Final Scientific/Technical Report

Ampaire

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CIRCUITS

DE-AR0001199

Award	DE-AR0001199
Sponsoring Agency	USDOE, Advanced Research Project Agency – Energy (ARPA-E)
Lead Recipient:	Ampaire Inc
Project Team Members	Ed Lovelace, Ben Grabowski, Arindam Chatterji, Alex Chapman
Project Title:	ARPA-E ELECTRIC FLIGHT TESTBED
Program Director:	Dr. Isik C. Kizilyalli
Principal Investigator:	Dr. Edward Lovelace
Contract Administrator:	USDOE, Advanced Research Project Agency – Energy (ARPA-E)
Date of Report:	06/23/2023
Reporting Period:	02/24/2020 – 06/23/2023

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0001199. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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Public Executive Summary

A hybrid-electric aircraft flying testbed was developed in this program with the intent to serve as a dedicated, enduring testbed to test and evaluate ARPA-e CIRCUITS Program and other electrified aviation technologies in relevant flight environments. This testbed enabled rapid development cycles of novel and innovative technologies in the electrified aviation space, maturing them from a research lab environment to flying in an aircraft. By providing research groups with the means to test their transformative technologies in a real-world, aircraft environment, the path to validating the safety and reliability of their technologies for future commercial opportunities was greatly accelerated.

Three core technologies were integrated and tested: an inverter/motor drive built by the University of Arkansas, a solid-state circuit breaker (iBreaker) built by the Illinois Institute of Technology, and a Flying Capacitor Multi-level (FCML) DC/DC converter built by the University of California, Berkeley. In each of these cases, the requirements established for safety of flight resulted in a holistic approach to the designs, evoking a deeper understanding of the potential failure modes and mitigations necessary to build a robust and flightworthy system. Further, the integration into a hybrid-electric aircraft de-risked the potential electrical and mechanical issues that cannot easily be experienced or replicated in a lab environment. The experiments were also required to undergo representative temperature, shock, and vibration testing as the FAA prescribes for this category of aircraft, facilitating familiarity with the relevant design and test guidelines necessary to commercialize the technologies.

This testbed unlocks the massive potential of core power electronics technologies necessary for a safe, robust, and efficient electric aviation future. With quick iterative design, test, and flight cycles, these core technologies are on a quicker path to technology readiness level maturity and commercialization, enabling a more sustainable future for the aviation industry.

Acknowledgments

Ampaire would like to acknowledge ARPA-e for its financial and technical support through this program. Additionally, Ampaire would like to acknowledge the CIRCUITS participants: the University of Arkansas, Illinois Institute of Technology, and University of California, Berkeley for their participation and collaboration.

Accomplishments and Objectives

This award allowed Ampaire Inc, in collaboration with the University of Arkansas, Illinois Institute of Technology and University of California, Berkeley to demonstrate a number of key objectives. The project focused on building an In-Flight Aviation Testbed Platform for ARPA-E Programs in Power Electronics. At the beginning of the project, a number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables. The actual performance against the stated milestones is summarized here:

Tasks	Milestones and Deliverables
M1.1 Go/No-Go: Refine tasks, milestones, and experiment schedule. Subtasks: • Refine tasks and milestones for the work plan. • Develop a detailed experiment schedule to ensure the timely execution of the experiments and tests.	Actual Performance: Completed [02/05/2022]: • Tasks were refined to provide CIRCUITS team's requirements and each team's progress was tracked using an MS Project file up to the final report submission. • This milestone is complete
M2.1 – Q1: Component Installation Specifications Report Subtasks: • Define and document specifications for CIRCUITS project components to be installed and tested on Aviation Testbed. • Selection of CIRCUITS projects to be tested on the Aviation Testbed. • Coordination of CIRCUITS components testing plans and interface details. • Acceptance of a component specification report by ARPA-E.	Actual Performance: Completed [06/23/2023]: • Component specification documents created and submitted along with the final report for acceptance by ARPA-e. • These specifications contain component ratings, installation guidance, and expected performance. • This milestone is complete.

M2.2 – Q3: Aviation Testbed Completed
 	
Subtasks:
• Configuration selection, conceptual design of engine truss and equipment packaging.
• Aircraft disassembly for upgrades.
• Test bench design (Iron Bird).
• Test bench build and checkout.
• Multiple fabrication items and iron bird assembly
• Aircraft assembly
• Certification
• Flight characterization
	Actual Performance:
	Completed [03/06/2022]:
	
	• Aviation testbed build, iron bird testing, and flight characterization were completed.
	• The following items were fabricated, assembled, and substantiated for flight:
	  ○ Motor and inverter/motor drive mount
	  ○ Battery module assembly tray
	  ○ Rear integration shelf for aircraft powertrain controls
	  ○ Forward experiment shelf for experiment integration
	• The following electrical powertrain components were integrated and endurance tested to ensure safety of flight:
	  ○ Battery modules and battery management system: 45kWhr, 745V
	  ○ Motor and inverter/motor drive: 130kW
	  ○ Powertrain controller
	  ○ HV to LV DC/DC converter
	  ○ HV and LV harnesses
	• FAA Experimental Airworthiness Certificate was granted
	• A flight test campaign was completed, verifying:
	  ○ System stability at high altitude
	  ○ Thermal margins of the electric powertrain
	  ○ Climb rate
	  ○ Single-engine cruise capability
	
	• This milestone is complete.

M2.3 – Q3: Iron Bird Component Testing
 	
Subtasks:
• Test selected CIRCUITS project technologies on ground in an actual 337 airframe (iron bird ground test setup) to ensure proper fit and functionality prior to component install in the actual flight testbed
• Acceptance of a component Iron Bird testing report by ARPA-e
	Actual Performance:
	Completed [06/22/2023]:
	
	• All CIRCUITS project technologies were tested in the iron bird and progress was presented in quarterly reviews
	• The experiments had the following high-level results:
	  ○ The University of Arkansas inverter passed this phase of testing at a lower power target level than initially required, however, it was deemed high enough for a safe flight.
	  ○ The IIT iBreaker passed this phase in a modified configuration, in series with the HV to LV auxiliary aircraft control power system
	  ○ The UC Berkeley converter did not pass this phase of testing
	• Reports submitted along with the final report for acceptance by ARPA-e. This milestone is complete

<table>
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<td>M2.4 – Q4: In-Flight Component Testing

Subtasks:
In-flight testing of selected CIRCUITS project technologies on Aviation Testbed
Acceptance of a component in-flight testing report by ARPA-e</td>
<td>Actual Performance:
Completed [06/22/2023]:
CIRCUITS technologies that were successful at the ground test phase (University of Arkansas and IIT) were flight-tested:
The University of Arkansas inverter successfully propelled the aircraft at a safe and acceptable climb rate
The IIT iBreaker successfully functioned in flight with no faults as part of the HV to LV 28V control power system
Reports submitted along with the final report for acceptance by ARPA-e.
This milestone is complete</td>
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Project Activities

This project's focus was to replace the rear aviation gas (i.e. avgas) engine of a Cessna 337 Skymaster with an electrical powertrain supplied by a high voltage lithium ion battery pack and configure the aircraft high voltage distribution system as a testbed for CIRCUITS project technologies with the aircraft shown in flight in Figure 1.

Figure 1: Hybrid-electric testbed

The electric powertrain shown in Figure 2 consists of the following key components integrated by Ampaire:

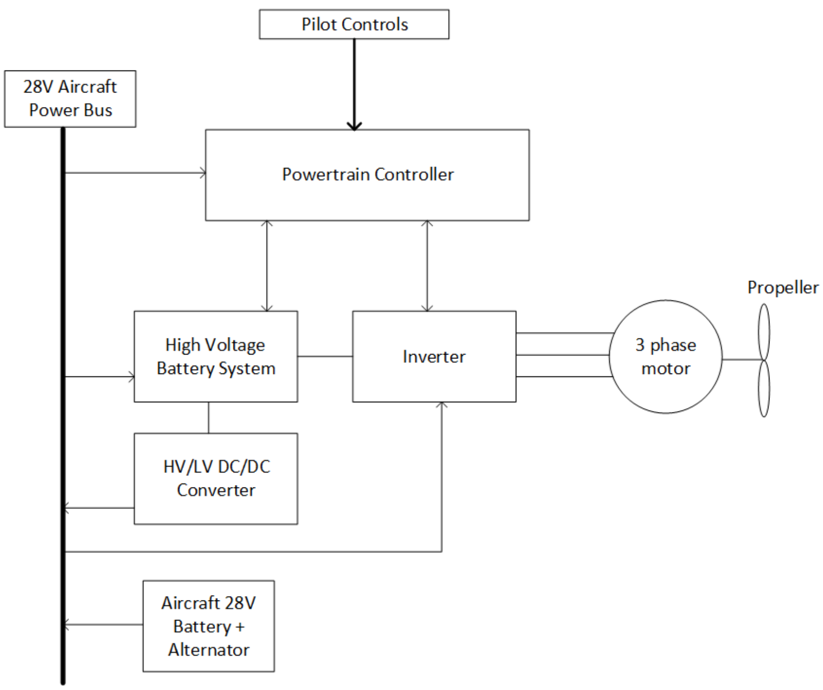

Figure 2: Ampaire Powertrain Architecture

- High Voltage Battery System: The electric powertrain is powered by a 725V max, 45kWhr battery pack and is controlled by a Battery Management Unit (BMU) which contains protective features and transmits data about the state of health of batteries.

- Electric Propulsion Unit: This consists of a 130kW inverter and 3-phase motor. The inverter converts the DC power from the batteries to AC power and drives the 3-phase motor and aircraft propeller, generating thrust for flight.
- Powertrain Controller (PTC): The PTC is responsible for bi-directional communication with the BMU and inverter, as well as any CIRCUITS experiments. Its functions include power management, fault handling, and converting pilot controls to powertrain actions.
- HV/LV DC/DC Converter: This is an auxiliary 28V power source derived from the high voltage battery pack for redundancy along with the aircraft combustion engine alternator and 28V battery.

This system was integrated into the aircraft and tested extensively on the ground to validate robustness and gain confidence in its ability to execute safe flights. This goal was achieved in the flight test campaign, where system stability, thermal margins, and aircraft performance estimates were validated at a high altitude of over 4000ft. Further, the flight test campaign proved the aircraft's ability to maintain level flight with a single engine, thereby enabling the ability to safely do in-flight restarts and testing of the electric system. System safety was thoroughly proven prior to any CIRCUITS technology integration.

The testbed was purpose-built for the integration of innovative, wide bandgap CIRCUITS technologies, including an experiment shelf in the cabin and an inverter mount in the rear truss. All three CIRCUITS experiments - the University of Arkansas SiC inverter (Figure 6), the IIT SiC iBreaker (Figure 7), and the University of California, Berkeley (UCB) Flying capacitor multi-level (FCML) (Figure 8) GaN DC/DC converter were ground tested in the aircraft. They were integrated into the powertrain as shown in Figures 5,6 and 7 respectively after passing FAA DO 160 derived shock, vibration, and thermal testing.

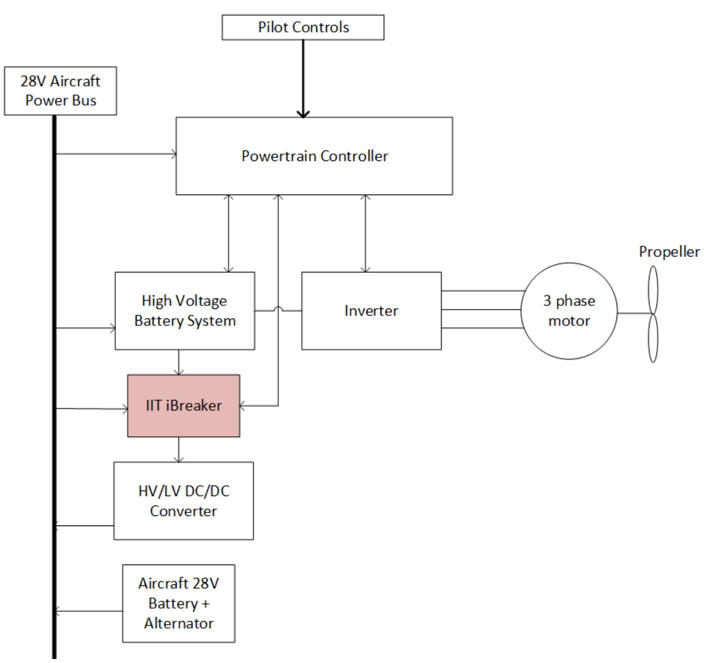

Figure 3: IIT Integration

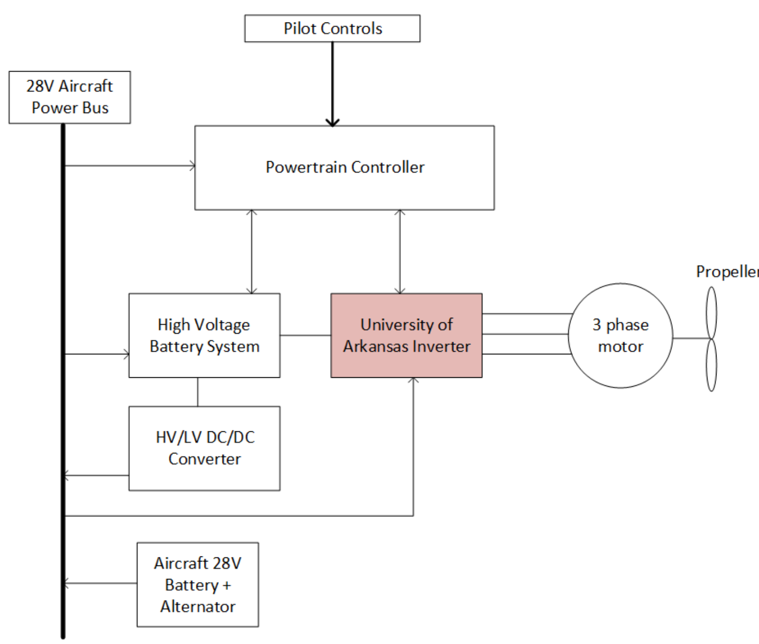

Figure 4: University of Arkansas Integration

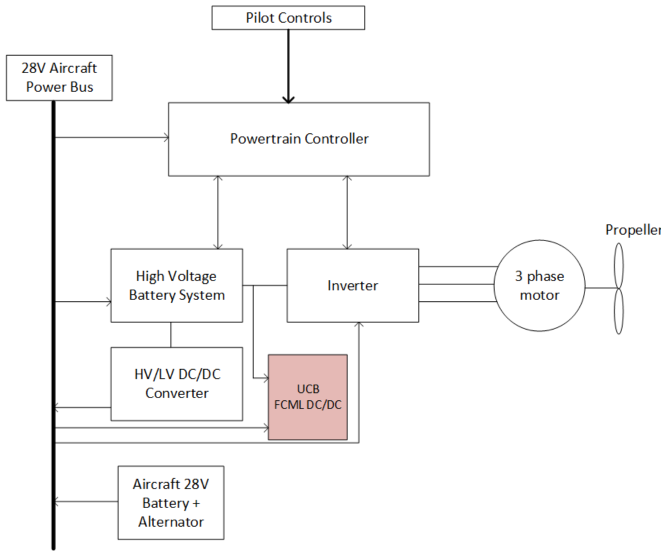

Figure 5: UCB FCML Integration

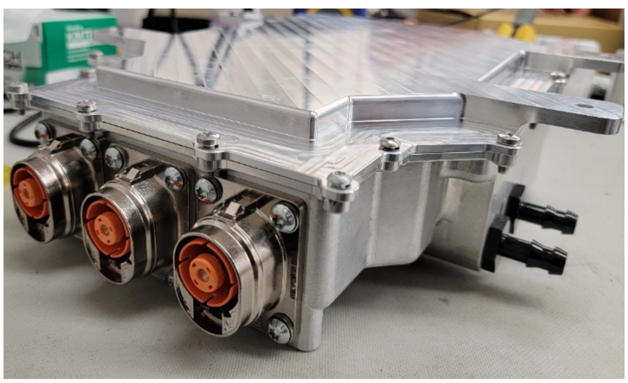

Figure 6: University of Arkansas Inverter/motor drive

Figure 7: IIT iBreaker

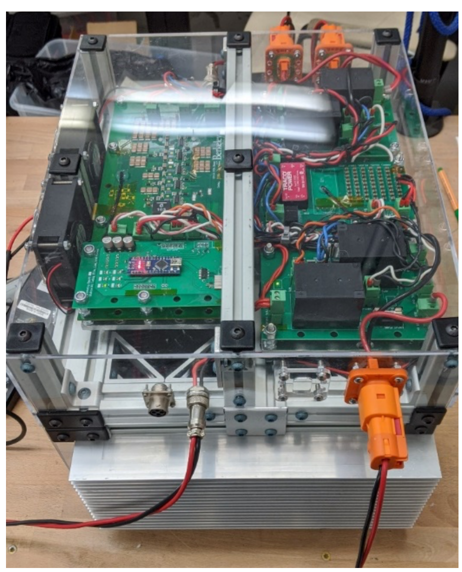

Figure 8: UC Berkeley Converter

The Arkansas inverter was the first successful CIRCUITS device to complete ground testing. There were several lessons learned along the way, primarily around system stability and EMI issues that were exposed in the real-world test environment. These were mitigated by lowering the power delivery capability of the inverter from 130kW to 65kW, a sufficient amount of power for safe flight. Having successfully conducted several simulated mission profiles on the ground, the inverter moved on to the flight test phase, where it successfully propelled the electric system in-flight with no faults or warnings. This was an industry-first achievement and a highly accelerated path from the lab bench to an actual aircraft flight.

The IIT iBreaker was the second successful CIRCUITS device to make it past ground testing. This device also had several challenges along the ground test phase, relevant to EMI. These issues were mitigated by modifying the installation configuration, moving it from the primary propulsion bus to the auxiliary aircraft control power bus. The iBreaker performed without issue in this configuration and conducted a successful flight test with no issues.

The UCB converter was unfortunately unable to make it past the ground test phase due to system stability issues, initially internal to the converter, and then inducing EMI to the aircraft powertrain. The UCB team is exploring next steps from the valuable lessons learned in the ground test phase and will be making modifications to add robustness to their design.

The key outcome of this project was an industry-first successful ground and flight test of emerging and innovative technologies, accelerating their path to commercial adoption and potential certification under FAA standards and regulations. The experience gained in this design, build, and flight cycle will be extremely valuable in improving future designs and making meaningful strides in the future of electrified aviation.

Project Outputs

1. Journal Articles
    a. None
2. Papers
    a. None
3. Status Reports:
    a. Quarterly reviews from Q3 2020 to Q2 2023
    b. CIRCUITS components specification reports
    c. CIRCUITS ground test reports
    d. CIRCUITS flight test reports
4. Media Reports:
    a. In collaboration with the University of Arkansas: “Electric Motor Drive Takes Off in Test Flight of Passenger Hybrid Electric Plane”
    b. Ampaire YouTube channel: “Ampaire's Progress on ARPA-e Circuits”
    c. Ampaire YouTube channel: “Ampaire's Electric EEL First Flight with ARPA-E”
    d. Ampaire YouTube channel: “Ampaire x ARPA-E: First-ever flight of a university build propulsion system”
    e. ARPA-e Annual Summit
        i. Participation in the showcase in 2022 and 2023
        ii. Tech Demo in 2022
        iii. Highlighted in the Summit Keynote in 2023

Left: Summit 2022; Right: Summit 2023

5. Invention Disclosures
    a. 3 disclosures related to hybrid architecture and high voltage electrified propulsion circuit technology (details are Proprietary Information until made public through patent)
6. Patent Applications/Issued Patents
    a. 2 disclosures are being draft as patent applications
    b. 1 disclosure is still in evaluation whether to retain as a trade secret, separate into multiple patent applications, or pursue as a single application

7. Licensed Technologies
    a. None
8. Networks/Collaborations Fostered
    a. University of Arkansas, NCREPT
    b. Illinois Institute of Technology
    c. University of California, Berkeley
    d. University of Illinois
9. Websites Featuring Project Work Results
    a. https://www.ampaire.com/projects/ARPA-E-Project
    b. https://www.youtube.com/@ampaireinc4562/videos
    c. https://arkansasresearch.uark.edu

Follow-On Funding

Since the beginning of the ARPA-e CIRCUITS project, Ampaire has received the following:

- 3 NASA Prime contracts totaling ~$10M in governement funding
- 1 Prime and 2 ARPA-e Subcontracts totaling ~$11M in government funding
- A Round of equity funding
- Cumulatively since the founding in 2016, Ampaire has received
    - ~$30M in investor funding
    - ~$20M in government contract funding