# Integrated Thermal/Power/Propulsion/Vehicle Modeling Issues Related to a More Electric Aircraft Architecture

**Mitch Wolff**
Air Force Research Laboratory RZPE
1950 Fifth Street
Wright-Patterson AFB, OH, USA, 45433-7251

james.wolff2@wpafb.af.mil

## *ABSTRACT*

*A new subsystem-based approach to solve aerospace vehicle energy management issues is described. The goal of this approach is to create an "Energy Optimized Aircraft" that will maximize energy utilization for broad capabilities while minimizing complexity. To support this goal, an advanced modeling and simulation ICD process is established. This process addresses several of the current challenges facing modeling and simulation of large integrated system. Two initial integrated models are presented. First at the mission level, AFRL has undertaken the development, integration and demonstration of a tip-to-tail thermal model. The major components of the integrated model include the Air Vehicle System (AVS), the Fuel Thermal Management System, the engine models, and Power Thermal Management System (PTMS). Second at the segment level, a model of the electrical system including the generator, electrical accumulator unit, electrical distribution unit and electromechanical actuators has been developed. Included in the model are mission level models of an engine and aircraft to provide relevant boundary conditions. It is anticipated that the tracking of the electrical distribution through numerical integration of these various subsystems will lead to more accurate predictions of the bus power quality. This tool is used to evaluate two architectures. The first architecture makes use of an electromechanical accumulator unit to handle the regenerative energy created by the electromechanical actuators. In the second architecture power resistors in the actuator electronic units are used for dissipation of regenerative energy. Transient evaluations and energy metrics were used in evaluating capability of the two systems.*

## 1.0 INTRODUCTION/BACKGROUND

The US Air Force Research Laboratory's Propulsion Directorate initiated the Integrated Vehicle & Energy Technology (INVENT) Program in 2008. Leading up to the INVENT initiative there has been focused interest on the part of thermophysicists and thermal engineers to solve a "new set" of challenging aerospace vehicle thermal management problems. These problems are, for the most part, a result of inefficiencies stemming from a variety of components and systems such as electrical power systems, propulsion systems, and high-energy electronics devices. The idea that these are a "new set" of thermal management problems is a misnomer in that the relative inefficiencies have remained constant while the power and power densities that these devices are expected to consume and/or provide have continued to increase. This has ultimately resulted in the increase in total heat load combined with high-flux heat generating components. One would think this would not be a particularly challenging problem considering the evolution of a variety of thermal management concepts such as high-flux thermal management components developed over the last twenty years. But when one looks at additional constraints such as on-demand requirements driven by duty cycle, operating temperatures, isothermality, total heat load, the availability of suitable heat sinks, and poorly-defined environmental boundary conditions; these "new sets" of challenging thermal management problems can quickly become a costly thermal management nightmare. However, the implication that only better thermal management concepts and technologies need to be developed ignores the fact that, from an energy perspective, it is only a symptom resulting from the failure to properly take into account the need for improved system integration and optimization.

INVENT was established to address these thermal management challenges in modern survivable military aircraft, from a vehicle energy perspective, through new system integration and optimization approaches. These new aircraft have three to five times the heat load of legacy platforms while being limited in their ability to reject heat to the environment. Rejecting heat to the engine cycle through various flow paths has become the preferred approach. The added heat load is the result of modern avionics, advanced mission systems, fueldraulic based vectored thrust control systems, increased use of composite structures, and larger more electric aircraft engine accessories such as generators, gear boxes, or environmental controls. The legacy approach to these systems has been to provide continuous infrastructure (hydraulics, fueldraulics, pneumatics, electricity, cooling, etc.) even though many of the loads are used a small percentage of the mission (low duty cycle). INVENT is addressing the potential use of on-demand, duty cycle based systems that can greatly reduce these heat loads overall by “turning-down” their infrastructure demands during idle periods.

The ability to provide on-demand power and cooling may be the key to reducing infrastructure needs as well as reducing energy demand that decreases heat loads as a result. This concept is referred to as the Energy Optimized Aircraft (EOA) by the INVENT program. The main EOA infrastructure subsystems being addressed are the adaptive power and thermal management system (APTMS), robust electrical power system (REPS), and high performance electric actuation system (HPEAS), and their associated load suites as well as the engine system integration. The focus of the INVENT EOA is to make aircraft and vehicle systems more energy efficient by maximizing overall system energy efficiency in lieu of sub-optimized components and subsystems. The ability to solve the thermal challenges requires the knowledge and integration of complex systems to reduce the heat loads by addressing the “entire” vehicle energy picture. INVENT seeks to demonstrate the potential EOA technologies integration using modeling and simulation (M&S) followed by validation testing in the laboratories using systems integration facilities in conjunction with engine and vehicle test laboratories. The complexity of these highly integrated systems necessitates an effective M&S analytical approach to avoid the costs and risks associated with “cut & try” approaches to system integration. The purpose of this paper is to highlight the advancements in M&S that make a virtual approach to complex aircraft systems integration possible and then provide two examples, a thermal and electrical analysis, of integrated M&S investigate.

## 1.1 Thermal Analysis

Traditionally, the aircraft thermal, power, propulsion, and vehicle systems have been designed and optimized at a subsystem level with little consideration toward the design of the thermal management system (TMS). Such a design philosophy was sufficient due to the low thermal resistance of the airframe skin, the addition of ram inlet heat exchangers, and the relatively small amount of power required by the electrical loads. Aircraft TMS design was conducted through analysis of the anticipated worst case steady state operating points [1, 2]. This approach has been satisfactory for traditional aircraft designs. Modern aircraft made with composite skins have a high thermal resistance thereby greatly reducing convective cooling. In addition, the cross-sectional areas of ram inlet heat exchangers have also been reduced. At the same time, the size of the power system has increased by nearly an order of magnitude to support numerous high-power loads that increase the internal heat generated within modern/future aircraft. These factors have led to the current thermal challenges facing modern/future aircraft.

The INVENT program was established, in part, to address the thermal challenges of modern, survivable military aircraft. These new aircraft have three to five times the heat load of legacy platforms while being limited in the ability to reject heat to the environment. Rejecting heat to the engine cycle through various flow paths has become the preferred approach. The added heat load is the result of modern avionics, advanced mission systems, fueldraulic based vectored thrust control systems, and larger more electric aircraft engine accessories (generators, gear boxes, environmental controls, etc.). The complexity of these highly integrated systems necessitates an efficient M&S analytical approach to avoid the costs and risks associated with hardware based approaches to system integration.

The goal of this thermal effort is to develop, integrate and demonstrate a mission level tip-to-tail thermal model. The major components of the integrated model include the aircraft six degree of freedom model (6-DoF) and the vehicle management system (VMS), the engine aerodynamic and engine thermal models, the vehicle thermal model (fuel tanks), the power thermal management system (PTMS), and various representative aircraft level heat loads. The integrated model is then flown over a complete aircraft flight mission from ground idle thru take-off, climb, cruise, landing and post-flight ground hold. Having established a baseline level of performance for the aircraft PTMS system over the full mission length, the PTMS model is then exercised to investigate some possible design space trades. The design trades are an effort to highlight the potential application of the integrated system model. This analysis is not constrained to actual hardware components. The components in this system are representative of modern/future aircraft. The motivation is to stimulate additional dialog and discussion as to the benefits of integrated aircraft system analysis with the long term goal of achieving a design system capable of analyzing future energy optimized aircraft.

## 1.2 Electrical Analysis

The widespread use of more electrical equipment on an aircraft is driving the need to evaluate electrical stability of the system [3, 4]. Military Standard 704F defines requirements for the behavior of such systems [5]. However, evaluation of these systems typically has been done with hardware and this late evaluation can lead to increased costs. However, if such evaluation can take place earlier in the development process before pre-production hardware is built considerable cost savings can be achieved. A tool is being developed that can better quantify electrical stability through simulation of integrated electrical systems. This modeling tool makes use of models developed with bandwidth up to one hundred kilohertz. These models are defined in the INVENT Modeling Requirements and Implementation Plan (MRIP) as segment level models [6]. The MRIP document further defines the interfaces between the various electrical systems. This document is not limited to electrical, but includes the entire aircraft systems (thermal, mechanical, aerodynamic, etc.).

In addition to the increase in power usage, there is an additional issue with regenerative power of the actuators. With the move to the more electric aircraft, the actuators have changed from conventional hydraulic actuators to electro-hydrostatic actuators (EHA) and electro-mechanical actuators (EMA). Use of these actuators forces a need to deal with large regenerative power to the bus. Most applications with actuators are using resistors to “burn off” energy regenerated by the actuator and prevent the energy from returning to the bus. However, the regenerative energy dissipated in the actuators is a concern for thermal dissipation and additional energy required to cool the actuators. Recently in the research field, electrical accumulator units have been identified as a potential technology for solving this problem [7]. An electrical accumulator unit (EAU) is a battery or capacitance technology that can absorb energy and store it for future usage. This technology can be used to store the regenerative energy, however, power stability of the bus needs to be examined and evaluated before use.

Lastly, there is a desire to understand the overall system integration impact of the EAU. There has been identified the potential of not just dealing with the regenerative energy produced by the actuators but also to handle some of the peak loads of the actuators thus reducing requirements on the generator. Therefore any weight increase due to the EAU may be partially offset by reduction in generator weights. If the regenerative resistors are removed and the actuators no longer require cooling out to the actuators, further benefits could be realized. This paper will not go into the evaluation of weight savings but will look at overall energy usage of the EAU versus the use of local resistors. Further, the integration testing can begin to ensure the design points that the individual component designers are using are correct.

## 2.0 MODEL DEVELOPMENT

The model integration effort for the thermal and electrical analysis employs the commercial Matlab/Simulink software package as a top level modeling environment. Many of the subsystem models are developed entirely within the Simulink environment. Simulink offers a wide range of numerical integration solvers well suited for transient problems. As a graphical programming environment, Simulink allows for a model development that can have the look of traditional flow schematics. This allows end-users to translate from a schematic layout to a Simulink model with relative ease.

### 2.1 Thermal Model

The thermal analysis is accomplished by simulating the following components and sub-systems:

Aircraft 6-DoF and VMS
Aircraft fuel thermal management system (tanks, etc.)
Engine performance (thrust, fuel burn rate, etc.)
Engine fuel thermal management system (fuel pumps, etc.)
Power thermal management system (PTMS – power turbine, heat exchangers, etc.)

A schematic of the model interconnectivity is given in Figure 1, followed by brief descriptions of the individual component and sub-system models.

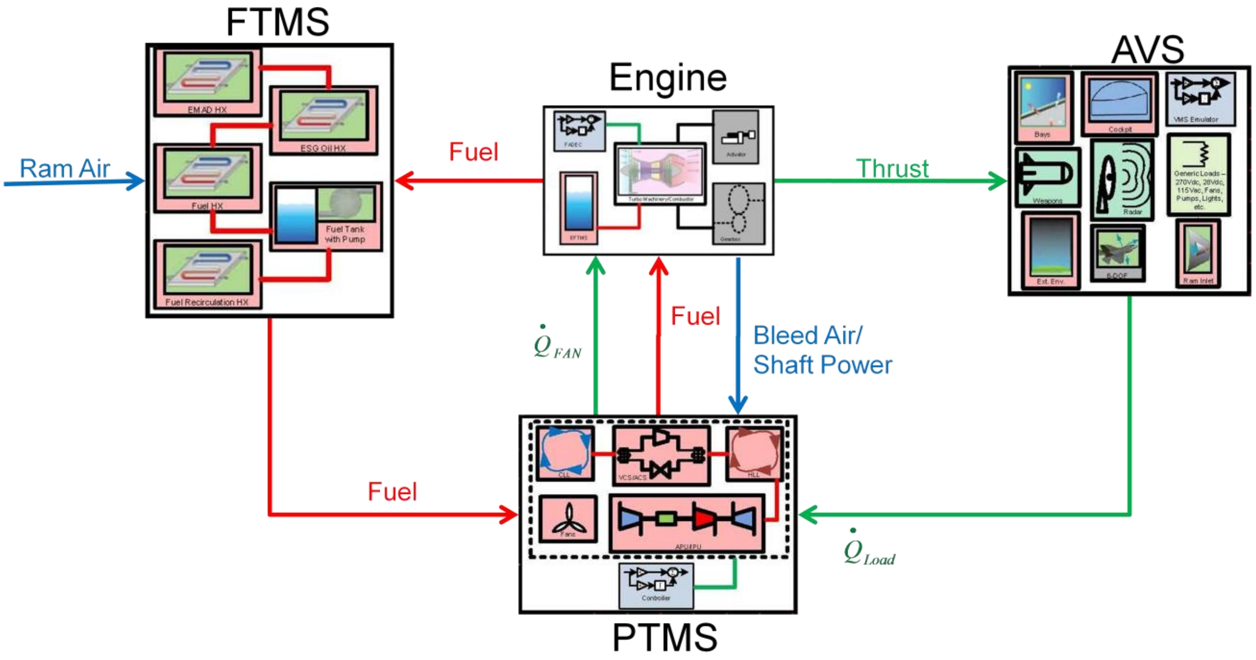

**Figure 1:** Top level schematic: integrated thermal model

### 2.1.1 Aircraft Models – Air Vehicle System (AVS)

The aircraft six degree of freedom model is a variable mass, rigid body model representative of a blended wing-body long range aircraft. The aircraft 6-DoF model is intended to serve as a mission level analysis tool with sufficient fidelity to enable relevant trade studies (e.g., accounting for additional ram air drag associated with a vapor cycle PTMS as compared to an air cycle PTMS) and yet with sufficient execution speed that full length mission performance metrics can be produced rapidly. The primary modeling objective for the 6-DoF model is to dynamically update the following data as a function of the aircraft flight condition: ambient atmospheric data, required engine thrust, and a coordinated set of control surface actuator loads. The model that has been developed for the present air platform is a MATLAB/Simulink application with the following features and capabilities:

- Trim and IC capability for steady level flight at any point within the flight envelope.
- Easily specified mission legs in terms of altitude, Mach number, roll angle and course.
- Aircraft weight, inertia tensor and cg location dynamically updated throughout the mission.
- Control effectors: wing-tip “clamshells” for directional and braking control; outboard elevons for roll control; beavertail and inboard elevons for pitch control.
- Symmetrical engine thrust – no differential thrust control, no thrust vectoring.
- Vehicle aerodynamics based on table look-up scheme; aerodynamic database developed using a vortex-lattice method.
- In standalone mode, inclusion of a very simple dynamic engine thrust model.
- Ability to integrate instantaneous data over the length of the mission to arrive at performance metrics such as range, endurance, total fuel burn, etc.
- Flight control loop closure providing cruise regulation and tracking of altitude, airspeed or Mach number, bank angle and heading.

- Feedback gains scheduled throughout the flight envelope as a function of gross weight and freestream dynamic pressure.

The top-level feedback architecture for the aircraft flight control computer is presented below in Figure 2.

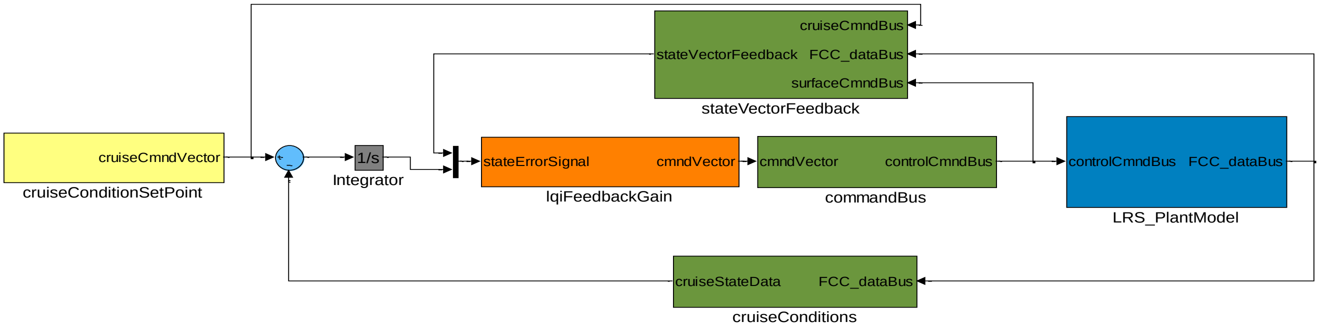

**Figure 2: Aircraft stabilization and tracking feedback design**

### 2.1.2 Aircraft Models – Fuel Thermal Management System (FTMS)

The air vehicle fuel thermal management system (FTMS) is modeled using an AFRL developed Simulink based toolset comprised of various FTMS components. Temperature of the fuel inside the fuel tank drives constraints throughout the system and therefore particular focus is given to the heat transfer model for each tank. The toolset is comprised of material heat transfer models capable of capturing solar loading, infrared radiation, and aerodynamic convection on the aircraft surface. The conductive heat transfer to the internal surface of the fuel tanks establishes heat transfer between the fuselage/fuel and external surfaces. Finite volume methods are implemented in the wall material along with standard lump capacitance approaches for fuel volumes [8]. Numerical integration in Simulink allows for time-domain analysis of the temperature response resulting from highly variable boundary conditions applied to fast responding (fuel tank wall) and slow responding (full fuel tanks) physical components.

In addition to the fuel tanks, the additional heat load attributed to flow through the fuel pumps is captured downstream of the fuel tanks, Figure 3. A variety of aircraft subsystems utilize fuel as a viable heat sink, and depending on the subsystem a significant temperature rise could be observed. Eventually the fuel temperature can rise to levels incapable of cooling temperature constrained components, and therefore increased fuel flow beyond engine demand is required to maintain component temperatures within appropriate operating ranges. The FTMS model utilizes circuit temperatures to determine if additional flow is needed, and any excess flow is returned to the tanks. The resultant ‘temperature runaway’ conditions under high levels of return flow and/or low fuel tank mass can be analyzed effectively using the FTMS models. Such mission critical responses will be highly dependent on the complicated interaction between all coupled subsystems, and therefore the appropriate hooks are in place to couple other essential aircraft subsystems. The detailed analysis of the interdependent subsystems will be essential in developing an EOA.

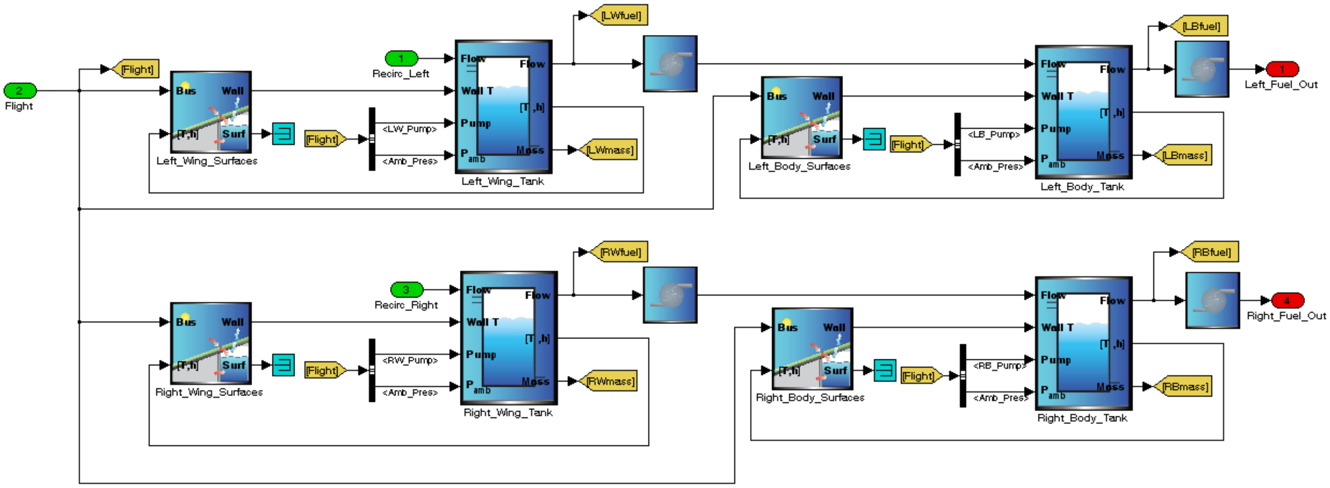

**Figure 3:** Aircraft fuel tanks, fuel tank wall heat transfer, and pump models

### 2.1.3 Power Thermal Management System (PTMS)

In order to investigate the potential performance benefits associated with PTMS architectures, trade studies with three PTMS architectures were implemented in the tip-to-tail thermal management mission level model. Two air refrigeration cycles and a single vapor refrigeration cycle were used to investigate the PTMS trade space.

Each of the air cycle PTMS architectures are implemented as closed air refrigeration cycles which are used to refrigerate the aircraft's liquid cooled and air cooled loads. A PAO loop is used to interface the PTMS with the liquid cooled avionics loads and engine bleed air provides cooling for the air-cooled loads as well as powering the refrigeration cycles. In addition, each of the air cycle PTMS architectures have two heat sinks used to cool the high temperature high-pressure closed loop air stream from the compressor. The primary heat sink is an air-to-air heat exchanger located in the fan stream of the main engine with an additional PAO loop, which interfaces the PTMS to the aircraft fuel, Hot Liquid Loop (HLL). The HLL heat sink is used when the primary heat sink is insufficient to remove the necessary heat to refrigerate the liquid and air-cooled loads. The primary heat sink location differs between the two air cycle PTMS architectures. In architecture #1 the primary heat sink is located at the engine second fan stage while in architecture #2 the primary heat sink is located at the first fan stage.

The vapor cycle PTMS architecture, as with the air cycle PTMS, is used to refrigerate the aircraft's liquid cooled and air cooled loads. Similar to the gas cycle PTMS, engine bleed air provides cooling for the air-cooled loads. A PAO loop interfaces with the engine bleed air to the evaporator, which cools the bleed air and provides cooling for the air-cooled loads. An additional PAO loop interfaces the liquid cooled loads to the PTMS. Main engine shaft extraction is used to power the vapor cycle. The primary vapor cycle heat sink is a ram air-fuel heat exchanger. A PAO loop is use to interface the condenser to the fuel similar to the HLL used in the air cycle architectures. In flight, the fuel is cooled with ram air; for ground operation, a fan is employed.

### 2.1.4 Integration Issues/Lessons Learned

In software engineering, cyclomatic complexity [9] is an example of a measure of software complexity. Software metrics such as these are intended to measure the capability to test and maintain software. Extensions of these methods could be made to physical model development in a graphical environment such as Simulink. When model complexity is high, maintainability, testability and integration are expected to be difficult. Certain model constructs can increase the measure of model complexity. Examples of these constructs may include callbacks or self-modifying code. By eliminating or reducing these constructs, the models become "easier" to debug and integrate. Lessons learned can be gathered in the MRIP or a similar modeling style guideline document.

A practical issue regarding integration of a collection of independently developed subsystem models concerns IP protection. Some of the models used were proprietary models and "locked" from viewing the contents. The locking prevented the integrator from understanding the exact nature of the model simulated without having to consult with the model developer every time there was an issue. Some issues were not easily reproduced outside of the integrated system, thus making the debug of the issue more difficult. On-going work with the model suppliers is occurring to encourage sending of unlocked models, or at least partially un-locked models. MathWorks, in collaboration with AFRL, is also researching methods to address this issue.

Simulation speed is paramount in almost all modeling. The faster the model can be executed the faster debug and system studies can be performed. However, when integrating a large collection of subsystems, simulation speed bottlenecks may occur that are not evident when executing the individual models. There are a number of improvements that can be made to increase simulation speed. Examples include use of lower fidelity component models to establish the model topology before integrating the high fidelity component, use of model referencing, use of Simulink's model accelerator, use of Distributed Heterogeneous Simulation (DHS) [8], or use of MathWorks' Parallel Computing Toolbox. However, use of these methods may require significant changes to the models to take advantage of these features. The stepped integration approach only aids in the initial debug but does not aid in running of trade studies. To make use of model referencing, there are more restrictions on the modeling approaches taken. For example, use of level 2 M-file S-Functions is restricted in that a target language compiler (TLC) file is required, all buses need to be explicitly defined, and all the signal elements in buses need to adhere to a naming convention. The accelerator has similar restrictions, although these are somewhat less stringent than those for model referencing. Lastly, use of DHS requires some work to determine the intercommunication intervals between models. The model referencing approach requires similar testing. Lastly, use of the MathWorks' Parallel Computing Toolbox (PCT) caused issues that are curr.ently being worked with MathWorks and AFRL. Some of those issues include use of model referencing, accelerator mode, networked computers, and use of legacy code with PCT. The performance goal is to execute mission level models 10X faster than real-time.

Data logging is another challenge with such a large system model. Simulink makes available several approaches for monitoring signals in the model. These methods include scopes, displays, signal logging, to-workspace blocks, and to-file blocks. Each of these methods has its own set of drawbacks. The scopes, displays, and to-workspace blocks seem to be the least beneficial. The main drawback with the signal logging capability is that it saves data to the workspace and there is no simple means to save that data to a file to limit memory usage during model simulation. The "to-file" block is limited in that it does not support buses directly, and requires all data to be of the same type. Workarounds exist for both methodologies, but may not be apparent to an inexperienced user. Currently we are using the "to file" block as the data logging methodology.

Lastly, a configuration management system was used to allow for continued development of the models while integration of a baseline set of models was being performed. As problems with models were identified, the integrator would inform the model owner and that owner could reproduce the problem - if necessary by using the same configuration as the integrator through the configuration management system - and then fix the problem. The owner could then post the fix in the configuration management system for the integrator and others to use. The main problems with the configuration management system and its use dealt with training of engineers; as integration continued on, the number of issues was reduced.

## 2.2 Electrical Model

The model integration effort employs Distributed Heterogeneous Simulation (DHS) software package as a top-level modeling environment [10, 11, 12]. The subsystem models are developed within the Simulink environment. One toolbox used extensively for the subsystem modeling effort was Graphical Automated State Model Generator (ASMG) [13]. Graphical ASMG is a tool similar to Spice and Saber that can create electrical models based on resistors, capacitors, diodes, etc. The tool will then construct a state space representation of the model and allow the use of Simulink's solvers. ASMG was primarily used for most of the electrical components. Simulink was used for the remainder of the electrical components and the other aerodynamic and mechanical components.

The MRIP was used as a guideline for definition of interface variables. The MRIP defines the interfaces for all subsystems including the robust electrical power system (REPS), the high-performance electrical actuation system (HPEAS), adaptive power and thermal management system (APTMS), aircraft vehicle system (AVS), engine, and fuel thermal management system (FTMS). Figure 4 shows the entire aircraft system and the interfaces with each system. For the electrical modeling performed with this tool, focus will be given to the REPS and HPEAS systems in addition to lower bandwidth models (mission level) of the AVS and engine systems. The FTMS system will not be modeled for this work.

The two architectures developed are pictured in Figures 5 and 6. The first architecture is composed of an aircraft model, four engine models, four generators, four feeders used for power distribution, nine actuators, and two generic loads. The two generic loads represent continuous loads the aircraft electrical system would experience during the mission segment defined below. Each of the architectural components will be defined below. In the second architecture, electrical accumulator units are added to the architecture via an additional feeder that can interoperate with the feeder to the actuators to allow regenerative current to flow into the EAU. It also allows peak current demands to flow from the EAU to the actuator.

An electrical distribution unit (EDU) was not modeled for two reasons: future work will be performed to validate the models developed here and currently an EDU is not available, it is planned in future work that such a model will be used and eventually validated with hardware.

Sets of actuation flight loads have been determined by flying the six-DOF aircraft model through simulated missions. The mission segment maneuvers of interest for this study have been designed to require high power, coordinated actions of most or all of the nine control surface actuators. Transient flight conditions at high dynamic pressure have thus been the flight segments of greatest interest. In particular, a step change in the heading command with a simultaneous pitch-up command has proven effective in involving all of the control surfaces.

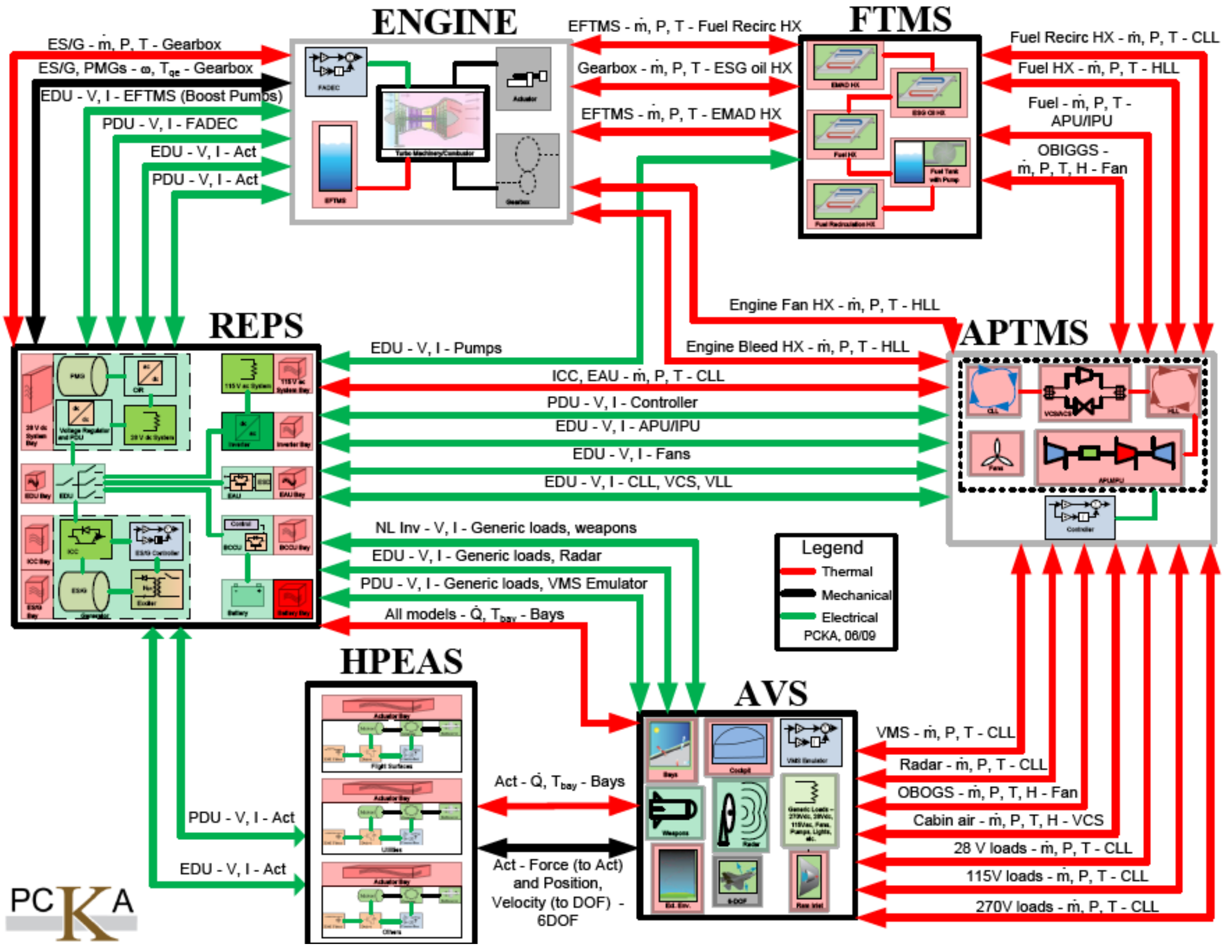

**Figure 4: MRIP Architecture for a Tip To Tail Model**

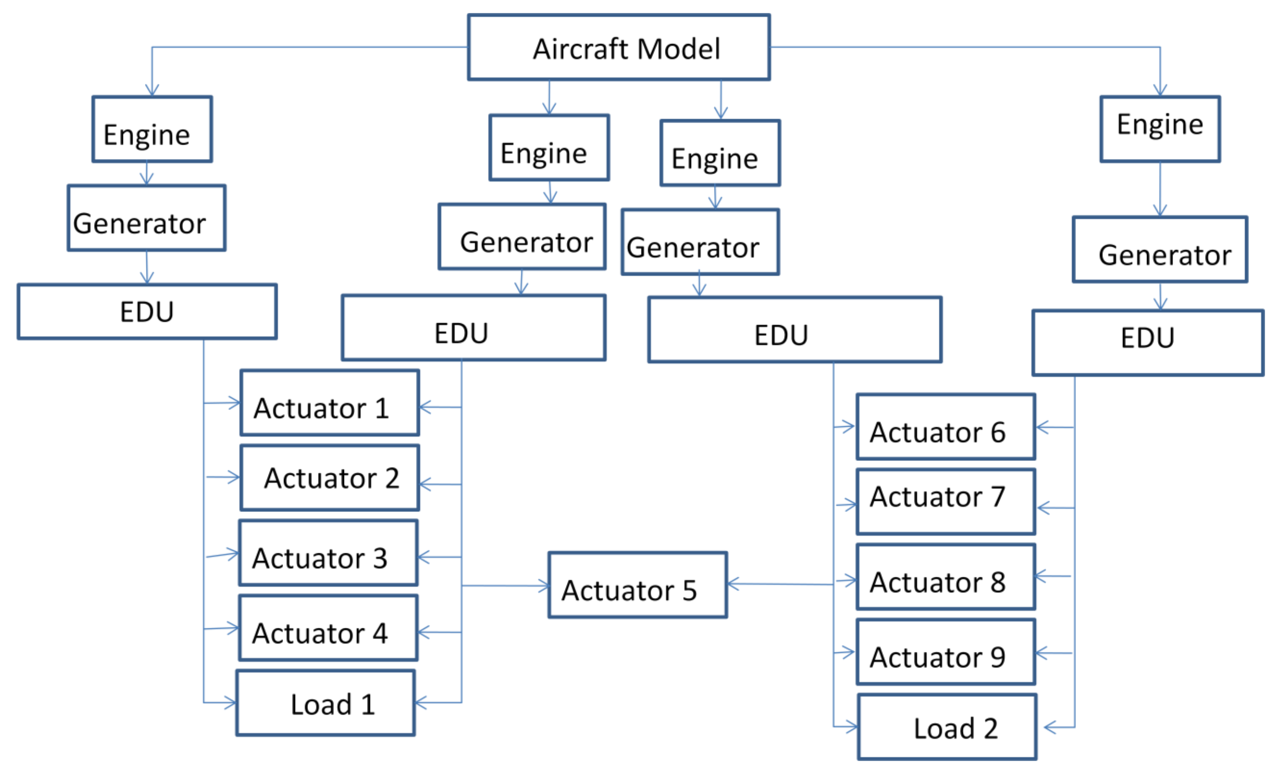

**Figure 5. Integrated electrical model without electrical accumulator unit**

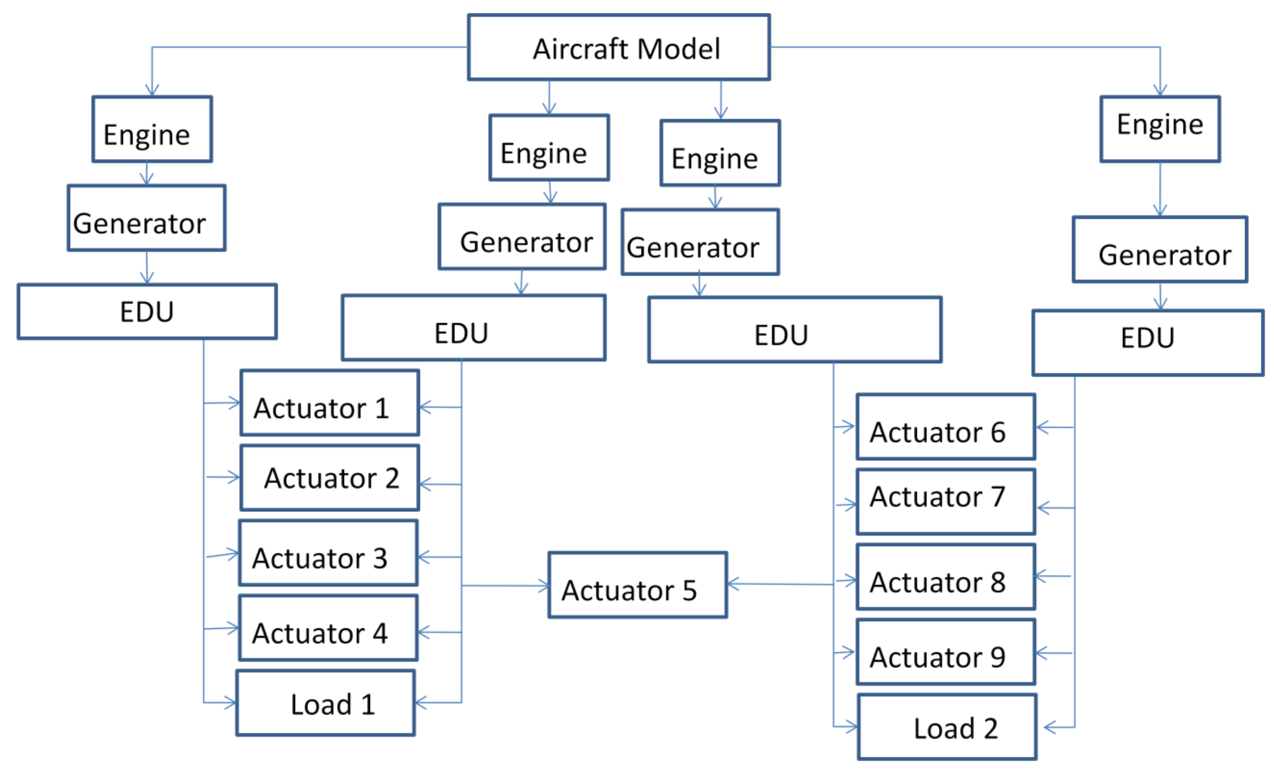

**Figure 6. Integrated electrical model with electrical accumulator unit**

### 2.2.1 Generator Model

The generator used for the modeling effort is a 270-volt DC generator. The switch level model includes an exciter, rotating rectifier, and diode bridge/inverter output stage. Magnetic effects such as saturation are included along with temperature dependence in the appropriate generator components (resistance, friction, etc…). A significant number of loss mechanisms are modeled including friction/windage, conductive, switch, and core losses. The generator has a base and peak power rating beyond which regulation within military specification is no longer guaranteed and device failure is likely (or life significantly reduced).

The generator interfaces to the engine through a gearbox and provides torque feedback to the engine. The engine supplies speed to the gearbox that feeds the generator model. At the generator terminals, feeder lines are attached in the form of a line impendence model that interfaces with the remainder of the electrical system. The generator is responsible for maintaining 270V on the bus during normal operation, and without an EAU is solely responsible for maintaining bus power quality. Power quality can be evaluated at the output of the generator terminals or the point of regulation downstream from the feeder impedances.

### 2.2.2 EDU Model

The EDU model represents the feeder electrical dynamics between the generator ICC, the actuator loads, and the generic loads. See Figure 7. EDU Simulink Diagram Figure 7 for Simulink diagram of the model. Within the bus block are the feeder resistance and inductance for each actuator. For this work, the feeder lines are all assumed to be the same. This model was developed in ASMG. Values for resistances and inductances have been obtained based on expected resistances and inductances that will be used for the hardware in the loop validation effort within the next steps. Inputs to this model are the ICC voltage, EAU voltage, the actuator current, and the generic load current. Outputs include voltages to the actuators and generic loads, and current to the ICC and EAU.

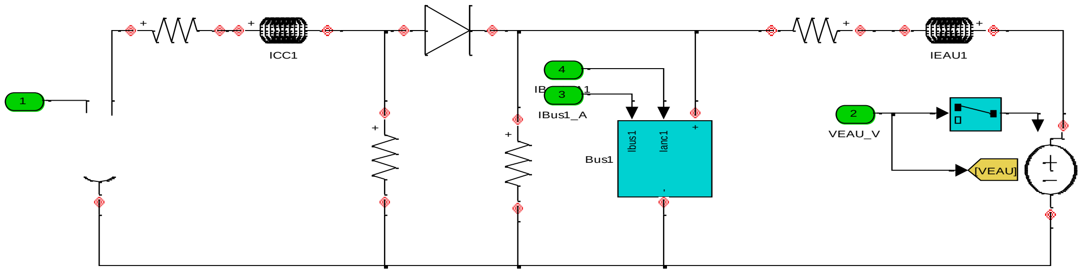

**Figure 7:** **EDU Simulink Diagram**

### 2.2.3 Electrical Accumulator Model

The EAU can be multi-functional by absorbing regenerated power, providing peak power under stressful loading situations, and serving as a battery backup during emergency conditions. The focus of this paper will be on the regenerative/peak power handling of the EAU and the associated impacts to bus power. Based on the generator current, load currents, and bus voltage the EAU can either absorb power or provide power through a power electronic interface in order to limit generator power draw and maintain bus power quality. The energy can be stored in or pulled from energy storage devices such as batteries or ultracapacitors.

The EAU is designed to be placed into a circuit and evaluated without significant architecture redesigns. For the studies considered in this paper, regenerative resistors were turned on for use without an EAU, and turned off (with diode blocking removed) for use with an EAU. The EAU interfaces to the main power distribution bus through feeder cables modeled as line impedance. See Figure 8 for a depiction of the electrical subsystem and the interconnections within the electrical subsystem and to other subsystems.

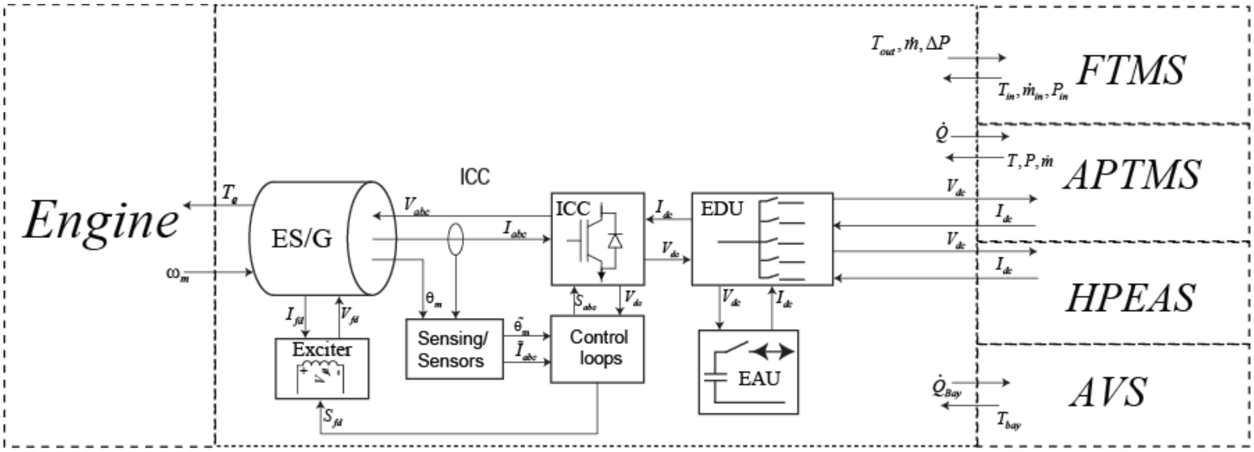

**Figure 8:** REPS model with generator, ICC, EDU, and EAU

### 2.2.4 Actuator Model

In this work the actuators represent the dynamic load applied to the bus. The segment level actuator models include input EMI filters, active switching, and a rotating machine model. Temperature dependence is captured in appropriate components including winding resistance and friction. The mechanical model includes gearing and a ball-screw for linear designs. The actuator models also contain a regenerative resistor model that can be toggled on/off by the user.

The actuators interface to the electrical system through the input stage of the EMI filter; bus voltage is provided by the EDU model and load current is returned by the actuator models. Position commands are generated by the vehicle management computer and provided to the actuators along with the hinge moments predicted by the air vehicle model. The actuators are designed to high response rates and therefore large peak power events are generated in response to rapidly changing position commands during maneuvering segments. The peak power events result from acceleration of the motor shaft inertia. As the actuators approach commanded position, the actuator motors are slowed rapidly through extraction of shaft power through electromechanical coupling resulting in power returning from the actuator to the bus. The regenerative circuit prevents this power from returning to the bus by redirecting the power through a resistor. As mentioned earlier, removal of this regenerative circuit allows power quality studies to be conducted with regenerative power returned to the bus. A generic actuator component layout is shown in Figure 9 along with the associated interfaces internal to the actuator model.

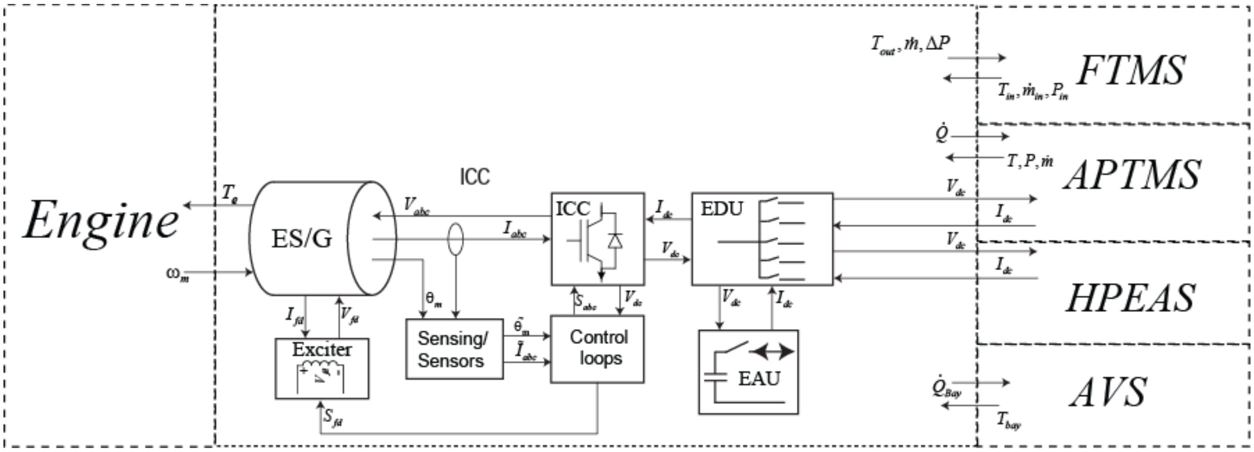

Figure 9: **HPEAS model does not include regenerative resistor**

### 2.2.5 Aircraft Model

The aircraft six degree of freedom model is a variable mass, rigid body model representative of a blended wing-body long-range aircraft. The aircraft six-DOF model is intended to serve as a mission level analysis tool with sufficient fidelity to enable relevant trade studies (e.g., accounting for additional ram air drag associated with a vapor cycle PTMS as compared to an air cycle PTMS) and yet with sufficient execution speed that full-length mission performance metrics can be produced rapidly. The primary modeling objective for the 6-DOF model is to dynamically update the following data as a function of the aircraft flight condition: ambient atmospheric data, required engine thrust, and a coordinated set of control surface actuator loads. The model that has been developed for the present air platform is a MATLAB/Simulink application with the following features and capabilities:

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- Flight control loop closure providing cruise regulation and tracking of altitude, airspeed or Mach number, bank angle and heading.
- Feedback gains scheduled throughout the flight envelope as a function of gross weight and freestream dynamic pressure.

The top-level feedback architecture for the aircraft VMS was presented before in Section 2.1.1 Figure 2.

### 2.2.6 Engine Model

A transient aerodynamic model of the engine us used to simulate engine behavior. The aerodynamic model simulates the temperature, speeds, pressures, and thrust of the engine cycle. The inputs to the aerodynamic engine model include thrust commands, ambient conditions, power extraction, bleed requests, and heat inputs. The power extractions from the engine are those calculated by the generator. For this work the gearbox is assumed to be ideal and has a gear ratio of one. The bleed request and heat input into the engine are set to zero for this work. The thrust command is generated by the aircraft six-DoF model. Outputs of the aerodynamic engine model include fuel burned, thrust achieved, and shaft speed. This model was based on work done for AFRL by Scientific Monitoring, Inc (SMI) [14]. The model previously developed was modified for the work here to be scaled to a twenty thousand pound thrust class engine.

## 3.0 RESULTS

The results will be presented in two sections. First, the results from the thermal analysis will be investigated followed by the electrical system analysis. These results are representative of the type of integrated tip-to-tail analysis, which is needed for any energy optimized aircraft model. In addition, this represents a beginning step in the process toward an EAO. A significant amount of research must be accomplished before our goal is reached – i.e. developing more transient models of other sub-systems, determining the proper energy metric for use in optimization, reducing the computational expense of the analysis so a multi-disciplinary optimization/analysis (MDOA) approach can be utilized, etc.

### 3.1 Thermal Tip-to-Tail

A generic modern long-range strike aircraft was modeled over a 200-minute mission. The intention of the mission profile, depicted in Figure 10, is to provide sufficient coverage of the flight envelope to demonstrate performance of the integrated model in each of the segments of interest: pre-flight ground hold, accelerate, climb, cruise, descent, low altitude flight, post-flight ground hold. The ambient conditions for the mission were as specified by the standards for a Mil-HDBK-310 10% Hot Day.

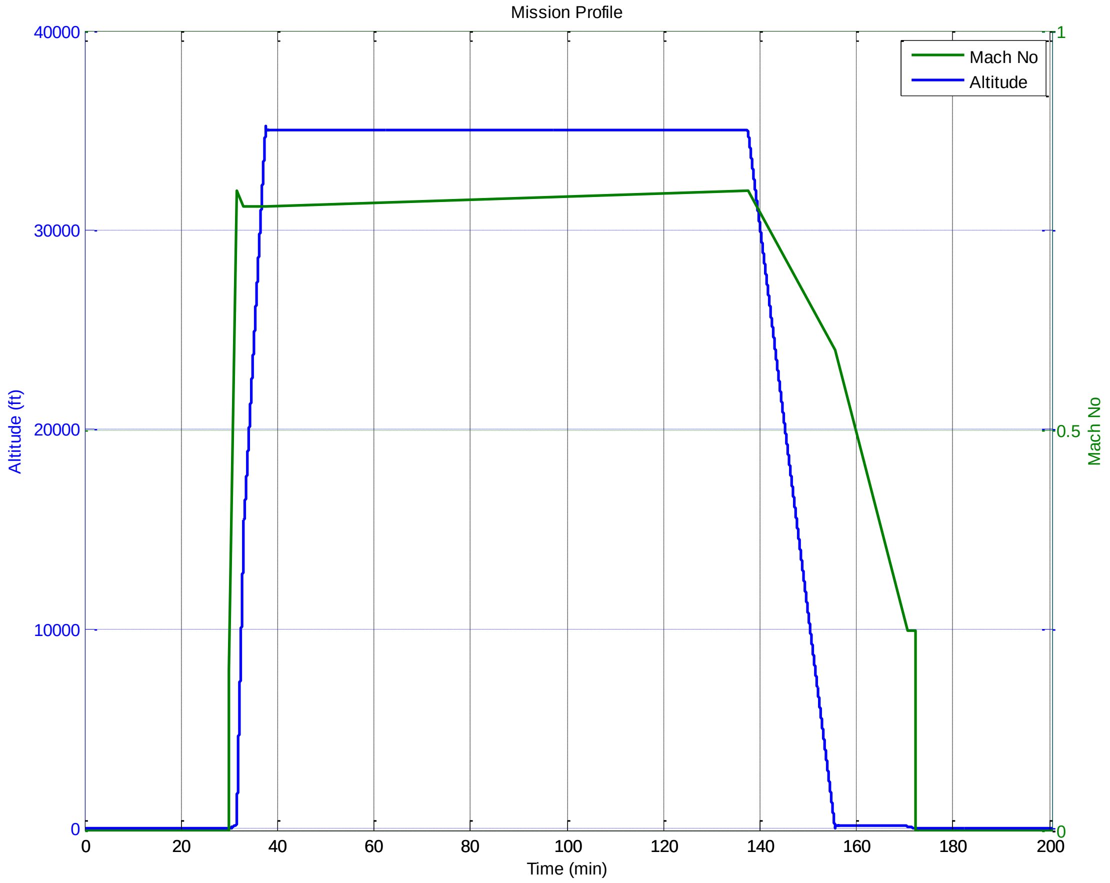

**Figure 10.** **Mission profile: altitude and Mach number**.

### 3.1.1 Trade Study Results

The objective of the trade study is to investigate the performance benefits associated with different PTMS architectures. The function of the PTMS is to cool the thermal loads on the aircraft and the performance of the PTMS can be assessed by the thermal margin and the required energy to refrigerate the loads. Improved PTMS performance will provide both an increased thermal margin, which would allow for increases in thermal loading or the extension of missions capabilities, and will also require less energy to refrigerate the aircraft loads.

One important measure for PTMS thermal margin is fuel tank temperature, which has a chosen maximum temperature limit of 138F. A metric for PTMS energy consumption is the fuel required to complete the mission with an improvement resulting in a reduction in fuel consumption. The performance associated with each PTMS is evaluated for fuel tank temperature as a function of mission time (Figure 12) as well as fuel weight as a function of mission time (Figure 11).

Figure 12 compares the fuel tank temperature of the three PTMS architectures over the mission. In air cycle architecture #1, the fuel tank thermal limit is exceeded after 170 minutes with a peak fuel tank temperature of 140F. The exceeded thermal limit would require alteration of the mission resulting in reduced mission capability. In air cycle architecture #2, the fuel tank thermal limit is not reached. The peak fuel tank temperature is 123F which results in a 17F increase in thermal margin as compared to air cycle architecture #1. Architecture #2 employs a lower temperature primary heat sink, main engine fan stage one in contrast to the second fan stage in architecture #1, which results in a reduced use of the secondary HLL heat sink. The HLL heat sink ultimately sinks heat to the fuel resulting in an increase in fuel temperature. The reduced use of the HLL heat sink results in a reduction in fuel tank temperatures. The peak fuel tank temperature of 137F is reached in the vapor cycle architecture. As in the second air cycle architecture, the fuel tank thermal limit is not reached.

Figure 11 compares the fuel consumed during the mission for the three PTMS architectures. Improved performance of air cycle architecture #2 results in a 205lb fuel savings compared to air cycle architecture #1. The lower temperature heat sink in architecture #2 results in lower power consumption compared to architecture #1. The vapor cycle architecture provides fuel savings compared to either of the two air cycle architectures: savings of 619 lb and 414 lb, respectively. The vapor cycle is powered from engine shaft extraction, which results in reduced bleed air extracted for the engine. The reduced extracted bleed air results in the reduced fuel consumption.

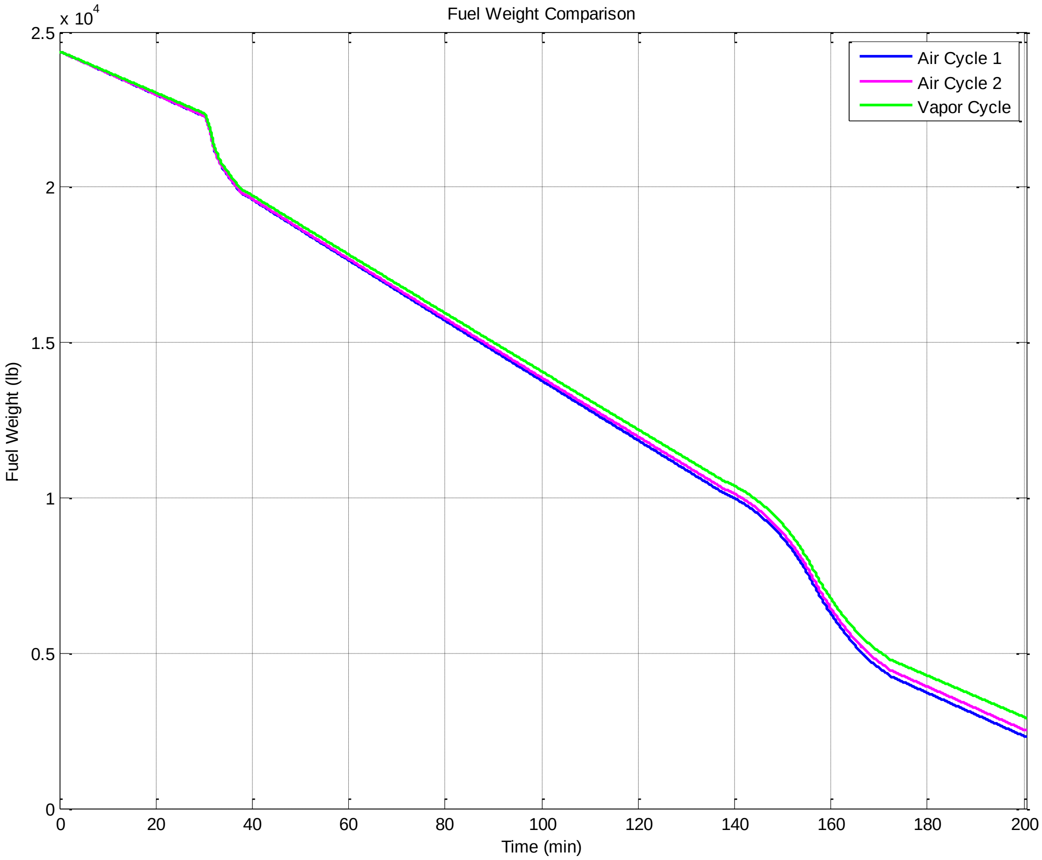

**Figure 11.** **Total fuel burn comparison**

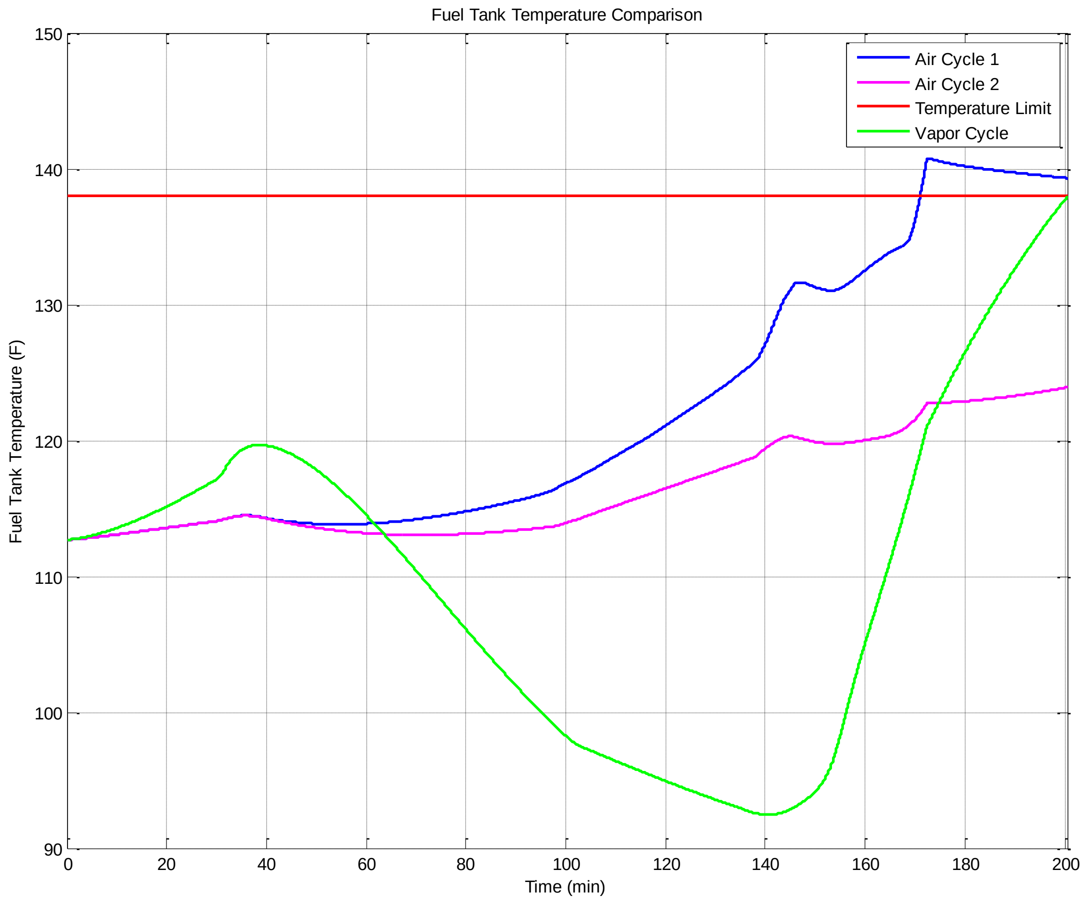

**Figure 12. Fuel tank temperature comparison**

## 3.2 Electrical Tip-to-Tail

Both architectures had difficulty staying within a band of 250 to 290 volts DC. The DC voltage band is representative of the MIL STD 704F steady state voltage requirements. Architecture one had a few points outside of the region (Figure 13), while architecture two had many points (see Figure 14) outside of the region and a few greater than 300 volts DC. One explanation for the improved stability of architecture one is that the regenerative resistor circuits have some capacitance associated with the circuitry and effectively act as mini-EAUs at each of the actuators.

One reason the EAU architecture (architecture two) did not perform as well is that the EAU used for this effort was designed to handle lower bandwidth power profiles then what was found in the simulation. The power draw bandwidth exceeded the bandwidth of the EAU to supply power and thus offered no improvements and to some extent caused performance detriments. To show the EAU does perform better when experiencing with lower bandwidth power draws, we created a simulation with a generator, EAU, simulated resistive load, and a simulated constant power load. The results of the simulation are shown in

Figures 15 and 16. In Figure 15, the loading of the system is exceeding the rated capability of the generator and causes the generator to go into a magnetic saturation region where it can no longer maintain a bus voltage and supply the necessary current. In Figure 16, the EAU is capable of supplying the power needed that is above and beyond what the generator can supply and does not result in reduction in bus voltage. In the main simulation the power requirements were not beyond the capability of the generator, so no reduction in voltage is seen with architecture one. When requesting power beyond the capability of the generator with the full system, the EAU architecture did not perform as well as what can be seen in Figure 16. Data for this test is not presented here.

The results of this work also showed that architecture two (with EAU) increased the amount of electrical energy usage of the system as seen in Figure 17. Note that for this experiment, electrical energy usage is only a small fraction (~ 0.01%) of the entire energy required to fly the aircraft on the mission as seen in Figures 17 and 18. The leading cause of the reduction in performance was indeed the EAU. One of the drivers of this reduction in performance is that the EAU was never operated in a manner where the net current from the system was negative thus allowing for regeneration of energy. The EAU operation in maintaining constant voltage, though does cause it to be used and thus due to its reduced efficiency compared to the regeneration circuit (for this experiment) the overall electrical energy usage was higher for the EAU architecture.

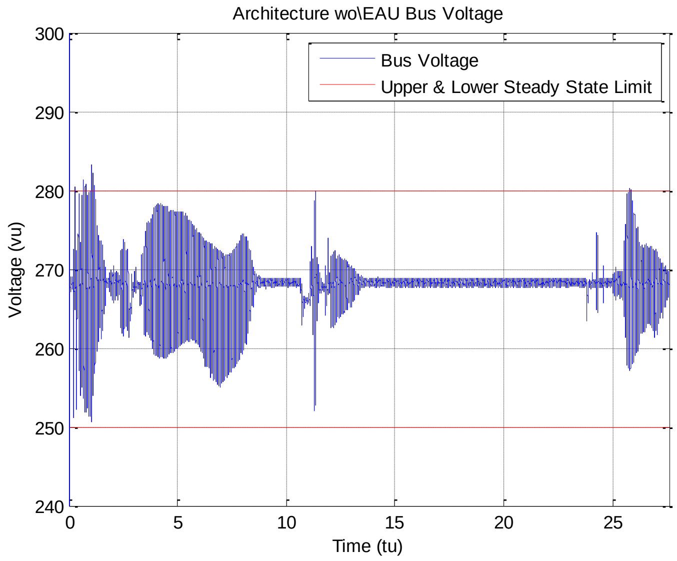

**Figure 13.** **Transient Voltage Response for Architecture 1 (without EAU)**

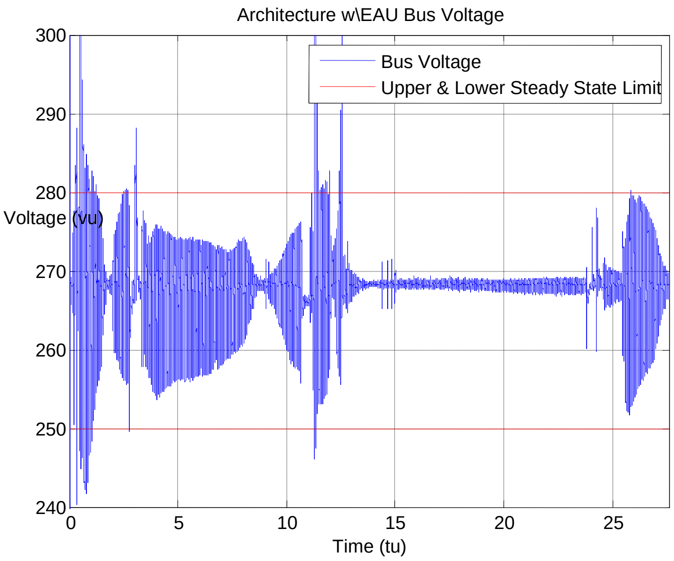

**Figure 14.** Transient Voltage Response for Architecture 2 (with EAU)

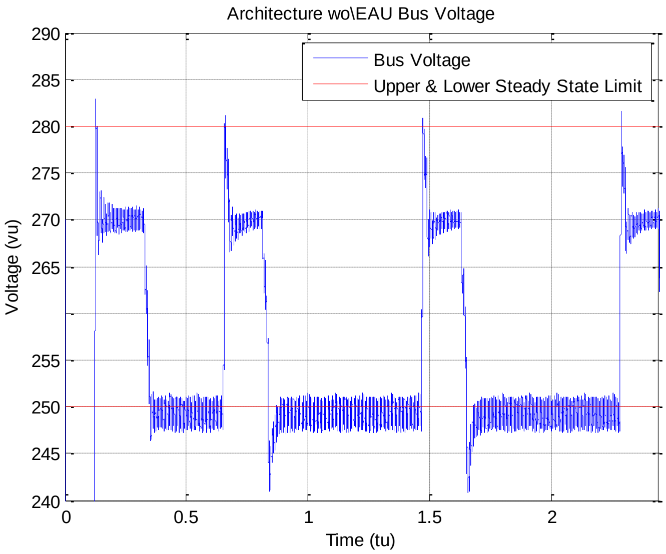

**Figure 15.** Generator Model with Load above Generator Rating and no EAU

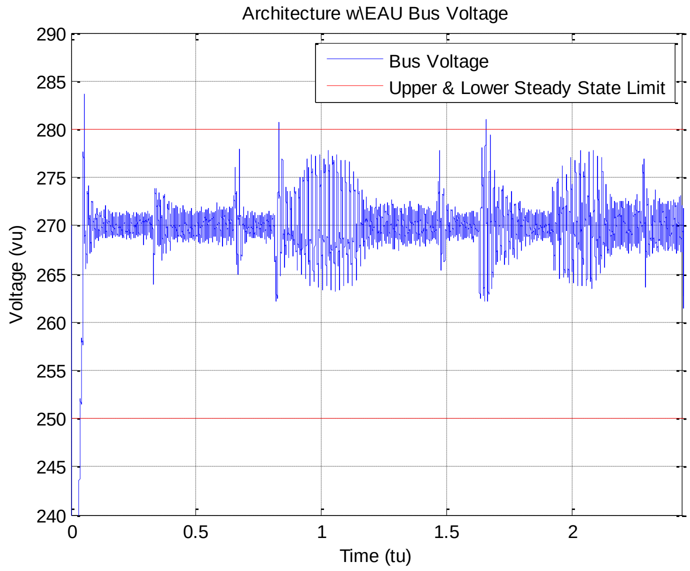

**Figure 16.** Generator Model with Load above Generator Rating with EAU

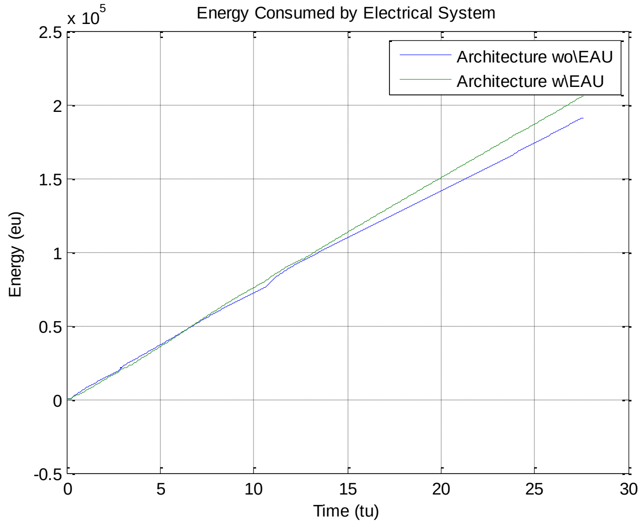

**Figure 17.** Energy used by electrical system

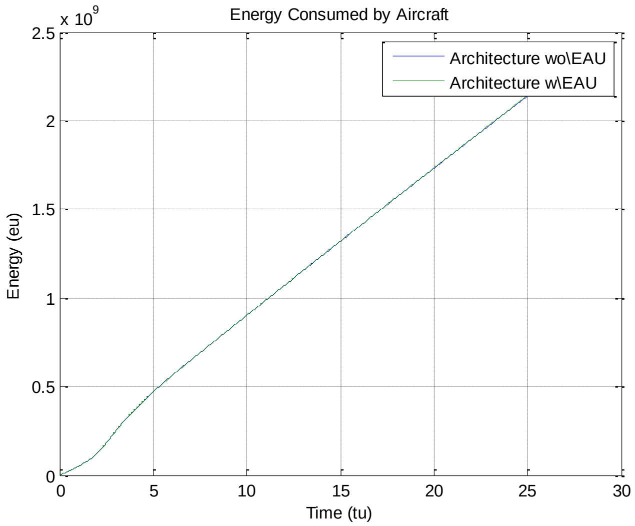

**Figure 18.** **Energy used by entire system**

## 4.0 SUMMARY/CONCLUSIONS

This effort is a first step toward the creation of a tip-to-tail aircraft thermal model. The model includes an aircraft 6 degree of freedom model (6-DoF), a vehicle management system (VMS) model, an engine aerodynamic model, an engine thermal model, a vehicle thermal model (fuel tanks), a power thermal management system (PTMS) model, and various representative aircraft level heat loads. Through this integration effort, a number of lessons learned have been captured to ensure future studies can progress at a faster rate. Lastly, the model created has shown the capability to perform parametric studies that can be used as a basis for future optimizations.

A segment level model of the electrical system including the generator, electrical accumulator unit, feeder lines and electromechanical actuators has been developed. Mission level models of an aircraft and engine were used to offer relevant boundary conditions for the models. Two architectures were examined in this work. The first architecture makes use of an electromechanical accumulator unit to handle the regenerative energy created by the electromechanical actuators. In the second architecture power resistors in the actuator were used for dissipation of regenerative energy. MIL-STD 704F and energy used were utilized in evaluating capability of the two systems. The EAU performance was not as expected due to the high bandwidth power requests from the actuators and lack of an actual regenerative event. Net power requested from generator was always positive. However, no evaluation was done on the impact the EAU would have on system weight (i.e., removal of regenerative resistor circuitry vs. adding of an EAU), thermal improvements (e.g., that could occur by removing the regenerative resistors from the actuators), or any reliability benefits that could be realized (e.g., operations of the aircraft with loss of a generator). Future work will explore some of the bandwidth requirements of the EAU and the aircraft system, validation of the models used in this work, and examination of other methods to handle regenerative energy. Lastly, the integration testing showed that some of the assumptions on the design point of the EAU may be in question. This design point is driven by a number of other subsystems (AVS, HPEAS, and REPS). The integration of transient models helps finds these drivers of system performance and can aid in definition of design points of subsystems.

## 5.0 FUTURE WORK

The present effort represents a first step in modeling and integration of a system level thermal aircraft model. The ultimate goal is to validate both the component and integrated system models against data measured from real-time hardware-in-the-loop test facilities. In turn, validated system level models will allow meaningful optimization studies to be pursued. Toward realizing this goal, future work is planned along a number of fronts, including upgrading the fidelity of the present component models as well as expanding the scope of the analysis to include interactions with the actuation and electrical power systems. Specifically, the vapor cycle model requires additional dynamic modeling to handle transient effects. The engine and the engine FTMS models require similar upgrades to model dynamic performance. Next, there are plans to explore the design and performance of a hybrid APTMS system that would combine vapor cycle and air cycle subsystems in one system. It is believed that a complex trade space such as that for a hybrid APTMS design can be best explored with an integrated aircraft level simulation such as the one developed here. Additional future work for mission level modeling includes plans for other aircraft platforms as well as for the inclusion of actuation and electrical power models.

The next steps for this work involve two items. First, validation of the results will be conducted with the use of an advanced load emulation (ALE) taking the place of the actuators. In this experiment the generator modeled along with EAU and the ALE will be used to replicate the results in the study for validation purposes. In this experiment we will look at the frequency response issues we found with the EAU and validate those are issues and determine if there are means to improve the frequency response of the EAU. Second, a look at regenerating energy to the engine will be examined. In this study, the generator will apply negative torque on the gearbox when large regenerative loads are realized. This study will include a detailed gearbox model. Third, work needs to be performed to understand the frequency content of the power requested by the actuators on an aircraft and what could be done to reduce the frequency content. This work would allow the existing EAU to better handle the power requirements in the system.

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