

Propulsion Electric Grid Simulator (PEGS) for Future Turboelectric Distributed Propulsion Aircraft

Benjamin B. Choi¹, Carlos Morrison², Timothy Dever³, and Gerald V. Brown⁴

National Aeronautics and Space Administration, Glenn Research Center, Cleveland, Ohio, 44135

NASA Glenn Research Center, in collaboration with the aerospace industry and academia, has begun the development of technology for a future hybrid-wing body electric airplane with a turboelectric distributed propulsion (TeDP) system. It is essential to design a subscale system to emulate the TeDP power grid, which would enable rapid analysis and demonstration of the proof-of-concept of the TeDP electrical system. This paper describes how small electrical machines with their controllers can emulate all the components in a TeDP power train. The whole system model in Matlab/Simulink was first developed and tested in simulation, and the simulation results showed that system dynamic characteristics could be implemented by using the closed-loop control of the electric motor drive systems. Then we designed a subscale experimental system to emulate the entire power system from the turbine engine to the propulsive fans. Firstly, we built a system to emulate a gas turbine engine driving a generator, consisting of two permanent magnet (PM) motors with brushless motor drives, coupled by a shaft. We programmed the first motor and its drive to mimic the speed-torque characteristic of the gas turbine engine, while the second motor and drive act as a generator and produce a torque load on the first motor. Secondly, we built another system of two PM motors and drives to emulate a motor driving a propulsive fan. We programmed the first motor and drive to emulate a wound-rotor synchronous motor. The propulsive fan was emulated by implementing fan maps and flight conditions into the fourth motor and drive, which produce a torque load on the driving motor. The stator of each PM motor is designed to travel axially to change the coupling between rotor and stator. This feature allows the PM motor to more closely emulate a wound-rotor synchronous machine. These techniques can convert the plain motor system into a unique TeDP power grid emulator that enables real-time simulation performance using hardware-in-the-loop (HIL).

I. Introduction

Turboelectric transmission uses electric generators to convert mechanical energy from a turbo shaft engine into electrical energy, and electric motors to convert it back into mechanical energy to power the drive shafts of propulsion fans. The world's first turboelectric drive was introduced in the American capital ship design of the USS New Mexico¹, launched in 1917. After initial construction, the extra weight of the turboelectric plants made their use prohibitive. But the concept has been revived for future warship design as a way to provide fuel-efficient, survivable, and reconfigurable electrical power for propulsion systems. Thus, its application has been extended to ships² (steam and more recently gas turbines) and some rail locomotives² (gas turbines, e.g. with the first TGV (*Train à Grande Vitesse*)). An advantage of the turboelectric drive is that it allows the adaptation of high-speed turbo shaft engines to the slowly-rotating propellers or wheels without the need of a heavy and complex gearbox. It also has the advantage of being able to provide electricity to the ship or train's electrical systems, such as lighting, computers, radar, and communication equipment.

¹ Aerospace Engineer, LMR, Materials and Structures Division, MS 49/8.

² Aerospace Engineer, LMR, Materials and Structures Division, MS 49/8.

³ Aerospace Engineer, LED, Power Division, MS 49/8.

⁴ Senior Research Engineer, LMR, Materials and Structures Division, MS 49/8.

Recently, the NASA Glenn Research Center (GRC), in support of the Subsonic Fixed Wing (SFW) project, has begun the evaluation of new technologies in order to make large reductions in aircraft energy use, emissions and noise in the N+3 (2030) to N+4 (2040) time frame^{3, 4}. One concept is a future hybrid-wing-body electric airplane, employing a turboelectric distributed propulsion (TeDP) system⁵ (see Figure 1 (Ref. 5)). This aircraft is powered by two turbo shaft engines driving two superconducting generators, which provide electricity to run 15 electric fans mounted on top of the fuselage. One TeDP system study on this aircraft⁵ estimated that cryogenic and superconducting turboelectric propulsion systems can be lightweight and highly efficient, resulting in at least 10% overall net fuel burn savings before iterating the aircraft sizing. Very recently, Glenn's researchers have started looking at the development of room-temperature high-power density motors⁶. In parallel to and in cooperation with the analytical system modeling and analyses for both cryogenic and room temperature applications, it is essential to design a subscale system to emulate the TeDP power grid to facilitate in-depth understanding of the system principles and to validate system model analyses and performance predictions. Hence, this paper presents research in the development of a Propulsion Electric Grid Simulator (PEGS) pursuant to the SFW's goal of "greenly" powering future turboelectric distributed propulsion aircraft. This simulator, composed of relatively small and inexpensive components, would enable rapid analysis and demonstration of the proof-of-concept of the TeDP electrical system and allow experimental characterization of components.

A literature survey was done first to investigate similar research on an electrical machine based simulator for a power grid. There have been some studies⁷⁻⁹ on wind turbine simulators based on induction motors and on permanent magnet synchronous machine (PMSM). A voltage source converter and vector control were used to simulate the torque characteristics of the wind turbine. Refs. 10 and 11 have also shown that a DC motor using direct torque control can serve as the prime mover of a wind turbine simulator because it is easy to control and its dynamic characteristics are excellent. Also, in order to provide an economic and flexible testing platform for the development of generators, several gas turbine engine emulators using vector controlled AC synchronous motors were developed in Ref. 12. The emulator replicated the performance of the engine responding to a reasonable subset of generator operating conditions, such as supplying a steady load, transient loading and unloading, and short- or open-circuit faults. In short, it has been shown that the electrical motor drive system enables the implementation of the power-speed characteristics of wind turbines and the emulation of the speed-torque characteristics of the gas turbine engines. However, most studies suggested the need for more accurate subsystem models and the details of the emulators were not fully described. Furthermore, an emulation of the propulsive fan maps using a closed-loop control of the electric motor drive system has not been published yet.

Thus, this paper presents how small electrical machines can emulate all the components of a TeDP power train using the Propulsion Electric Grid Simulator (PEGS). As shown in Figure 2, a line of the subscale power train consists of a set of four identical motors and associated motor drive/control systems. This set of four motors and drives emulates the power distributed from the turbine to the propulsive fan. The first motor and its drive emulate the speed-torque characteristic of the gas turbine engine, while the second motor and drive act as a generator for the torque load. The third motor and drive emulate the wound-rotor synchronous motor that drives the propulsive fan, which is emulated by the fourth motor and drive. Finally, the fourth motor and drive provides the torque load that the fan would produce, which can be derived from the flight conditions and implementation of fan maps. The system has been expanded to two sets of engines/generators and three sets of motors/propulsors to simulate the TeDP system.

The ironless composite stator of the PM motor was modified to provide an extra degree of freedom so that the stator and rotor can be off. This axial motion of the stator can vary the magnetic field so that it allows the PM motor to more closely emulate a wound-rotor synchronous machine. The whole system model for all the components in a TeDP power train in Matlab/Simulink will be introduced. Also, the control algorithm for the emulator will be developed and tested through a simulation model.

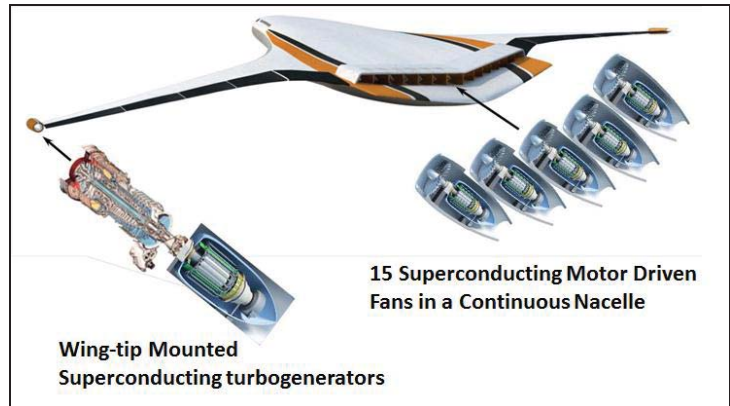


Figure 1. N3-X Hybrid Wing Body (HWB) Aircraft with a Turboelectric Distributed Propulsion (TeDP) System (Ref. 5).

II. Gas Turbine System Model and Motor Based Emulator

The goal of this section is to develop a method by which an electric motor drive system can be controlled so as to emulate the steady-state and dynamic characteristics of a gas turbine engine as the first power train component. The control algorithm for the emulator will be developed and tested through a simulation model prior to implementation in the test rig.

A. Modeling of Gas Turbine Engine and Its Control System

The analytical modeling work aims to develop a control algorithm that enables an electric motor drive system to emulate the speed-torque behavior of a gas turbine engine as it drives an electric generator supplying power to electrical loads. Figure 2 shows the concept of the proposed engine emulation system. In principle, the performance of the engine is emulated by setting the speed reference of the motor drive according to the performance predicted by a real-time model of the gas turbine engine. When the generator is driven by the engine, its speed can be affected by variations in the speed reference of the free turbine governor and the generator torque when changes of electrical load occur. Therefore, the motor drive system includes closed-loop speed control in order to minimize the error between the reference signal for the motor controller from the engine observer and the actual motor speed.

For the first step, a gas turbine engine model must be developed and replaced with the turbine engine observer. A literature review reveals that in recent years, considerable research activities have been carried out in the field of modelling and simulating gas turbines. Many researchers¹³⁻¹⁶ employed a simple methodology to estimate the parameters of a Rowen's model¹⁷ for heavy-duty single-shaft gas turbines. They applied simple physical laws and thermodynamic assumptions in order to derive the gas turbine parameters using the performance and operational data. A variety of simulated tests were performed in a Simulink/Matlab environment, and the results were compared with the manufacturers' test data, and verified against the results of scientific articles in the literature. Furthermore, it is noticeable that the applied methodology can be applied for any size of gas turbines.

Figure 3 shows the transfer function block diagram based on Rowen's model for a heavy-duty gas turbine for dynamic simulation, including fuel and control systems. The load-frequency control is the main control loop during normal operating conditions. The temperature control takes action to reduce the output power of the gas turbine if the temperature of the exhaust gases exceeds the limit value. The output of the two control loops are the input to a minimum value gate so that the loop which takes control is the one with the lower output of the two. In the simulation, a 48 MW turbine base was used, and the associated parameter values in Ref. 17 were used. To check the

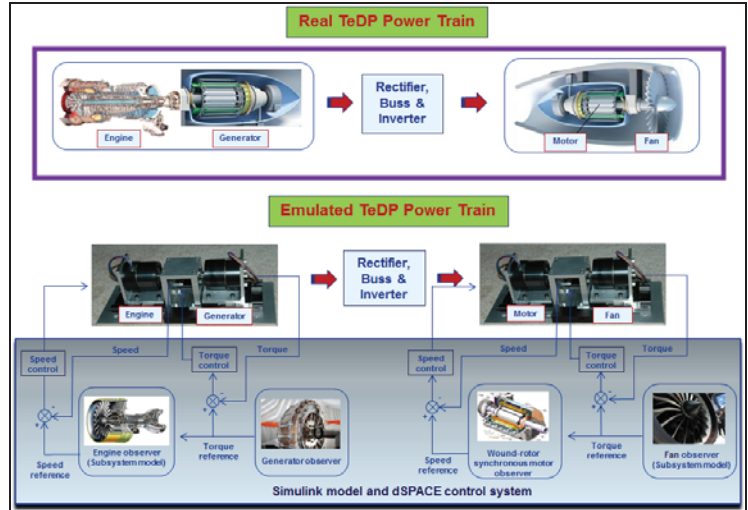


Figure 2. Single line of electric grid with feedback architecture of speed control and torque control.

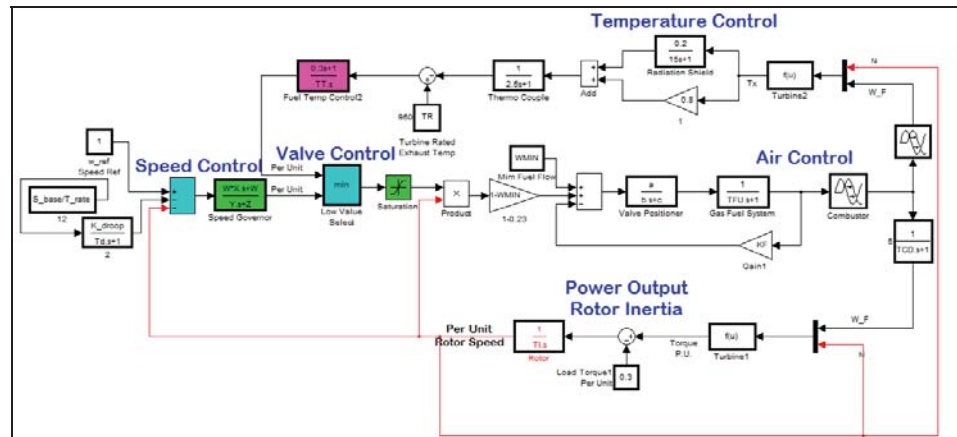


Figure 3. Gas turbine model in Matlab/Simulink

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performance of the two control loops, time domain simulations of several disturbances have been conducted. For varying given torque loads, a speed controller modulates the fuel input so as to maintain the rotational speed constant.

Next, it is described how to achieve the speed-torque characteristic of the gas turbine model at different speeds. For the fixed rotational speed, the speed is kept constant as the load is increased. When the torque reaches the maximum value, the speed begins to decrease as the fuel supply reaches its limit just after the engine has reached its maximum power output. Figure 4 shows the simulation results of using three different speeds, and all three curves present a similar tendency. This analytical model will be called a turbine engine observer in the following discussion.

B. Simulink Modeling of Turbine Engine-Generator Coupled by Shaft

The goal of this section is to describe an analytical model for a two-motor drive system coupled by a mechanical shaft, which simulates a coupled turbine engine-generator. The load torque from the electrical loading of the generator goes to the turbine engine observer, and it generates the speed reference that goes to the motor speed controller. Hence, this model enables an emulation of the speed-torque characteristic in the closed-loop control.

Figure 5 shows a complete two-motor drive system that consists of an AC motor drive model from the simulator library and a DC motor drive model from the library, coupled by a mechanical shaft model. The AC motor drive model is a three-phase synchronous motor-based drive system that produces sinusoidal output, while the DC motor drive model is a three-phase motor drive system that produces trapezoidal output. For step changes in commanded torque, the trapezoidal output provided a simulation with less numerical noise. This coupled model can emulate the speed regulated turbine engine and the torque regulated generator. Note that the motor type represented can be easily changed by changing the commutation method. The signs of the AC electric torque and speed should be the same for the motor that emulates the turbine engine when it is driving. The torque and speed should be of opposite signs for the motor that emulates the generator. The tracking performance of the developed speed controller and torque controller is analyzed following step changes in the electrical loading and unloading of the generator.

Figure 6 shows the simulation results of the AC motor drive startup at reference load followed by the application of speed ramp and

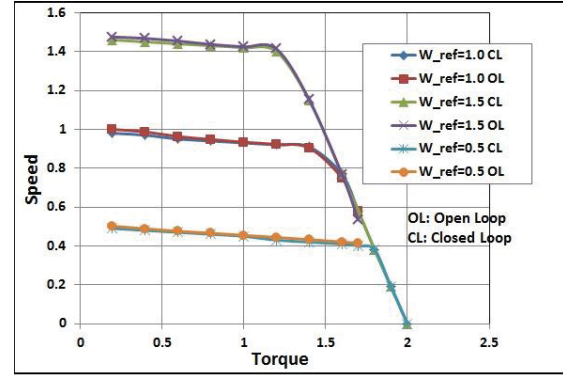


Figure 4. Speed vs. torque characteristics of gas turbine model (open-loop) and motor drive emulation in closed-loop.

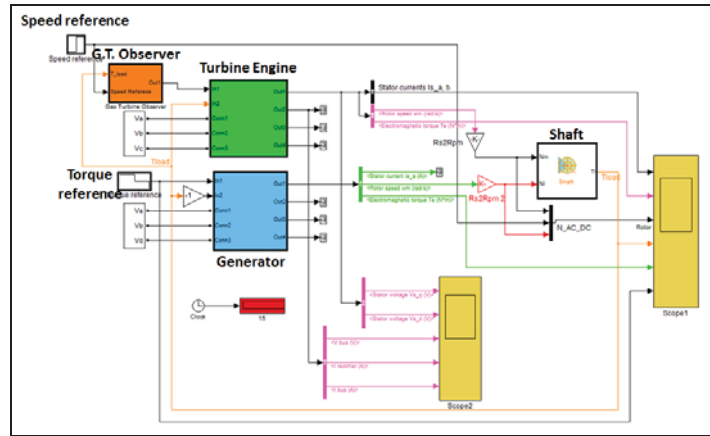


Figure 5. M Simulink model of two motor drives with mechanical coupler.

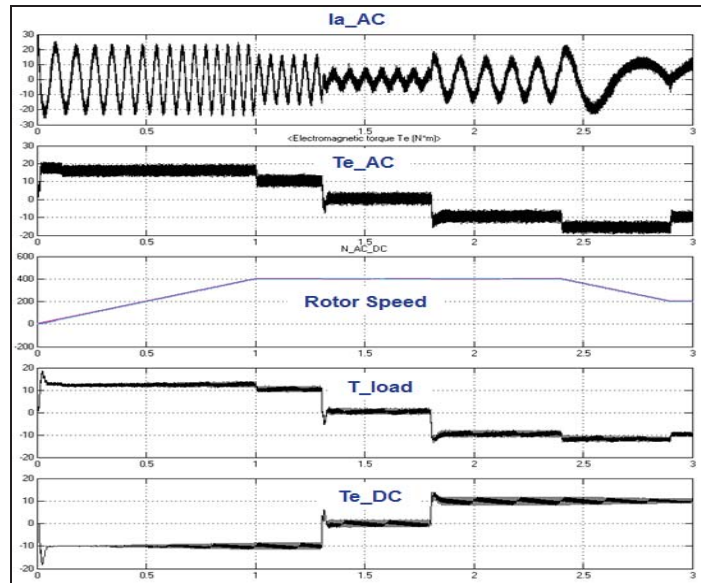


Figure 6. Speed ramp and load disturbance torque responses of the AC motor drive. I_a is the current in Phase A; T_e is the electromagnetic torque; T_{load} is the torque load.

load disturbance torques. The AC motor speed reaches the reference value of 400 rpm at $t = 1.0$ s. At that moment, the AC electric torque drops down to 10 N-m. Then at $t = 1.3$ s, a reference torque of 0 N-m is applied to the DC motor drive; the AC motor drive electric torque immediately drops down to zero in order to maintain the regulated speed. At $t = 1.8$ s, a reference torque of +10 N.M is applied to the DC motor drive, forcing AC motor drive to operate as a generator and DC motor drive as a motor. Finally, a negative reference speed ramp of -400 rpm/s is applied to the AC drive at $t = 2.4$ s. A new steady state is reached at $t = 2.85$ s, and the AC motor drive electric torque stabilizes at -10 N-m. It was noticed that the AC motor drive responded well accordingly to a variety of the speed ramps and load disturbance torques.

C. Implementation of Gas Turbine Observer into Motor-Generator Drive

This section describes a method by which the AC motor and drive can be controlled so as to emulate the steady-state and dynamic characteristics of the gas turbine engine model in Figure 3. This can be implemented by inserting the engine observer block between the torque reference from the generator and the speed reference into the motor. In such a setup, the AC motor gets its speed reference from the model of the gas turbine engine, given the load torque from the DC motor. The whole system model is tested in simulation, and the results have shown that the controlled AC motor and drive with speed closed-loop control is able to operate in accordance with the speed-torque characteristic of the turbine engine model. Figure 4 shows the closed-loop simulation results of using three different speeds, and all three curves enable tracking of the reference behavior of the gas turbine model with tracking error below 1 percent. The next step is to create a real time observer for the gas turbine model such that a practical hardware implementation can be realized. This work will be discussed in the later section.

III. Propulsive Fan System Model and Motor Based Emulator

The goal of this section is to develop a method by which the fourth motor drive system, emulating the last power train component, can be controlled so as to emulate the fan that would be a load torque applied to the fan shaft. The reference torque can be obtained by given fan maps of specific model and corresponding flight conditions. The closed-loop torque control algorithm for the emulator will be developed and tested through a simulation model in Matlab/Simulink prior to implementation in the test rig.

A. Modeling of Fan Map

Complete fan maps are either based on fan rig test results or are predicted by a special computer program. A fan map is important, since it is an integral part of predicting the performance of a gas turbine engine, both at design and off-design conditions. However, these maps are difficult to use in a computer simulation due to their steep gradients and multiple independent variables. Thus, beta maps were developed as a technique to reduce conventional component characteristic maps into a number of simpler maps. More maps are required for the beta format because they take the variables from a conventional map and split them into maps that contain only one dependent variable as a function of one independent variable used in generally corrected speed.

Figure 7 shows fan maps used in the simulation, which can generate an equivalent power level of a Boeing 787 GENx fan at high speeds. This fan has the dependent variable pressure ratio (P_{exit}/P_{inlet}) on the ordinate, the first independent variable, corrected mass flow on the abscissa. The second independent variable, corrected speed, is shown as lines of constant corrected speed that extend from surge to choked conditions. Using the beta line technique, two sets of data can be achieved. One set of data would be the pressure ratio as a function of corrected speed. This collection of data would provide one beta line on the fan pressure ratio on beta map. The second set of data would be the corresponding corrected mass flow as a function of corrected speed. The corrected mass flow data would also provide one beta line on the fan corrected mass flow on beta map. By collecting data for a number of pressure ratios and corrected mass flow beta lines as a function of corrected speed, mass flow beta map versus speed and pressure ratio beta map versus speed can be obtained from the original fan maps. Figure 8 shows the airflow beta map and pressure ratio beta map

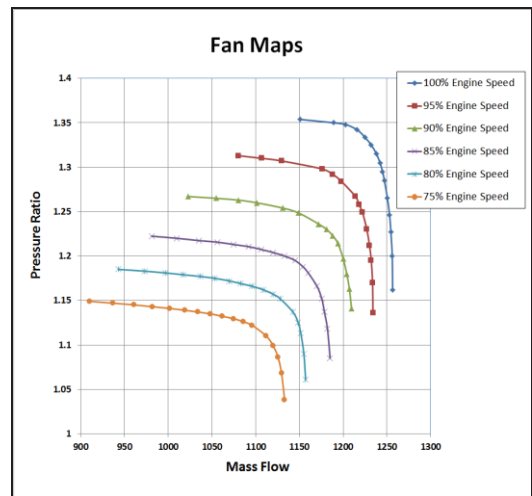


Figure 7. Fan maps at high speed used in the

necessary for the computer simulation. These two beta maps have been implemented into the simulation code as lookup tables accordingly.

Figure 9 shows a proposed block diagram for the motor-fan drive system. First, engine speed and beta coordinates go to the lookup table blocks in order to predict the values of flow and pressure ratio. Then these two values in conjunction with flight conditions and engine parameters go to the analytical model for the fan power out

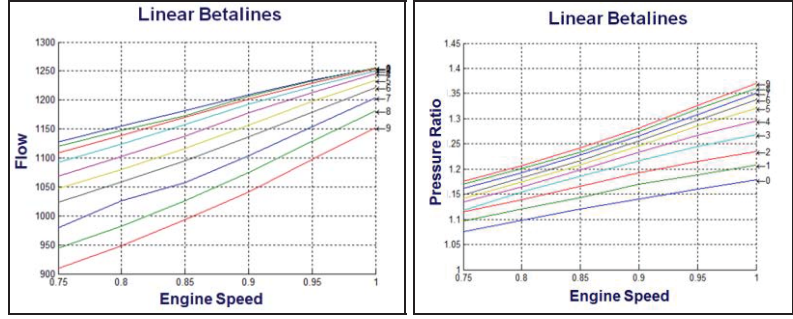


Figure 8. Linear betalines. a) Flow vs. engine speed. b) Pressure ratio vs. engine speed.

calculation, which is the power delivered to the air by fan. This output power with the given engine speed go to the torque block to calculate the torque load supplied to the fan shaft. Through the motor constant block, the current for the fourth motor to generate the required torque is eventually obtained. This current from the fan observer becomes a reference signal for the closed-loop control of the current of the DC motor. This current is regulated to match with the desired torque by the PI (proportional-integral) controller, so that the motor torque is equal to the output torque of the simulated fan.

For modeling of the fan power out calculation, several modeling techniques have been tested in order to investigate which could generate the best prediction, and the Wayne Sexton's fan power out formula¹⁸ has been selected for the simulation work. Note that the fan efficiency can be obtained similarly from the given fan maps, but its value is assumed in this study, omitting its long process. The flight conditions and engine parameters used in the simulation are described in Table I.

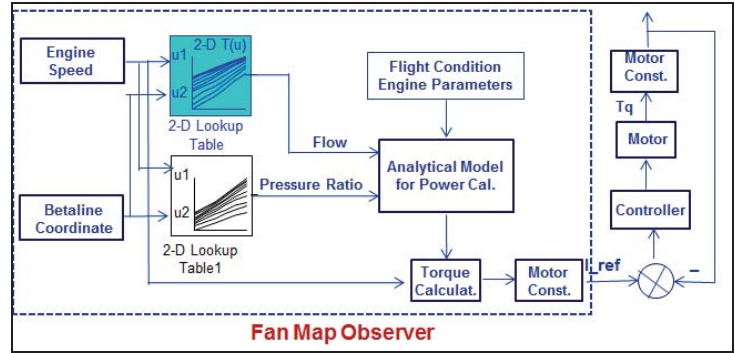


Figure 9. Proposed block diagram of the motor-fan drive.

Altitude	35000 ft
Mach number	0.8
Density	0.4135 kg/m ³
Engine speed	75% of the maximum speed
Mass flow rate	495.3 kg/s
Pressure ratio	1.117
Absolute pressure	2.65 x 10 ⁴ N/m ²
Fan efficiency	0.96

Table 1. Flight conditions and engine parameters.

B. Simulink Modeling of Motor-Fan Coupled by Shaft

Similar to the motor drive system model described in section II-B, another two-motor drive system that consists of coupling an AC motor drive model to a DC motor drive model by the use of the mechanical shaft model has been developed to emulate a coupled motor-fan. The AC motor drive is a three-phase synchronous motor-based drive that can emulate a wound-rotor synchronous motor. The three-phase DC motor drive system can emulate a fan that would generate various load torque conditions. Hence, this coupled model can emulate the speed regulated wound-rotor motor and the torque regulated fan. Again, the motor type represented can be easily changed by changing the commutation method. The signs of the AC electric torque and speed should be the same for the motor that emulates the wound-rotor synchronous motor when it is driving. The torque and speed should be of opposite signs for the motor that emulates the fan.

C. Implementation of Fan Map Observer into Motor-Fan Drive

This section describes a method by which the DC motor and drive, acting as a fan, can be controlled so as to emulate the characteristics of the fan maps and flight conditions described. This observer block can generate a load

torque reference, and through a motor constant block, its signal is converted into a current reference into the closed-loop current control block for the fourth motor. In such a setup, the AC motor drive gets its speed reference from the observer model of a wound-rotor synchronous motor under the load torque from the DC motor. The whole system model is tested in simulation, and the simulation results have shown that the characteristics of fan maps and operating conditions can be achieved (less than 1% steady-state error) by means of DC motor and drive with torque closed-loop control.

IV. Propulsion Electric Grid Emulator Setup

This section presents how to create the real time observers for the gas turbine model and fan map model such that a practical hardware implementation can be realized as shown in Figure 2. For this purpose, Matlab/Simulink and Real Time Workshop were used to generate C code for the observers and associated closed-loop control laws, and the executable control code is downloaded into the dSPACE control system for the hardware in the loop (HIL) implementation. The motor models in the simulation code have been replaced with Thin Gap permanent magnet (PM) brushless motors coupled by a mechanical shaft. The ironless composite stator is designed to travel along the rotating axis so that the main flux can be varied by changing the surface coverage between the rotor and stator. This feature allows the PM motor drive system to more closely emulate a wound-rotor synchronous machine. All power electronics used to drive the motor systems are from Advanced Motion Controls (AMC).

Recently, the system has been expanded to multiple power grids that consist of two engine/generator sets and three motor/fan sets as shown in Figure 10. This inexpensive simulator will emulate two turbine engines and three fans, interconnected by generators, rectifiers, a DC bus, inverters and fan drive motors. A TeDP system utilizing all ten motors and drives with closed-loop controllers makes it possible to emulate a representative part of the TeDP power train. Currently, a Rolls-Royce fail-safe code¹⁹ of TeDP for future hybrid-wing-body electric airplane is under investigation for implementation using the PEGS.

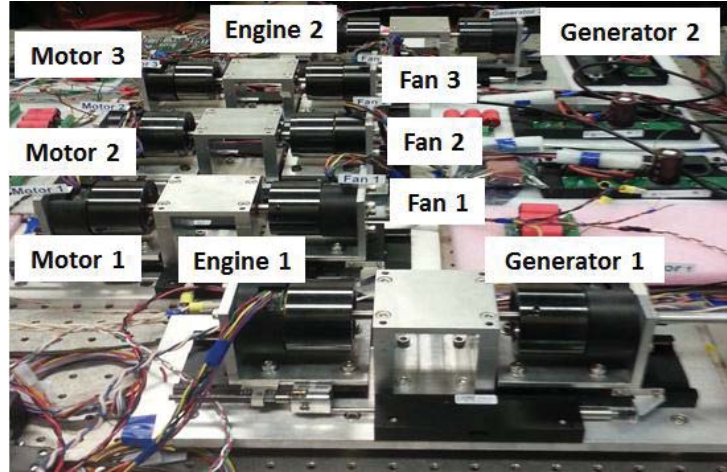


Figure 10. Experimental setup of Propulsion Electric Grid Simulator (PEGS).

V. Conclusion

In this paper, we have presented (a) the development of an analytical model of all the components in a TeDP power train using Matlab/Simulink, and (b) the subscale experimental system to emulate the power distributed from the turbine to the propulsive fan. The operation principle behind the technology is that all rotating components can be represented by torque and speed curve sets. Simulation results have shown that their dynamic characteristics can be implemented by using the closed-loop control of the electric motor drives. In the near future, additional turbo-generators and electrically driven fans will be added in order to further replicate the full propulsion power train. Planned future study includes (1) characterizing the experimental interaction of the many electrical components, (2) testing and evaluating parametric performance, (3) validating system model analyses and predictions, and (4) analyzing transient response (including faults), grid stability, and internal autonomy experiments.

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