

Integrated Power and Thermal Management System (IPTMS) Demonstration Including Preliminary Results of Rapid Dynamic Loading and Load Shedding at High Power

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ABSTRACT

An IPTMS hardware facility has been established in the laboratories of the Aerospace Systems Directorate of the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB). This hardware capability was established to analyze the transient behavior of a high power Electrical Power System (EPS) coupled virtually to a Thermal Management System (TMS) under fast dynamic loading conditions. The system incorporates the use of dynamic electrical load, engine emulation, energy storage, and emulated thermal loads operated to investigate dynamics under step load conditions. Hardware architecture and control options for the IPTMS are discussed. This paper summarizes the IPTMS laboratory demonstration system, its capabilities, and preliminary test results.

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INTRODUCTION

Fuel efficiency is of paramount importance for Energy Optimized Aircraft (EOA) of the future. EOA attributes are particularly important for future military aircraft which must fly farther, faster and consume less fuel [1]. More electric aircraft such as the Boeing 787 have proved that electric aircraft appliances can be efficient and reliable on a platform capable of delivering in excess of a megawatt of electrical power. As electrical systems become more prevalent on aircraft [2, 3] the removal of low grade heat becomes more and more important and is less easily accomplished on these aircraft [3, 4], particularly if they are compact, fast-flying military aircraft. In addition to the aeronautical and housekeeping electrical requirements of commercial aircraft, military aircraft of the future must face rapidly escalating weapon electricity demands which can involve short duration megawatt load application and shedding. As these electrical systems are operated, system inefficiencies will generate considerable thermal loads that need to be managed by the TMS. The operating range of the rapid transient load profile to be investigated with the IPTMS, shown in Figure 1, evaluates the electrical power load (P_a) applied for time (L_a), accounting for load application transient time Δt_a and load removal transient time Δt_r . The power rise and fall is typically assumed to be

linear. With the use of load emulation, any load application or removal can be programmed, including multiple power pulses over any defined duty cycle and sequence.

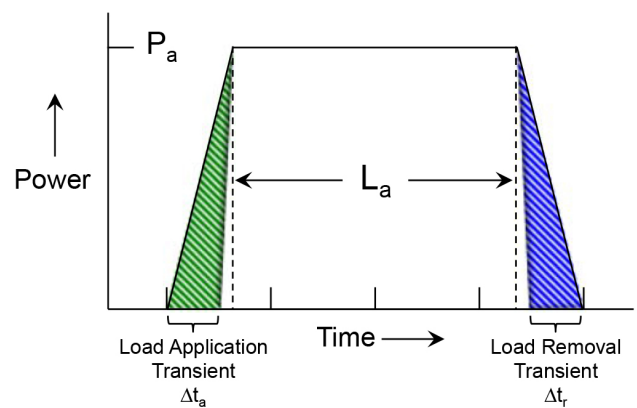


Figure 1. Example of transient load profiles for a single electrical power pulse.

To accomplish EOA efficiency, architectures for military aircraft, which undergo large dynamic electrical and thermal load, can be dramatically different than for quasi-steady loads. Both electrical and Thermal Energy Storage (TES) must be optimized to manage dynamic

loads. Moreover, electrical system dynamics generated by high-power fast dynamic loads can have significant implications for both the control and operability of the coupled turbomachinery; when not anticipated in engine system design requirements, such fast dynamic loads can lead to engine surge conditions, rotordynamic excursions, and faults in the Full-Authority Digital Electronic Control (FADEC).

To better understand high-power rapid dynamic loading of aircraft electrical and thermal systems, an experimental laboratory has been established by AFRL to investigate the system interactions of an IPTMS. To minimize initial laboratory cost, both EPS and TMS subsystems were constructed of predominantly commercial off-the-shelf (COTS) equipment. A real-time turbine engine emulator controlled a dynamometer, which provided shaft power to an electrical generator. Both steady state and dynamic thermal and electrical loads were emulated, providing significant flexibility. The EPS has a capacity in excess of 400 kW and the equivalent TMS is capable of managing 240 kW of heat waste.

Modeling and Simulation (M&S) are very important parts of this work for both the component and system level. M&S has proved valuable in the early stages of checking out the IPTMS by enabling quick resolution of control and dynamic issues. Eventually validated M&S should enable credible tradeoffs of Size, Weight and Power (SWaP) which are of critical importance to military trade studies before designs of future military aircraft are executed in hardware.

IPTMS ARCHITECTURE

The IPTMS laboratory's architecture anticipates the requirements of future aircraft power and thermal applications [1]. Military power and thermal architectures must respond to more challenging conditions than commercial architectures [2, 3]. The selected IPTMS architecture is primarily oriented toward military applications where megawatt-class rapid-transient power may be demanded.

Economical development of such significant capability within the existing laboratory facilities at WPAFB required compromises. In addition to maximizing the use of COTS hardware, both the turbine engine and the rapid dynamic electrical and thermal loads were accomplished by emulation, which eliminated large amounts of capital expenditures. Available AFRL capabilities were also exploited, including an electric motor drive stand capable of delivering up to 660 kW shaft power for a generator and a Vapor Cycle System (VCS) equipped to provide cooling to multiple dynamic loads.

Because the drive stand and the VCS were separated by approximately a city block, the EPS and TMS subsystems needed to be virtually integrated via a digital link by a System Level Master Controller (SLMC). A rendering of the EPS and TMS laboratories coupled by the digital link for real time integration is shown in [Figure 2](#). The EPS drawing shows the emulated components above the mezzanine, which include the dynamic electrical load bank and the motor drive electronics for the drive stand which emulates a turboshaft gas turbine engine. The EPS components located below the mezzanine include the existing electric motor drive stand, the

battery, power rectification/conversion units and the generator. The left side of the TMS drawing is the existing VCS while the right side depicts the remainder of the TMS.

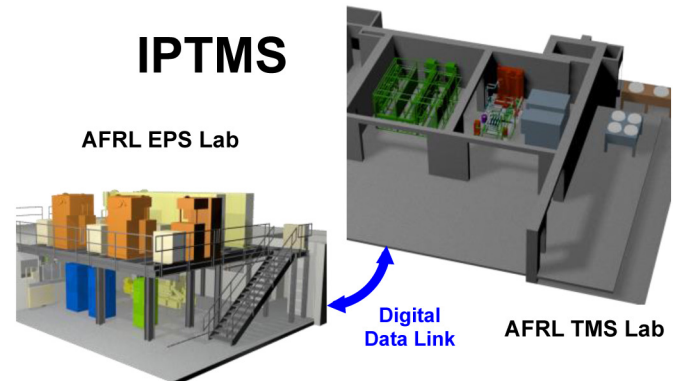


Figure 2. An artist's concept of the IPTMS as configured in hardware at AFRL.

Commercial hardware has been utilized for the majority of the hardware components. Exceptions to commercial hardware include the TES modules, which required development since none were commercially available for this service, the DC to DC power converters, and the Thermal Load Emulator (TLE) was designed to simulate rapid dynamic loads in excess of 240 kW equivalent to the 400 kW EPS.

The IPTMS demonstration hardware and SLMC have been installed. The SLMC was being checked out at the time of the writing of this paper. The data presented below must still be considered preliminary because the data were obtained with some manual operation and some emulation of the hardware components. Description of the IPTMS architecture is subdivided below for the EPS and TMS remembering that they will be coupled by the digital data link when the SLMC becomes fully operational.

[Figure 3a](#) shows the component layout of the simulated electrical and thermal subsystems. The IPTMS is operated by specifying a power demand on the transient electrical load emulator of the EPS with a corresponding transient thermal load on the TMS TLE. This electrical power is extracted from a DC bus that is actively regulated and fed by the electrical generator which is driven by the electric motor drive stand commanded by the turbine engine emulator. A battery provides additional power to stabilize the electrical bus and to provide a buffer to improve turbine engine operability. The heat generated from the TLE and the ancillary TLE in the TMS is transported to and stored in the TES which significantly reduces the peak heat load through the evaporator to the VCS that ultimately sinks to air via the condenser. [Figures 3b](#) and [Figure 3c](#) illustrate the load cross coupling of the EPS and TMS for the complete IPTMS operation. In [Figure 3b](#) electrical power required from the EPS to drive pumps and the VCS compressor of the TMS is simulated by the EPS auxiliary load emulator so that the EPS must also respond to the rapidly changing electrical consumption of the TMS. In [Figure 3c](#) the transient thermal loads of the EPS components are communicated to the ancillary TLE so that the TMS must also respond to the rapidly changing thermal losses in the battery, DC-DC converters and the rectifier. The electrical power generator and turbine engine thermal losses are

assumed to be handled by the turbine engine cooling loop that is not represented. It was not economically feasible to cross couple all the EPS thermal loads and the TMS electrical loads, so only the most critical dynamic loads are represented.

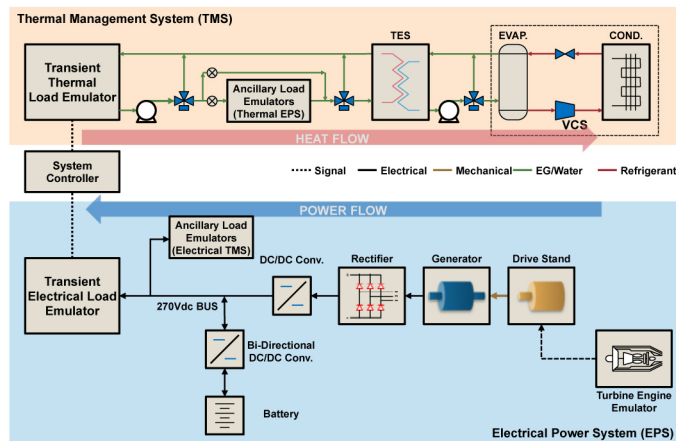


Figure 3a. A simplified IPTMS block diagram shows the separated EPS and TMS subsystems with electrical power flow and heat flow.

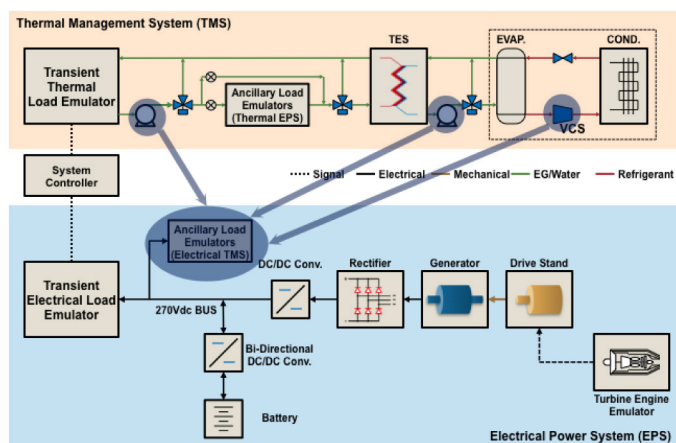


Figure 3b. TMS Electrical Loads captured on EPS Ancillary Load Emulator.

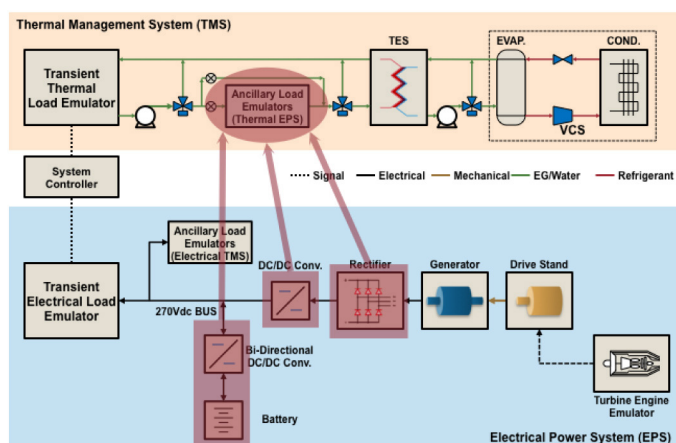


Figure 3c. EPS Thermal Loads captured on TMS Ancillary Load Emulator.

It is important to note that this IPTMS demonstration was designed for a federated system: The IPTMS demonstration does not include other aircraft housekeeping or flight actuator loads [1]. A generic electrical load profile range is shown in Figure 1 to assess the dynamic performance of the IPTMS.

EPS DETAILED ARCHITECTURE

The investigation of dynamic response in the EPS demands a rapidly responding electrical load. The EPS includes a modular transient electrical load emulator, which has been demonstrated to respond in 10 msec. The main part of the load emulator is made up of five modules, each capable of managing 80 kW of transient load. The load modules can be commanded individually or in concert to match electric load profiles of the type shown in Figure 1. Five identical 80 kW load banks, as presented in Figure 4, were purchased and modified for IPTMS test purposes from Energy Development Associates (EDA). In addition a 30 kW EDA load is available to simulate ancillary electrical loads associated with the TMS electrical requirements.



Figure 4. One module of the load emulators used by the EPS showing the load emulator and associated transformers.

This unique EDA dynamic electric load is essential to assess the dynamic response of the IPTMS. The shortest response time requires detailed controlled response in matching the EDA loads to the rest of the EPS. The EDA loads are configured to return electrical power back to the utility grid while performing as a flexible electric load for IPTMS. The AC line transformer, as seen in Figure 4, coupled to the EDA load modules is required to convert delta to wye 3-phase.

Additional dynamic load capability is now becoming available in a 30 kW advanced load emulator and 100 kW Advanced Power Emulator (APE). These rapid response loads, combined with the greater than 400 kW EDA loads, can provide a suite of simulated loads of various power levels and dynamic responses with which to assess the IPTMS performance under highly dynamic load conditions.

A gas turbine engine emulator is employed to command a dynamometer which drives the rotating electrical power generator. The scope of the IPTMS could not include turbine engine hardware so LibertyWorks provided the engine emulator shown in Figure 5. The engine used for the baseline IPTMS investigation was a Rolls-Royce Allison AE1107-C turboshaft turbine engine. This engine was selected primarily for its existing validated real-time transient engine modules, which had been used in previous military and defense large scale emulation packages. This engine is rated for more than 4 MW shaft power. The engine emulator is coupled to the IPTMS using a scale factor, allowing investigation of a wide range of percent engine shaft load to be investigated. Specifically, engine loading from 10% to 100% capacity is under investigation so as to explore engine operability limits under fast transient conditions. During operation, the real time rotor model delivers speed requests to the drive stand motors through their electronic drives. The motor then turns the generator, as commanded by the engine emulator, and provides electrical power to the EPS as demanded. The electrical response to the power demand is translated into shaft torque, which is fed back to the engine emulator, which responds as if the engine were under an actual shaft load.

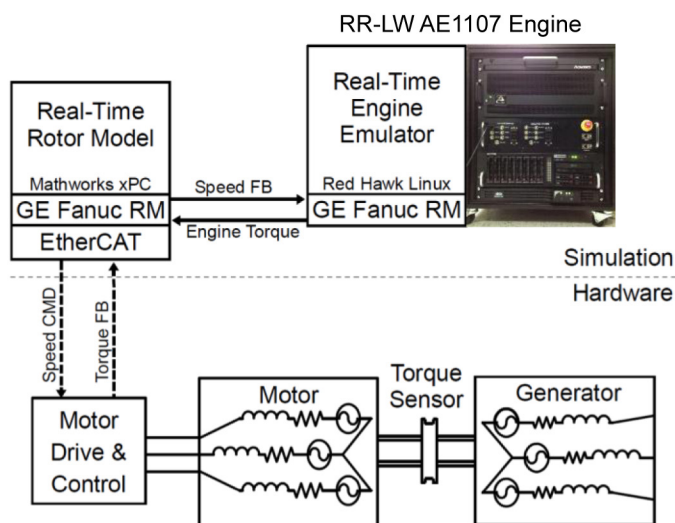


Figure 5. Coupling of engine emulator to existing drive stand and generator.

To impart shaft power to a generator with emulation of engine shaft torque and speed, an engine emulator commands an electronic drive of a 660 kW drive stand which can be split into 2 separate drive motors of 330 kW each, as seen in Figure 6. The Torquemeters Inc. drive stand is very low inertia and can be reversed in less than a second, which allows it to simulate low inertia aero derivative engines. This fast response drive stand is adequate to follow the engine emulator commanded acceleration and speed. The drive stand is equipped with a torque sensor to convey the mechanical load torque back to the real-time simulation. The real-time rotor model provides the link between the simulated dynamics of the engine and the measured dynamics of the generator. The rotor model uses Newton's law of rotational motion to translate the simulated engine torque and the measured generator torque into a shaft speed that is then used both by the engine model and drive stand. Accurate

characterization and modeling of the EDA load and the LibertyWorks engine emulator is critical to system level validation of system interactions and emulator artifacts.



Figure 6. The drive stands (a) and the motor controllers (b) utilized in IPTMS. The engine emulator controls this hardware.

The generator shown in Figure 7 is a commercial Synchrony 300 kW synchronous AC generator, which delivers 480 VAC at high frequency. A 500 kW rectifier was built at AFRL. A 400 kW power converter controls the rectifier power flow to the 270 VDC bus as shown in Figure 8. The 400 kW DC-DC power converter was designed and built by LibertyWorks and utilizes four 100 kW Semikron switched electronic modules designed for automotive service. While the DC-DC power converter is sufficient for initial IPTMS testing, demonstration activity has revealed limitations of the original controls, leading to improvements such as additional customization of droop-control tuning, new feed-forward terms, increased-frequency operation, and an optional master controller.

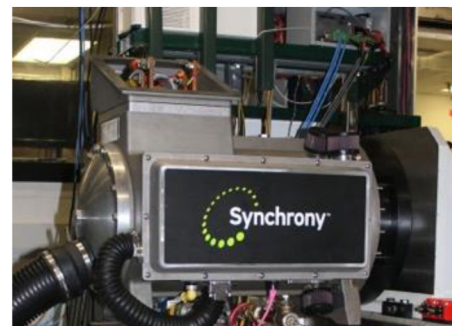


Figure 7. The 300 kW Synchrony electrical generator installed on the motor drive stand provides electrical power to the IPTMS.

To manage power quality and voltage limits, a 537 kW Li-polymer battery was supplied by XALT. Additionally, it is used in the IPTMS tests to evaluate the blending of battery and generator power to mitigate the turbine engine limits that prevent it from accepting instantaneous high-power demand transients. The battery can also be recharged with excess turbine engine power from the generator when the shaft load is rapidly removed. This battery is comprised of ten line replaceable units as shown in Figure 9. The battery system can be split into two independent batteries. The battery was required to supply at least 300kW at a duty cycle of at least 20% for at least 120 seconds. The cells are rated to deliver up to 537kW with a maximum voltage capability of 617 VDC and a minimum of 397 VDC; however, the bus is currently fused at 350 Amperes. The cell modules are passively cooled in the laboratory environment, for this reason heavy use of the battery system may require overnight cool down.