

# Mitigating Power Systems Variability in More Electric Aircraft Utilizing Power Electronics Implemented Dynamic Thermal Storage

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**Abstract**—Increased power levels in more electric aircraft (MEA) bring opportunities to optimize energy flow in multi-physics domains to benefit the power system’s stability and aircraft fuel economy. This paper introduces thermal energy inherent in the cabin air and aircraft fuel as a dynamic management solution to offset stochastic load power in the MEA power system. Focus is on power electronic controlled environmental control system (ECS) drives, which can provide dynamic thermal inertia and act as an effective electric swing bus to mitigate power variability. The generator’s output power becomes substantially more constant as a result, decreasing the demand from fast generator responses or dedicated energy storage such as batteries. In practice, the motor drives operate on a suitable bandwidth in the sense of filtering unwanted frequencies in the stochastic energy band. The lower update frequency limits air temperature variations in the cabin, and the higher update frequency, combined with ramp-rate and acoustic limits, lets the ECS to respond without generating annoying noise. A high-level implementation builds upon a feedforward control loop. A more sensitive virtual synchronous machine concept added to the loop boosts desirable inertia in the MEA power system. The combination is illustrated in simulation and with experimental results based on realistic load power demand over a mission profile using Boeing 787 as a platform.

**Index Terms**—More electric aircraft (MEA), environmental control systems (ECS), thermal storage, power systems energy storage, power electronic drives, complex system energy management

## I. INTRODUCTION

MORE electric aircraft (MEA) development, such as the Boeing 787, has resulted in nonbleed architectures in which traditional pneumatic systems are replaced by electrical systems [1]. Because of this change, the largest motors and power electronics converters are for the environmental control system (ECS), which contains compressors, fans, pumps, and heat exchangers [2]. The ECS along with other loads requires peak power approaching 1.00 MVA from four engine-tied generators. With auxiliary power units (APU) for ground support and redundancy purposes, a total of 1.45 MVA is installed on the Boeing 787 compared to 0.35 MVA on the Boeing 777 [2]. Increased power ratings challenge the stability and optimal management of an aircraft power system. Similar to a microgrid, the Boeing 787 power system must address

power generation limits as well as limited system inertia when power variation occurs. Onboard electrical loads can change quickly relative to the total generation capacity. Generators are often oversized to accommodate transients and short period overloads. Generators are less efficient and impose extra fuel consumption under these derated conditions. To help mitigate the load-side power variability, external storage solutions have been proposed, such as batteries, fuel cells, flywheels, etc. [3], [4] However, these introduce extra volume, weight, costs, and impose reliability issues.

In energy systems, integration across multiple energy domains has increased the degrees of freedom available for control. For example, many systems (e.g., buildings and aircraft) have enclosed spaces containing large volumes of air or liquid (e.g., water and fuel tanks). The air and liquid hold thermal energy, which can be controlled to consume more or less electrical energy via a power electronic enabled electrical-mechanical-thermal mechanism [5]-[9]. Hence the thermal storage carries a potential to act like an electrical swing bus and to boost power system inertia. The most obvious effects of changing stored thermal energy can be observed in increase or decrease of room temperature, while such temperature fluctuation is maintained in a small range to avoid occupant discomfort.

Recent research activities [5]-[8] utilize building HVAC (heating, ventilation, and air conditioning) systems as energy management of building thermal storage and discuss grid-side benefits. Emphasis is on enhancing electric grid regulation with reduced external assistance from spinning reserves. Research in [9]-[13] extends the idea by offsetting onsite stochastic solar power generation through HVAC filtering concepts in energy-efficient buildings. Focus is on determination of a feasible bandwidth and implementation of a realistic controller incorporating motor drive controlled HVAC systems. In [9]-[11], temperature and acoustic constraints are studied, and strategies that reduce conventional energy storage such as batteries are explored. By taking advantage of existing thermal storage and installed variable frequency drives, mitigation of source and load variability in power systems is relatively cheap and easy to implement. This concept has not been explored for mobile applications such as transportation.

An aircraft can be considered a “flying building” that encloses a large volume of air and liquid (fuel tanks). The ECS is equivalent to a building HVAC system. Thus, the same

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thermal storage, creating useful power system inertia, as described above can be applied to MEA, although there are noticeable distinctions. One difference between MEA and energy efficient buildings is power variability shifting from the source side to the load side. Jet engines operate with slow, intentional changes in power, but electrical loads can change substantially within a short period relative to the total on-board generation capacity. Many aircraft loads are generally predictable due to pre-programmed flight missions. A second difference, or rather an advantage, comes from fixed sizes of existing aircraft. Unlike buildings of many shapes and usages, the limited commercial configurations of MEA simplify estimation of thermal storage filtering bandwidth as well as motor characterization for controller look-up tables. A third difference is the airtight enclosure in MEA. This adds degrees of freedom in controlling cabin air pressure (i.e., thermal mass), and separates thermal storage into multiple zones (e.g., passenger and cargo). In this paper, the emphasis is on the first difference – implementation of power electronics to control thermal storage, particularly temperature related, as an effective means to mitigate variability in MEA power systems using the ECS (including fans, pumps, compressors, etc.).

## II. ROLE OF THERMAL STORAGE IN MEA POWER SYSTEMS

It is important to first recognize some properties of the thermal storage to be integrated in an MEA power system. As described in Section I, air and fuel enclosed in an aircraft can be treated as thermal storage. These thermal masses are inherent and thus do not introduce extra weight or cost. Power electronics, including converters and control, links thermal storage to the MEA electric grid, as shown in Fig. 1. The MEA electrical power system includes the generator and dc power systems connected to the distribution system, which interfaces 28 V and 270 V dc buses, 115 V and 230 V ac buses, and provides power to the fans, pumps, actuators and other general loads, as described in Fig. 2. When ac or dc loads change, thermal storage can replace part of the role of the generators or batteries to match a portion of load power variations. As a result, a relatively constant load is imposed on the generators. Although batteries are not used for power balancing on the Boeing 787 [1], future aircraft described in [2] will benefit from less battery dependency in this regard.

There are certain limitations of thermal processes used to mitigate variation. One is that the proposed thermal storage approach does not provide energy back to the grid. The premise is that thermal masses consume a nominal power with the flexibility to draw more or less power (e.g., ECS fans blowing warm or cold air faster or slower). In another word, the “nominal power” here can be viewed as the “zero average power” as provided by the engines so that the thermal storage can have the same effect as a bidirectional power source or load about this nominal, hence the valid double arrows as displayed

in Fig. 1. In prior work, this effective bidirectional action of a unidirectional energy process has been termed “virtual storage” [9].

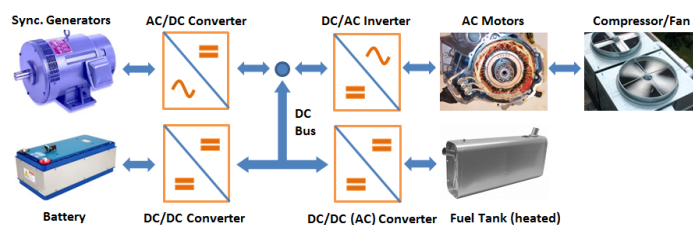


Fig. 1. Energy storage and conversion in the proposed energy system.

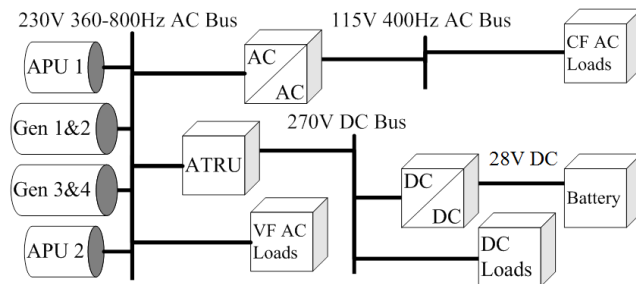


Fig. 2. Boeing 787 electrical power system architecture [1], [2].

Another limitation is that only a certain bandwidth of power variation can be mitigated by thermal storage when treating the ECS system as a power filter. A lower frequency limit, meaning the slowest update rate for ECS fan speed and power commands, is established to shield passengers from substantial temperature or pressure swings, ideally keeping variations imperceptible. An upper frequency limit, meaning the fastest update rate for ECS fan speed and power commands, is needed such that the following conditions are met: 1) ECS drives must be capable of responding, 2) undue wear and tear is not imposed on drives or mechanical parts, and 3) update rates avoid discomforting audible pitch or amplitude changes. Larger-scale thermal storage units such fuel tanks could be used to absorb excess energy change when the ECS reaches its lower frequency boundary. In [6], [7], [9], [11], [13], the thermal storage filtering bandwidth and its impact on the overall energy mitigation capability has been explored. In particular, [7], [9], [13] agree that  $\sim 1$  mHz-2 mHz (the inverse of about 10-15 min) is an appropriate lower frequency bound, and [9], [11] determined that  $\sim 0.1$  Hz (the inverse of  $\sim 10$  s) is a suitable higher frequency bound. In addition, motor drive ramp-rate limits and amplitude limits are imposed to further restrict energy flow [9]. In this paper, the same lower and upper frequency bounds and other limits are assumed. However, ECS filtering capability is likely to improve compared to the HVAC system in a solar powered building because 1) fewer rapidly varying electrical loads generate counterproductive impacts, and 2) the aircraft size, mission profile, and weather sensitive loads are known in advance.

A fundamental advantage of ECS adjustment for effective dynamic thermal storage is that it is relatively easy to



from the control diagrams in Fig. 5, given the instantaneous output currents ( $i_{ga}$ ,  $i_{gb}$ ,  $i_{gc}$ ) and rotating frequency ( $\omega_g$ ), as well as desired real power and reactive power. The main equations are the VSM torque ( $\tau$ ) and angle ( $\theta$ ) calculations, including the damping factor ( $D$ ):

$$\tau_{vm} - \tau_{ve} = \frac{J}{p} \frac{d\omega_r}{dt} + D(\omega_r - \omega_g) \quad (4a)$$

$$\theta_r = \theta_0 + \int_0^t \omega_r dt \quad (4b)$$

where  $J$  is the VSM moment of inertia, and  $p$  is the pole pair. Note that  $J$ ,  $p$ ,  $D$ , and  $M$  values can be arbitrary but should be chosen in realistic ranges so that the converter performance is not compromised. Instantaneous output real power and reactive power are given by

$$P = \frac{3}{2} M i_f i_q \omega_r = \tau_{ve} \frac{\omega_r}{p} \quad (5a)$$

$$Q = \frac{3}{2} M i_f i_d \omega_r \quad (5b)$$

For in-depth discussion of VSM approaches, see [15], [18].

#### IV. MODELING OF MEA ELECTRICAL-THERMAL POWER SYSTEMS WITH DYNAMIC THERMAL STORAGE

Demonstrating the thermal storage benefit for MEA power systems requires system-level power flow tools. Multi-physics domain (i.e., electrical, thermal, mechanical, hydraulic) modeling and simulation provides one means to test the efficacy. The electrical subsystem must include generators, power converters, motor drives, motors, and electrical loads, while the thermal subsystem must accurately provide temperature, air and liquid flow, and pressure information. It is desirable to develop an accurate and fast model that captures the dynamics of multiple energy domains over the course of candidate mission profiles.

The model meeting the criteria to be used is a retrofitted Boeing 787 system model [19] developed from an in-house Boeing 737 model [20]-[21]. Major changes in the MEA electrical system include a variable voltage variable frequency 230 Vac (nominal) bus from the main generators, a 270 Vdc bus and its attached motor driven loads, and an ac-dc-ac conversion process from the 230 Vac bus to a regulated 400 Hz 115 Vac bus, as matched in Fig. 2. In the thermal system, pneumatic compressors, pumps, and fans are replaced by electrical motor based mechanisms.

The electrical power system contains the exciter/generator and dc power systems connected to the electrical distribution system, which interfaces the 28 V and 270 V dc buses and 115 V and 230 V ac buses, and provides power to the fans, pumps, actuators and other general loads. Each component has power loss models interfacing with the ECS to track the total rejected heat within the aircraft thermal model. Engine models provide the low-pressure spool and APU speeds and deliver the load

torque to the generators. Fig. 6 shows the electrical load distribution (kW) and major energy conversion efficiencies (%) in Boeing 787 at a nominal cruising condition [22]. This chart provides scaling information for model development as well as a basic data check for simulation results.

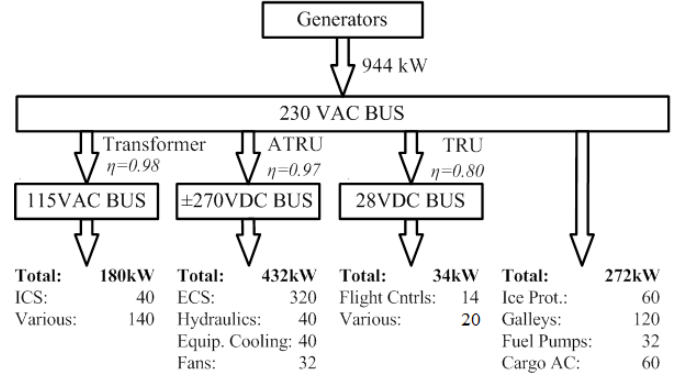


Fig. 6. Typical electrical system loads and efficiencies at cruise condition in Boeing 787 (data from [22]).

Fig. 7 highlights the electrical system and its interaction with other mechanical and thermal systems. The combined electrical-thermal model must run fast but not lose necessary information. Thermal models usually have step rates of seconds or slower, whereas electrical models step at microseconds to milliseconds. To address this, steady-state and dynamic behaviors of electrical components are captured by averaged switching modeling and  $dq0$  reference frame techniques, without sacrificing computational speed. For complete model details, see [19]. Although temperature behaviors of electrical components are described in [19], thermal analysis at the aircraft cabin level was not addressed.

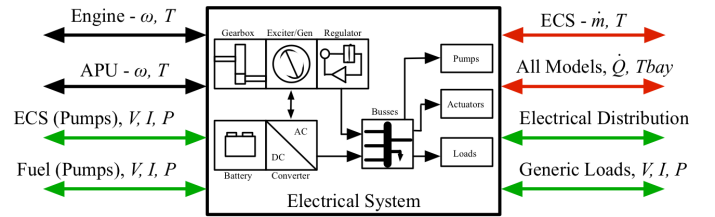


Fig. 7. Electrical power system diagram in MEA.

A thermal management system is required to model the ECS, including temperature, pressure, and air flow dynamics. The system contains air-air heat exchangers, valves, compressors, passenger cabin models, re-circulation fans and mixing junctions. Some of the components, such as fans and cabin, are linked to the electrical system through thermal/electrical sinks and sources. Also modeled are the fuel and oil cooling systems. The fuel system supplies fuel to the engine in addition to acting as a thermal sink for heat loads. A high-level of the thermal system described is shown in Fig. 8.

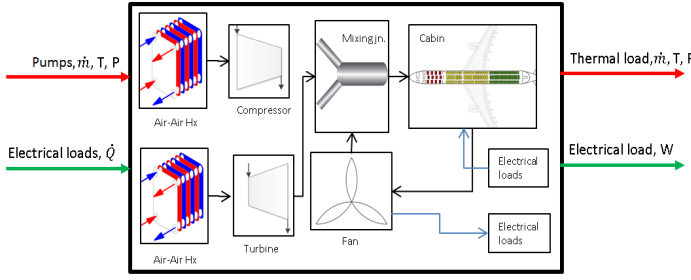


Fig. 8. Thermal management system diagram.

The passenger cabin model is a 1-D lumped parameter model, whereby the properties of the air inside the cabin are considered as uniform throughout the cabin. The pressure and temperature inside the cabin are derived through conservation of mass and energy inside the control volume (cabin). The passengers inside the cabin are considered as the source of sensible heat. Heat transfer due to radiation and due to kinetic heating is accounted through approximate heat transfer coefficients. In most aircraft systems, conditioned air (subscript  $SA$ ) is supplied to the cabin at desired pressure and temperature. A fraction of the supplied air, known as the recirculated air (subscript  $RA$ ) is driven out of the cabin by fans and is mixed with the upstream supplied air. The cabin pressurization is maintained by ejecting the rest of the cabin air (subscript  $EA$ ) to the environment. The energy and mass balance inside the cabin is given by the differential equations

$$\frac{dT_{cabin}}{dt} = \left( \frac{\dot{m}_{SA} C_{P,SA}}{m_{cabin} C_{P,cabin}} \right) T_{SA} - \left( \frac{\dot{m}_{RA} C_{P,RA}}{m_{cabin} C_{P,cabin}} \right) T_{cabin} + \left( \frac{n_{passenger} \dot{q}_{passenger}}{m_{cabin} C_{P,cabin}} \right) \quad (6)$$

$$\frac{dm_{cabin}}{dt} = \dot{m}_{SA}(1 - RAR) - \dot{m}_{EA} \quad (7)$$

where  $T$ ,  $m$ ,  $C_p$ ,  $q$ , and  $RAR$  stand for temperature, mass, specific heat, heat flux, and recirculation ratio, respectively.

## V. SIMULATION STUDIES AND HARDWARE IMPLEMENTATION

A five-hour flight (or mission) profile was used to test the modeled electrical-thermal system. Electrical load magnitudes are based on Boeing 787 total electrical loading variations documented in [22]. Fig. 9 shows total electrical loads on all generators for various flight phases under maximum ice conditions. With the Boeing 787 having 1 MVA installed generator capacity, these conditions are near maximum operational capability. From the figure, there exist a few tens of kVA differences among the six flying conditions, and one non-cruising event may last many minutes.

Notice that the ECS and fans together consume approximately 350 kVA. Hence the power difference and event duration seem to fit in the thermal storage filtering capability. Also there are brief periods when total power drops or increases noticeably. For example, as landing gear is retracted the ice protection is turned off briefly, resulting in a dip in the load.

Events such as this require extra inertia in the power system to ensure stability. Using Fig. 6 and Fig. 9 as reference, a customized baseline electrical loading profile is generated for this 5-hour flight, as shown in Fig. 10, which includes taxiing, taking off, climbing, cruising, descending, and landing.

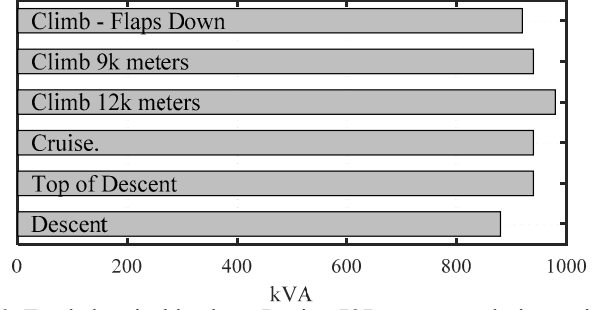


Fig. 9. Total electrical loads on Boeing 787 generators during major flight segments with maximum ice conditions (data from [22]).

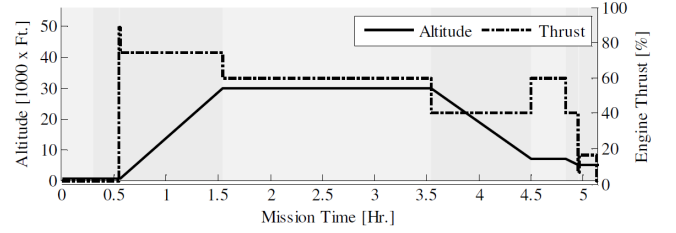


Fig. 10. Mission altitude and thrust settings for simulation of aircraft power flow [20].

For this paper, the proposed power electronics control laws discussed in Sections II and III for thermal storage integration are incorporated with the Boeing 787 model. Fig. 11 shows one generator's output power with and without the ECS thermal storage mitigation of load power variability. With the assistance from the thermal storage, the generator avoids power variations in the bandwidth of 1 mHz to 1 Hz (inverse of 15 min to 1 s). Dynamics faster than 1 Hz may seek buffering from batteries although the battery size is limited compared to what would be required without thermal storage. Slower dynamics can take advantage of the fuel and oil heating systems. In Fig. 12, cabin temperature is plotted for both scenarios. It can be observed that there are periods when up to 3 °C changes due to long and large power variations, while during the majority of the mission only minor temperature fluctuations occur.

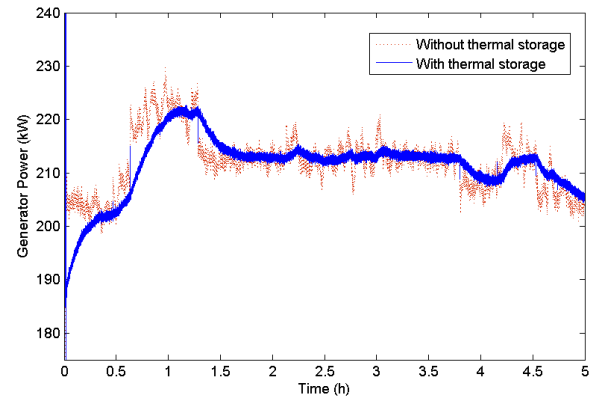


Fig. 11. One generator output power during the mission.

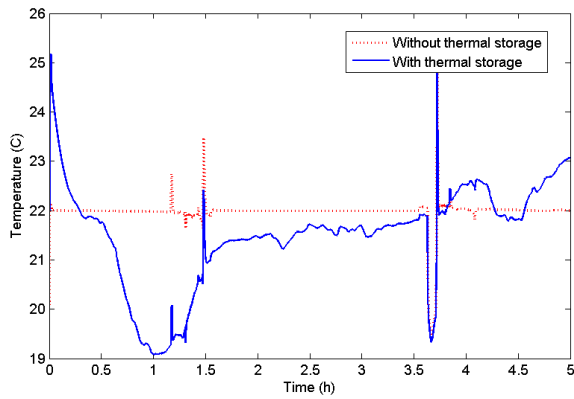


Fig. 12. Cabin temperature change during the mission.

To demonstrate and validate the potential of dynamically controlled ECS thermal loads that implement mitigation of stochastic energy content, a small fan drive was used to follow scaled responses to various band-limited load power profiles. A programmable commercial grade three-phase 480 V Yaskawa Z1000 drive was characterized, and a 1/2 HP, three-phase, four-pole, induction machine was coupled with a squirrel-cage fan tied to a 4 m duct, representative of typical blowers found in full-scale air conditioning systems. For direct tests, the drive with motor and duct was fed with two speed command profiles for approximately two hours. As shown in Fig. 13, the first speed profile is a piecewise constant signal to represent conventional loop control, and the second speed profile implements the ac signal injected control loop. The ac signal is generated from band-passed (1 mHz to 1 Hz) load power.

Experiments collected two sets of power consumed by the fan system and measured the difference, which represents the fluctuating power to be mitigated. This measured power difference and the modeled result are plotted in Fig. 14. Except during short transients when the motor steps, the modeled curve follows the experimental curve closely, providing an accurate basis for a large scale simulation and hardware realization.

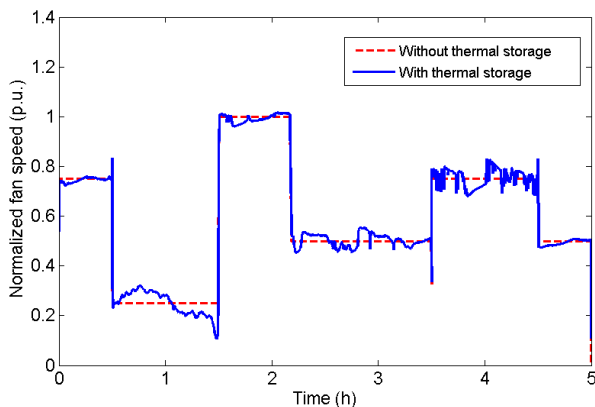


Fig. 13. Fan drive speed responses with and without dynamic thermal storage.

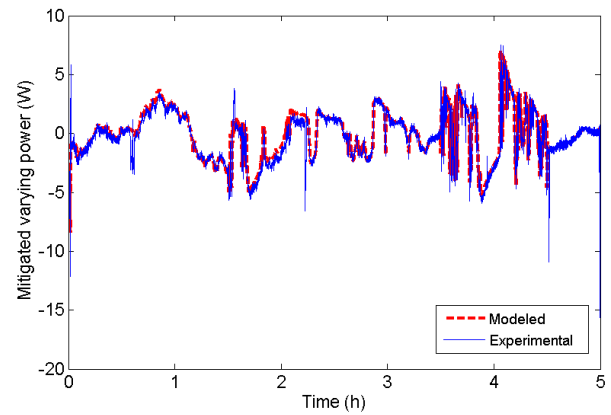


Fig. 14. Experimental results for power difference consumed by the fan drive between the two speed profiles.

## VI. CONCLUSION

This paper discusses the use of power electronics to implement dynamic thermal storage to offset varying generator load power in MEA, resulting in relatively constant generator power consumption and a robust onboard power system. The paper builds on recent work [5]-[11] to set up a dynamic energy balancing and storage solution linked to ECS systems. In a practical implementation, the ECS system-tied power electronics is controlled via a simple bandlimited power injected feedforward loop. For fast transients to boost the power system inertia, a VSM concept is included. A system-level electrical-thermal model developed from [19]-[21] on Boeing 787 serves as a suitable platform to demonstrate the thermal storage concept using a sample five-hour flight mission. Scaled fan drive experiments implement the power electronics controls and provide a basis for future realization.

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