key drivers in interfacing the systems in a way which maintains integrated performance [20].

A review of existing circuit breakers and a discussion of potential approaches to create high power, high performance circuit breakers for a 50MW superconducting aircraft power system was conducted under a NASA study by Armstrong [21], and Dyson describes some of the challenges and approaches for circuit breakers for EAP aircraft [22]. Shahsavarian outlines partial discharge testing of some existing IGBTs that might be applicable to circuit interrupters or converters for EAP aircraft [23]. NASA is currently developing MW class, high speed circuit interrupters under industry and university efforts.

NASA has made some exploratory investments to improve cable insulation [24,25]. and consider alternate conductor materials in order to reduce cable weight and losses while improving temperature and voltage limits. As these efforts mature, results will be used to inform the cable metrics.

Significant resources are being applied worldwide to improve batteries. These investments are driven by large existing markets such as mobile computing and automotive applications. The aerospace industry can leverage the advancements; however, some additional requirements are required in order to make the batteries airworthy, safe, and reliable for the aircraft operating environment. Zu and Li provide an excellent overview of battery energy density progress since the 1900s: "The average increase in the rate of the energy density of secondary batteries has been about 3% in the past 60 years" [25]. SUSAN uses both primary (single use) and secondary batteries (rechargeable). Select NASA work includes sizing and safety studies for solid-state lithium-sulfur batteries by Dornbush [27], investigating lithium-sulfur and lithium-selenium for high energy [28,29] and investigating lithium-oxygen for high energy and pack design/scale-up [30-32]

VII. Conclusion

This paper introduced the basic drivers for the power system design, an overview of the EAP system architecture, and a parametric range of required electrical component performance for the SUSAN concept. A brief overview of certain technical efforts that are underway to develop electrical components with the required performance was presented.

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