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System-Level Control Concepts for Electrified Aircraft Propulsion Systems

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System-Level Control Concepts for Electrified Aircraft Propulsion Systems

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Abstract

Electrified aircraft propulsion (EAP) relies on the generation, storage, and transmission of electrical power for aircraft propulsion purposes. It enables system designers to apply advanced propulsion concepts that offer multiple potential benefits including reductions in fuel burn, emissions, and noise. Due to their complex integrated nature, EAP systems present novel propulsion control challenges and opportunities. To introduce EAP control needs, this paper will consider nine EAP concept vehicles. For each vehicle, the propulsion system architecture will be discussed along with the control concept of operations.

1.0 Introduction

Electrified aircraft propulsion (EAP) systems offer flexibility in storing and transmitting electrical power, which enables aircraft designs that apply advanced propulsion concepts such as distributed electric propulsion and boundary layer ingestion fans. These concepts offer benefits such as reduced emissions, fuel burn, and noise. EAP systems can take the form of several potential architectures as shown in Figure 1 (Refs. 1 and 2). These EAP architecture options include:

- All electric: Batteries provide the sole source of propulsive power.
- Hybrid electric: A combination of batteries and combustion engines provide propulsive power. Architecture subclasses include:
  - Parallel hybrid: A battery-powered motor and a turbine engine are both mounted on a shaft that drives a fan, so that either or both can provide propulsive power.
  - Series hybrid: Only the electric motors are mechanically connected to the fans; the gas turbine drives a generator, which produces electrical power to drive the motors and/or charge batteries.
- Turboelectric: Combustion engines provide propulsive power with all (full turboelectric) or some (partial turboelectric) of the engine power output also converted to electricity.
- Series/parallel partial hybrid system: Has one or more fans that can be driven directly by a gas turbine as well as other fans that are driven exclusively by electrical motors. These motors can be powered by a battery or by a turbine-driven generator.

While EAP systems do offer benefits, they are in general more complex, more distributed, and more tightly integrated than conventional aircraft propulsion system designs. Control technology will play a vital role in ensuring the robust and efficient operation of these systems. To introduce the system-level control needs associated with EAP, this paper will discuss the control concept of operations for nine different EAP aircraft concepts that have been proposed under NASA Aeronautics Research Mission Directorate (ARMD) projects. These concepts, which are shown in Figure 2, include the following:

- STARC-ABL partial turboelectric (Ref. 3)
- Boeing SUGAR Volt parallel hybrid (Ref. 4)

- NX-3 blended wing body with distributed turboelectric propulsion (Ref. 5)
- X-57 Maxwell all-electric (Ref. 6)
- PEGASUS parallel hybrid + electric propulsion (Ref. 7)
- ECO-150 distributed turboelectric (Ref. 8)
- Side-by-side hybrid electric helicopter (Refs. 9, 10, and 11)
- Tiltwing aircraft with turboelectric propulsion (Refs. 9 and 11)
- Lift + Cruise Vertical Take-Off and Landing (VTOL) with turboelectric propulsion (Refs. 10 and 11)

The remainder of this document will individually introduce and discuss the architectures and associated system-level controls for the nine concepts. This will be followed by a discussion of control development needs and approaches for EAP as well as a summary.

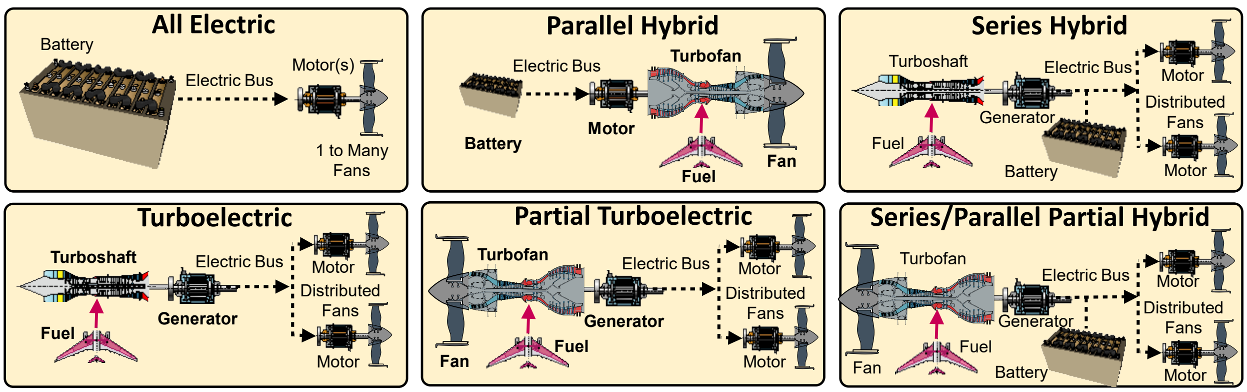

Figure 1.—Electrified aircraft propulsion architectures (from Refs. 1 and 2).

Figure 2.—NASA electrified aircraft concept vehicles (from Refs. 3 to 10).

2.0 STARC-ABL

The NASA Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL) is a partial turboelectric design (Ref. 3). It consists of two wing-mounted geared turbofan engines and a tailfan propulsor driven by electric motors as shown in Figure 2. In addition to producing thrust, the two geared turbofan engines also supply mechanical offtake power delivered to generators to produce electricity delivered to the tailfan. The generator alternating current (AC) power is converted to direct current (DC) power by a rectifier power convertor and transmitted to DC buses. Motor controllers command inverters to deliver the necessary power to the tailfan motors to achieve the desired tailfan speed. A block-diagram of the coupling between STARC-ABL subsystems along with the overall control concept of operations is shown in Figure 3. The numbers provided in the figure illustrate the following control features:

1. Supervisory control receives power lever angle (PLA) requests from the aircraft flight controller.
2. Supervisory control sends PLA requests to the two geared turbofans and the tailfan.
3. Geared turbofan PLA request is converted to a fan speed setpoint command by the turbofan controller and the turbofans operate in closed-loop control where fuel flow is adjusted to achieve the commanded fan speed.
4. Generator converts mechanical power extracted from the turbofan low pressure shaft to AC electrical power. Generator control is designed to hold DC bus voltage constant.
5. Tailfan PLA request is converted to a speed command by tailfan controller, and tailfan motors operate under closed-loop control where motor power is adjusted to achieve the commanded tailfan speed.
6. Motors are connected to tailfan through freewheeling clutches and gearbox to account for potential “one power string inoperative” scenarios.
7. Motor controllers exchange torque signals to ensure torque matching and proper load sharing between motors (similar to a twin-engine helicopter torque matching approach).

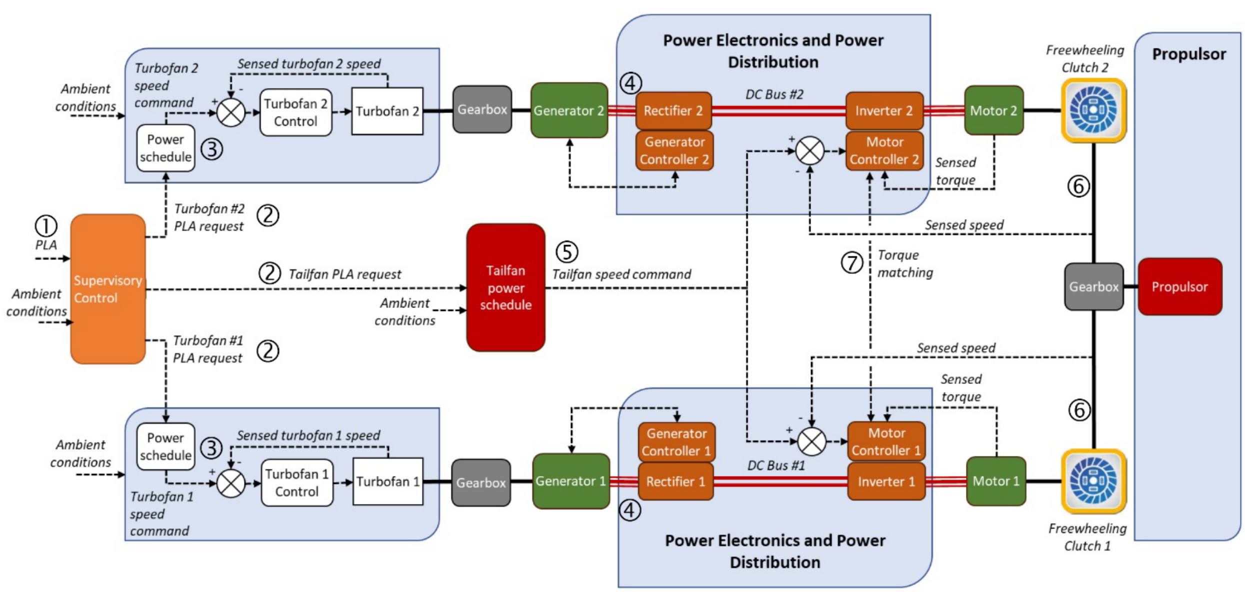

Figure 3.—STARC-ABL Control Concept of Operations.

3.0 SUGAR Volt With Parallel Hybrid Propulsion

The Boeing SUGAR Volt is an advanced truss-braced wing aircraft with a parallel hybrid propulsion system (Ref. 4). It is equipped with two turbofan engines, which are electrically augmented by battery-powered AC motors applying mechanical power to the low pressure spool of each turbofan. A block-diagram of the coupling between SUGAR Volt subsystems along with the overall control concept of operations is shown in Figure 4. The numbers provided in the figure illustrate the following control features:

1. Supervisory control receives PLA request from the aircraft flight controller.
2. Supervisory control sends PLA requests to the two turbofans.
3. Turbofan PLA request is converted to a fan speed command by turbofan controller, and the turbofans operate in closed-loop control with fuel flow adjusted to regulate fan speed.
4. Supervisory control also sends PLA requests to each AC motor controller based on flight condition.
5. Each AC motor operates under closed-loop power control, calculated based on sensed feedback measurements of torque and speed. Motor power output is applied to turbofan low pressure shaft.
6. Each motor controller/inverter draws power from DC bus.
7. Battery system maintains target DC bus voltage level and stability.

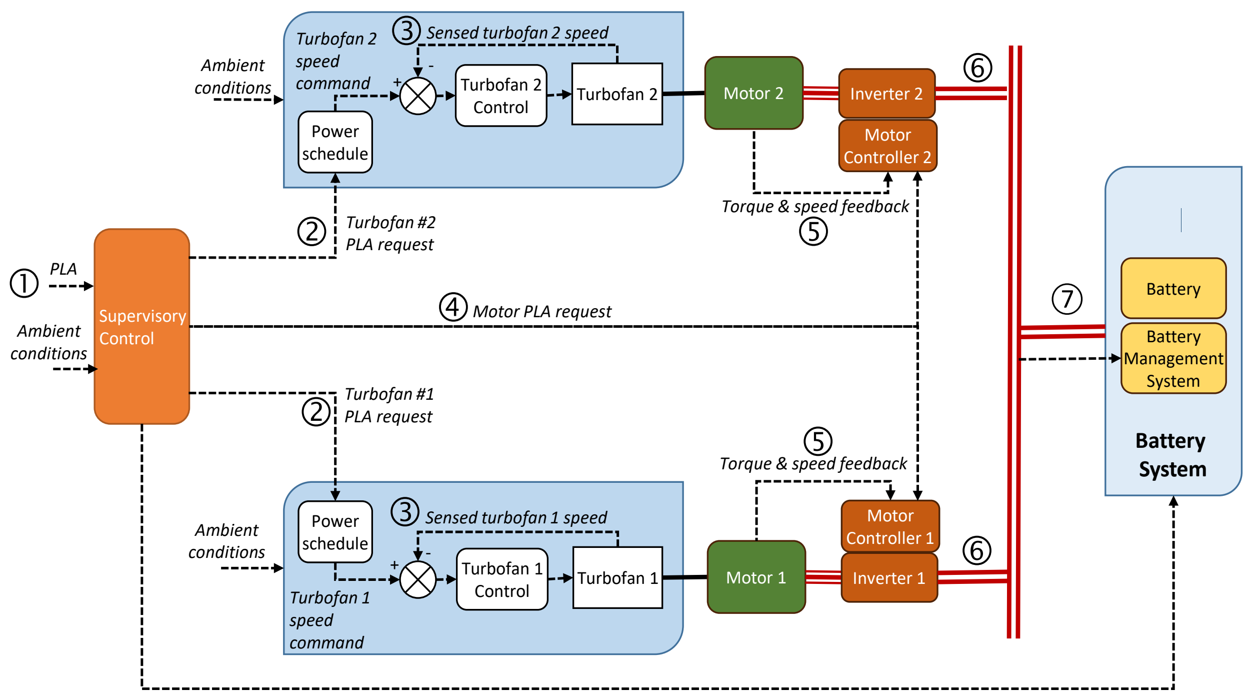

Figure 4.—Sugar Volt Parallel Hybrid Control Concept of Operations.

4.0 N3-X

The “N3-X” is a NASA conceptual hybrid-wing-body (HWB) aircraft with a superconducting Turboelectric Distributed Propulsion (TeDP) system (Ref. 5). The N3-X, shown in the upper portion of Figure 2, has 14 distributed fan propulsors driven by superconducting electric motors with power provided by two turboshaft engines, each driving two generators. The HWB airframe provides a high lift-to-drag ratio design. It allows the distributed electric fans to ingest large amounts of thick upper fuselage boundary layer flow resulting in significant reduction in vehicle drag, which reduces fuel burn. The two turboshafts are located at the aircraft wing tips in undisturbed free stream conditions to maximize their power output.

Figure 5 shows a block-diagram of the N3-X TeDP system. The two turboshaft engines are designed to operate at a constant power turbine shaft speed. Each generator is a variable-frequency AC design, and its controller regulates generator output voltage to a target set point value (Ref. 12). The generator AC power output is converted to DC power by a rectifier power convertor and distributed to the motor driven propulsors over a DC bus. Energy storage devices are attached to each DC bus to aid in maintaining bus stability and to provide contingency power in the event of a failure. Power is drawn from the DC buses, converted to AC, and supplied to the motors driving the propulsors. Each motor/propulsor is individually controlled and operated. This enables the thrust output of the 14 propulsors to be modulated in a coordinated fashion for integrated flight control purposes such as aircraft yaw control. The labeling of the 14 motors/propulsors designates the installation location of each propulsor on the aircraft. The letters “L” and “R” indicate motor/propulsor installation left or right of the aircraft center line, respectively. This propulsor installation arrangement helps to mitigate adverse vehicle yawing in the event of a failure resulting in the loss of bus power (Ref. 13). The power distribution architecture shown in Figure 5 allows the four generators to each supply power to a separate DC bus.

The instantaneous power requirements within the NX-3 TeDP system are dictated by the commanded propulsor speeds. All other subsystems (and their controls) will respond to these propulsor commands (Ref. 12). The overall control concept of operations is summarized as follows corresponding to the numbers shown in Figure 5:

1. Supervisory control receives 14 individual PLA requests from the aircraft flight controller corresponding to the desired thrust output from each propulsor.
2. The PLA commands are converted to propulsor speed commands based on current operating conditions and forwarded to each respective motor controller.
3. The motor controller acts as a speed controller, adjusting the power supplied to the motor to drive the propulsor to the commanded speed.
4. The motor controller/inverter draws power from its associated DC bus.
5. The generator controller/rectifier holds DC bus voltage at a setpoint value. The generator controller adjusts generator load as required to maintain the target bus voltage level.
6. The turboshaft control adjusts fuel flow in order to maintain the target turboshaft power turbine speed.
7. The energy storage device is used to maintain DC bus stability and to provide contingency power in the event of a loss of power generation capability.
8. The supervisory control provides set point commands (rotational speed and voltage) to the turboshaft controller, the generator controller, and the energy storage devices. Other than during fault conditions or startup/shutdown phases of operation, these set point commands are fixed values corresponding to system design conditions.

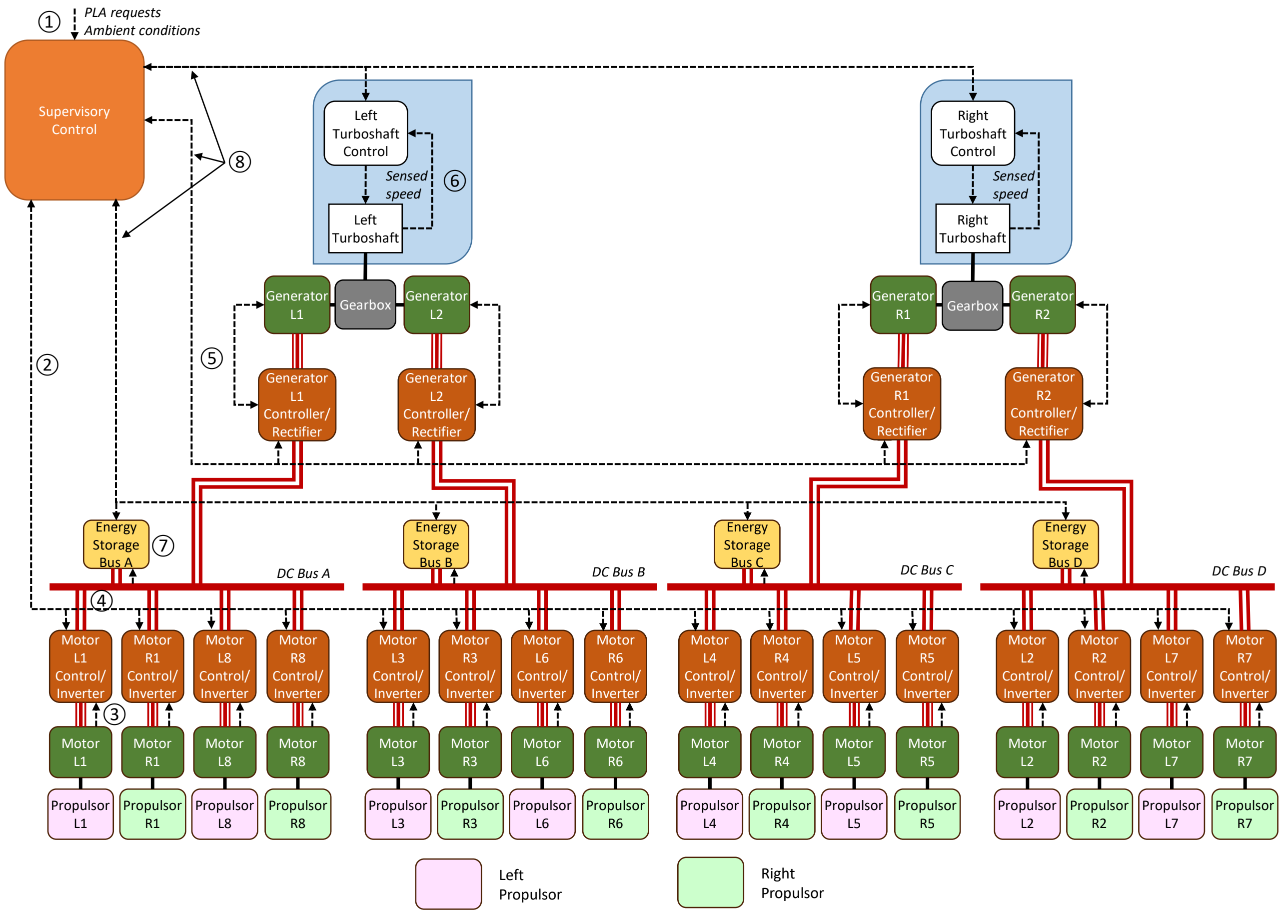

Figure 5.—NX-3 Control Concept of Operations

5.0 X-57 Maxwell

The X-57 Maxwell is an all-electric flight demonstrator aircraft (Ref. 6). This experimental aircraft is designed to demonstrate radically improved aircraft efficiency enabled by a re-designed wing and an electric propulsion system. Its design applies propulsion airframe integration (PAI) techniques taking advantage of small electric propulsors strategically placed on the aircraft wings. The X-57 has two cruise propellers located at the aircraft wingtips for improved propulsive efficiency. Additionally, it has 12 high-lift propellers located at the leading edge of the wing (six on each side) to achieve high lift at low airspeeds. All power to drive the motor driven propulsors is supplied by two battery power supplies (labeled “A” and “B”). A block diagram of the X-57 electric propulsion system is shown in Figure 6. The two wingtip cruise propulsors each have two electric motors, one driven by power supply “A” and the other by power supply “B”. This allows the cruise propulsors to continue to operate in the event that one of the batteries or one of the cruise propulsor motors fail. The 12 high-lift propellers are each driven by a single motor. Power supply “A” provides power for odd numbered lift-motors while power supply “B” provides power for even numbered lift-motors. This helps to minimize thrust asymmetries in the event of a battery failure. The X-57 is equipped with conventional vehicle flight control surfaces. The motor

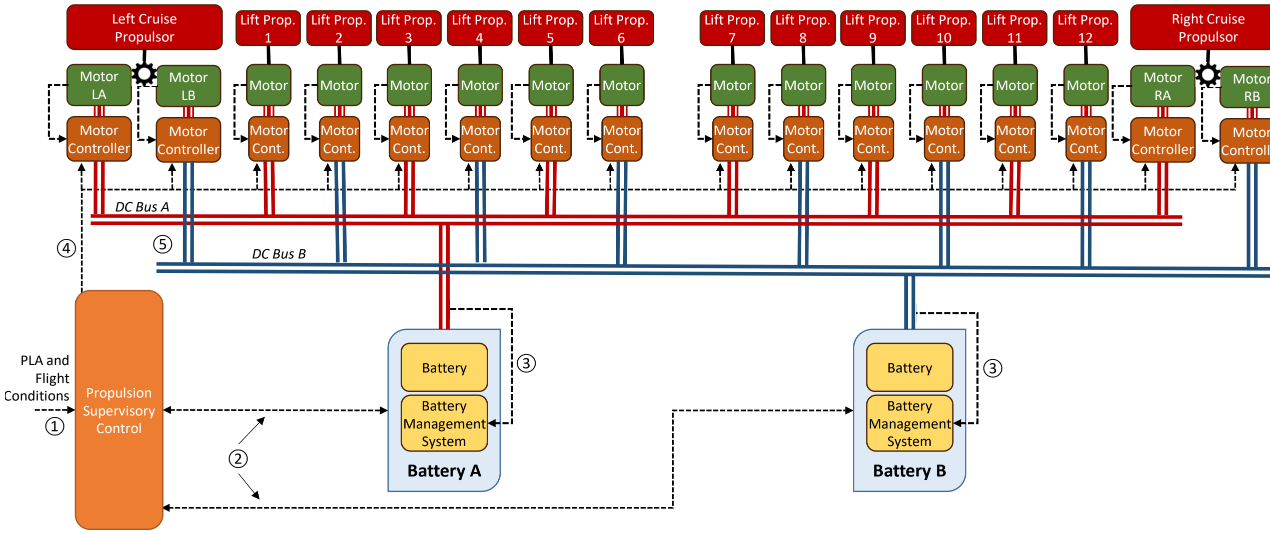

Figure 6.—X-57 Maxwell Control Concept of Operations.

driven propulsors do not provide any intentional differential thrust for yaw moments or other flight control purposes. Therefore, the two cruise motor/propulsors are designed to run at the same thrust output. Similarly, the 12 lift motor/propulsors are design to run at a common speed/thrust output. The overall control concept of operations is summarized as follows corresponding to the numbers shown in Figure 6:

1. The supervisory controller receives a PLA command and flight condition information from the aircraft flight controller. This information is converted into command information sent to each of the motor controllers. During low airspeeds all motors/propulsors will be operating including the cruise and lift propulsors. During the cruise portion of flight, only the cruise motors/propulsors will be operating.
2. Supervisory control sends startup and shutdown commands to each of the battery management systems along with a target DC bus voltage. Each battery management system returns its state-of-charge and health status to the supervisory control.
3. Each battery management system adjusts its battery's power output to maintain a target constant bus voltage on its respective DC power bus.
4. Supervisory control sends operating commands to each of the motor controllers and the motors operate under torque control (Ref. 6).
5. The motor controllers draw the necessary power from the DC buses to drive their respective propulsors to the target command setting.

6.0 PEGASUS

The Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) is a novel parallel hybrid + electric propulsion regional aircraft with strategically located electric and hybrid electric propulsors to obtain aerodynamic benefits (Ref. 7). PEGASUS uses parallel hybrid turboprops at the aircraft's wingtips to decrease downwash effects. Two electric propulsors providing additional thrust for takeoff and climb are located inboard on the wing. These propulsors are capable of folding mid-flight to decrease windmilling effects during cruise. PEGASUS also includes a boundary layer ingestion electric propulsor on the tail of the aircraft. A battery system supplies electrical power to the shafts of the two parallel hybrid turboprops, the two wing-mounted electric propulsors, and the tail propulsor. Given the distributed nature of its propulsion design, the PEGASUS aircraft is well suited for integrated flight and propulsion control studies that NASA is currently considering. A block diagram of the PEGASUS propulsion system is shown in Figure 7. The overall control concept of operations is summarized as follows corresponding to the numbers shown in the figure:

1. Supervisory control receives PLA request from the aircraft flight controller for all five propeller/propulsors on the vehicle.
2. Vehicle flight control system sends pitch commands to the four wing-mounted propellers. (Note: this paper assumes that all propellers are designed to run at a fixed speed and equipped with a variable pitch control mechanism to regulate their thrust output. This is consistent with most aviation turboprop designs. Alternatively, variable speed, fixed pitch propeller designs could be implemented).
3. Supervisory control commands turboprop power turbine to operate a fixed speed.
4. Turboprop controller adjusts fuel flow rate to hold power turbine speed constant.
5. Supervisory control commands turboprop electric motors to supply additional torque to turboprop shaft based on PLA command. Controller/inverter commands motor to deliver requested torque.
6. Supervisory control commands inboard wing propeller motors to hold a fixed speed, and motor controller/inverter controls the system to hold this requested speed.
7. Supervisory control commands tail propulsor motor to operate at a target speed setting based on PLA command, and motor controller/inverter controls the tail propulsor motor to this target speed.
8. Supervisory control commands battery management system to hold a fixed DC bus voltage. Battery management system discharges battery to bus to supply all electrical power requested by the system.

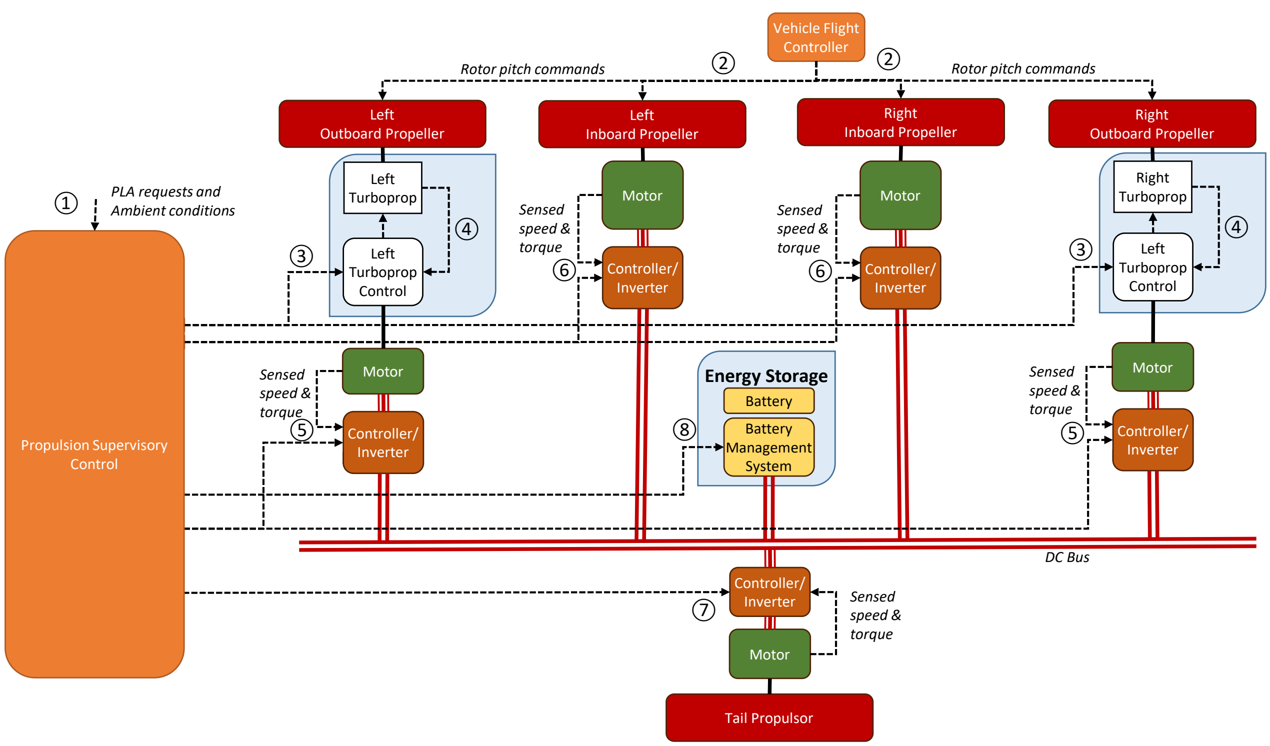

Figure 7.—PEGASUS Parallel Hybrid + Electric Propulsors Control Concept of Operations.

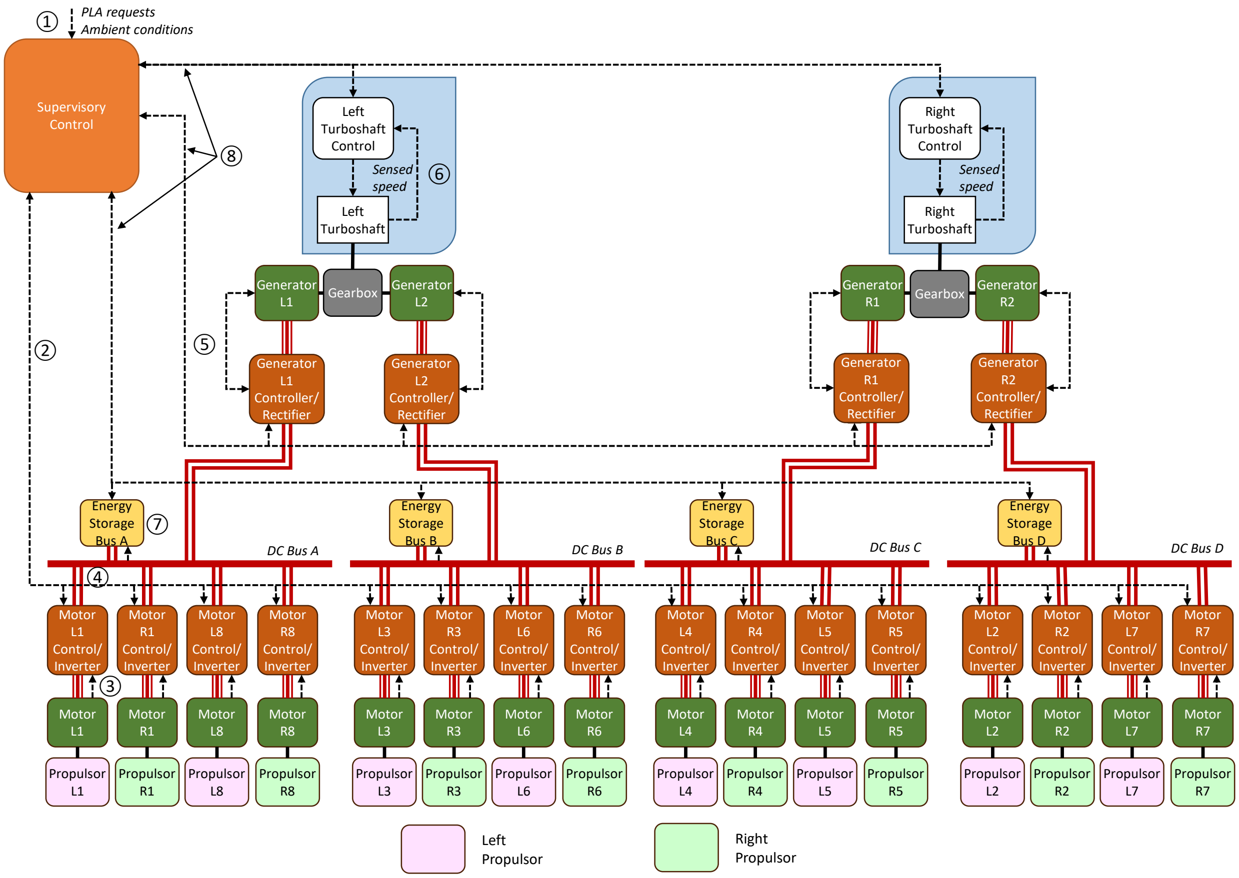

Figure 8.—ECO-150 Control Concept of Operations.

7.0 ECO-150 Aircraft with Turboelectric Propulsion

The Environmentally COnscious 150 passenger (ECO-150) is an EAP aircraft proposed by ESAero (Ref. 8). It is a regional airliner that includes a turboelectric distributed propulsion system embedded within the inboard section of the wing. The ECO-150 applies a "split-wing" design with outboard turboshaft engines and generators that power an array of electrically-driven fans mounted within the wing. As with the PEGASUS aircraft, the distributed propulsion nature of the ECO-150 makes it well-suited for integrated flight and propulsion control studies being considered by NASA. The propulsion system architecture for the ECO-150R was directly influenced by the study performed by Rolls-Royce for the "N3-X" aircraft which showed that symmetric thrust distribution can be maintained in the event of an engine or fan failure with a properly designed electric microgrid (Ref. 13). A block diagram of the ECO-150 propulsion architecture and its concept of operations in shown in Figure 8. The ECO-150R architecture and its control concept of operations is identical to that previously presented for the NX-3 aircraft in Figure 5, but it is also included here for completeness.

1. Supervisory control receives individual PLA requests from the aircraft flight controller corresponding to the desired thrust output from each propulsor.
2. The PLA commands are converted to a propulsor speed command based on current operating conditions and forwarded to each respective motor controller.

3. The motor controller acts as a speed controller, adjusting the power supplied to the motor to drive the propulsor to the commanded speed.
4. The motor controller/inverter draws power from its associated DC bus.
5. The generator controller/rectifier holds DC bus voltage at a setpoint value. The generator controller adjusts generator load as required to maintain this bus voltage level.
6. The turboshaft control adjusts fuel flow in order to maintain the target turboshaft power turbine speed.
7. The energy storage device is used to maintain DC bus stability and to provide contingency power in the event of a loss of power generation capability.
8. The supervisory control provides set point commands (rotational speed and voltage) to the turboshaft controller, the generator controller, and the energy storage devices. Other than during fault conditions or startup/shutdown phases of operation, these set point commands are fixed values corresponding to system design conditions.

8.0 Side-by-Side Helicopter With Hybrid Electric Propulsion

The side-by-side helicopter with hybrid electric propulsion is a concept aircraft proposed under the NASA Revolutionary Vertical Lift Technology (RVLT) Project (Refs. 9, 10, and 11). This vehicle, shown in bottom left image of Figure 2, has two side-by-side rotors. The rotors operate at a fixed rotational speed during flight and their blade pitch angle can be modulated in a collective or cyclic fashion for flight control purposes. The vehicle’s propulsion system includes two turboshaft engines, a motor/generator, and a battery. The turboshafts and the motor/generator are attached through gearboxes to a common interconnected shaft used to drive both rotors. This provides the capability to drive both rotors in the event of one-engine-inoperative or all-engines-inoperative scenarios (Ref. 10). The motor draws battery power and supplies mechanical power to the interconnected shaft during hover and low speed phases of flight. During cruise, the motor switches to generator functionality and is used to charge the battery by extracting mechanical power from the shaft. A block diagram of the side-by-side helicopter hybrid electric propulsion system is shown in Figure 9. The overall control concept of operations is summarized as follows corresponding to the numbers shown in the figure:

1. Vehicle flight controller sends blade pitch commands to both rotors for vehicle flight control purposes.
2. Supervisory control commands turboshaft power turbine to operate at a fixed speed. Each turboshaft controller returns its sensed torque output to supervisory control, which enables the supervisory control to balance the torque load supported by each turboshaft engine.
3. Turboshaft controller adjusts fuel flow rate to hold power turbine speed constant.
4. Supervisory control commands motor/generator to either supply or extract power to shaft.
5. Supervisory control commands battery management system to cause battery to either supply or absorb power to/from the motor/generator. Battery management system returns battery state-of-charge to supervisory control.

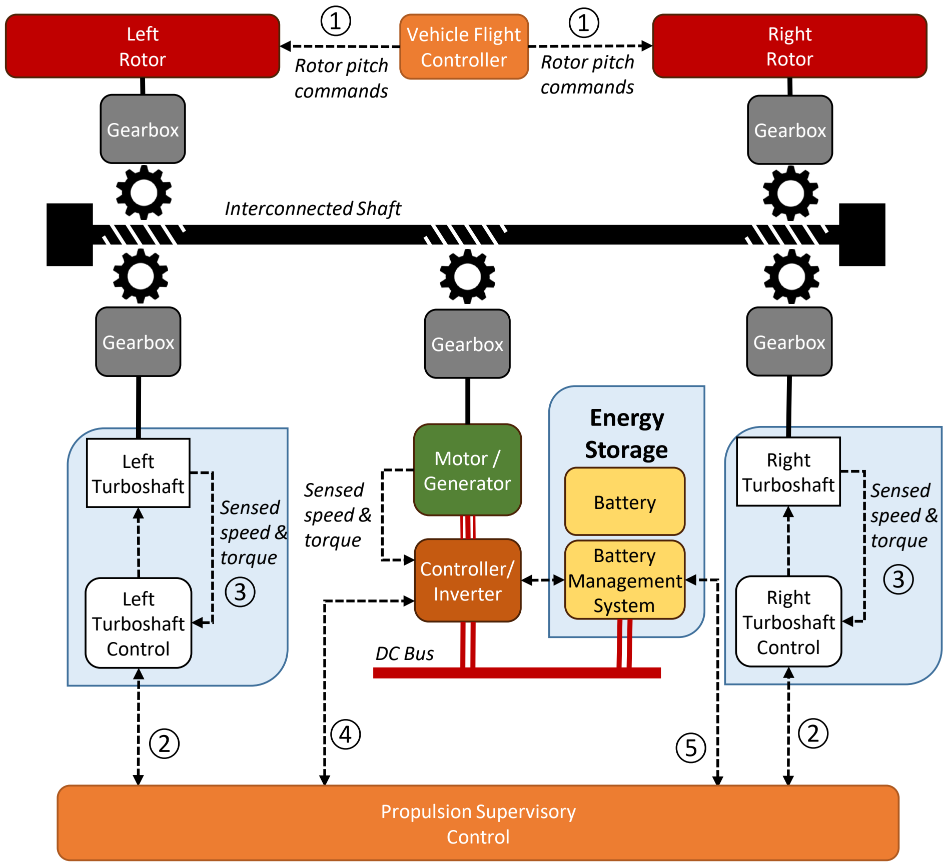

Figure 9.—Side-by-Side Helicopter Control Concept of Operations.

9.0 Tiltwing Aircraft With Turboelectric Propulsion

The tiltwing aircraft with turboelectric propulsion is also a concept aircraft proposed under the NASA Revolutionary Vertical Lift Technology (RVLT) Project (Refs. 9 and 11). This vehicle, shown in bottom center image of Figure 2, has four propellers installed on a tilting wing. The vehicle is capable of vertical takeoff, vertical landing, and hover when in “helicopter mode” with the wing tilted upwards, and forward flight when in “airplane mode” with the wing tilted forwards. The aircraft uses single-axis cyclic control on the propellers for flight control during helicopter mode and pitch and yaw trim during aircraft mode. During conversion between the two flight modes, the aircraft is trimmed at fixed aircraft pitch angles using rotor collective pitch and wing flap.

The vehicle’s propulsion system includes a single turboshaft engine, an AC generator, four electric motors (one for each propeller), and a battery. The turboshaft drives the generator, and the generator’s AC power output travels through a rectifier to supply power to a DC bus. Motor controllers command inverters to deliver the necessary power to the motors, which supply torque to four gearboxes driving the propellers. The gearboxes are coupled via an interconnected shaft for one motor inoperative scenarios and to ensure speed synchronization of the four propellers. The battery, which is connected to the DC bus, is sized for a 2-minute hover in the event of a turboshaft or generator failure. A block diagram of the

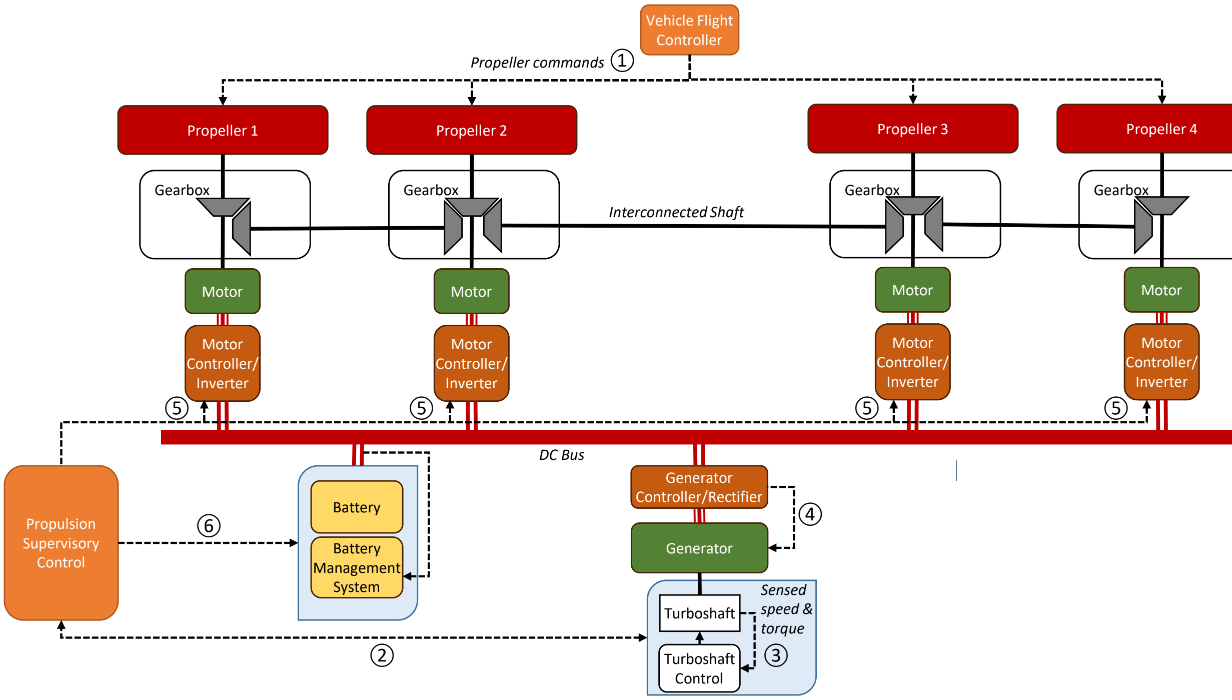

Figure 10.—Tiltwing Aircraft Control Concept of Operations.

tiltwing turboelectric propulsion system is shown in Figure 10. The overall control concept of operations is summarized as follows corresponding to the numbers shown in the figure:

1. Vehicle flight controller sends cyclic commands to all four propellers for vehicle flight control purposes.
2. Supervisory control commands turboshaft power turbine to operate a fixed speed.
3. Turboshaft controller adjusts fuel flow rate to hold target power turbine speed.
4. Generator converts mechanical power extracted from turboshaft to AC electrical power, which the rectifier converts to DC power supplied to bus. Generator controller holds DC bus voltage constant.
5. Supervisory control commands all four motors to operate at a fixed speed. Motor controller returns speed and torque information to supervisory control.
6. In the event of a turboshaft or generator failure, supervisory control commands battery to maintain DC bus at target voltage level.

10.0 Lift + Cruise Aircraft With Turboelectric Propulsion

The Lift + Cruise aircraft with turboelectric propulsion, shown in the bottom right of Figure 2, is also a concept aircraft proposed under the NASA Revolutionary Vertical Lift Technology (RVLT) Project (Refs. 10 and 11). Eight two-bladed “lift rotors” are installed across the vehicle’s wingspan enabling VTOL operation during takeoff and landing phases of flight. A single “pusher propeller” is installed on the vehicle’s tail, providing forward propulsive force during cruise. The eight rotors for lift are distinct from the tail propeller used for forward-flight propulsion, and the lift rotors are not used during cruising flight (they are stopped and aligned with flow during cruise). All rotors and the propeller are variable speed, fixed pitch designs. Central to the vehicle’s propulsion system is a high voltage battery network and DC bus. Motor controllers/inverters draw power from the DC Bus to operate each of the AC motors. There are nine AC motors in total, one for each of the propulsors. Also included is a turboshaft engine,

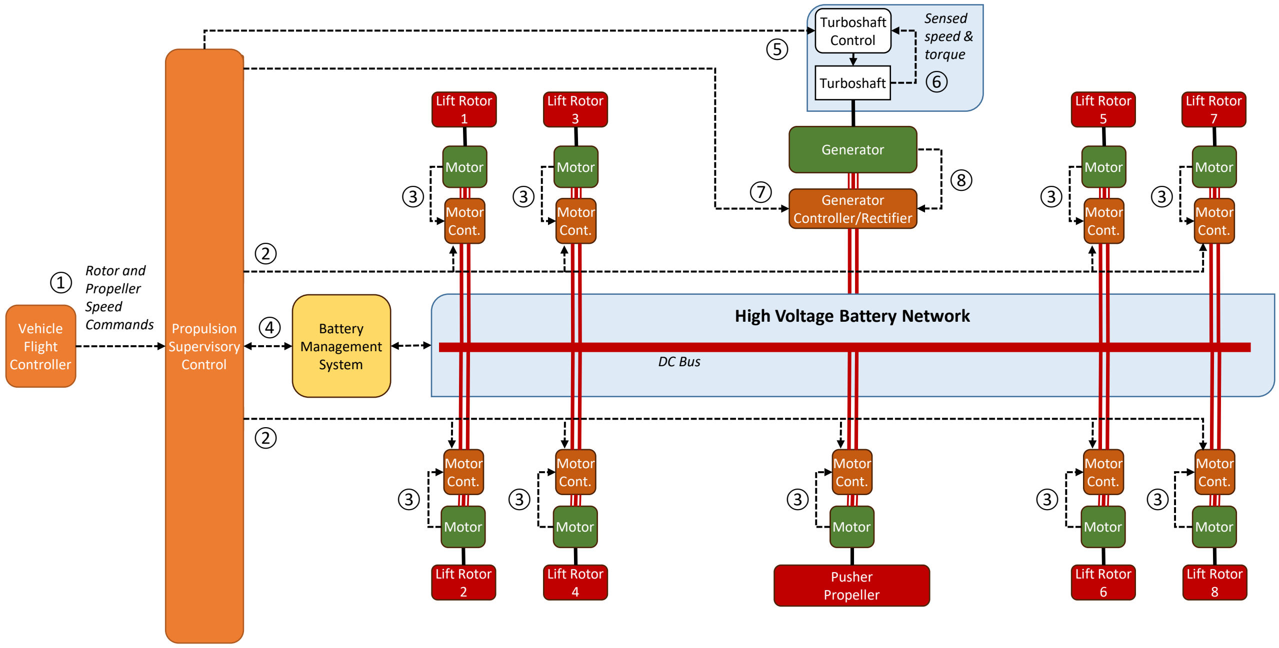

Figure 11.—Lift + Cruise Aircraft Control Concept of Operations.

which drives an AC generator. The generator's power output travels through a rectifier to supply DC power to the high voltage battery network. This architecture enables the flight control system to independently control the speed of each propulsor and it is assumed that a single propulsor failure can be safely mitigated. A block diagram of the Lift + Cruise propulsion system is shown in Figure 11. The overall control concept of operations is summarized as follows corresponding to the numbers shown in the figure:

1. The vehicle flight controller sends rotor and propeller speed commands to the propulsion supervisory control.
2. The propulsion supervisory control sends motor speed commands to each of the electric motor controllers.
3. Rotor and propeller motors operate under closed-loop speed control.
4. Propulsion supervisory control sends commands to battery management system to control the operation of the high voltage battery network. This includes holding the DC bus at a constant target voltage.
5. Supervisory control commands turboshaft power turbine to operate a fixed speed.
6. Turboshaft controller adjusts fuel flow rate to hold target power turbine speed.
7. Supervisory control commands generator to deliver a requested amount of power to the high voltage battery network.
8. Generator converts mechanical power extracted from turboshaft to AC electrical power, which the rectifier converts to DC power supplied to bus.

11.0 General Considerations and Research Areas for EAP Controls

The EAP architectures presented in this paper are large-scale systems that consist of several interconnected local subsystems. They contain a high dimensionality of state variables and input/output states. Given these characteristics, there are several system-level control methods that can be applied to EAP systems, each with individual pros and cons. This includes (Refs. 14 and 15):

- Centralized Control: All subsystems are combined into one large model, and control logic is developed following traditional multivariable control design methods.
- Decentralized Control: The system is decomposed into a manageable number of subsystems, and control logic for each subsystem is developed following traditional control design methods.
- Hierarchical Control: Includes a supervisory controller tasked with coordinating the operation of multiple underlying subsystem controllers. The supervisory controller acts in an outer-loop control fashion supplying command information to, and receiving feedback information from, the individual subsystem controllers.
- Multi-Agent Control: Based on artificial intelligence research. The control development problem is approached as a networked system of cooperative intelligent agents capable of sensing and directing actions towards the environment seeking to achieve specified goals.
- Federated Control: Each subsystem has its own local control, but also has partial observation of the states of other subsystems. The local control is conducted to satisfy performance requirements at the both the local-level and the overall system-level.

In general, the control concept of operations for the EAP architectures discussed above have all been presented as “decentralized” control approaches in the sense that each underlying subsystem controller (e.g., gas turbine, generator, motor/fan, battery) has its own dedicated local controller that operates independently of the other subsystem controllers. Future research is recommended to evaluate and compare of the performance of different EAP control strategies such as decentralized, centralized, and federated control strategies. Key evaluation factors will be stability, robustness, and design complexity of these various candidate control design methods. Related design considerations will include whether energy storage devices (e.g., batteries, capacitors) are required on electrical buses to dampen the effects of power load variations or whether there is sufficient inertia within the rotating gas turbine engines to accommodate expected power load variations without compromising engine operability. Other EAP design considerations are system-level thermal management requirements and the role of control in addressing those requirements. Electrical components are expected to present significant thermal management challenges and optimized control of subsystem operation and interaction throughout the mission profile is expected to play a key role in helping to address these challenges.

In additional to offering a multitude of system-level control design opportunities, EAP also offers designers the capability to revolutionize the design and control of gas turbine engines. Given their integrated nature and inclusion of electrical energy storage, EAP architectures allow designers to apply advanced control concepts that electrically adjust the torque applied to turbomachinery shafts. NASA is currently pursuing research in this area, applying a control concept known as Turbine Electrified Energy Management (TEEM) (Refs. 16 and 17). TEEM incorporates motor/generator electric machines and energy storage devices in addition to conventional fuel control actuators. This “electrification” of the gas turbine enables mechanical power to be added, extracted, or transferred between the shafts of the engine. This is especially beneficial during engine transients where it can aid in promoting engine stall margin operability or reducing peak operating temperatures.

12.0 Summary

Due to their increased complexity and integrated designs, electrified aircraft propulsion (EAP) systems present additional integration challenges and opportunities not found on conventional aircraft propulsion designs. In order to maximize their efficiency and ensure necessary robustness, a system-level approach towards EAP control design and analysis will be necessary. To introduce the complexity and challenges of EAP control design, this document provided a high-level review of the control concept of operations for several EAP systems spanning a variety of architecture options. Such information can be used for future EAP system modeling, control design, and evaluation efforts.

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