The Space Power System Standard: Architecture, Behavior, and Connectivity

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Abstract— **The Space Power System standard is an emerging standard for space power systems being developed by NASA and industry in both the USA and the UK [1]. This paper first introduces the Space Power System standard explaining the rationale behind the standard. It then outlines the architecture of the Space Power System and details its various functional components, the power modules, which include power sources, energy stores, power converters, and power switches. The behaviors of the various power modules are then considered. Finally, the way in which the power modules are connected using power channels, power interfaces, power links, and buses, is addressed.**

Keywords— Space Power Systems, Power Architecture, Power Modules, Power Module Behavior. Power Links, Power Buses.

1. Introduction

The Space Power System (SPS) standard [1] specifies the power systems for future space missions ranging from small satellites to large ones, from planetary rovers to manned missions, from launchers to landers. It covers the overall power system architecture, the power distribution, regulation and management units, along with the cables and connectors that make up the physical layer. The overall goal of the Space Power System standard is a unified power system architecture for space applications which will support the development of future power systems.

The Space Power System standard is a work in progress and this paper aims to give an overview and update of its current status.

2. Architecture

This section describes the power system architecture. Two ways of looking at the system architecture are presented. The first is an abstract block diagram showing the functional elements of the power system and how they connect. In [1] the abstract block diagram is elaborated using the Universal Modelling Language (UML). The second view of the system architecture is an implementation perspective looking at the structure of a power unit comprising several power modules. This is described in section 3.

The Space Power System architecture, shown in Fig. 1, comprises three main parts:

- The Power System which is responsible for power generation, energy storage, regulation and distribution.
- The Power Management subsystem which is responsible for monitoring and control of the Power System and possibly of the power in the End User Loads.
- The End User Loads which are the consumers of the power provided by the Power System.

Power System

The power system comprises one or more voltage domains, e.g. Voltage 28V in Fig. 1. A voltage domain is a collection of power sources, energy stores, and power switches, all operating at the same voltage, that are interconnected by power channels.

Two voltage domains, at different voltages, can be interconnected by a power converter which transfers power from one voltage domain to the other voltage domain. A voltage domain can be regulated or unregulated.

Power Source

A power source, e.g. a solar array or radioisotope thermoelectric generator (RTG), generates the power that is required by the end user loads. The power source provides regulated or unregulated DC power to the power system.

Energy Store

An energy store, e.g. a battery, receives power either from a power source in the same voltage domain as the energy store, or from a power converter connected to that voltage domain, which is receiving power from a different voltage domain. The energy store holds the power it has received until that power is required later, e.g. when a solar panel is in eclipse, when it provides power back to the voltage domain to which it belongs to.

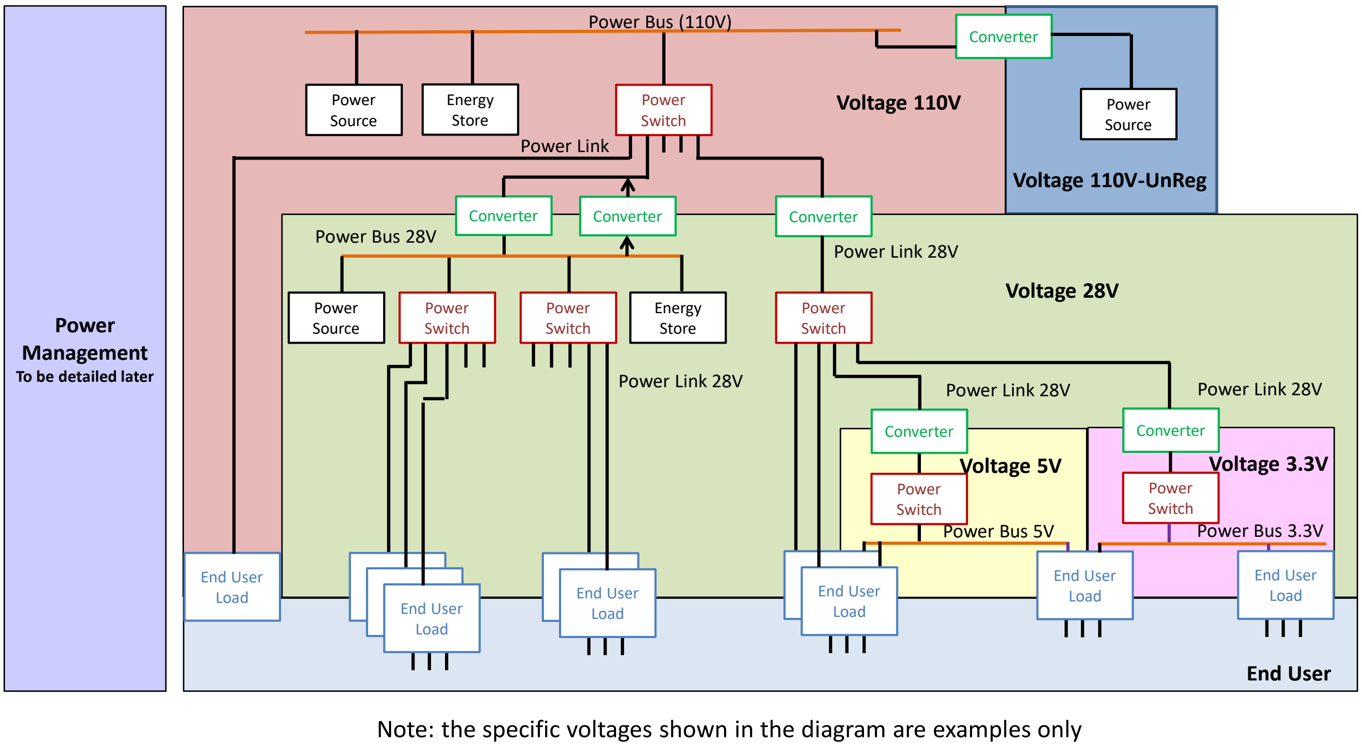


Fig. 1. Space Power System Architecture

Power Converter

A power converter is the interface between voltage domains. It transfers power from one voltage domain to another voltage domain. It sinks power from its input power domain and sources power to is output voltage domain.

Power Switch

A power switch connects one power channel to another power channel, both at the same voltage and hence in the same voltage domain.

Power Channel

A power channel conducts power from one power module (power source, energy store, power converter, power switch) to another power module or to an end user load. A power channel can either be a *power link* conducting power from one unit to another unit or a *power bus* conducting power from one or more units to many units. Power channels operate within a single voltage domain.

End User Load

An end user load is the user of the power generated and distributed by the power system. The end user load has its power input in a voltage domain from which it sinks power.

Power Management

The power management subsystem configures, controls and monitors the power system. It comprises a power management computer and a network that sends power management commands from the power management computer to the various elements of the power system and receives replies from those elements.

3. Power Units and Power Modules

This section describes the structure of power units, which comprise a backplane, rack and a set of power modules. There are two types of power unit:

- Power units with external power connections via the front panel. Modules in this type of unit have substantial connectivity, with backplane and front panel connectors on each module, and can therefore handle more current. Having connectors on the front panels, however, complicates maintenance. This is generally only a problem for manned spacecraft.

- Power units with external power connections via the backplane. This type of unit has no power connections on the front panels of the modules in the unit, which substantially eases maintenance at the expense of fewer possible connections to a modules but reduces the current that can be handled.

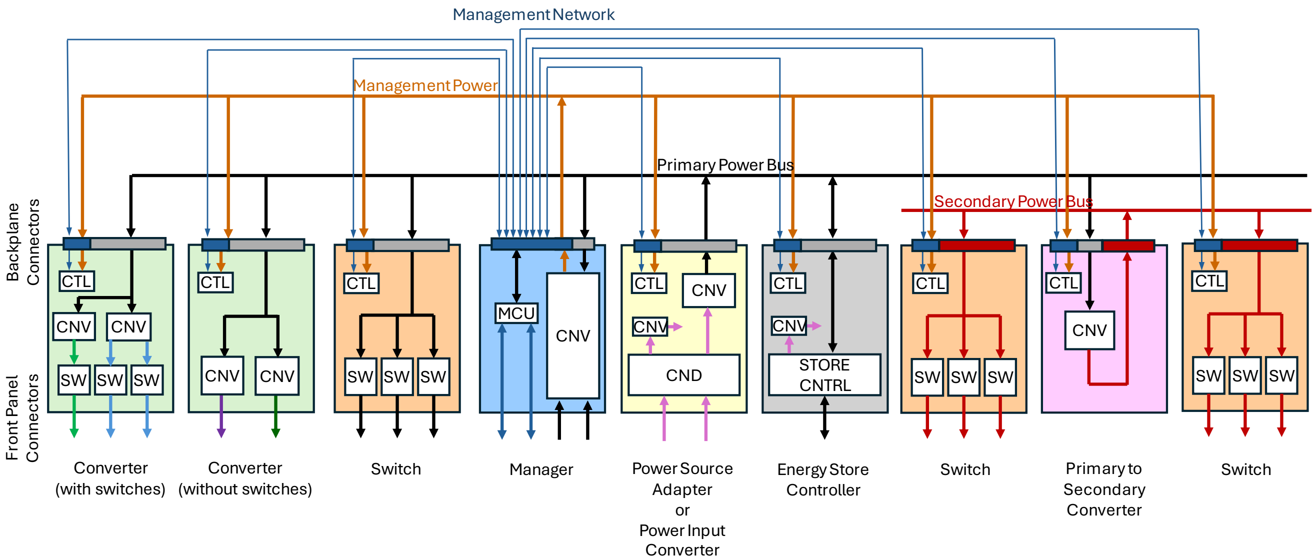


Fig. 2. Power Unit Architecture with External Power Interfaces on Front Panels

The power unit architecture with external power interfaces on the module front panels is illustrated in Fig. 2. It contains several different types of power module.

The backplane connections are shown at the top of Fig. 2 the various modules in the middle, and the front panel connections at the bottom. There are four parts to the backplane:

- Primary power bus, which distributes power within a particular voltage domain to other power modules that require power from that voltage domain. The primary power bus receives its power from an external power source via a power source adapter or from an external energy store via an energy store controller. The primary power bus is connected to the power modules via a large group of power pins on the backplane connector, represented as the grey rectangle at the top of several modules. The primary power bus is represented by the black lines in Fig. 2.

- Secondary power bus, which distributes power within a particular voltage domain to other power modules that require power from that voltage domain. The particular voltage domain is different from that on the primary power bus. The secondary power bus receives its power from a primary to secondary converter module. The secondary power bus uses the same pins on the backplane connectors as the primary power bus. Those pins are either connected to the primary power bus (gray rectangle in Fig. 2) or to the secondary power bus (red rectangle). The secondary power bus is represented by the red lines in Fig. 2. There can be more than one secondary power bus, if additional voltage domains are to be supported in a power unit. Each secondary power bus requires its own primary to secondary power converter. Additional secondary power buses use the same backplane connector pins as the primary or other secondary power buses. This allows a power unit, such as a switch, to be used on any of those power buses, provided it can handle their voltages. In Fig. 2, the same type of power switch module is shown connected to the primary power bus and to the secondary power bus.

- Management power bus, which provides auxiliary power to the power unit management circuitry on all of the modules. Power for the management power bus comes from the manager module, which receives power from the primary power bus, converts it to the voltage required by the management circuitry, and passes it to the management power bus. When external power is delivered to the power unit, the power source adapter generates the primary power. The manager module then powers up to control the other modules in the power unit, providing them with management power via the management power bus.

- Management network, which distributes commands from the manager module to each of the other power modules so that the manager can configure, control and monitor them. The management network is a series of point-to-point connections from the manager module to each of the other power modules.

There are six types of module that can plug into a power unit:

- **Power source adapter,** which has two possible functions: adapting from an external power source that uses voltages not specified in the SPS standard, or converting a power input in one voltage domain to a different voltage domain required for the modules in the power unit. A power source provides power via a connector on the front panel of the power source adapter. The power source adapter conditions and, if required, converts the external power to the required voltage domain for the power unit primary power bus. The power source adapter may be connected to a power source or to the output of a power converter or power switch in another power unit.

- **Energy store controller,** which controls the flow of power to and from an energy store. The front panel connector of the energy store controller is connected to a battery. It is also possible for the energy store controller to include an internal battery, in which case the front panel connector is not needed or might be used to add further external storage capacity.

- **Primary to secondary converter,** which takes power from the primary power bus on the backplane and provides converted power to a secondary power bus on the backplane. It may also provide the secondary power to a front panel connector either directly or via one or more power switches.

- **Converter,** which takes power from a primary or secondary power bus on the backplane, converts it to another voltage domain and provides the converted power to the front panel connector(s) either directly or via one or more power switches.

- **Switch,** which takes power from the primary or a secondary power bus on the backplane and feeds it via some power switches to power interfaces on the front panel connector.

- **Manager,** which contains an MCU (Micro-Controller Unit) which is used to control all the other modules in a power unit. The microcontroller is connected to each of the other modules via a point-to-point communication link. A converter in the manager module takes power from the primary power bus or from power inputs on the front panel, converts it to a regulated voltage, and distributes it via a management power bus to all the other modules in the power unit, where it is used to power the control circuitry in those other modules.

The connectors used for the backplane and for the front panels are described in [1].

A power unit without front panel connectors is illustrated in Fig. 3. The module functions are the same as in Fig. 2, but the front panel connections now pass through the backplane connector, then out of the power unit. The part of the backplane connector carrying these power connection is shaded purple. Passing the connections through the backplane in this way, requires a significant number of the backplane connector pins, which reduces the current that can be handled. The external connections may be taken to bulkhead connectors on the chassis of the power unit or connected to the backplane in some other way. The chassis with its backplane is considered to be part of the infrastructure, directly wired into the spacecraft, similar to a residential load center or 'breaker box'. Modules can be plugged and unplugged rapidly, supporting easy maintenance and rapid customization of a system.

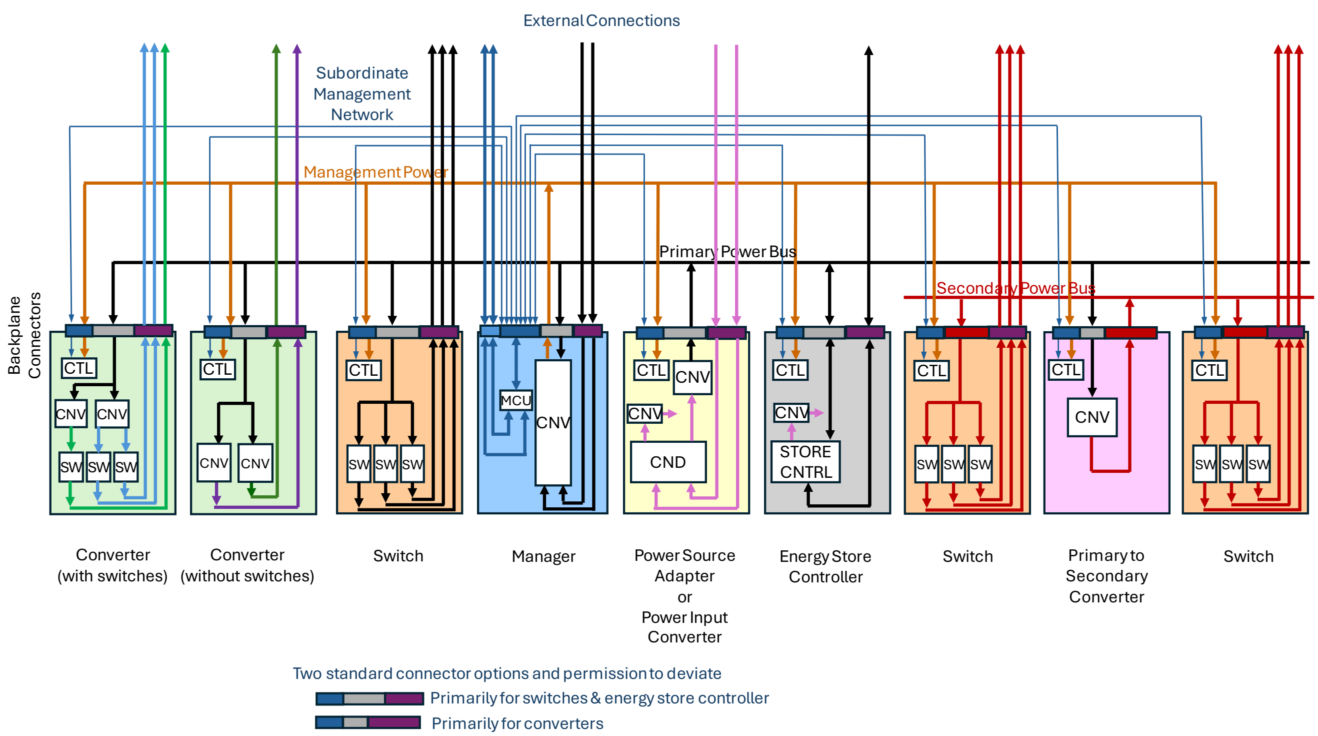


Fig. 3. Power Unit Architecture with External Power Interfaces via the Backplane

4. BEHAVIOR

Power modules exhibit behavior, responding to commands, conditions, and faults. The behaviors of the various power elements are described in the Space Power Systems Standard using state diagrams. This section looks at the behavior of one type of power switch using a state diagram to define its behavior.

Fig. 4 shows the state diagram of a current limiting switch.

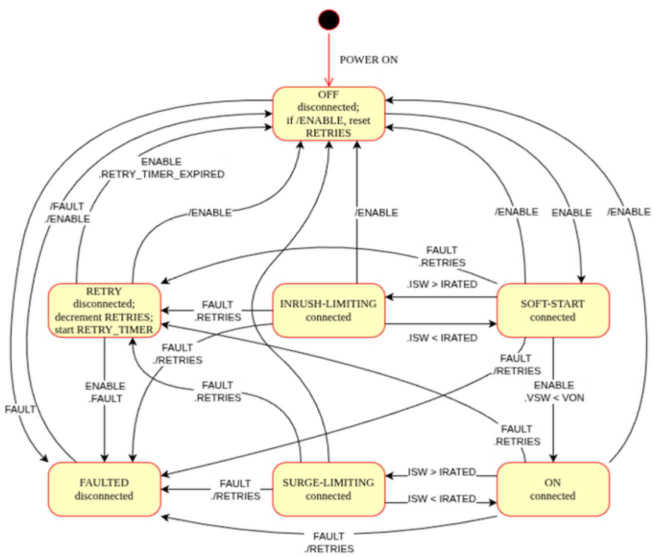


Fig. 4 Current Limiting Switch

The behavior of the current limiting switch is represented by a series of states and the transitions between those states. In the standard, the state diagram is described using formal requirements. A walk-through the state diagram will illustrate the way in which the state diagram describes the behavior of a switch.

The power switch has the following control signals and parameters:

- Enable, which enables the switch so that it can start making a connection;
- Number of Retries, which is the number of restart attempts following a fault;
- Slew Rate, which is the rate at which the voltage across the switch is decreased when enabled;
- Von, which is the voltage across the switch when it is fully connected;
- IRated, which is the current limit threshold for the switch; and
- Current Limit Value, which is the level of current that the switch is limited to when managing excessive inrush or surge current.

When power is turned on, the switch enters the OFF state. In the OFF state the switch is disconnected, i.e. no significant current flows through the switch. If the switch is not enabled when the OFF state is entered, a RETRIES variable is reset to the Number of Retries value.

When the Enable signal is asserted the switch moves to the SOFT-START state. In this state, the voltage across the switch is decreased gradually according to the specified Slew Rate. Eventually the voltage across the switch drops to less than the Von value. The switch then moves to the ON state. In the ON state the switch is fully connected.

When in any state, if the Enable signal is de-asserted the switch will return to the OFF state.

While in the ON state, should the current being passed through the switch exceed the IRated value, the switch will move to the SURGE-LIMITING state where the current is limited to the Current Limit Value. If the current subsides below the IRated level, the switch will move back to the ON state.

It is mandatory (shall) for the switch to detect the following fault conditions:

- Severe over current;
- Persistent over current.

It is desirable (should) for the switch to detect the following fault conditions:

- Over temperature;
- Over voltage;
- Soft-start time-out;
- On-state disconnection;
- Off-state connection.

When a fault occurs in the SOFT-START, ON, INRUSH-LIMITING or SURGE-LIMITING states, the switch moves to the RETRY state if the RETRIES variable is non-zero, or to the FAULTED state if the RETRIES variable is zero, i.e. all the required retry attempts have been made.

In the RETRY state, the switch disconnects and decrements the RETRIES variable. It then waits for a period of time to allow the switch to recover from the fault condition and then moves to the OFF state. Assuming that the switch is still enabled, it will then move to the SOFT-START state and attempt to connect again.

In the FAULTED state, the switch has attempted the required number of retries. It disconnects and waits until Enable is de-asserted, and will then move to the OFF state.

Requirements from the Space Power System standard for the Soft-Start state are provided below to illustrate how a star-diagram is transformed into normative requirements.

6.2.11.1.3 Soft-Start state

a. The power switch element shall enter the Soft-Start state on one of the following conditions:

1. From the Off state, when the Enable signal is asserted;

2. From the Inrush-Limiting state, when the current is less than the current limit threshold.

b. When in the Soft-Start state, the power switch element:

1. Shall decrease the voltage difference between the two power interfaces of the switch element gradually, according to a specified slew-rate.

NOTE 1 As the voltage across the switch element decreases, the voltage across the load will normally increase.

NOTE 2 There are two ways of measuring the voltage across a switch with power interfaces: firstly to measure the input voltage and the output voltage subtracting one from the other, and secondly measuring directly across the two terminals (interfaces) of the switch. The latter directly measures the voltage across the switch element.

NOTE 3 The soft-start state is about controlling voltage not about controlling current.

2. Should indicate that the switch is in the process of soft-starting.

3. May indicate that the switch is in the On state.

c. The power switch element shall leave the Soft-Start state on one of the following conditions evaluated in the order given:

1. When there is a Fault condition,

(a) If there are Retries left, enter the Retry state;

(b) If there are no Retries left, enter the Faulted state.

2. When the Enable signal is de-asserted, enter the Off state;

3. When the current is more than the current limit threshold, enter the Inrush-Limiting state;

4. When the voltage difference across the switch is less than maximum on-state voltage drop of the switch, enter the On state.

5. Connectivity

Power modules are connected together by power links or power buses. A power link connects two power modules together and a power bus connects three or more power modules. This is illustrated in Fig. 5.

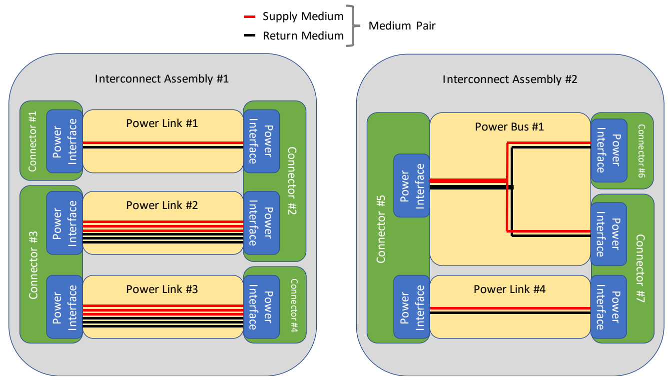


Fig. 5 Example Interconnect Assemblies

Power links and power buses are types of power channels. A power channel carries power at the voltage of a voltage domain with a maximum derated current, which is specified in multiples of 2.5 A. 2.5 A is the bundled, derated current that can be carried by a 22 AWG insulated copper wire.

A power channel is formed from one or more medium pairs, the medium being 22 AWG wires, PCB tracks or bus bars. One half of a medium pair is the supply, and the other half is the return (shown as red and black lines respectively in Fig. 5). The two halves of a medium pair run adjacent to one another. A power channel of a current higher than 2.5 A is formed using multiple medium, or using a single medium pair with sufficient current rating.

A power channel is delimited by power interfaces. Power interfaces are normally contained in connectors, but may also be a collection of solder joints or other form of electrical connection. A connector can contain one or more power interfaces, which can be for different voltage domains and different current carrying capacity.

An interconnect assembly is made of one or more power links and/or power buses terminated in connectors (or other form of electrical connection). The left hand side of Fig. 5 shows an interconnect assembly comprising three power links and four connectors. Connector #1 has a single power interface which interfaces to Power Link #1. Power Link #1 has a single medium pair so its maximum current is 2.5 A. The power interface at the other end of Power Link #1 has its power interface in Connector #2, which contains two power interfaces. The other power interface in Connector #2 interfaces to Power Link #2 which comprises three medium pairs, so can carry a maximum of 7.5 A. The right hand side of Fig. 5 shows a power bus which has three power interfaces, each in a different connector.

The following terms are used to describe connectivity in the Space Power System standard:

- A **power interface** is an interface between elements in a power system with a supply and return.

- A **power channel** is a physical power medium delimited by at least two power interfaces, operating at the specified voltage of a voltage domain, that carries supply and return up to a specified, derated, maximum current.

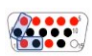
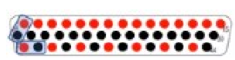
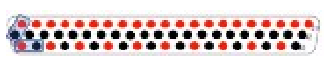
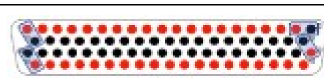
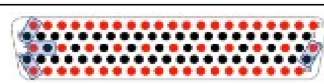
- A **power link** is a type of power channel that has exactly two power interfaces.

- A **power bus** is a type of power channel that connects more than two power interfaces together.

- A **power module** is a device with one or more power interfaces.

There are two types of power connector defined in the Space Power System standard: the front panel connector and the backplane connector. The front panel connector is High Density D-Sub connector [2] fitted with 22 AWG contacts conforming to SAE AS39029 [3]. The characteristics of various sizes of front panel connector are shown in Table 1.

Table 1: Front Panel Connector

Number Contacts (a)	Max. Number Power Channels	Max. Total Current (A)	Contact/Channel Assignment (c) Supply Return Channel
15 (b)	7	17.5	
26	13	32.5	
44	22	55	
62	31	77.5	
78	39	97.5	
104	52	130	

Notes: For voltage less than 150V (derated from 300V, dependent on insert material). (a) High Density 22 AWG contacts, (b) 1 unused contact (position 15), (c) only minimal channels shown, supply/return patterns repeated.

The backplane connector is a Smiths Interconnect KA-series connector, with 96 contacts over 4 rows [4]. This connector is illustrated in Fig. 6. The contact arrangement for a backplane connector on a power module, which also has front panel connectors, is shown in Fig. 7.

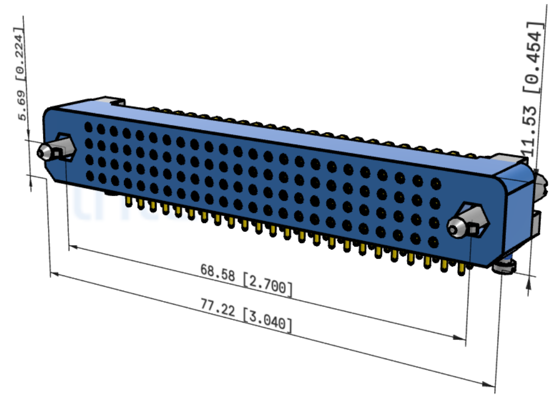


Fig. 6 Backplane Connector

Column	1	2	3	4	5	6	7	8	...	...	...	23	24
Row				PWR-CH1	PWR-CH1								PWR-CH1
A	CTL_TXp	12V_MGR	12V_RET	PWR_1_RET	PWR_2_RET				...	...	...		PWR_N_RET
B	CTL_TXn	12V_MGR	12V_RET	PWR_N+1_RET	PWR_N+2_RET				...	...	...		PWR_2N_RET
C	CTL_RXp	ENABLE	12V_RET	PWR_1	PWR_2				...	...	...		PWR_N
D	CTL_RXn	STATUS	12V_RET	PWR_N+1	PWR_N+2				...	...	...		PWR_2N
				PWR-CH1	PWR-CH1								PWR-CH-1

Fig. 7 Contact Arrangement for Backplane Connector on a Power Module

6. CONCLUSION

The Space Power System standard currently outlines the purpose and architecture of a space power system. It contains requirements for voltage domains, power channels, power interfaces, power unit architectures, and for power switch modules. The Space Power Consortium is currently working on the backplane connector pin-out definition and then plans to address the requirements for the other types of power module.

7. REFERENCES

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