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Solid-State Secondary Power Distribution

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Final Report

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16. Abstract

Aircraft electrical power systems have traditionally been designed using thermal circuit breakers mounted on panels centrally located in the cockpit, protecting the aircraft wiring that runs from the circuit breaker panel to the loads throughout the aircraft. Heavy bus power wires are daisy-chained to provide power to the breakers and loads. With the increased use of electronic monitoring, airframe power designers are exploring new methods of power distribution and continuous monitoring. Some of the new methods are distributed power (no load center) and continual load data monitoring. These new power distribution systems have the ability to monitor current and voltage information in real time on any specific load. The effects of the changes will be reduced power conductor bundles, reduced weight, and shorter power runs.

This report documents the details of a 4-year research project in solid-state circuit protection for aircraft electrical systems. The report provides insight into many of the design tradeoffs, certification issues, benefits, and retrofit issues in design of a solid-state power distribution system.

17. Key Words

Solid state circuit breaker, Arc fault, Aircraft distributed electrical power, Solid state power controller, Electronic controlled circuit breaker, Aircraft secondary power distribution

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LIST OF ABBREVIATIONS AND ACRONYMS

A	Amperes
AC	Alternating current
AFCB	ARC Fault Circuit Breaker
APU	Auxiliary power unit
ARINC	Aeronautical Radio, Incorporated
BIT	Built-in test
BJT	Bipolar junction transistor
CAN	Controller Area Network
CBP	Circuit breaker panel
CFR	Code of Federal Regulations
CPU	Central processing unit
CRC	Cyclic redundancy check
CSV	Comma separated value
DC	Direct current
E-STOP	Emergency stop
EMI	Electromagnetic interference
FAA	Federal Aviation Administration
FET	Field effect transistor
GSE	Ground support equipment
GUI	Graphical user interface
HIRF	High Intensity Radio Frequency
I/O	Input/output
IGBT	Insulated-gate bipolar transistor
IOCBB	I/O communications breakout box
LED	Light-emitting diode
LRU	Line replaceable unit
MCDU	Multi–Purpose Control Display Unit
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
PBIT	Power-up built-in test
PCAN	Personal computer CAN
PCAN-USB	Personal computer CAN to USB
PCB	Printed circuit board
PDU	Power distribution unit
PWM	Pulse-width modulation
RCCB	Remote control circuit breaker
REPU	Remote electrical power unit
RF	Radio frequency
RTCA	Radio Technical Commission for Aeronautics
RX	Receiver/Receive
S/N	Serial number
SAE	SAE International
SCR	Silicon-Controlled Rectifier
SOA	Safe operating area

SOF	Safety of flight
SPDU	Secondary power distribution unit
SSPC	Solid-State Power Controller
TL	Test level
TRIAC	Triode for Alternating Current
TX	Transmitter/transmit
USB	Universal Serial Bus
WHCU	Windshield heater control unit
WOW	Weight on wheels

EXECUTIVE SUMMARY

Traditionally, aircraft electrical power systems are designed using thermal circuit breakers mounted on panels centrally located in the cockpit, protecting the aircraft wiring that runs from the circuit breaker panel (CBP) to the loads throughout the aircraft. Heavy bus power wires are daisy-chained to provide power to the breakers and loads. Over the years, thermal circuit breakers have proven to be reliable and simple components with interfaces and operations that have become common knowledge for aircraft designers, pilots, and technicians. Most aircraft thermal circuit breakers are designed to meet documented industry standards, and conform to existing operating and maintenance manuals. The circuit breakers are sourced by multiple vendors, making it easier for air framers to continue designing and maintaining the existing electrical system. Additionally, an aircraft can be in service for 30 to 50 years with only a few large-scale updates during its life, and replacing and rewiring the working electrical system is cost prohibitive without proper justification.

As power expands in functionality throughout the aircraft and begins to replace many of the functions traditionally owned by mechanical systems, the centralized power distribution model becomes difficult to maintain and implement. Issues of system weight, wire routing complexity, and ease of reconfigurability, along with the need for additional monitoring and feedback, all become barriers with economic and safety impact. With the emergence of an aircraft solid-state system, many of the issues with traditional aircraft power systems can be addressed.

Solid-state can provide a key safety feature of overcurrent and arc-fault protection for both wiring and loads, as opposed to the wire-only protection offered by thermal breakers. Besides the ability to directly replace the CBP and relay junction box, thus freeing up cockpit real estate, solid-state also provides weight savings, lower power dissipation, remote load control, power modulation, load monitoring, automated load shedding, and other prognostic or diagnostic maintenance features.

When comparing solid-state to thermal circuit breakers and mechanical relays, there are advantages and disadvantages with either system. The traditional thermal systems can handle higher currents and do not require quiescent power or a display controller for operation. The solid-state system offers fast switching with the ability for pulse-width modulation (PWM) and increased lifetime switching cycles. Its flexibility can accommodate various load types with fewer part numbers by using configuration files that are adapted to each aircraft system. With software controlled switching and protection, the solid-state system has the potential to reduce pilot workload and provide load and built-in test information to aid aircraft maintenance. However, the solid-state benefits come with the cost of protecting the solid-state device from damage and updating documentation, training, and operating manuals.

To validate the solid-state power system technology for aircraft use, a secondary power distribution unit (SPDU) was used as an industry example to gain practical knowledge of solid-state implementation and compare it with the existing thermal circuit breaker and mechanical relay system. Both 115 VAC and 28 VDC power control was considered in the initial SPDU study, but only 28 VDC technology was employed in the SPDU because of the limitations of

existing metal-oxide semiconductor field-effect transistor (MOSFET) technology. A separate, relatively large alternating current (AC) power distribution unit (PDU) (compared to thermal circuit breakers) was used only during the Boeing 737 on-aircraft test and a companion study was performed that affirms the less practical trade off of heat, size, and cost in AC applications. Whether AC or direct current (DC) is used, the choices of architecture and design of the SPDU are critical in achieving the existing and future objectives of a distributed power system. There are many design considerations that must be made to achieve a balance in performance, reliability, flexibility, safety, expandability, and maintainability without being too complex or costly.

One design objective of the SPDU was to supply power efficiently with low power dissipation while protecting loads and wiring with a more accurate and precise trip curve than thermal circuit breakers over temperature. The SPDU was also designed to save weight on new build applications because the SPDU can be installed remotely, away from the cockpit and near the loads it controls. Only new builds and retrofits that perform complete rewires and use display computers have the potential to maximize the benefits of solid-state power distribution.

For retrofit applications, there are several options available to minimize risk, cost, and complexity. The SPDU can be added to control a single subsystem, such as cabin lighting or fuel pumps, or the SPDU can replace a single CBP that may be connected to various subsystems. To understand retrofit feasibility and mitigate risk for the program, a CBP was replaced with a solid-state power distribution unit on a decommissioned B-737. The replacement took only one day and tests confirmed that the solid-state can be used to both power and protect critical aircraft loads.

The SPDU test activities provided valuable design feedback over the course of the program. Testing helped determine methods of heat sinking and minimization of dissipation to meet critical aircraft performance needs. Aircraft tests were performed by using up to three SPDUs controlling more than 100 different loads. The air-framer was instrumental in architecting the command-response communication for control of critical loads by using an additional layer of communications to confirm actions. Aircraft tests also assisted in understanding the performance of the shunt-based current measurement technique of solid-state technology. The logged hours of operation confirmed the accuracy of the trip curve during flight conditions and mitigated risk and concern of noise immunity, nuisance indications, and false-trip occurrences.

The proof of system safety goes beyond the performance and testing of a new technology. Achieving the design assurance level A is not a small effort for microcontroller-based technology. Thousands of man-hours are required by the technology developer to validate and verify software to the highest criticality level, Radio Technical Commission for Aeronautics (RTCA) DO-178B Level A, and evaluate commercial off-the-shelf integrated circuits (ICs) through RTCA DO-254, RTCA DO-160G, and other standards. Technology developers must become familiar with additional guidance in the form of Federal Aviation Administration Certification Authorities Software Team position papers and European Aviation Safety Agency Certification review items. However, by carefully developing a reusable core of both hardware and software, the technology developer and the air-framer can treat many of these costs as a one-time investment and spread them across future applications and platforms.

1. INTRODUCTION.

1.1 PURPOSE.

The purpose of this report is to provide the aerospace community insight into solid-state secondary power distribution by discussing the benefits and tradeoffs when transitioning away from traditional power distribution using thermal circuit breakers. This report provides both technical and certification considerations for a solid-state secondary power distribution unit (SPDU) that is installed on various aircraft as an industry example.

1.2 BACKGROUND.

Before discussing solid-state secondary power distribution, it is important to understand the traditional electrical system, from electrical power generation to power distribution and bus architecture. This section describes the traditional aircraft electrical system as necessary background material, while section 1.3 provides further details of the traditional system using thermal circuit breakers.

Depending on the type of aircraft, the electrical system may be designed differently. For example, transport aircraft generate 400 Hz 115V and use transformer rectifier units to create direct current (DC), and then additional step-down transformers to create 28 VDC. The typical business jet aircraft 28 VDC power system is derived from one or more batteries and a starter/generator attached to each engine. Producing aircraft electrical power begins when the starter/generator uses electrical power from the batteries to create the mechanical torque required to start the engine. The running engine's mechanical torque is then used to generate 28 VDC electrical power for the aircraft. In some aircraft electrical systems, the 28 VDC is converted to a 28V 400-cycle alternating current (AC) power and provided to lighting circuits and certain avionic equipment, as required for their operation. This conversion to AC requires an inverter.

Each aircraft generator is typically connected to a generator control unit and a primary power distribution unit (PDU). For a two-engine aircraft, the two interconnected PDUs perform the primary power distribution function for the 28 VDC aircraft power system. The PDUs employ electromechanical power contactors to provide bus connectivity and transfer. The PDUs also provide circuit protection for the connected buses through a combination of current limiters (fuses) and circuit breakers, which are designed to open when excessive current is being drawn on the bus, thus removing it from the powered aircraft system.

There are three ways the PDU's electrical buses can be named: (1) geographically (left, right, aft, and forward), (2) describing which electrical components are being powered from the bus (e.g., Avionics Bus), and (3) by the source of the bus power (e.g., Battery Bus or Generator Bus). Adding to the previous bus-naming conventions, aircraft systems typically categorize buses into groups that give priority to certain equipment during normal and emergency operations. Main or Primary buses are typically used to supply most of the aircraft's electrical equipment while Essential or Emergency buses exclusively provide power to flight-critical equipment. To meet safety and redundancy requirements, aircraft electrical systems are usually designed so that any buses can be energized by any of the power sources. Figure 1 shows the right and left generator buses are normally powered by the right and left generators. These buses will be connected by an open switch that is located within the PDU, isolating them from each other during normal operation. If one generator fails, then the power to that bus will be lost. It can be restored by closing a bus tie switch within the PDU. In this case, both buses will be powered from the one operating generator.

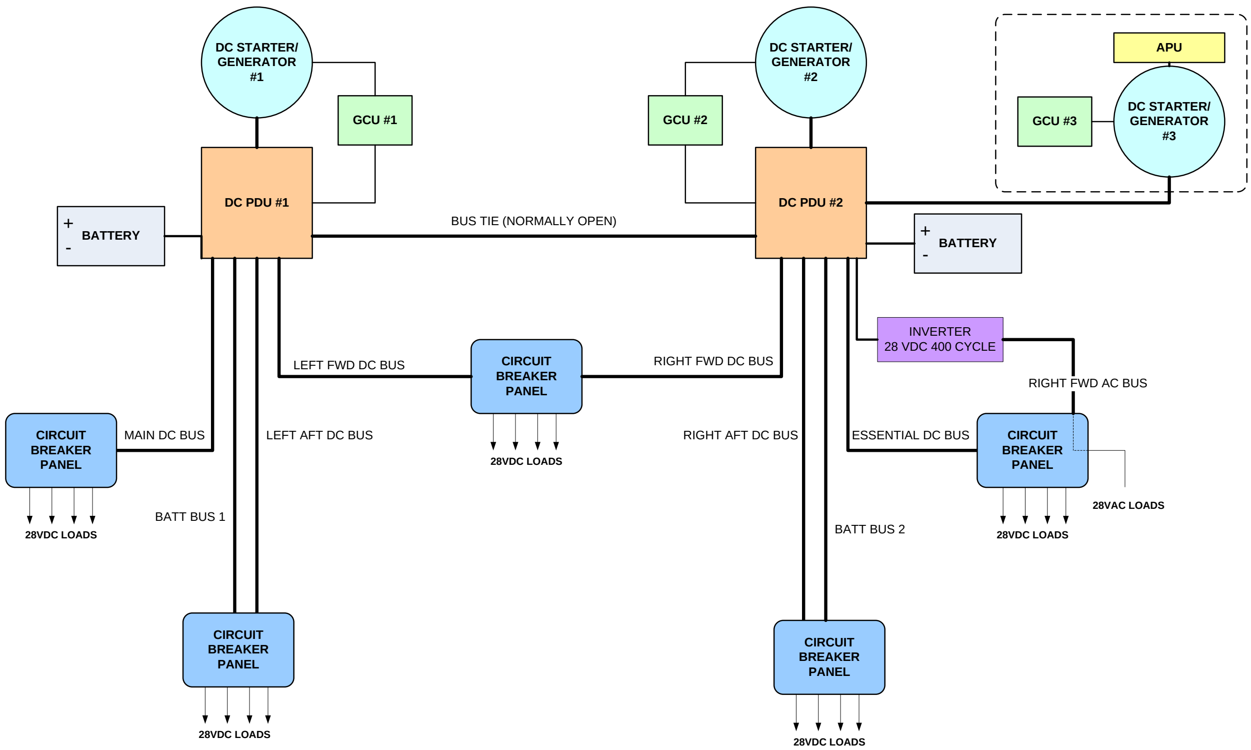

Figure 1. Traditional Business Jet Electrical System

The buses distributed from the PDUs are connected to circuit breaker panels (CBPs) containing thermal circuit breakers. The CBP is normally located in the cockpit, allowing the individual circuits to be accessible to the pilot. From the CBP, individual wires are run to the loads throughout the aircraft. The thermal circuit breakers within the CBP can be used to manually connect and disconnect power to the loads while providing over-current protection for the wiring and loads. The thermal circuit breakers are the first line of defense for separating individual loads from the electrical system. If the thermal circuit breaker fails to open the circuit during excessive current draw before the current limiters (fuses) open in the PDU, then the entire bus is disconnected from the electrical system.

1.3 TRADITIONAL POWER USING THERMAL CIRCUIT BREAKERS.

Traditional power distribution systems, like the one shown in figure 1, consist of simple logic, thermal circuit breakers, electromechanical relays, and wires routed the length of the aircraft. Figure 2 shows how power is generated from the engine and routed to the front of the aircraft. The circuit breaker panels (CBPs) are centrally located in the cockpit area and are distributed to loads throughout the aircraft.

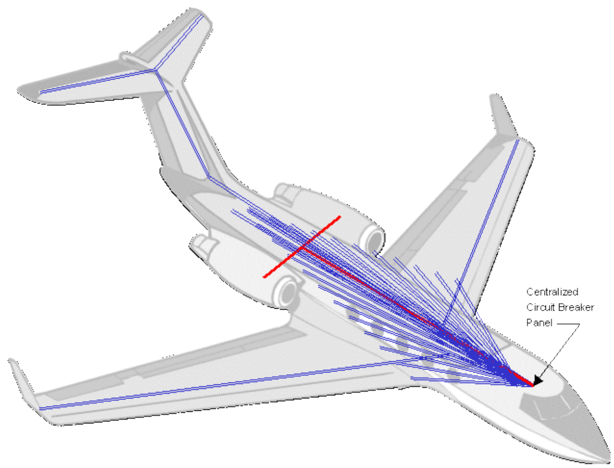

Figure 2. Traditional Aircraft Electrical Wiring

Figure 3 shows a CBP. The panel contains 55 thermal circuit breakers totaling 357.5 amps and the face-plate area is approximately 6.25 in. by 16.25 in. (101 in.^{2}).

Figure 3. Circuit Breaker Panel

Behind the panel are the mounted thermal circuit breakers and the wiring from each thermal circuit breaker to a pin on the CBP output connector, eventually routing to the individual loads. The initial wiring, as shown in figure 4, was conducted on the CBP shown in figure 3.

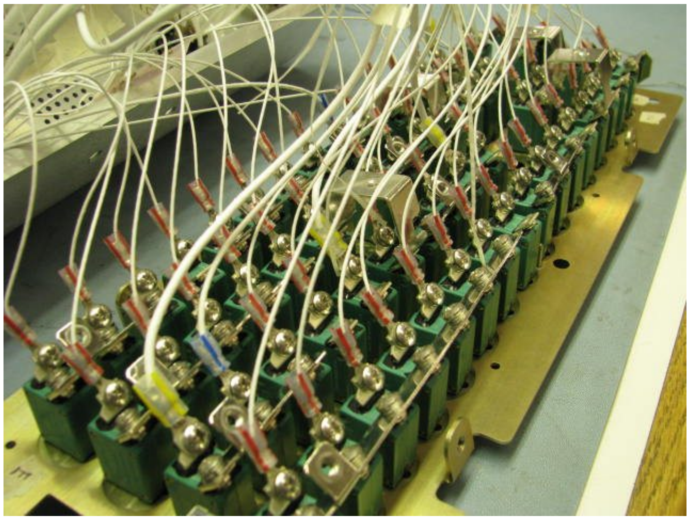

Figure 4. The CBP Thermal Circuit Breaker Wiring

The CBPs shown in figures 3 through 5 contain other accessory type electrical hardware, such as light panel dimming, indicator lamps, and discrete switches. Although the accessories are necessary for added functionality and human-factor requirements, they add to the overall cost and weight of the CBP.

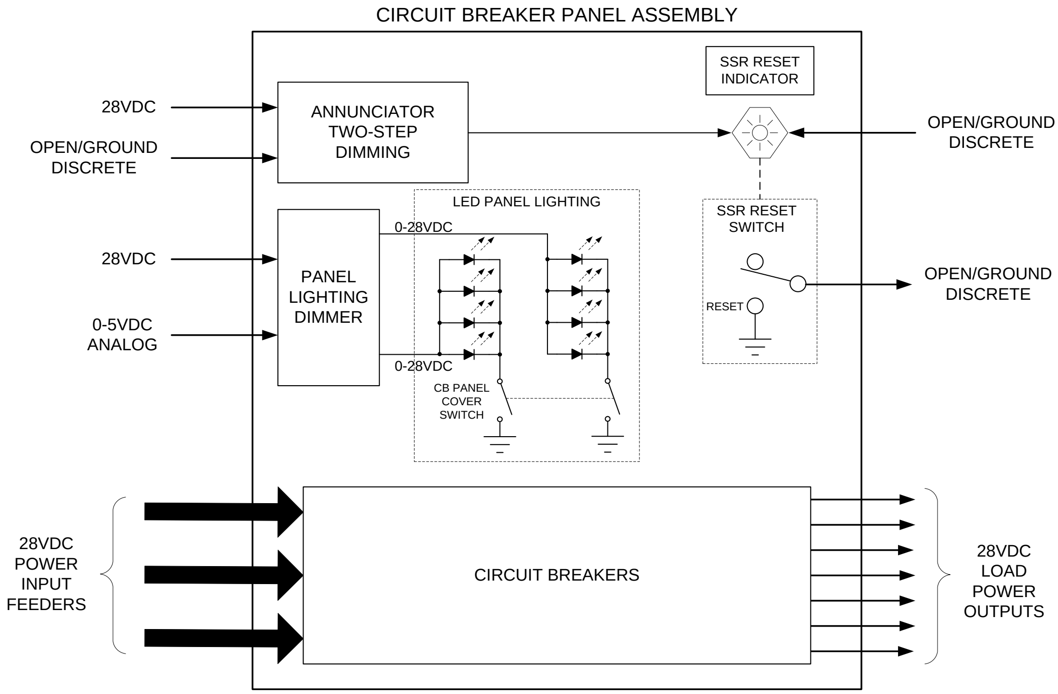

Figure 5. The CBP Block Diagram

The thermal circuit breakers may not be the only necessary equipment when controlling and protecting loads in a traditional aircraft electrical system. The diagram in figure 6 shows how to wire the CBP to a switch and relay for individual load control via a switch. The source power to the CBP is typically connected to very heavy gauge wire, sized to handle hundreds of amps, that is daisy-chained to supply a power source for each individual circuit breaker. The switch is typically located in the cockpit for pilot access. The switch and relay provides load control independent from the thermal circuit breaker push-pull operation. It increases reliability and time between maintenance and allows for the CBP to be used solely for circuit protection. As described in the notes section in figure 6, wire length and number of termination points are increased when adding switch and relay control to the traditional circuit breaker system.

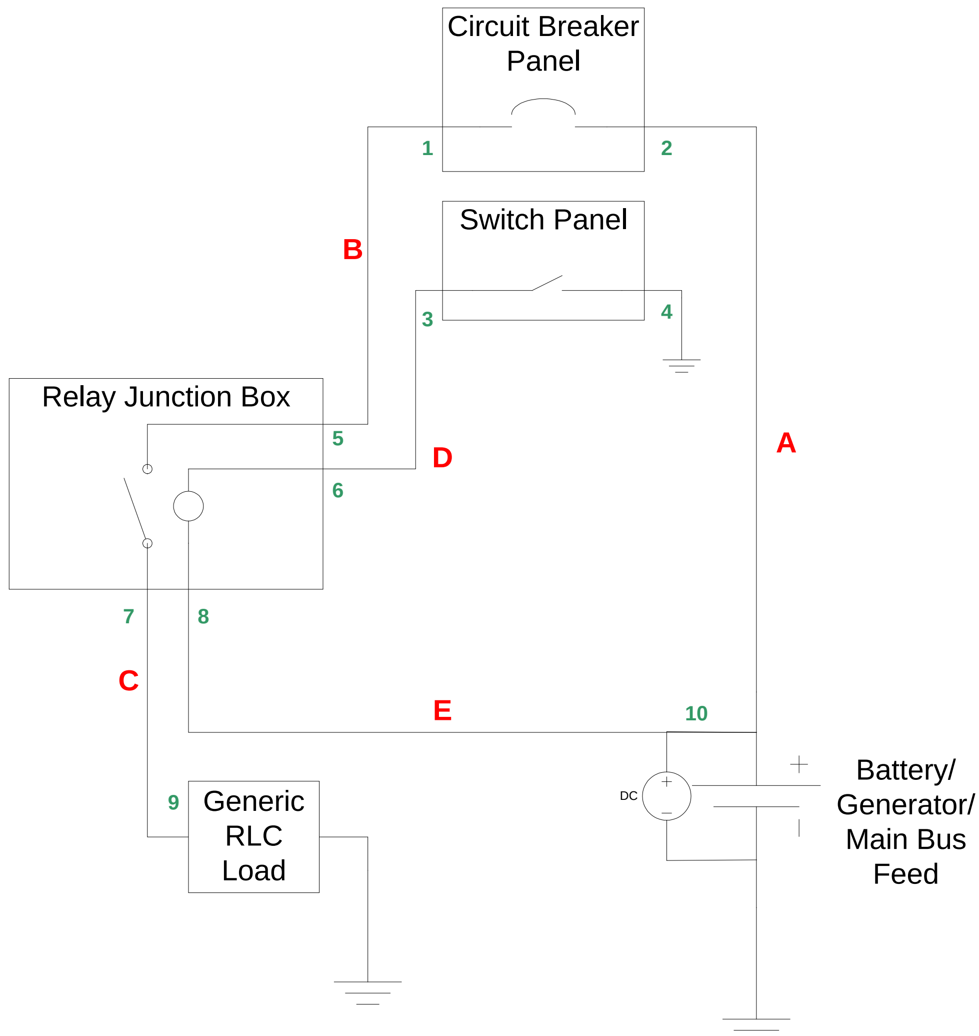

Figure 6. The CPB Interface to Switch/Relay

(Note: cable length D is repeated for each relay within the J-Box; cable lengths A and E may be one large bus line or several individual wires; cable length B is repeated for each protected circuit requiring switch control; cable length C is repeated for each individually controlled and protected load; the numbers in the diagram indicate the number of unique termination points and the total number of termination points is dependent on the number of loads serviced by the breaker box and relay junction box.)

The electromechanical thermal circuit breaker will open the circuit during overcurrent conditions. The typical thermal circuit breaker trip event occurs when the bimetal strip (two types of metal with different rates of expansion over temperature) expands and releases a latch that allows a spring mechanism to open the circuit to the load. There is usually an audible indication in conjunction with the visual indication that the circuit breaker has tripped.

Figure 7 shows the circuit breaker connected to an electromechanical relay used for load switching. The electromechanical relay contains an attracted core and attracted armature. A heavy armature spring provides fast switching and minimizes vibration susceptibility. A polarized magnetized armature can be used to eliminate the spring. In this configuration, the electronic field can be intentionally opposed to slow switching.

Some of the shortcomings of electromechanical relays include slow switching, pitting of contacts, welding, vibration sensitivity, and a larger size footprint. The electromechanical relay is typically rated for a limited number of switch cycles over its life. Most high-power relays are rated at a maximum of 50K cycles.

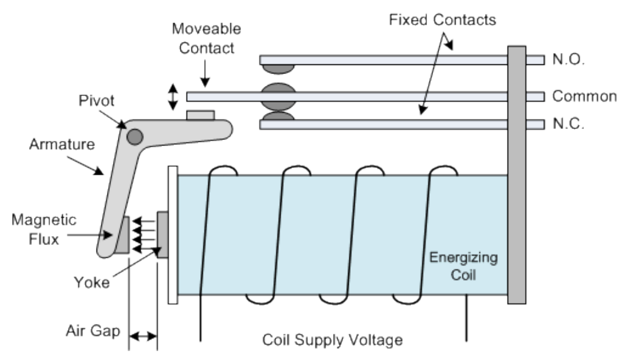

Figure 7. Electromechanical Relay

Many of the electrical and reliability characteristics for relays are governed by the contact material used in fabrication. Some of the available contact material and associated characteristics are described in table 1.

Table 1. Contact Material Characteristics

Contact Tip Material	Characteristics
Ag (fine silver)	Electrical and thermal conductivity are the highest of all metals; exhibits low contact resistance; is inexpensive and widely used. Contacts tarnish through sulfur influence.
AgCu (silver copper)	Hard silver; better wear resistance and lower tendency to weld, but slightly higher contact resistance.
AgCdO (silver cadmium oxide)	Very little tendency to weld; good wear resistance; and good arc extinguishing properties.
AgW (silver tungsten)	Hardness and melting point are high; arc resistance is excellent. Not a precious metal. High contact pressure is required. Contact resistance is relatively high and resistance to corrosion is poor.
AgNi (silver nickel)	Equals the electrical conductivity of silver; excellent arc resistance.
AgPd (silver palladium)	Low contact wear; greater hardness. Expensive.
Platinum, gold, and silver alloys	Excellent corrosion resistance; used mainly for low-current circuits.

1.4 SOLID-STATE POWER SYSTEM.

In recent years, improvements in solid-state technology have been underrated. Today, solid-state technology exists that can eliminate the need for thermal breakers and electromechanical relays in the majority of aircraft applications. This allows the aerospace industry to consider replacing thermal-mechanical technology with solid-state electronic load management or consider using solid-state in addition to thermal circuit breakers, thus creating a mixed system of thermal and solid-state. The shift to solid-state provides advantages in electrical system safety, performance, flexibility, and maintainability. The traditional and solid-state systems are compared in section 1.5.

An example solid-state power distribution system is similar to the traditional system described in section 1.2, except CBP are replaced with solid-state SPDUs. The SPDUs can be remotely located near the aircraft loads, allowing for shorter wires from the protection to the loads. Figure 8 is a diagram of a business jet solid-state power distribution system that replaces circuit breakers with two different solid-state PDUs, the SPDU for critical loads, and a cabin PDU for less-critical loads.

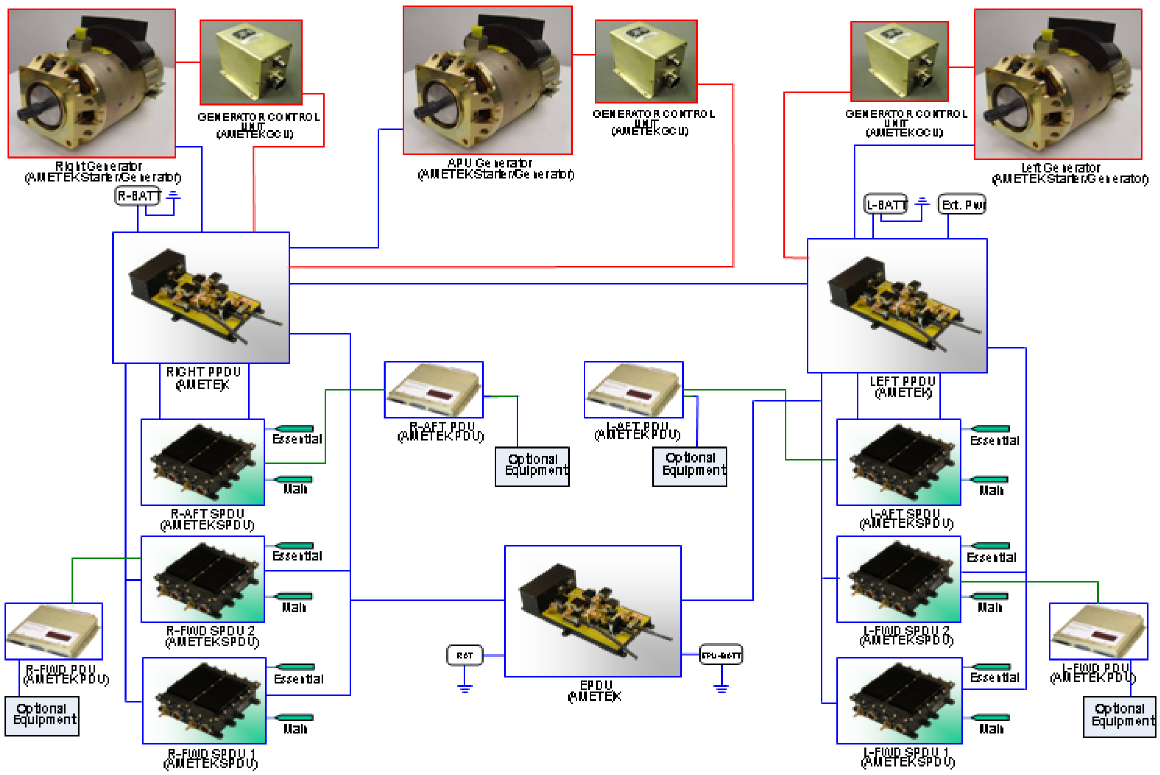

Figure 8. Solid-State Power Distribution System

Figure 9 shows the connections using a solid-state PDU connected to a display computer with a communications bus. In a solid-state system using a PDU or SPDU, the load management is handled through a communication bus, such as Aeronautical Radio, Incorporated (ARINC) 429. The display is used to provide a human interface for the controlling and status reporting of attached loads. If the aircraft doesn't have a display component, it is possible to provide simple control and status using discrete inputs and outputs. However, the communications bus can provide important information to the pilot, such as trip status, load voltage, load current, and built-in test (BIT) status. The aircraft diagram depicts the four SPDUs distributed along the aircraft near each SPDU's controlled loads. Because the SPDU can be controlled remotely, the SPDUs can be installed in locations that are only accessible by aircraft maintenance personnel, allowing the aircraft designer to utilize space that might otherwise be unoccupied. With the SPDUs installed near the controlled loads, the heavier gauge wire is kept shorter while the communication bus is lengthened to route up to the cockpit for connection to the display computer.

Because each SPDU can handle two independent and internally isolated bus power inputs, the loads are grouped within the SPDU depending on their power source, like battery (BATT) bus or DC Main bus or DC Essential bus. Each of the solid-state power controllers (SSPCs) installed within the SPDU can be configured by aircraft designers and maintenance personnel using ground support equipment (GSE). The GSE connection to the SPDU allows for trip curve adjustments to match the attached load, such as changing the trip rating from 5A to 7A.

The solid-state technology provides a means for fast switching. This is used for protection of the wiring and the loads from arc faults or direct shorts to ground. Pulse-width modulation (PWM) of loads is another available feature of solid-state control.

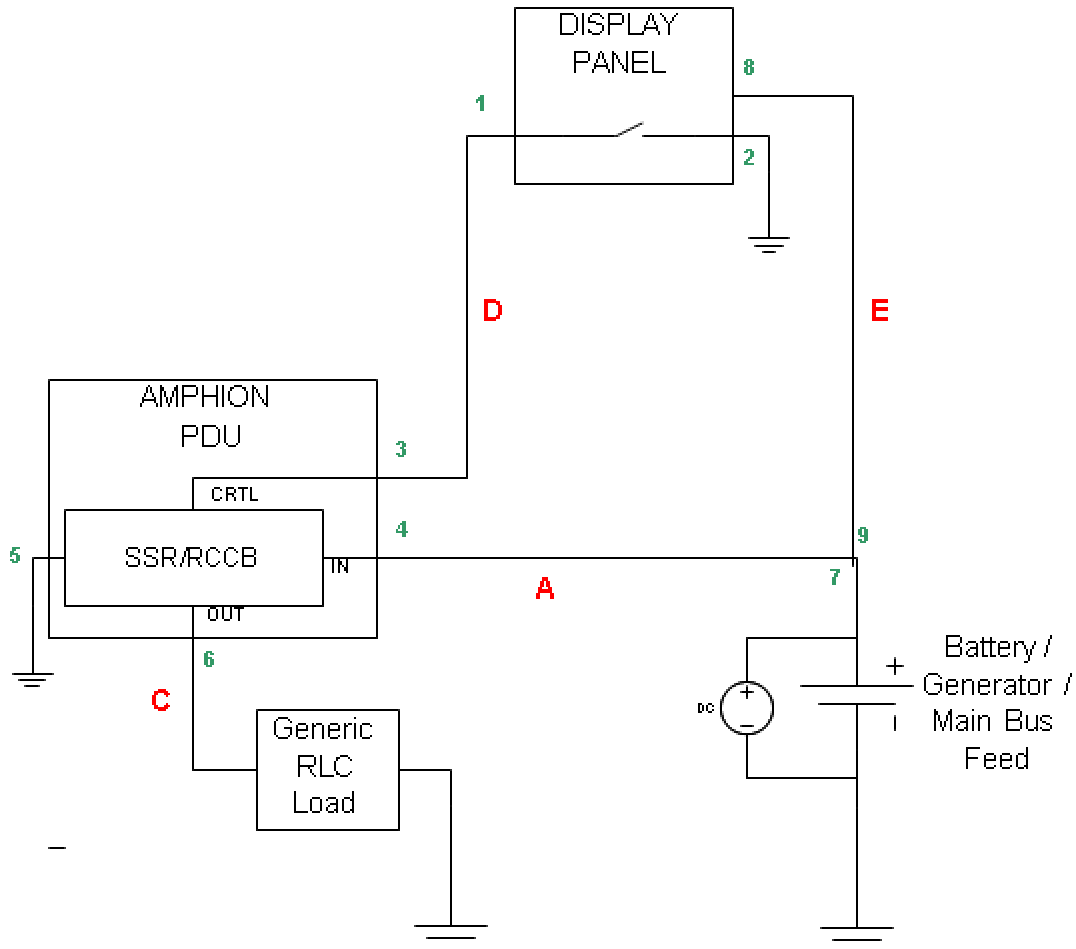

Figure 9. Solid-State Aircraft Interface

(Note: cable length D is one single wire for all AMPHION devices within the PDU because communication is performed over a serial bus; cable lengths D and E will likely require two runs to separate sources for critical loads; the numbers in the diagram indicate the number of unique termination points and the total number of termination points is dependent on the number of loads serviced by the AMPHION PDU.)

<u>1.4.1 Solid-State Technology</u>.

Section 1.4 described how solid-state power is used in aircraft but, to further understand the limitations and benefits of solid-state, this section provides information on solid-state technology.

In the past, researchers have provided the following explanations as to when solid-state underperforms.

- Solid-state has high power dissipation.
- Solid-state devices cannot handle highly inductive/capacitive sources and loads.
- Solid-state devices are unable to interrupt a short circuit without damage.
- Solid-state devices always fail shorted, leaving the load and wiring unprotected.

Advancements in semi-conductor technology have addressed and solved the underperformance issues. Solid-state devices are available with low-power dissipation and have the ability to be interrupted quickly to protect the load and wiring in the aircraft. There are also protective devices that can be used to protect the solid-state device and the load and wiring of the aircraft if the solid-state device fails shorted or is subjected to high voltages or high currents due to the attached load's electrical characteristics.

There are several solid-state technologies available, which are discussed in appendix A. They include:

- Silicon Controlled Rectifier (SCR)
- Triode for alternating current (TRIAC)
- Bipolar Transistor
- Insulated Gate Bipolar Transistor
- Field Effect Transistor (FET)

The Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET) has several advantages including:

- It has significantly less power dissipation than SCRs.

- It can be paralleled to reduce power dissipation.

- It can interrupt current at any time during the AC cycle.

- It is capable of more accurate zero crossing, better harmonics management, and dissipation based on resistive channel (>1.8 mohms).

As MOSFETs are paralleled, the surface area is doubled, but reduced power dissipation benefits become significant.

1.4.1.1 Protecting Solid-State.

Surges and spikes can cause electrical overstress to the semiconductor die. Fast switching results in voltage spikes that can damage switching devices.

A fast opening of a switch or large change in current will cause a significant voltage spike when using the formula:

$$V=Ldi/dt, \quad tc=L/R \tag{1}$$

Using the test circuit from figure 10, the switch is opened, removing current almost instantly and causing a large negative voltage spike, shown in the waveform in figure 11.

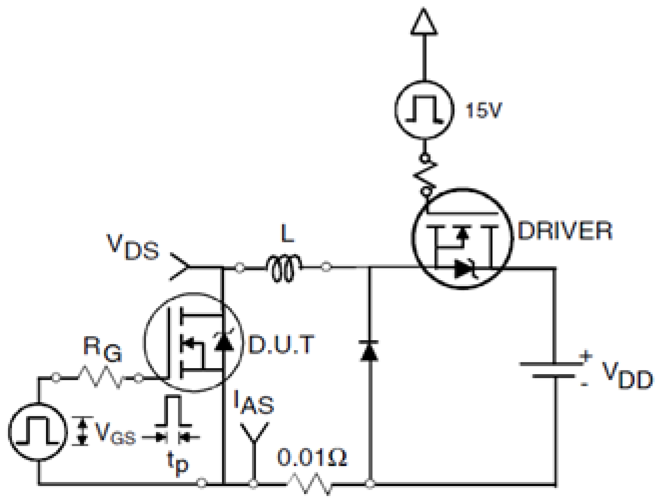

Figure 10. Unclamped Inductive Test Circuit

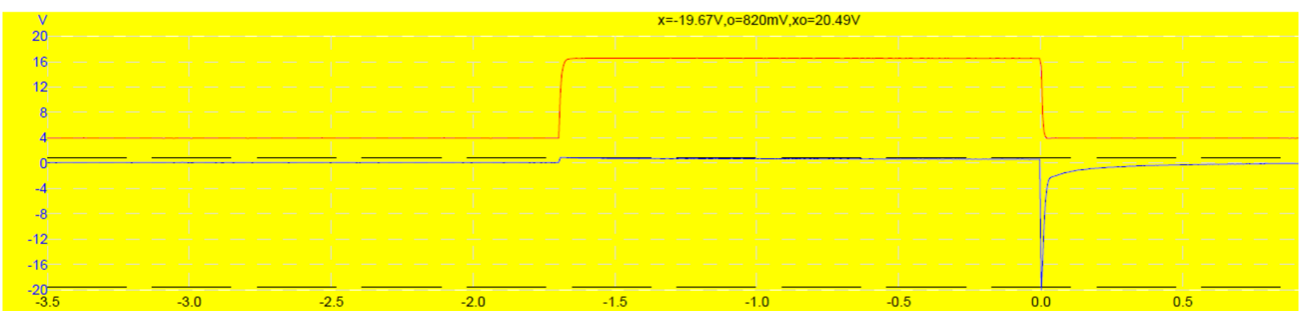

Figure 11. Voltage Spike From Inductive Test

To protect a FET from negative inductive spikes and back electromagnetic field from loads, a diode can be placed across the output. An example of this is shown in figure 12.

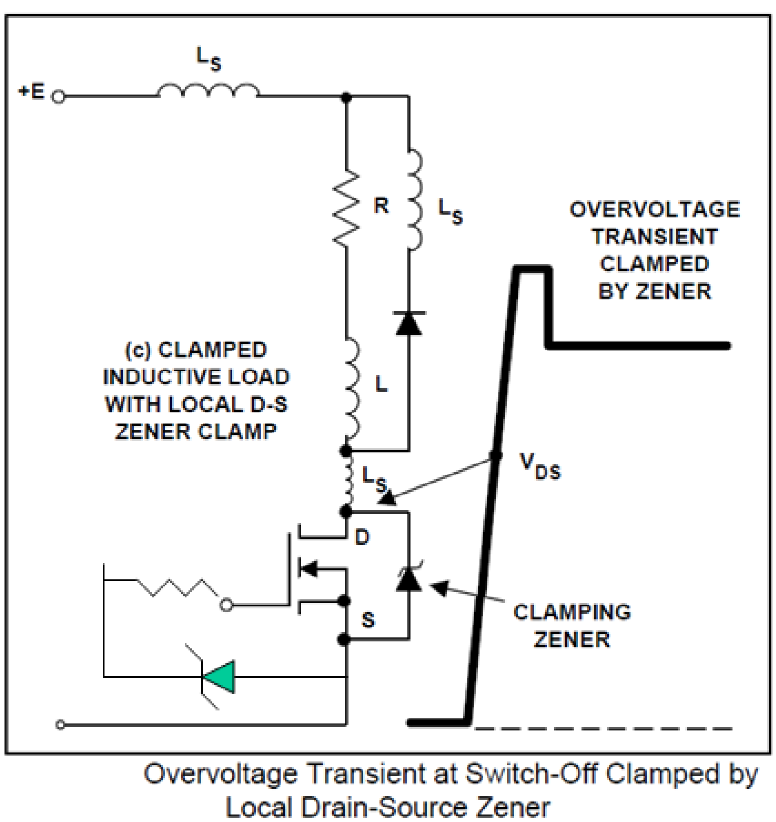

Figure 12. The FET Over-Voltage Protection Circuit

Figure 13 shows how a tranzorb or R-C snubber placed across the FET switch can handle positive inductive spikes. The tranzorb placed across the gate also prevents gate puncture protection.

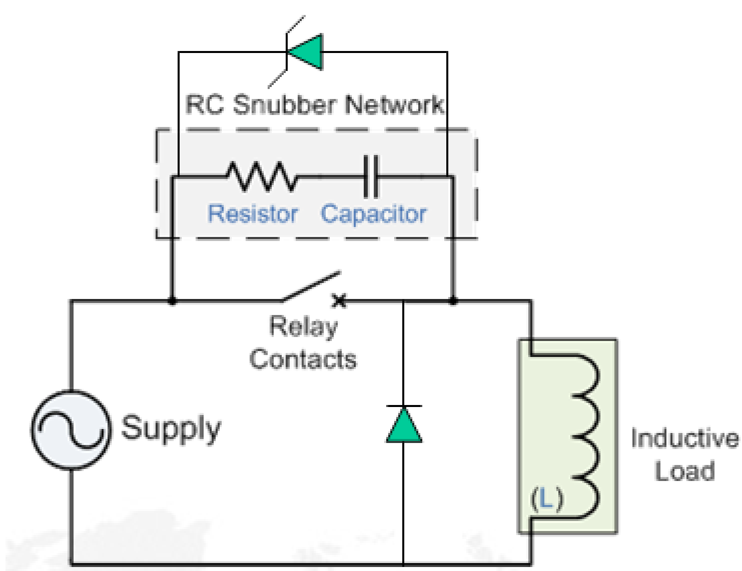

Figure 13. The RC Snubber Network

In addition to the passive protection described in section 1.4.11, current sensing and trip circuitry is added to guarantee operation within the semiconductor's safe operating area (SOA). For example, if the FET is rated for 10A continuous, then an overcurrent trip threshold can be set at 10A to protect the load, the wiring, and the solid-state switching device.

1.4.1.2 The AC Solid-State Considerations.

When using solid-state for AC solid-state switching and circuit protection, there are several areas that must be considered: drive size, power dissipation (heat), and cost.

The solid-state device's breakdown voltage drives both size and cost. Ideally, the breakdown voltage needs to be sized to meet the potential overvoltage conditions on the aircraft. Voltage testing guidelines provide the following maximum voltage values:

- MIL-STD-704A – Severest Overvoltage 180 Vrms
- Radio Technical Commission for Aeronautics (RTCA) DO-160F – Maximum Abnormal Steady State Voltage: 134 Vrms

However, sizing the breakdown voltage of the solid-state devices requires the peak voltage.

Single Phase Peak Voltages:

- 180 Vrms*Sqrt(2) = 254 Vpk for 100 msec
- 134 Vrms*Sqrt(2) = 189.5 Vpk continuous

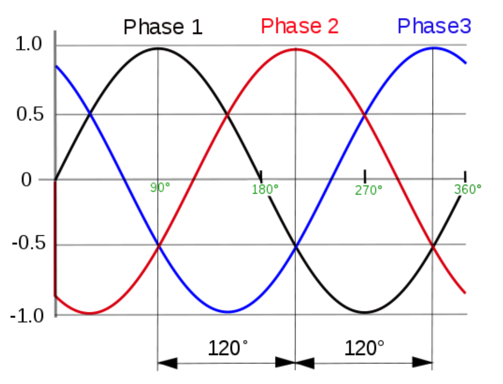

Figure 14. The AC Waveform (3-phase)

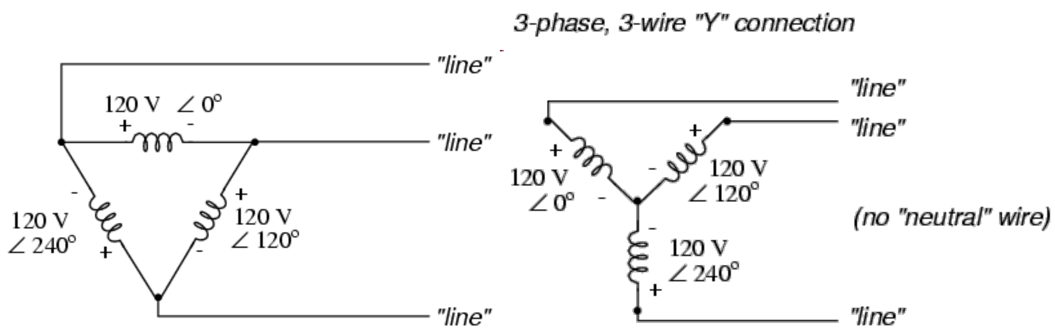

Figure 15. The AC Delta and Y Configuration

Multi-phase loads require switching devices to have a higher breakdown voltage without a neutral wire.

Phase to phase peak voltage is:

- Vpk = Vrms*(Sqrt(2) * Sqrt(3))
- Vpk (100 msec) = 180 Vrms* 1.414 * 1.732
  = 440 Vpk
- Vpk (continuous) = 134 Vrms*1.414 * 1.732
  = 328.23 Vpk

Inductive loads and transients due to fast current interruption can further increase the amplitude of voltage across the switch, leading to an ideal switch breakdown voltage of greater than 500V.

The MOSFETS, which were ideal for DC applications, are compared in table 2 using breakdown voltage, package size, and cost to determine if they are the best solution for AC applications.

Table 2. Snapshot of Industry Leading MOSFETs

Manufacturing	Part Number	Vbr (V)	R_{dson} (Ohms)	Package	L (in.)	W (in.)	Normalized Footprint Ratio	Cost
ST	STY112N65M5	710	0.022	TO-247	1.1	0.635	2.81	$25.00
ST	STW77N65M5	650	0.038	TO-247	1.1	0.635	2.81	$12.32
IXYS	IXKK85N60C	600	0.036	TO-264	1.105	0.760	3.38	$18.00
IRF	IRFP4242	300	0.049	TO-247	1.1	0.635	2.81	$2.40
IXYS	IXTT69N30P	300	0.049	TO-268	0.757	0.632	1.93	$4.02
IXYS	IXFH52N30P	300	0.066	220SMD	0.729	0.433	1.27	$3.30
IXYS	IXTA50N28T	280	0.060	TO-263	0.625	0.405	1.02	$TBD
IRF	IRFP4768	250	0.0175	TO-247	1.1	0.635	2.81	$4.50
IRF	IRFS4229	250	0.042	D2PAK	0.625	0.420	1.05	$2.00
IRF	IRFS4227	200	0.022	TO-262	0.591	0.420	1.00	$2.00

When high voltage AC, high currents, and size are concerns, silicon-controlled rectifiers (SCRs) and Insulated Gate Bipolar Transistors (IGBTs) are useful.

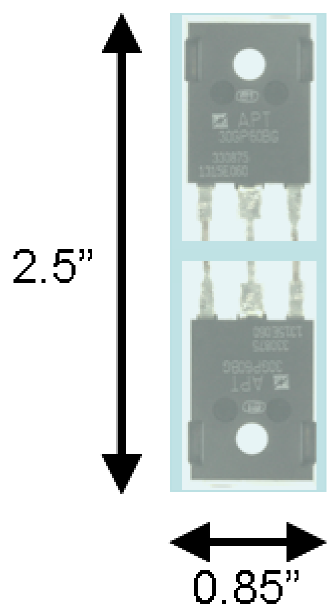

Figure 16. The FET Pair Footprint

With the goal of finding a 500V or better part, the series MOSFET pair is compared against SCRs and IGBTs with poor results. Given the steady-state current, the power dissipation for the single series pair MOSFETS is too high. From a 10A steady-state, the power dissipation is more than 10W and quickly declines as steady-state current increases.

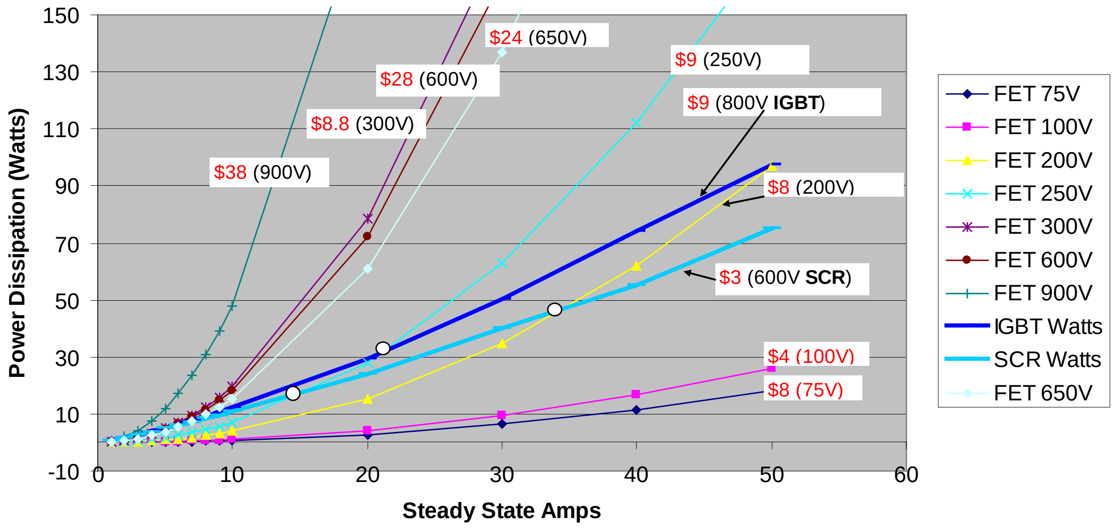

Figure 17. Single MOSFET, IGBT, and SCR Power Dissipation Comparison

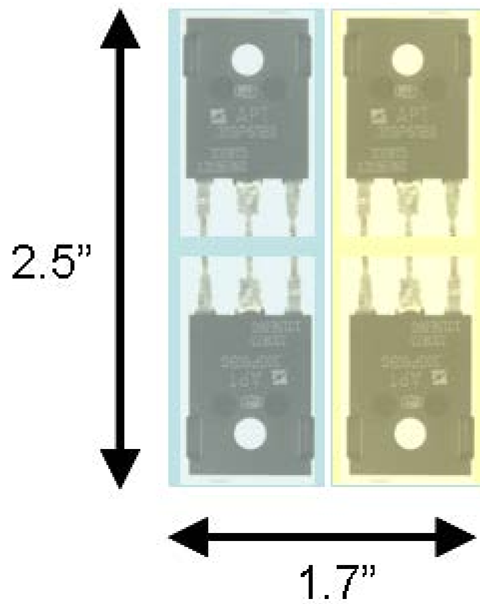

Figure 18. Paralleled FET Pair Footprint

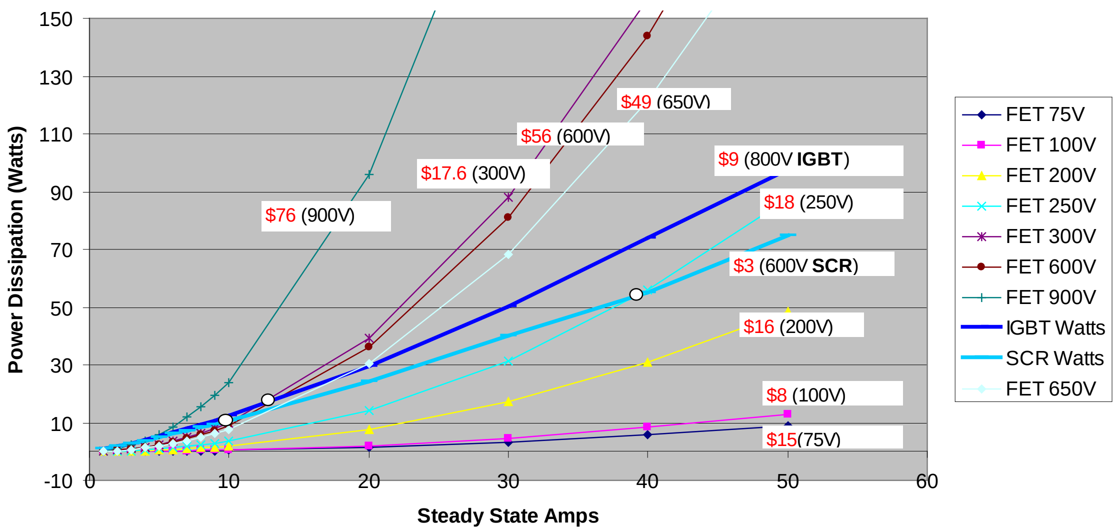

Figure 19. Paralleled MOSFET, IGBT, and SCR Power Dissipation Comparison

Reduced power dissipation benefits become significant as MOSFETs are paralleled and surface area is doubled. The 250V FETs have 30 to 50% less power dissipation over SCRs when steady-state current is less than 30A. In this configuration, the 600V FETs are useful only when the steady-state current is less than 10A.

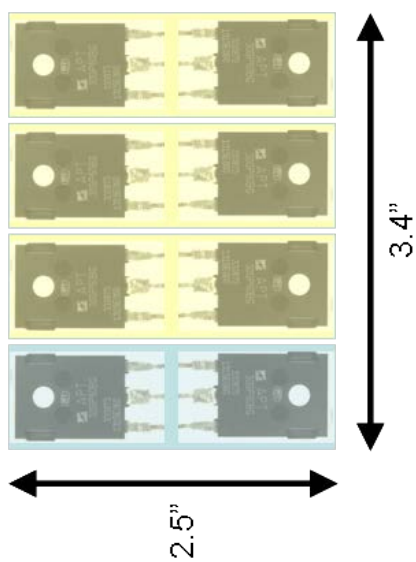

Figure 20. Quadruple-Paralleled FET Pair Footprint

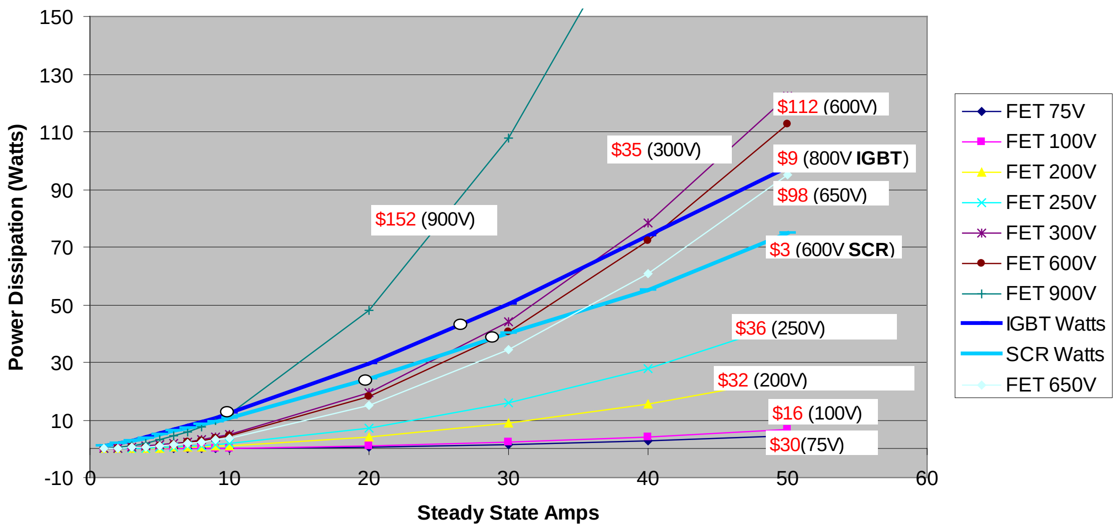

Figure 21. Quadruple-Paralleled MOSFET, IGBT, and SCR Power Dissipation Comparison

Paralleling more MOSFETs produces diminishing returns as power sharing and on resistance become less effective. With a quadruple pair of MOSFETs, there are significant cost increases and space requirements.

With the exception of DC power only, the 900V FETs are not useful for solid-state control in aircraft applications. All other FETs with breakdown voltages between 250V and 650V show benefits over SCRs and IGBTs, especially at currents under 20A.

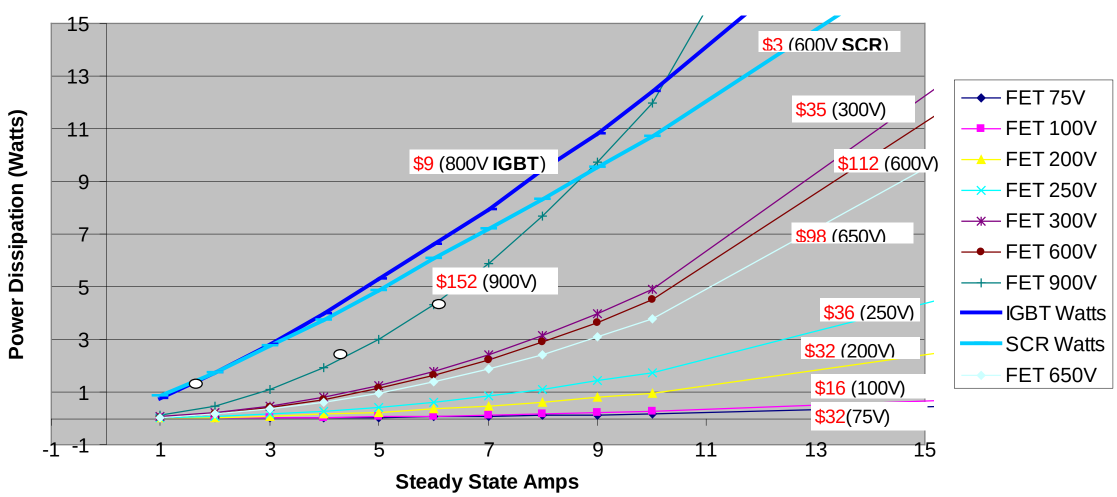

Figure 22. Quadruple MOSFET, IGBT, and SCR Power Dissipation Comparison

At 7.5A, the 300V and 650V FETs produce one third of the heat produced by SCRs or IGBTs.

At 3A, the 300V and 650V FETs produce 0.5W versus 3W for SCRs and IGBTs.

At 15A, the 600V FETs dissipate 10 to 12W versus 2 to 4.5W (3x to 5x) more heat for the 200V and 250V FETs. Again, the tradeoff is an increase in cost and size for less heat. Table 3 compares power dissipation.

Table 3. A 15A x 3 Channel Power Dissipation Comparison (Loading Scenario 1)

Switching Device	R_{other} (Ohms)	R_{dson} (Ohms)	R_{dson} (Ohms)	$V_{forward}$	P_{active} (W)	$P_{passive}$ (W)	P_{total} (W)
SCR	0.012			1.25	64.35	6.96	71.31
650V-TO-247	0.012	0.038			33.75	6.96	40.71
300V-TO-268	0.012	0.049			41.175	6.96	48.135
200V-D2PAK	0.012	0.022	0.022		22.95	6.96	29.91
250V-TO-262	0.012	0.042	0.042		36.45	6.96	43.41
Current PDU	0.012	0.022	0.042		22.95	6.8	29.75

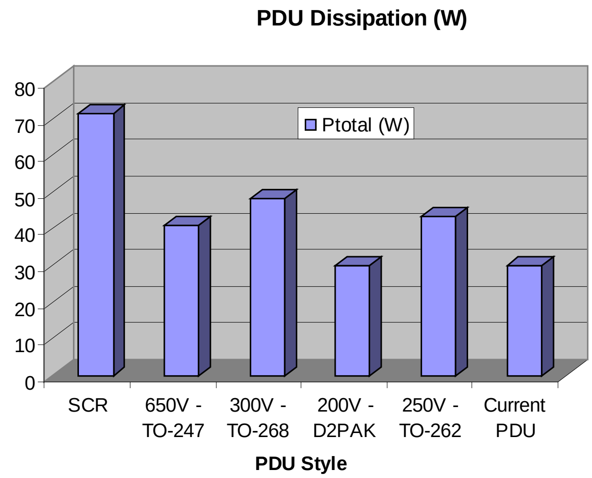

Figure 23. A 15A x 3 Channel Power Dissipation Comparison

Table 4. The 3.75A x 12 Channel Power Dissipation (Loading Scenario 2)

Switching Device	R_{other} (Ohms)	R_{dson} (Ohms)	R_{dson} (Ohms)	$V_{forward}$	P_{active} (W)	$P_{passive}$ (W)	P_{total} (W)
SCR	0.012			1	47.025	6.96	53.985
650V-TO-247	0.012	0.038			8.4375	6.96	15.3975
300V-TO-268	0.012	0.049			10.29375	6.96	17.25375
200V-D2PAK	0.012	0.022	0.022		5.7375	6.96	12.6975
250V-TO-262	0.012	0.042	0.042		9.1125	6.96	16.0725
Current PDU	0.012	0.022	0.042		8.26875	6.8	15.06875

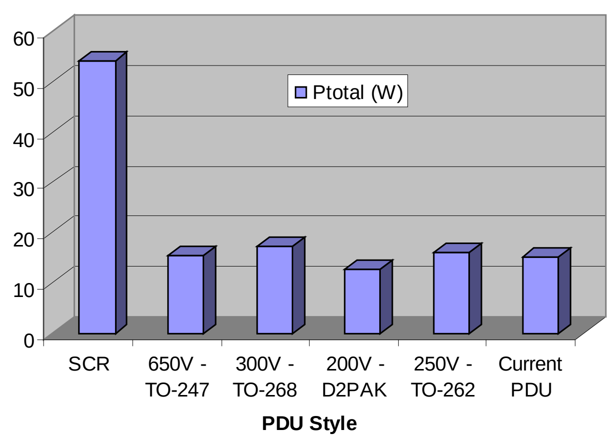

Figure 24. The 3.75A x 12 Channel Power Dissipation

In summary, the 650V MOSFETs are the best option for AC applications. They are superior when steady-state current is between 0 and 15A, but the power dissipation performance tradeoff is increased space.

The 300V MOSFETS are good solutions for AC applications. They dissipate slightly more heat than the 650V MOSFETs, but have a smaller footprint and a lower cost. To use the lower voltage FET, the worst-case transients will need to be passed to the load or shunted elsewhere.

Generally, the SCR's cost and size (as shown in figures 25 and 26) are much lower than the FET's, but heat dissipation makes the technology less practical (as shown in figure 27) based on existing installation, environment, and component temperature limitations, unless currents greater than 30A are switched.

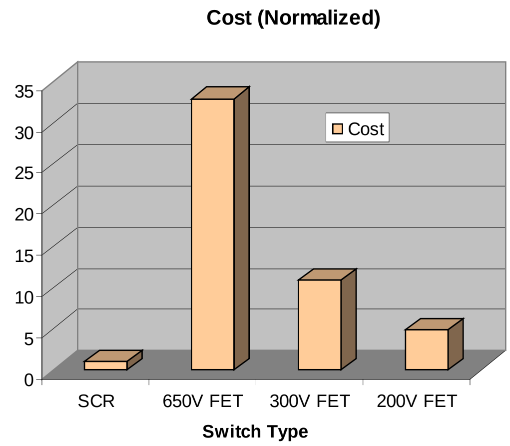

Figure 25. The SCR and FET Cost Comparison

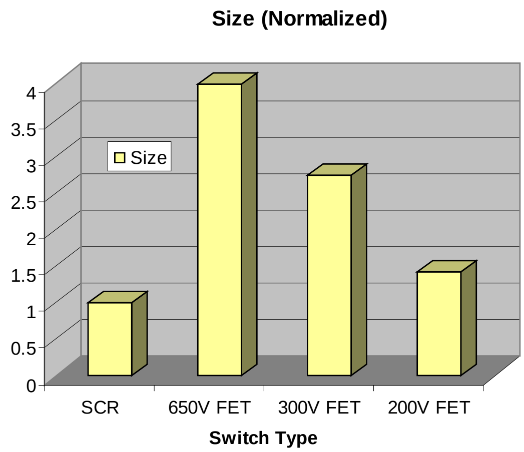

Figure 26. The SCR and FET Size Comparison

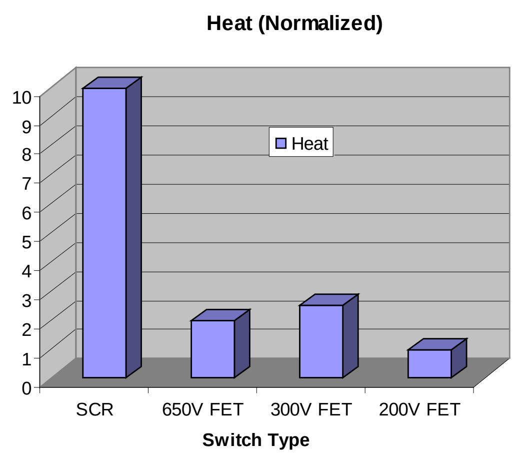

Figure 27. The SCR and FET Heat Comparison

One of the pitfalls of SCRs and IGBTs is that the turn-off is driven by the zero-cross. This means that SCR and IGBT trip response times are synchronous to the AC source frequency (400 Hz to 800 Hz) on the aircraft; therefore, an AC trip response time of less than 1 or 2 milliseconds requires use of MOSFET over SCR or IGBT. During high current surges or direct shorts to ground, the trip response time is too slow to protect the device and the load.

The MOSFET allows fast turn-off, in tens of microseconds, and trip responses to be asynchronous of the AC source frequency. The turn-off being independent of the zero-cross also allows for back-end dimming of the 115 AC output where SCR- and IGBT-based controls only allow for front-end dimming. This may be important when interfacing with various lighting transformers.

1.5 COMPARISON OF SOLID-STATE AND TRADITIONAL POWER.

To have solid-state secondary power as the potential replacement for traditional systems with thermal circuit breakers it is important to compare the two systems. This is done by listing the benefits seen in both systems and the additional benefits when choosing one system over the other. The comparison is shown in table 5.

Table 5. Traditional Thermal Circuit Breaker System vs. Solid-State System

Feature Description	Traditional System Using Thermal Circuit Breakers	Solid-State System
Protection from over current for wiring	✓	✓
On/off control of load	✓	✓
Load currents between 2A and 30A	✓	✓
Trip indication	✓	✓
Reset of tripped output	✓	✓
Lock-out (tag)	✓	✓
Fail-safe protection mechanism (open circuit)	✓	✓
AC/DC capability	✓	
Bidirectional protection	✓	
Separate power capable	✓	
Conform it to existing maintenance practices and operational procedure manual	✓	
Performance driven by industry standards	✓	
Multiple supplier sources	✓	
Minimal electromagnetic interference (EMI) susceptibility	✓	
Maximum current capability	✓	

Table 5. Traditional Thermal Circuit Breaker System vs. Solid-State System (Continued)

Feature Description	Traditional System Using Thermal Circuit Breakers	Solid-State System
AC thermal breakers have smaller form factor than solid-state AC	✓	
Wider temperature range	✓	
No quiescent power consumption	✓	
No display/software control required	✓	
Protection from over current for wiring and loads		✓
Faster/improved protection (arc fault)		✓
Accurate/precise tripping over temperature range		✓
Trip curve flexibility without changing parts		✓
Reduced load wire lengths (weight)		✓
No CBP (weight)		✓
Remote control using display/digital communications bus		✓
Minimal/no cockpit space required		✓
Improved input to output voltage drop		✓
Load trend monitoring for predictive maintenance		✓
Fast switching (PWM capable)		✓
Reduced power dissipation; Reduced noise (electrical and acoustical)		✓
Ability to load-shed		✓
Coordinated load management		✓
Integration with other systems		✓
No contact bounce		✓
No vibration sensitivity		✓
Increased reliability (switching cycles)		✓
Reduced size per output (DC)		✓
Reduced pilot workload		✓
Block after reached maximum allowed resets		✓
Soft start capable (extend load life)		✓
BIT to annunciate failures		✓
No relay coil drive for switching		✓
Improved efficiency and system control/response time		✓
Reduced labor for wiring in new install		✓

1.5.1 Trip Response Time.

An important difference between thermal and solid-state circuit breakers is the trip curve over temperature (see figures 28 and 29). Looking at several thermal circuit breaker datasheets, the trip is typically guaranteed within 1 hour when the current is between 125% and 150% of the rated current. If the rated current is 5 amps, the trip is not guaranteed to occur until the current exceeds 7.5A (150%) for at least 1 hour. The reason for this wide specification point is that thermal breakers protect the wire differently depending on the ambient temperature at the thermal breaker. Taking into account that most loads are not co-located with the thermal breaker, this is not a beneficial feature and leads to inaccurate and imprecise tripping over temperature. This means that if the ambient temperature is elevated, possibly due to heat generated from surrounding equipment, then the thermal breaker will trip faster at the same load current. Conversely, if the ambient temperature is decreased and the circuit breaker is located in a partial or uncontrolled environment within the aircraft, the load will trip slower. The SSPC trip curve accuracy typically is ±7% over temperature (-40°C to +70°C) while the thermal circuit breaker trip curve accuracy is ±70% at 25°C.

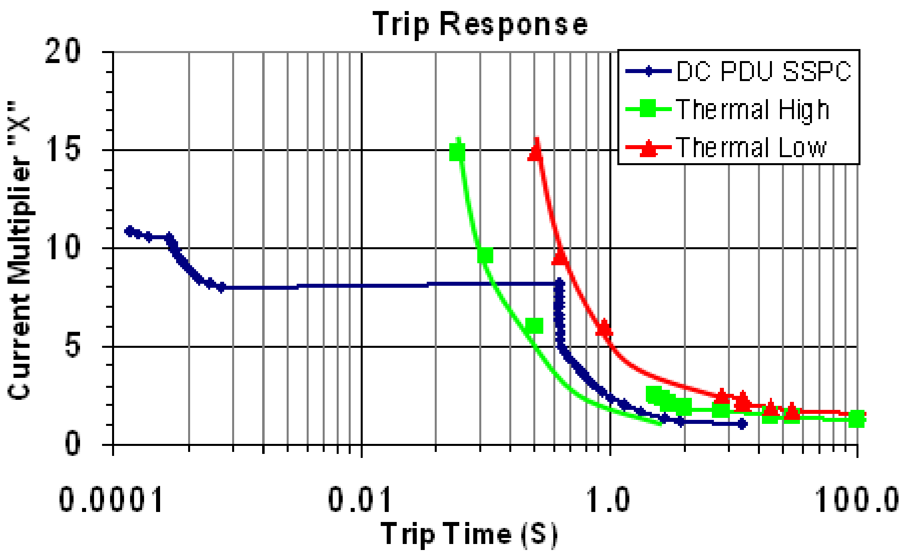

Figure 28. Trip Response—Thermal Breaker vs. Solid-State

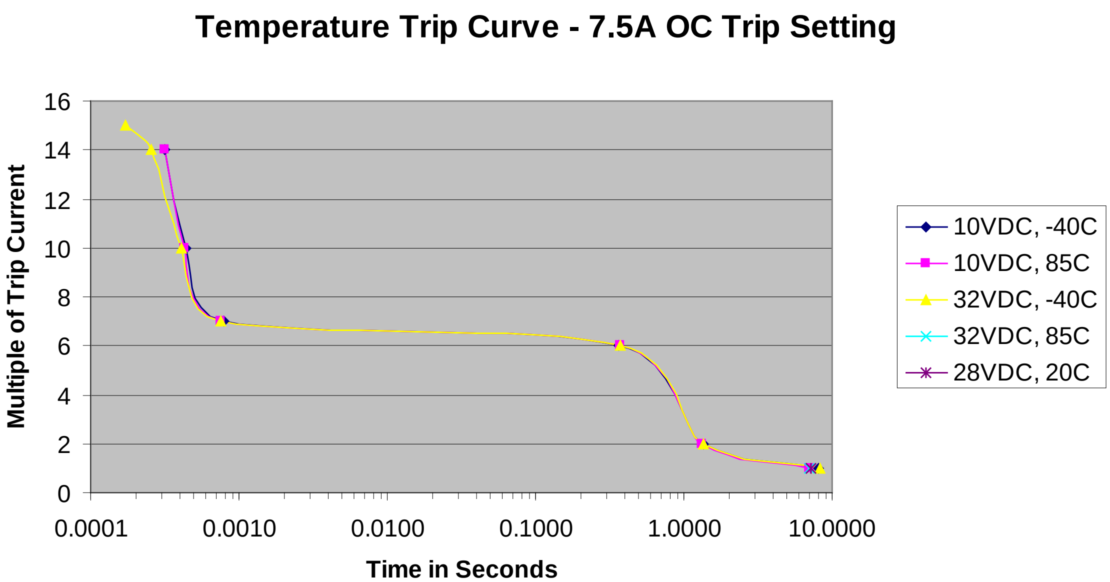

Figure 29. The SSPC Trip Performance

Besides over-current conditions, the SSPC can detect parallel arc faults, series arc faults, and short circuits, and can react quickly to open the circuit and protect the wiring and load. Using figure 29 as an example, currents above 10 times the nominal rating of the breaker will result in a trip within a few hundred microseconds. This reaction time cannot be accomplished using a standard thermal circuit breaker. For parallel and especially series arc fault detection, the SSPC typically employs a trip detection algorithm in software using a microcontroller, microprocessor, or complex logic device. The algorithms can range from simple to complex and may be implemented with various reaction times and a trip criterion until a minimum standard is identified conforming to SSPCs used in aircraft. The Federal Aviation Administration's (FAA's) Technical Standard Order, or equivalent, would be an example of a standard needed for SSPCs. As an example, the trip curve shown in figure 29 is a composite of arc fault and over-current protection. The trip curve is shaped to avoid nuisance trips and protect the load and wiring.

1.5.2 Trip Accuracy.

Solid-state technology using the SPDU could have been designed to have increased accuracy. During the initial joint development phase, air-framers were requesting 1% to 2% trip accuracies over temperature (a 10-to-1 or 20-to-1 improvement over thermal breakers). After further research, the accuracy came at a cost of increased power dissipation and circuit complexity. The SSPC design goal was to outperform existing traditional thermal breaker accuracy, but relax the accuracy requirement enough so that heat dissipation could be reduced and common electronic parts could be used for SSPC manufacturing. This resulted in an SSPC with single-digit milli-ohm on-resistances and current measurement accuracies that were a 2-to-1 or 4-to-1 improvement over thermal breakers.

1.5.3 Weight.

The entire power distribution system must be considered rather than just the SPDU itself for the total weight impact. This includes the wires, circuit breakers, breaker panels, relays, switches, and all connecting hardware. The important shift in thinking is that the SPDU doesn't just replace the circuit breaker. It also replaces the breaker panel, acts as a remote-control switch and a trend monitoring device, and is a convenient means of connecting power to tens of circuits without the need to individually wire each output. The ability to locate the SPDU local to the loads, as shown in figure 30, provides the largest weight benefit as it eliminates running large gauge wires to the cockpit.

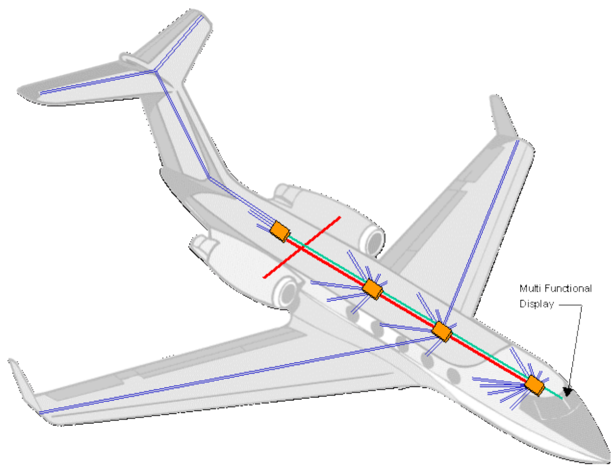

Figure 30. Solid-State Distributed System

A spreadsheet tool was developed to estimate the amount of weight savings that could be realized with an SPDU system. It attempts to account for the individual weight of components using a generic schematic for the traditional- and SPDU-based system.

Figure 1 shows a generic schematic for a traditional power system. When considering weight, the length and gauge of the wire are implemented as variables that can be adjusted in the spreadsheet. Weights can be assigned for the individual components. The weights for the CBPs and relay panels are also calculated based on the thickness and amount of aluminum and copper used. Cost of these items can be calculated using this spreadsheet, but is not populated in figure 31.

An estimate of system weight can be derived once it is populated into the spreadsheet. Figure 31 shows a spreadsheet of a sample weight calculation of 12 generic aircraft circuits.

Total Number of Circuits	12
Subset of Circuits Requiiring Switch Control	12

Material Cost and Weight Analysis

Aluminum	0.098	lb/in^3	density
Copper	0.32	lb/in^3	density

Teflon Wire Prices, Weight and Current Handling Capacity

AWG	100ft price	$/ft	10% vol discount	weight/kFt lb	Max. Amps
14	$ 148.28	$ 1.48	$ 1.33	12.43	17
16	$ 102.38	$ 1.02	$ 0.92	7.82	13
18	$ 83.93	$ 0.84	$ 0.76	4.92	10
20	$ 62.33	$ 0.62	$ 0.56	3.09	7.5
22	$ 43.76	$ 0.44	$ 0.39	1.94	5
22	$ 51.30	$ 0.51	$ 0.46	1.94	5
24	$ 35.10	$ 0.35	$ 0.32	1.22	2.1

Labor Hours (Used in the first row of the Labor Costs)

Cable	Cable Component	# of Circuits	Size	Length (ft)	Weight	Cost		Assembly	Installation	Ext Assy	Ext Install
A	Gen/Batt to CB Panel	12	16	30	2.815					0	0
B	CB Panel to Relay Panel	12	16	10	0.938					0	0
C	Relay Panel to Load	12	16	20	1.877					0	0
D	Switch Panel to Relay Panel	12	22	10	0.233					0	0
E	Buss to Relay Coil	12	22	20	0.466					0	0
	Cable Subtotal			90	6.329	$ -		-	-	-	-

LRU	Quantity	Unit Cost	Unit Weight	Ext. Weight	Cost	Qty/Box	Length	Depth in.	Hieght In.	Thickness
Circuit Breaker	12		0.055	0.660	$ -					
Relay	12		0.09	1.080	$ -					
Relay Socket	12		0.08	0.960	$ -					
Terminations	24		0.002	0.048	$ -					
Switch	12			0.000	$ -					
Breaker Panel	1		1.09368	1.094	$ -	12	8	6	3	0.062
Relay J-Box	1		0.874944	0.875	$ -	12	6	6	3	0.062
Breaker Panel Bus Bar	2		0.0128	0.026	$ -	1	7	0.5	na	0.04
Jbox Bus Bar	1		0.0064	0.006	$ -	1	5	0.5	na	0.04
Heat Sinking										
Fans/Cooling										
Strain Relief										
Other Sub Total				4.75	$ -					

	Total Weight (lb)	Total Mat"l
Material Total	11.08	$ -

Figure 31. Traditional System Weight Analysis

A similar spreadsheet is used for an SPDU-based system. The generic schematic for an SPDU-based system is shown in figure 32. A key advantage is that the wire gauge to the display panel in the cockpit is a shared digital wire eliminating significant wire weight. Other key points are that panels are eliminated and wiring terminations are simplified by multiple connectors. These combined with the idea that the weight of the digital display is split between approximately 50% of the aircraft loads, giving it a value of only 0.24 lb. per channel, provides additional weight benefits.

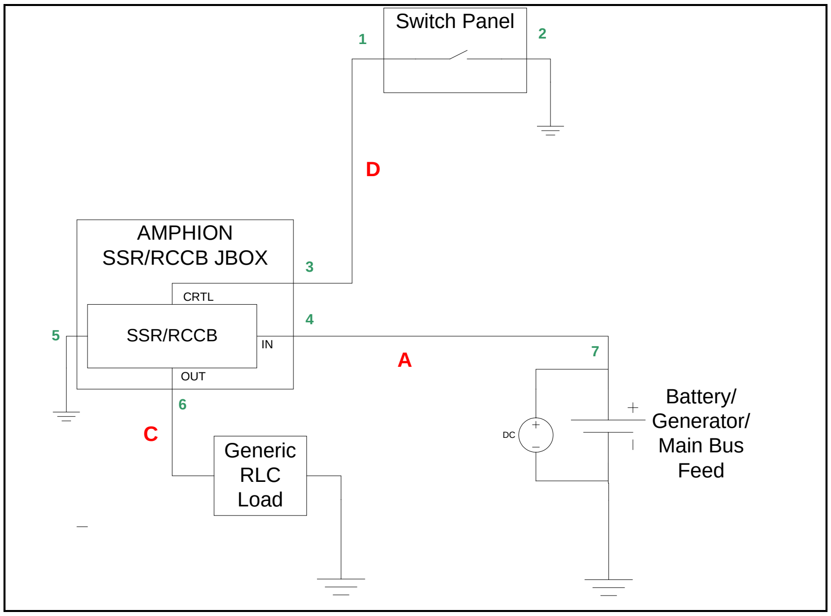

Figure 32. The SPDU-Based Power System Schematic

(Note: cable length D is a discrete signal and is repeated for each SSR requiring switch control. Current through this line is very small since the solid-state device uses a small signal versus relay coil current; cable length A may be one large bus line or individual power wires from the source to the J-box; cable length C is repeated for each individually controlled and protected load; the numbers in the diagram indicate the number of unique termination points. The total number of termination points is dependent on the number of loads serviced by the AMPHION relay junction box.)

When comparing the calculations of the two systems, a weight savings between 15% and 25% may be possible. Using the same 12 circuits, figure 33 shows the traditional system is approximately 30% heavier than the SPDU-based system.

Total Number of Circuits			12
Subset of Circuits Requiiring Switch Control			12

Material Cost and Weight Analysis

Aluminum	0.098	lb/in^3	density
Copper	0.32	lb/in^3	density

Teflon Wire Prices, Weight and Current Handling Capacity

AWG	100ft price	$/ft	10% vol discount	weight/kFt lb	Max. Amps
14	$ 148.28	$ 1.48	$ 1.33	12.43	17
16	$ 102.38	$ 1.02	$ 0.92	7.82	13
18	$ 83.93	$ 0.84	$ 0.76	4.92	10
20	$ 62.33	$ 0.62	$ 0.56	3.09	7.5
22	$ 43.76	$ 0.44	$ 0.39	1.94	5
22	$ 51.30	$ 0.51	$ 0.46	1.94	5
24	$ 35.10	$ 0.35	$ 0.32	1.22	2.1

Labor Hours (Used in the first row of the Labor Costs)

Cable	Cable Component	# of Circuits	Size	Length (ft)	Weight	Cost		Assembly	Installation	Ext Assy	Ext Install	Total
A	Gen/Batt to Relay Panel	12	16	20	1.877	$ 221.14		0.05	0.1	0.6	1.2	$ 90.00
	CB Panel to Relay Panel	12	16	0	0.000	$ -		0	0	0	0	$ -
C	Relay Panel to Load	12	16	20	1.877	$ 221.14		0.05	0.1	0.6	1.2	$ 90.00
D	Switch Panel to Relay Panel	12	24	10	0.146	$ 37.91		0.05	0.1	0.6	1.2	$ 90.00
	Buss to Relay Coil	12	22	0	0.000	$ -		0	0	0	0	$ -
	Cable Subtotal			50	3.900	$ 480.19		0.15	0.30	1.20	3.60	$ 270.00

LRU	Quantity	Unit Cost	Unit Weight	Ext. Weight	Cost	Qty/Box	Length	Depth in.	Hieght In.	Thickness	in^3
Relay	12	$ 175.00	0.11	1.320	$ 2,100.00						
Relay Socket	12	$ 30.00	0.132	1.584	$ 360.00						
Terminations	72	$ 0.05	0.002	0.144	$ 3.60						
Switch	12	$ 8.00		0.000	$ 96.00						
Breaker Panel	0	$ 55.00	1.09368	0.000	$ -	12	8	6	3	0.062	11.16
Relay J-Box	1	$ 27.50	0.874944	0.875	$ 27.50	12	6	6	3	0.062	8.928
Breaker Panel Bus Bar	0	$ -	0	0.000	$ -	1	7	0.5	na	0.04	0
Jbox Bus Bar	1	$ 0.76	0.0064	0.006	$ 0.76	1	5	0.5	na	0.04	0.02
Heat Sinking											
Fans/Cooling											
Strain Relief											
Other Sub Total				3.93	$ 2,587.86						

	Total Weight (lb)	Total Mat"l				
Material Total	**7.83**	**$ 3,068.05**	**0.652**	**lb/channel**	**$ 255.67**	**per channel**

Figure 33. The SPDU System Weight Analysis

Although this study is simplistic, it does not include the weight savings of eliminating other line replacement units (LRUs) in the aircraft by absorbing the processing and functionality within an SPDU. An argument for moving to a distributed solid-state power system becomes stronger when the features of prognostics, trending, and troubleshooting are also included with no additional weight penalty.

The weight savings are highly dependent on the aircraft system design. With a new install, the solid-state system can be distributed saving load wire weight, as used for the previous analysis. In a retrofit where the load wiring converges on the CBP, it may not be cost effective to remove and rewire to meet the distributed system architecture for increased weight savings. In this case, the SPDU weight can be directly compared to the weight of the CBP, with all other aircraft wiring the same. The SPDU used as an example in this report controls up to 54 outputs and weighs approximately 13 lbs, giving a weight per output of approximately 0.25 lb. For the CBP thermal circuit breaker approach, from the discussed analysis excluding wire weight savings, estimates the weight at 4.75 lbs for 12 outputs. This equates to a per output weight of 0.39 lb. This analysis still shows solid-state to be lighter per output than using thermal circuit breakers, because each system is different, weights can vary. This analysis can be done specifically for the aircraft system considering the conversion to solid-state.

1.5.4 Handling Various Trip Curves.

The aircraft system contains various types of loads, all with potentially different characteristics, requiring thermal circuit breakers that are tailored to protect the wiring, without causing nuisance trips. The vast array of part numbers can be a burden for aircraft maintenance. The various parts must be in stock for replacement, and there is always a potential for accidentally changing the circuit breaker rating during replacement. This can lead to reduced wire protection or nuisance tripping.

In addition, solid-state can offer various trip curves within the same form factor, all configurable using a maintenance computer communicating to the SPDU. The configuration can be validated after loading to ensure the trip curves have not changed. This reduces part numbers and the potential for nuisance trips and protection loss.

1.5.5 Separate Power Capable.

The thermal circuit breakers need an input bus for providing protected power to the loads. In the thermal circuit breaker system, the input bus can be connected to any of the available buses. However, in a solid-state electrical system, a fixed number of SSPCs can only be connected to one bus. The example SPDU has two bus inputs per LRU and each bus supplies power to 27 SSPCs.

1.5.6 Quiescent Power Consumption.

One advantage of the thermal circuit breaker over solid-state is the ability to be directly connected to the battery. Unlike a thermal breaker, SSPC devices require quiescent power to operate. When considering aircraft design, many SSPC devices attached to the battery can sum up to significant current draw that, when the aircraft is sitting for days, may accumulate and consume a noticeable amount of capacity from the battery. This is undesirable when the energy storage is required for emergency operation and engine starts. For circuits on this bus, air-framers have typically employed thermal breakers for three reasons: (1) thermal breakers require no quiescent power to provide protection, (2) thermal breakers have a long, well-known history of use in standby and critical systems, and (3) thermal breakers are a dissimilar method of protection compared to solid-state technology and offer a layer of protection from common-mode failures.

1.5.7 Solid-State vs. Electromechanical Relays.

When switching the power to the load, the traditional system requires an additional component, mechanical relays, while the solid-state protection and switching is performed using the same component. In table 6, the mechanical relay outperforms solid-state in several categories that involve high voltage, high current, or electrostatic sensitivity. However, the remaining parameters show that solid-state is more successful when using lower load currents. To further benefit solid-state, a majority of aircraft loads are less than 5A.

Table 6. Solid-State and Electromechanical Relay Comparison

Parameter	Mechanical Relays	MOSFET	SCRs and IGBTs
Breakdown voltage	115V-7.5KV	25V-600V	300V-7.5 KV
Minimum on-resistance	50-100 mohms	2.5 mohms	Vdrop - .7 to 4V
Minimum response	5000 usec	20-1 usec	3-30 usec
Load current range	2.5-1500A	.1-120A	.1-200A
Quiescent current or coil current	100-300 mA	15-20 mA	10-30 mA
Cycle life	~20K-100K cycles	>10,000,000 cycles > 1M hours	>10,000,000 cycles >1M hours
Interrupting current	5 KV	Current limited 600A	Current limited 600A
Contact bounce	Yes	No	No
Acoustic noise	Yes	No	No
Electromagnetic interference noise	High	Low	Low
Digital level drive	No	Yes	Yes
Arcing	Yes	No	No
Vibration Sensitivity	Yes	No	No
Size (AC applications)	Med	Large	Small
Size (DC applications)	Large	Small	Small
Static sensitive	No	Yes	Yes
Typical failure mode	Pitted or welded contacts	55% Short, 30% Open	55% Short, 30% Open

Relay (PRD type 20A):

- The coil is 300 Ohms; dissipation is (28)2/300 = 2.61 watts
- Contact drop is 150 mV; dissipation at 20A = 3 watts
- Typical relay power loss at 20A is therefore 5.61 watts

Thermal circuit breaker (28V, 20A):

- Contact drop is 150 mV; dissipation at 20A = 3 watts
- Thermal element loss is typically an additional 2 watts
- Typical thermal breaker loss at 20A is therefore 5 watts
- Total power dissipation: 10.61 watts at 20A

NOTE: De-rating by up to 60% of published value at 100C ambient.
DC SSPC, each FET Ron = 0.01 Ohm, 4 in parallel yields 0.0025 Ohm (1 watt at 20A)

- Measurement Shunt is 0.001 Ohm (0.4 watt)
- Quiescent Electronics (0.4 watt)
- Total Power Dissipation: 1.8 watts at 20A
- 3 to 6 times cooler than electromechanical technology.

1.5.8 Load Trend Monitoring.

In the traditional system, electronic subsystems and components are forced to provide control loops and self-monitoring functions. Using the inherently "dumb" circuit protection and loads, the load monitoring is compromised because of pressures to preserve weight, cost, and complexity. With the solid-state system, at a minimum the loads' current and voltage can be captured periodically within the system and used to determine maintenance cycles for the attached loads.

2. THE SPDU.

As discussed in section 1.1, this report details an SPDU as an industry example to provide insight into design and certification issues. This section will discuss an SPDU designed, produced, and preparing for certification.

2.1 TRADEOFF AND PERFORMANCE DECISIONS.

When defining the SPDU, feedback from multiple customers and end-users across many aircraft platforms was used to identify the features that provided the best value and benefit. A significant amount of time was spent educating customers who had experience only with traditional circuit breakers and electromechanical relays. It was important to discuss the benefits of solid-state prior to determining features with the best value and benefit.

Key items, such as SSPC current handling range, number of SSPC channels, and other performance parameters, were traded-off with size and weight. The idea that 80% of the loads were under 7.5A was a key driver in the SSPC mix within the SPDU. Additionally, the fixed overhead of communications, power supplies, and central processing in both weight and size drove a significant amount of the decision toward determining the count of 27 SSPC channels per SPDU bus. For other features, tabulations were put into a Pareto chart to help with additional tradeoff decisions.

The top SPDU goal for many customers was to reduce the overall system weight by eliminating wire, circuit breakers, relays, and panels. A secondary goal was to note an increase in reliability over a traditional thermal and electromechanical system. The idea of remotely controlling loads, gathering maintenance data, and having arc-fault protection and PWM capability were items that were not completely understood. Once these features were explained, expectations shifted to future possibilities of replacing other systems and taking advantage of predictive maintenance to save costs in manufacturing and to support the fleet.

A market analysis was conducted. Figure 34 shows the rank of importance for customer requirements for an individual SSPC that could provide circuit protection and remote load control. It was noted that PWM and reliability were important because the point for handling this amount of current was for controlling windshield heat and the PWM function provided better heat control and longer life than an electromechanical relay and circuit breaker performing the same function. While this does not precisely relate to the SPDU, it does show that a paradigm shift in power distribution and control is needed when determining the value of a feature.

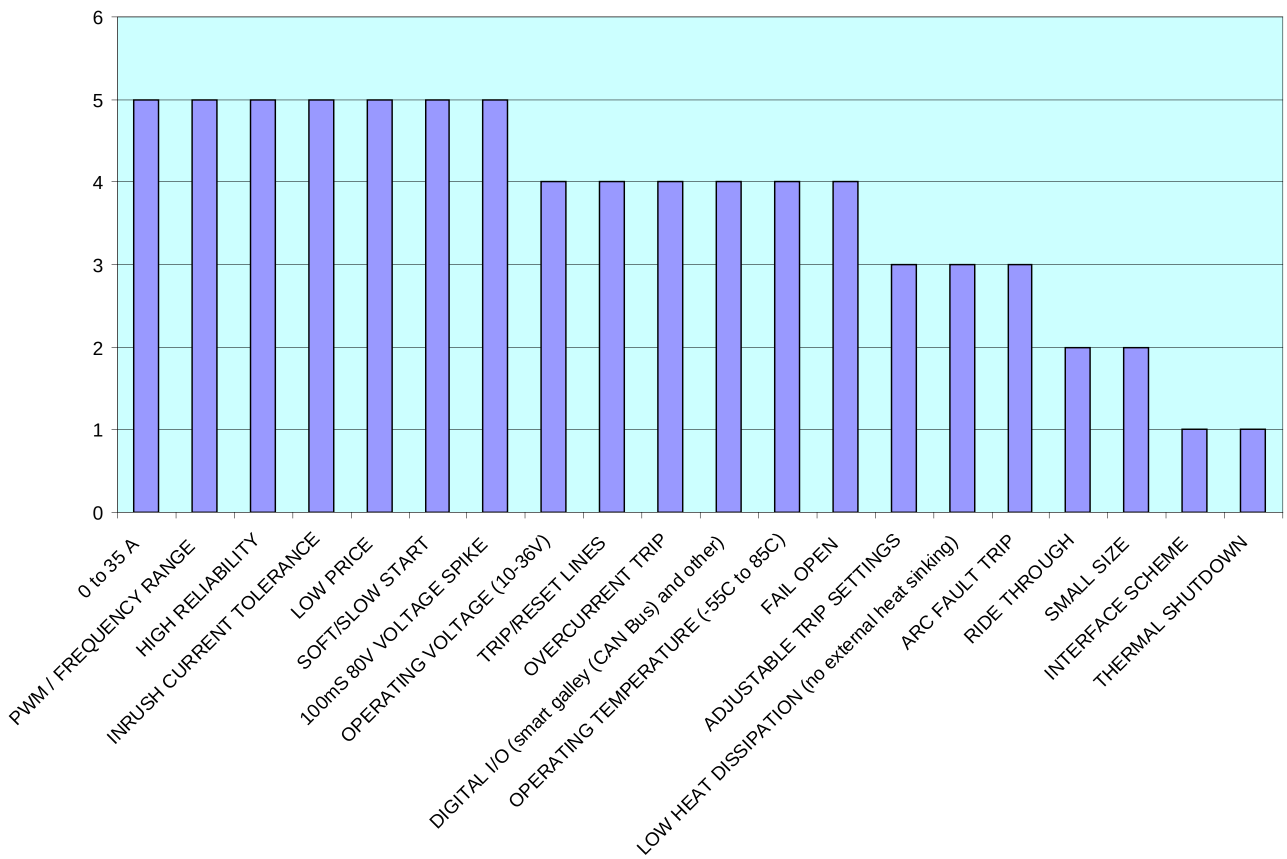

Figure 34. Voice of Customer—The Customer Requirements

The customer's wants and needs were weighed against the feasibility and practicality of implementation. Some of the tradeoffs included size, weight, the count and maximum current of discrete outputs, and the ability to update firmware without opening the enclosure.

Size and weight were the important tradeoffs to meet the current capacity performance and number of SSPCs. The increased current carrying capability and high failure criticality (level A) increased the need for heat sinking and additional fail-open components, adversely affecting the SPDU weight. For the original launch, the customer's requirement for SPDU weight was 8 lbs. After the launch, the customer increased the number of SSPC circuits, and thus the weight requirement increased to 12 lbs. The current weight is approximately 13 lbs, depending on the SSPC configuration used. A significant portion of the SPDU weight was the additional mechanical features required for the vibration levels of rotary aircraft and the need to conductively remove heat due to internal power dissipation. A lightweight version of the SPDU was created to survive fixed-wing vibration levels and reduced the overall SPDU weight by approximately 2 lbs. The lightweight version design is equivalent to the standard SPDU with regard to electrical hardware and software. The design changes to the lightweight SPDU were solely mechanical and focused on optimization of the enclosure.

The current carrying capacity of individual SSPCs within the SPDU was capped at 30A. This value accommodated 98% of the aircraft loads without having a need to modify the modular design of the SPDU and maintain the ability to support many smaller current SSPCs or choose to combine slots to produce higher current outputs. Values higher than 30A showed significant limitations in circuit board, trace width, and connector selection and proved to not provide the return on investment of space and cost. The SSPCs currently designed for the SPDU come in three basic configurations of 7.5-, 15-, and 30-A outputs. As a compromise and an enhancement to the design, the concern for providing remote-control capability for higher current loads was added into the design by implementing four remote control circuit breaker (RCCB) outputs. These outputs mimic the traditional 1A circuit breaker control functionality for an RCCB and can provide enough current to drive coils of relays. This allows the SPDU to control loads through external RCCBs or contactors with currents as high as 150 to 300A. When comparing and RCCB output to an SSPC output, the sacrifice in features is the inability to have direct and real-time monitoring of the current traveling through the remote device and have programmable overcurrent trip protection.

A similar tradeoff was made with the capability of the discrete outputs and the size of the unit. The initial target of the high-current output discretes was 2A. Because of the real estate needed and the importance of adding overcurrent protection, these outputs were reduced to 0.5A. This value provides sufficient current to support annunciation devices, such as incandescent lamps, and has the capacity to drive mid-range relays without increasing the envelope of the SPDU enclosure.

Another compromise in the SPDU implementation was the ability to update SSPC firmware without opening the SPDU. As currently designed, the end-user is able to provide firmware upgrades to the main processor through the external connector, but needs to remove the lid and pull the SSPC cards if an update to the SSPC software is required. The reasons for the main drivers lacking external programmability of the SSPCs was to increase the mechanical envelope and to provide space to implement independent traces and chip selects for each of the SSPC processors. Another reason would be to invest in a significant software effort to design a boot loader that uses the existing Ethernet, ARINC, and inter-integrated circuit communication to program the SSPCs through the external maintenance connector. The final decision was to leave the mechanical design unchanged and make the software effort a future option.

2.2 OVERVIEW.

The SPDU (see figure 35) is capable of switching between 200 and 300A of 28 VDC current and controlling up to 54 independent channels using SSPCs. The 54 SSPCs are mechanically divided between two separate cavities of an aluminum enclosure. Each cavity has its own power and signal inputs/outputs (I/Os). To achieve the necessary safety level, the control circuitry architecture for the SPDU provides full dual redundant control for all SSPCs in each SPDU. An internal cross-channel link allows for redundant communication and control of the 54 SSPCs from either channel's redundant communications buses. The dual redundant architecture also extends to the internal power supplies for the central processing unit (CPU) and SSPC control power to eliminate any single-point failures in the control power and logic electronics.

Figure 35. The SPDU

The SPDU can distribute and control power to high-current loads as well as feed lower current loads and PDUs. The flexible SSPCs can be programmed by software configurable trip points, communicate via ARINC 429 and Controller-Area Network (CAN) data buses, and interface with Ethernet-enabled GSE. Up to 16 SPDUs can be installed on one aircraft backbone.

2.2.1 Sub-System Control.

In addition to providing secondary power distribution and control, the SPDU has the capability to incorporate functionality typically performed by other independent systems. Because an internal processor, digital communications, and available spare I/O exist in the design of the SPDU, functions such as heating control, motor control, pump control, fire suppression control, and lighting control can be absorbed within the SPDU with virtually no extra hardware. The value of this benefit is an overall reduction in aircraft weight, installation time, and box count without the sacrifice in performance.

2.2.2 Power Distribution Interface.

Interface with and control of any of the SPDUs (and PDUs) is performed by a multi-functional display unit in the avionics suite. The display can be as simple as a "dummy terminal" for I/O with the logic incorporated into the power-distribution components rather than the avionics. Communication with the SPDUs and PDUs occurs via a serial data bus and provides the pilot, cabin crew, and maintenance personnel with information about the electrical system. For security purposes, the SPDUs and PDUs can be configured so that only authorized personnel can control specific channels and loads.

2.2.3 System Architecture.

The SPDU addresses the safety and isolation concerns of multiple buses within the same LRU by physically separating and isolating the control and switching circuitry of its two sections. The two power inputs can be connected to the same aircraft bus or can be connected to two different buses, such as essential or non-essential, as is necessary for the application.

Figure 36 shows the implementation of six SPDUs to distribute all aircraft power. The six-SPDU configuration is selected to provide the flexibility and spare capacity for growth potential of both circuit-protected outputs and spare discrete inputs.

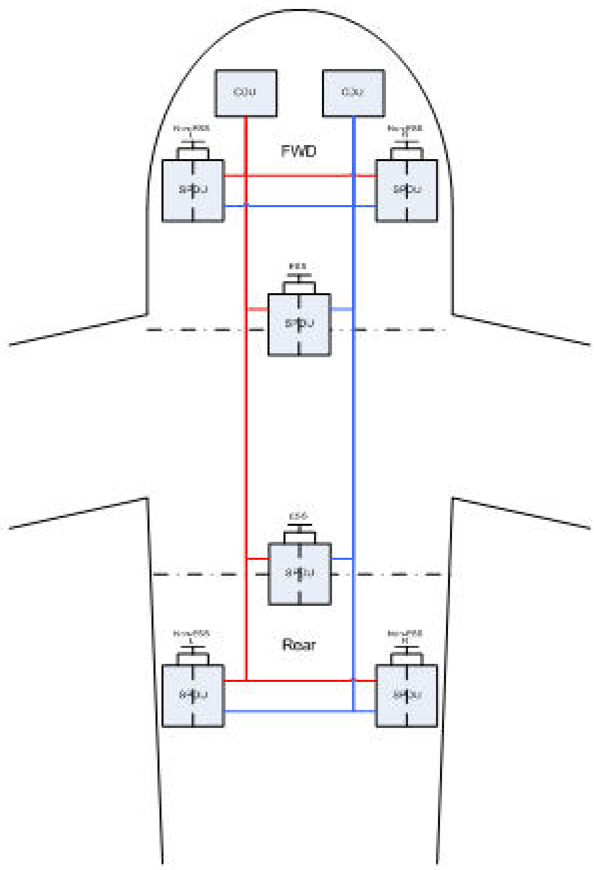

Figure 36. Example Secondary Power Distribution System

This architecture is compatible with a split aircraft bus system to achieve the Civil Aviation Authority, FAA, Joint Aviation Authorities, and EASA safety requirements. It supports the need for redundant critical loads to be powered by physically and mechanically isolated distribution paths throughout the aircraft. To achieve a distributed system and gain the advantage of wire-weight savings, the system would be split into three zones within the aircraft: forward, center, and rear locations.

During development, the exact allocation of loads among SPDUs is determined. Regardless of the final configuration, a spare capacity to accommodate the customer's requirements is followed.

2.3 FLEXIBILITY.

In the engineering and systems design field, flexibility refers to the product's ability to adapt when external changes occur. From the perspective of the SPDU manufacturer, the customer's procurement personnel, the aircraft maintenance personnel, and the end users of the product (i.e., pilots and owners), multiple levels of flexibility have been incorporated into the SPDU design to minimize the effort and cost of portability onto new platforms and into new applications.

One objective of flexibility is the ability of the SPDU to support both metal and composite airframe structures and support installation in severe and electrical environments. This feature, combined with alternate mounting arrangements for thermal and electrical grounding, maximizes where the SPDU can be installed and used.

Another objective is the desire to use only one part number throughout the aircraft to simplify procurement and inventory management. Coupling this objective with an SPDU architecture that uses remote programming to implement system changes will greatly reduce the need to disassemble the aircraft or open the SPDU for system modifications.

A third objective is to offer a wide current range of circuit protective devices so that the circuitry breaker and relay panels can be substituted with one or more SPDUs. This helps alleviate the need to continue both technologies within the aircraft and simplify the overall power distribution system. Offering programmable ranges of circuit protective devices reduces the need for hardware modifications because trip settings and other performance criteria can be established by uploading new values rather than replacing hardware.

In addition to the programmability of individual circuit protective devices, the SPDU incorporates a layer of mechanical modularity that affords a more simple method of adding, swapping, or removing circuitry and allows a quicker method of performing upgrades or repairs without impacting other devices in SPDU assembly.

Another important flexibility objective for the SPDUs architecture and design involves adapting to changing rules and regulations. With the forward-looking notion of attempting to protect the loads as well as the wires through prognostic measurements and arc fault detection, the desire for the SPDU to have a simple means of altering or customizing the protective trip curve and logic is a significant benefit to the air framer and equipment installer.

As aircraft move toward higher speed or less cumbersome communication protocols, flexibility in providing multiple means of communication with the SPDU is also important. Some air framers are more aggressive than others in using newer technologies and bus communication schemes. By equipping the SPDU with a widely used and accepted bus protocol such as

ARINC429, and also offering a later, faster, but less used automotive based CANBUS 2.0, air framers have a choice to select the bus communication that best fits their application.

2.3.1 Aircraft Installation Flexibility.

2.3.1.1 New Build.

A new build or complete rewire maximizes the benefits of solid-state secondary power distribution. The weight savings is maximized because the SPDU is local to the controlled loads, reducing load wire length. Also, the new build has a greater potential for interfacing to other aircraft systems using the SPDU's integral discrete inputs and discrete outputs, further reducing weight and cost.

New builds can also reduce labor costs for wiring the aircraft as compared to the standard CBP system. The cost to run each load wire to the cockpit in a centralized system is greater than running communication wires to the cockpit and running shorter load wires from the SPDU to local loads.

Unlike a retrofit application, a new build typically has a display component already designed into the aircraft system, which can be used to integrate with each SPDU using a communications bus. Although no additional weight is added by using an existing display, software is required to interface with the SPDU, allowing the pilot to control SSPC outputs and view SPDU and SSPC status.

2.3.1.2 Retrofit.

In the aerospace industry, including military aircraft, there are a greater number of potential retrofit applications over new builds. Commercial aircraft can be in service for more than 30 years and military aircraft for more than 50 years, which are updated when required by the aircraft's maintenance schedule. The aircraft maintenance D check, or heavy maintenance visit, is scheduled every 5 years and major upgrades can be influenced by leaps in technology that offer vast improvements in performance, weight, and safety. Solid-state power systems fit into the technology leap classification and offer enough advantages over the traditional power systems for air-framers to consider when performing aircraft updates. It is possible that an aircraft maintenance C check can be used to replace a single CBP or a single system, such as a fuel system or heating system, with an SPDU.

The SPDU can be installed as a direct replacement of a CBP and relay junction box in a retrofit application. As a feasibility test, a retrofit was performed by replacing a CBP with an SPDU on a decommissioned Boeing 737. Two days were required for planning and preparation work to understand load locations and load properties, and to create an SPDU configuration table. To prevent disrupting the existing system, the replacement required wiring parallel control from the existing CBP to the SPDU. This was accomplished in one day.

The replacement was followed by several tests, including a bus transfer, powering 28 VAC loads with the PWM SSPC outputs, and tripping by intentionally causing a wire insulation breach.

This is described further in section 2.8.2. To minimize impact, the retrofit can also be accomplished without changes to aircraft load wiring, thus keeping the centralized system. In a retrofit application, if a controlling display is not available, one can be added to the aircraft system as part of the retrofit or limited control can be available using discrete I/Os. If a display component exists, the software requires an update to control the SPDU. The display SPDU status and communication wires would need to be run between the two devices.

The SPDU also allows for the potential to remove some other equipment, such as inverters that create 28 VAC, RCCBs, data bus converters for discrete I/O, and load current monitoring sensors. An SSPC PWM output can also be used in conjunction with display software and sensors to provide windshield heating for de-ice, cabin environmental control, and dimming for lighting loads.

To achieve weight savings of 20% to 30% over the traditional system, the retrofit activity would require a complete rewire of loads powered by the SPDU, changing from a centralized system to a distributed system. Space would be required at various locations throughout the aircraft to fit the SPDU and associated wiring. Because the SPDU is environmentally sealed and tested for +50,000 ft altitude, the SPDU can be installed outside the pressure vessel if required.

In the aerospace industry, considerations should also be made for documentation updates spawned by the switch to solid-state. The pilot operating manuals would require updating, possibly reducing pilot workload, to describe the new procedures for controlling loads, and detecting and resetting tripped outputs as examples. Maintenance manuals that describe the procedures for troubleshooting, repairing and replacing thermal circuit breakers or mechanical relays, would require updates and re-writes to comply with the new solid-state system. It is likely that troubleshooting time will be reduced with the availability of extensive BITs and indications on the digital buses. Using the SPDU maintenance log and maintenance log analyzer, the manual can include a means to perform predictive maintenance on attached loads as described in sections 2.6.3 and 2.7. The time difference between replacing an SSPC versus a thermal circuit breaker is not completely understood at this time, but may be negligible.

2.3.1.3 The SPDU Installation Location Flexibility.

The SPDU has an environmentally sealed enclosure primarily because aerospace products, driven by the customer, are required to pass several tests that require an environmentally sealed product. Because of this enclosure design (see figure 37), the SPDU unit can reside outside the pressure vessel. Having an environmentally sealed enclosure helps keep fuel, sand and dust, condensation, and hydraulic fluids out of the internal chassis and, therefore, out of the electronics. It also aids the product when testing in an explosive vapor environment. Testing for exposure to sand and dust, fuel, hydraulic fluids, and explosive vapor environment are typical requirements within the aerospace industry.

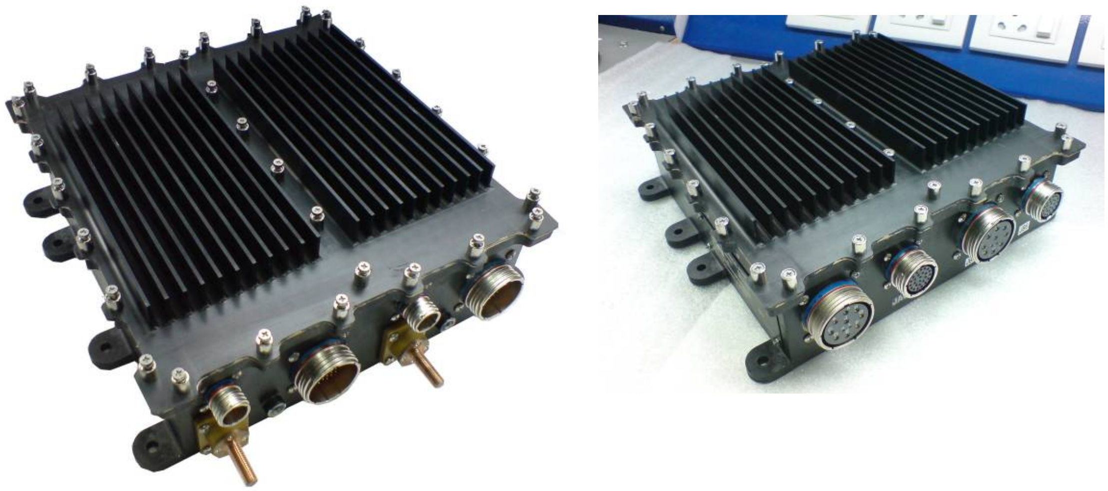

Figure 37. The SPDU Enclosure

2.3.1.4 Composite and Metal Aircraft Flexibility.

The SPDU has been designed for both composite and metal aircraft structures. Three key areas of concern are Electromagnetic interference (EMI), lightning, and enclosure temperature. For EMI and lightning on a composite aircraft, an alternate and secondary grounding means has been provided on the enclosure. This is a backup to the grounding already supplied through the mounting feet of the SPDU. Two dedicated studs are supplied on each SPDU to allow for the connection of grounding straps. Because composites may be temperature sensitive and overheating may cause the composite to delaminate, the SPDU has been designed so the maximum enclosure temperature will always remain below 85°C under the specified operating conditions.

2.3.1.5 System Expandability.

The requirement, as given by a customer for an application, was to create a system containing six SPDUs where each SPDU would control approximately 40 loads. However, all of the design work has been expanded to 16 SPDUs to satisfy needs of multiple customer applications. The primary driver for the SPDU design to reach 16 was four address discrete inputs. Because the address discrete inputs could allow for up to 16 SPDUs, all subsequent design had that number in mind, thus the four address discrete inputs was a design decision to have enough built-in margin for future programs (figure 38). Using three discrete inputs would allow for a system of eight SPDUs, leaving only two for any future growth from the required six SPDUs.

The SPDU system can contain up to 16 SPDUs for which each SPDU contains 54 SSPC circuits. This extrapolates to the SPDU system being capable of controlling up to 864 loads, where each SPDU can have a unique and independent configuration for trip settings and configurable features.

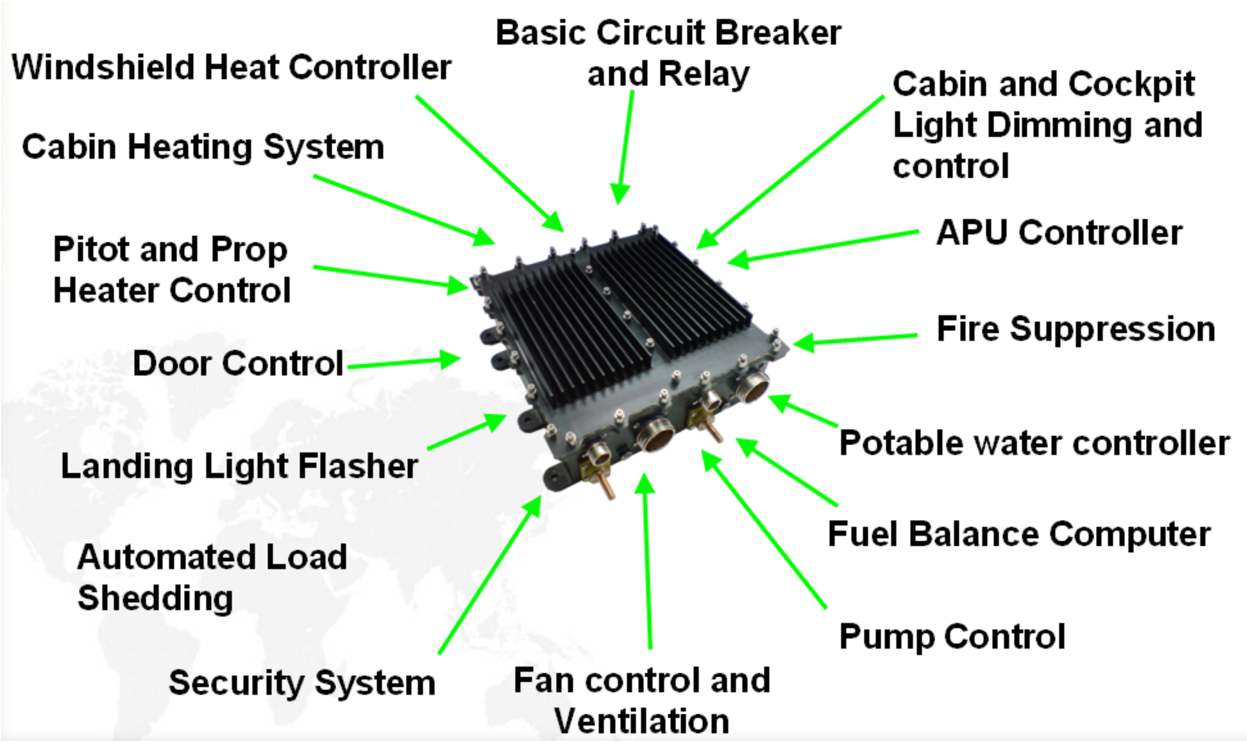

Figure 38. The SPDU Interface Capability

2.3.1.5.1 Multifunction Capable.

Weight, cost, and size reductions can be realized by integrating functions into the SPDU that previously required additional LRUs. Many lighting, heating, and other control and monitoring functions can be readily implemented in the SPDU software and hardware, combining circuit protection and smart control into one LRU.

2.3.1.5.2 Windshield Heater Control.

Current-to-windshield segments are controlled via PWM to tightly regulate windshield temperature and prevent over-temperature damage. Windshield temperature feedback is read from a resistance temperature detector embedded in the windshield. When using mechanical relays to switch power, the window heating element stress is prioritized over mechanical relay switch life. This leads to frequent relay replacements as switch cycles near its maximum lifetime. To protect the heating element, separate circuit protection must be added, typically using a fuse or circuit breaker. With solid-state, switch and circuit protection are integrated and switch life is increased.

2.3.1.5.3 Cabin Lighting System.

For cabin lighting applications, SPDU SSPCs are capable of performing independent, multi-channel lamp dimming to accommodate different light-intensity needs of pilots, copilots, crew members, and passengers. The wide PWM duty cycle range of 4% to 100% permits full range dimming of incandescent and solid-state light sources.

To drive cabin accent lighting, precise control of SSPC PWM allows coordinated multicolor dimming of solid-state lighting to provide full-spectrum chromatic adjustability to match interior color schemes and provide novel lighting options. The powerful and lightly loaded main processor in the SPDU can be used to perform the dimming calculations and leave the SSPC to handle the PWM functionality.

2.3.1.5.4 Fuel Balancing.

To trim fuel balancing, which is important during landing procedures, the SPDU can be responsible for reading the fuel level data via inputs from ARINC, CAN, or discrete sensors and can trigger SSPCs to control the fuel balancing transfer pumps and activate the cross flow valve. The fuel pump is also arc-fault protected, which is an added benefit.

2.3.1.5.5 Cabin Environmental Control.

Power to cabin or cargo heating units is controlled via PWM to regulate duct and ambient temperature and to prevent overheat damage. Ambient or duct temperature feedback is read from RTDs distributed within the heated volume.

2.3.1.5.6 General PWM.

The SPDU receives PWM variables for frequency and duty cycle via ARINC or CAN interface. These data are relayed from the main SPDU CPU to the SSPC microcontrollers. The PWM timing is handled by each independent SSPC, rather than the main CPU. Any number of SSPCs can use PWM at any time and their frequencies and duty cycles are all independent of one another. Continuous frequency and duty cycle updates are passed from the avionics data bus to SSPCs for real-time applications such as heater control and lamp dimming. Each SSPC PWM frequency is adjustable from 1 to 200 cycles-per-second and duty cycle from 4 to 96%.

Depending on the application, various frequencies can be used:

- 15 to 30 Hz for window heat power control
- 80 to 120 Hz for lamp dimming and interior lighting
- 30 to 200 Hz for motor and fan
- Pulse frequency above 120 Hz is well within the SSPC bandwidth and will minimize visual and aural artifacts.

2.3.2 Modular Design.

A design goal of the SPDU was to provide a level of modularity that allows for the easy removal of subassemblies and a logical separation of functionality. A modular architecture provides more advantages of flexibility than a fixed or unistructural design. Breaking down the SPDU into functional subassemblies provides a convenient means to mix and match modular pieces to meet specific aircraft installations. It also provides a convenient means of implementing upgrades on a modular basis without impacting other subassemblies. Modularity, if implemented properly, can also provide the necessary electrical and mechanical isolation that is needed for high-safety applications.

From the repair and servicing standpoint, a modular design provides a less costly means of maintaining spares inventory. Subassemblies, rather than entire power distribution units, can be stocked. Thresholds of subassemblies with higher run rates and usage can be individually maintained. These same subassemblies can be quickly installed and removed to assist in trouble shooting and simplify the repair operation.

2.3.2.1 Pluggable SSPC Modules.

The SPDU evolved into a more flexible solution when the design allowed the SSPC modules to be capable of fitting into multiple locations, depending on the current carrying capacity of the connector pins and traces. Figure 39 shows a cross-sectional view of the placement of modules within a channel of the SPDU. The modularity of the design allows for many of possible configurations in future versions of the SPDU.

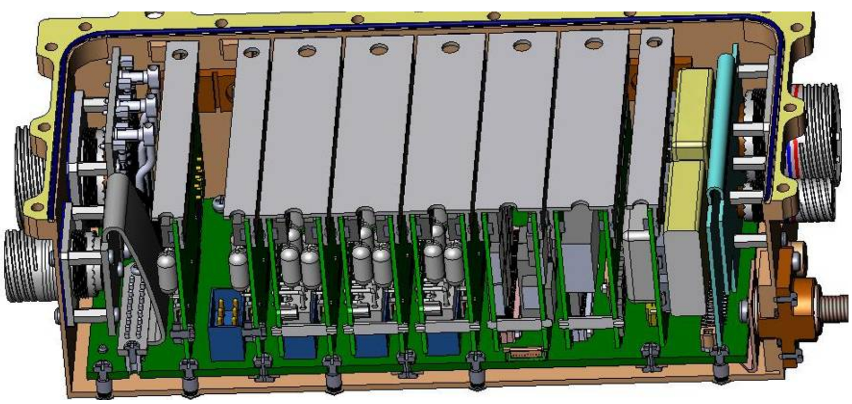

Figure 39. Channel Cross-Section

In the current design shown in Figure 39, the end user can configure the SPDU to place SSPC modules depending on current rating desired.

2.3.2.2 Electrical Modularity.

Modularity was also a primary goal of the SSPC electrical design. There are three different SSPC module types defined for SPDU. Table 7 shows the range of current ratings that each module type can support and how many channels are provided with that capability.

Table 7. Existing SSPC Module Types

SSPC Module Type	2A	2.5A	3.75A	5A	7.5A	10A	15A	20A	25A	30A
1	6 Channels					X	X	X	X	X
2	X	X	3 Channels					X	X	X
3	X	X	1 Channel					X	X	X
	X	X	X	X	1 Channel					

The concept of pluggable modules, containing multiple, configurable SSPC circuits, introduced opportunities for standardization. Electrical circuit design, printed circuit board layout and connectors, heat sink design, and module packaging are similar among the three SSPC module types. Module differences include the number of power switching FETs installed on each circuit board and the number of circuit boards installed in each module type. This standardization reduced the number of unique parts and cost associated with maintaining different circuit designs. Because of pluggable modules, the SPDU requires configuration control to manage the many options available for populating the SPDU. Once the configuration has been chosen for the SPDU, the SPDU must safeguard against subsequent tampering or changes by alerting the aircraft installer and pilot. The SPDU must conform to a single configuration until actively configured otherwise using the SPDU maintenance software.

2.3.3 Programmability.

2.3.3.1 Programmable Trip Curves and Ratings.

Because each SSPC output, independent of current capacity, has a similar circuit, the software could be duplicated for all SSPC module part numbers. This requires the SSPC software to be flexible enough to handle multiple trip curves and current ratings.

Multiple current ratings were required to support the various loads that may be connected to the SPDU. The following current ratings were created to accommodate the vast majority of secondary power distribution loads:

- 7.5A
- 15A
- 30A

Continuous current rating is the key differentiator between the SSPC module Printed Circuit Board (PCB) cards. Along with this current handling capability is the added ability to customize the trip curves to support loads with high in-rush currents or support the detection of arc faults. The SSPC trip curve has multiple stages that are calculated using different timing and amplitude parameters. The first stage is the thermal or overcurrent portion of the trip curve. This is meant to protect against failed loads and draw more current than expected. The current rating, chosen by the installer, will be some marginal percentage above the nominal current to allow the load to operate without tripping under normal conditions. The second stage is the surge portion of the trip curve. It is meant to protect against high currents that could damage wiring (such as arcing or extended surges) in the aircraft. The final stage is the instant-trip portion that must react fast to prevent damage to the SSPC in the case of shorts circuits. The instant-trip feature was introduced as a reactionary measure based on experience with the previous generation of SSPCs that were damaged when an extreme and rapid direct short circuit was applied to the output.

Figure 40 shows the SSPC trip curve. This trip curve was created using a set current ratings and set time constants. The thermal trip has a single time constant that creates a symmetric balance for charge and decay. The surge trip has two time constants, one for the rising edge and another for the falling edge to create, if desired, an asymmetric charge and decay characteristic. This was intended in the design for multiple reasons. The first involves different rise and fall time constants for the surge trip region provided additional flexibility to tailor the trip characteristic to complex load curves that have non-linear or non-monotonic in-rush and power-up curves. The second reason was to be flexible when defining the surge trip curve so that when the SAE International (SAE) DC arc fault specification was released, the SSPC would be able to adapt and comply. The SAE DC arc fault specification was released in June 2012 as SAE AS6019.

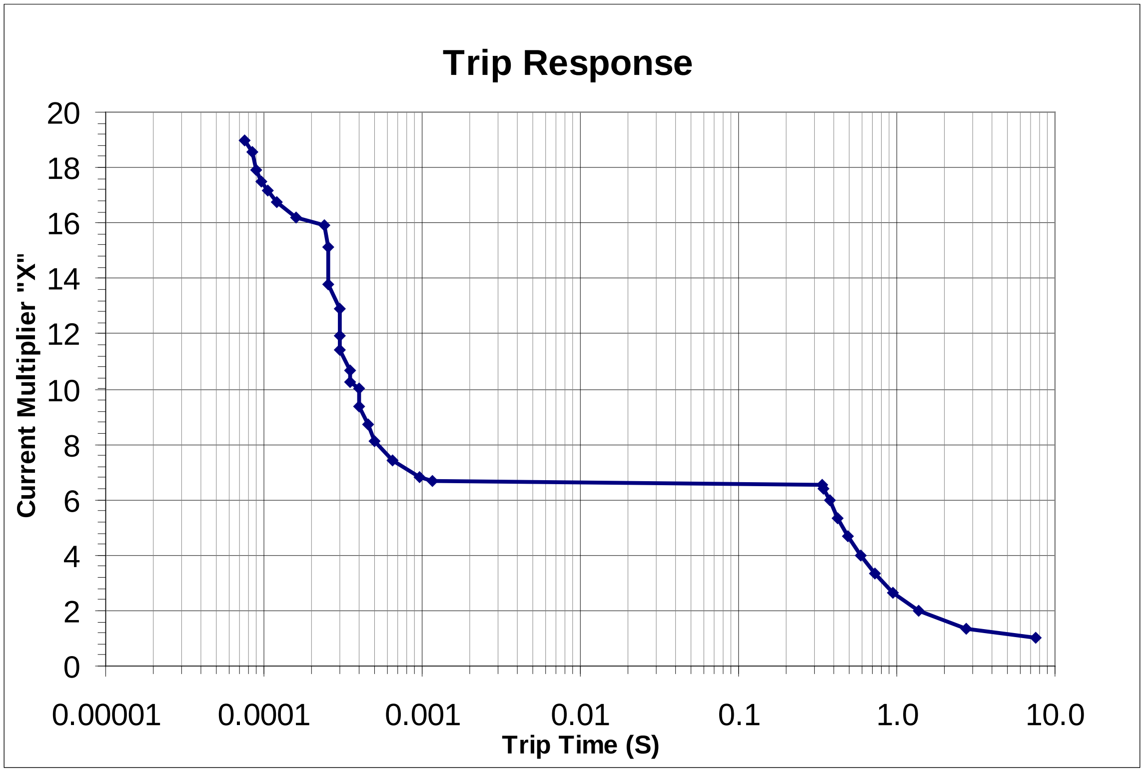

Figure 40. The SSPC Trip Curve

Because the trip curve and parameters are flexible and can be modified by the SPDU installer, the software had to contain the trip algorithm and have enough resources from the microprocessor to trip with accuracy. The goal of the trip curve was to mimic the analog trip circuitry from the previous generation SSPC. The circuit from the previous generation SSPC used an RC curve. A decision was made to keep the same trip curve so that the comparison can be made between the two generations, with the differences being the software trip curve versus the analog/hardware trip curve. One of the main reasons for moving to a processor-based trip curve is the ease of manipulating the curve through constants and lookup tables. This also makes the implementation of I^2T-shaped trip curves easier than with hardware requirements.

2.3.4 Configuration Table and Ground Support Equipment.

Software is one of the largest cost and schedule drivers when tailoring systems to interface with other systems or modify the system for new applications. The overhead of DO-178B makes software changes document- and certification-intensive effort. When developing the SPDU architecture, a driving goal was to minimize software changes when installing an SPDU in an aircraft and to avoid the need to reverify and approve software changes. The configuration table is a method of preverifying software functionality based on the use of a range of adjustable constants. The variables that may exist during an installation are adjustable by modifying constants in a table. These constants apply to features of the SPDU and its SSPCs that pertain to the control, communication, and trip detection functionality of the unit.

The GSE in the SPDU project is a software graphical user interface (GUI) that is installed on a laptop to be used by the aircraft installer or maintenance technician. Typical use of the GSE is the downloading of maintenance log data. However, the GSE was expanded to allow the installer to change the settings of the SPDU. The GSE then became an infinitely flexible platform for configuration of the SPDU. Any setting that the team or customer agreed was important or needed could be added to the SPDU.

One of the flexibility features of the SPDU system is that a unique configuration table, shown in figure 41, can be created for each SPDU in the 16-SPDU system and, depending on the address of discrete inputs, the corresponding configuration table is chosen for operation.

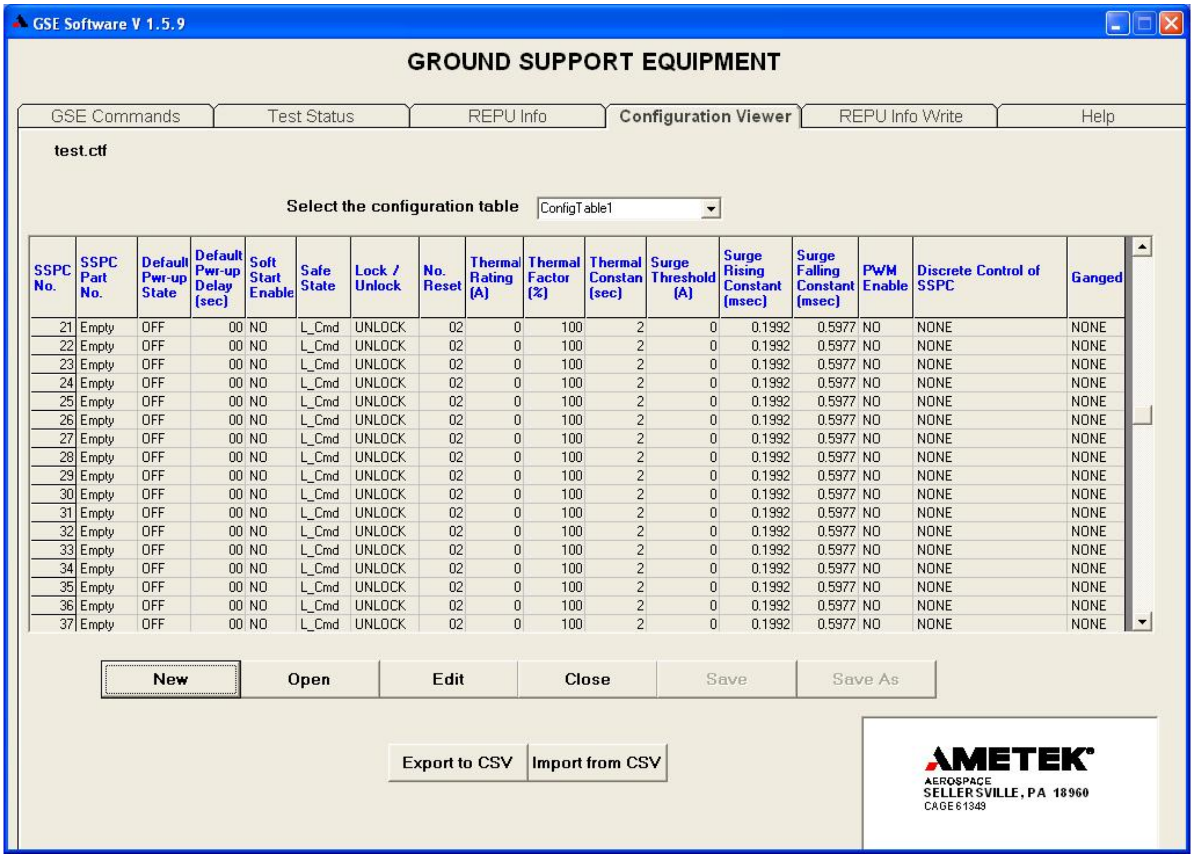

Figure 41. The GSE Configuration Table

This allows the air-framer to choose one SPDU hardware configuration and allow the address pin-strapping to determine which trip curve settings are used for each SSPC output. The configuration table settings are described further in appendix C.

<u>2.3.5 Remote Control</u>.

<u>2.3.5.1 The ARINC/CANBUS Control Communications</u>.

Multiple communication buses are used on aircraft today. The ARINC has a proven history of reliability in the aerospace industry. It has built-in data integrity, uses a differential communication pair to reduce susceptibility to noise or bit errors, and provides wiring redundancy that can be tailored to the application by using full-duplex communications where transmit and receive communication are resident on their own wires. The data are unidirectional because an ARINC bus contains one transmitter and up to 20 receivers.

The CAN or CANBUS is another proven communication bus that was developed for the automotive industry but has, in recent years, been used as the primary communications bus in mid-size jets, although not yet widely accepted in the aerospace industry. Airbus is creating more opportunities for the industry to accept CANBUS by incorporating CAN on the A380 superjumbo jet. The CANBUS, similar to ARINC, also contains built-in data integrity and uses a differential pair for communication; however, it has higher speed data rates, contains data collision detection, and is bidirectional.

For the SPDU design, ARINC or CAN communication was required for any installation. To keep the system flexible, the SPDU will listen for either ARINC or CAN and whichever communication is heard first will be the communication used for the duration of that powered state. The ARINC communication wiring for the SPDU system is shown in figure 42 and the CAN communication wiring is shown in figure 43. Using CANBUS over ARINC affords air-framers reduced wiring and flexibility to add other non-SPDU devices to the CANBUS.

The use of fiber optics for discrete I/O communications and digital data bus communications should be given more thought in a future version of the SPDU. Significant effort and board space was used to provide filtering of the serial data lines and I/O. Moving to an optical means of communications may reduce the overall size of the SPDU, reduce the component count, improve the reliability, and reduce EMI sensitivity. Additionally, higher data rates would be possible.

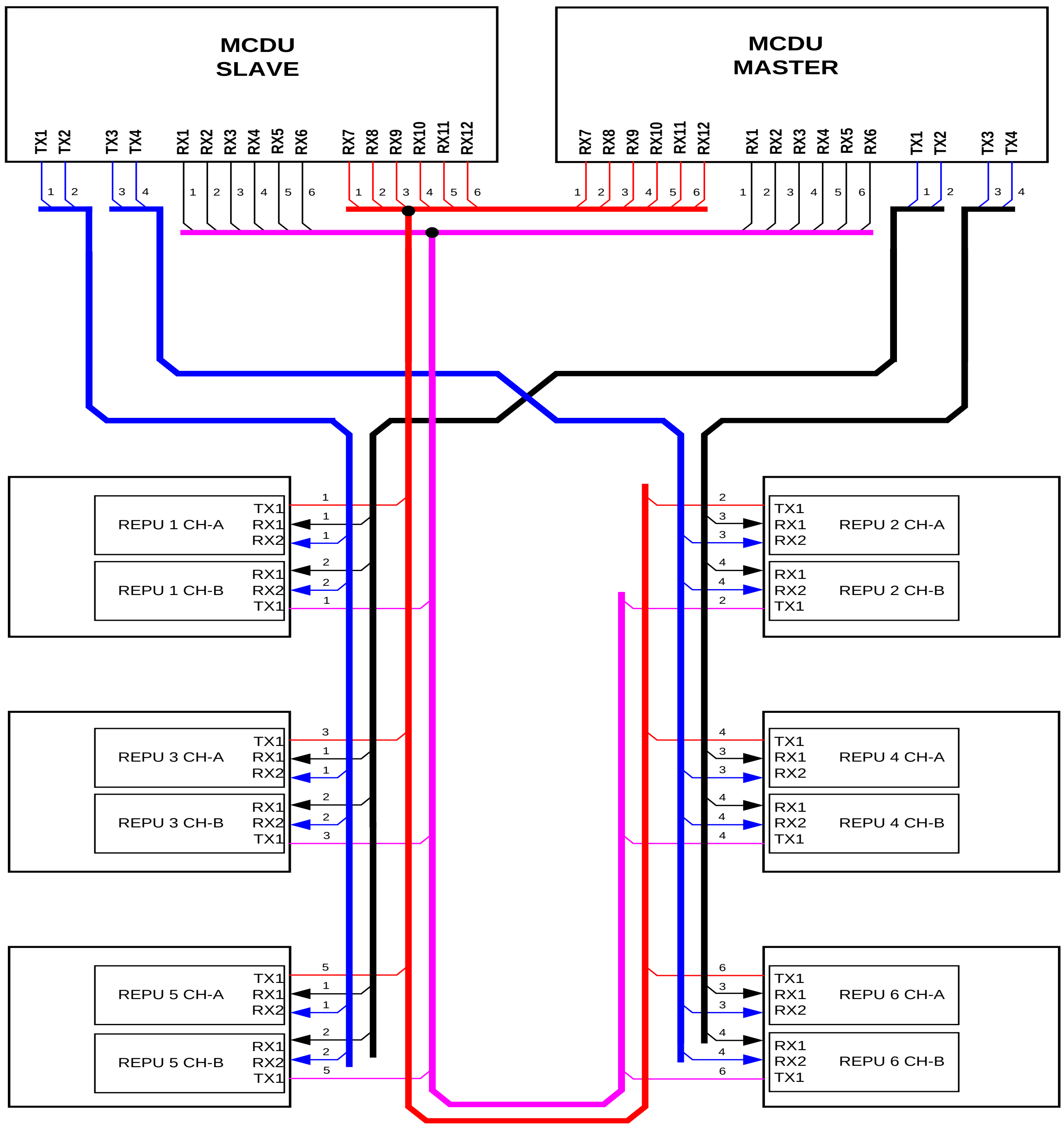

Figure 42. The SPDU ARINC Bus Wiring

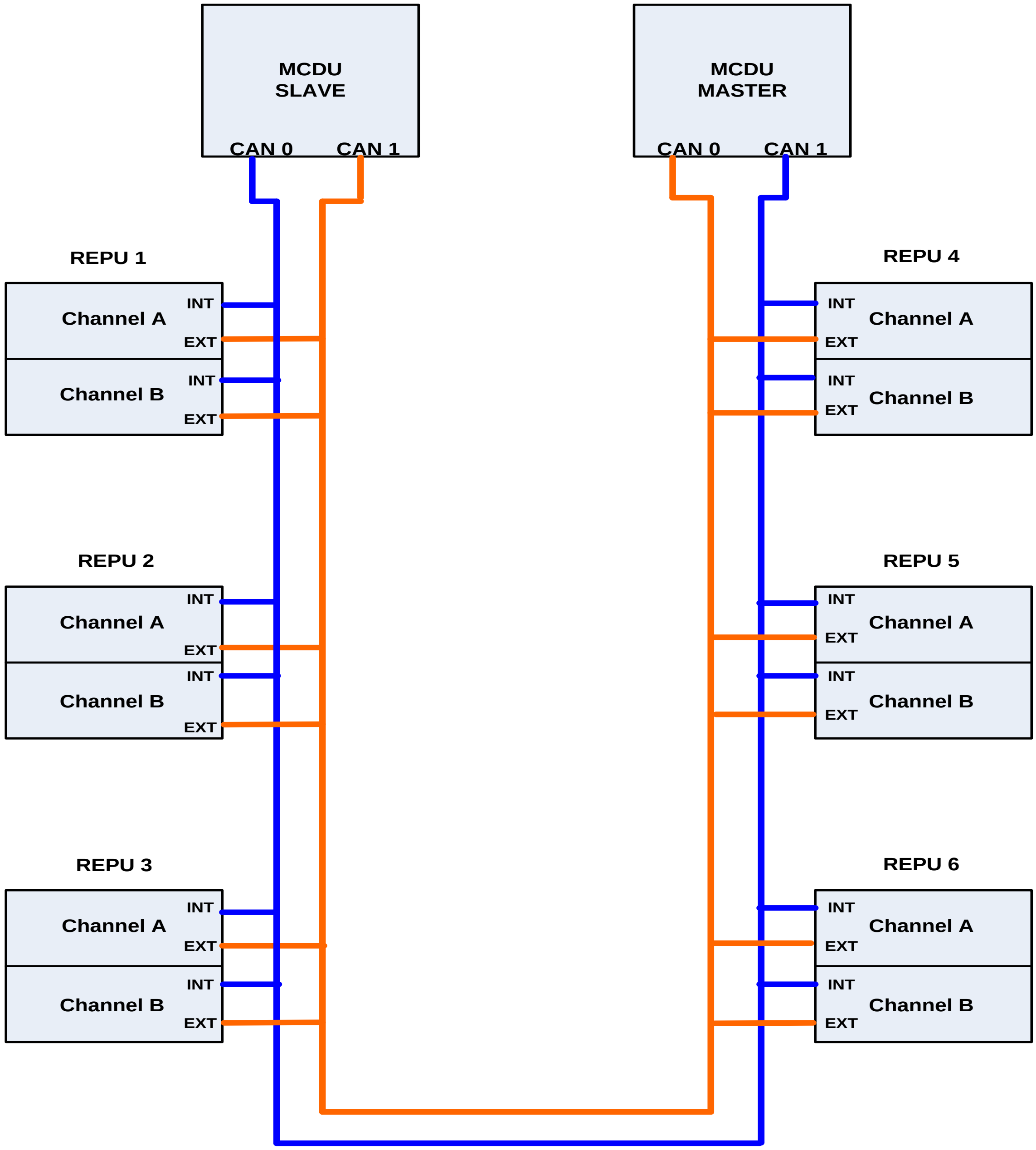

Figure 43. The SPDU CANBUS Wiring

2.3.5.2 Communication Bandwidth.

In its modular form, the system can handle 54 loads per SPDU. The SPDU itself can be replicated and placed throughout the aircraft an infinite number of times. The control portion of the SPDU remained the only limiting factor. The SPDU was designed with two control options, ARINC-429 or CANBUS.

One set of ARINC transmit and receive pairs can connect to a maximum of four SPDUs. This wiring convention can be duplicated four times to produce a 16-SPDU system. The ARINC bus communicates at high speed, 100 kHz, allowing the 32-bit ARINC message to be transmitted to a single SPDU in less than 2 milliseconds. This gives the design a comfortable margin for transmitting control commands to the four SPDU sub-system. The status or information polling from the SPDU may contain a significant amount of data, especially when the maximum 54 SSPCs are populated in each of the four SPDUs. For example, a query of SSPC output voltage would return 54 ARINC messages. This query of all four SPDUs could take approximately 250 milliseconds. The cockpit display can query the higher priority information more frequently and the lower priority information less frequently to have an effective balance of feedback. It is recommended that command messages are given the highest priority.

For CANBUS, when looking only at the CAN interfacing protocol and addressing, a single bus can connect to up to 16 SPDUs. However, the CANBUS running at 500 kHz and containing more overhead than ARINC-429 may not have enough bandwidth to operate with a cockpit display controller in a timely manner. To avoid this, the 16-SPDU system would use multiple CANBUSES similar to the ARINC method. Providing a dedicated CANBUS for every four or eight SPDUs would decrease overall traffic required for control and feedback. This can be adjusted depending upon the number of SSPCs and amount of feedback that is required for the operation of the cockpit control display.

2.3.5.3 Discrete I/O for Custom Control.

Discrete I/Os not assigned to SPDU internal functionality offer flexible custom control to the aircraft installer.

Designing components with the possibility to control or monitor other equipment in the aircraft is becoming an industry trend. The SPDU system, because of its communication bus architecture, can have units placed in several locations throughout the aircraft at the minimal cost of running communications and an input power feed. This means that SPDUs are placed throughout the aircraft next to other systems or controls. Some of these may be simple, only offering contact closure style interfacing. These third-party devices can connect to the discrete I/Os on the SPDU. This means that control of these discrete outputs can be done through the existing communications bus to the SPDU and the SPDU can close or open the contact to control the third-party device. The third-party device can change state and offer this information via a discrete output that interfaces to a discrete input on the SPDU. The status of discrete inputs can be polled from the cockpit display to update the pilot.

This type of flexibility is low cost and offers the flexibility desired by aircraft manufacturers. Currently the SPDU has nine spare discrete inputs (ground/open), three discrete inputs (28V/open), four high-current discrete outputs (ground/open), and two discrete outputs (28V/open) that are available for this feature per channel.

2.3.6 Maintenance and Ground Support Equipment (GSE).

The GSE in the SPDU project is a software GUI that is installed on a laptop to be used by the aircraft installer or maintenance technician. Typical use of GSE is the downloading of maintenance log data. However, it was decided to expand on this and allow the installer to change the settings of the SPDU using the GSE software. The GSE then became an infinitely flexible platform for configuration of the SPDU. Any setting that the team or customer agreed was important or needed could be added to the SPDU.

The GSE software provides the field engineers an interface to the SPDU system for downloading maintenance logs, uploading and downloading configuration data, performing software installation, testing the SPDU interfaces, and retrieving important SPDU-like part numbers, serial numbers (S/Ns), and software cyclic redundancy check (CRC) values.

A key feature of the GSE software is the ability to have multiple SPDUs on the communications bus and to selectively communicate or program an SPDU by its Internet Protocol (IP) address. For the GSE, heritage has been to employ RS-232 communications for ground support and servicing of electronic boxes. However, because of the large maintenance logs and amount of data that may be transferred, Ethernet is preferred because of the higher data rates. Previous experience with RS-232 communicating at 115,200 baud would download maintenance logs in tens of minutes. Ethernet, given the same amount of data, can download the data in tens of seconds.

2.4 PERFORMANCE.

The goal of the SPDU design was to balance weight, output current, accuracy, power dissipation, and functional feature set to produce the most beneficial solution for remote power distribution. The following sections cover areas of performance and the choices made when developing the SPDU design.

2.4.1 Accuracy and Resolution.

2.4.1.1 Circuit Protection Accuracy.

Solid-state power control offers several advantages over the traditional electromechanical power distribution system. One difficult conclusion to reach was the overall accuracy of the current measurement and the trip-detection circuitry. As this technology was introduced to the aircraft community, air framers wanted trip and reporting accuracy to be as low as 1% to 2% over temperature. As the design developed, it was clear that these accuracies could be achieved, but would come at a cost penalty because of material cost, size, and power dissipation, because of Code of Federal Regulations (CFR) Title 14 Part 23.1357 and CFR Part 25.1357 were driving requirements. Design iterations and collaboration with multiple customers from both the fixed wing and rotary wing markets ultimately culminated with the conclusion that a tight trip accuracy of 1% to 2% was not necessary because maintenance personnel and air framers were looking at aircraft power distribution from the standpoint of thermal mechanical circuit breakers that had tolerances of over ±20% in the operating temperature range of -54°C to +70°C. A final compromise was achieved by choosing an accuracy goal that would be an improvement over traditional thermal-breaker-based technology yet be mindful of heat, cost, and complexity. By employing fairly common electronic parts and expertise in precision shunt measurement, a goal of ±6% tolerance was chosen and achieved. For new and future aircraft programs, this nearly four-fold improvement in trip detection accuracy may lead to additional aircraft weight savings by allowing higher gauge wire to be used in applications for which a thermal breaker does not have the trip resolution. The improved accuracy may also provide the ability of protecting not just the wire but the end load from damage.

2.4.2 Power Dissipation.

In aircraft applications, performance-to-weight ratios, and performance-to-size ratios are important for achieving aircraft fuel efficiency and payload goals. Weight and power inefficiencies when switching and transferring power to the loads directly impact aircraft performance by requiring larger engines, bigger batteries, and heavier wire to supply additional power to remain in flight. In addition, more power dissipated by heat requires larger heat sinks and the inclusion of fans or other cooling devices to manage temperature. For these reasons, low power dissipation was a primary design goal with the SPDU. By reducing self-heating, SPDU operating temperature range, component reliability, and current carrying capacity are all improved. This was accomplished by focusing on both active and passive sources of excess power dissipation.

Active power dissipation is the heating produced by the SSPCs because of the current they are supplying to the load. This includes the losses within semiconductor switching devices and current monitor shunt resistances, as well as the copper losses of I/O connectors, internal bus bars, and circuit traces.

Quiescent power is the SPDU self-heating caused by the electrical current draw of internal circuitry. Sources include switch mode power supplies, CPU, memory, communication interfaces, current monitor circuits, BIT hardware, etc.

Figure 44 shows the total SPDU power dissipation of an SPDU containing approximately 44 circuits and delivering 200A, with an almost even split between active and quiescent power.

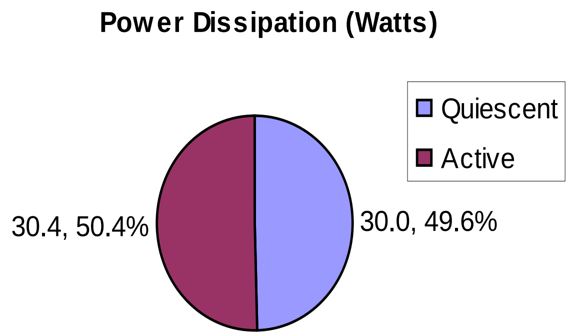

Figure 44. The SPDU Power Dissipation

2.4.2.1 Reduction of Switching Losses.

The choice of switching technology is important when attempting to minimize the power dissipation of a switch connecting power to a load. Traditionally, electromechanical relays have played the part of delivering power to high-current loads (10A to 400A). In the last 20 years, technology improvements in semiconductor devices have driven a steady conversion of medium-to-high current aircraft switching from electromechanical solid-state devices. For currents greater than 100A, such as those coming directly off the generator or main bus feeds, mechanical contactors still offer the best option in both weight and performance. However, for currents under 100A, solid-state relays, SCRs, bipolar junction transistors (BJTs), IGBTs, and MOSFETs now offer a switching technology that overshadows electromechanical devices.

As pertaining to power dissipation, two primary drawbacks to mechanical relays are contact resistance and coil power. Mechanical contacts on new relays can produce voltage drops of 150 mV and greater when delivering 20A of current. This translates to 3 watts of power dissipation. For 28 VDC bus applications, the power to pull in the coil can run another 100 to 300 mA, yielding another 3 to 8 watts of power. The delivery of 20A of power can sometimes produce up to 10 watts of power heat dissipation.

When considering solid-state devices, each of the various technologies has its specific "sweet spot" when switching power. The SCR are relatively inexpensive, but when used in 28 VDC aircraft applications, these devices have a high forward voltage drop in comparison to a MOSFET and can yield heat dissipation in excess of two to three times that of a MOSFET. The same issue of high forward voltage drop also pertains to TRIAC, BJT, and IGBT. At higher voltages, MOSFET on-resistances begin to exceed the dissipation of these other solid-state devices, making MOSFETs less desirable for power applications with source voltages in excess of 200V. For mid-sized jets and helicopters, for which the power is typically 28 VDC, MOSFETs provide the lowest switching losses and, when implemented properly, can be paralleled for high-current performance. Even when the power is inverted to produce 115VAC for cabin power and other loads up to 20A, the latest MOSFETs still provide the best choice in terms of overall switching performance and minimal heat dissipation.

The resistance of the MOSFET switching devices required to switch SSPC channels is among the greatest sources of power dissipation in high-current distribution boxes. The SPDU uses a MOSFET with an ON resistance lower than 3 milliohms, while maintaining a 100V drain-to-source voltage. Its high tolerance to surge current is important to handle bolted short circuit faults to ground without damage. It is also important for the switching device to have an avalanche voltage great enough to tolerate transient voltage events typical during aircraft operation.

2.4.2.2 Reduction of Current Monitor Shunt Resistance.

An important feature of the SSPC is its ability to act as a circuit breaker in addition to its use as a switch. The thermal breaker inherently dissipates power to cause a bimetallic junction to separate when currents exceed the circuit breaker's rating. This means the circuit breaker not only has a contact resistance similar to that of a relay, but also has intentional resistance to separate the bimetallic strip. For circuit protection functionality, a thermal breaker adds an additional 3 watts of power to a circuit that is delivering 20A of current.

In contrast, an SSPC device does not use a bimetallic strip. Instead, it uses a calibrated internal resistor in series with the switch to monitor the amount of current delivered to the load. The goal is to make that resistor as small as possible, yet still perform as well as, or better than, the existing thermal technology.

Shunt resistance values of 5 to 10 milliohms are commonly used for current measurements in the 2- to 10-A range. These high shunt values produce large signal amplitude, maximizing signal-to-noise ratio and measurement accuracy. However, high shunt values produce significant SSPC power dissipation and localized heating on SSPC circuit cards.

The latest technology in shunt monitoring has provided a five-fold improvement in shunt sizing. This directly impacts heat dissipation and, when compared to a thermal breaker, the same 20A load produces only 0.4 watts, a three- to four-fold improvement in heat dissipation.

2.4.2.3 Reduction of Copper Losses.

Similar to a CBP, the SPDU employs a bus bar to deliver power from a single bus feed input stud to each of the SSPCs. Increasing the bus bar cross-section can reduce the overall bus bar power dissipation, but the savings are exchanged with the weight of the additional copper bar material.

2.4.2.4 Reduction of Quiescent Power.

Quiescent or passive power is the heating attributed with the housekeeping functions of the SPDU. This includes the power to drive the CPUs, memory devices, and communication circuits. It also includes the power to operate BIT circuitry, bias transistor states, linear regulators, and any losses associated with internal power supply inefficiencies. Methods of reducing this type of power consumption include using high-efficiency switching power supplies, implementing low quiescent current analog and digital devices, employing power-saving techniques in software, and keeping the overall component count at a minimum.

2.4.2.5 CPU Optimization.

A Certification Review Item asked for software to disable unused peripherals if the ability is available within the microcontroller or microprocessor architecture. Removal of the power or clock signal to an unused peripheral saves a small amount of power for the given circuit. However, for repeated circuits containing microcontrollers or microprocessors, such as in the SPDU, the benefits can be substantial, saving several watts of quiescent power by adding a few lines of software code.

2.4.3 Cooling Techniques.

The initial design intended for the SPDU to be passively cooled. The constraints on size and reliability of the product made passive cooling an obvious choice when moving forward. In addition, using an active cooler, such as a fan, may reduce the durability of the box by requiring the need for large openings where contaminants and other foreign objects may enter the enclosure.

The SPDU enclosure lid has parallel fins to increase surface area and provide sufficient passive cooling.

2.4.4 Power Distribution Capacity.

2.4.4.1 High Power Capacity.

With each SPDU, overhead costs in terms of weight, electrical power consumption, and available space become increasingly significant as more power distribution boxes are added into the system. Because most midsize aircraft are typically DC powered and employ between 100 and 300 circuit breakers in a dual 300 to 400A generator system, it was important to understand the optimum number of boxes that would be required to distribute this power. Previously developed power distribution boxes incorporated between 12 and 16 individual SSPC channels. With an aircraft containing 250 circuits, this would result in the need for 16 boxes distributed throughout the aircraft, each box being nearly fully loaded. This number proved impractical from the standpoint of system cost, finding locations for the boxes, and the overhead each box required in terms of having a dedicated processor, an enclosure, connectors, etc. Instead air-framers basically split the aircraft into three main sections; cockpit, center, and aft. Each of these sections required loads with different criticality levels and power from separate sources. This was typically split into right, left, and battery-powered loads as defined by the primary power distribution system. With this understanding, a count of at least six dual-channel SPDUs was determined to be the most beneficial solution. This conclusion drove the design team to choose a dual-channel box that could support at least 50 loads and conservatively provide 200A of service. With this configuration, critical loads could be isolated and assigned to various power sources, sufficient spares could be made available for growth, and wire weight savings could still be achieved with relatively short runs from localized boxes. Because a higher density of loads is often present near the front of the aircraft, an additional SPDU could be added to the system or the center SPDUs could be installed closer to the cockpit to share some of the forward electrical loads. For helicopter applications, fewer loads are typically required and the overall aircraft length is typically shorter. In these cases, the SPDU count can be between three and four SPDUs with an option of adding one or two additional boxes for supplemental functionality.

Splitting the SPDU into smaller groupings could be used to more effectively distribute weight for smaller aircraft installations. The SPDU cost can be summarized as a cost per SSPC output. The overhead, given this cost breakdown, is distributed amongst the main CPU, enclosure, communication buses, and discrete I/O. Since the current SPDU offers the capability to populate up to 54 SSPCs, and considering the overhead cost is fixed for any number of SSPCs ranging from 3 to 54, the cost per SSPC output decreases as the SPDU is populated closer to its full 54 SSPC output capacity. If the air-framer requires only 27 SSPCs in an aircraft location, then the fixed overhead cost is roughly doubled. In an attempt to remedy this situation, an SPDU could be designed that is only half of the original SPDU, reducing the overhead cost and the cost per SSPC when the SSPC count is less than or equal to 27. For noncritical loads, a single cavity with up to 27 SSPC outputs can be used in an aircraft without redundancy. For critical loads, the redundancy can be added with another remotely located SPDU cavity using cross-cavity communication.

2.4.4.2 High Capacity Construction.

To handle 54 SSPC channels and more than 200A of service, SSPC current-carrying paths within the SPDU are comprised of bus bars, robust PCB circuit traces, and heavy flexible interconnect wiring.

When focused on transferring high amounts of current through the SPDU, careful consideration was needed regarding trace and wire resistance and the location of these current-carrying mediums.

2.4.4.3 Ganging of SSPC Outputs for Higher Current.

The SPDU can be populated with SSPCs with ratings of 7.5A, 15A, and 30A. For loads that require more than 30A, the current options are to use the RCCB to control a higher current relay external to the SPDU. The current SPDU system limits the system designer to four RCCB high-current outputs per SPDU. This design option adds weight and limits space because of additional wiring and relays.

The SPDU currently has a placeholder for a software configuration setting of ganging within the configuration table. This could be used to group SSPC outputs so that if any one SSPC in the group is controlled ON or OFF, the remaining SSPCs within the group would be automatically controlled ON or OFF by the SPDU. The SSPC contains a back-feed protection so when the SSPCs are controlled ON or OFF in sequence, any SSPC that is OFF while one or more SSPCs are ON will automatically disable the thermal cutout to protect the SSPC from opening the fail-safe mechanism. The end benefits are increased current that is slightly less than the sum of the individual ganged SSPCs. This is partly due to the de-rating of the current-carrying capacity because load sharing across the power MOSFETs of various SSPCs may not be evenly distributed.

2.4.5 Weight.

Weight-reduction options were investigated to obtain the goal weight. Figure 45 is a pareto chart created for components that contribute to the weight of the SPDU. Most of the weight is concentrated at the cover with thermal pads and the enclosure case. The case, cover, and external connectors represent more than 50% of the SPDU weight.

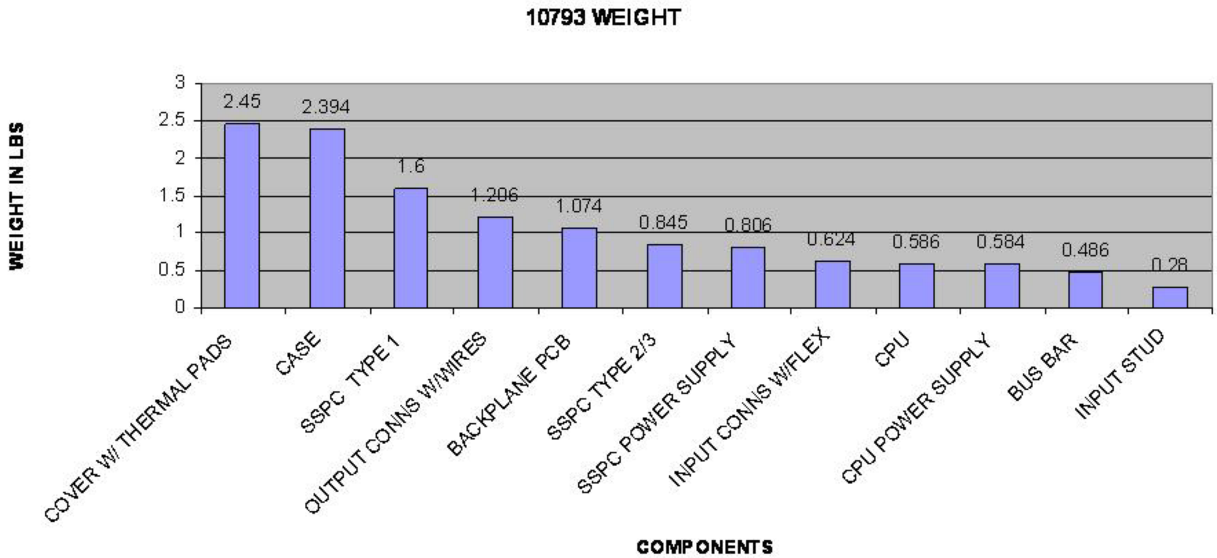

Figure 45. The SPDU Weight Pareto

The SPDU went through at least three major weight-reduction programs and started at approximately 18 lbs before it ended at approximately 12.4 lbs when loaded with 44 channels of SSPCs and servicing over 200A of 28 VDC current. The major weight drivers of the SPDU are the enclosure, connectors, and lid. These items represent more than 50% of the total SPDU weight. The removal of the AC power option for the SPDU was driven by the extra weight it posed on the enclosure size and that the circuits may not always be used in every installation. With the removal of the AC cavity, the development of the centralized supply, and the reduction of the enclosure, fins, and wall thicknesses, the SPDU was within 0.2 lb of the original weight goal.

2.5 SAFETY.

Unlike previous solid-state power distribution units that were designed for cabin power distribution, non-flight-related mission electronics, and the powering of unmanned air vehicles, the SPDU has the goal of replacing all aircraft circuit breakers and relays including those critical for flight. Numerous safety considerations were made in all disciplines of the design. Because the SPDU has the potential to have an essential bus powering one of its cavities and a nonessential bus powering the other SPDU cavity, it was necessary to produce an enclosure that meets the DO-160E flammability and electronic isolation requirements for continued operation of the essential bus.

The architectural design must include sufficient redundancy to eliminate single-point failures and achieve the safety numbers for failures that are considered catastrophic, hazardous, or major. Within the SPDU are redundant power supplies, microprocessors, communications channels, current measurement circuits, and fail-open protection circuits. These add to a system that meets the tough safety numbers needed for catastrophic-level load control.

It is also important to have an SPDU that can withstand long power interruptions. Should a power interruption cause the SPDU to reboot, the delay time while the SPDU reboots and reactivates its outputs may cause many other downstream electronics to lose power and force them into a rebooting mode. This may cause unwanted periods of extended time where aircraft functions are not fully present. For the SPDU, it was important to include hold up capacitance and diode blocking that isolated the control power from the SSPC switched output power. With this scheme, the SSPC CPU can remain alert and active and maintain MOSFET switch bias until power returns.

The arc fault and instant-trip protection are added safety features that address issues at the LRU and system level. Arc fault protection is the ability of the SSPC to sense and open when a parallel fault occurs on the protected wiring. This feature is geared more toward addressing faults in the aircraft system wiring and preventing catastrophic damage. Conversely, instant-trip protection is intended to protect the SPDU and is the ability of the SSPC to protect itself from extremely high currents that can be catastrophic. Essentially, instant-trip is a quick turnoff feature for avoiding SSPC circuit damage.

It is extremely important that the SPDU has the ability to disconnect power from, and wiring to, the load. Loss of circuit protection of more than one device is considered catastrophic and the probability of occurrence must be less than 1 x 10 - 9 failures per million hours. A cornerstone of the SPDU is a secondary means of opening the switch if the MOSFET fails. To compensate for the fact that 60% of MOSFET failures occur with the drain and source of the MOSFET shorting, a fail-open circuit has been incorporated in each SSPC channel that will mechanically disconnect the output if the output voltage disagrees with the commanded state. To achieve the safety levels, two independent circuits have been employed in series with the MOSFETs and allow the SPDU to achieve the necessary safety numbers. This approach provides an independent and symmetrical means of ensuring circuit protection.

2.5.1 Redundancy.

Redundancy is a key element to aerospace designs and is typically driven by aircraft system safety using a table of failure events that signify critical operations with their criticality failure level. Table 8 was communicated from the customer and is specific to the SPDU. Each of the failure events listed in table 8 must meet or exceed the required failure probability and must not exhibit a single point of failure.

Table 8. The SPDU Failure Criticality Table

Failure Event	Required
DUTY CYCLE STUCK AT MINIMUM	1.00E-5
LOSS OF SERIAL COMMUNICATION WITH DISPLAY	1.00E-5
LOSS OF AIRCRAFT STATUS (WEIGHT ON WHEEL) SIGNAL	1.00E-5
INABILITY TO SWITCH ON SSPC (TWO OR MORE SSPC OUTPUTS)	1.00E-5
UNNECESSARY TRIP: THE DEVICE (SSPC) TRIPS EVEN IF AN OVERCURRENT DOES NOT OCCUR	1.00E-07
UNNECESSARY TRIP: THE DEVICE (SSPC) TRIPS EVEN IF AN ARC FAULT DOES NOT OCCUR	1.00E-07
INABILITY TO SWITCH OFF SSPC	1.00E-07
UNWANTED SWITCH OFF OF SSPC	1.00E-07
DUTY CYCLE STUCK AT MAXIMUM	1.00E-07
UNWANTED SWITCH ON OF SSPC	1.00E-09
FAILURE TO PROTECT WIRING FROM OVER CURRENT: THE DEVICE (SSPC) IS NOT ABLE TO DETECT AN OVERCURRENT	1.00E-09
FAILURE TO PROTECT WIRING FROM OVER CURRENT: THE DEVICE (SSPC) DETECTS AN OVERCURRENT BUT IT IS NOT ABLE TO TRIP	1.00E-09
FAILURE TO PROTECT WIRING FROM ARC FAULT: THE DEVICE (SSPC) IS NOT ABLE TO DETECT AN ARC FAULT	1.00E-09
FAILURE TO PROTECT WIRING FROM ARC FAULT: THE DEVICE (SSPC) DETECTS AN ARC FAULT BUT IT IS NOT ABLE TO TRIP	1.00E-09
ERROR IN SERIAL COMMUNICATION WITH DISPLAY	1.00E-09
ERROR IN CONFIGURATION TABLE	1.00E-09

Table 8 heavily influenced the redundant design of the SPDU.

The SPDU contains many redundant features to meet the failure rates required for critical functions. However, the SPDU does not contain a fully redundant path for I/O control.

Effort went into making the SPDU design more economic by using common parts, common assemblies, and a modular design, but dissimilar and redundant functional paths become increasingly important as the system increases with criticality. Shunt measurement and power supply topology features are two examples of how the SPDU could have been made more dissimilar to make it easier to convince certification authorities of its safety level.

2.5.2 Hardware and Software Partitioning.

There are several characteristics that make the channel separation robust. One of the keys to this strength is that each channel can work independently. The opposite channel can have a myriad of failures, but the channel in question should run without issue. The enclosure provides the physical channel separation and is meant to protect against a channel failure, possibly resulting in a fire, from causing the opposite channel to fail. To accomplish this task, the enclosure has two isolated cavities, one for each channel. Isolating each channel prevents damage from a catastrophic failure in one channel affecting the operation of the other channel. Interpretation of CFR Title 14 Part 23 paragraph 23.1309 and flammability requirements of RCTA DO-160 Section 26 generated the internal requirement to have a robust physical separation of the channels. In addition, CFR Title 14 Part 25 Subpart H paragraph 25.1707 System Separation: EWIS specifically states that if units or channels cannot be installed with adequate physical separation of distance, then the separation is to be achieved by a barrier that provides protection equivalent to having separation to that distance.

The 28 VDC bus entering the SPDU originates at the aircraft primary power system and is protected with a 150A fuse. Because of the tremendous amount of power available, it is essential that potential opportunities for short circuits to ground be minimized within the SPDU.

2.5.3 Arc Fault and Instant-Trip Protection.

A key advantage of the MOSFET over traditional thermal breakers is its switching speed and ability to turn off in microseconds. While a traditional circuit breaker may take 40 milliseconds or more to detect a hard fault, an SSPC with arc trip detection algorithm and microsecond switching can limit the energy content in the parallel arc to a benign level.

But the advantage in switching speed of the MOSFET is also countered by a weakness in robustness when compared to a thermal breaker. This drives the need for short-circuit protection. Thermal breakers have the mass and natural physical tendency to separate when exposed to extremely high-fault currents, making them difficult to damage. Conversely, the MOSFET is a semiconductor device consisting of a small silicon die with a micron-thick diffusion layer that creates a very narrow junction and low body mass, which is unable to withstand the same energy and heat produced by extended current surges. One of the key designs of the SPDU was to optimize the use of multiple MOSFETs in parallel to distribute the energy across the junctions. Because of part-to-part variations, it can be very difficult to ensure that all parts share current evenly. This is especially true during the MOSFET switching event, when one MOSFET may turn on or turn off prior to others and assume or relinquish the majority of the load current. It is in this event that board layout, stray capacitance, and gate switching speed are extremely important to protect the MOSFET. In the SPDU, each SSPC channel has been designed with an ultra-fast gate drive circuit that ensures microsecond switching of the MOSFETs. This minimizes the possible time that any MOSFET can assume the majority of the switching current. Switching speed, however, is not enough. It is also important that the overcurrent detection circuit be equally fast. Although the SSPC uses a software algorithm to detect arc faults in a range up to 12x the nominal current, it is also equipped with a parallel and ultra-fast hardware circuit that immediately commands the MOSFETs to switch off if current exceeds the 12x range. This additional layer of trip detection and FET switching is key to surviving low-impedance bolted faults.

Detecting high currents and turning off quickly doesn't solve all of the problems when using MOSFETs for switching large currents on aircraft. An unfortunate byproduct of changing current quickly is the tendency to create high-voltage surges across the switch whenever inductive sources or loads are in the circuit. The voltage produced is mathematically described as:

$$V = L*di/dt \qquad (2)$$

Under these conditions the stress on the FET is focused on the avalanche breakdown current produced through the intrinsic body diode that exists between the drain and the source. For fast-current transients, the voltage exceeds the MOSFET breakdown voltage and causes an avalanche current to be produced. If the current and its persistence exceed the rating of the MOSFET, the MOSFET eventually fails, most often in the shorted condition.

Generators, motors, and even long runs of wire can be sources of inductance. When interrupting a 200A surge, a voltage of 1000V can be achieved across the MOSFET if the circuit inductance is 100 microhenries and the load is switched off in 20 microseconds.

Although very high voltages can be built up, the energy stored by the inductive aircraft sources and loads are limited and can be managed appropriately with the proper transient suppression circuitry. When designing the SPDU electronics, care was taken to employ enough transient protection to absorb or clamp the inductive transient voltages. Sizing of the suppression circuitry was based on the sum of the various inductances and calculation of the stored energy. Mathematically, the common formula describing energy stored in an inductor is:

$$E = ½*L*I\text{^}2 \qquad (3)$$

2.5.4 Extensive BIT.

The BIT is a major requirement for all aerospace products and is a large element in the SPDU design.

The SPDU has a four-level BIT, which includes power-up built-in test (PBIT), warm start-up BIT, continuous BIT, and initiated BIT. Also, the PBIT must have fault coverage greater than 95% of the functions.

From a design standpoint, the goal was to test as much as possible in the shortest amount of time without degrading or disturbing the normal operation of the SPDU. For BIT, this meant testing communication ports; analog-to-digital converters; and inputs, memory, stored data, discrete inputs, discrete outputs, watchdog, temperature, address parity, and software CRC.

2.6 SERVICEABILITY.

Serviceability is an important design aspect that can have a large impact on maintenance costs, inventory, and servicing times. This section briefly discusses the various features intentionally designed into the SPDU to simplify and reduce the touch time and servicing of an SPDU. Features such as replaceable modules, captive hardware, keyed assemblies, use of standard tools, extensive BIT, and maintenance logging make maintenance and support activities manageable tasks. With the incorporation of arc fault trip detection and circuit protection, an attempt is also being made to have the SPDU assist in the location of the wiring fault using the combination of the existing diagnostic information recorded by the SPDU and knowledge of aircraft wiring and load details. This advanced benefit can reduce the amount of disruption necessary to expose and correct wiring system faults.

2.6.1.1 Part Numbering, Marking, and Upgrades.

The issue of upgrading hardware and software in the field and assigning a unique and legal part number to the configuration without relabeling the unit is still not convenient. It would be beneficial if a technology or process was developed with which software could be reconfigured in the field and the nameplate updated without having the need to have access to the LRU. While the idea of downloading all of the part number information of a particular LRU through an external connector is already widely used in aerospace to determine the software configuration of a remote LRU, the notion of eliminating the need to update the nameplate when the software update is performed has not been accepted by all air framers and certification authorities. This feature could be exceptionally valuable to completion centers that outfit each aircraft based on the customer's specific requirements.

2.6.2 Captive Hardware.

The cover has passivated stainless steel captive hardware. This feature allows the lid to contain all the necessary hardware for its replacement. Captive hardware is crucial for any application for which the SPDU lid may be removed while installed on the aircraft. With captive hardware, the screw remains captive within the lid at all times, allowing for effortless removal and replacement, even when the unit is installed inverted.

2.6.2.1 Keyed Assemblies.

Circular connectors are index keyed differently so there is no error in connection of the SPDU to the airframe. Keying is also done so that SSPC and non-SSPC modules cannot be plugged into the same card slot. This keying is done mechanically using a unique backplane connector arrangement.

2.6.3 Maintenance Logging.

Besides installing new software and populating the configuration tables, the GSE is intended to extract the maintenance log. The intention of this feature is for the aircraft technician to spend a few minutes using the GSE to download the maintenance log before/after each aircraft flight. This would ensure that the aircraft technicians would have continuous archives of maintenance logs for the life of the system. It is not assumed that the maintenance log would be downloaded for every flight, so a margin was built into the design to handle multiple flights prior to maintenance log download.

Displaying the data in an effective manner is an important part of the maintenance log feature and may often take a secondary position to collecting the data. However, displaying the data in a manner that can be interpreted or used by the end customer is paramount.

A comma separated value (CSV) file was determined as the best option for displaying the maintenance log. This opened up several opportunities because CSV can be imported into Microsoft® Excel® and used to analyze data by graphing, performing math operations, using logic formulas, etc.

Because the amount of raw data created for the maintenance log was overwhelming for the aircraft technician to analyze, a separate maintenance log analyzer tool was developed to reduce the burden of determining failures and performing predictive maintenance.

2.6.3.1 Maintenance Log Analyzer.

Maintenance log analyzer software was developed that uses existing SPDU data logging and ground support features—both developed using RTCA DO-178 guidelines—and adds the benefit of automatically analyzing the maintenance log data for SPDU failures or load trend monitoring.

The SPDU provides data in single minute resolution for the last 24-hour window of operation. Using the GSE and Ethernet, the maintenance log can be extracted to a laptop. On the laptop, the maintenance log analyzer software can open, parse, and process the maintenance log files (see figure 46), and provide simple to understand SPDU and load status.

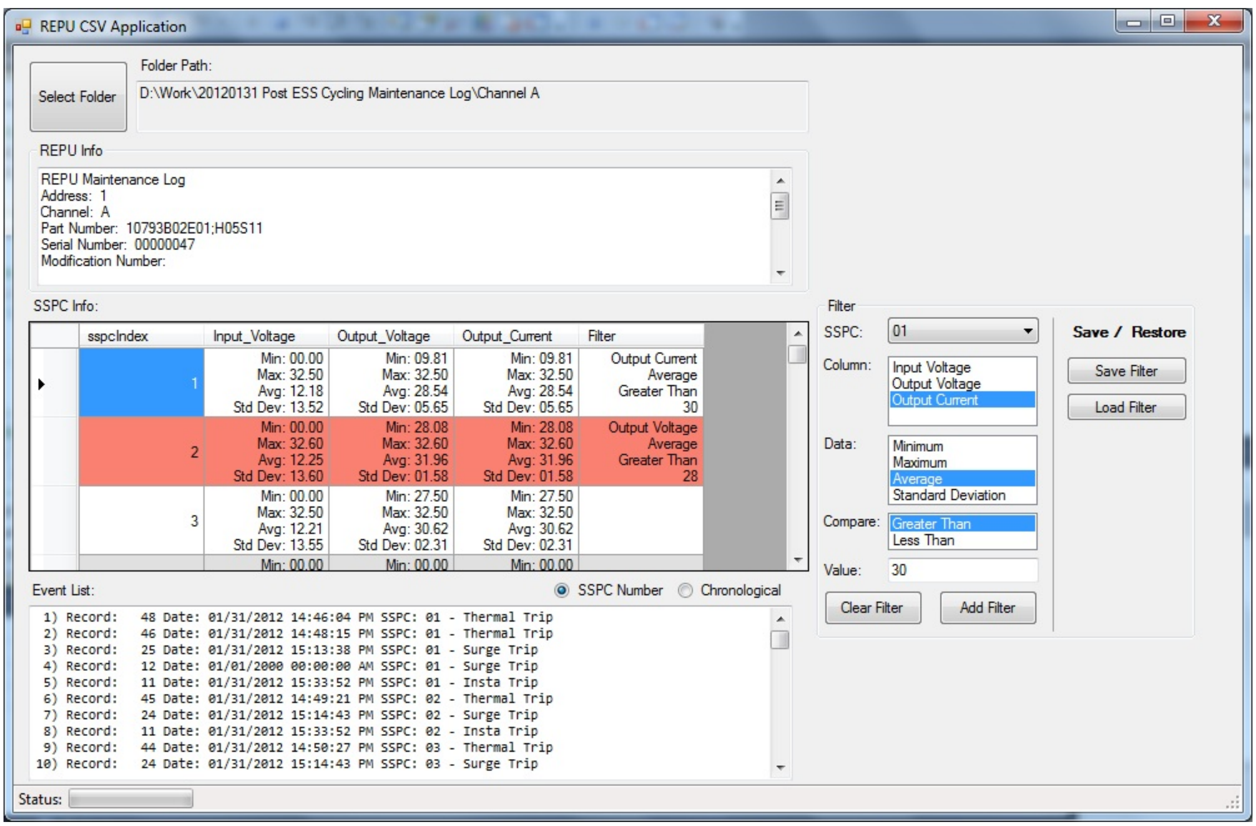

Figure 46. The SPDU Maintenance Log Analyzer

The maintenance log analyzer performs the following functions:

- Displays statistics for each load attached for current and output voltage. This includes minimum, maximum, and mean (when SSPC is ON). It may include standard deviation and other meaningful statistics.

- Displays event list for critical items including any BIT failure, trip event, or SSPC failed or blocked indications.

- Displays SPDU configuration information such as part numbers, serial numbers, and software CRCs.

- User-defined criteria for each attached load to aid in determining if the attached load requires service. There can be potentially three levels created from the criteria. These criteria drive an easy-to-interpret color scheme where green = OK, yellow = load may require maintenance soon, and red = load requires maintenance. The criteria may be thresholds for average (mean) current, standard deviation, etc. The user-defined criteria are saved in a file for repeated use.

The maintenance log data for each SSPC output can be compared against the expected tolerances for the given load. This gives the customer the ability to determine when a load is drifting out of tolerance for a key characteristic, such as current consumption. This allows the aircraft maintenance personnel to perform proactive maintenance on equipment attached to the SPDU. The major benefit is improved safety, but also improvement of flight on-time percentage because of the reduced maintenance required on aircraft post-equipment failure.

2.7 TREND MONITORING AND LOAD CHARACTERIZATION.

Because of the trip speed and accuracy improvements that solid-state devices provide, the ability to evolve from just wiring protection to both wiring and load protection becomes more possible. However, because of overhead and probable changes to load characterizations over time, it is not recommended that load characteristic data be included within the SPDU software. Because it is difficult to account for all possible load variables or characteristics, the SPDU is subject to recertification each time it is adapted to load performance changes.

2.8 SOLID-STATE TEST MILESTONES.

2.8.1 The AC to DC Short Circuit.

During the test level (TL) validation, tests were performed in which a 115 VAC short was applied to a 28 VDC output of the SPDU. The simulated AC short test used SPDU part number 10793B02E01, S/N 0034. Within SPDU S/N 0034, all boards on channel B were removed and SSPC modules in slots 1 through 4 on channel A were removed, leaving one SSPC slot populated with a 10838 SSPC card containing one 15A and one 30A rated output. The 15A rated output at SSPC location 27 was used for the AC short test.

The 28 VDC source was supplied to the SPDU during all tests and the output 27 was OFF when each short to 115 VAC was applied. The SSPC output 27 was functionally tested (ON/OFF control and verifying the DC output voltage) after the removal of each AC short condition. Figure 47 shows the test setup.

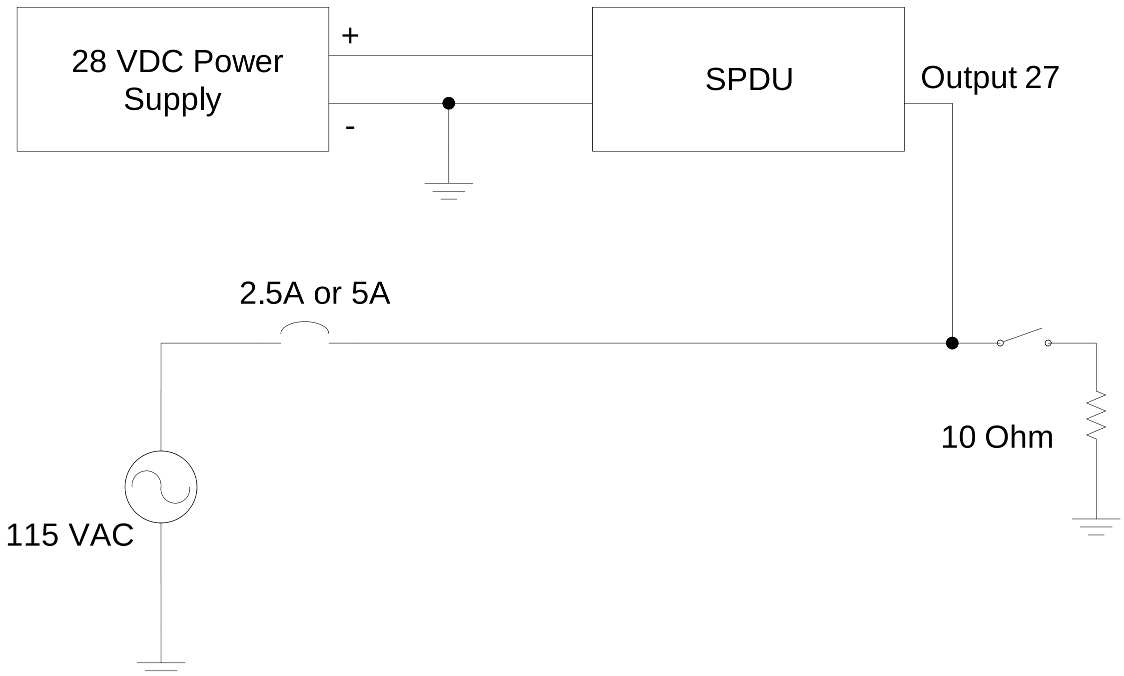

Figure 47. The AC Short Test Setup

The first three tests used a 2.5A standard push/pull mechanical circuit breaker in series with the 115 VAC line. The test began with the circuit breaker in the open position (pulled). To apply the 115 VAC short, the circuit breaker was pushed to close the electrical connection and to short the AC line to the DC output of the SSPC. After each application of the 115 AC short, the 2.5A circuit breaker tripped and opened the circuit, disconnecting the 115 VAC from the SSPC DC output. With the circuit breaker still in the open position, the SSPC DC output was tested in ON and OFF states, measuring DC output voltage and observing for any internal BIT failures. After each application of the 115 AC short using the 2.5A circuit breaker, three in total, the SSPC functioned normally and no damage was observed to the SSPC circuit board. Next the circuit breaker was changed from a 2.5-A rating to a 5.0-A rating and the test resumed. The breaker was pushed in to apply the 115 VAC to the SSPC DC output and the circuit breaker tripped shortly after to remove the 115 VAC from the SSPC DC output. The SSPC failed the functional test as the output remained in the ON state, even when commanded OFF, and the internal BIT resulted in an output voltage failure. The SSPC card was removed from the SPDU and analyzed.

The analysis concluded that the transorbs used for lightning and surge protection failed open during test. Also the power FET that provides the solid-state output control was failed shorted. No visible damage was found on the SSPC under test. During this specific test, the output current was 0A because the removed SSPC output load and the thermal cutout did not require activation.

The thermal cutout is designed to protect the wires in case of a shorted FET and 0 current means there is no danger of damaging the aircraft wiring provided the aircraft wiring can handle up to 200 mA of current (28 AWG or lower). If a constant load of greater than 200 mA had been applied during this test, the fail safe would have activated and opened the circuit.

Test 1—With the 10-Ohm load connected, the 2.5-A circuit breaker was closed. The circuit breaker tripped, and the SSPC output operated normally after the test.

Test 2—With the 10-Ohm load not connected, the 2.5-A circuit breaker was closed. The circuit breaker tripped, and the SSPC output operated normally after the test.

Test 3—With the 10-Ohm load not connected, the 2.5-A circuit breaker was closed. The circuit breaker tripped, and the SSPC output operated normally after the test.

Test 4—With the 10-Ohm load not connected, the 5-A circuit breaker was closed. The circuit breaker tripped, and the SSPC output was shorted after the test. The SSPC 27 output FET failed shorted.

Note: After an FET failed short condition, the SSPC 27 output is commanded OFF, and the thermal cutout protection device activates to open the circuit and disconnect the power source from the output load.

The purpose of this specific test was to understand what would happen if the AC power and DC power lines were shorted together during a wiring failure event. This can occur during aircraft wiring and initial power-up checks of the aircraft system, when it is more likely to have miswires that were not found during systematic checks. This condition can also occur during aircraft operation when there is a connector fault or two breeches of insulation on aircraft wiring. The SPDU was not required to survive such a test; however, before the testing began, the SPDU circuitry was analyzed to predict the effects of this type of abusive test. Analysis concluded that the output transorbs would eventually fail and as a result the SSPCs power FET would fail shorted. The test results aligned with this pre-test analysis and, thus, the test was successfully completed.

2.8.2 Retrofit FAA B-737 Tests.

In a joint effort with the FAA, the SPDU and AC PDU were installed and operated on a decommissioned B-737 (see figure 48) located at the FAA William J. Hughes Technical Center. The goal of this test was to understand the feasibility of retrofitting an aircraft by removing CBPs and thermal circuit breakers, then replacing them with solid-state controls. A set of specific functions was tested using SPDU and AC PDU integrated with the B-737 aircraft system:

- Arc fault detection
- Normal overload
- Thermal memory
- Pulse-width modulation

- Load current monitoring
- Source power quality checks and switching
- Heat monitoring

Figure 48. Boeing 737

The tests required several days of planning and wiring of the SPDU to the existing CBP (figures 49 through 54). A custom harness was wired to the back of the CBP and connected to the SPDU and AC PDU. To keep the aircraft operational when the solid-state system was removed, the governing rule of performing wiring within the aircraft was to not disturb any existing thermal circuit breaker wiring or load wiring. If wiring had to be removed for a test, it was to be restored after the test was complete. To accomplish this for a majority of the tests, the SPDU was wired parallel with the existing CBP, as shown in figures 49 and 50.

The wiring was tagged with color stripes and strain relieved approximately every 6 in. The SPDU harness, as shown in figures 50 through 52, is the bright white wire with red, blue, and yellow tape stripes. The colors indicated the terminal landing strip location for the load wire. As shown in figure 52, blue signaled terminal strip A; yellow terminal strip B; and red terminal strip C. Wiring was completed in one day on the B-737 and was expected to be shorter for a typical retrofit, as the wires from the existing CBP would be removed or reused as necessary and not kept in parallel.

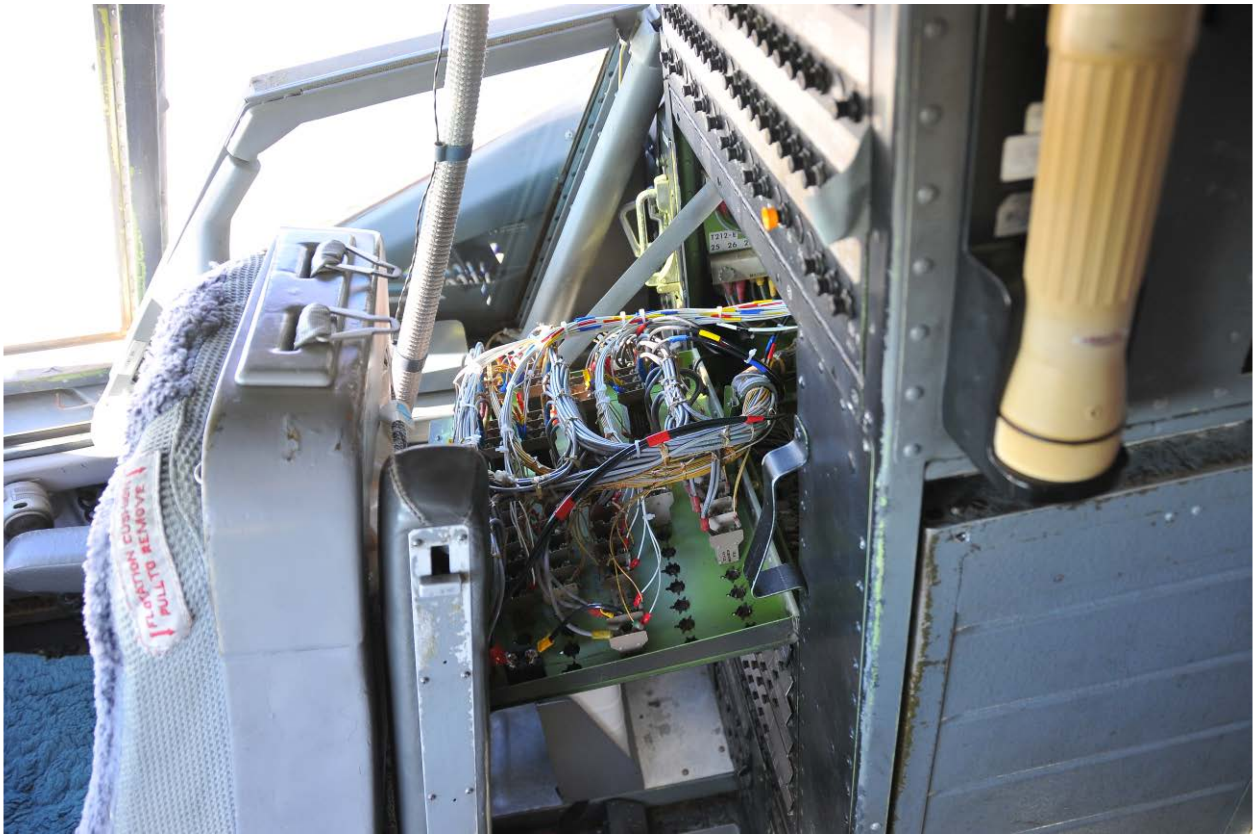

Figure 49. Boeing 737 Circuit Breaker Panel

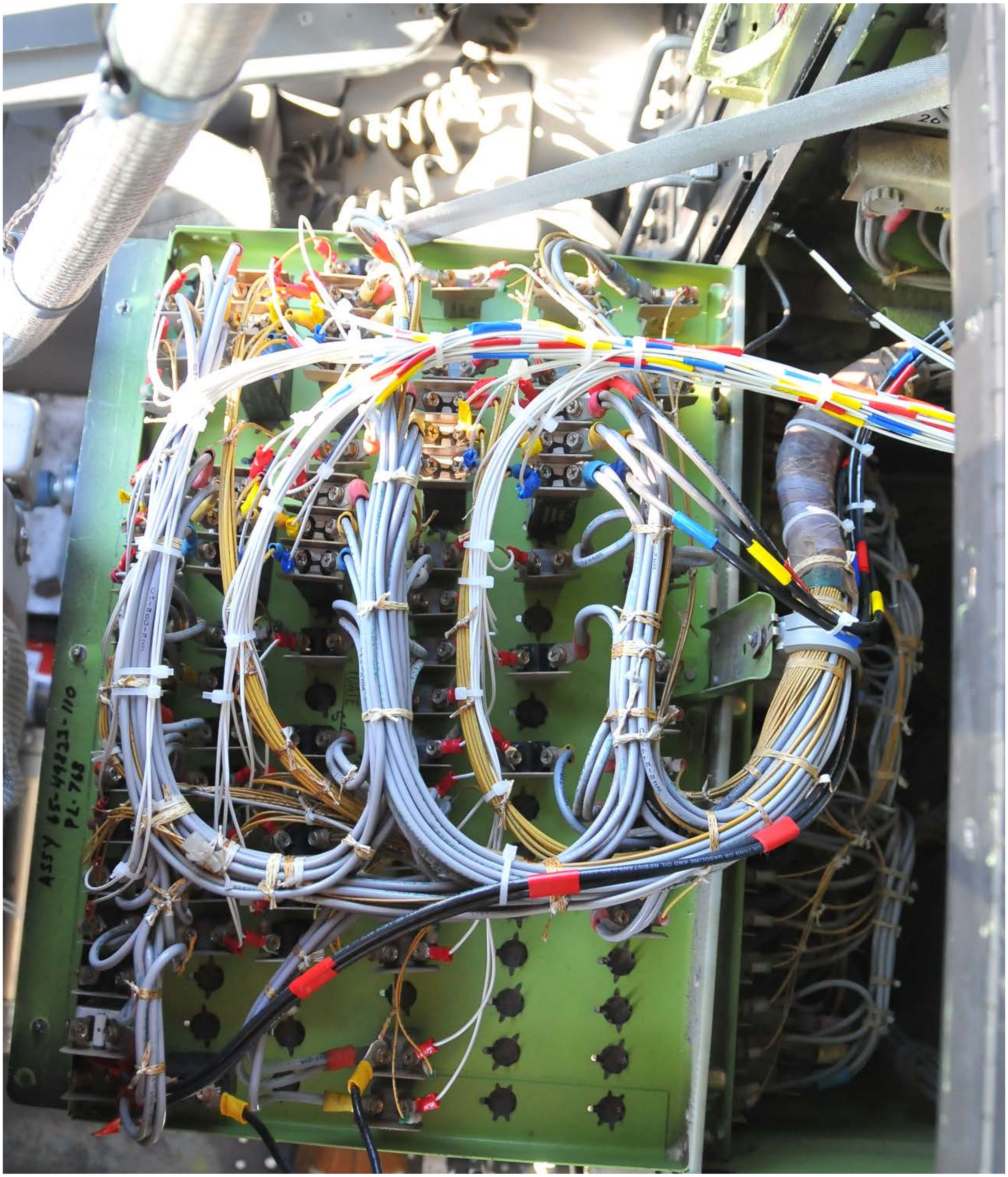

Figure 50. The CBP With SPDU Wire Harness

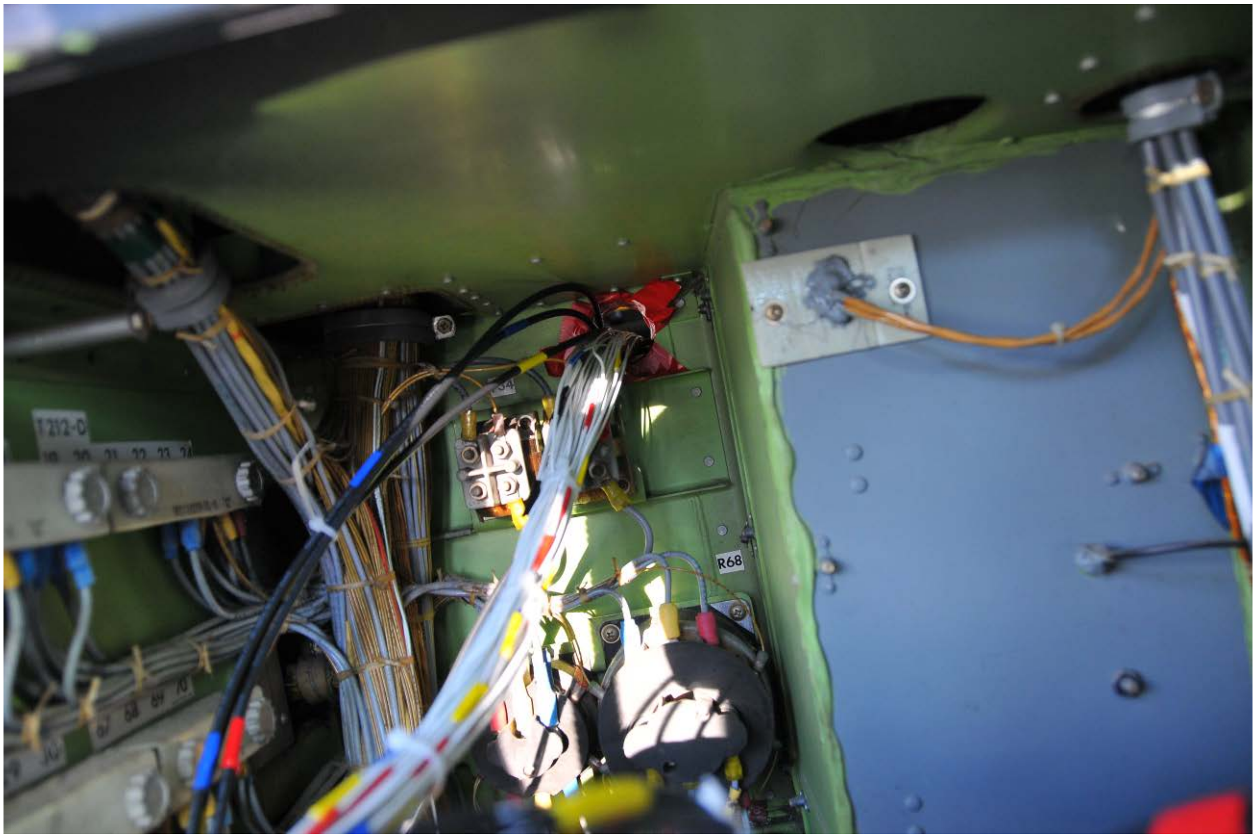

Figure 51. The SPDU Wire Harness Routing

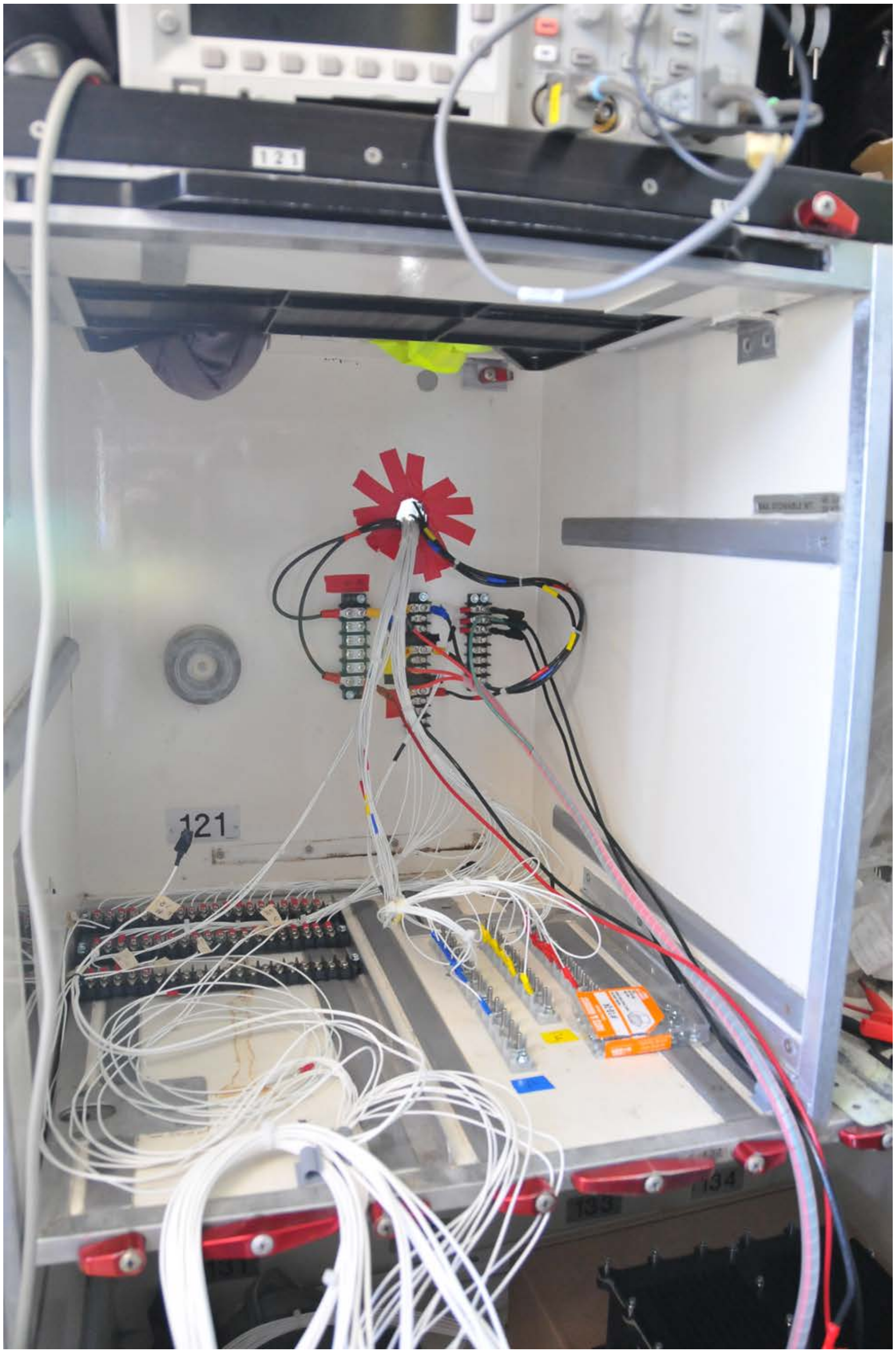

Figure 52. The SPDU Wire Harness and Terminal Strips

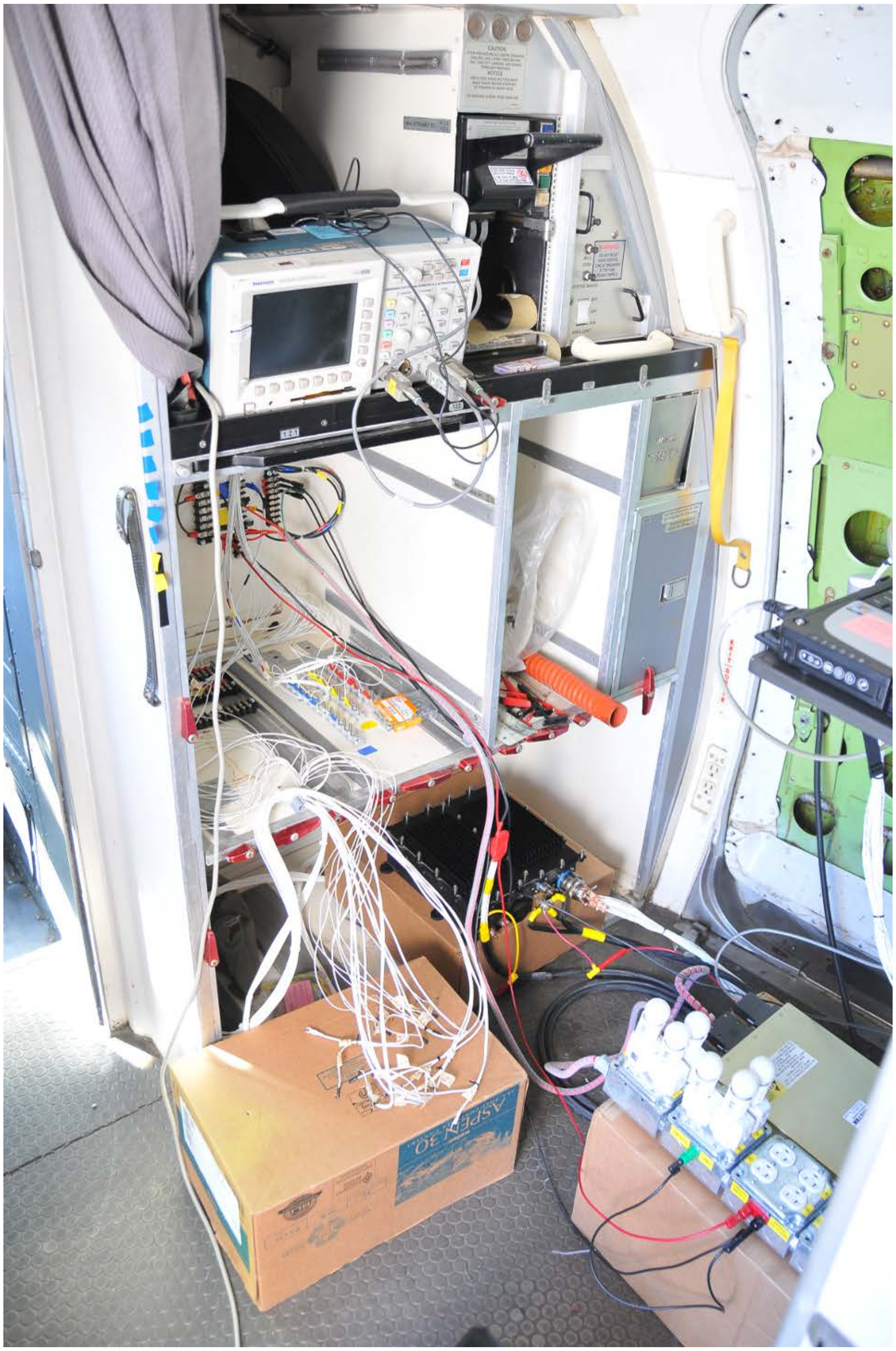

Figure 53. Boeing 737 SPDU Test Setup

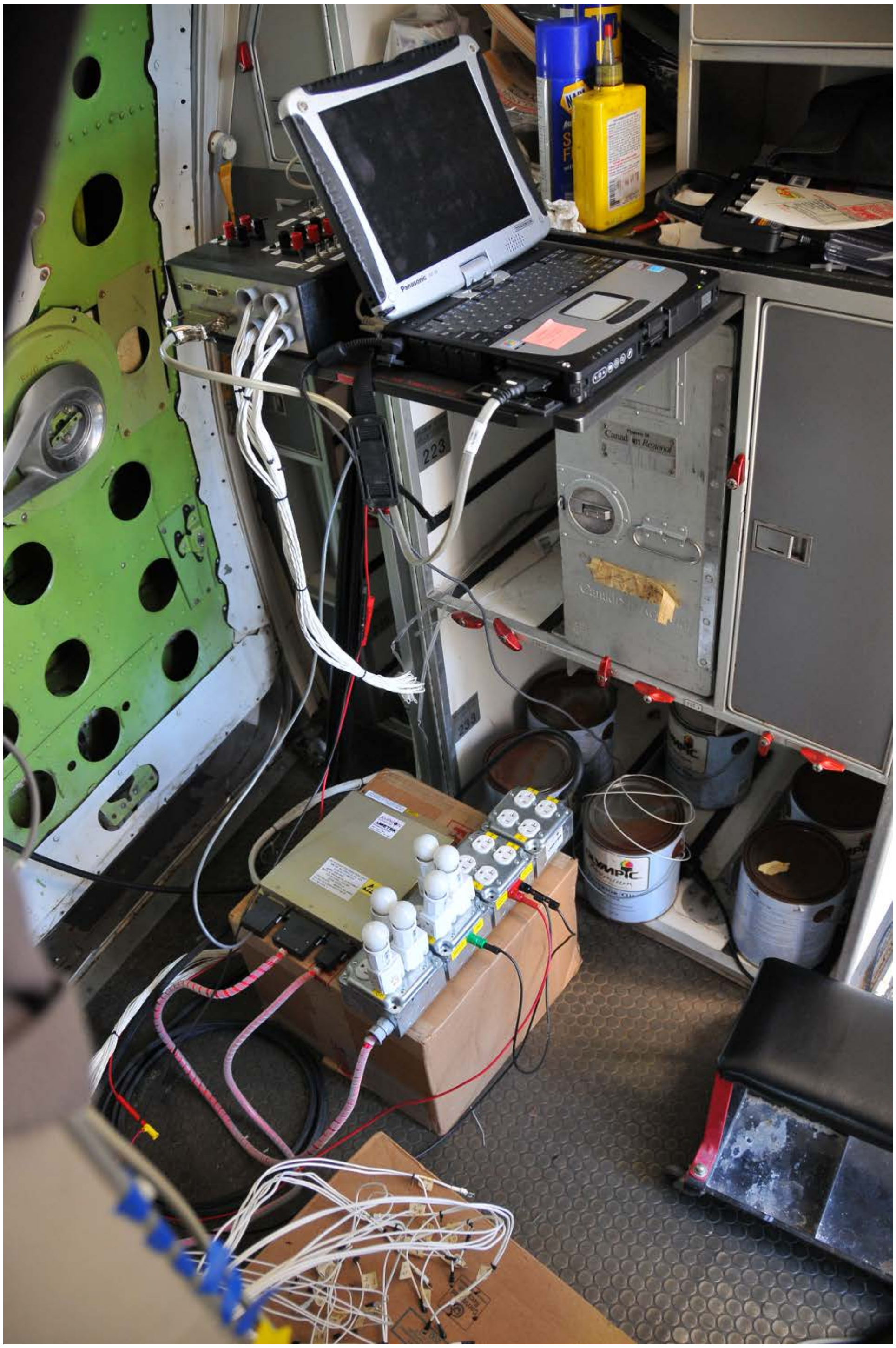

Figure 54. Boeing 737 AC PDU Test Setup

2.8.2.1 Load Selection.

The SPDU configuration table designed prior to tests on the aircraft (table B-1) was designed to control the loads specified in the FAA B-737 aircraft, given the CBP information provided in appendix B. During the exercise on the FAA B-737, the aircraft loads were moved to different SSPCs, mostly because of aircraft load availability.

2.8.2.2 The AC Load Tests.

2.8.2.2.1 Background Lighting (28 VAC Lighting Load).

The load was attached to SSPC 2, which was configured to a 15% duty cycle and 200 Hz PWM. The SSPC 2 trip settings were set to 3A for overcurrent trip threshold and 21A for surge trip threshold. When output was turned on using the SPDU, the SSPC 2 surge tripped. The oscilloscope captured an inrush current that peaked at 25A and lasted approximately 400 microseconds.

A second attempt was made to turn on the SSPC using a 5% duty cycle. The initial peak current was approximately 3.8A. After load warm up, the current draw (peak) was approximately 5.8A.

A third attempt was made to turn on the SSPC with the peak current draw at approximately 20A. Without the lamp illuminated, the load was still drawing 20A peak at a 7% duty cycle. It was concluded that the SSPC output was powering not only the 28 VAC load, but a transformer as well. The test successfully proved that the lights get brighter as the duty cycle is increased.

2.8.2.2.2 Fluorescent Light (115VAC, 400 Hz).

The load was attached to SSPC 1 of AC PDU. The unit powered the output but had some difficulty finding the physical lamp. As shown on the AC PDU display screen (see figures 55 and 56), no current was being drawn.

The second attempt tried SSPC 2 on the AC PDU and found a working light that, when powered, consumed 100 mA, 115 VAC, and 400 Hz.

Figure 55. Fluorescent Light Off

Figure 56. Fluorescent Light on via AC PDU

<u>2.8.2.3 Pump and Valve Control</u>.

Tests on the B-737 aircraft involved a bus transition from the ground cart (figure 57) to the auxiliary power unit (APU). With the aid of an FAA technician, the APU was successfully tested without SPDU and PDU integration. Initially, the APU did not start because the battery needed to charge for approximately 15 minutes.

Figure 57. Ground Power Cart

The SPDU and PDU were then integrated into the system of the B-737 per the configuration table. A first attempt was made to perform the transition, but the generator would not start because the boost pumps were not operating. Investigation revealed that the boost pumps and fuel control were not operating because they were connected to the outputs of an unpowered PDU and SPDU. The AC PDU was then disconnected and the aircraft control of the boost pumps was re-enabled.

Using the SPDU, power was applied to the fuel control and the engine manifold valve. The aircraft was powered again and the pump status indications were correct. The SPDU's SSPCs 7, 8, and 9 were used to control the P69 center tank boost pump left.

The aircraft was repowered with the ground power cart and the SPDU and PDU were subsequently powered. The SSPC outputs 7, 8, and 9 were turned on and the pump indicated 116 VAC. The FAA technician then turned on the boost pump from the cockpit switch and the current registered on the PDU display software as 4.5-4.9A (see figure 58).

Figure 58. Display of SSPC 6, 7, and 8

Prior to the bus transition, a software tool was enabled to monitor the SPDU for any upsets. Once this was established, the FAA technician performed a bus transition from the ground power to the APU. As shown in figure 59, an oscilloscope was used to capture the power interruption and the monitoring software logged any upsets reported by the SPDU. The duration of power interruption was roughly 20 msec and the monitoring reported no issues.

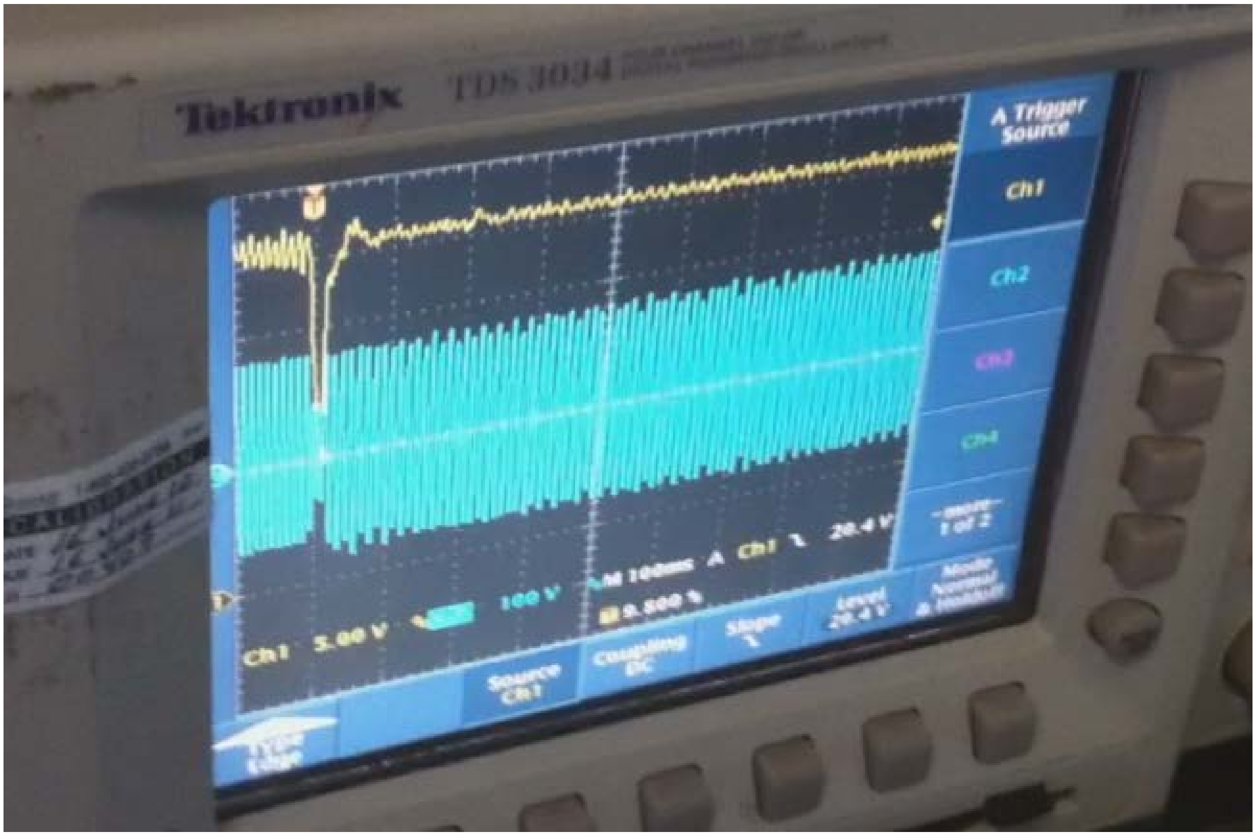

Figure 59. Scope Tract of Bus Transition

The FAA technician then transitioned back to ground power from APU and the monitoring software indicated that the SPDU was able to continue with no issues.

2.8.2.4 Dimming Through PWM.

2.8.2.4.1 Dome Light.

The SSPC 3 was attached to the dome light (see figure 60). One of the two lights was drawing approximately 1A.

Figure 60. Dome Light On

The lamps had a 2 Hz PWM and a 50% duty cycle (see figures 61 and 62). One of the two lamps was not working because of the lack of light output and total current draw.

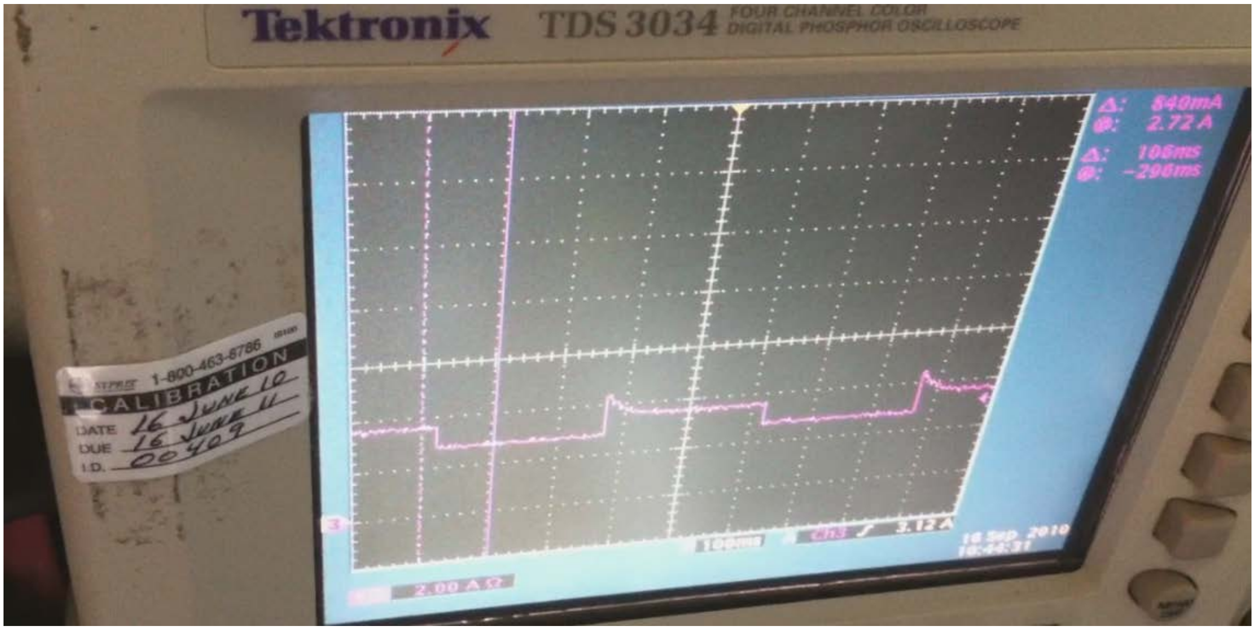

Figure 61. Dome Light on Current Trace

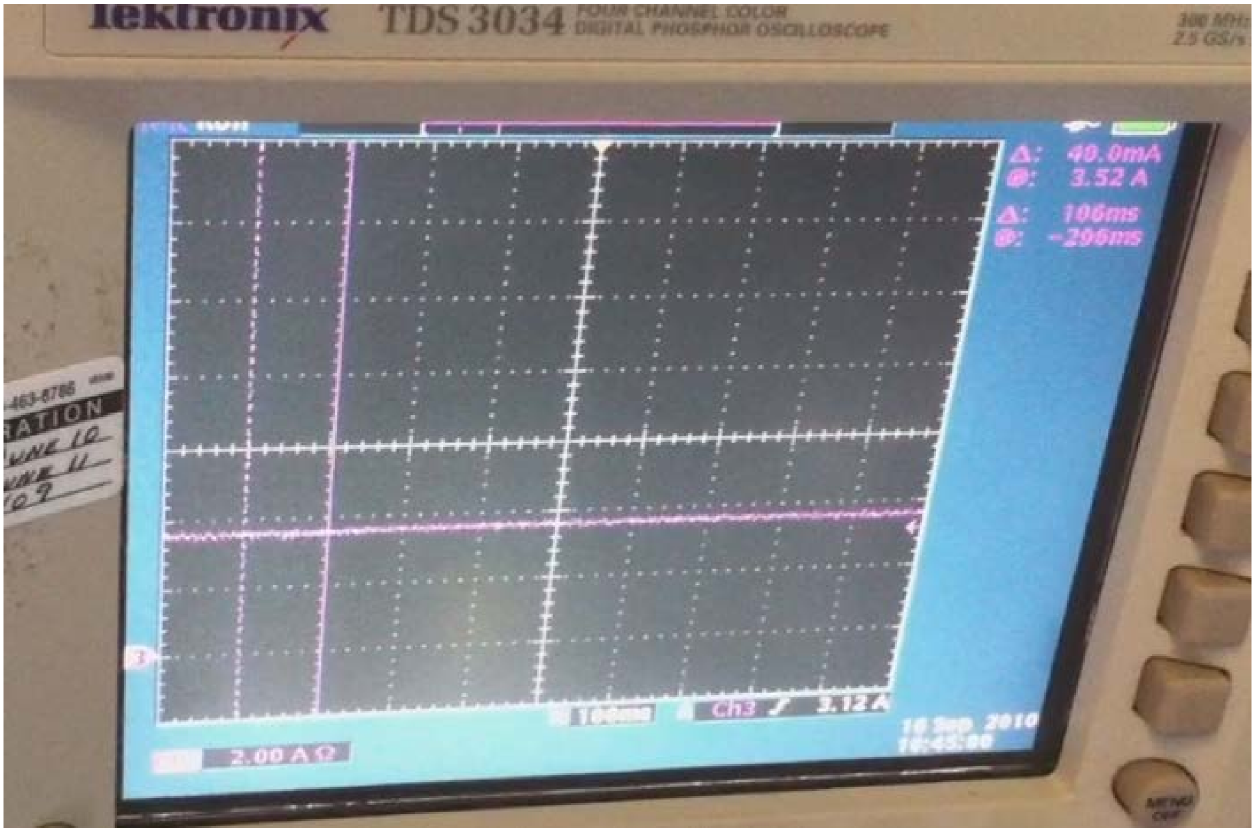

Figure 62. Dome Light off Current Trace

Using the dome light as the test load, the configuration table was changed to utilize discrete control of the SSPC output. This allowed a discrete input on the SPDU test breakout box to be used like a toggle switch to control the dome light. No ARINC or CAN communication was required for the dome light on/off control.

<u>2.8.2.4.2 Observer's Reading Light</u>.

The SSPC 19 was used to supply power to a map and kit light. The light draws approximately 250 mA at a 70% duty cycle and 200 Hz PWM. Terminal 43 was used to make the connection to the reading light.

Then one lamp was powered from the thermal breaker power and one from the SPDU. The SSPC settings were modified in an attempt to compare the intensity of the non-SPDU powered reading light.

Tests at a 70% duty cycle and then down to a 50% duty cycle are shown in figure 63. The SPDU controlled lamp was dimmer than the thermal breaker driven lamp. At 200 Hz, there was no observable modulation.

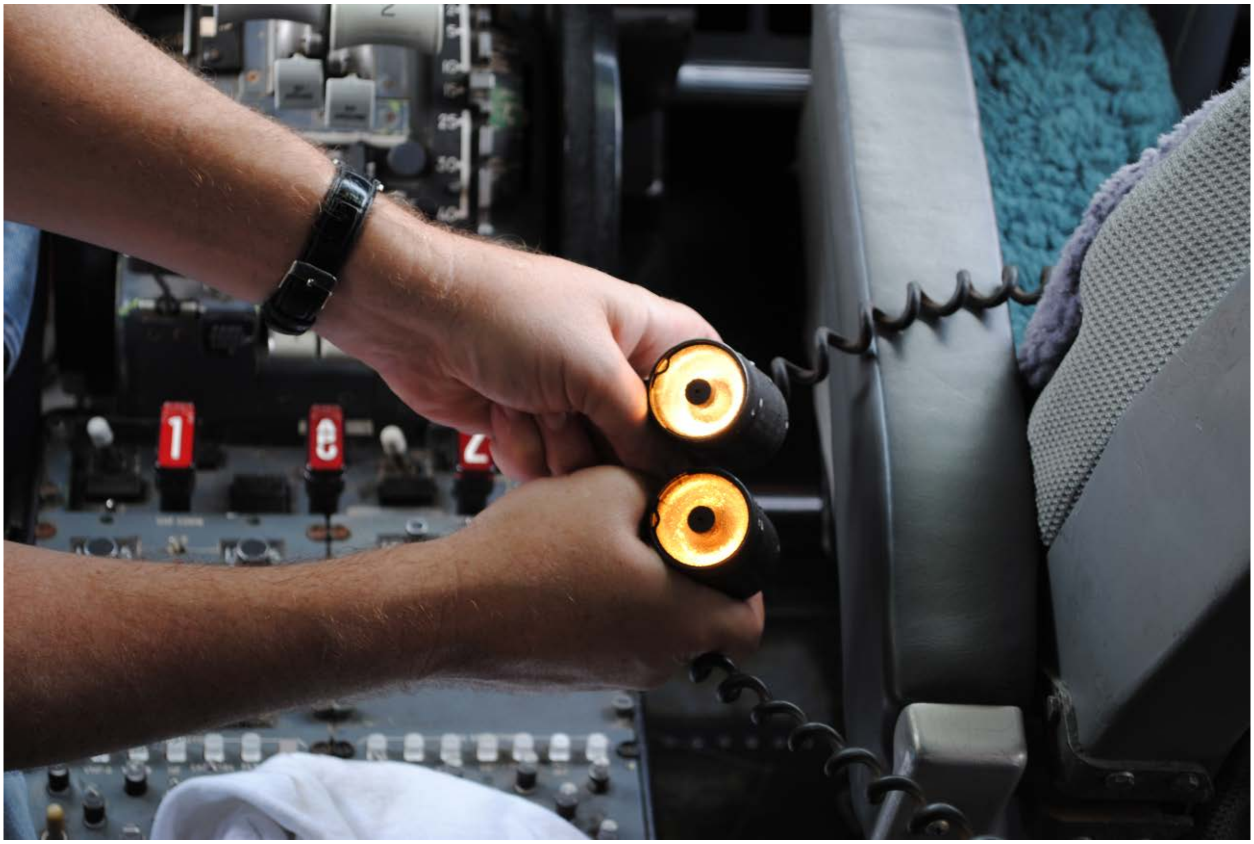

Figure 63. Dimming at 50% Duty Cycle (bottom light)

The duty cycle was increased to 80% and then to 90%. As shown in figure 64, at a 90% duty cycle, the brightness of the two lamps was not easily distinguishable.

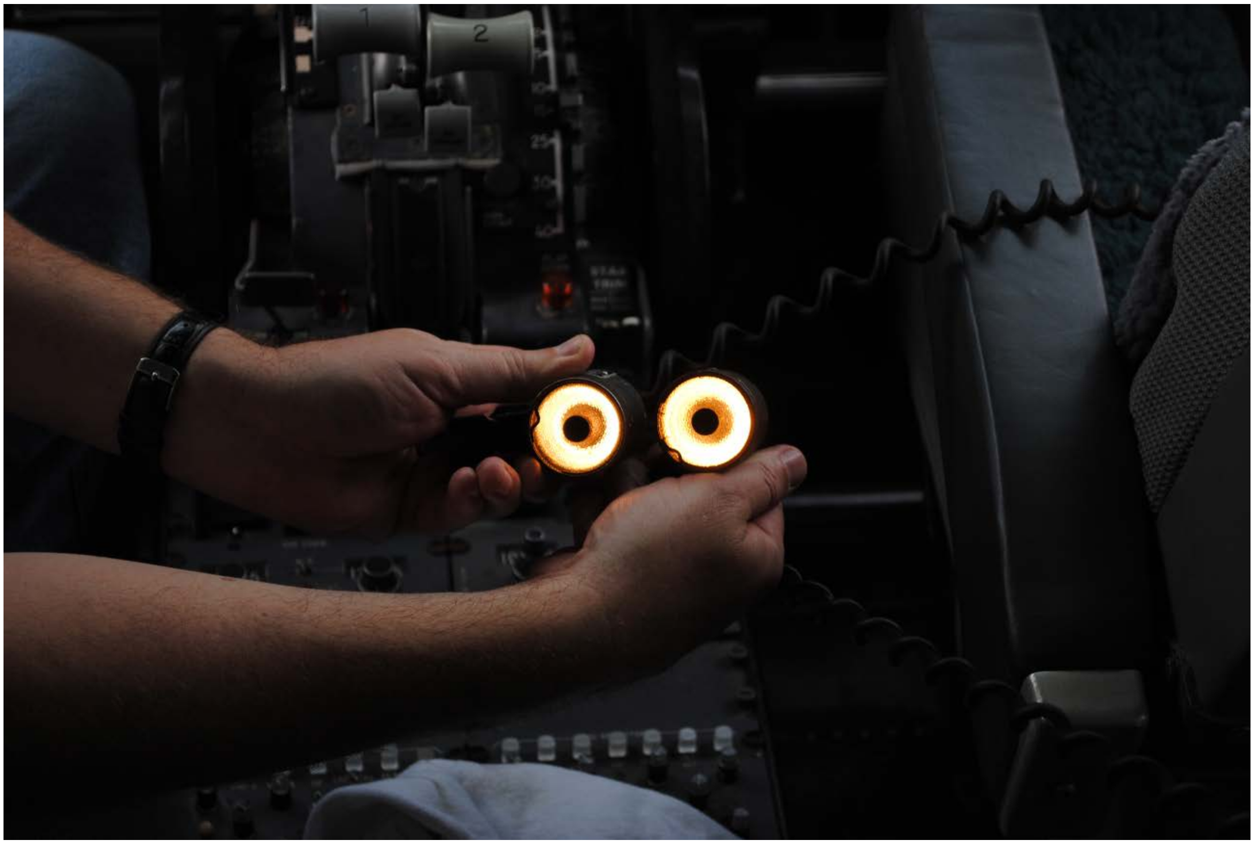

Figure 64. Dimming at 90% Duty Cycle (right light)

2.8.3 Arc Fault Performance Tests.

2.8.3.1 Wire Insulation Breach Using Guillotine.

A test was set up using two parallel wires (20 AWG). One wire was attached to the power output and one was attached to ground, meaning a direct short across these two wires would result in a direct short to ground for the given output. This test is meant to simulate a wiring fault where a breach of insulation occurs on the aircraft. Guillotine hardware (with a sharp blade) was used to cut into the wire insulation of both conductors at approximately the same time, resulting in a low-impedance electrical short between the two adjacent conductors.

The first guillotine test was performed using a standard thermal circuit breaker. During the test, visible arcing was observed, which caused visible damage to the wires. The arcing caused some melting deformations of the insulation, which is an indication of the heat produced during the test. This is shown in figure 65.

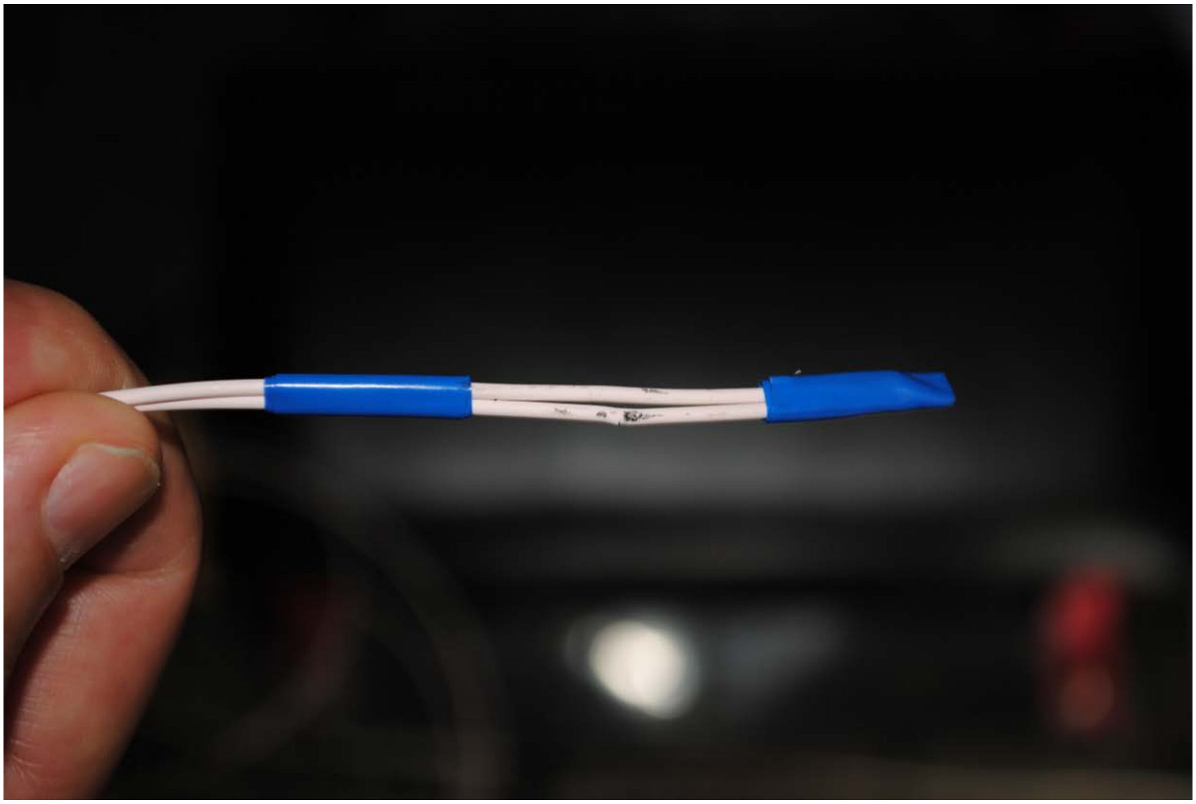

Figure 65. Guillotine Test—Thermal Circuit Breaker

For the second part of the test for the one conductor an SSPC output was used at the feed. The other conductor remained unchanged as aircraft ground. The SSPC output contains surge (arc) protection, which reacts to high-current surges beyond the set threshold within hundreds of microseconds. For this test, the SSPC overcurrent threshold was set to 7A and the surge threshold was set to 49A. The test results, as shown in figure 66, are wires with no visible damage and a clean view of the cut made by the guillotine blade.

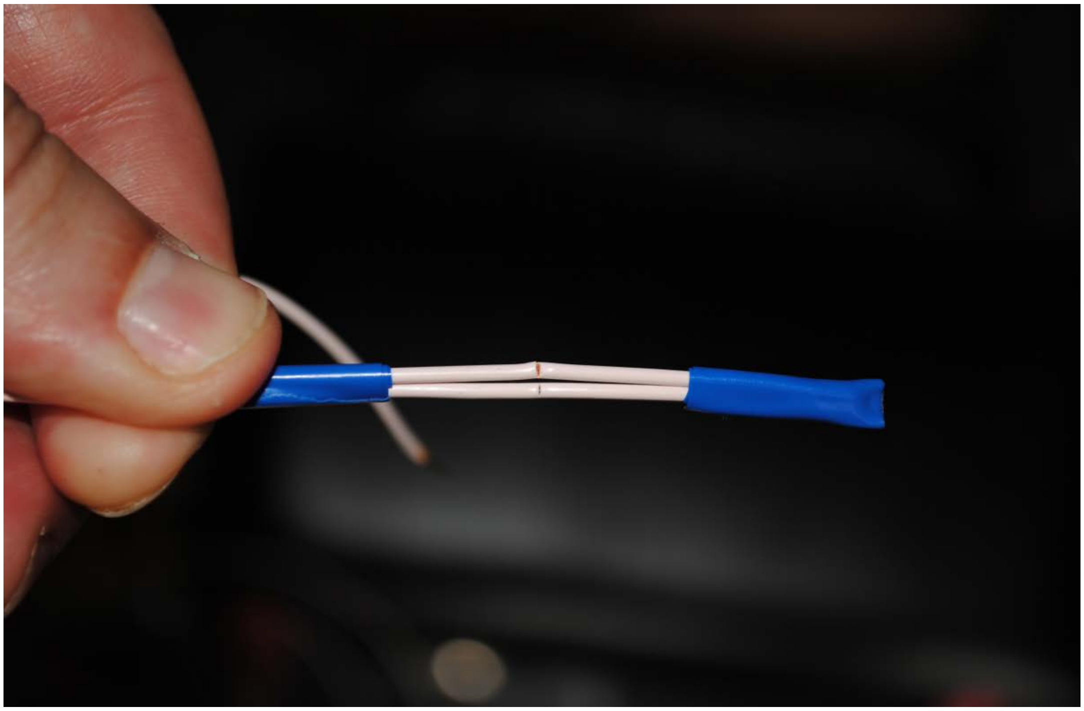

Figure 66. Guillotine Test—SSPC With Arc Protection

As shown in figure 67, the SSPC properly indicated the arc trip event to the display computer.

Figure 67. The SSPC Arc Trip Indication via ARINC 429

2.8.4 The SSPC Stress Testing.

The thermal image shown in figure 68 was taken during the surge trip test. Tests were performed using a single-power MOSFET to understand the surge limit of the SSPC. The surge current and time allowed between tests was increased so the power MOSFET could cool before the next surge level was applied.

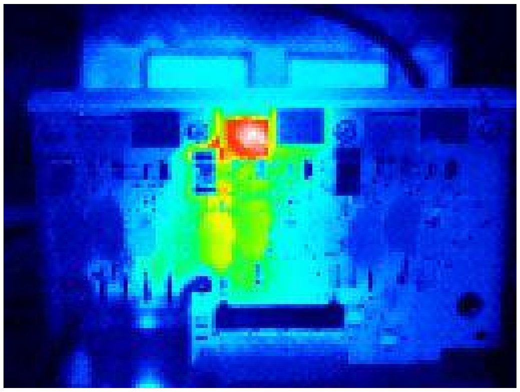

Figure 68. Thermal Image SSPC Surge Trip

2.8.5 Series Arc Fault Testing.

Series arc tests were performed on the B-737 using a vibration platform and a loose terminal (see figure 69). The vibration causes repetitive disconnects between the conductor of the wire and the loose terminal. This created several arcing events that were observed during the test.

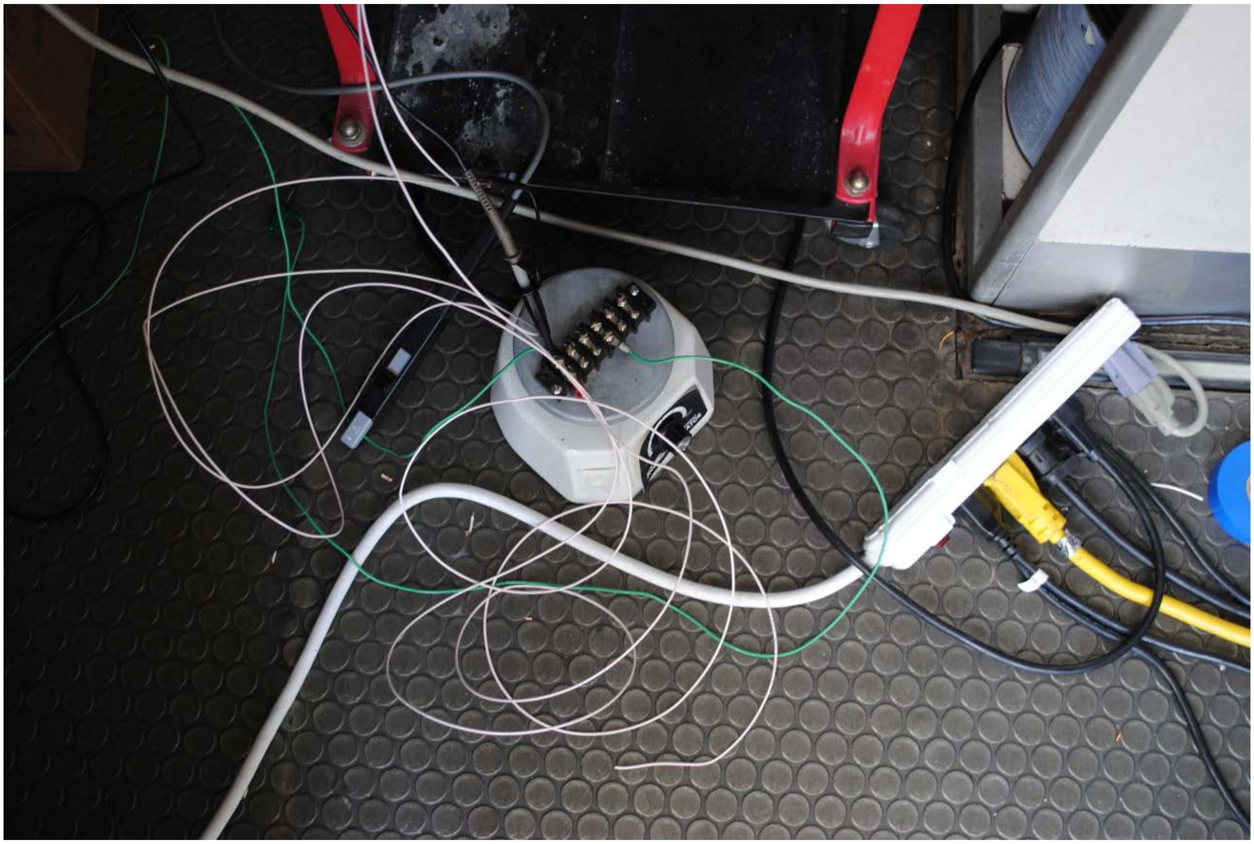

Figure 69. Series Arc Testing on Boeing 737

The series arc test on the B-737 was unsuccessful. The series arcing software, which had previously been bench-tested, did not perform as expected. The software modification for series arc was originally done with an older version of the SSPC software and the series arc software from this older version was extracted and ported to the new version of the SSPC software. It was determined that the porting created a regression that caused the series arc detection to be ineffective. In the final version of the SPDU, the software will be certified using RTCA DO-178B level A guidelines and any changes to the software will require recertification, which includes verification tests.

Further series arc tests and investigation were performed on the windshield heating control unit (WHCU) that uses SSPC technology. The test was conducted using a ring terminal on the output wire and a desktop vibration unit (see figure 70). The ring terminal was loosely connected to a mounting stud that was attached to the vibrator. Two setups were used during the test. Initially, the setup was connected with a metal washer between the ring terminal and the mounting stud.

The washer was then removed and the ring terminal had more freedom of movement because of vibration. The series arc test and results are described in appendix D.

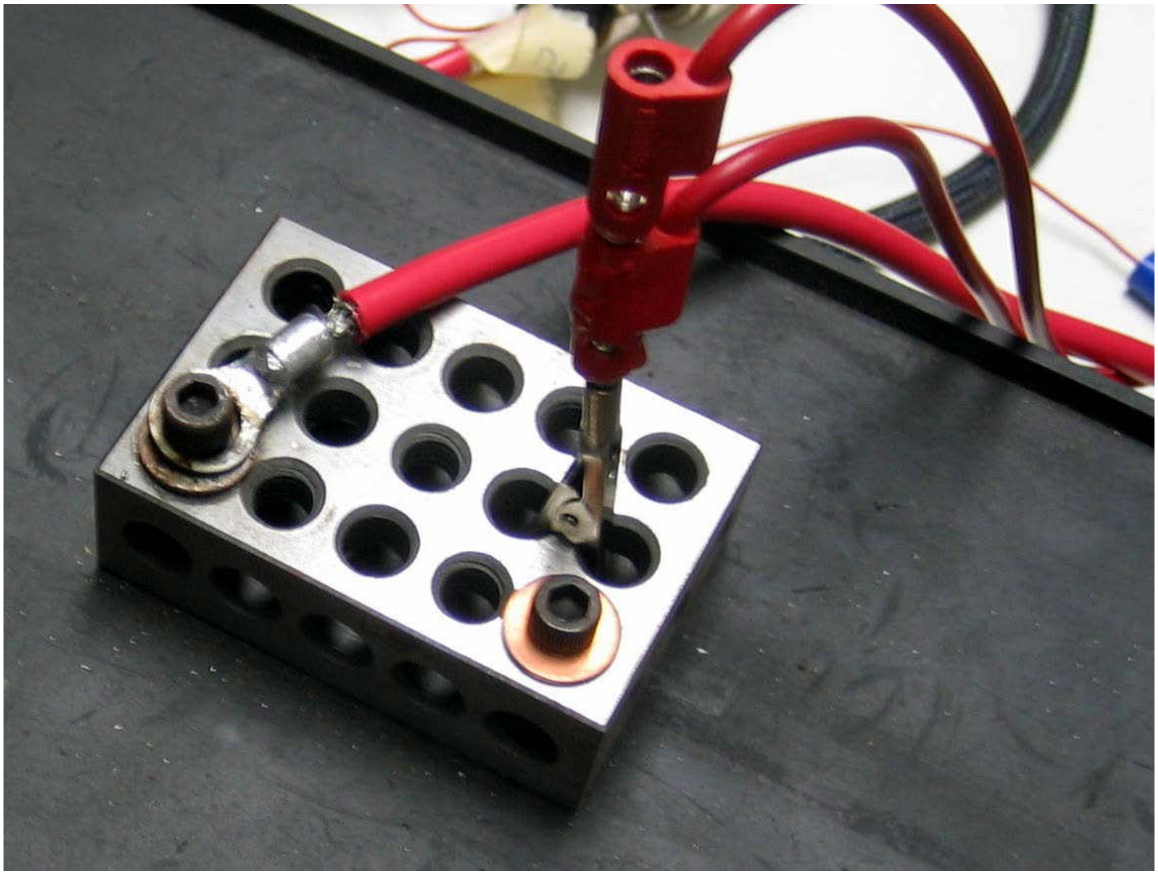

Figure 70. Series Arc Test Using WHCU

2.8.6 Air-Framer Tests.

The launch customer conducted a large portion of SPDU tests on a three-SPDU test platform that mirrored the aircraft system. Once the test results were approved for a given SPDU configuration, it was installed on an aircraft for flight testing. The test flights would record data and the customer would extract the maintenance logs from the SPDUs for analysis. The maintenance logs could also be used to understand the SSPC loading, flight times, temperature variations, supply voltages and frequency of SSPC on/off control.

Air-framer tests were a critical part of the SPDU success. The air-framer test platforms are different from the test lab described in section 2.10 in many respects, such as SSPC output loading, ARINC/CAN communication activity, and configuration table activity. This allowed each test to contribute to the goal of making the SPDU flexible for a wide variety of aircraft systems. Aircraft tests also assisted in understanding the performance of the shunt-based current measurement technique of solid-state technology. The logged hours of operation confirmed the accuracy of the trip curve during flight conditions and mitigated risk and concern of noise immunity, nuisance indications, and false-trip occurrences.

During the initial air-framer ground test on the aircraft, the power source was unintentionally dropping and browning out, causing failures to connected systems, one being the SPDU. The air-framer captured voltage waveforms of the power source issue and was able to reproduce these issues in the simulated aircraft test lab. The lab test found several issues related to power sequencing and power interruptions that drove several software changes. The air-framer tests increased power interruption times and frequencies well beyond the RTCA DO-160G test requirements. This exposed a critical issue related to the startup of the current sense amplifier on the SSPC that resulted in nuisance trips. A current sense amplifier is the integrated circuit used to measure the load current by using a shunt resistor, something that thermal circuit breakers do not encounter. An engineering software release to the customer confirmed resolution of the issues.

Because a majority of SPDU and SSPC features existed in software, planned engineering software releases delivered to customers electronically reduced the overhead in the joint development and integration phase. Correcting a few software issues in a short time and having the customer confirm the resolution is an improvement over the previous method of returning the product to incorporate hardware or software changes with months elapsing before the customer can confirm the resolution. The overhead is also decreased if most issues are addressed early on test platforms prior to the customer need for safety of flight (SOF). This is because many air-framers, from the direction of certification authorities, are requiring a portion of formal software verification to be completed prior to aircraft SOF. This allows the air-framer to reduce risk and also take credit for testing done during SOF as the software development is under tight configuration control during the verification phase.

2.8.6.1.1 The PWM of Inductive Loads.

The SSPC test was performed using various load types attached to the SSPC output throughout development, including controlling a motor load during an SPDU test. When the motor load was controlled with PWM, the SSPC failed after approximately 5 minutes of operation while it was controlled ON and OFF using the Multi Control Display Unit (MCDU) display software. After failure, the SSPC output turned OFF and the SPDU reported the SSPC NO GO failure on the communication bus. Further investigation found that the motor load caused the SSPC's thermal cutout to open circuit, making it a hard failure. This failure removed voltage from the SSPC output as the thermal cutout is in series with the SSPC's internal power MOSFET. Analysis of the failure and the load characteristics determined that root cause was due to the inductance of the motor load causing output voltage to be offset from the power MOSFETs control signal and the enable signal to the thermal cutout. When the fail-safe mechanism is enabled, voltages seen on the SSPC output cause it to eventually open. With a PWM frequency of 200 Hz, the fail-safe mechanism will be enabled 200 times-per-second, allowing 200 instances in which voltage can be present at the enabled fail-safe mechanism because of the load inductance. Duty cycle has no effect on this issue because it controls only the width of the thermal cutout enable and not the frequency of the thermal cutout enable. With a voltage present even for a short time (microseconds), every 5 milliseconds the fail-safe mechanism opened after approximately 5 minutes of operation.

The solution was implemented in software to leave the fail-safe mechanism disabled during PWM operation. This means that the fail-safe mechanism is enabled only when the SSPC output is controlled to OFF using the communication bus or discrete control.

2.9 THE SPDU REQUIRED TESTS.

Qualification test levels were selected by the customer based on RTCA DO-160 and MIL-STD guidance related to the SPDU's aircraft installation location, safety criticality, and aircraft system integration. A test requirement, such as being explosion proof, is required based on the aircraft's usage in military applications.

The customer's SPDU installation will be in a non-temperature-controlled or partially temperature-controlled internal section of the aircraft. The SPDU's launch aircraft is a rotary aircraft and, therefore, the altitude requirements are lower than a fixed-wing aircraft. The SPDU was tested at both +25,000 ft, as required for rotary aircraft, and +50,000 ft, as required for fixed-wing aircraft.

The customer also imposed some of the highest available categories for radio frequency susceptibility because of the potential for the aircraft's end-use to be near high power radar systems (i.e., Aegis).

For qualification tests, the customer has a vested interest in understanding the SPDU's overall performance. To address this need, a comprehensive external monitoring system comprised of both software and hardware monitoring was deployed. The SPDU operating conditions were defined to exercise the SPDU near its limits. The SSPCs that are controlled ON are loaded to 90% of the trip threshold during the test and some are configured for PWM at the highest frequency (200 Hz) and duty cycle (95%). The SSPC operating current level provides only a 10% margin and a greater opportunity to find nuisance trips during the test. The SPDU is also fully loaded to 288A during most qualification tests. This is especially important during temperature, temperature variation, and altitude, when elevated ambient temperatures combined with the SPDU's internal heat dissipation will stress the SPDU's overall thermal performance. More than 40 different internal temperatures are monitored during the test and analyzed for temperatures beyond component specifications. The SPDU required tests, test setup, and results are described in appendix E.

2.10 TEST LAB.

The test lab is meant to simulate an aircraft secondary power electrical system, which typically contains between 150 and 200 electrical loads and up to six different power buses. The typical aircraft contains the essential, non-essential, and auxiliary bus, which can be split as one set of buses for the left side and one set of buses for the right side of the aircraft.

The overarching goal of the test lab is to mitigate risk by producing an environment that is relevant to the aircraft community and provides a safe and simple means to simulate aircraft control and loads and to test solid-state power control. Conversely, the test lab afforded designers the opportunity to run various tests without the need to be installed on an aircraft. Thus, the architecture for the test lab was designed to achieve four main purposes:

1. To closely emulate a true aircraft configuration,

2. To be portable and support various test lab layouts and test environments,

3. To offer convenient and useful features that speed up or simplify common system tests and functions,

4. To provide a safe environment when exercising experiments or investigating new ideas and technology.

2.10.1 Aircraft Emulation.

The test lab architecture was selected to match the basic power bus structure that would typically be available on a twin-engine aircraft. With each SPDU having two independent power input channels, a three-SPDU test lab architecture provides the capability to have up to six independent power buses. The most basic aircraft power system would likely have a power source from each engine and a battery. An example of the various buses would be: Left Main, Right Main, and Battery buses. This structure is typically expanded into additional buses as load criticality and battery power consumption are considered. Most often Essential (ESS), Auxiliary (external power cart connections), and Battery 2 or similarly named buses are added. To support these bus structures, the test lab has been constructed in a modular fashion in which each SPDU is supported with its own bus tie/shed contactor for each SPDU bus input and its own I/O breakout boxes for signal and load connections. This allows maximum flexibility for connecting or isolating any SPDU; selecting or disconnecting digital communication to any SPDU channel; providing discrete I/O command and reporting to any SPDU channel; and having accessibility to each and every SSPC output on every SPDU.

The control interface is another critical piece of the aircraft simulation. The personal computer (PC) display has the function of representing the display used by the pilots, crew, and maintenance personnel to manage the power system and the loads on the aircraft. The display was intentionally designed using a ruggedized PC with a small footprint. Because panel space is extremely valuable, the idea was to create a visual interface on a surface that is similar to the size most likely allocated for power management or multifunction displays on an aircraft. Equal attention was also given to the wire selection connecting the display to the rest of the lab setup. Both length and type of wire was chosen to match the aircraft installation to provide the shielding, twisting, and terminations needed in a real aircraft application.

Figure 71 shows a block diagram of the TL. The completed TL and three SPDUs are shown in figure 72.

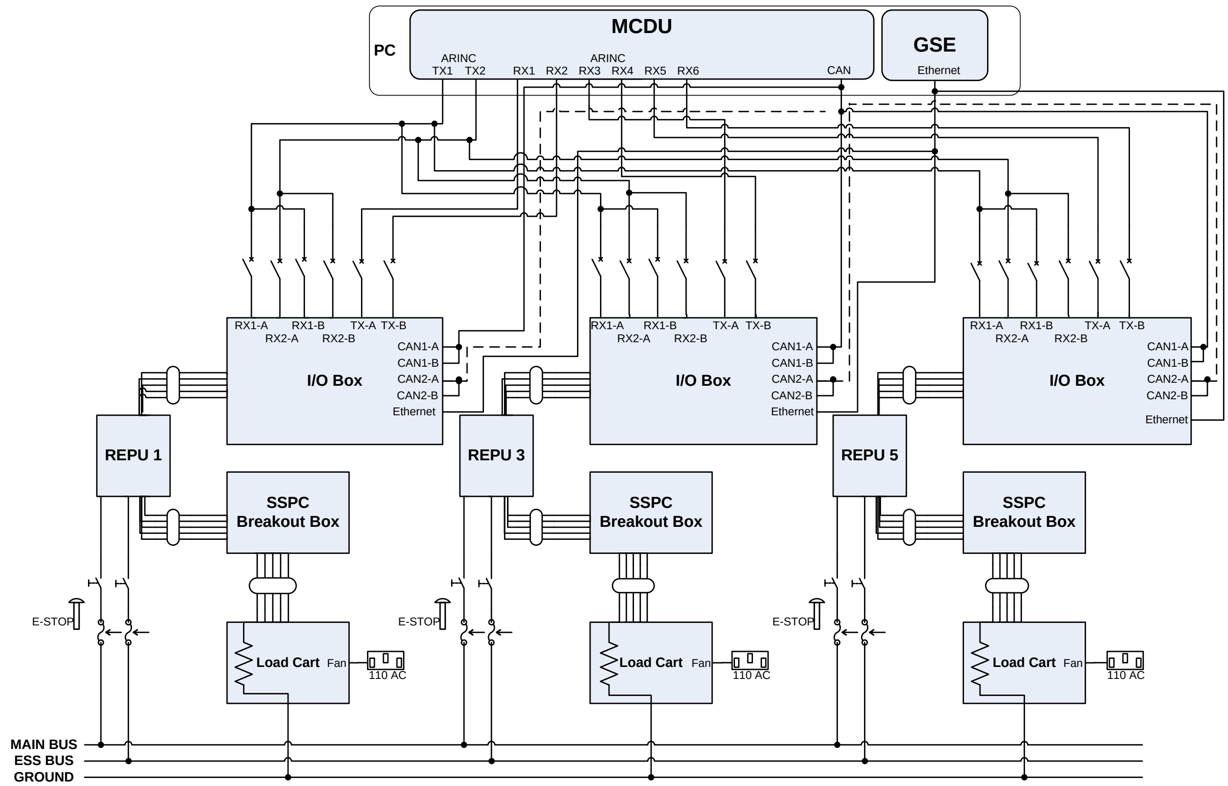

Figure 71. The SPDU Test Lab Block Diagram

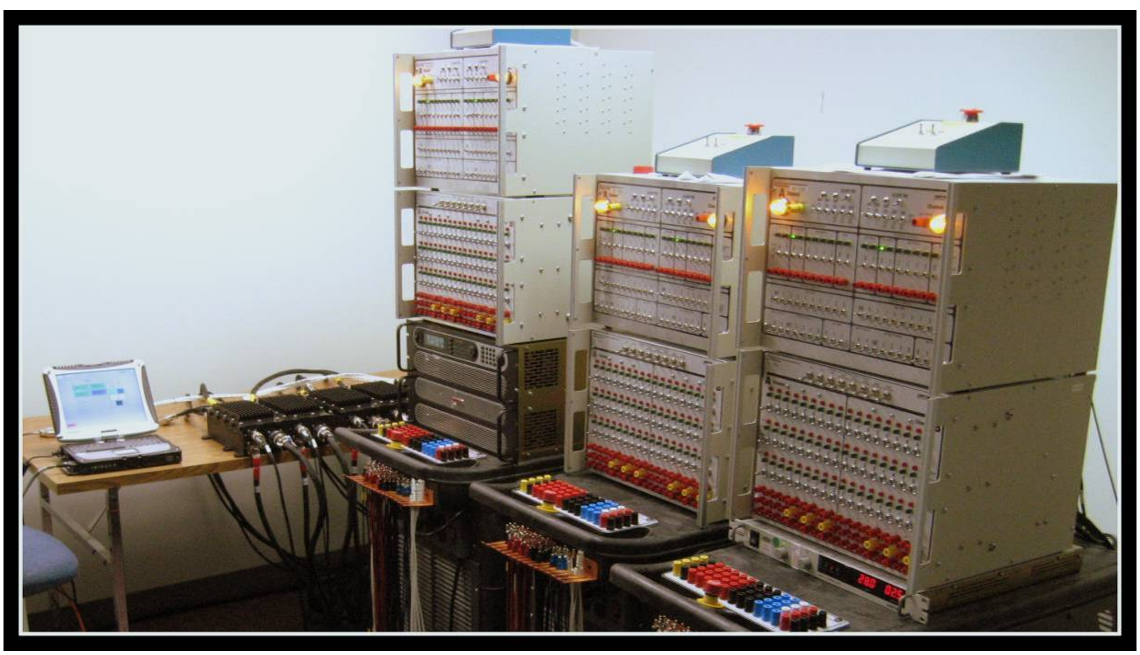

Figure 72. Test Lab

2.10.2 Portability and Flexibility.

To build a lab that simulates an aircraft power system, a space is needed to accommodate large power supplies, current monitoring equipment, programmable and custom loads, and all of the necessary breakout boxes for each of the SPDUs. The test lab was intentionally designed to be modular so that SPDUs, power supplies, and load boxes could be easily repositioned depending on the test or experiment being performed. This is especially important when working in tight spaces or with loads that may not be moveable.

Each SPDU has its own load cart and breakout boxes for transportability and repositioning. The carts are wheeled structures that offer easy maneuverability. These carts have the necessary equipment to add an SPDU into the power system test lab and the ability to conveniently fit into a minivan. This is especially useful for offsite testing. In addition to transportability, the interconnections between the SPDU and the cart have connector terminations on both ends of the harness. This feature allows for custom cables or cables of different lengths to be easily configured into the system and support special setups, such as temperature or EMI testing, for which cables of specific length, type, and termination are required.

2.10.3 Convenience.

For clarity and simplicity, each SPDU is attached to a dedicated I/O box and SSPC breakout box. This provides the user a visual and physical distinction when operating a specific SPDU or when controlling specific test loads. Having identical boxes also allows them to be easily swapped or disconnected from the system if service or repair is needed without making the entire setup unavailable or inoperable.

The I/O box is used as an interface to the SPDU for discrete inputs, discrete outputs, and communication. This makes all signal I/O for each SPDU easy to monitor by providing one viewing and control surface. It also makes interconnections between the PC and SPDU simplified to a few connectors. Each SSPC breakout box connects to a load cart, which contains resistive loads for testing the individual SSPC circuits of the SPDU and provides a number of features that offer a convenient means to attach custom loads and perform the most typical system performance tests. This can be especially useful when characterizing new loads or understanding how new loads may impact the operation of a solid-state power-controller-based system.

For convenience, a ruggedized touch-screen laptop is used and serves multiple purposes by running two separate applications that aid in controlling, monitoring, and configuring the SPDU. Essentially, except for the discrete I/O, any SPDU in the system can be fully operated and settings manipulated through a ten-inch display. The first program is the MCDU software (SW). The MCDU application simulates the control display that may be found in the cockpit of the aircraft and provides the function of a smart CBP. The MCDU uses ARINC-429 or CAN communication to control and monitor the SPDU. To simplify the test lab setup, the ARINC and CAN communication wires are routed to the SPDU via the I/O box. These digital buses provide the command and reporting information to control loads and monitor the status of the loads and the health and status of the SPDU. The second application is the Ground Support Equipment

(GSE) SW. This software is typically found in the hands of the aircraft maintenance personnel and is only meant for use while the aircraft is on the ground. For convenience and speed, the GSE uses Ethernet to upload configuration settings and download maintenance data to or from any of the multiple SPDUs connected to the power distribution system. For the test lab, the Ethernet communication wires are also routed to the SPDU via the I/O box to keep interconnections logical and simple.

At the load box end of the system, many other convenience features have been added to allow the user to quickly and accurately measure individual currents, swiftly select from a series of fixed loads, create overcurrent and surge events, and easily add custom loads to SPDU outputs. The result is a highly flexible and capable system that is intuitive in operation.

2.10.4 Safety.

The test lab can be an excellent environment for experimenting with new load configurations, exploring the limitations of solid-state power control, and understanding the integration issues of an SPDU system. This environment can be dangerous because of the possibility of hundreds of amps flowing between various components of the system. For this reason, significant thought has been put into the test lab architecture to assure a safe test environment. Many of the design enhancements are a culmination of findings and enhancements discovered from previous experience with solid-state power control testing and are a sum of the wants and needs determined from previous test setups.

Some of the key safety features include:

- Fuse protected inputs for feeds into each SPDU
- Multiple locations of emergency stop buttons to disconnect all power sources from all SPDUs
- Thermal monitoring of loads and overheat protection
- Non-metallic and plexiglass construction to provide a non-conductive work surface
- Protective shielding to contain damage or catastrophic events
- Momentary switches for large current tests to minimize accidental high current settings
- Annunciation lights to indicate power availability and test lab operation

2.10.5 Interface.

2.10.5.1 The MCDU.

The MCDU is a touch screen-inspired interface designed to monitor and control up to four SPDUs using ARINC or CAN communication. The touch screen was specifically chosen to provide the user a quick and intuitive method of sending commands to the SPDUs. The MCDU sends commands and polls status similar to that of an aircraft cockpit display. However, the real cockpit display would be customized for control of specific known loads and interfaces. For the purpose of this deliverable, the MCDU output control is not labeled with the name of the attached load as it would be in the typical cockpit display, but rather with the assigned number of the SSPC output channel.

The overall goal of the MCDU software was to exercise every ARINC label or CAN command via polling and button-press events and to simulate the commands and responses from a real aircraft MCDU. The button-press events are driven by the user and are converted to digital bus commands and sent to the SPDUs. This command and monitor functionality is what allows the SPDU development team and the test lab operators to complete acceptance testing of the SPDU and the test lab by exercising each SSPC, RCCB, discrete input, and discrete output with real-time control and feedback. The MCDU, as used to provide control for the TL, is shown in figure 73.

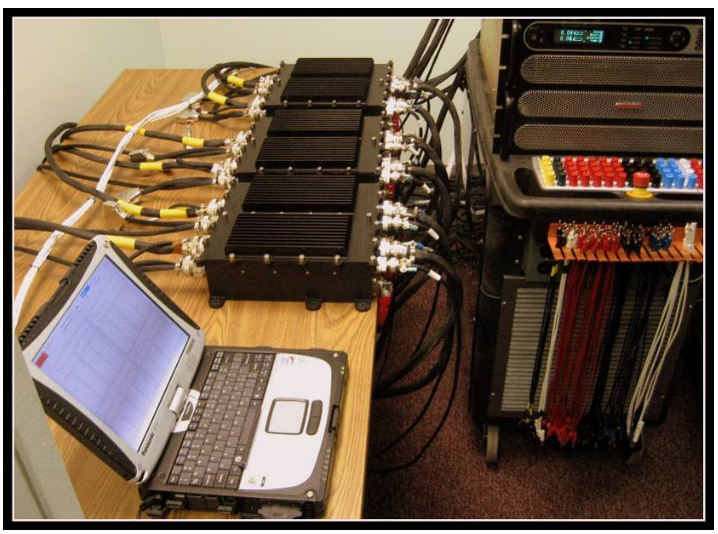

Figure 73. The MCDU Controlling Three SPDUs

2.10.5.1.1 The ARINC 429 Communication.

Each SPDU has high-speed (100kHz) ARINC 429 communication buses and DO-178B level A software to allow for control and monitoring of its power-control features. The MCDU in the test lab interfaces with the SPDUs, using an ARINC interface card.

The MCDU SW was designed to the installation specification for the launch customer's aircraft. Figure 74 describes the ARINC 429 installation within the aircraft. The MCDU transmitter/transmit (TX)1, from the block diagram, is the primary communication to the SPDU, while the MCDU TX2 is the redundant backup. In the aircraft installation diagram, the slave MCDU transmits to the second receiver/receive (RX)2 on each SPDU channel. Only the master display computer sends commands to all SPDUs (if operating normally), while the slave display computer is silent. The change of role of the display computer is performed when the master is failed. In this case, the master display computer does not transmit any commands and the slave display computer takes control of the system, becoming the new master. Both TX1 and TX2 send the same command at the same time. Both TX3 and TX4 perform the same functionality as TX1 and TX2, but on different SPDUs.

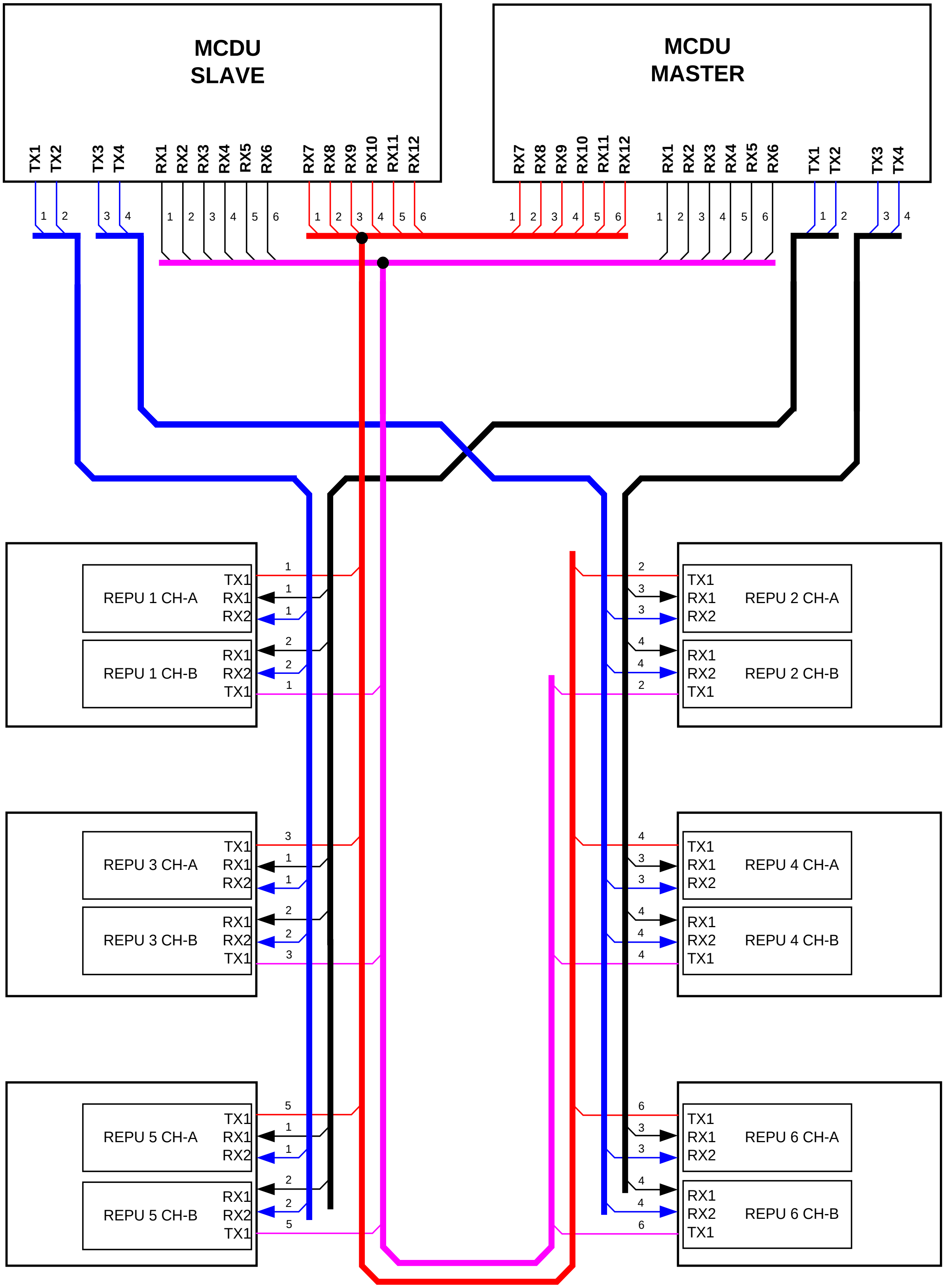

Figure 74. The ARINC Aircraft Topology

2.10.5.1.2 The ARINC Communication Switches.

To test the redundant communication buses on the SPDU, the ability to disconnect individual branches of the ARINC bus is necessary. The TL has been equipped with six open/close switches to accomplish any combinations of communication failure for each SPDU. The six switches allow for independent control of RX1-A, RX2-A, TX-A, RX1-B, RX2-B, and TX-B. The A and B notation signify the channel within the SPDU.

2.10.5.1.3 The CAN Communication.

The CANBUS communication has been widely accepted throughout the automobile industry and newer aircraft architectures are also implementing this serial bus protocol because of its speed, data integrity, and wire-weight-saving advantages. For this reason, the SPDU has been equipped with a redundant CANBUS architecture with which all of the SPDUs share the same CANBUS.

Unlike the ARINC bus, the multidrop nature of the CAN eliminates the need to have independent transmitters for each SPDU. In the CAN architecture, only two personal computer CAN to Universal Serial Bus (USB) (PCAN-USB) interfaces are required in the MCDU for the entire SPDU system because data for all units are shared on the same wire. However, for the test lab implementation, a single PCAN-USB controller will be used to simplify the system and a provision will be made that allows the test lab user to switch from the primary CANBUS to the secondary for testing. The higher data rate of the CANBUS becomes more important as additional SPDUs are added to the communications bus.

The CAN wiring for the SPDU system is shown in figure 75. The CANBUS speed is configured for 500 Kbit/s communications allowing for a maximum total wire length of 100 meters (328 feet). With the bidirectional bus, the same wiring is used for both transmit and receive communications as well as connections to both channel A and B chassis.

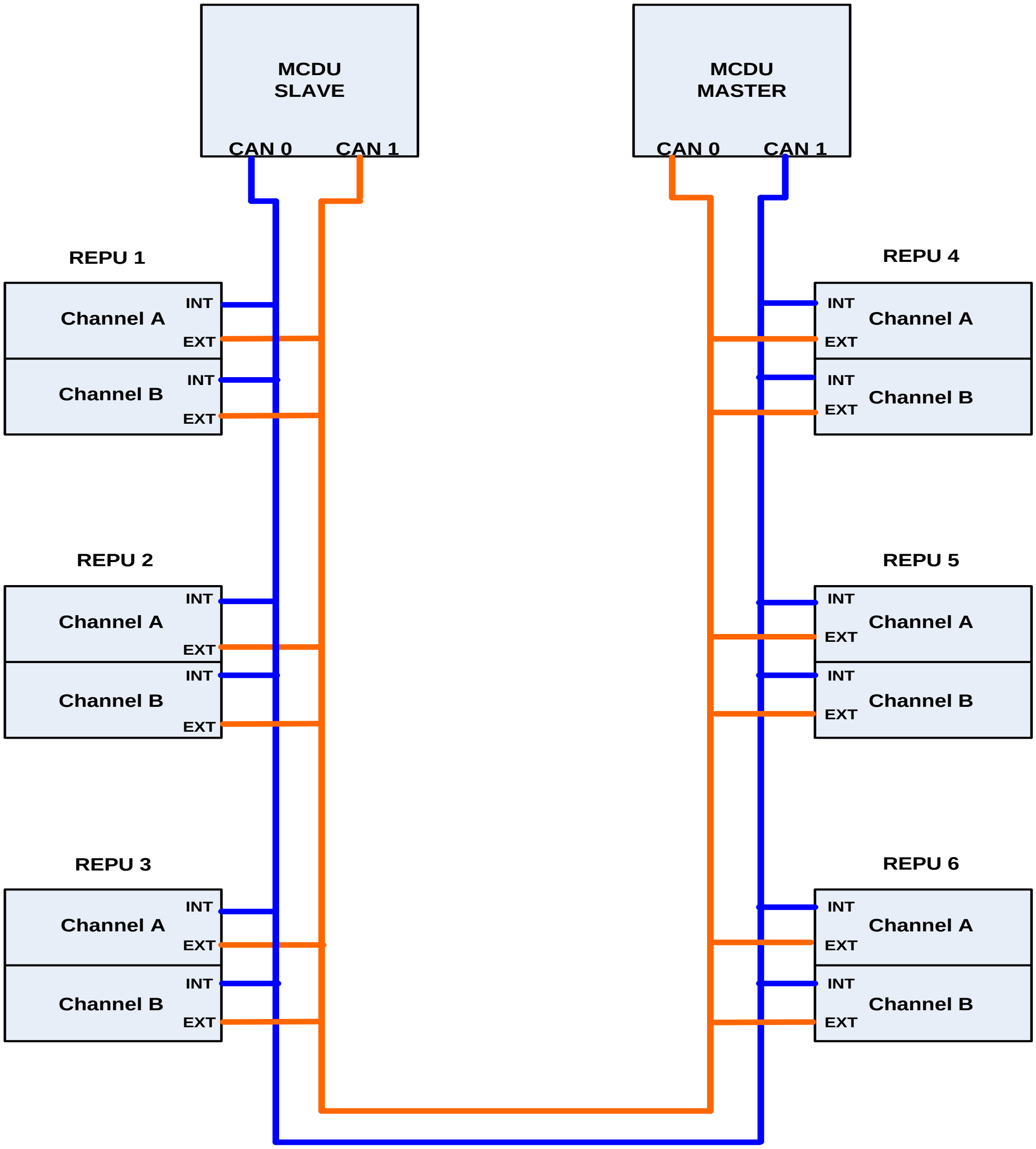

Figure 75. The SPDU CANBUS Wiring

Multiple communication buses are used on aircraft today. The ARINC has a proven history of reliability in the aerospace industry. It has built-in data integrity, uses a differential communication pair to reduce susceptibility to noise or bit errors, and provides wiring redundancy that can be tailored to the application by using full-duplex communication where transmit and receive communication are resident on their own wires. An ARINC bus contains one TX and up to 20 RXs, making the data unidirectional.

The CAN or CANBUS is another proven communication bus that was developed for the automotive industry, but, in recent years, has been used as the primary communications bus in mid-size jets, although not yet widely accepted in the aerospace industry. Airbus is creating more opportunities for the industry to accept CANBUS by incorporating CAN on the A380 superjumbo jet. The CANBUS, similar to ARINC, also contains built-in data integrity and uses a differential pair for communication; however, it has higher speed data rates and data collision detection, and is bidirectional.

For the SPDU design installation, it was required that communication be either ARINC or CAN. To keep the system flexible, the SPDU listens for either ARINC or CAN. Whichever communication is heard first is the communication used for the duration of that powered state.

The ARINC wiring diagram in figure 76 describes an actual aircraft installation with redundant wiring and an additional MCDU (slave).

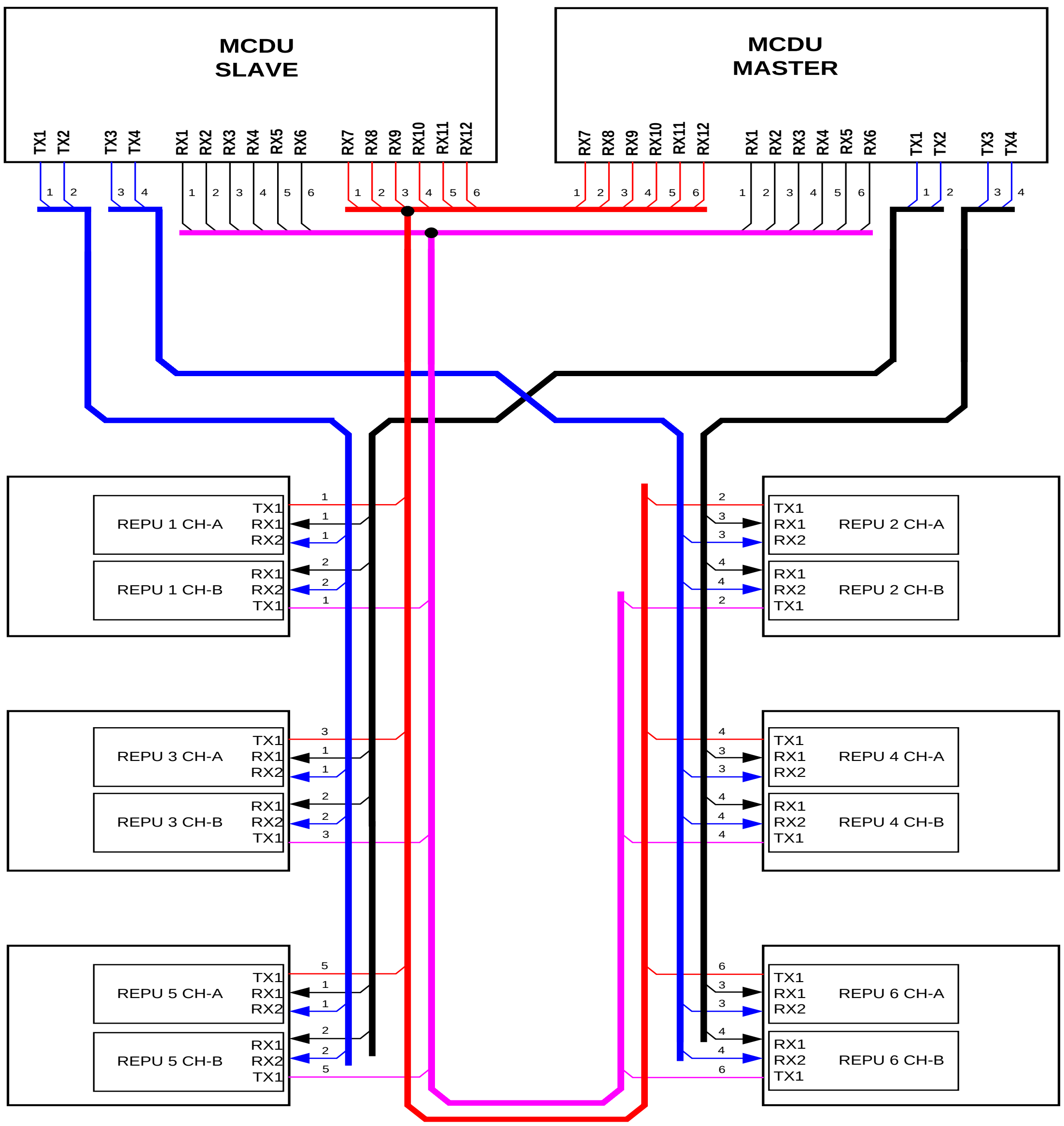

Figure 76. The SPDU ARINC Bus Wiring

Display computer 1 is the master unit (hard wired to be the master) and display computer 2 is the slave unit (hard wired to be the slave). Only the master display computer sends commands to all SPDUs (when operating normally), while the slave display computer is silent. Switching the display computer occurs when the master is failed; in this case, the master does not transmit any commands and the slave unit takes control of the system, becoming the new master. Both TX1 and TX2 send the same command at the same time, as do TX3 and TX4. Each SPDU has its own identification code (hard wired). The SPDU is addressed using ARINC 429 SDI field, as shown in table 9.

Table 9. The SPDU SDI Mapping

SDI	Display Computer TX1	Display Computer TX2	Display Computer TX3	Display Computer TX4
00	SPDU1 CH-A	SPDU1 CH-B	SPDU2 CH-A	SPDU2 CH-B
01	SPDU3 CH-A	SPDU3 CH-B	SPDU4 CH-A	SPDU4 CH-B
10	SPDU5 CH-A	SPDU5 CH-B	SPDU6 CH-A	SPDU6 CH-B
11	SPDU7 CH-A	SPDU7 CH-B	SPDU8 CH-A	SPDU8 CH-B

Both display computers receive data from all of the SPDUs. Each display computer has $2*N$ receivers, where N is the number of SPDUs.

If display computer 1 fails in an actual aircraft installation, the SPDUs would receive and use the data from display computer 2 TX1, TX2, TX3, and TX4.

Figure 77 is a wiring diagram used for the display test lab. The COMP1 connector mates with the ARINC-715 interface cable. The SPY1 connector mates with a CEI-400 ARINC adaptor in another computer used to monitor the ARINC 429 data on the bus. This was useful during MCDU application development to debug software and communication timing issues. Each of the SPDU connectors attach to I/O boxes, from which the I/O boxes interface directly with the circular connectors on the SPDU.

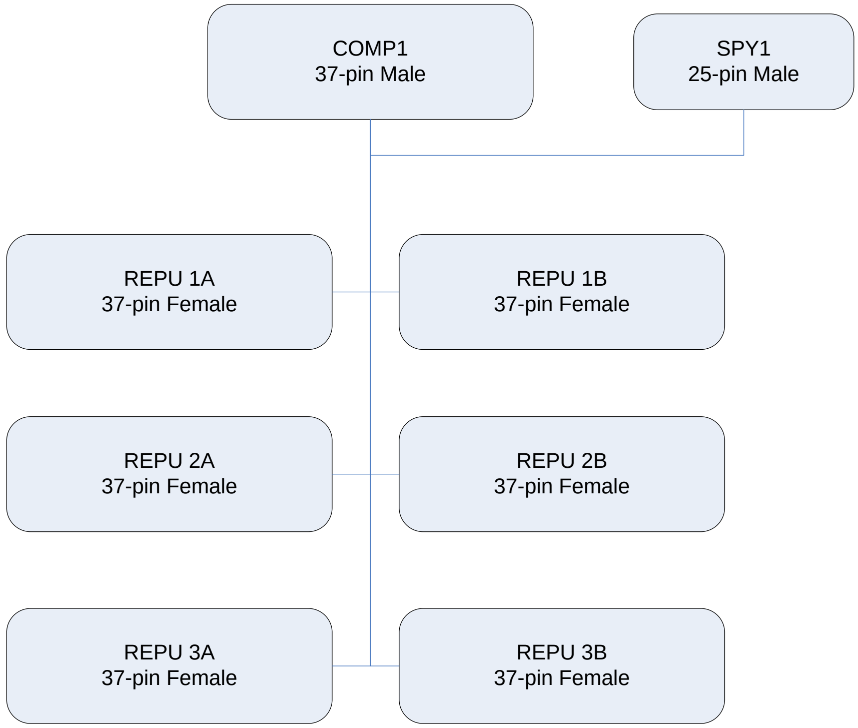

Figure 77. The ARINC Wiring Topology

Unlike the ARINC bus, the multidrop nature of the CAN eliminates the need to have independent transmitters for each SPDU. In the CAN architecture, only two PCAN-USB interfaces are required in the MCDU for the entire SPDU system because data for all units are shared on the same wire. The higher data rate of the CANBUS becomes more important as additional SPDUs are added to the communications bus.

The CAN wiring for the SPDU system is shown in figure 78. The CANBUS speed is configured for 500 Kbit/s communications, allowing for a maximum total wires length of 100 meters (328 feet). With the bidirectional bus, the same wiring is used for both transmit and receive communications, as well as connections to both the channel A and B chassis.

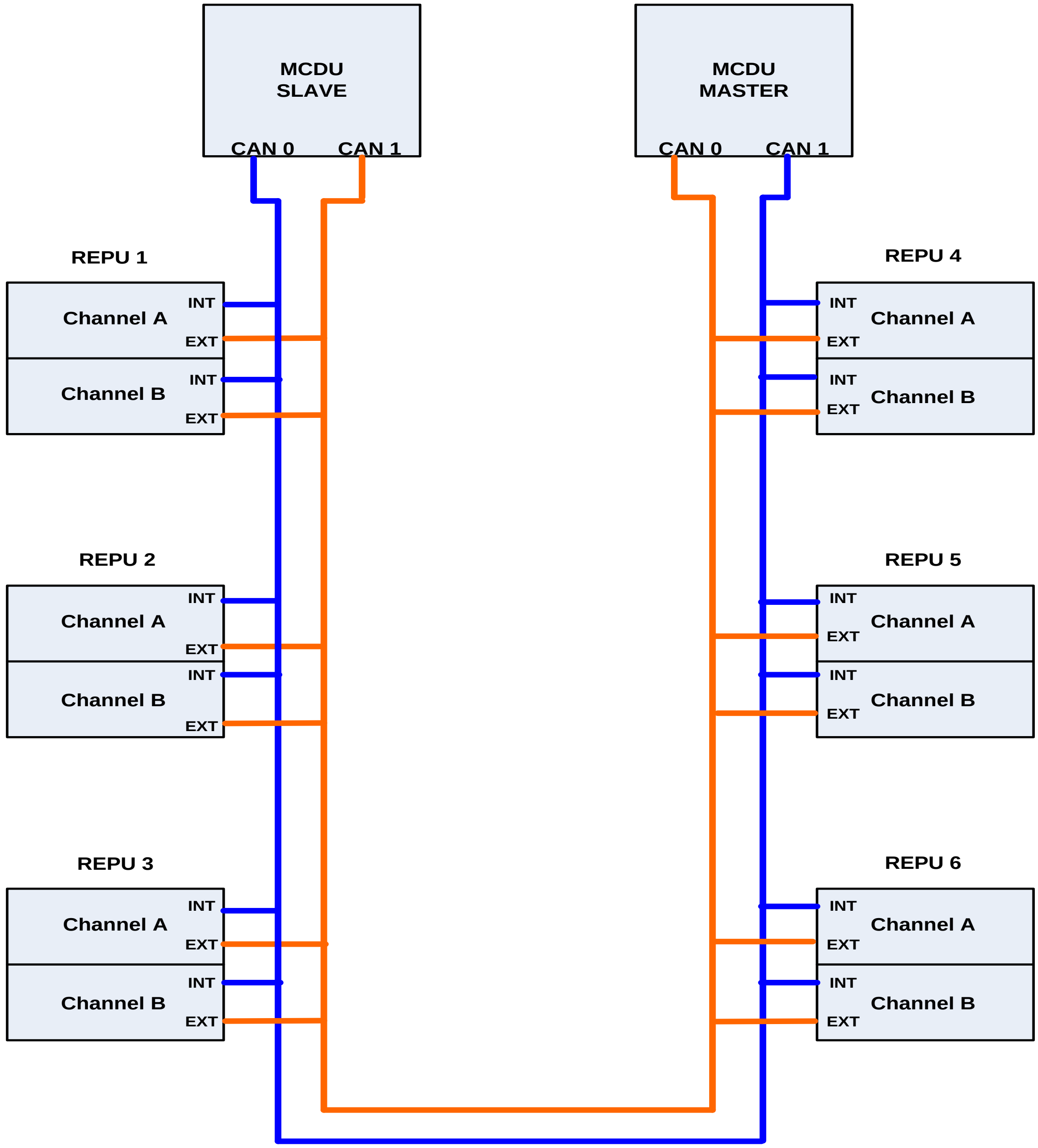

Figure 78. The SPDU CANBUS Wiring

Figure 79 shows the SSPC window, which displays the information for every SSPC, as well as discrete I/O statuses.

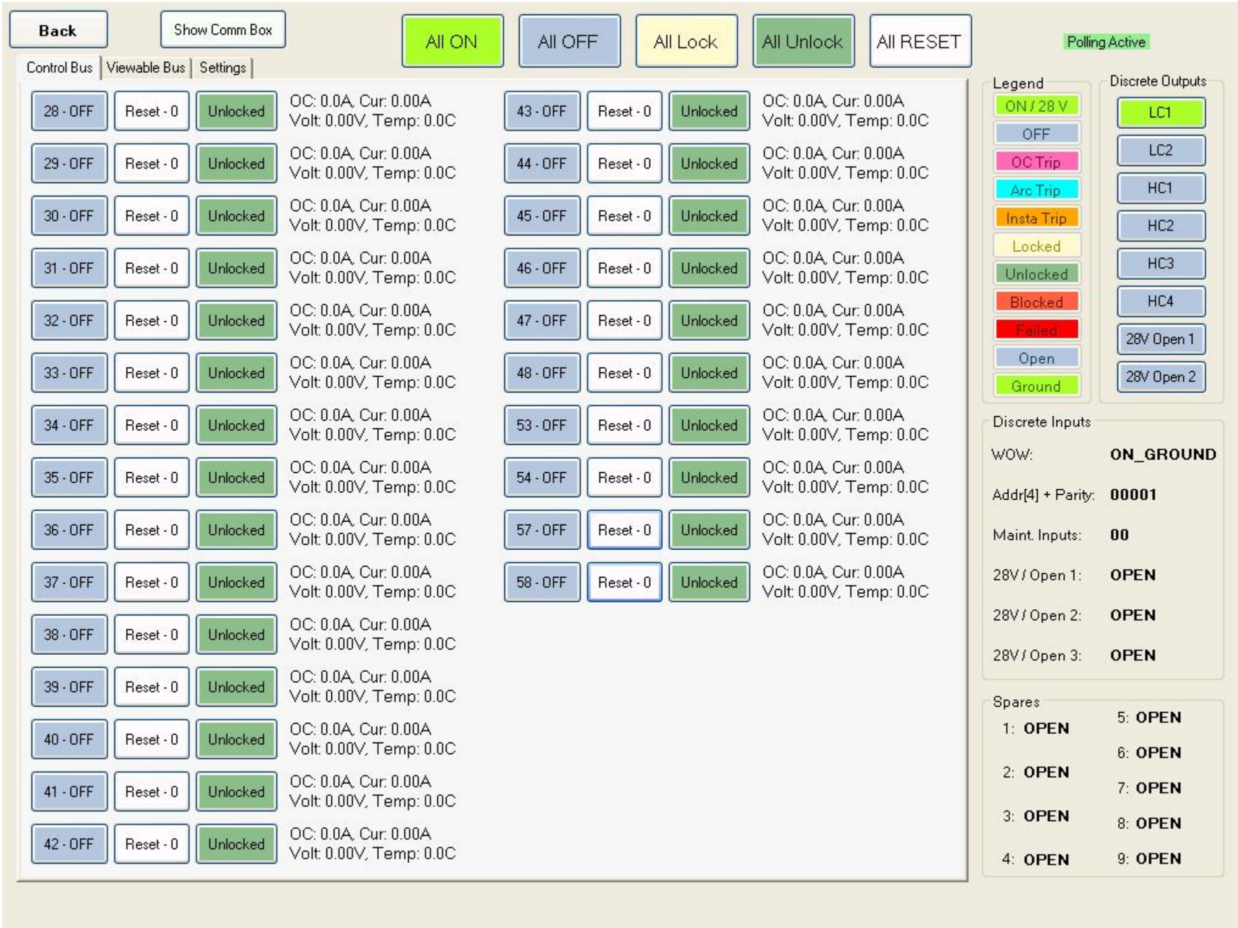

Figure 79. The MCDU SSPC Window

The MCDU displays the thermal rating, thermal factor, surge threshold, default power-up state, PWM duty, PWM frequency, temperature, BIT status, and operation status (see figure 80).

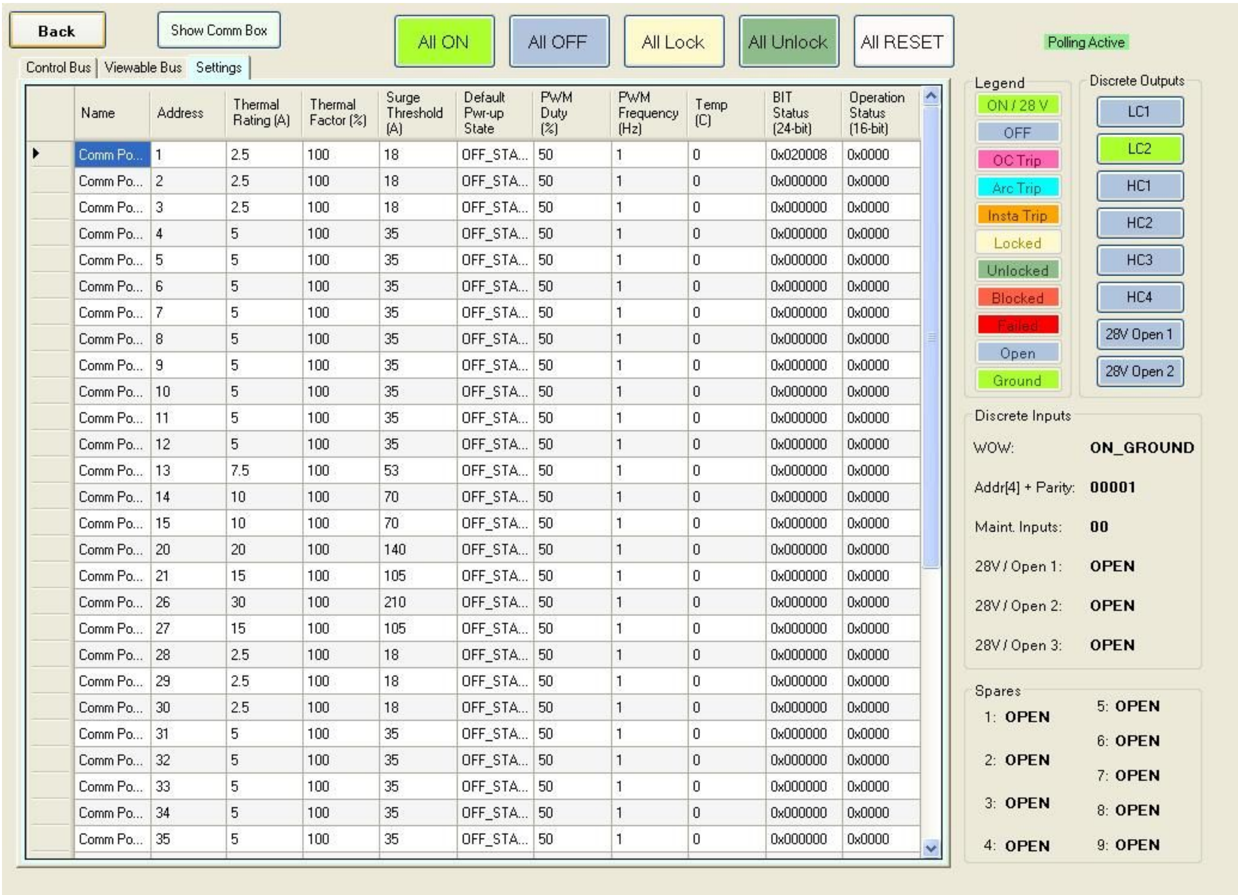

Figure 80. The SSPC Form (settings)

The MCDU allows SSPC control (On, Off, Reset, Lock, and Unlock) and displays output voltage and current as shown in figure 81.

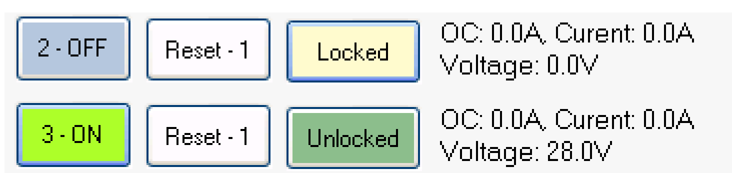

Figure 81. The SSPC Control

See appendix F for more details about the SPDU test lab.

2.11 PORTABLE TEST LAB.

The portable test lab, shown in figure 82, provides a smaller form factor test bed that can travel to an aircraft or set of loads for testing. Contrary to the full test lab, which contains three SPDU breakout boxes and load carts, the portable test lab contacts two foldable travel cases to allow for integration with a limited number of SSPCs and discrete I/O. Additional information about the portable test lab can be found in appendix G.

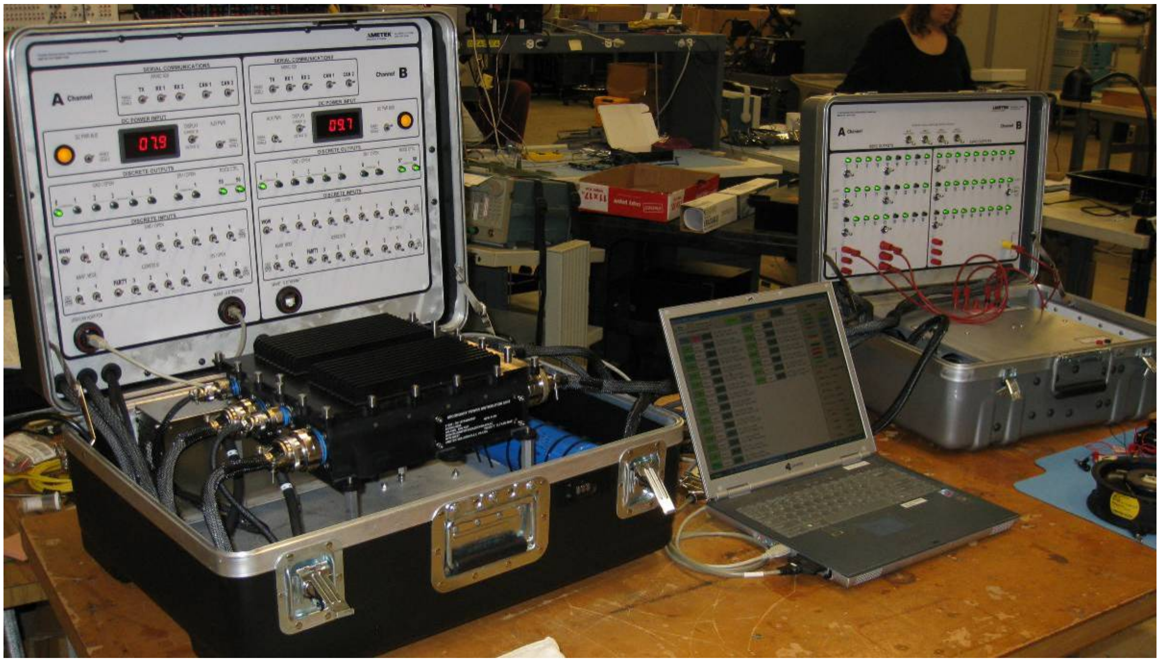

Figure 82. The SPDU Portable Test Lab

3. CONCLUSIONS.

Solid state provides several advantages from the traditional thermal circuit breaker system with regard to safety and performance. However, the advantages come at the cost of implementing proper control and status monitoring using a display computer, updating existing operating and maintenance manuals, training pilots on operation, and potentially rewiring the aircraft. For retrofit, these costs can be broken into smaller pieces by using only solid state for specific sub-system control or replacing one circuit breaker panel at a time during aircraft D-check maintenance. Cost and complexity can also be reduced by using discrete input/output (I/O) control instead of integrating with a display computer. However, the maximum benefits of solid state are realized when the system is controlled using a display computer and wired as a distributed system, rather than the traditional centralized system.

At this time, alternating current (AC) applications of solid-state technology require significantly more vehicle space and cost to replace a traditional system. The higher voltage requirements of AC power and the Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET) device limitations require multiple high-voltage MOSFETs to be paralleled to withstand damage from abnormal voltage surges and achieve the desired voltage drops and power dissipation to avoid the use of active cooling. The Silicon-Controlled Rectifiers (SCRs) are a lower cost alternative to MOSFETs and occupy less space. However, for currents up to approximately 10A, SCRs dissipate two to three times more power because of their fixed forward voltage drop. The SCRs cannot be used for arc-fault protection and cannot be paralleled to improve current capacity or reduce dissipation. In the near future, as MOSFET technology keeps improving with higher voltage ratings and lower on-resistances, solid-state AC power control can offer more justification for use on aircraft.

Many of the advantages of solid-state usage in aerospace were verified by tests of the secondary power distribution unit (SPDU) on various platforms and performing analyses for certification. Shunt-based current measurement and trip curves were tested in various environmental conditions per Radio Technical Commission for Aeronautics DO-160G, MIL-STD-810, MIL-STD-461, and MIL-STD-464. Power dissipation and thermal advantages were measured while the SPDU was exposed to extreme temperatures and maximum load current. Compatibility with various loads, including highly inductive and capacitive devices, was tested during integration with simulated aircraft laboratories and flying aircraft. Modulation of lamp loads typically designed for 26 VAC operation was also proven to be feasible with minimal retrofit requirements. Parallel arc-faults were simulated in the lab and on the aircraft to prove safe and fast removal of power from the wires. These tests, combined with mean time between failures, failure mode and effects analyses, failure mode effects and criticality analyses, and safety analyses, provide data indicating that solid-state is a safe alternative to a traditional thermal breaker system.

A paradigm shift is required to understand the benefits of using solid-state power control on aircraft. Confirmed by the tests on the Boeing 737, the SPDU can be used to replace other systems that typically require another line replaceable unit (LRU). The SPDU can be used to replace a lighting system with dimming control, a windshield heater control unit, and a power modulator for blowers or pumps to regulate air or fluid flow. The possibility for replacement of other systems should be factored into the decision to use solid-state power.

Flexibility, performance, safety and robustness, expandability, and serviceability were the main drivers for the design of the SPDU. Flexibility was an important factor in the SPDU design in terms of part-number logistics, anticipating customer needs, adjusting to regulatory changes, and tailoring the power system to various types and sizes of aircraft. The multiple-bus communications inputs of the SPDU, its rugged enclosure, its ability to be installed on composite and metal airframes, and customizable I/O allow the SPDU to be installed on all sizes and types of fixed-wing and rotary aircraft. The SPDU was intentionally designed to install as a standard SPDU configuration in multiple locations with the ability to tailor their protection and load control through a field-uploadable configuration file without the need for additional software certification. This flexibility reduces part number count on the aircraft and simplifies configuration management.

Determining the SPDU performance levels involved many tradeoffs and conflicting customer needs. Power dissipation, current capacity, and accuracy performance increases had adverse effects on the size, weight, and overall cost. Accuracy, resolution, and trip curve flexibility are SPDU features that offer two to four times improvement over thermal breaker technology. Air-framers were not interested in accuracy if it meant more electronics, higher weight, and less reliability. This improvement made the argument of replacing traditional thermal breakers easier because its performance was equivalent or better. This compromise in accuracy also allowed the use of fewer and less-expensive components, and the ability to concentrate on the size and weight of the SPDU.

The number of Solid-State Power Controller (SSPC) channels within the SPDU was based on the mid-sized jet and helicopter markets. Air-framers were driving to have no more than six LRUs in their aircraft. With the need to support multiple power buses and up to 250 loads, the goal became approximately 50 channels per SPDU. Originally, the goal was to support up to 200A per SPDU; however, because of the thermal performance of the enclosure and the design of heat removal from the SSPC modules, each SPDU can deliver between 250 and 300A to aircraft loads. This added performance helps extend the reliability of the SPDU while increasing the power-to-weight ratio.

In regard to safety, solid-state technology, when used with the appropriate level of redundancy, component selection, and internal protection mechanisms, can be equally as effective as the traditional thermal breaker system. The SPDU discussed in this report provided redundant communications, power supplies, current sensing, and redundant, dissimilar circuit protection. Appropriate mechanical and electrical separation was also implemented. These features were needed to meet the safety numbers for use in critical and hazardous systems. The SSPC's ability to handle parallel arc faults with microsecond timing and inrushes from incandescent and highly capacitive loads indicates a level of protection unachievable with thermal breakers. Additionally, as wires carrying different power and signals are routed in close proximity, protection of short circuits to other power sources becomes more important. The tests of shorting AC power to the output of a direct current solid-state device indicated that the SSPC is capable of interrupting the shorting condition with and without damage to the SSPC, depending on specific conditions. Ultimately, solid state is able to quickly isolate powerline short circuits and shorts to the airframe.

Serviceability can significantly increase the aircraft's maintenance costs. One advantage of a traditional system is the well-known indication that a tripped circuit breaker provides and, if the breaker or relay is damaged, the familiar methods and tools of replacing a failed component. The downside is that the thermal breaker is unable to tell the type of failure that may have occurred or indicate whether the breaker itself is damaged. For solid-state devices, the level of detail in the failure indication, the modularity and common components in the design of the solid-state distribution unit, and the simplicity of replacing the parts is significant with minimizing maintenance costs. With solid state, a level of knowledge is required by the maintenance person to understand how to obtain this information and perform the maintenance action. When implemented correctly, microcontroller-based solid-state protective devices can provide benefits that simplify the maintenance effort and reduce workload. Using SPDUs can provide an advantage in locating the component that has failed and reduce the amount of aircraft disassembly, troubleshooting, and reassembly effort.

While not every conceivable condition was applied to the SPDU and SSPC to assess its performance, testing will continue for the foreseeable future. One program goal was to produce a test lab that could be used experimentally to expose solid-state technology to new loads and aircraft scenarios. The test lab, consisting of a Multi Control Display Unit (MCDU) simulator, three SPDUs, three load carts, and three sets of I/O boxes, provides a means to test over 120 loads and support future Federal Aviation Administration programs. The test lab developed under this contract was instrumental in evaluating the performance of the SPDU under various environmental and electrical conditions.

Much consideration was given to make the SPDU design satisfy current needs, but attention was also given to anticipating future needs. The modularity of the SPDU allows for the creation of custom modules with unique aircraft functions not typically performed by the power distribution system. The key driver to this feature was the ability to remove additional aircraft weight and LRU count by taking advantage of the computing power and I/O capability of the SPDU used for controlling other aircraft system functions. Additionally, the availability of alternate communications buses provides a supplemental means of connecting to other systems and providing unique sensor interfacing and measurement.

Given the specific needs of the aircraft system for retrofit or new installation, the air-framer should be able to find a solution using solid state or a mixture of solid-state and traditional thermal circuit breakers. The future of solid-state power systems looks promising for the aerospace community. The semi-conductor industry will find ways to improve aspects of solid-state devices by eliminating weaknesses through technology advancements. Standards will be developed to better define solid-state circuit protection, key performance aspects, and operation. As the advantages of the traditional thermal circuit-breaker system are few, solid-state will continue to improve to replace the traditional power system and other aircraft system functions.

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Silicon controlled rectifier (SCR) (see figure A-1)

- Used for alternating current (AC) and direct current (DC) power control
- Used in motor drives and heater applications
- Used in overcurrent protection circuits
- Voltage ratings
  - Up to >1000V at forward voltage of 1V to 2V
- Current Ratings
  - Continuous currents of 10A-20A in 0.5"sq.
  - Surge ratings up to 500A
- Safe Operating Area (SOA)
  - Must be commutated off
- Issues: Power Sharing

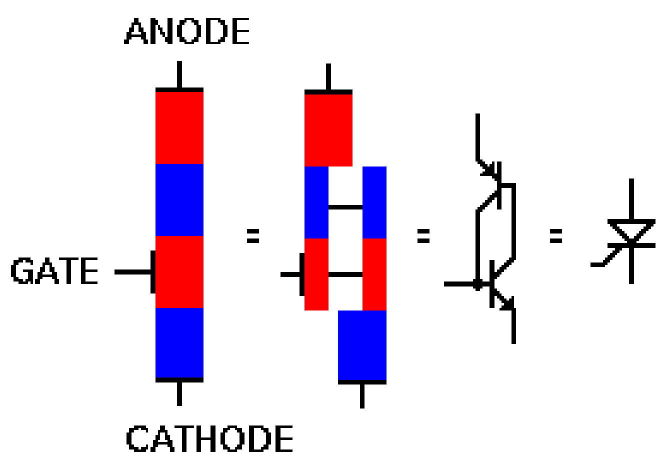


Figure A-1. The SCR Symbol

Some of the SCR advantages are smaller circuit foot prints, simpler zero-cross implementation, and lower cost due to both quantity and component cost.

Some SCR disadvantages include requiring a zero-cross to shut off (switch off power to load), sometimes having a higher operating junction temperature, and dissipation is based on forward voltage (0.7V-3.0V).

Trade for Alternating Current (TRIAC) (see figure A-2)

- Equivalent of back-to-back SCRs.
- Used in simple AC circuits, such as household lamp dimmers
- Voltage ratings
- Up to 1000V at forward voltage of 1V-2V
- Current ratings
  - Continuous currents of 10A to 20A in 0.5" sq.
  - Surge ratings up to 500A
- SOA
  - Must be commutated off
- Other issues
  - Noisy (harmonic noise)

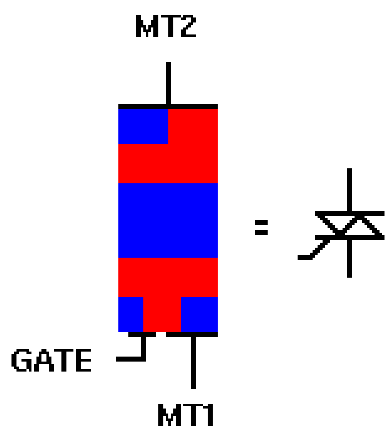


Figure A-2. The TRIAC Symbol

Insulated gate bipolar transistor (IGBT) (see figure A-3)

- Used in high-voltage applications
- Has the control features of a Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET) and the drive features of a bipolar junction transistor
- Voltage ratings
  - Lowest on-resistance using voltages above 300V and power above 2 KW

- Current ratings
  - Continuous currents of 15A to 30A in 0.5" sq.
- Speed
  - Not as fast as MOSFETs, but successful up to 50-100 KHz depending on voltage.
- Control voltage based
- Virtually no control current
- Still needs diode bias voltage to conduct
- Logic drive compatible
- Issues:
  - Often has no avalanche protection, which must be added externally
  - Can be difficult to share power
  - Can latch-up if not driven properly

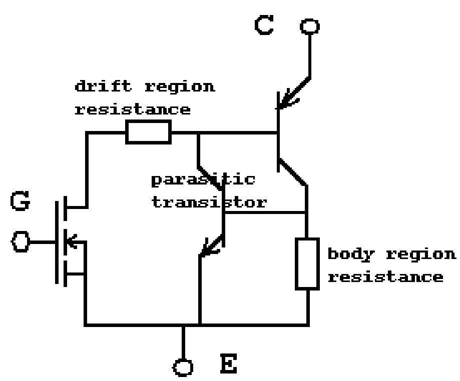


Figure A-3. The IGBT Symbol

Field effect transistor (FET) (see figure A-4)

- Used in AC and DC applications
- Voltage ratings
  - N-channel enhancement mode has best Rds ON
  - Lowest on resistance with voltages up to 250V
- Current ratings

- Continuous currents of 10A to 20A in 0.5" sq.
- Surge ratings up to 500A

- SOA

  - 5000 Joules before rupture

- Intrinsic avalanche diode
- Speed

  - Good for frequencies in excess of 100 Khz

- Control

  - Voltage based
  - Virtually no control current
  - Logic-drive compatible

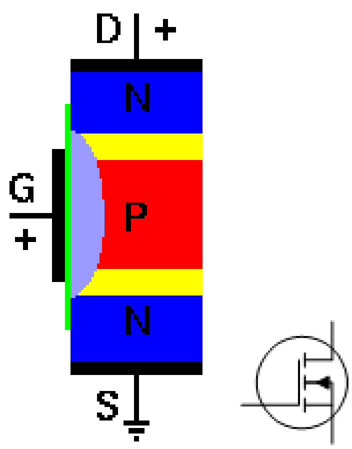


Figure A-4. The FET Symbol

APPENDIX B—BOEING 737 TESTING LOAD CONFIGURATIONS

Table B-1. The Secondary Power Distribution Unit (SPDU) Federal Aviation Administration (FAA) 737 Configuration Table

FAA Panel	FAA Circuit Number	FAA Circuit Description	REPU Harness	SSPC No.	SSPC P/N	Default Power-up State	Default Pwr Up Delay (sec)	Soft Start Enable	Safe State	Lock / Unlock	Reset #	Therm Rating (A)	Therm Factor (%)	Thermal TC (sec)	Surge Thresh (A)	Surge Rising TC (ms)	Surge Falling TC (ms)	PWM Enable	Discrete Control (1) of SSPCs	Discrete Action (1) of SSPCs	Discrete Control (2) of SSPCs	Discrete Action (2) of SSPCs	Ganged
P6-3	C117	28VDC Service	JA6-U	1	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C209	Door Warning	JA6-C	2	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C335	First Officers Panel	JA6-D	3	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	YES	NONE	NA	NONE	NA	NONE
P6-3	C311	No 1 DC	JA6-H	4	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C312	No 2 DC	JA6-E	5	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C582	Auto Brake Fail Warn	JA6-V	6	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C583	Brake Control	JA6-A	7	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C581	Press Comptr	JA6-W	8	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA6-B	9	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA6-K	10	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA6-J	11	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA6-G	12	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C325	28V Secondary OH Lights	JA7-Y, -N	13	10837	OFF	0	NO	L_Cmd	UNLOCK	2	7	100	2	49	0.199	0.598	YES	NONE	NA	NONE	NA	NONE
			JA7-M, -W, -X	14	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-3	C331	Capt & Center Panel Lights	JA7-K, -L	15	10837	OFF	0	NO	L_Cmd	UNLOCK	2	7	100	2	49	0.199	0.598	YES	NONE	NA	NONE	NA	NONE
				16	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
				17	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
				18	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA7-B, -G	19	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA7-A, -R, -Z	20	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA7-J, -P	21	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
				22	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
				23	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
				24	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
				25	Empty	OFF	0	NO	L_Cmd	UNLOCK	2	0	100	2	0	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA7-T, -U, -D	26	10838	OFF	0	NO	L_Cmd	UNLOCK	2	8	100	2	64	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JA7-S, -C	27	10838	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE

P6-2	C286	Yaw Damper	JB6-U	28	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C369	Roll Control	JB6-C	29	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C365	Pitch Control	JB6-D	30	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C277	Thrust reverser	JB6-H	31	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C276	Thrust reverser	JB6-E	32	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C211	Flap Position	JB6-V	33	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C457	Mach Trim	JB6-A	34	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C440	Auto Spd Brake	JB6-W	35	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C363	Flight Control ShutOff Valve	JB6-B	36	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C204	Spoiler ShutOff Valve	JB6-K	37	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C362	Standby Rudder	JB6-J	38	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C210	Flap	JB6-G	39	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C566	Flap Load relief	JB7-N, -Y	40	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C84	Service Interphone	JB7-M, -W, -X	41	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C129	Lever Latch and Press	JB7-K, -L	42	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C195	Anti-Skid Outboard	JB6-M	43	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C407	Engine 2 - Fire Protection	JB6-L	44	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C403	APU	JB6-F	45	10836	OFF	0	NO	L_Cmd	UNLOCK	2	5	100	2	35	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
P6-2	C405	Engine 1 - Fire Protection	JB7-B, -G	46	10836	OFF	0	NO	L_Cmd	UNLOCK	2	3	100	2	21	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB7-A, -R, -Z	47	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB7-J, -P	48	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB6-R	49	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB6-P	50	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB6-N	51	10836	OFF	0	NO	L_Cmd	UNLOCK	2	2	100	2	16	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB7-E, -F	52	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB7-D, -T, -U	53	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE
			JB7-C, -S	54	10837	OFF	0	NO	L_Cmd	UNLOCK	2	4	100	2	32	0.199	0.598	NO	NONE	NA	NONE	NA	NONE

REPU = Remote control circuit breaker
SSPC = Solid-state power controller

TYPE I
TYPE II
TYPE III
No Place
Not Avail

Table B-2. Boeing 737 P6-3 28 VDC Test Loads

Load 28V	TermStrip #	28 VDC	28 VAC	12 VRMS	Location	Source	Schematic Page	Notes	SSPC	TripSet	PIN
C84 Fuel Control Ctr Lft	1	2.5			P71						
C85 Fuel Control Ctr Rht	2	2.5			P67				6	2	JA6-V
C323 Overhead primary	3		7.5		P65		33-12-01	Primary feed for breaker C325			
C325 Secondary	4			7.5	P63		33-12-01	Fed from C323; C325 also feeds C330			
C164 Lav Mirror Ext Pwr	5				N73	External Power Bus		120VPeak? - 84VRms?			
C360 Eng 2 Shutoff Valve	6	5			N71			Weird damped sinusoid noise on this			
C359 Eng 1 Shutoff Valve	7	5			N67			Weird damped sinusoid noise on this	5		JA6-E
C571 Air Cond (M Caution)	8	2.5			N66	28V Battery Bus	33-18-21				
C573 Anti Ice	9	2.5			N65	28V Battery Bus					
C572 Fuel	10	2.5			N64	28V Battery Bus					
C132 No 1 Batt Bus	11	2.5			N63		33-18-20	Diode or'd with C132, PWM candidate			
C131 Battery (M Caution)	12	2.5			N62		33-18-20	Diode or'd with C131, PWM candidate			
C316 Section 4	13	2.5			N61		33-18-11	Powered by C310, 311, 312			
C317 Section 5	14	2.5			N60		33-18-11	Powered by C310, 311, 312			
C318 Section 6	15	2.5			N59		33-18-11	Powered by C310, 311, 312			
C570 Pitot Fst Officer Static	16	2.5			N57			This is where we are getting 28 VDC from the source side	8	2	JA6-W
C569 Pitot Captains Static	17	2.5			N56				9	2	JA6-B
C137 Door Lock	18	2.5			M73				10	2	JA6-K
C361 Manifold Valve	19	5			M69	28V Battery Bus	28-22-01	Candidate for actuation	4		JA6-H
C284 Electronic Panel	20		2.5		M65						
C219 Crkt Brkr Panel	21		2.5		M63		33-15-01	PWM	13	7.5	JA7-Y
C133 Dim & Test	22	5			M62	28V Battery Bus	33-18-11	Powers the relays to do the lamp on and dim test			
C313 Section 1	23	2.5			M61			Powered by C310, 311, 312			
C314 Section 2	24	2.5			M60			Powered by C310, 311, 312			
C315 Section 3	25	2.5			M59			Powered by C310, 311, 312			
C335 **CAP** 28V Prim PNL & Instru	26	2.5			L64				11	2	JA6-J
C331 Capt and Center 28V Pnl Instru	27		7.5		L62						
C310 Mstr DIM Bus Indicator [Battery]	28	5			L61	Battery Bus	33-18-11	Diode ored with C311, C312, Powers C313, C314, C315			
C311 " [No 1 DC]	29	5			L60	DC Bus 1	33-18-11	Diode ored with C310, C312	1	5	JA6-U
C312 " [No 2 DC]	30	5			L59	DC Bus 2	33-18-11	Diode ored with C310, C311			
C209 Door Warning DC	31	2.5			K72				12	2	JA6-G

Load 28V	TermStrip #	28 VDC	28 VAC	12 VRMS	Location	Source	Schematic Page	Notes	SSPC	TripSet	PIN
C355 Temp Indicator (Fuel System)	32		2.5		K71						
C397 Quantity (Fuel System)	33				K70	AC Standby Bus	28-41-01	Good single phase load			
C382 IND (Fuel Flow) (Fuel System)	34				K68				1AC	7.5	
C398 EP Ground Fueling (Fuel Sys)	35				K67	External Power Bus	28-41-01	Good single phase load			
Flashlight	36	1			K66						
C282 Dome White Cabin lighting	37	2.5			K65			Straight forward DC light	3	3	JA6-D
C283 Control Stand Light	38		2.5		K64			Switch and rheostat			
C159 Background Lighting No 1	39		2.5		K63				2	3	JA6-C
C160 Fluorescent lights	40				K62				2AC		
C161 Standby Flood & Compass	41	2.5			K61		33-11-51	PWM candidate	14	4	JA7-W
C308 Map & Kit	42		2.5		K60			Switch and rheostat - same as observers reading lamp (C309)			
C309 Observers Reading	43		2.5		K59		33-17-01	Switch and resistor (There are two lights on this circuit)	19	4	JA7-G
C284 Electronic Panel	X		2.5		?		33-11-41	Feeds a bunch of 5V stuff			
C845-A Center Tank Boost Pump Left	61-A				P69				7AC		
C845-B Center Tank Boost Pump Left	61-B				P69				8AC		
C845-C Center Tank Boost Pump Left	61-C				P69				9AC		
C846-A Center Tank Boost Pump Right	62-A				N69						
C846-B Center Tank Boost Pump Right	62-B				N69						
C846-C Center Tank Boost Pump Right	62-C				N69						
C828-A Tank 2 Boost Pump Aft	63-A				M71						
C828-B Tank 2 Boost Pump Aft	63-B				M71						
C828-C Tank 2 Boost Pump Aft	63-C				M71						
C826-A Tank 1 Boost Pump Aft	64-A				M67						
C826-B Tank 1 Boost Pump Aft	64-B				M67						
C826-C Tank 1 Boost Pump Aft	64-C				M67						
C829-A Tank 2 Boost Pump Forward	65-A				L71						
C829-B Tank 2 Boost Pump Forward	65-B				L71						
C829-C Tank 2 Boost Pump Forward	65-C				L71						
C827-A Tank 1 Boost Pump Forward	66-A				L67				10AC		

Load 28V	TermStrip #	28 VDC	28 VAC	12 VRMS	Location	Source	Schematic Page	Notes	SSPC	TripSet	PI N
C827-B Tank 1 Boost Pump Forward	66-B				L67				11AC		
C827-C Tank 1 Boost Pump Forward	66-C				L67				12AC		

APPENDIX C—THE SECONDARY POWER DISTRIBUTION UNIT CONFIGURATION TABLE SETTINGS

C.1 DEFAULT POWER-UP STATE.

The primary reason for a default power-up state is to provide the power system designer with the flexibility to have certain loads power ON when power is applied to the secondary power distribution unit (SPDU) without the need for any digital or discrete command. This feature can be convenient for purposes of powering certain cabin lighting loads or instruments when power is first applied to the aircraft.

The default power-up state is the state that the SPDU main central processing unit commands the solid-state power controller (SSPC) upon power-up start. This feature was implemented in the previous generation of the SPDU and was ported directly to the current generation SPDU without change. Each of the 54 SSPCs can be configured as ON, OFF, or Last Commanded.

C.2 DEFAULT POWER-UP DELAY.

The default power-up delay was created for current generation SPDU and can be useful for the aircraft power system because each SSPC output can be given a different delay from startup. This means that if a group of SSPCs was defaulted to ON for the power-up state, the delay could be used to turn ON the SSPCs sequentially, rather than all at the same time. This could be used to alleviate stress on the power generator during startup, especially if loads have a higher inrush current. It can also help with coordinating the power-up of loads so that systems come up in a known and controlled manner. The range of 0 to 60 seconds was chosen so that all 54 SSPCs can be spaced 1 second apart with some margin.

C.3 SOFT START.

The soft start feature was triggered by the need to handle loads with high initial inrush currents. Enabling of this function would command the SSPCs to initiate a short sequence of modulating the power during turn-on to minimize and manage in-rush current, to ramp up lighting loads, and to provide the potential to extend the life of sensitive loads.

C.4 SAFE STATE.

Safe state is a feature that allows the power system designer to assign the state of an SSPC output or SPDU function when a critical failure exists in either the interface between the SPDU and display or within the SPDU itself. For the SPDU, the applicability of safe state is complicated by whether the aircraft is in air or on ground. Depending on the situation, it may be necessary to have outputs in different states. The SPDU provides three possible states of the SSPC outputs, ON, OFF, and Last Commanded. Last Commanded state is based on the state of the SSPC before a fault is detected.

C.5 LOCK/UNLOCK.

The lock feature provides a means to lock an SSPC output from the ability to turn ON or OFF using Aeronautical Radio, Incorporated (ARINC), Controller Area Network (CAN), or any of the discrete inputs specified by the configuration table. The software lock is synonymous to the collar placed on a circuit breaker to prevent the breaker from being turned to the ON position when the output should not be used or the load is being serviced by a technician. This specifies if the SSPC output is locked or unlocked upon the SPDU power-up start. This feature was a part of the previous generation SPDU.

The configuration table implementation of the lock feature allows the SSPC to always be locked. Also, the locked status is maintained through power cycle, even if set by the ARINC or CAN command. For this feature, the valid settings are LOCK or UNLOCK.

C.6 NUMBER OF RESETS.

The configuration table also allows the number of resets to be set before entering the blocked state. Depending on the criticality of the load or safety concerns, the number of allowed resets may differ. The aircraft installer would have the flexibility to change each load to the desired number. When you create a new configuration table, the value is defaulted to two resets as it was in the previous generation SPDU.

C.7 THERMAL RATING AND THERMAL FACTOR.

The load at which an SPDU SSPC will trip because of an overcurrent event is based on an algorithm that attempts to closely match that of a thermal circuit breaker. The formula used by the SSPC to set the point at which the SSPC will trip on an overcurrent fault is as follows:

$$\text{SSPC Overcurrent Trip Point (amps)} = \text{Thermal Rating (amps)} * \text{Thermal Factor (\%)} \qquad \text{(C-1)}$$

The thermal rating variable is intended to equate to what the equipment installer would see on the head of the pushbutton switch of the thermal circuit breaker. The thermal factor is a scaling factor that compensates for the fact that thermal breakers do not trip at the current level indicated on their pushbutton switch. Because different thermal breakers have trip points that vary as much as 115% to 140% of the value printed on its pushbutton, the thermal factor is used to add a multiplier that allows the SSPC to act similarly.

For example, a thermal breaker with 10A designation on its push button will likely overcurrent trip when current is somewhere between 115% and 140% of its designation. Exactly where it will trip depends on the make and manufacturer, preloading, and environmental conditions. This means that the 10A breaker will not trip until it reaches currents ranging between 11.5 to 14.0A. When defining the trip threshold for an SSPC in the SPDU, the thermal rating value would be set at 10A and the thermal factor would be set between 115% and 140%, based on the installer's preference. Setting the SSPC's thermal factor to 125% would then result in an SSPC trip point of 12.5A (10A * 125%).

The purpose of implementing the thermal factor in the configuration table was to provide the air-framers and installers with a comfortable transition from thermal breakers to SSPCs. By having a thermal factor, circuit breaker ratings can be entered into the configuration table using the same thought process that was used when implementing thermal breakers. Installers would be able to continue to use the same rating system printed on the thermal breakers when determining trip setting and holding current levels for SSPCs. However, careful attention should be given to sizing because the trip ratings between solid-state and thermal breakers are widely different when comparing trip response times. The thermal circuit breaker rating of less sensitive could have allowed overcurrent conditions without tripping, whereas the SSPC with the same rating may be prone to nuisance tripping if trip ratings remain the same.

C.8 THERMAL (TIME) CONSTANT.

This is the RC component of the overcurrent trip detection curve calculation. Varying this value sets the time sensitivity of the thermal portion of the SSPC trip curve. The thermal (time) constant is needed for the trip curve algorithm.

C.9 SURGE THRESHOLD.

The surge portion of the trip curve was engineered to protect against arc faults and damaging surges in wires. This is one of the key benefits of using fast MOSFET switching technology for current protection instead of thermal breakers. A thermal breaker is not able to respond to this type of fault fast enough to limit damaging current from creating catastrophic events.

To support most motor loads, incandescent loads and electronics with significant input capacitance, the surge threshold is typically set between eight to ten times the thermal current rating. This setting provides rapid protection from parallel arc faults, but is robust enough to avoid nuisance trips that could occur during power-on of loads causing an inrush current event.

C.10 SURGE RISING CONSTANT AND SURGE FALLING CONSTANT.

The rising and falling constants used during surge are critical in helping to determine if the rapid change in current is due to a surge or attributed to an arc fault. These values were intentionally made variable in the SPDU design to allow the SPDU to adapt to future interpretations for the definition of an arc and how to respond to an arc fault.

C.11 THE PWM ENABLE.

In traditional aircraft architecture, dedicated boxes would be required to offer power modulation of loads because mechanical relays and thermal breakers do not have the speed, switch life, or ability to perform the function. Using the SPDU in place of these traditional components provides the air-framer the ability to control the speed of rotating devices, regulate heat produced by heating elements, and provide dimming or flashing functions to lamp loads.

The adjustability of the pulse-width modulation (PWM) frequency of the SSPCs is from 1 to 200 Hz. The PWM duty cycle range is fully on, fully off, or in a range from 4% to 96%. The maximum frequency of the SSPC outputs of the SPDU was based on fast switching to avoid detection by the human eye. This makes the SPDU useful in light-dimming applications. For motor control and heat control, higher frequency switching was unnecessary. With these facts in mind, no useful reason to modulate beyond 200 Hz was seen.

The PWM enable field was added to the configuration table to give a layer of protection to prevent loads from being mistakenly modulated in flight. This setting locks out any acknowledgement of the Aeronautical Radio, Incorporated (ARINC) or Controller Area Network (CAN) command to activate PWM. When PWM is enabled for a given SSPC, the ARINC or CAN command need only set the PWM frequency above 0 Hz to activate PWM for that load.

C.12 DISCRETE CONTROL OF SSPCS.

Discrete control of SSPC was introduced as a result of feedback from multiple customers who wished to use discretes to control multiple SSPCs simultaneously based on specific events. Some examples include activating a pump if a fuel imbalance is detected, shedding loads in case of a detected failure, or activating fire-suppression devices on command. Additionally, the use of a discrete as a backup means the ARINC is valuable for control of critical loads.

The feature was designed so multiple SSPCs can be assigned to a single discrete input. This allows discrete input to toggle and turn OFF all SSPCs. This could be useful for the aircraft system as another way to control SSPC loads when digital communications with the SPDU fail.

C.13 GANGED.

Conceptually, SSPC outputs can be grouped to control a single load. This grouping provides a capability of increasing the current carrying capacity to a specific load and would require special control to ensure that SSPCs are controlled in a timely manner to avoid tripping and back feeding damage to other SSPCs (i.e., one SSPC is ON and the other SSPC is OFF, but their outputs are connected).

APPENDIX D—SERIES ARC TESTING

D.1 SERIES ARCING TEST RESULTS.

D.1.1 OBSERVATIONS.

The addition and removal of the metal washer inserted between the ring terminal and the mounting-stud head made a significant difference for series arc events. With the metal washer installed, the series arc events were better distributed (hundreds of milliseconds to seconds). The distributed series arc events still contributed to extreme heating of the ring terminal and wire to the point that the ring terminal connection desoldered. With the metal washer removed and the ring terminal loosened, the series arc events were tightly grouped and more closely matched the SAE International (SAE) definition of the series arc period and series arc confirmed arc period. The distributed series arc events do not meet the SAE criteria (analysis of test data), and cause damage to the terminal connection over time. This should be considered an update to the SAE specification for series arc.

The SAE specification states that a series arc event occurs when the voltage drops below 20 VDC and above 8 VDC for a time greater than 100 µs. Observations during tests confirmed this statement when the nominal voltage was 28 VDC (table D-1). The initial windshield heater control unit (WHCU) settings defined the series arc as a voltage below 50%, or 14 VDC (half of nominal). During the tests, series arc events rarely reached below the 50% voltage threshold. The falling edge threshold was adjusted to 75% of nominal to allow for better detection of the majority of series arc events. For the SAE specification, a nominal 28 VDC signal dropping to 20 VDC is approximately 70% of nominal. Tests revealed that the voltage drop during a series arc event is consistent. Therefore, it is not accurate for the SAE specification to depict the final result (20 to 8 VDC), (shown in figures D-1 through D-6) but rather to quantify the voltage drop that constitutes a series arc event. Based on empirical tests, the series arc event should be defined as a minimum drop of 8 VDC from nominal or as dropping below a percentage of the nominal voltage.

Table D-1. Series Arc Test Results

Test #	Pulse Min (ms) ($T_{pw\,(min)}$)	Pulse Max (ms) ($T_{pw\,(max)}$)	Falling Current Threshold (TH_{fall})	Rising Current Threshold (TH_{rise})	Pulse Count (AP_{event})	Pulse TO (sec) (TO_{event})	Arc Period Count ($CAP_{arc\,period}$)	Arc Period TO (sec) ($TO_{arc\,period}$)	Load (A)	Time to Trip (sec)	Observations
1	0.5	100	75%	75%	10	0.10	10	10	40	3.5	Sparks. Ring terminal hot. Wires are cool
2	0.5	100	75%	75%	10	0.10	10	10	40	5.6	Sparks. Ring terminal hot. Wires are cool
3	0.5	100	75%	75%	10	0.10	10	5	40	4	Sparks. Smoke, ring terminal hot. Wires are cool.
4	0.5	10	75%	75%	10	0.10	10	5	40	20	Heater resistance fails. Enough sparks.
5	0.5	10	75%	75%	10	0.10	10	5	40	12	Sparks. Wire is warm.
6	0.5	100	75%	75%	20	0.10	10	5	40	10	Sparks. Wire is warm.
7	0.5	100	75%	75%	20	0.10	10	5	40	105	No Trip - sparks
8	0.5	100	75%	75%	20	0.10	10	5	40	90	No Trip - sparks
9	0.5	100	75%	75%	10	0.25	10	5	40	7	Sparks
10	0.5	100	75%	75%	10	0.25	10	5	40	70	No Trip - sparks
11	0.5	100	75%	75%	10	0.25	10	5	40	70	No Trip - sparks
12	0.5	100	75%	75%	10	0.50	10	5	40	46	Tripped at end with a lot of pulses
13	0.5	100	75%	75%	10	1	10	5	40	3	Lots of pulses right at start
14	0.5	100	75%	75%	10	1	10	5	40	47	
15	0.5	100	75%	75%	10	1	5	5	40	18	
16	0.5	100	75%	75%	10	1	2	5	40	42	
17	0.5	100	75%	75%	10	1	2	5	40	65	No Trip - sparks
18	0.5	100	75%	75%	10	2	2	5	40	29	
19	0.15	100	75%	75%	20	2	1	10	40	2	
20	0.15	100	75%	75%	20	2	1	10	40	2	
21	0.15	100	75%	75%	10	3	2	20	40	1	
22	0.15	100	75%	75%	10	3	2	20	40	<1	
23	0.15	100	75%	75%	10	0.02	2	2	40	4	
24	0.15	100	75%	75%	10	0.02	2	2	40	1	

Pink	Failed
Green	Passed
No Color	Did not trip on series algorithm

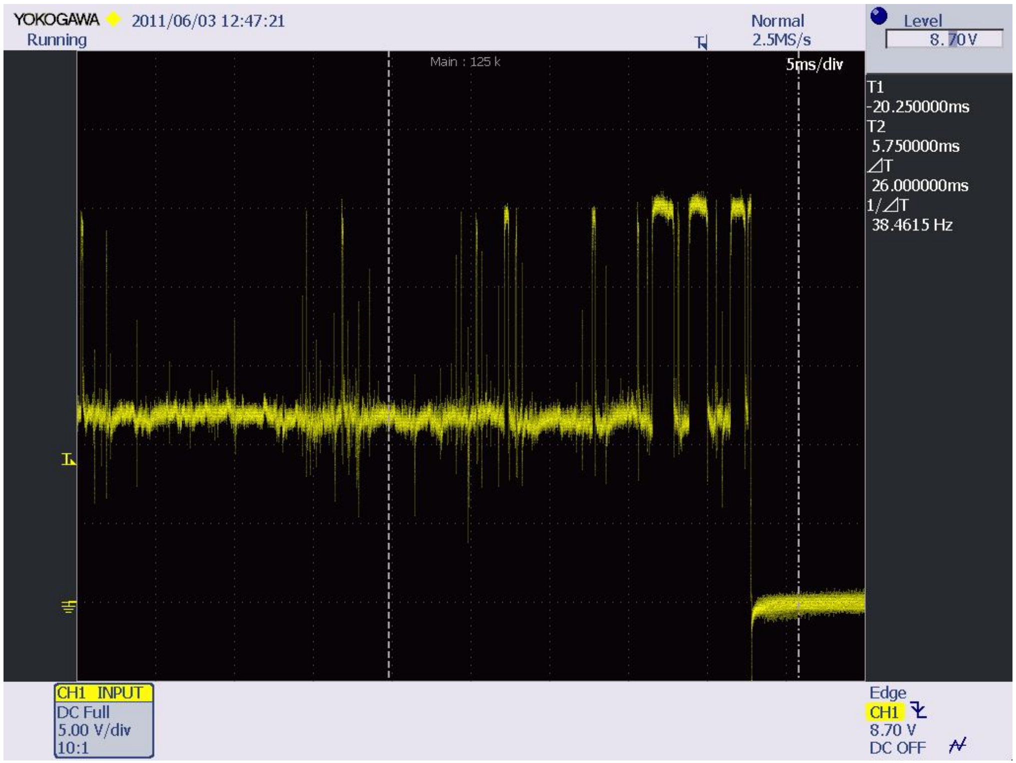


Figure D-1. Series Arc Test 22

Figure D-2. Series Arc Test 23

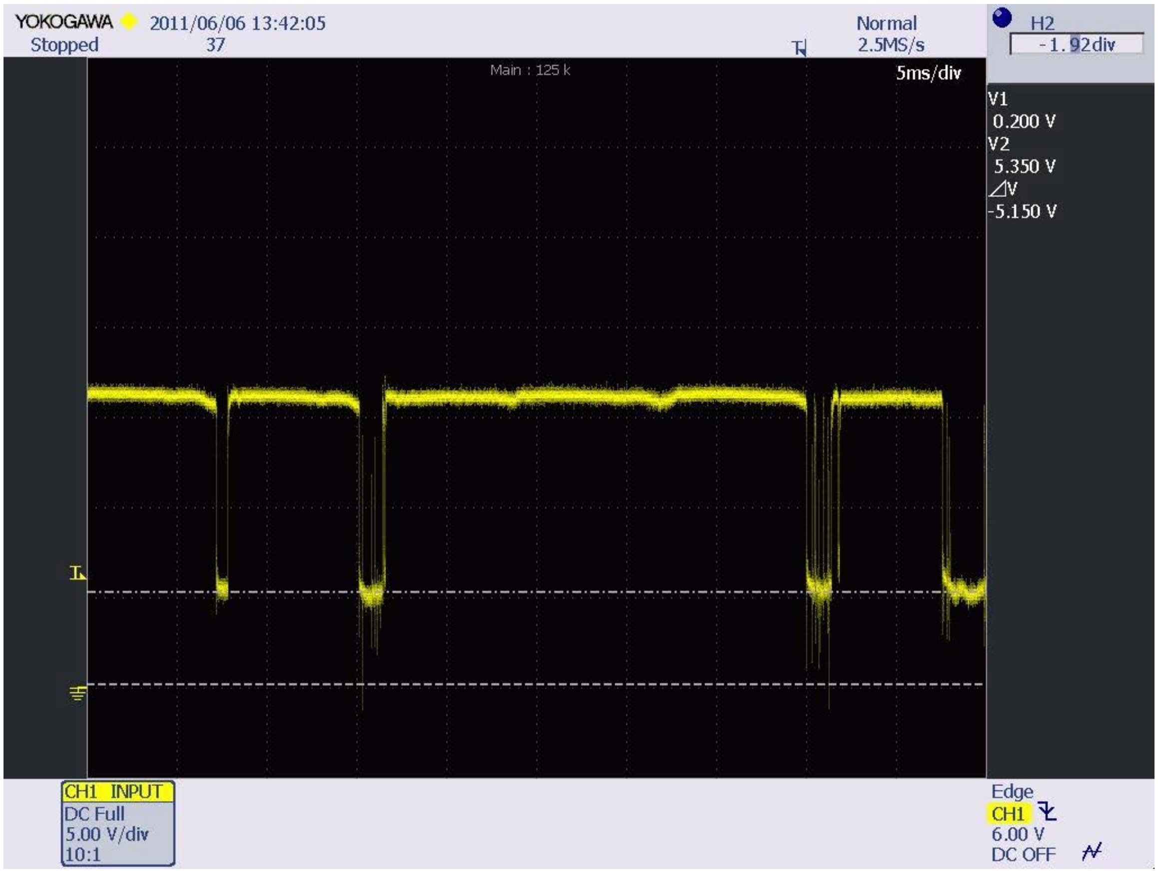


Figure D-3. Power Supply, 18 VDC

Figure D-4. Power Supply, 18 VDC

Figure D-5. Power Supply, 32 VDC

Figure D-6. Power Supply, 32 VDC

The SAE specification defines the arc period as 10 msec of cumulative arcing or 10 individual arc events in a 100 msec sliding window. The timings listed in the SAE document for arcing period and confirmed arcing period have a tight acceptance range for the timing of series arc events and series arc periods. Tests revealed that the time between series arc events could be in the hundreds of ms range (some greater than 1 second) (see figures D-7 through D-9). This can continue to heat and potentially damage the terminal connection and wire over an extended period of time, even more so with the increased load current (40A). Based on test results, it is recommended that the sliding window for an arc period should be extended from 100 msec to a 1 to 2-second range. It is also recommended that the sliding window for a confirmed arc period be extended from 2 seconds to a 10 to 20-second range.

Figure D-7. Distributed Series Arc Events

Figure D-8. Distributed Series Arc Events

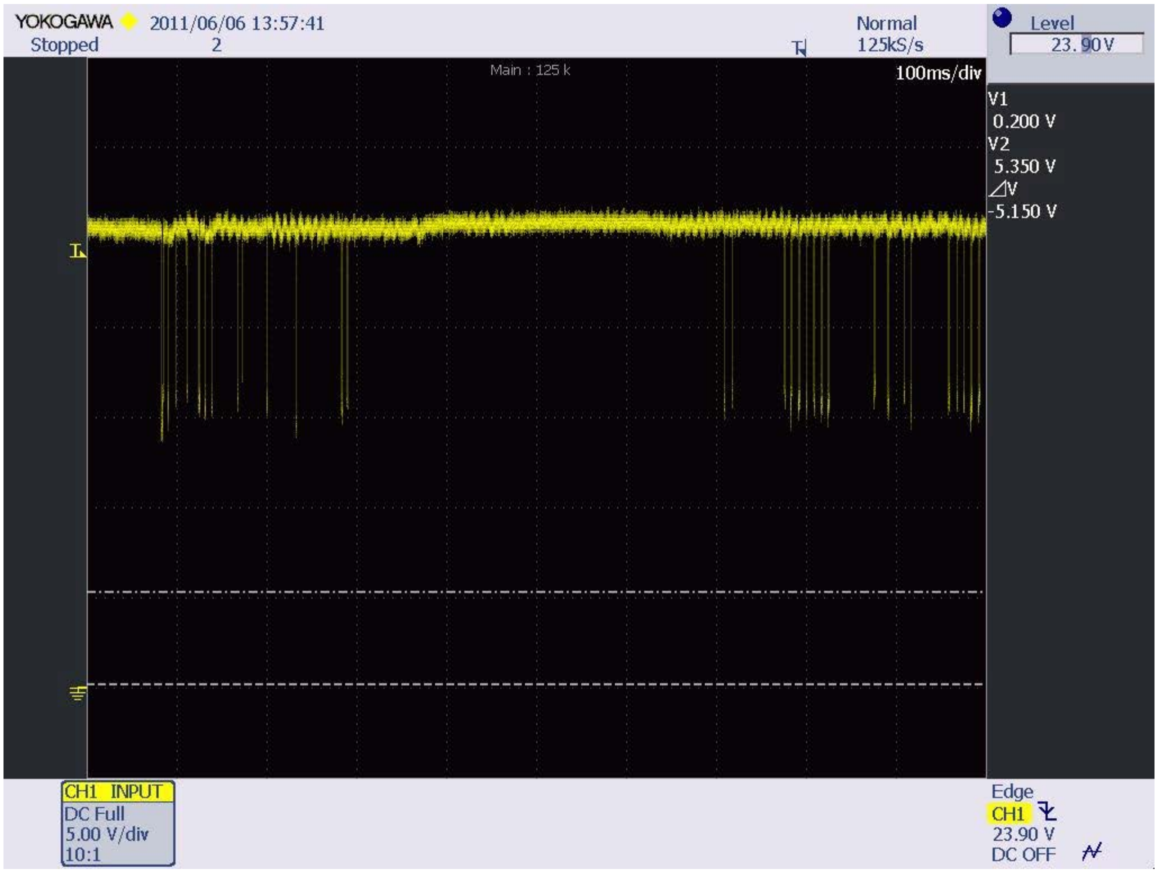


Figure D-9. Grouped Series Arc Events

A test was conducted to desensitize the series arc detection. This was accomplished by adjusting the arc trip settings to difficult criteria (i.e., 20 series arc events in a short window). For this test, the unit was allowed to arc for 60 seconds. During the test the ring terminal was hot enough to de-solder itself from the wire. There was also a small amount of smoke generated from the arcing events. Because of these results, it is recommended that the criteria for series arc events, series arc periods, and series confirmed arc periods be changed to reduce the time to trip.

Recommended settings are highlighted in green in table D-1. With these settings, the WHCU was able to trip within 1 to 2 seconds of arcing start. The criteria still meets the general SAE specification definition of ten series arc events and two series arc periods (i.e., confirmed arc period). The changes were made to the times associated with the sliding windows to encapsulate varying series arcing conditions.

APPENDIX E—SECONDARY POWER DISTRIBUTION UNIT REQUIRED TESTING

E.1 THE SPDU REQUIRED QUALIFICATION TESTING.

This Appendix summarizes the procedures of environmental testing used to evaluate the product readiness of an aircraft Secondary Power Distribution Unit (SPDU). The intent of environmental Testing, as stated in RTCA DO-160E, is a set of standard environmental test conditions and test procedures that can provide a high level of confidence in performance during operation under environmental conditions representative of those which may be encountered in airborne operation.

The SPDU shall meet the environmental requirements in accordance with DO-160E as defined in table E-1.

Table E-1. The DO-160G Requirements

DO-160G Section	DO-160G Category	Test Description
4	B2 (1)	Temperature and Altitude (+25,000 ft, +50,000 ft)
5	B	Temperature Variation
6	C	Humidity
7	B	Operational Shock and Crash Safety
8	U2, curves F and F1	Vibration
9	H	Explosion Proofness
10	W	Water Proofness
11	F (2)	Fluids Susceptibility
12	S	Sand and Dust
13	F	Fungus Resistance
14	S	Salt Spray
15	Z	Magnetic Effect
16	Z (5)	Power Input
17	A	Voltage Spike
18	Z	Power Input—Audio Frequency Conducted Susceptibility
19	ZCE	Induced Signal Susceptibility
20	Y (3)	Radio Frequency Susceptibility
21	M	Emission of Radio Frequency Energy
22	A4 + WF 5A Level 4 (4)	Lightning Induced Transient Susceptibility—Pin Injection
22	H4J4K4L4 + M4 (for shielded cable)	Lightning Induced Transient Susceptibility—Single Stroke/Multi Stroke/Multi Burst
23	Not Required	Lightning Direct Effects
24	A	Icing
25	A	Electrostatic Discharge
26	C	Fire, Flammability

1. Temperature limits/Operating temperature: -40°C to +70°C; storage or stop engine +85°C

2. Fluids required for testing:

   - Hydraulic fluid i.a.w. MIL-H-5606 and MIL-H-83282C

   - Cleaning fluid D.T.D.5507

- Oils i.a.w. MIL-L-7808G (grade 3) and MIL-L-23699B

- Fuels i.a.w. MIL-G5572 (grade 100/130), MIL-T-5624 (grade JP5) and MIL-T-83133 (grade JP8)

- Deicing fluids AL5, AL34, AL36

3. Test level requirements for High-Intensity Radio Frequency (HIRF) as shown in table E-2.

Table E-2. Test Level Requirements for HIRF

Frequency Range	Average Field Strength (V/m)
400 – 700 MHz	200
700 MHz – 1 GHz	240
1 – 2 GHz	360
2 – 4 GHz	490
4 – 6 GHz	400
6 – 8 GHz	330
8 – 12 GHz	330
12 – 18 GHz	300
18 – 40 GHz	420
400 – 700 MHz	730
700 MHz – 1 GHz	1700
1 – 2 GHz	5000
2 – 4 GHz	6000
4 – 6 GHz	7200
6 – 8 GHz	2000
8 – 12 GHz	5000
12 – 18 GHz	3500
18 – 40 GHz	1000

4. For Aeronautical Radio, Incorporated 429 and Controller Area Network buses, the requirement is A3 + WF 5A level 3 and H4J4K4L4 + M.

5. Power Interruption requirements for equipment with digital circuits from DO-160G are shown in table E-3.

Table E-3. The DO-160G Power Interruption Requirements for Equipment With Digital Circuits

Test Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Requirement	R	R	R	R	S	S	S	S	R	R	R	S	S	S	S	R	R	R	R

R: The secondary power distribution unit (SPDU) shall ride through the power interruption.

S: The SPDU may reboot. If the SPDU reboots, its behavior shall maintain functional performance given in the SPDU functional requirements document after power interruption and shall have the same state as before the event. The SPDU shall go into a well-defined state and be fully controllable. Manual reset is not permitted.

The SPDU will ride through a power interruption of 75 msec. Manual reset is not permitted.

Double Interruption Requirement for direct current (DC) equipment with digital or memory devices, shown in table E-4.

Table E-4. Double Interruption Requirement for DC Equipment With Digital or Memory Devices

Test Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Requirement for T2 = 10ms	S	S	R	R	S	R	R	S	S	R	S	S	S	S	S	S	S
Requirement for T2 = 50 ms	S	S	R	R	S	R	R	S	S	R	R	S	S	S	S	S	S

R: The SPDU shall ride through the power interruption.

S: The SPDU may reboot. If the SPDU reboots, its behavior shall maintain functional performance given in the SPDU functional requirements document after power interruption and shall have the same state as before the event. The SPDU shall go into a well-defined state and be fully controllable. Manual reset is not permitted.

E.2 OTHER QUALIFICATION REQUIREMENTS.

In addition to DO160, several Mil specifications and SAE specification were used to test the robustness of the SPDU, see tables E-5 through E-7.

Table E-5. The MIL-STD-810 Requirements

Test	MIL-STD-810E Test Method
Temperature and Altitude	500.3, 501.3, 502.3
Humidity	507.3
Operational Shock and Crash Safety	516.4
Vibration	514.4
Gunfire Vibration	514.5 and 519.5
Acceleration	513.5
Explosive Atmosphere	511.3
Water Proofness (Driving Rain or Spray)	506.3
Sand and Dust	510.3
Fungus Resistance	508.4
Salt Spray	509.3

Table E-6. The MIL-STD-461 Requirements

Test	MIL-STD-461E Test Method
Audio Frequency Conducted Susceptibility – Power Input	CS 101
Radio Frequency Susceptibility	CS 101, CS 114, CS 115, CS 116.
Emission of Radio Frequency Energy (Conducted and Radiated)	CE 101, CE 102, RE 101, RE 102

E.3 THE MIL-STD-464 REQUIREMENTS.

An evaluation of the equipment performance in the external electromagnetic environment defined in MIL-STD-464A for Army Rotary Wing Aircraft is required as a "test and declare" activity. The applicable procedures and modulations are per Radio Technical Commission for Aeronautics/DO-160G, Section 20.

Table E-7. The MIL-STD-704 Requirements

Test	MIL-STD-704E Test Method
DC Voltage Power Input—Normal Operation Characteristics	LDC 102, LDC 105
DC Voltage Power Input—Normal, Emergency, and Abnormal Operation Characteristics	LDC 301, LDC 302, LDC 401
DC Power Interrupt and Power Failure	LDC 201, LDC 601
DC Voltage Power Input—Electric Starting	LDC 501

E.4 THE AS-5692 AND AS-6019 REQUIREMENTS.

The initial design of the SPDU allowed for expansion of the modules to allow for three alternating current (AC) outputs. The AC portion, which was listed as a future option in the customer specification, required the application of AS-5692, ARC Fault Circuit Breaker (AFCB), Aircraft, Trip-Free Single Phase 115 VAC, 400 Hz – constant frequency. In the current SPDU design, this document is not applicable because of absence of AC modules.

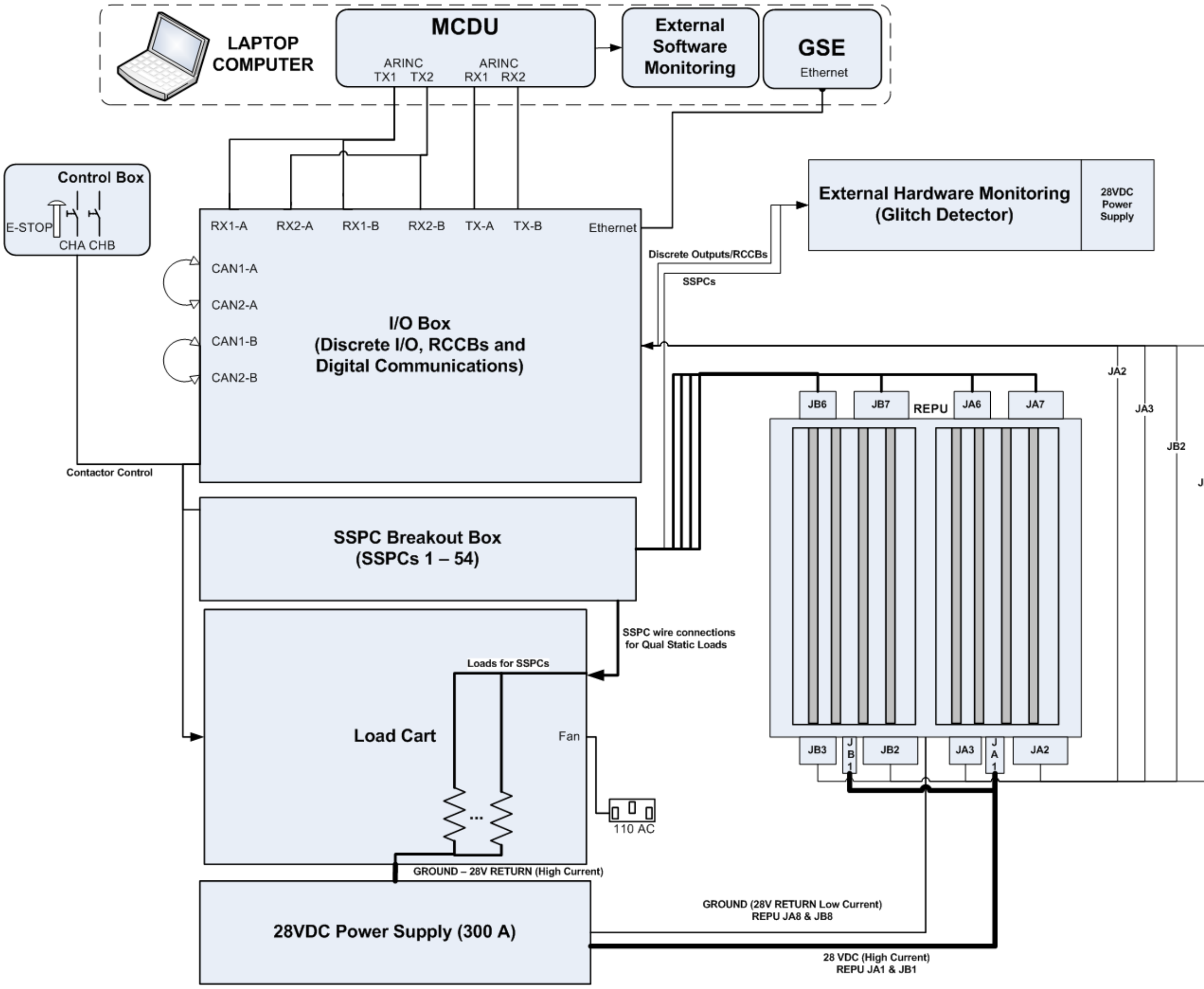
The AS-6019 is titled ARC Fault Circuit Breaker (AFCB), Aircraft, Trip-Free 28 VDC.

There are no references to the DC ARC fault specification because at the time of development only the AC version of this specification existed and the DC specification was still in development.

E.5 TESTING CONSIDERATIONS.

E.5.1 CABLE HARNESS AND SETUP CONSIDERATIONS.

For qualification testing purposes, the cable lengths had to be greater than 3 meters (figure E-1). The 3-meter length was required for some of the DO-160 tests, but was also useful for running the test equipment and power supplies in the ante room for radio frequency (RF) emission testing and RF susceptibility testing.



MCDU = Multi Control Display Unit; GSE = grouped support equipment; I/O = input/output; RCCB = remote control circuit breaker

Figure E-1. The SPDU Qualification Test Setup

E.5.2 DETERMINATION OF STATIC CONDITIONS.

The static load configuration was chosen for qualification tests to maximize the total current loading while maintaining the functional performance of the SPDU and keeping the temperatures in the SPDU within the component's valid temperature range. Within the SPDU are up to 56 temperature sensors, depending upon solid state power controller (SSPC) configuration. These temperature sensors were used to track temperature rise during high temperature testing (+70°C), with the loading per the following tables. The SPDU was loaded to 288A, with 144A per channel. The distribution of current was chosen to maximize current on each type of SSPC module, 7.5, 15, and 32A.

Channel A contains a static loading configuration where the current resides on high-current SSPC outputs, which are intentionally located near the output side of the SPDU. This provides a shorter distance for the high-current outputs to travel within the SPDU, leading to lower series impedance and, therefore, lower internal power dissipation. This configuration represents a worse case for a configuration that only provides loads 15A and 30A SSPCs.

Channel B contains well-distributed static loading across the entire channel, using more of the 7.5-A SSPC outputs. This configuration represents a structure that equally shares the burden of internal power dissipation and heat across the entire channel.

The loading variation between the two channels provides a stable platform for all possible SSPC configurations with a maximum current of 288A and 144A per channel. The qualification goal was to maximize the allowable current within the SPDU's formal specification. Using this configuration in qualification tests in conjunction with thermal data provides the necessary confidence to use any loading up to the maximum limits.

The customer requested that the SSPC outputs be loaded to 90% of the overcurrent trip threshold. This provides confidence that the SPDU can maintain functional performance and not trip given this 10% margin.

The customer also requested that some loads be turned ON and some OFF with a variation to the loading, including no load. This requirement created the following SSPC configurations:

- SSPCs that are ON with load
- SSPCs that are ON without load
- SSPCs that are OFF with load
- SSPCs that are OFF without load

The PWM is not used by the launch customer but, to meet functional performance requirements during qualification, several SSPC outputs were configured to output at the highest frequency (200 Hz) and duty cycle (96%).

E.6 MINIMUM SAFETY OF FLIGHT REQUIREMENTS.

To be able to test on an aircraft, a subset of qualification tests is necessary. They are outlined in tables E-8 and E-9.

Table E-8. Commercial Aircraft Safety of Flight Requirements

DO-160G Section	DO-160G Category	Test Description
4	B2	Temperature and Altitude
5	B	Temperature Variation
7	B	Operational Shock and Crash Safety
8	U2, curves F and F1	Vibration
15	Z	Magnetic Effect
16	Z	Power Input
17	A	Voltage Spike
20	Y (1)	Radio Frequency Susceptibility
21	M	Emission of Radio Frequency Energy
25	A	Electrostatic Discharge

May perform Category Y without additional HIRF average and peak requirements.

Table E-9. Military Aircraft Safety of Flight Requirements

Test Standard	Test Method	Test Description
MIL-STD-810E	500.3, 501.3, 502.3	Temperature and Altitude
MIL-STD-810E	507.3	Humidity
MIL-STD-810E	514.4	Vibration
MIL-STD-810E	511.3	Explosive Atmosphere
MIL-STD-461E	CE101, CE102, RE101, RE102	Emission of Radio Frequency Energy

E.7 QUALIFICATION TESTING.

Table E-10 describes the required SPDU qualification tests.

Table E-10. The SPDU Qualification Test Results

No.	Test	Description
1	DO-160E, Section 4	Altitude
2	DO-160E, Section 4	Temperature
3	DO-160E, Section 5	Temperature Variation
4	DO-160E, Section 7	Operational Shock
5	DO-160E, Section 7	Crash Safety
6	DO-160E, Section 8	Vibration
7	DO-160E, Section 16	Power Input Normal Voltage Power Interruption Under-voltage Abnormal Steady State Abnormal Surge Ripple
8	Method 514.4	Vibration During Transport
13	DO-160E, Section 15	Magnetic Effect
14	DO-160E, Section 17	Voltage Spike
15	DO-160E, Section 20 (DO-160F limits) MIL-STD-464	RF Susceptibility
16	DO-160E, Section 21	RF Emissions
17	DO-160E, Section 25	Electrostatic Discharge

APPENDIX F—TEST LAB

F.1 THE MULTI-PURPOSE CONTROL DISPLAY UNIT.

This is the control for a single solid state power controller (SSPC). There are three buttons and a status label. The leftmost button shows an ON/OFF indication and control. To toggle the ON/OFF status, press this button. If the command is successful, the indicator will update; otherwise it will display as FAILED for a brief period before reverting. If the SSPC expected state does not match the actual state, the FAILED will remain on this button. The legend in figure F-1 shows the mapping of background colors and status text. With many additional features beyond traditional power control, many new color assignments were necessary to distinguish status. An attempt was made to preserve the traditional meanings for colors: Gray was specifically chosen for OFF and OPEN; green was chosen for ON or Grounded to show that it has been activated; and red was reserved for a failure indication. Beyond these colors, failures of overcurrent and arc fault trips used bright orange and light blue, respectively, and items such as locked, unlocked, and blocked were given relatively neutral colors.

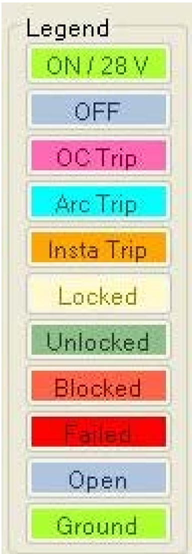


Figure F-1. Display Legend

The middle button is the RESET control. It displays the current count of RESETs available to the SSPC before it becomes BLOCKED. To RESET, click the button and the command will be sent. Upon successful RESET, the indicator will update.

The rightmost button is the LOCK/UNLOCK control. To toggle LOCK/UNLOCK status, press this button. If the SSPC is LOCKED, UNLOCKED, or BLOCKED, the indicator will make this information visible.

The SSPC status on the SSPC Control form displays such information as the current at which the SSPC will overcurrent trip as well as the real-time voltage and current.

F.2 CONTROL BOX.

The test level (TL) control box is a small enclosure that includes a safety shutoff switch and bus control switches that control the coil power to contactors that supply power to the secondary power distribution unit's (SPDU's) main power inputs. Figure F-2 shows a design drawing of the control box on the left and the actual control box made for the TL on the right. Similar boxes would be used for SPDUs #1 and #5.

Because there are three SPDUs, the test lab has three control boxes. All boxes contain a safety shutoff switch that disconnects power from all three SPDUs simultaneously. The control boxes only have switches to control power to the local SPDU cart.

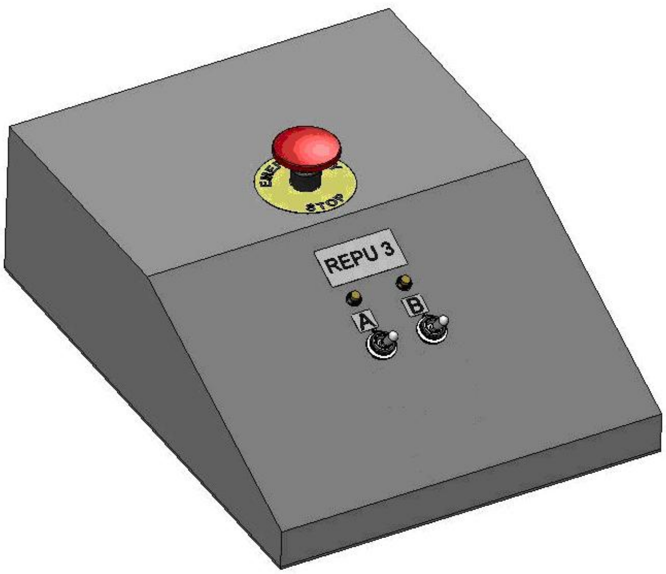


Figure F-2. Control Box

F.3 EMERGENCY STOP.

As a safety measure, all of the emergency stop (E-STOP) buttons are tied together so that if any E-STOP button is pressed on any control box, all contactors to all SPDUs will be opened. Because the test lab may be spread throughout the laboratory and the focus of experiments may be at the load cart or near the main display, a means to disconnect power within reach is required for safety reasons. Power to the system can be resumed only if all E-STOP buttons are pulled out.

F.4 BUS CONTROL SWITCHES.

Actuating these bus switches will either connect or disconnect the power from the SPDU, depending on the position. Each power bus input to the SPDU will have independent control during non-emergency use. The switches allow for ON/OFF control of each channel of each SPDU. The switches are labeled for SPDU 1A, SPDU 1B, SPDU 3A, SPDU 3B, SPDU 5A, and SPDU 5B. The availability of the switch will depend on the location of the control box.

F.5 INPUT/OUTPUT (I/O) COMMUNICATIONS BREAKOUT BOX (IOCBB).

Control and status reporting of the SPDU is performed using the Aeronautical Radio, Incorporated (ARINC) 429 digital serial bus, the Controller Area Network (CAN) digital serial bus, and a combination of dozens of discrete I/Os. To utilize this functionality in the test lab, each SPDU load cart is accompanied by an I/O Communications Breakout Box (IOCBB). The IOCBB, shown in figures F-3 and F-4, provides a means to control discrete inputs, access discrete outputs, pass communication wires, and view status indicators.

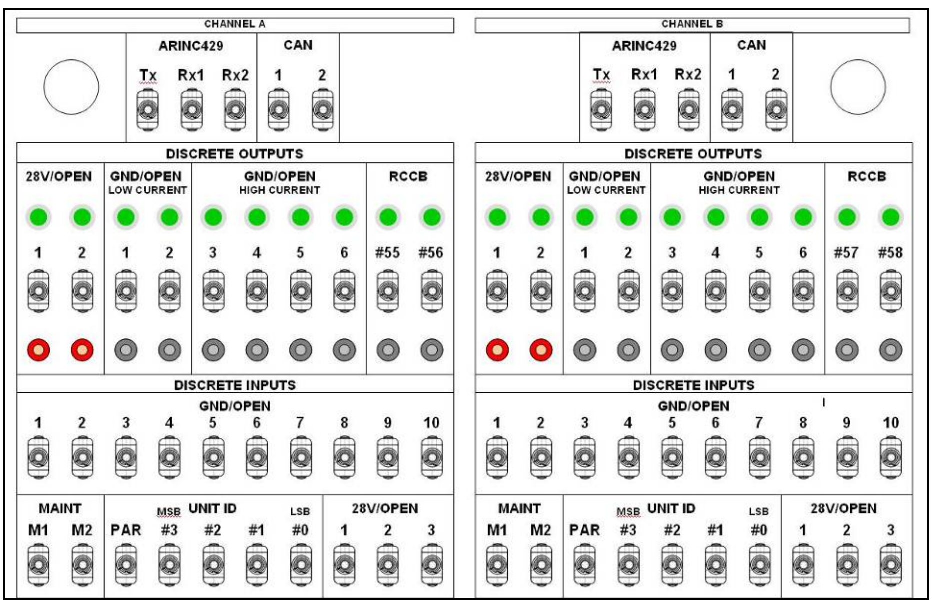


Figure F-3. The IOCBB designed for Critical Design Review

Figure F-4. The IOCBB

The front panel of the IOCBB panel is also fabricated from a standard 19 in.-rack panel. The panel can be split down the middle and is considered identical in function to the left half connected to channel A of the SPDU and the right half connected to channel B. The layout consists of four distinct rows of switches, each having specific functionality for configuring, controlling, and monitoring. The top row is assigned to controlling the presence or absence of ARINC and CAN communication to the channel. The top row also contains a switch to apply auxiliary power to the adjacent channel. The second-highest row contains all of the discrete output functionality. The third highest row captures all of the assignable Ground/Open input discretes and the weight on wheels (WOW) discrete, and the lowest row is predominately for SPDU configuration discretes. These discretes are preassigned for specific functions and are necessary for putting the SPDU in various operating modes and assigning it a unique ID in the power-distribution system. Three other 28V/Open input discretes appear on this lowest row. They are assignable similar to the Ground/Open discretes and are not part of the SPDU configuration. The preferred method would be to place these discretes in the same row as the assignable Ground/Open inputs, space limitations forced them to this lowest row. The following sections provide more detail on each of these panel areas and provide insight into their design.

F.6 DISCRETE INPUTS.

The bottom half of the IOCBB is dedicated to discrete inputs. Each SPDU channel has 20 discrete inputs, as shown in figure F-5. The D28VO represents the 28V/Open inputs and the DGO represents the Ground/Open inputs. The WOW, Channel Select, and Maintenance Mode discrete inputs are also DGO type. The status of these discretes is shown by the position of the individual discrete switch itself, but the switch status is also reported on the laptop through the Multi Control Display Unit (MCDU) software if it is detected by the SPDU.

To simulate real aircraft installations, the IOCBB uses more than just simple switch circuits to stimulate the SPDU. Equipment on aircraft must be robust enough to handle signals that may not be ideal as a result of dirt, corrosion, poor isolation, and poor grounding. Because these are all realistic scenarios on an aircraft, the discrete inputs within IOCBB have been intentionally degraded using series and parallel resistors in series with the switches to simulate poor aircraft connections and leaky switches. Values of resistors have been chosen so the SPDU is guaranteed to operate properly under the worst-case conditions. As an example, ground connections have been intentionally contaminated with 200 Ohm resistances to simulate a poor ground and open signals have been intentionally compromised by using 200K Ohm resistors in parallel with the switch. Because the SPDU has been designed for these poor signals, operation of the SPDU should remain unaffected and should guarantee performance on the aircraft.

A similar method was also used on all of the 28V/Open input discretes. To simulate a leaky switch, all circuits contain a 200 Ohm resistance to 28 VDC and a 200K Ohm resistor in parallel with the IOCBB switch. The resistor blocks used to simulate a leaky switch are contained in the black modules below labels JB4, JB5, JA5, and JA4 in figure F-5.

Figure F-5. The IOCCB Rear Connections

F.7 DISCRETE INPUT ASSIGNABILITY.

Discrete inputs that are described as assignable have the ability to control SSPC outputs within the SPDU. Besides the discrete status being reported over the ARINC 429 and CAN buses, any assignable discrete can also be designated to control the state of an SSPC output using the SPDU configuration table. Because commands from discretes may conflict with the commands from the serial databus, the SPDU uses an event-driven priority scheme and follows whichever command, discrete, or databus has most recently been received.

To help clarify, here is an example. In the configuration table, it is possible to configure the settings of a particular SSPC, for instance SSPC 1, and assign the control of SSPC 1 to discrete input 28V/Open 1. It is also possible to assign the polarity of the discrete switch so that the SSPC can be either OFF or ON when the 28V/Open input discrete is enabled. If the SSPC 1 channel has been configured to turn on when the 28V/Open 1 discrete is active, the toggling of the input switch in the upward (on, closed) direction will cause SSPC 1 to turn on. Should a valid ARINC 429 or CAN command be received in the next moment, the discrete input control of SSPC 1 will be overridden by that command because the SPDU is programmed so the last valid command to the SPDU wins, be it databus or discrete. If the 28V/Open 1 input discrete is toggled, it will then command the SSPC 1 on again.

F.8 DISCRETE OUTPUTS.

Each SPDU channel has eight discrete outputs and four remote control circuit breaker (RCCB) outputs, as shown in table F-1 and figure F-4.

For convenience, each discrete output has a terminal connection on the I/O box for attachment to external circuits and a current limit protected light-emitting diode (LED) lamp to indicate whether the discrete output is on or off. The types of discrete outputs are GO (Ground/Open) and 28 VO (28V/Open). Of all the discrete output circuits, only the 28 VO outputs source current. The others sink current to ground.

There are three important characteristics of these discretes:

1. Must be able to deliver or sink the specified amount of current
2. If required, must be overload protected
3. Each output must not exceed its maximum allowed leakage current

The features in the IOCBB provide an easy means to test and confirm all three of these functional aspects.

F.9 PANEL SWITCH FUNCTIONALITY.

Every discrete output employs a three-position switch to attach loads in series with the discrete outputs except for the low-current discrete outputs. The three-position switch is used for outputs that have overload protection. Since the low current Ground/Open outputs do not have overload protection, the IOCBB will use only a two-position switch in these locations for On/Closed and Off/Open.

The three-position switches on the protected outputs help facilitate load handling and overload protection testing. The middle position of each switch is designated as the Open or Off position.

However the Up and Down positions of the switch will apply loads to the output that are out of range and in range, respectively. When testing the maximum holding current for a discrete output, the switch position can be placed in the downward direction. The SPDU should be able to continuously hold this current without failure. When the same switch is placed in the upward position, a load value equivalent to the trip threshold of the discrete output will be applied to the discrete and should cause the output to go into a circuit protective mode. The 28 VO outputs have rated currents of 250 mA. The High Current discrete outputs have a rated current of 500 mA, and the Ground/Open RCCB driver outputs can withstand sustained currents as high as 900 mA continuously.

Because all of the SPDU switches are solid-state in nature, leakage current is an important factor in both performance and safety. The IOCBB design makes measuring this leakage current simple. The test only requires a standard ammeter to be connected between the binding post and ground for any of the discrete outputs. Per the SPDU specification, the maximum leakage current of the low current GO, high current GO, and RCCB discrete outputs is 250 microamperes while the maximum leakage current of the 28 VO outputs is 100 microamperes.

F.10 THE RCCB OUTPUTS.

Each SPDU has four RCCB outputs as shown in table F-1. Each RCCB output has a terminal connection on the I/O box for attachment to external circuits and a lamp indication. The RCCBs 55 and 56 are controlled by SPDU channel A, and RCCBs 57 and 58 are controlled by SPDU channel B.

Table F-1. The SPDU RCCB Outputs

RCCB_55
RCCB_56
RCCB_57
RCCB_58

F.11 THE ARINC ENABLE SWITCHES.

The SPDU ARINC communication was designed with several layers of redundancy. First, the ARINC from the MCDU to the SPDU has redundant transmitters, or from the SPDU's perspective, redundant receivers. Redundant SPDU transmitters were not seen as a valuable addition for the cost of wire weight. However, the additional SPDU receiver provides a redundancy for important functions such as SPDU control commands. In the aircraft, each SPDU receiver is connected to the transmitter of an MCDU. The aircraft system uses two MCDUs, one master and one slave, to control and monitor the SPDUs. For the purpose of the TL, a single PC emulates an MCDU and both receivers are driven from the single MCDU. This is also a viable architecture if redundant MCDUs are not required to meet safety requirements. For the TL, if one receiver fails, the MCDU can use the remaining receiver to control SSPCs, RCCBs, and discrete outputs as desired.

To test this redundant operation, several ARINC enable switches were added to the TL. These switches can enable or disable any given ARINC wire during a test by opening or closing the electrical connection. A receiver wire can be disabled, leaving the additional receiver wire responsible for operation. In this scenario, there should be no effect to the functional performance. If both receiver wires were disconnected, the SPDU would not detect any ARINC communication and would enter a fail-safe mode. When onground, fail-safe mode will command SSPCs and RCCBs to the off state. When in the air, fail-safe mode will command SSPCs and RCCBs to their respective safe state, as configured in the ground support equipment (GSE) configuration table.

Another test case involves disconnecting the SPDU's ARINC transmitter. This operation renders the SPDU unable to provide status feedback to the MCDU; however the MCDU still has the ability to send commands to the SPDU. This error is undetectable from the perspective of the SPDU and is detectable only by the MCDU, in which case the MCDU shows the SPDU as non-responsive.

The second layer of redundancy is duplication of ARINC communication to both channels of the SPDU. One of the key features of the SPDU is the redundancy of the main central processing unit (CPU), which controls the SSPCs. The CPUs are referred to by their respective channels or cavities. Namely there are two channels, channel A and B. The TL uses the ARINC enable switches to completely remove a channel from ARINC communication to test the redundant control from the opposite channel. For this test, all ARINC enable switches from channel A or channel B can be opened and the technician can verify that control and status of all components are handled by the remaining ARINC communication channel.

Overall, the ARINC enable switches give the TL the ability to simulate broken wires, failed ARINC transmitters and failed ARINC receivers. The benefit of having this capability within the TL is that it allows the technician to verify that the functional performance matches expectations for these types of communication failures.

F.12 THE CAN ENABLE SWITCHES.

Because the CAN is a multidrop bus, the redundancy of the CAN within the SPDU architecture is more straightforward. The SPDU has redundant CAN transceivers for channels A and B. In a test similar to that of ARINC, the CAN enable switches can be used to disable an individual CAN transceiver on either channel. One test is to verify that the redundant CAN works for each channel by disabling one CAN transceiver on each channel. This, similar to the ARINC enable description, would not affect any of the SPDU's functional performance. The next test is to disable both CAN transceivers on a channel to verify that the channel redundancy handles the SPDU control and monitoring. Unlike the ARINC communication within the TL MCDU, the TL MCDU uses a universal serial bus (USB)-CAN converter and a single CANBUS control. The TL CAN enable switches are used to allow the single CANBUS to connect to both the primary and secondary CANBUSES. During normal operation, one CAN enable switch per channel should be left in the open position to avoid collisions.

Additionally, the CAN enable switches give the TL the ability to simulate communication failures, whether on the wire or contained within the CAN transceivers. The benefit of having this capability within the TL is to verify the functional performance of the SPDU's CAN communication.

F.13 THE SSPC BREAKOUT BOX.

Shown in figures F-6 and F-7, the TL SSPC breakout box is designed to provide status feedback, access to each SSPC output, and a means to thermal trip and surge trip each SSPC output. The TL SSPC breakout box design takes advantage of three previous generations of breakout boxes and incorporates numerous convenience and performance features that make SPDU testing intuitive, uncluttered, efficient, and accurate. For the test laboratory, there are three breakout boxes, one for each SPDU. Each breakout box sits directly on the top surface of an SPDU's load cart and is conveniently positioned in a vertical orientation for easy viewing. The panel is fabricated from a standard 19 in.-rack panel aluminum and accommodates all 54 possible SSPC outputs of the SPDU.

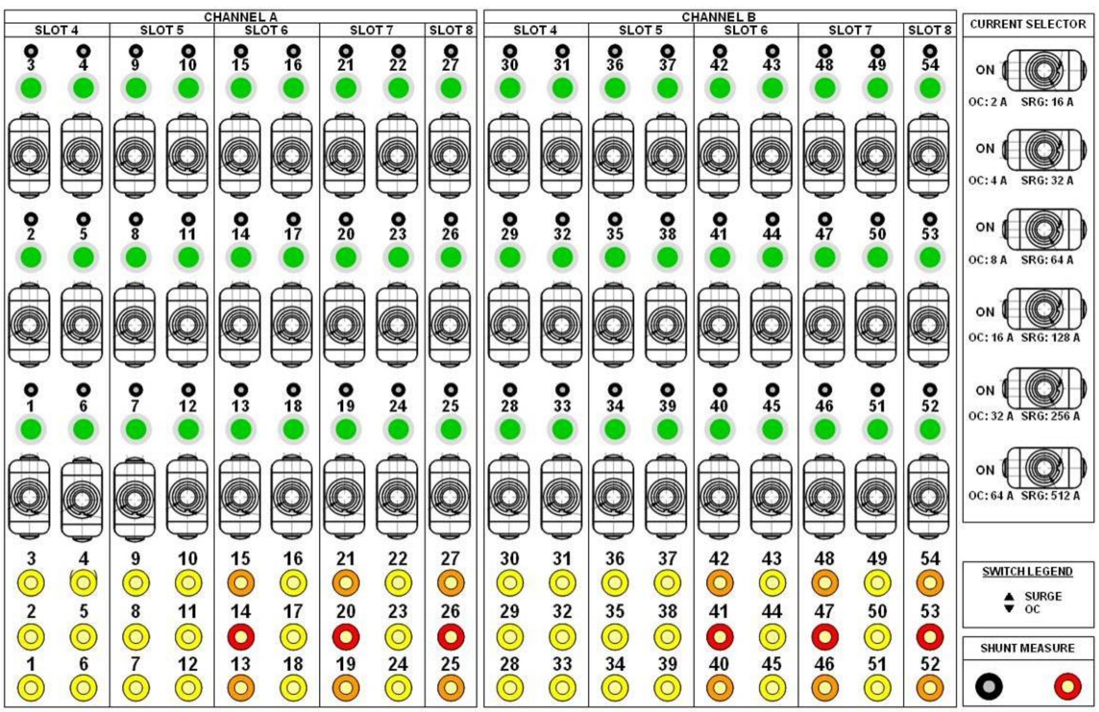


Figure F-6. Initial SSPC Breakout Box Design

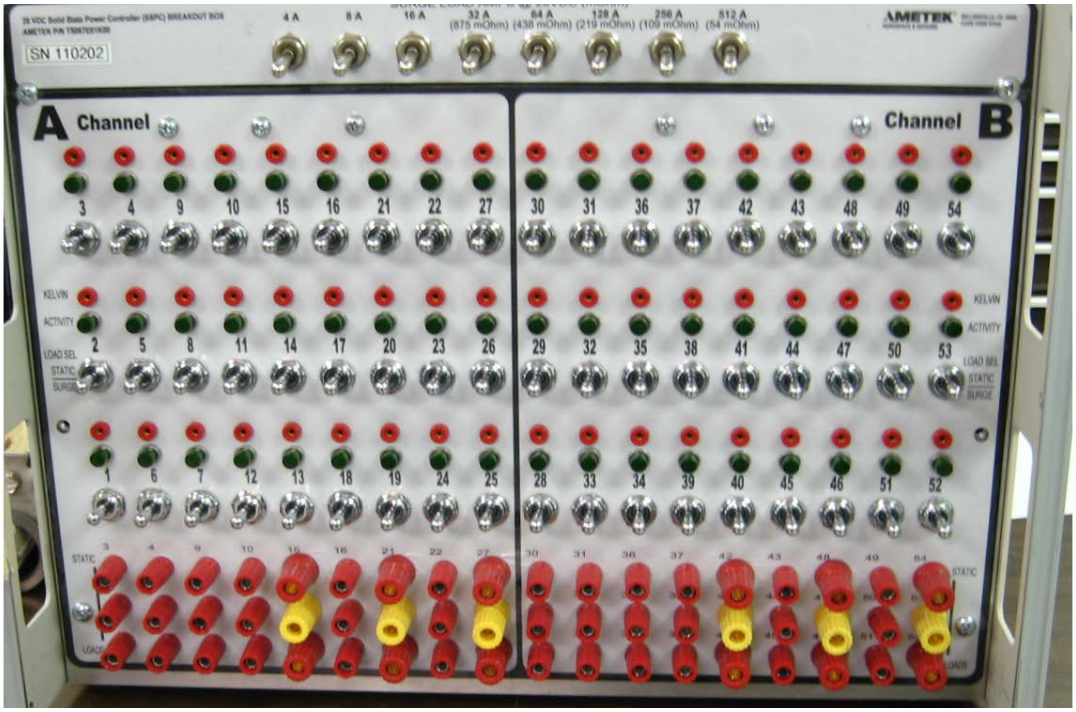


Figure F-7. The SSPC Breakout Box Interface

F.14 BREAKOUT BOX LAYOUT.

The layout has several convenience features. First, the box has two sections clearly labeled as Channel A and Channel B to match that of the SPDU and a third that is dedicated for programming preset loads that can be applied to any one of the SPDU SSPCs. Second, the configuration of the switches, LEDs and output banana jacks are oriented in the same fashion as architecture and placement of the SSPC channels within the SPDU. Labeling on the panel clearly denotes the specific SSPC slot within the SPDU that is associated with each output. Each SSPC output is clearly numbered and matches the numbered output of the SPDU. This allows matching the output to the physical location within the SPDU intuitive.

Another notable feature of the layout is the positioning of the LEDs and control switches in reference to the banana jacks. In previous designs, the LEDs were located right next to the banana jacks. Unfortunately, when the box is completely populated with loads, the wires obscure the visibility of the LEDs. In this revision, we separated the jacks from the LEDs and switches so that the LEDs would remain clearly visible, but still retain the logical orientation, by vertically aligning and labeling the load jacks to match the SPDU layout. Positioning the load wires at the bottom of the breakout box also reduced the length of wire and clutter associated with connecting an output to a load.

Another feature of the layout was the color coding of the banana jacks to distinguish the SSPC module outputs that, if the SPDU is populated appropriately, indicate which modules are capable of sourcing up to 7.5, 15, or 30A loads. Loads with 7.5A ratings have a red color and smaller binding posts. Loads with possible ratings of 15A are yellow with larger binding posts, and those that are red with larger binding posts are rated for currents as high as 30A. A change was made to the binding posts color coding from Critical Design Review to the final TL breakout box. This was because of the availability of materials during assembly and was deemed acceptable because the different current ratings were still coded using different colors. This difference can be seen when comparing figure F-6 and figure F-7. Also in the comparison, it can be seen that the current selector switches moved from the side to the top and the shunt measurement moved to the load cart assembly, as discussed in section F.20.1.

The third area of the breakout box layout is a column of two-position switches located on the right hand side of the panel. These switches allow the user to select different preset load currents that can be applied to a specific SSPC output when used in conjunction with the individual switches for each SSPC output. To avoid confusion, each switch position is clearly labeled with the specific load that it can attach to SSPC output. The bottom of this area is again reserved for wires that can be separated from the switches and LEDs. The banana jacks on the load cart labeled as Shunt Measure allow the user to monitor the current of the selected current switch settings and confirm proper loading. The Shunt Measure provides a 1 mV per amp relationship.

F.15 THE SSPC SWITCHES AND THE CURRENT SELECTOR SWITCH.

Each SSPC output has a two-position momentary switch with center position detent. The purpose of the switch is to provide a quick means of applying a momentary preset load as selected by the current selection switches to the SSPC output for overcurrent, surge/arc and instant trip testing. Previous breakout boxes did not include this feature and it required a custom load to be applied individually and manually to the banana jack outputs of each SSPC. This prolonged evaluation of the SPDU presented the potential for making procedural mistakes. With these switches in the TL breakout box, the user can select a load from the current selector switch and then momentarily apply the selected load to an SSPC by toggling the SSPC output switch down.

For example, to test the overcurrent trip of SSPC 1 with a 7.5A trip setting, the user could select the 16 amps overcurrent selector switch for a 200% load test and then momentarily toggle the SSPC output switch for SSPC #1 downward to connect the load. For a surge trip test the selector switch for 128A can be closed with the 16A switch opened and another downward toggling of the SSPC 1 switch will engage a surge current of 128A.

The initial design had preset overcurrent and surge current settings that are matched to provide an 8x differential and required an upward momentary toggle for the overcurrent trip and a downward momentary toggle for the surge trip. The instant trip was initially thought to use the other position of the momentary switch. During fabrication, the design team felt the selection of currents was complicated by this dual step and changed this to contain a set number of loads that can be used for overcurrent, surge trip, or instant trip. Using the current selector switch, the current can be selected from 4 to 512A. This selection of loads allows the full range of the SSPC trip curve to be tested for all three types of SSPC modules. The wiring contained within the box and throughout the entire harness is not intended to carry abnormally high currents for an extended period of time. This is a primary reason for making the SSPC load selector switches a momentary action. If the SSPC tripping does not occur when expected, the momentary switch should be released.

For reliability purposes, the circuit design of the SSPC breakout box has been electrically designed to minimize the wear and tear on the SSPC panel switches as high currents are switched. This has been achieved by incorporating a high-current mercury switch in series with the SSPC panel switches and intentionally delaying the activation of the mercury switch so that the panel switch is completely closed before current is flowing. This is achieved with a resistor-capacitor filter on the coil drive of the mercury switch.

F.16 THE SSPC OUTPUT LED.

Each SSPC output has a dedicated LED to indicate whether power is available on the SSPC output. These LEDs are current-limited and capable of surviving the voltage variation and power input requirements of DO-160E. The LEDs were chosen for both ruggedness and speed. Lamp filaments tend to be vibration-sensitive and have a much shorter life than LEDs. Also, when operating in pulse width modulation (PWM) mode, unlike a filament lamp, the LED can respond quickly to changes in current and provide a good visual indication of PWM capability at higher frequencies.

F.17 THE SSPC TERMINAL POSTS FOR BANANA JACKS.

All of the wiring and components within the breakout box and harness have been sized to withstand and operate safely at the maximum sustained SSPC current rating of 7.5, 15, or 30A. Female terminal posts were intentionally chosen to avoid the possibility of shorting outputs together.

F.18 KELVIN VOLTAGE MEASUREMENT.

An additional advancement in the TL design is the incorporation of separate current-limited voltage sense wires in the SPDU harnesses. One of the key performance measures of the SPDU is its overall input-to-output voltage drop when supplying its rated current to loads. These values give a good indication as to the overall on-resistance of the SPDU and each SSPC channel and is one of the primary reasons the SPDU has a lower power dissipation in comparison to traditional electromechanical technology. A Kelvin test point has been provided on the breakout box test panel for each SSPC output (figure F-8). This connection is provided as a small banana jack receptacle next to each LED. When a voltmeter is connected between this test point and the appropriate input bus test point on the SPDU cart, the measured voltage can be used to determine the exact on-resistance of the SPDU from bus input to SSPC output without the concern of including voltage drops due to harness impedances. The Kelvin voltage drop measurement must be conducted when a load is attached to the SSPC output and is commanded ON and providing power to the load.

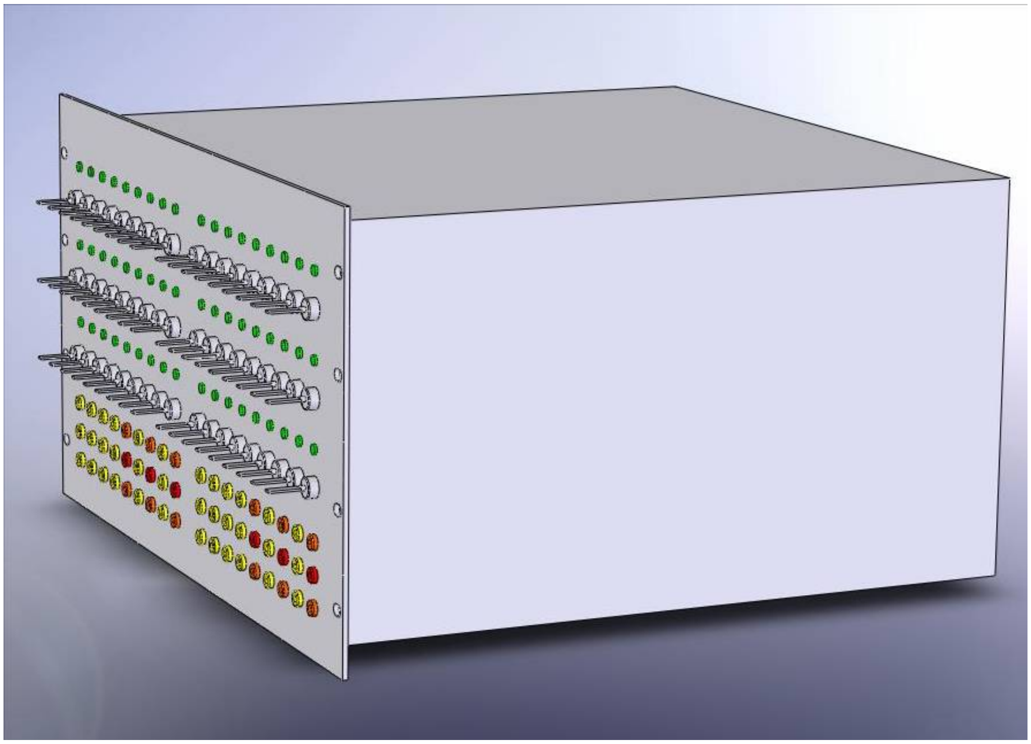


Figure F-8. The SSPC Breakout Box

F.19 The SSPC Output Jacks.

As discussed in section F.14, the terminals for each SSPC are color coded to represent the potential current-carrying capacity or rating of an SSPC output in corresponding location within the SPDU, as described in table F-2.

Table F-2. The SSPC Breakout Box Color Coding

Output Jack Color	Potential Current Capacity (A)
Red (small)	7.5
Yellow (large)	15
Red (large)	30

F.20 LOAD CAPABILITY.

F.20.1 LOAD CART.

The load cart is designed to provide a variety of resistive loads to properly test the SSPC outputs and is also a mobile platform to house the other components of the TL (figure F-9). The load cart is designed to house the required resistive loads while maintaining a compact size convenient for transport to remote facilities and for use in confined test areas. The load cart contains a total of 52 high-power adjustable resistors. With full use, a single load cart will dissipate nearly 8000 watts of power. This requires a design with sufficient cooling and safety features to prevent damage due to accidental overheating.

Figure F-9. The TL Load Carts

F.20.2 THE 28V POWER ENTRY.

The load cart also serves as the central power entry point for a remote electrical power unit (REPU) system. Two 500-A contactors, each protected by a 200-amp fuse are located within the load cart. Power enters and exits the rear of the load cart by way of high-capacity 200-A power feed through studs. See section F.2 for details regarding contactor control.

F.20.3 RESISTIVE LOADS.

Each load cart contains a bank of resistive loads capable of fully loading a REPU. The selection of resistive loads was chosen to meet requirements by the customer for aircraft representative loading during qualification testing. The SPDU must be loaded to 90% of the trip threshold for the aircraft SSPC configuration. Additional loads were added to provide flexibility for future REPU configurations and to allow for lab experimentation. Resistor power dissipation capability was derated 20 to 50% to allow for short-term operation without damage even during loss of load cart cooling.

The shunt measurement was moved from the SSPC breakout box to the top of the load cart because of the location of the 1 milliohm shunt within the load cart structure. The Critical Design Review version of the SSPC breakout box included the shunt measurement, but this was not possible because of space limitations on the front panel. The shunt measurement is now located on the right side of the load access binding post assembly, shown in figure F-10.

Figure F-10. Load Cart Resistive Load Binding Posts

F.20.4 LOAD ACCESS BINDING POSTS AND PATCH CABLES.

Access to the internal loads is gained through 52 color-coded binding posts and corresponding patch cables. The binding posts are organized above the cart handle within easy reach of the target SSPC breakout box. A convenient patch cable storage rack is located just below the cart handle keeping cable clutter to a minimum.

The above qualification test and static load configuration (see figure F-11) requires the following resistive loads on the load cart (as in table F-3).

Figure F-11. The SPDU Qualification Test Load Configuration

REPU QUALIFICATION TEST AND STATIC LOAD CONFIGURATION - REV_2 (B02_Config)

NOTE 1	Violet denotes deviations from customer configuration.
NOTE 2	Gray denotes SSPC address that is not tested but is covered by tests on opposite channel
	Bright Green and "1" indicated SSPC is ON
NOTE 3	Bright Red and "0" indicated SSPC is OFF

Channel **B**

Slot	SSPC_Type	Subslot	SSPC	TTHRES (A)	LOAD (A)	STATE	Subslot Current
4	TYPE-1	LEFT	30	8.9	8	1	20
			29	4.5	4	1	
			28	8.9	8	1	
		RIGHT	31	4.5	4	1	16
			32	8.9	8	1	
			33	4.5	4	1	
5	TYPE-1	LEFT	36	8.9	8	1	20
			35	4.5	4	1	
			34	8.9	8	1	
		RIGHT	37	4.5	4	1	16
			38	8.9	8	1	
			39	4.5	4	1	
6	TYPE-1	LEFT	42	1.0	0	0	0
			41	1.0	0	0	
			40	1.0	0	0	
		RIGHT	43	8.9	8	1	20
			44	4.5	4	1	
			45	8.9	8	1	
7	TYPE-1	LEFT	48	8.9	8	1	20
			47	4.5	4	1	
			46	8.9	8	1	
		RIGHT	49	4.5	4	1	16
			50	8.9	8	1	
			51	4.5	4	1	
8	TYPE-2	LEFT	54	4.5	4	0	16
			53	1.0	0	0	
			52	17.9	16	1	

Bus Bar Leg 1 Current	40
Bus Bar Leg 2 Current	32
Bus Bar Leg 3 Current	10
Bus Bar Leg 4 Current	36
Bus Bar Leg 5 Current	26
CH_B_Total	144

Channel **A**

Slot	SSPC_Type	Subslot	SSPC	TTHRES (A)	LOAD (A)	STATE	Subslot Current
4	TYPE-1	LEFT	3	1.0	0	1	0
			2	4.5	4	0	
			1	1.0	0	1	
		RIGHT	4	4.5	4	0	0
			5	1.0	0	1	
			6	4.5	4	0	
5	TYPE-1	LEFT	9	1.0	0	1	0
			8	4.5	4	0	
			7	1.0	0	1	
		RIGHT	10	4.5	4	0	0
			11	1.0	0	1	
			12	4.5	4	0	
6	TYPE-2	LEFT	15	17.9	16	1	48
			14	17.9	16	1	
			13	17.9	16	1	
	TYPE-2	RIGHT	16	1.0	0	1	0
			17	4.5	4	0	
			18	1.0	0	1	
7	TYPE-2	LEFT	21	17.9	16	1	48
			20	17.9	16	1	
			19	17.9	16	1	
	TYPE-2	RIGHT	22	4.5	4	0	0
			23	1.0	0	1	
			24	4.5	4	0	
8	TYPE-3	LEFT	27	17.9	16	1	48
			26	35.7	32	1	
			25		0	0	

Bus Bar Leg 1 Current	0
Bus Bar Leg 2 Current	0
Bus Bar Leg 3 Current	72
Bus Bar Leg 4 Current	0
Bus Bar Leg 5 Current	72
CH_A_Total	144
REPU_TOTAL	288

Table F-3. Resistive Loads

Resistive Load Current Label	Quantity	Color Code
1A	4	YELLOW
2A	4	GREEN
4A	20	RED
8A	12	BLACK
16A	9	BLUE
32A	3	WHITE

F.21 DESIGN LIMITATIONS.

F.21.1 INSTANT TRIP LIMITATIONS.

The SPDU instant trip is designed to protect the power MOSFETs on the SSPCs when very high current is seen on the SSPC output (possibly a short to ground). The SSPC hardware will detect this scenario and open the power MOSFET. To cause an instant trip in the test lab, the test equipment needs to provide approximately 2A per microsecond rise time on the current waveform. This requires some additional components on the test lab. A bulk capacitor (63,000 uF/100 V) was added on each power input to the SPDU to meet the high-current demands that were beyond the capability of the power supply.

Wire length was reduced where possible on the power input and output cables. Shortening the power input is more beneficial because it can help increase the rise time for all SSPCs on that channel. Shortening the output cables can only increase the current rise time on the outputs of that cable.

In addition to the test lab modifications, the power source is a 300-A switching power supply required to reach the necessary instant trip limits.

F.21.2 MAXIMUM CURRENT CAPACITY.

The SPDU test lab is capable of supplying a continuous 288A. A large exhaust fan is used to provide active cooling (by removing the heated air) of the resistive loads contained in the load cart.

The input cables, which are attached to the power supply, are sized to provide current to the SPDU (up to 288A) and the SSPC output cabling is sized to meet the maximum loading for each SSPC.

Using the bulk capacitor (63,000 uF) and the 300A power supply, the SPDU test lab can achieve short trip currents near 500A. The trip currents near 500A can be used to test and simulate the instant trip event on the higher current SSPCs (the 30-A module).

F.21.3 RESISTIVE LOADS—VARIABILITY TO VOLTAGE.

The resistive loads provide a simple means to load all SSPCs within the SPDU. The alternative to using resistive loads is to use electronic loads. This is not feasible when requiring a load on all SSPCs at the same time to achieve 288A. The disadvantages of resistive loads are the variability with voltage and heat. During SPDU power input tests, careful consideration had to be taken prior to the test to determine the effects to total load current when increasing the voltage to 32.2 VDC or decreasing to 10 VDC. During long tests, the resistive loads would heat and their effective resistance would increase slightly. When considering up to 54 SSPCs, a slight increase in resistance of each load has an impact on the total load current during test. To compensate for this reduction, the power supply can be adjusted to increase the input voltage by a few tenths of a volt to reach the required 288A.

APPENDIX G—PORTABLE TEST LAB

G.1 DESIGN AND ARCHITECTURE.

The Secondary Power distribution unit (SPDU) portable test lab includes everything necessary to test key SPDU functions with minimal setup time. With only a laptop PC and a 20-A 115 VAC power receptacle, an engineer is equipped to operate the SPDU and integrate with aircraft loads as necessary for testing of solid-state.

G.2 THE SPDU LOCATED CENTER STAGE.

The product is elevated on 5-in. standoffs, making it easy to attach circular connector harnesses. The wire harnesses with mating MIL-DTL-38999 cylindrical connectors are permanently connected to the portable test lab. Connector keying eliminates cable connection errors for easy setup.

G.2.1 POWER SUPPLY.

The entire portable test lab is powered by a single direct current (DC) power supply. It is capable of providing up to 65A of current at 28 volts DC. The supply has a universal input voltage range to accommodate any power source likely to be available at the test site, domestically or abroad.

G.2.2 UNIVERSAL POWER INLET.

The alternating current (AC) power enters the portable test lab via standard IEC AC power inlet with inline 20-A circuit breaker switch. A light-emitting diode (LED) indicator lights when AC power is applied.

G.2.3 THE AC INPUT CIRCUIT BREAKER.

The AC power passes through a 2-pole, 20-A resettable circuit breaker and on its way to the power supply. Though there is no guarantee that the portable test lab circuit breaker will trip first, this breaker provides a known level of protection in addition to that assumed to be present on the test location's power source.

G.2.4 INTEGRATED COOLING.

Two DC brushless fans provide cooling airflow across load resistors to support continuous full load (1800 watt) operation. Exhaust air temperature rise is less than 30 degrees centigrade over the ambient intake air temperature.

G.2.5 SERIAL INTERFACES.

An internal universal serial bus (USB) to Controller Area Network (CAN) adapter is included to reduce clutter and minimize interconnections. A single USB type B panel mount connector provides access to the internal USB-to-CAN interface adapter. Support for ARINC 429 is also included.

One DB-37 cable, supporting ARINC 429 serial communication, is available to connect to a laptop PC containing an ARINC 429 interface.

G.2.6 ACCESSIBLE SOLID STATE POWER CONTROLLER OUTPUTS.

Ten select Solid-State Power Controller (SSPC) outputs are accessible via standard panel mount binding posts. Six 1-field effect transistor (FET), three 2-FET, and one 4-FET SSPCs are available for connection to external or internal loads.

G.3 LOAD CURRENT MONITOR CONNECTION.

An internal 1 milliohm shunt resistor is included to permit load current monitoring via multimeter or oscilloscope. Kelvin connections to shunt resistor are current limited through 1000 ohm resistors to tolerate connection errors during tests. Ten select SSPC outputs are accessible via standard panel mount binding posts. Six 1-FET, three 2-FET, and one 4-FET SSPCs are available for connection to external or internal loads.

G.4 ACCESSORIES.

Each transport case includes storage areas for zippered pouches containing helpful accessories:

- 10 ft length United States standard power cord
- 10 ft length Schuko European standard power cord
- 6 ft length USB cable
- Portable Test Lab instruction manual
- USB-CAN adapter driver CD
- Banana patch cables

G.5 ADJUSTABILITY FEATURES.

G.5.1 THE 400A CONTACTORS.

Each DC bus is controlled by its own contactor. This allows the operator to control DC power to each SPDU channel independently, simulating various aircraft load shed scenarios.

G.5.2 DISCRETE INPUT SWITCHES.

One toggle switch is attached to every SPDU discrete input, including unit ID. These 40 switches provide full control of SPDU discrete input capabilities. This is especially useful to test the mapping of discrete inputs to control SSPC states and intentional mismatch of unit ID between channels.

G.5.3 STATIC LOAD RESISTORS.

Load resistors, totaling 64A, are included in three sizes. Six 4-A loads, three 8-A loads, and one 16-A load are available individually or can be connected in parallel. Each load resistor is accessible via standard binding post.

G.5.4 DISPLAY FEATURES.

G.5.4.1 The DC Bus Status Indicator.

Each DC bus is connected to a bright 1 in.-diameter LED panel lamp. This helps clarify whether or not a DC bus is powered.

G.5.4.2 Voltage/Current Display.

Each DC bus is monitored by a panel mount numeric LED display with 5/8 in.-high digits, as shown in figure G-1. The meter is switch selectable between voltage and current. These large LED displays are visible from afar so large groups may see their displayed data.

Figure G-1. The DC Bus Status Indicator and Voltage/Current Display

G.5.4.3 DISCRETE OUTPUT LEDS.

Each 20 discrete output is monitored by its own LED indicator lamp. Not only does this communicate the output states, but it reminds the audience of the total number of outputs available.

G.5.4.4 THE SSPC OUTPUT LEDS.

All 54 SSPC power outputs are monitored by individual LED indicator lamps. SSPC ON/OFF states are clearly indicated. The PWM of SSPC outputs can create dramatic blinking and dimming combinations that emphasize the power of independent SSPC processing.

G.6 THE SSPC STEERING SWITCHES.

Ten toggle switches are included to direct SSPC output current to various test loads, as shown in figure G-2. These switches permit the operator to steer SSPC output to a panel-mounted binding post or to internal surge load. This adjustability is available on six 1-FET, three 2-FET, and one 4-FET SSPCs.

Figure G-2. Case #2 Showing 54 SSPC Output LEDs and 10 SSPC Steering Switches

G.6.1 PORTABILITY.

The SPDU portable test lab is contained within three transport cases that can be checked as baggage on any airline. A significant effort is still required to travel with the test lab when total weight approaches 140 pounds. Alternatively, the portable test lab may be packed in protective cartons and shipped ahead of the required test dates.

Current airline restrictions on baggage size allow bags under 60 linear inches without penalty. The design team identified a rugged transport case with exterior dimensions (L x W x D) 25" x 19 1/2" x 13 3/4", which provide adequate volume without oversize penalties.

Originally, the design team aimed to produce a fully functional SPDU portable test lab within a single rugged transport case. Weight quickly became the greatest concern as airline baggage policies have significant penalties for overweight baggage (see table G-1). In domestic travel, bags over 50 pounds carry a $100 surcharge while 70-pound bags cost an additional $200. Bags in excess of 70 pounds are not permitted on flights between the United States and Europe.

The solution chosen to circumvent these charges while retaining full functionality was to split the test lab hardware into three transport cases.

- Case #1 – Power supply Input/Output and communication, 48 pounds
- Case #2 – SSPC load, 48 pounds
- Case #3 – Standard SPDU shipping carton, 35 pounds

Table G-1. Weight Budget

Description	Case #1	Total 47.62 lb	Case #2	Total 47.7 lb	Case #3	Total 30.5 lb
SPDU, (loaded)					1	12.3
Case, Empty	1	18.2	1	18.2	1	18.2
Power Supply, 2 Contactors, Switch, Brackets	1	12.6				
Capacitor, 63000 UF 63V	1	1.4				
Power Cord, 115V IEC	1	0.92				
Harness, Jx2	2	3.5				
Harness, Jx3	2	2				
Harness, Jx6			2	2		
Harness, Jx7			2	5		
Cable, DC Bus A	1	0.8				
Cable, DC Bus B	1	1.1				
Cable, DC Return (between 2 cases)			1	2		
Load Resistor Ladder			1	12.4		
SSPC Switches			10	1		
Top Panel (18 x 24)	1	3.7	1	3.7		
Bottom Panel	1	3.4	1	3.4		

G.6.2 POWER INPUT CONCERNS.

Most commercial buildings in the United States are expected to have access to one or more 20-A 115 VAC power receptacles. The portable test lab is designed to operate at full capacity with this available power. Occasionally, if it is necessary to operate with an extension cord, performance expectations should be reduced accordingly. If the voltage drop in the extension is significant, then the corresponding increase in current draw may trip the supply circuit breaker.

G.6.3 PERFORMANCE LIMITATIONS.

Readily available 20-A 115 VAC input power limits test lab input power. This limits SPDU load current to just over 60A.

Higher performance has been achieved in more demanding tests by using dual 28 VDC power supplies each plugged into separate 20-A AC receptacles. Increasing available input power increases the need for DC loads to make use of that power. The test lab design approach is intended to optimize the trade-off between size and power.

G.7 OPEN ISSUES.

- Presently, the cooling fans are driven by the SSPC output current via high-side diode OR circuitry. This powers the fans only when it is necessary to cool the loads, but adds about 3A to the reported SSPC current. A design change is planned to drive the fans directly from the power supply and enable them via low-side relay so that fan current draw is not added to SSPC reported current.

- Oscilloscope monitoring of load surge current via oscilloscope is now possible. The addition of a single binding post near surge selection resistors to monitor surge voltage is planned.

- During surge tests, a 28 VDC power supply droop was observed, which made calibration less accurate. Replacement of the existing 63,000 uF, 100V capacitor with a 220,000 uF, 40V capacitor is planned to reduce the input power supply source impedance.