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Space Station Freedom Power Management and Distribution System Design

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SPACE STATION FREEDOM POWER MANAGEMENT AND DISTRIBUTION SYSTEM DESIGN

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Abstract

This paper describes the design of the Space Station Freedom Power Management and Distribution (PMAD) System. In addition, the paper describes the significant trade studies which have been conducted, which led to the current PMAD system configuration.

Background

NASA has been engaged in the definition, design and development of the Space Station Freedom and Platforms since 1984. Phase B contracts were awarded by four work packages (WP) centers for definition and preliminary design of Space Station and Platforms and their various systems. These contracts were completed early in 1987. NASA then awarded Phase C/D contracts for the design and development of the Space Station and Platforms in late 1987.

The Space Station Electric Power System (EPS) is the responsibility of the NASA Lewis Research Center, also known as work package-04 (WP-04) in the Space Station program. WP-04 is responsible for the end-to-end EPS architecture for the Space Station, including photovoltaic and solar dynamic power generation and storage, and power management and distribution (PMAD). This responsibility includes system design, and DDT&E and production of system hardware and software.

The EPS design at the start of the Phase C/D contract is documented in Ref. 1. This design included an end-to-end 20 kHz PMAD system. The subject of this paper is the current design of the PMAD system, including a summary of the trade study results which led to this configuration.

Trade Studies

Recently, a major trade study on PMAD system design was conducted. This section describes the key applicable PMAD system requirements; the PMAD options considered; quantitative and qualitative trade study results; preferences of the program participants; and the trade study decision. The key applicable PMAD system requirements and ground rules are presented in Table 1. The EPS and its PMAD system must deliver 75 kW average power to the user loads (including housekeeping and experiments), and up to 100 kW of peak power, with the peak occurring either during sunlight or shadow periods. In addition, the installed PMAD primary distribution cabling must be sufficient to allow future growth to a level of 175 kW average power. The EPS must provide two-fault-tolerant power for critical functions. Electrical isolation must be provided for major elements, including each module, node and pallet. This allows a single point ground for each element, and also prevents the propagation of faults and other electrical disturbances and noise between elements. It also allows piecewise ground verification of systems which are only fully assembled and integrated on orbit.

The PMAD options considered in the study are defined in Table 2. Simplified schematics for the four options are shown in Fig. 1 and 2. Option 1 is the baseline system at the start of Phase C/D, and at the start of the trade study. It consists of an end-to-end 20 kHz system. Power from the photovoltaic source (solar arrays and batteries) is converted to 440 V, 20 kHz, 1Ø power for primary distribution. This is accomplished by the main invertor unit (MIU). This same 20 kHz power is distributed at 208 V to the final user interface in all modules - U.S. hab and lab, ESA (Columbus) and Japan (JEM). The transformer unit (TU) at the module interface provides electrical isolation and steps the voltage down to 208 Vac. The 20 kHz power is also distributed at 208 V to all attached payloads on the truss. Option 2 is the same as option 1, except that the 20 kHz power is bulk converted to 120 Vdc for distribution in the ESA and Japan modules. The ac/dc bulk converter (ADCU) provides isolation in addition to the power conversion. This option was motivated by the strong desire on the part of Japan (NASDA) and the European Space Agency (ESA) to have dc power distribution in their modules. However, the option of reconverting to 20 kHz for distribution to U.S. users in these modules/was retained. Option 3 consists of 20 kHz primary distribution and 120 Vdc secondary distribution in all elements. The 20 kHz power is bulk converted to 120 Vdc at the interface to all U.S. and International modules, and the 120 Vdc power is provided at the user interfaces. In addition, the 20 kHz power is converted to 120 Vdc for distribution to all attached payloads and other users on the truss. Finally, Option 4 is an all-dc system. Primary distribution is at 160 Vdc, as obtained from the solar arrays and batteries. The 160 Vdc power is converted to 120 Vdc for secondary distribution in all modules, and for distribution to external users on the truss.

A quantitative comparison of the four options is presented in Table 3. Included in the comparison is end-to-end efficiency, including user power supplies to convert to the required final power type; the total number of orbit replaceable unit (ORU) boxes; total mass; total volume inside pressurized areas (nodes and modules) required for ORUs; thermal load for cooling of PMAD ORUs; logistics mass per year; development cost compared to the baseline, including the cost of additional solar arrays and batteries required to provide 75 kW to users for PMAD systems of different end-to-end efficiency; and life cycle cost, which includes development cost.

Options 1 and 4 have the highest and essentially equal efficiency. This is because each option has a single in-line converter in the distribution path - a MIU for Option 1 and a DDCU for Option 4. Option 2 has a single in-line MIU for the path to U.S. users, but has two converters (MIU plus ADCU) for the path to International users. Option 3 has these same two in-line converters for all users; thus Option 3 has the lowest efficiency.

The ORU box count, ORU volume inside pressurized areas, thermal load for cooling of PMAD boxes and total mass are higher for Options 3 and 4 because of the large number of ADCUs and DDCUs. Option 3 has the highest logistics mass because of the requirement to supply both MIUs and ADCUs, in addition to the other PMAD equipment. Development cost and life cycle cost are also greatest for Option 3, because both MIUs and ADCUs must be developed, produced and resupplied. In addition, Option 3 has the lowest efficiency. Therefore, there is additional cost associated with the larger solar arrays and batteries required to provide 75 kW of power to the users.

Table 4 presents a qualitative comparison of the four options. The development risk was judged to be lowest for Options 1 and 2; higher for Option 3; and highest for Option 4. Because a 20 kHz end-to-end system (Option 1) has been baselined for several years, key components have been developed to breadboard level as part of the Space Station Advanced Development program, and a 20 kHz system has been tested at a 25 kW power level. On the other hand, the all dc system (Option 4) requires breadboard development of a 25 kW dc/dc converter, as well as 800 A dc switchgear to interrupt dc fault currents. The dc switchgear development is the greatest risk, because hybrid dc switchgear having 800 A current interrupt capability have not been demonstrated to date. Furthermore, at least 1 year would be required to have an operational dc system testbed, which is equivalent to the 20 kHz system testbed already in operation.

Option 3 has lower risk than Option 4 because high current dc switchgear are not required. However, additional work is required to develop and demonstrate the system concept at a breadboard level.

A dc user interface (Options 3 or 4) is preferred by many from the standpoint of integration risk, user power supply inputs, and ground support equipment. Element designers strongly desire to use their prior experience with 28 Vdc on spacecraft, and believe they can integrate a dc system more readily than a 20 kHz system. Subsystem and scientific users can develop power supplies which convert from 120 Vdc based on their experience with 28 Vdc. Also, 120 Vdc power supplies, cabling and connectors are readily available for ground support equipment applications.

Options 1 and 2 are more readily grown to higher power levels. The high voltage 20 kHz cables are much lighter than the 120 Vdc cables required for the all dc system (Option 4). Furthermore, isolation of additional elements is provided with high efficiency, lightweight transformers. By comparison, Options 3 and 4 require ADCUs and DDCUs for isolation of additional elements; and these are lower in efficiency, heavy, and expensive compared to 20 kHz transformers.

The selection was influenced greatly by the preferences expressed by the various program participants (Table 5). Work Package 4, which is the architect for the end-to-end EPS, expressed a preference for a 20 kHz end-to-end system. They were influenced by their experience with 20 kHz components and system testbeds, which gave them confidence that straightforward solutions existed to potential 20 kHz integration problems. Furthermore, the 20 kHz system appeared to give the highest performance and lowest cost. Canada also expressed a preference for 20 kHz. They had made an early investment in 20 kHz components, and felt that 20 kHz provided the lowest cost solution. However, all other program participants expressed a preference for a 120 Vdc user interface, based on a perceived integration risk associated with a 20 kHz user interface.

The program decision was to select Option 3, consisting of 20 kHz primary distribution and 120 Vdc secondary distribution. The decision was based on the strong preference expressed by most program participants for a 120 Vdc user interface. Furthermore, this decision allows a common user interface between the ESA, Japan and U.S. modules. In addition, Option 3 retains the use of ac switchgear, and zero current switching, to handle the high power fault currents.

PMAD Architecture

The selected PMAD Architecture is shown in Figs. 3 to 6. The overall architecture is shown in Fig. 3. DC power from the solar arrays and batteries is converted to 20 kHz and transmitted to outboard main bus switching units (MBSU) for paralleling and fault protection. The 20 kHz power is transmitted across the rotating a-joints and fed to inboard MBSUs, which provide fault protection and further distribution to the load centers in the modules, nodes and attached pallets. A star architecture is utilized for distribution of power from the inboard MBSUs to the load centers - several dedicated cables provide power to each load center. At each load center, an ADCU converts the power flowing on each cable to 120 Vdc. The ADCU also provides for electrical isolation of the downstream load center (also known as EMC element); limits current to the load center in case of a fault; prevents the propagation of fault currents from the load center to the power source; and regulates voltage. The power distribution and control units (PDCU) attached to each cable and ADCU provide for further distribution of power to the loads, and provide control and protection functions.

Figure 4 provides an expanded view of the PMAD architecture outboard of the a-joint. PV array power is regulated to 160 Vdc by the sequential shunt units (SSU), and transmitted across rotating B-joints to dc switching units (DCSU). During sunlight, some of the array power is used to charge the batteries. Battery charge and discharge is controlled by the Battery Charge-Discharge Units (BCDU), which regulate the charging of the batteries and step up and regulate battery discharge voltage to 160 Vdc. The 160 Vdc power from the arrays and/or batteries is converted to 440 V, 20 kHz, 10 power by the MIUs. some of the power is also converted to 120 Vdc by dc-to-dc converter units (DDCU) for distribution to loads outboards of the a-joints via PDCUs. Photovoltaic controllers (PVC) provide overall management of the outboard PMAD functions.

Figure 5 shows the distribution of power to a typical module. Power is provided by up to four feeders, each which is fed from a different MBSU, in order to provide the required level of fault tolerance to assure continuous power for critical functions. Similarly, power is provided to the various pallets attached to the truss, as shown in Fig. 6.

Status and Plans

Additional details of the PMAD architecture, such as system regulation, fault protection, grounding and power system startup are being developed. Initial specifications have been written for the various components and ORUs, and will be adjusted as system specifications and design mature. Initial breadboard hardware is under development - RBIs and MIUs are undergoing testing. Design activities are continuing and will result in a preliminary design review (PDR) of the PMAD system in May 1990. In addition, initial PMAD system testing is scheduled to begin February 1990.

Reference

Teren, F., "Space Station Electric Power System Requirements and Design," Proceedings of the Twenty-Second Intersociety Energy Conversion Engineering Conference, Vol. 1, AIAA, New York, 1987, pp. 39-47.

TABLE 1. - KEY REQUIREMENTS AND GROUND RULES

- 75 kW average, 100 kW peak power delivered to user interface
- 175 kW growth
- Two-fault tolerance
- Electrical isolation of "major elements"
- Fault isolation

TABLE 2. - POWER DISTRIBUTION OPTIONS

Option	Primary	Secondary				Comment
		U.S.	ESA	Japan	TRUSS	
1	20 kHz	20 kHz	20 kHz	20 kHz	20 kHz	Baseline all ac system
2	20 kHz	20 kHz	120 Vdc	120 Vdc	20 kHz	Bulk conversion for ESA and Japan with 20 kHz reconversion for U.S. payloads
3	20 kHz	120 Vdc	120 Vdc	120 Vdc	120 Vdc	All dc secondary with full payload interoperability
4	160 Vdc	120 Vdc	120 Vdc	120 Vdc	120 Vdc	All dc system

TABLE 3. - QUANTITATIVE EVALUATION VARIABLES SUMMARY

	Option 1	Option 2	Option 3	Option 4
Efficiency (end-to-end including user power supplies), percent	80.4	78.5	75.5	80.4
ORU box count U.S. (total)	184 (190)	184 (212)	216 (234)	208 (226)
Mass U.S. (total), lb	67.5K (68.3K)	68.5K (69.6K)	76.9K (77.9K)	73.5K (74.5K)
ORU volume inside pressurized areas U.S. (total), ft^3	158 (176)	158 (198)	222 (260)	254 (292)
Thermal (total/pressurized volumes), kW	17.6/8	18.8/9.2	22.1/10.6	19.7/11.2
Logistics (U.S. only), lb/year	7400	8200	10 150	8300
Delta development cost, $M	Base	+7	+52	-4
Delta life cycle cost (10 year), $M	Base	+18	+111	+44

TABLE 4. - QUALITATIVE EVALUATION VARIABLES SUMMARY

	Option 1	Option 2	Option 3	Option 4
Development risk	+ Key 20 kHz components developed to breadboard level + 20 kHz system testbeds at 25 kW have demonstrated key parameters	+ Key 20 kHz components developed to breadboard level + 20 kHz system testbeds at 25 kW have demonstrated key parameters	+ Low risk dc components with well understood system technology for modules - Testbed augmentation required	- 25 kW dc/dc converter and 800 A hybrid dc switchgear require breadboard development - At least 1 year to have equivalent testbeds in operation
Integration risk	- Lack of familiarity with 20 kHz	- Lack of familiarity with 20 kHz	+ Familiarity with dc systems	+ Familiarity with dc systems
User power supply impacts	- Limited experience with 20 kHz	- Limited experience with 20 kHz	+ 120 V dc more familiar to users based on 28 Vdc experience	+ 120 V dc more familiar to users based on 28 Vdc experience
Interoperability	+ Full interoperability for all payloads	- Achieved for U.S. payloads	+ Full interoperability for all payloads	+ Full interoperability for all payloads
Ground support	- Lack of equipment availability	- Lack of equipment availability	+ Availability for power supplies, cabling and connectors	+ Availability for power supplies, cabling and connectors
Ease of growth	+ Easiest, most efficient, and cost effective growth	+ Easy, efficient and cost effective growth (except international modules)	Power transmission growth easy	- Difficult to grow - requires heavy, channelized approach or additional development of high current switch

TABLE 5. - PREFERENCES OF PROGRAM PARTICIPANTS

[Integration risk is the basis of the dc preference.]

Program partners	Secondary power distribution	
	20 kHz	120 Vdc
WP1		X
WP2		X
WP3		X
WP4	X	
Canada	X	
ESA		X
Japan		↓
PR&A (LII)		↓
Utilization (LII)		↓

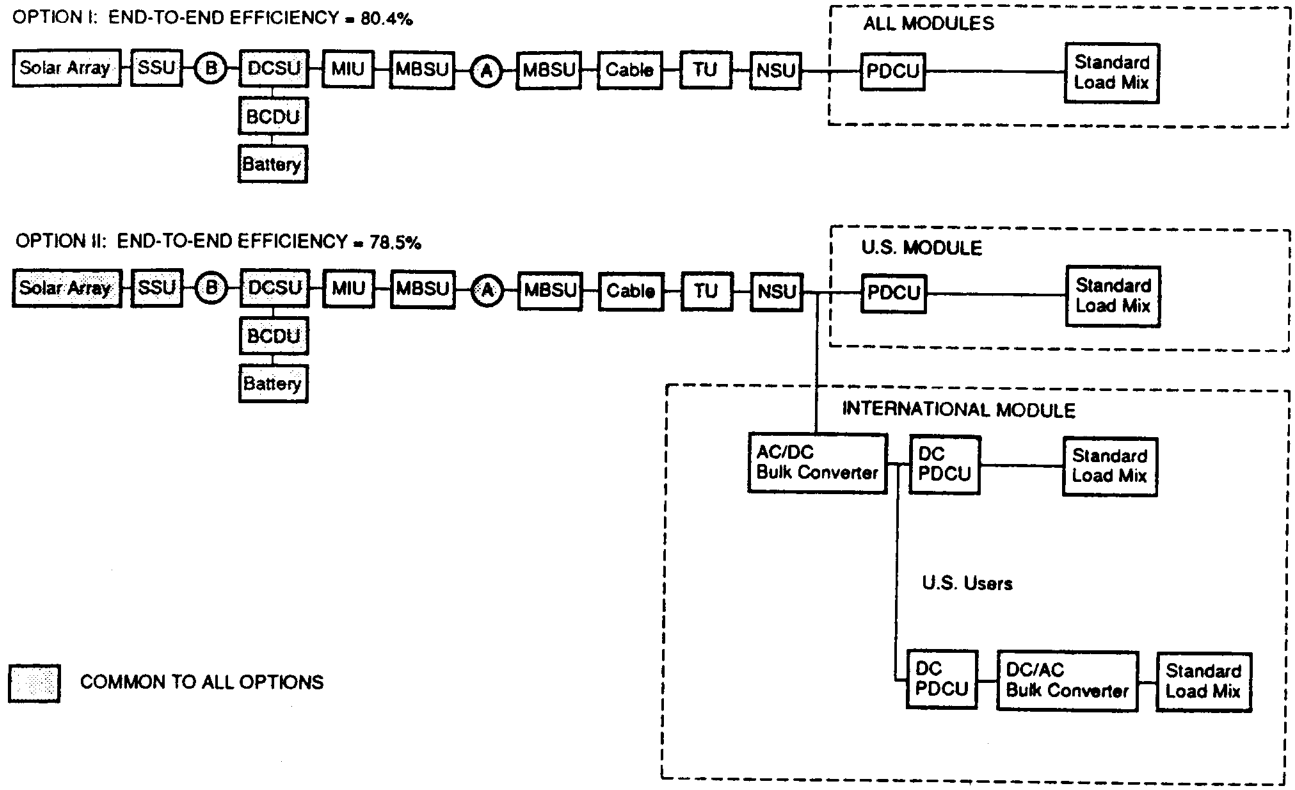

Figure 1. - Space station distribution models.

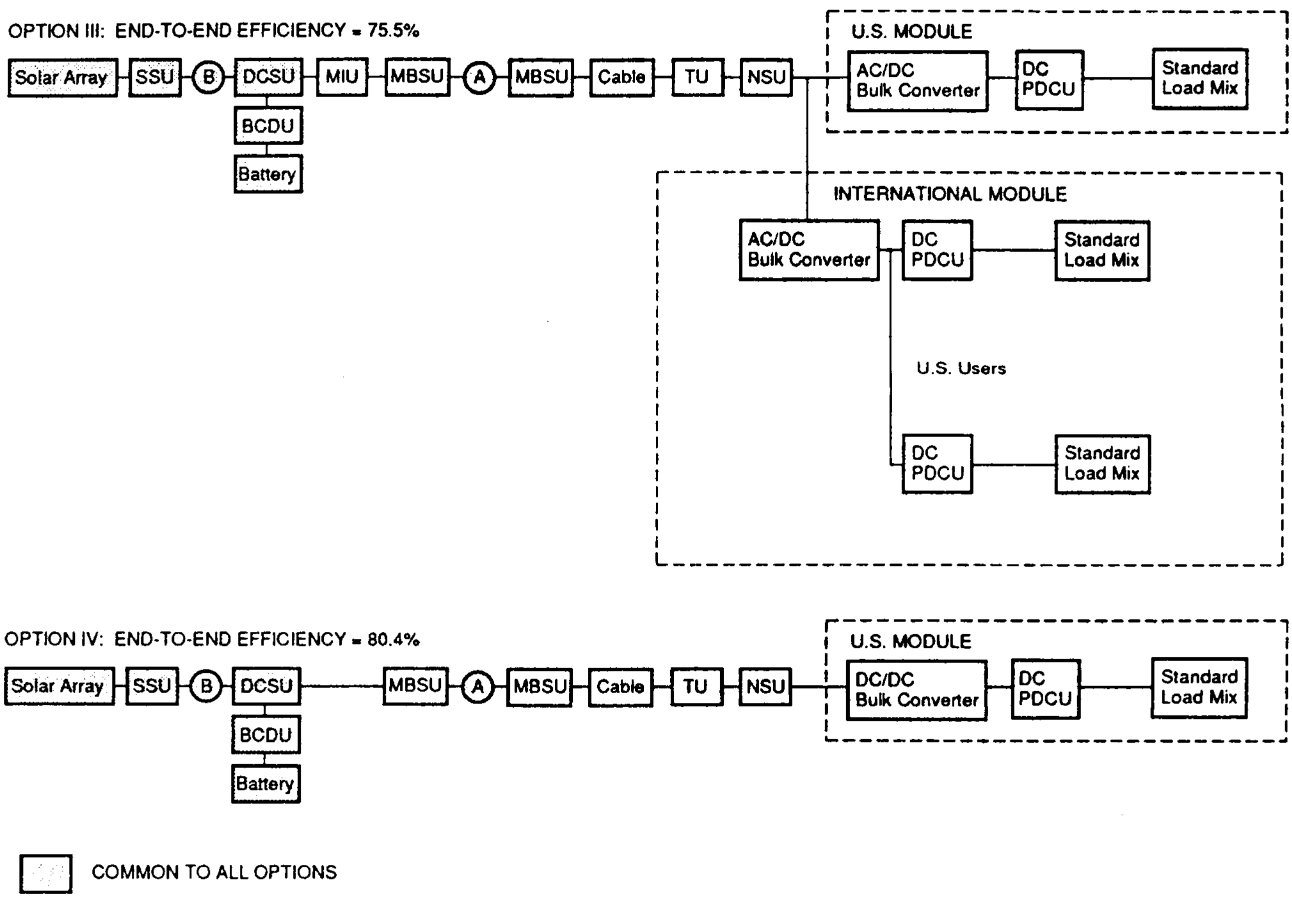

Figure 2. - Space station distribution models.

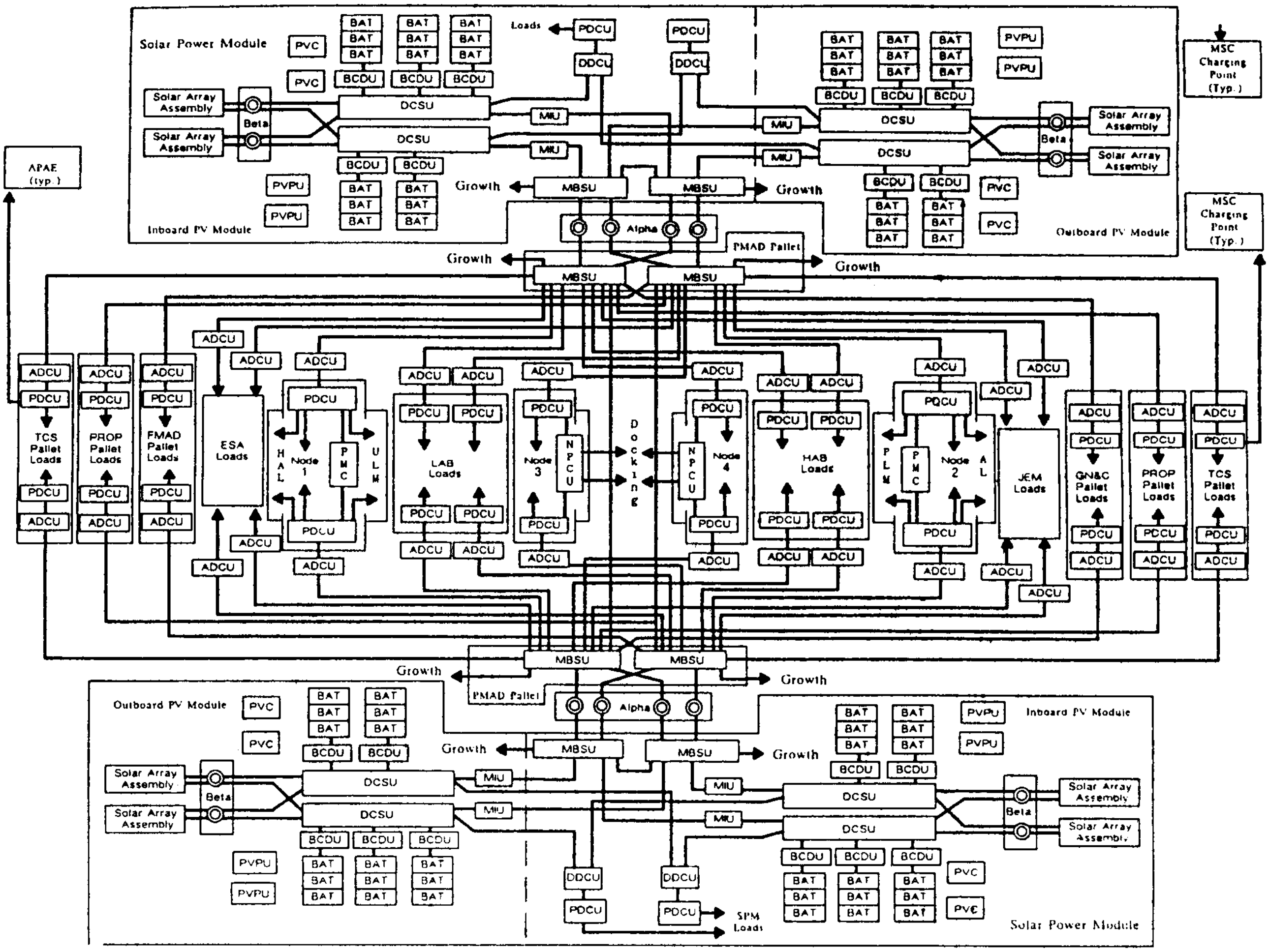

Figure 3. - EPS end-to-end architecture.

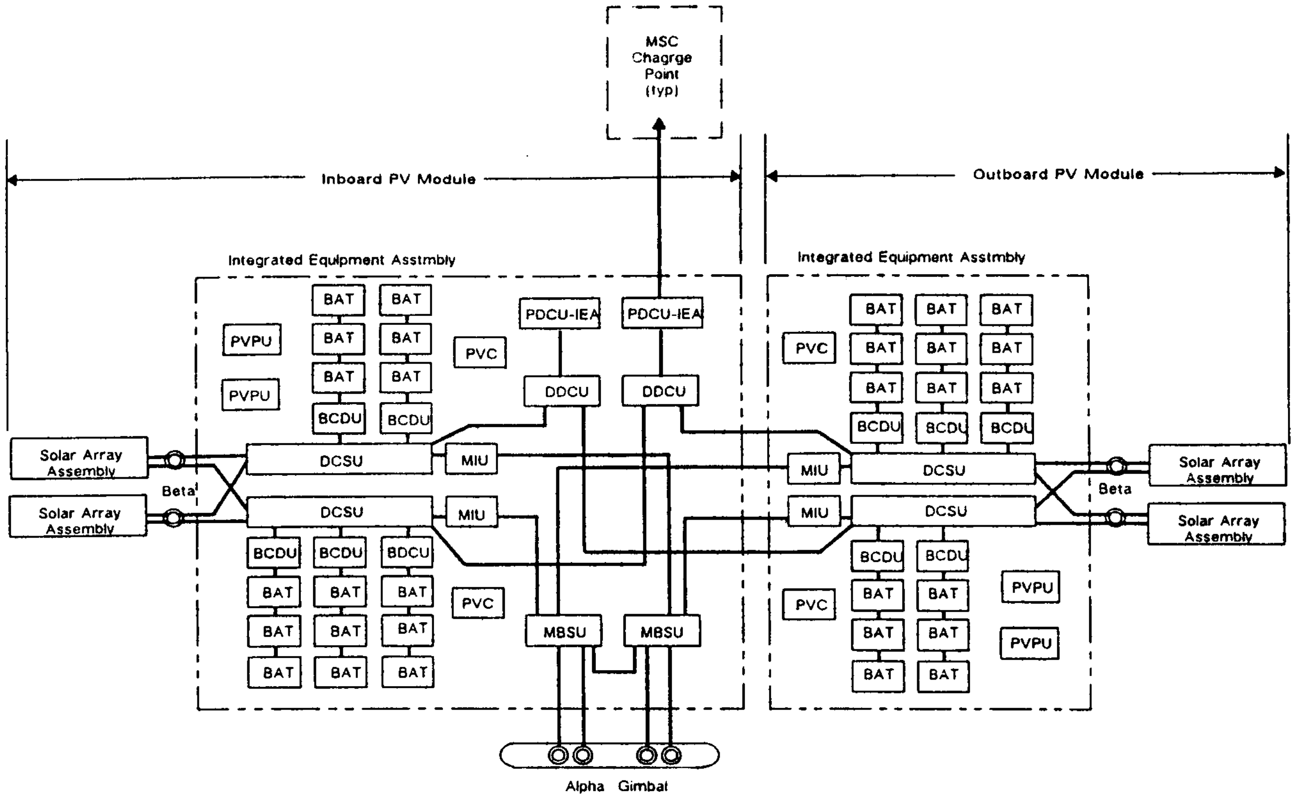

Figure 4. - PV power module architecture.

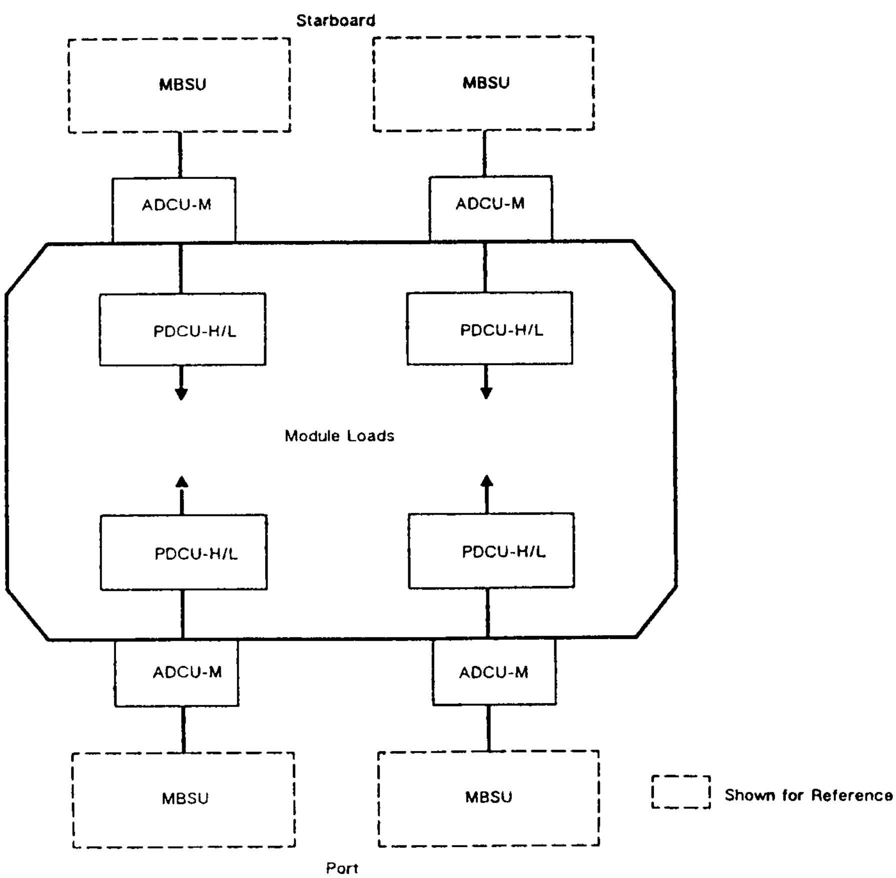

Figure 5. - Common module architecture.

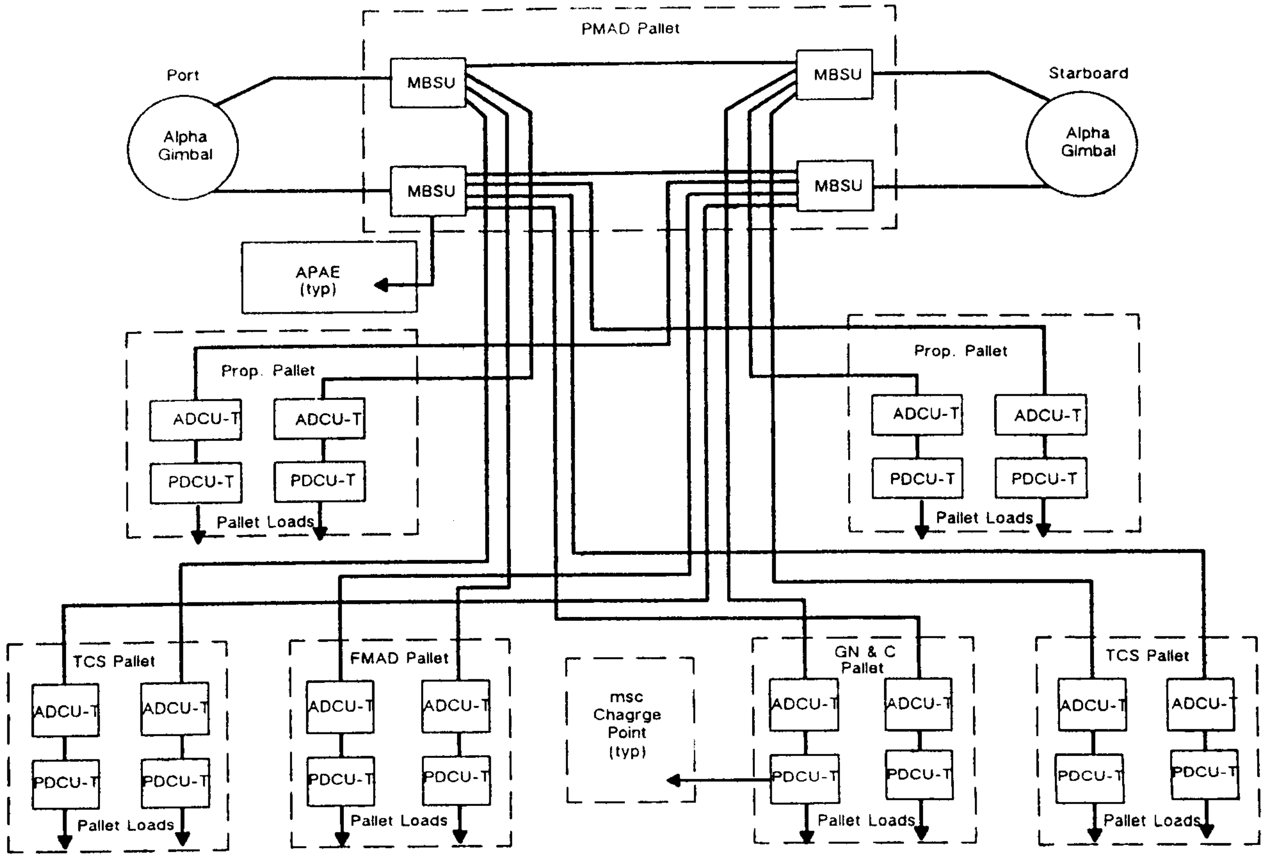

Figure 6. - Truss pallet architecture.

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16. Abstract

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