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FINAL REPORT

SPACE VEHICLE ELECTRICAL POWER PROCESSING DISTRIBUTION AND CONTROL STUDY

VOLUME II - TECHNICAL REPORT

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TABLE OF CONTENTS

			Page
1.0	INTRODUCTION		1-1
2.0	ANALYSIS OF REQUIREMENTS AND INTERFACES		2-1
	2.1	RELIABILITY AND SAFETY REQUIREMENTS	2-3
	2.2	CHARACTERISTICS OF LOAD UTILIZATION EQUIPMENT	2-8
		2.2.1 Electronic Loads	2-8
		2.2.2 Electromechanical Loads	2-11
		2.2.3 Electrical Heaters	2-18
		2.2.4 Lights	2-19
		2.2.5 Electrical Energy Storage	2-19
	2.3	REFERENCE LOAD REQUIREMENTS	2-20
		2.3.1 Space Station Reference Model	2-20
		2.3.2 Load Requirements for Space Shuttle	2-29
		2.3.3 Reference Load Model for Aircraft	2-39
	2.4	ELECTRIC POWER GENERATION	2-42
		2.4.1 Solar Array/Battery Power Generation Subsystem	2-43
		2.4.2 Fuel Cell Generators	2-47
		2.4.3 Rotating Generators	2-48
	2.5	HEAT REJECTION INTERFACE	2-53
		2.5.1 Space Station Characteristics	2-53
		2.5.2 Shuttle Orbiter Heat Rejection	2-54
		2.5.3 Thermal Control for Aircraft	2-54
3.0	COMPONENT ANALYSES		3-1
	3.1	LOAD POWER PROCESSING EQUIPMENT	3-1
		3.1.1 Standardized Requirements	3-2
		3.1.2 Circuit Configurations	3-4
		3.1.3 Design Procedure and Assumptions	3-12
		3.1.4 Parametric Performance Results	3-15

CONTENTS (Cont.)

	Page
3.2 TRANSMISSION AND DISTRIBUTION	3-29
3.2.1 Circuit Considerations	3-29
3.2.2 Cabling Configurations	3-31
3.2.3 Effect of Frequency	3-33
3.2.4 Transmission Voltage	3-34
3.2.5 Reliability and Safety	3-40
3.3 CONTROL AND PROTECTION EQUIPMENT	3-41
3.3.1 Requirements Analysis	3-42
3.3.2 Electromechanical Switchgear	3-49
3.3.3 Solid State Switchgear	3-56
3.3.4 Command and Display	3-61
3.4 CENTRAL POWER CONVERSION	3-66
3.4.1 Standardized Requirements	3-67
3.4.2 Circuit Configurations	3-68
3.4.3 Performance Analysis	3-71
3.4.4 Summary	3-74
4.0 DYNAMIC PERFORMANCE AND FILTERING	4-1
4.1 POWER QUALITY REQUIREMENTS	4-2
4.2 GENERATION OF INTERFERENCE	4-7
4.2.1 Relay Switching Transients	4-8
4.2.2 Interference From Power Processing Units	4-10
4.2.3 Power Source Interference Voltage	4-14
4.3 INTERFERENCE COUPLING	4-14
4.3.1 Interference Transfer Via Common Impedance	4-14
4.3.2 Interference Transfer Via Mutual Inductance	4-16
4.3.3 Capacitive Coupling	4-18
4.3.4 Electric and Magnetic Field Coupling Via Radiation	4-19
4.4 FILTER DESIGN	4-20
4.4.1 DC Input Filter Design and Performance Characteristics	4-22
4.4.2 AC Input Filters	4-27

CONTENTS (Cont.)

		Page
5.0	CANDIDATE SYSTEMS EVALUATION	5-1
5.1	CANDIDATE CONFIGURATIONS	5-1
5.2	SUBSYSTEM RELIABILITY AND SAFETY	5-11
5.2.1	Personnel Hazard	5-12
5.2.2	Space Station PDCS Reliability	5-12
5.2.3	Space Shuttle PDCS Reliability	5-14
5.2.4	Aircraft Power System Reliability	5-15
5.3	DYNAMIC PERFORMANCE COMPARISON	5-16
5.3.1	Effect of Voltage and Frequency on PPU Filters	5-16
5.3.2	Coupling of Transients	5-17
5.3.3	Parallel Operation	5-20
5.4	WEIGHT ANALYSIS	5-21
5.4.1	Space Station Weight Analysis	5-21
5.4.2	Shuttle Weight Analysis	5-27
5.4.3	Aircraft Weight Analysis	5-29
5.5	COST ANALYSIS	5-32
5.5.1	PDC Equipment Cost	5-33
5.5.2	Indirect Costs	5-36
5.6	SUMMARY	5-39
6.0	TECHNOLOGY REQUIREMENTS	6-1
6.1	DEVELOPMENT OF HIGH VOLTAGE SWITCHGEAR	6-1
6.2	HIGH VOLTAGE DC POWER PROCESSING, DISTRIBUTION AND CONTROL TECHNOLOGY BREADBOARD	6-3
6.3	ELECTRIC POWER SYSTEM STANDARDIZATION	6-8
6.4	COMPONENT IMPROVEMENTS	6-9
7.0	REFERENCES	7-1
8.0	APPENDIX	
	A - Power Processing Unit Design Data	
	B - Input Filter Design	
	C - Calculation of Wire Size	

SPACE VEHICLE ELECTRICAL POWER PROCESSING, DISTRIBUTION AND CONTROL STUDY

VOLUME II - TECHNICAL REPORT

1.0 INTRODUCTION

The primary purpose of this study is the definition of a practical generalized concept for electrical power processing, distribution and control applicable to manned space vehicles and future aircraft with special emphasis on the needs of the currently envisioned Space Station and Space Shuttle configurations.

The program tasks and objectives may be summarized as follows:

- Develop a data base for rational selection and evaluation of electric power processing, distribution and control methods for manned space vehicles.
- Recommend system voltage, frequency, power switching, and control standards to be used for manned space vehicles.
- Establish the need for a new power quality specification or recommend changes to MIL-STD-704 applicable to manned spacecraft and future airplanes, as appropriate.
- Identify any significant deficiencies in technology.
- Recommend areas for improvement and suggest methods for early feasibility demonstrations to reduce cost and development risks.

This study program is concerned only with the power processing, distribution and control subsystem (PDCS) of complete on-board electrical systems (EPS) and concentrates on the fundamental issues which lead to a logical choice of power system voltage, frequency, control, and protection standards for a broad range of manned vehicles. The electrical power generation subsystem (EPGS) is considered only in terms of its influence on the power processing, distribution and control subsystem. No attempt is made to prescribe the actual PDC subsystem for a specific vehicle such as the Shuttle Orbiter since detailed subsystem design can only be performed as part of the actual vehicle design. We have considered four types of manned aerospace missions and have defined typical power system requirements for each mission. They form the baseline or model systems for the trade studies which were carried out to arrive at the recommended PDC configuration. The baseline requirements represent a 12-man Space Station, a Shuttle Orbiter, and large future commercial or military aircraft missions.

The PDCS may be partitioned into the following functional equipment or component groups:

- Load power processing and conditioning units (PPUs)
- Control, display and protection (CDP) equipment
- Transmission/Distribution wires and cables
- Central power conversion equipment (CPUs)

Load power conditioning is generally performed by electronic power supplies which form part of the load utilization equipment. Since they process and control electric power and have a significant influence on the distribution voltage, they are properly included as part of the PDC subsystem and will not be considered part of the load.

Control, display and protection equipment consists of switchgear, sensors, monitoring devices, and circuitry which provides for on/off control of individual loads, monitors EPS status, and performs switching functions to avoid dangerous overloads. Cabling and connectors provide for transmission of electric power from a source to a local bus and for distribution from a local bus to several nearby loads. Central power conversion equipment is used to convert the generated voltage or frequency to a level more suitable for transmission or to change the transmitted voltage to one or more voltages for distribution.

Selection of a PDCS configuration must be based on the requirements of the installed electrical load equipment and the characteristics and constraints imposed by the power generation subsystem (EPGS). Our study therefore consists of comparative evaluations of the performance of candidate PDCS configurations for typical load requirements and different types of EPGS as will be encountered in future Space Station, Shuttle, and aircraft missions.

In addition to the power requirements of the load utilization equipment and the design of the EPGS, the remaining independent input variables which determine a PDCS configuration are:

- Transmission voltage and frequency
- Distribution voltage and frequency
- Redundancy and backup modes
- Control, display and protection method
- Checkout and maintainance procedure

As indicated in Figure 1.1, our study started with a parametric analysis of the performance of each functional element of the PDCS as a function of these configuration input variables. Depending on the particular component in question, performance is evaluated in terms of weight, power dissipation, failure rate, cost, and availability or development status. Results of these studies are described in Section 3.0, "Component Analyses". They provide the desired data base for selecting candidate PDCS design configurations.

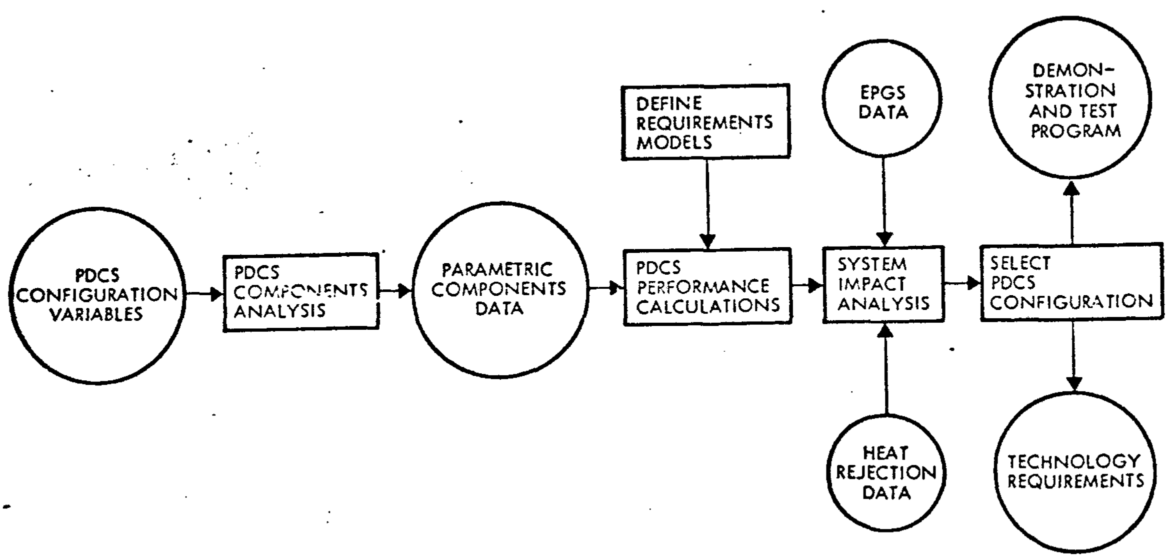


Figure 1.1. Study Procedure

Since the performance of a PDC subsystem depends on the number, location, and power requirements of the loads which must be served, different PDCS configurations can only be compared for equal load requirements. Based on concurrent Phase B Space Station and Space Shuttle study programs, we therefore have defined reference or model requirements for purposes of PDCS tradeoff studies. These models define the number of separate load utilization equipments by type, their locations with respect to the power source, the number of local power distribution buses, the average and peak power requirement seen by each bus, and the redundancy level for a typical modular 12-man Space Station and a Shuttle Orbiter. Simplified models for future commercial aircraft power requirements based on results of a recent study performed by AiResearch Corp. under NASA Contract NAS12-659 (Reference 1) and typical requirements for a future military aircraft based on the power profile of the B1 aircraft were also defined. The derivation of these models is presented in Section 2.3.

Having developed parametric performance data for each element of the PDCS and after establishing all the detailed PDCS and vehicle interface requirements as presented in Section 2.0, it is possible to calculate the complete subsystem performance for each candidate configuration and for each of the model load requirements. Since the basic parametric input data exists in terms of curves and specific performance parameters such as weight per KW output, most of these calculations can be performed manually. This has the added benefit of providing better insight into the relative importance of various component changes and their effect on subsystem performance. Included in these calculations is the required EPGS output power and the reflected EPGS and heat rejection system weight due to the power losses of the PDCS equipment. Selection of the candidates and comparative performance calculation also includes consideration of the dynamic performance requirements and characteristics as described in Section 4.0.

The final task of the program consists of an analysis and critical evaluation of the comparative performance calculations leading to realistic and practical recommendations for future electric power distribution and control standards. This also discloses requirements for new technology and component improvements and enables definition of experimental feasibility and technology demonstration programs.

A summary of the conclusions and recommendations is contained in Volume I of this report.

2.0 ANALYSIS OF REQUIREMENTS AND INTERFACES

The ultimate purpose of the power processing, distribution and control subsystem is to deliver electrical power of proper quality to every item of load utilization equipment when and if required. Design of the PDCS therefore requires a complete understanding of the load equipment, its location, power quality and quantity requirement, and its duty cycle. Detailed definition and sizing of the PDCS can be accomplished when the complete set of load utilization equipment and its usage aboard a given vehicle is defined and the generator configuration has been chosen. Before PDC configuration trade studies can be made, all the requirements imposed on the PDC subsystem for a specific type of vehicle must be determined. In this section we will present the following results of our investigations:

- Implication of reliability and safety requirements
- Voltage and frequency requirements of different types of load utilization equipments
- Typical load lists and power requirements for Space Station, Shuttle, and aircraft missions which serve as "requirements models" for PDC performance analyses
- Electric power generation subsystem (EPGS) and heat rejection interface requirements for each type of aerospace vehicle.

Before embarking on a study of detailed electric power requirements for different missions, let us consider briefly the basic function for which electric power is utilized. This will prove useful for categorizing different types of load utilization equipment.

Electric power is used for the following purposes:

- Intelligence functions

    Communications
    Data processing and recording
    Computation
    Sensing and display
    Instrumentation
    Other

- Mechanical Functions

  Rotary motion (motors)
  Linear motion (actuators)
  Development of force

- Heating and Cooling

- Lighting

- Electrical Energy Storage

  Battery charging
  Electrolysis

- Experiments and Special Applications

  Scientific laboratory
  Electronic countermeasures
  Laser weapons
  Electric propulsion
  Welding
  Other

Detailed power requirements for each function depend on the mission and the mission phase. In general, intelligence functions are performed by electronic or avionic equipment and always require high quality electric power. Mechanical functions may be performed by electric motors and actutors or by hydraulic and pneumatic devices. Although the vehicles considered in this study use both electric and hydraulic motors, only the electric motors are included in the load analysis. Heating and cooling can be provided by means other than use of electric power, but for safety reasons generally use electricity. Lighting and electrical energy storage always require electric power. Table 2.1 gives rough estimates of electric power utilization by category for the basic aerospace missions of interest to this study program. It shows that the proportions of power delivered to the different types of loads depend strongly on the mission so that we should not expect that the same PDC concept would be optimum for all missions.

Table 2.1. Utilization of Generated Electric Power

End Use	Space Station	Space Shuttle	Commercial Aircraft	Military Aircraft
Intelligence Functions	15%	34%	11%	7%
Mechanical Functions	6%	22%	36%	12%
Heating and Lighting	7%	18%	43%	8%
Payload and Experiments	20%	4%	-	63%
Power Distribution and Processing	10%	22%	10%	10%
Elec. Energy Storage	42%	-	-	-
Total Useful Load	40 KW	10 KW	125 KW	200 KW

2.1 RELIABILITY AND SAFETY REQUIREMENTS

Reliability is usually expressed as the probability that a given piece of equipment, a subsystem, or a system will function as intended in a specified environment for a stated length of time or number of operations. The basic reliability requirement for the PDC subsystem is that the presence of the PDCS should not significantly degrade the reliability of the overall vehicle. In other words the PDCS reliability shall be compatible with the reliability of other essential subsystems. In this PDC study program we are concerned with the relative reliability of alternative configurations and will not attempt to make absolute reliability assessments.

Since there is always some finite probability of equipment failure, requirements are placed on the consequence of failures. For the Shuttle and aircraft where on-board repair is not possible, we have assumed that operational capability must be maintained after any two credible independent equipment failures and safe return of the crew or passengers must be possible after a third failure. This is normally referred to as FO/FO/FS reliability. For the Space Station we have assumed that FO/FS reliability will be adequate and that main bus failures are not credible.

Safety requirements are intended to prevent hazards to the crew either through direct contact with the equipment (such as electrical shock) or as a result of failures which prevent a safe return and landing of the vehicle. Redundancy of power sources, cabling, and load equipment needed for return and landing along with physical separation so that destruction by fire of one set of equipment does not automatically destroy the redundant set is a safety requirement applicable to all manned missions considered herein.

A single set of equipment consisting of a generator, power conditioning, distribution and control equipment, plus loads required for mission operation and crew safety shall be called a channel. By definition, a single failure in a channel causes mission failure or loss of crew if alternate channels or back-up operating modes are not available. For purposes of this study program we have assumed that the PDCS must serve essential load equipment even if alternate modes which require reconfiguration of load equipment are available. To meet multiple failure effect criteria such as FO/FO/FS or FO/FS requirements, channel redundancy must be provided including redundancy of EPGS and PDCS equipment.

Figure 2.0 diagrammatically illustrates a three-channel electric power system and connected essential and non-essential loads Z_1 thru Z_n.

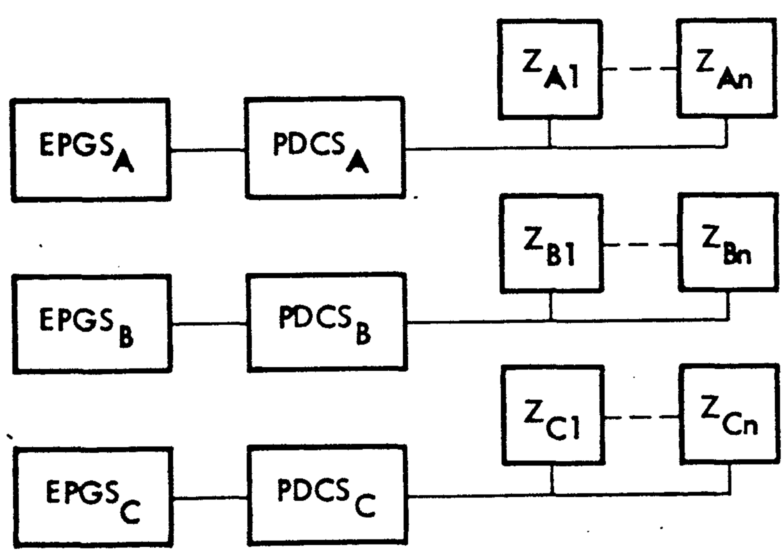


Figure 2.0. Isolated Three Channel System

If essential loads are triple redundant and loads required for mission success are dual redundant, the three-channel system meets the FO/FS failure effect criterion. The system reliability, however, can be improved if interconnections between channels can be made. The following possibilities exist:

- Paralleling of EPGS
- Paralleling of loads
- Interchange of EPGS among channels (cross strapping of generator)
- Interchange of loads among channels (cross strapping of loads)
- Combinations of above

In each case, it must be possible to remove a failed element from a given channel and use the unfailed elements of this particular channel in combination with unfailed elements of any other channel to form a new operational channel. The switching may be done manually or automatically, but in either case we have assumed that the probability of a switching failure is negligible. If channels are connected in parallel, frequency synchronization and load balancing must be provided to avoid instability or circulating currents among paralleled channels. In the case of cross strapping the remaining channels are isolated and may have slightly different voltage and frequency. They also can be loaded differently.

The reliability of a single isolated channel is

$$R_{ch} = R_g R_p R_z \qquad (2.1)$$

where

R_g = Reliability of EPGS

R_p = Reliability of PDCS

R_z = Reliability of critical load equipment supplied by PDCS

In general if n identical channels are available, and only one channel is required for successful system operation, then the system reliability, if there are no interconnections among channels, is given by

$$R_s = 1 - (1 - R_{ch})^n \tag{2.2}$$

or $$S_s = S_{ch}{}^n \tag{2.3}$$

where S_{ch} is the single channel failure probability

and S_s is the probability of system failure

With interconnections at the generators so that any generator can feed any load channel through the appropriate PDCS, the system reliability becomes

$$R_s = (1 - S_g^n)\ (1 - S_L{}^n) \tag{2.4}$$

and $$S_s = 1 - (1-S_g{}^n)\ (1 - S_L{}^n) \approx S_g{}^n + S_L{}^n \tag{2.5}$$

where $S_g = 1 - R_g$ = generator failure probability

$S_L = 1 - R_p\ R_z$ = PDC and load failure probability

The same equations with appropriate redefinitions of S_g and S_L apply for paralleling or cross strapping at the load side of the PDCS. Equation 2.5 is plotted in Figure 2.1 for a three-channel and four-channel system and can be used to determine how the reliability of the PDCS affects the system reliability, and hence is all that is necessary to check whether the PDCS reliability requirement is met once values for load, generator, and PDCS reliability are established. This reduces the reliability trade-off problem for different PDC configurations to a single-channel PDCS reliability study.

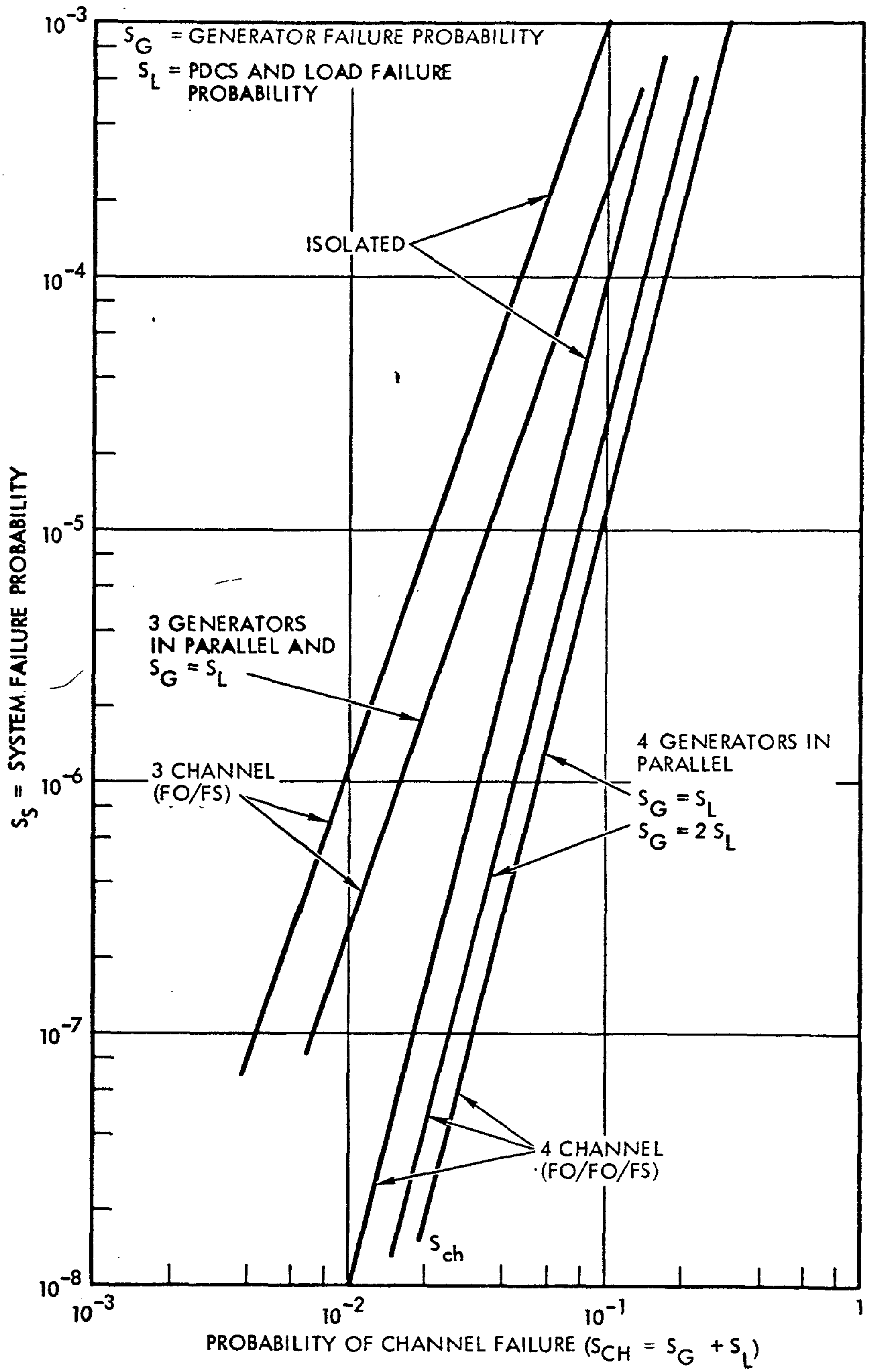


Figure 2.1. Effect of Paralleling or Cross Strapping on Redundant Systems

2.2 CHARACTERISTICS OF LOAD UTILIZATION EQUIPMENT

Power utilization equipments can be classified according to the type of electric input power required for their operation or in accordance with the basic function the load equipment performs. Since a particular load may operate successfully with several kinds of input power, we have classified load utilization equipment according to its basic function and will now discuss the input power requirements for each functional category. The following types of load utilization equipment will be considered:

- Electronic Equipment
- Electromechanical Equipment
- Heaters
- Lights
- Experiments and Payloads
- Electrical Energy Storage

2.2.1 Electronic Loads

This category of power utilization equipment covers a broad spectrum of units which perform many kinds of "intelligence" functions. It includes computers, amplifiers, transmitters, receivers, instrumentation, electronic displays, and many other devices. For purposes of this study, we will assume that electronic loads are characterized by the fact that they require regulated input power at one or more voltage levels and therefore cannot be supplied directly from the primary power bus. Every electronic load is assumed to require a power processing unit (PPU) which converts the distributed (primary) power to the several regulated voltages (secondary power) required by the load. We further have assumed that the PPU is packaged so that it forms part of the line replaceable unit (LRU) which contains the electronic load. The PPU thus constitutes the power supply section of the electronic equipment which we have considered as a single electronic load. It should be noted, however, that there is no loss of generality if the PPU itself forms one LRU and the load utilization equipment is contained in a separate LRU. In every instance we have considered the PPUs (or power supplies) as part of the PDC subsystem no matter where they are located or whether they are furnished as part of the load equipment.

The secondary voltage and power quality requirements depend on the circuit designs within the electronic load equipment and therefore cover the full range from low dc voltages to very high voltages. Ac voltages are required for synchros, small torquers and gyros which form part of certain electronic loads. Reduction or standardization of secondary power requirements would simplify the choice of primary power especially if the secondary voltage and frequency could be the same as the primary (distributed) voltage and frequency. Unfortunately, standardization of all secondary power requirements for electronic loads does not appear feasible because of the large variety of circuit design approaches which are possible and required to implement the many functions provided by electronic equipment. It is useful, however, to make a distinction between digital electronic equipment and non-digital or analog equipment because partial standardization already exists in digital circuit design so that some generalizations regarding secondary power requirements may be made.

Table 2.2 lists secondary power requirements for some typical digital electronic loads. This type of equipment consists largely of low power logic circuits and arrays of memory elements. If bipolar transistors are used in the logic circuits, the supply voltage is typically 5 Vdc regulated to $\pm5\%$. If field effect transistors are used for logic, then the required supply voltage is typically in the range of -12 to -18 Vdc. In either case integrated circuits are available so that standardization of voltage at least within a given family of IC logic elements may be assumed. The memory elements of digital electronic equipment can be mechanized in a

Table 2.2. Typical Power Requirements for Digital Electronic Equipment

Type of Load	Power Range in watts	Voltage	Voltage Regulation	Maximum Current Amp	% of Pwr. to Load	Notes
Digital Processors	3-300	+ 5 Vdc	±5%	50	83	Assumes TTL or DTL
		- 5 Vdc	±3%	5	8	1-50 mw per gate
		+15 Vdc	±3%	1.5	8	t_{rise} < 50 nsec
		-15 Vdc	±3%	0.3	1	
Processor (High Voltage Logic)	3-300	+15 Vdc	±6.6%	16	80	
		-15 Vdc	±5%	1	5	t_{rise} <100 nsec, 50 mw/gate
		+28 Vdc	±5%	1.6	15	
Core Memory	50-250	+40 Vdc	±4%	0.75	12	Current source
		+20 Vdc	±4%	6.5	52	Current source
		+ 5 Vdc	±5%	15	30	
		- 5 Vdc	±5%	3	6	
Plated Wire Memory	85	+10 Vdc	±5%	1.3	15	Current source
		+ 5 Vdc	±5%	9.0	53	
		- 5 Vdc	±5%	1.5	9	
		-10 Vdc	±5%	1.5	18	Current source
		-15 Vdc	±5%	.3	5	
MOS Memories & Logic	5-130	+14 Vdc	±5%	0.3	5	250 KHz clock
		+ 5 Vdc	±5%	9.0	35	
		-14 Vdc	±5%	4.0	43.	
		-28 Vdc	±3%	0.8	17	

variety of ways: core memories, plated wire memories, and use of IC logic elements being the most prevalent. For core and plated wire memories the power supply must have the characteristics of a current source. In addition to logic and memory elements, digital electronic equipment contains wave shaping circuits and buffer amplifiers which require dc voltages in the range of 5 to 20 Vdc of either polarity. In summary, digital electronic equipment requires dc secondary power in the range of 5 to 20 Vdc. Both positive and negative voltages are required. In order to avoid dynamic interactions due to the large output current pulses, the output impedance of the secondary power supply (PPU) must be low and the PPU must be located in close proxmity to its output load.

Table 2.3 lists secondary power requirements for a variety of non-digital or analog type of electronic power utilization equipment. No conclusions can be drawn from the brief survey of existing avionic and spacecraft electronic equipment which was conducted to prepare this table except that one or more regulated dc voltages are required even for very simple loads such as sensors and indicators.

Table 2.3: Typical Power Requirements of Miscellaneous (Analog) Electronic Equipment

Type of Load	Power Range (watts)	Voltage (volts dc)	Voltage Regulation (%)	Current (amp)	% of Load Pwr.	Notes
Amplifiers	1-100	+28	±5	3.3	92	
		+15	±2	0.3	5	
		-15	±2	0.2	3	
Transmitter/ Receiver	10-100	-4000	±0.1	.055	85	Depressed collector TWT type
		-2500	±0.1			
		+250	±1	.0005	-	
		+5	±5	3.0	15	
Transponder	5-200	+28	±1	5.5	76	
		±15	±5	0.8	12	
		+5	±5	5.0	12	
Data Recorders	10-30	+28	±10	0.7	66	
		±15	±2	0.2	20	
		+5	±5	1.0	14	
CRT Displays	100-200	14,000	±1	neg.	<1	
		5,000	±1	neg.	<1	
		+200	±3	.025	4	
		±60	±3	.16	18	
		±15	±3	.66	18	
		±5	±5	7.0	58	
		-100	±3	.05	4	
Gyro Package	5-20	+28	±1	0.7	100	
Spark Igniter	3-300	+28	+10	.1-4	100	1-10 msec pulses for 1 to 5 sec
		10,000	-	neg.	-	

2.2.2 Electromechanical Loads

This section deals with motors and actuators designed to provide mechanical motion or force. Although the terms are often used interchangeably, motors generally provide continuous rotary motion while actuators move a mechanical object through a short distance against a restraining force.

In the types of vehicles of interest to this study motors are used to drive fuel pumps, fans, coolant pumps, large valves, and for deployment of aerodynamic surfaces or structural elements. Their output power requirement falls within the range of 0.1 to 10 horsepower. Smaller motors such as gyro spin motors are considered part of the electronic load. Motors driving loads greater than 10 hp usually are hydraulic motors and hence not part of the vehicle electric power utilization equipment. Solenoid type actuators are used to operate hydraulic and pneumatic valves, remotely controlled mechanical latching devices, electromechanical relays and contactors. Low power valve drivers such as those which operate the pilot valves in a hydraulic flight control subsystem generally are supplied directly from the flight control electronic package which also contains the circuits for solving the flight control logic equations. In that case the actuator does not constitute a load seen by the PDC subsystem but has been considered part of the flight control electronic unit.

The types of motors which may be used aboard advanced manned aerospace vehicles are shown schematically in Figure 2.2. Because of the stringent reliability and life requirements placed on all vehicle equipment, we have excluded all motors which use brushes and slip rings or mechanical commutators from further consideration.

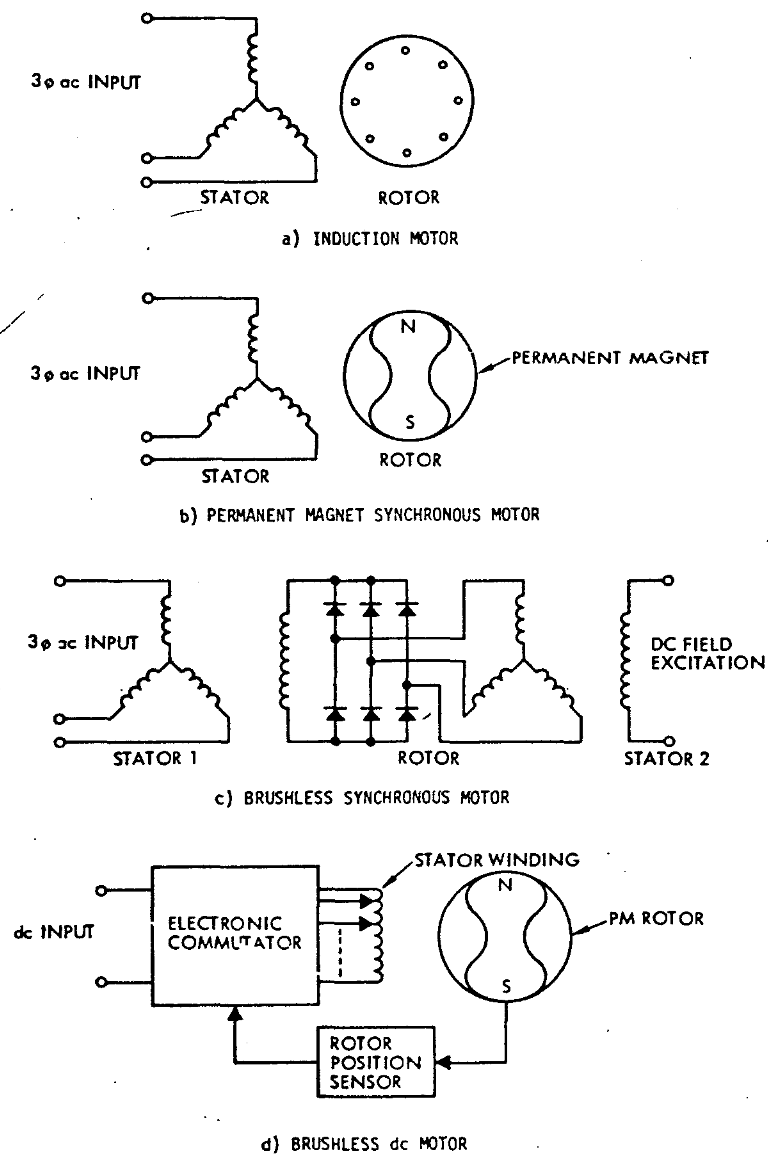


Figure 2.2. Electric Motors

a) <u>Induction Motors</u>

The ac induction motor is the most common type for airborne applications because of its simplicity and low weight. Performance curves for a series of typical 12,000 rpm 400 Hz, 3 phase aircraft motors are shown in Figure 2.3 (Reference 2). Specific weight, efficiency, and power factor of 400 Hz motors are plotted as a function of rated torque in Figures 2.4 and 2.5 (Reference 1).

PER UNIT VALUES FOR VARIOUS STATOR STACK LENGTHS

WEIGHT (LBS)	12.2	13.2	15.0	17.3
STACK LENGTH (IN.)	1.5	2.0	2.625	3.25
HORSEPOWER	4.0	6.0	8.4	11.0
TORQUE (OZ-FT)	30.0	45.0	63.0	82.0
AMPS	12.3	18.7	24.4	32.0

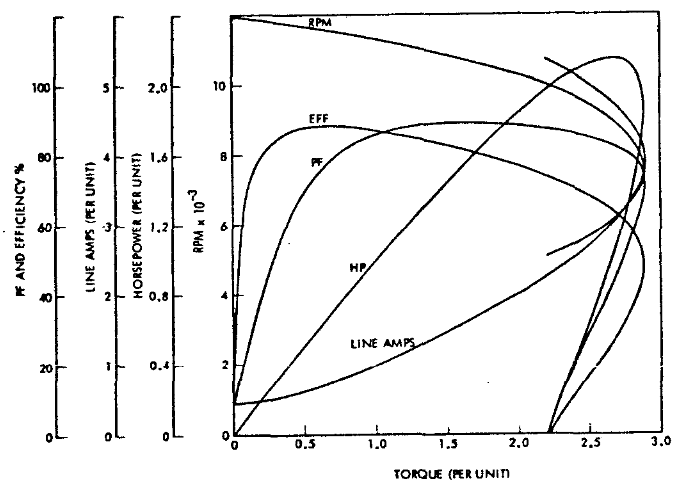


Figure 2.3. Typical Motor Performance Curves

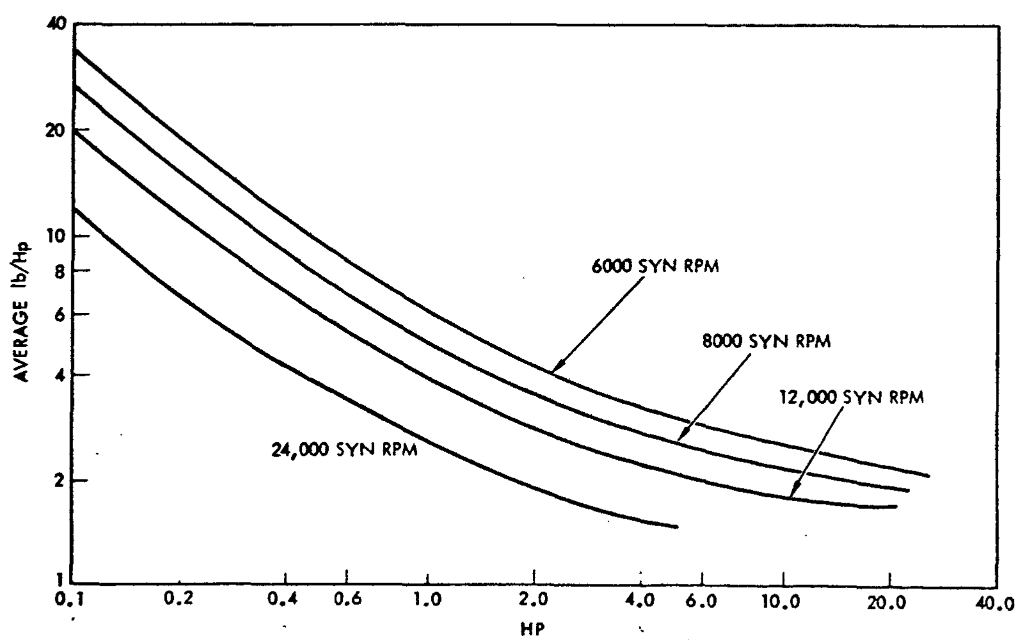


Figure 2.4. Average lb/hp versus hp, Aircraft ac Induction Motors, 400 Hz, 115 v/phase

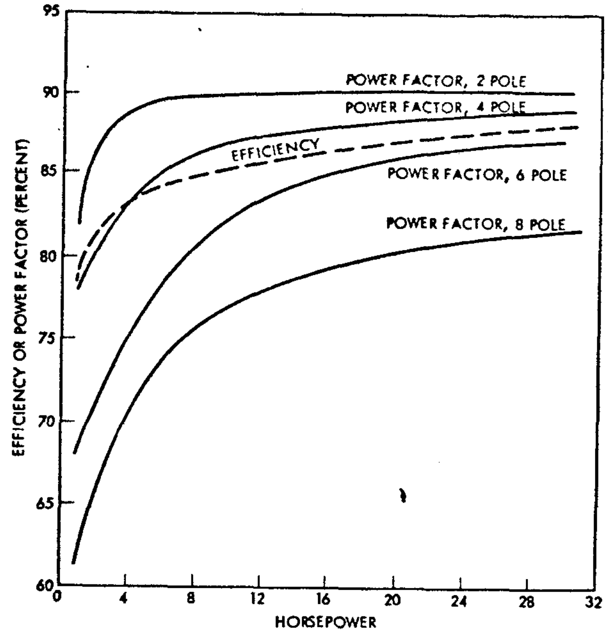
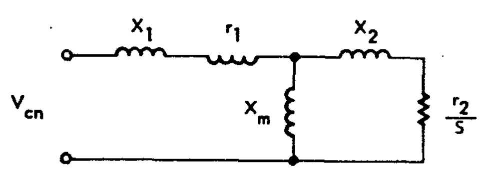


Figure 2.5. Approximate Efficiency and Power Factor, 400 Hz, 3 Phase Aircraft Induction Motors, Conventional Materials

The equivalent circuit of the induction motor is shown in Figure 2.6.



r_1 = STATOR RESISTANCE

x_1 = STATOR LEAKAGE INDUCTANCE

x_2 = ROTOR LEAKAGE INDUCTANCE

x_m = MAGNETIZING INDUCTANCE

r_2 = ROTOR RESISTANCE

S = SLIP = $\frac{\omega_s - \omega_b}{\omega_s}$

ω_s = SYNCHRONOUS SPEED (RAD/SEC) = $\frac{4\pi f}{p}$

f = SUPPLY FREQUENCY

γ = NUMBER OF STATOR POLES

ω_b = ROTOR VELOCITY IN RAD/SEC

Figure 2.6. Equivalent Circuit for ac Induction Motor

As viewed from the ac input power lines, an induction motor looks like a conventional transformer with variable load impedance. At zero speed ($s = 1$), the input current has its maximum value which may be several times as great as the rated current under normal running conditions. Any circuit breaker in the power lines must therefore be rated for the inrush current during starting, or the line voltage must be reduced until operating speed is reached. Speed control of induction motors is generally not required in aerospace vehicle applications but can be provided by changing the amplitude or frequency of the applied line voltage. For nominal supply frequency of 800 Hz or higher a gear train is required to keep the load rpm at reasonable values. The relative weight of high frequency motors and gearing as a function of frequency is shown in Figure 2.7 (Reference 3).

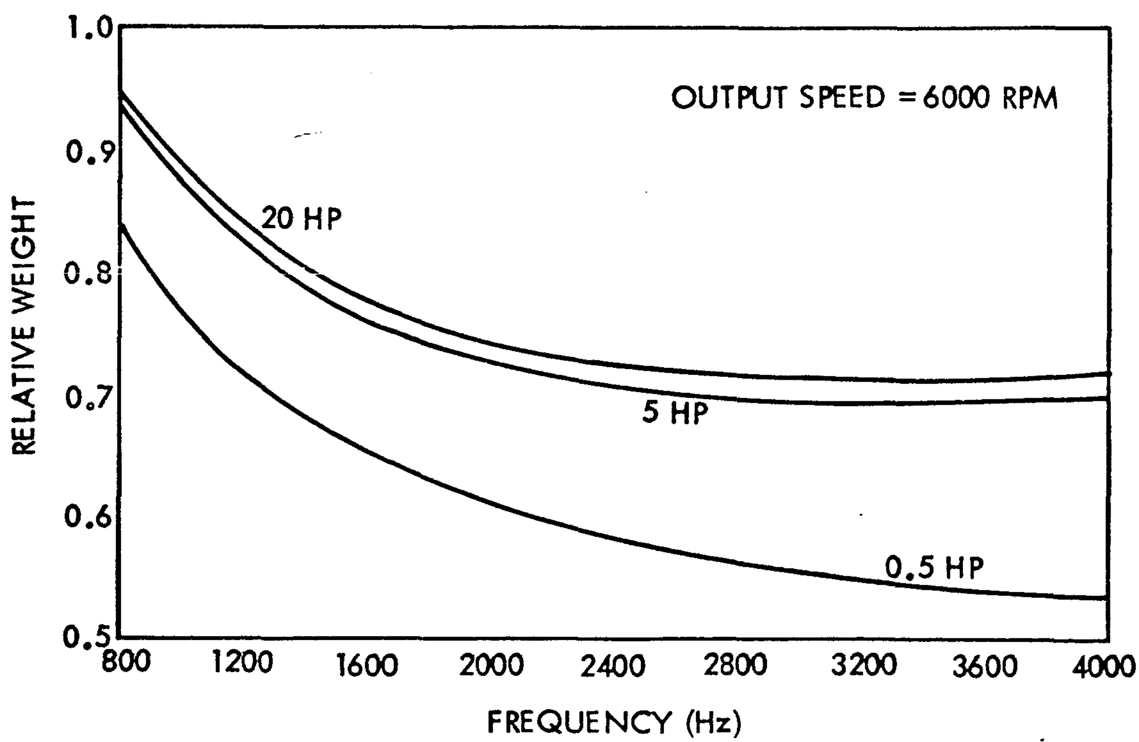


Figure 2.7. Relative Weight of Gear Motor to Direct Drive Motor for 6000-rpm Output Speed

If only dc power is available from the load bus, a power processing unit or inverter which converts dc to 3 phase ac is needed to drive an induction motor. Such an inverter need not deliver sinusoidal voltage and can be designed to limit the inrush current during start up. Design and performance characteristics of motor drive inverters are described in

Section 3.4 of this report. If the inverter and motor are integrated in one package, the combination is sometimes called an inverter type brushless dc motor.

b. Synchronous Motors

Permanent magnet synchronous motors are not as common as induction motors and have different speed torque characteristics. They are available in fractional horsepower ratings but will not be considered further in this study since their impact on the PDC subsystem is similar to that of the induction motor.

Brushless synchronous motors of the type shown in Figure 2.2c are used extensively for large industrial drives because of their high reliability and favorable speed-torque characteristics. They are not competitive with induction motors in the power ratings of interest to this study.

c. Brushless DC Motor

As indicated in Figure 2.2d,slip rings and brushes can be eliminated in a dc motor by use of an electronic commutator and a permanent magnet instead of a wound magnet rotor. An alternate method would be use of an ac exciter and rotating rectifiers with a wound field rotor as shown in Figure 2.2c. Because of limitations on semiconductor ratings, brushless dc motors have been restricted to relatively low horsepower ratings. Although several different circuit approaches for mechanizing the electronic commutator have been proposed, they all rely on sequential switching of transistors or SCRs to produce a rotating stator field. A typical approach is described in Reference 4. The electronic commutator is a special purpose power processing unit whose weight, reliability, and cost depend on specific design techniques, motor rating, and control characteristics. It may be expected to be somewhat heavier and more complicated than an inverter for an induction motor. Since the motor itself is also somewhat heavier than an induction motor of equal rating, only inverter type brushless dc motors have been included as possible load equipment for this study. Research and development work on electronic commutator type brushless dc generators, however, may yield advanced designs which represent improvements over inverter/induction motors and hence should be included in future studies.

d. Actuators

In all electromagnetic actuators current supplied to a coil changes the energy stored in a magnetic field and produces mechanical motion which changes the inductance of the coil. In a simple solenoid actuator the force is given by

$$f = 1/2\ i^2 \frac{dL}{dx} \qquad (2.6)$$

Actuators can be designed to operate on either ac or dc current. In order to save electrical energy, they often contain a mechanical latching mechanism so that the input power can be removed after the desired mechanical motion has been achieved.

Solenoid actuators present an inductive load L with series resistance R to the power lines and generate a counter emf during the time that the mechanical motion occurs. Upon application of voltage the current will increase exponentially with time constant L/R but the rate of change of current will drop as soon as the actuated elements start to move. Figure 2.8 shows the power required by typical pilot valve actuators as a function of valve port diameter.

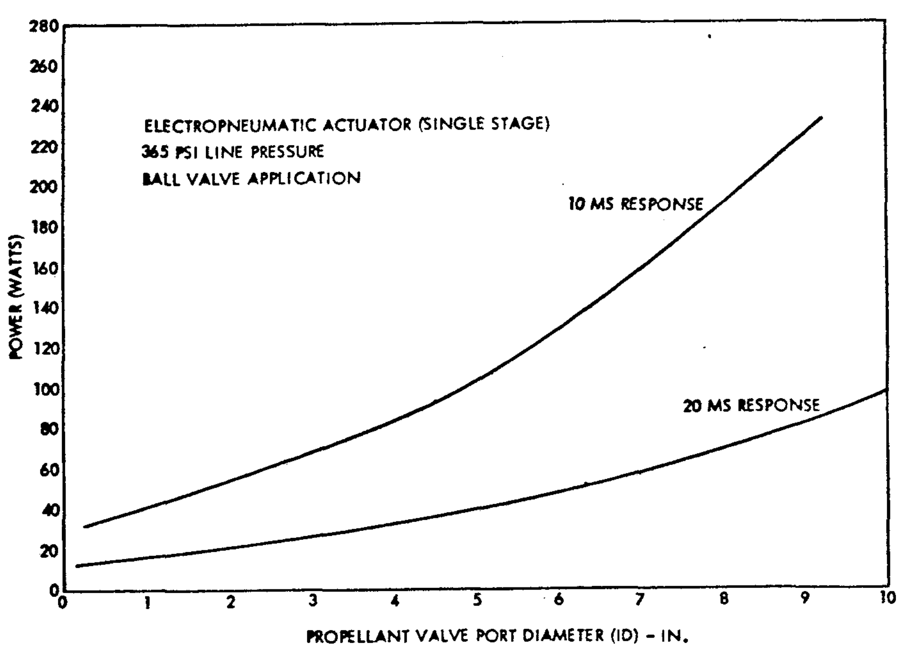


Figure 2.8. Pilot Valve Power

Conventional aerospace actuators are designed to operate on 28 Vdc aircraft power. Typical power requirements and operating times are shown in Table 2.4.

Table 2.4. Actuator Power Requirements

Application	Power in Watts	Duration, Sec.
Small Pilot Valve (Hydraulic)	40	Cont.
Pneumatic Valve	10	Cont.
Landing Gear Deployment	170	30
Engine Deployment	350	15
Fuel Valve	80	Cont.
Remotely Controlled Switch		
Power Contactor (40 KVA, 3Ø)	60	<1
Feeder Circuit Breaker (100A, 28 Vdc)	7	<1
Load Control Relay (10A, 28 Vdc)	<2	<1

2.2.3 Electrical Heaters

Electrical heaters consist of resistive elements which provide environmental or localized equipment heating. The electric cooking ovens aboard a commercial aircraft represent a large heating load consisting of ordinary Calrod units. There are no limitations on the input voltage or frequency since heating elements can be obtained with almost any resistance characteristic.

2.2.4 Lights

Interior lighting can be provided by means of fluorescent or incandescent lights. Fluorescent lights are more efficient and are preferred for area lighting. They must be operated on ac for good efficiency and long life and have increased light output as the frequency increases to about 10 KHz. Fluorescent lights require an inductor (ballast) to provide a high voltage transient for starting and therefore present a lagging power factor load to the ac source.

Incandescent lights are used for spot lights and for indicators such as pilot lights. In order to withstand vibration and shock environments encountered on aircraft and boost vehicles, the filament diameter must be made sufficiently large which implies low resistance and low applied voltage. Presently available aircraft incandescent lights are designed for voltages from 3 to 28 volts and may be used on either ac or dc. Incandescent lamps have very low resistance when dark and hence cause a large inrush current following turn-on. The peak of inrush current can be 8 times normal current in large incandescent lamps. Exterior lights use incandescent filaments which are normally rated for 28 volt operation so that the filament can be made sufficiently rugged. For higher voltage and larger bulb diameters, higher voltage ratings are possible.

2.2.5 Electrical Energy Storage

Space vehicles may contain rechargeable batteries or H_2/O_2 fuel cells which constitute an electrical load on the electric power system during the time when they are being recharged. In each case a power processing unit is required which provides dc power at the proper regulated voltage or current level. The efficiency and weight of such a battery charger or power supply for electrolysis of water, as required for the rechargeable fuel cell, depends on the voltage and frequency of primary power and the number of battery or electrolysis cells in series during recharge. The results of the power processing studies contained in Section 3.1 may be used to obtain reasonable estimates.

2.3 REFERENCE LOAD REQUIREMENTS

This section describes the derivation of the PDC requirements models for different types of vehicles which will serve as reference power utilization models or specifications for purposes of PDCS configuration trade studies.

2.3.1 Space Station Reference Model

2.3.1.1 Description

The most advanced manned space mission contemplated for the foreseeable future is a large earth orbiting space station which provides living quarters for up to 12 men and serves as a base for conducting a broad range of experiments and observations from orbit for up to 10 years. A number of basic design configurations for such a station have been proposed in the past. As part of our Power Processing, Distribution and Control Study, we reviewed the results of the Space Station Phase B studies performed by McDonnell Douglas Astrionics Company (MDAC) and North American Rockwell Space Division (NAR) under contract NAS8-25140 and NAS9-9953 respectively (References 5 to 10). These programs provided conceptual designs for two radically different approaches, namely

- A single vehicle 33' Space Station launched by a Saturn booster into a 94 minute earth orbit, and
- A modular Space Station which is built up in orbit from completely assembled modules transported into space by the Space Shuttle.

Reports covering the configuration, electric power requirements, and proposed power system configurations for a 33' Space Station became available shortly after the start of our study program. Design studies for the modular Space Station were performed after completion of the 33' Station definition and concurrently with our own PDC studies. Although no formal reports were available, we were able to establish electric power requirements and load equipment inventories which are representative of any future Shuttle based modular Space Station on the basis of informal meetings with NAR and MDAC electrical power system designers, during which copies of preliminary design calculations and informal briefing charts were obtained.

Since it is unlikely that a very large single-section Space Station will ever become a reality, only modular Space Station configurations have been considered in our studies. The characteristics of such Shuttle launched Space Stations which influence the design of the PDC subsystem may be summarized as follows:

The Modular Space Station (MSS) will operate in a 94 minute earth orbit and experience a maximum eclipse time of 36 minutes. Its operational life will be from 5 to 10 years during which it will be resupplied every 6 months or more often. The MSS is composed of several individual modules which are transported into orbit one at a time by the Space Shuttle. They are permanently linked up in orbit. Figures 2.9 and 2.10 illustrate the NAR and MDAC versions of the 12-man MSS configurations resulting from their Phase B studies and show the sequences in which the modules are docked. Each module fits within the 15' diameter by 60' cylindrical payload space of the Shuttle Orbiter.

Although the purpose and equipment inventory of each module is different they fall into four basic categories, namely Power/Support types, Crew/Operations types, Service/Labs types, and Research/Applications Modules (RAM). Power/Support type modules are the first ones launched and carry a solar array and fuel cells or batteries to supply power for its own operation and for subsequently launched station modules. Crew/Operations modules contain the crew living quarters and various subsystems. The Service/Labs modules contain general purpose laboratories, cargo space, and various support equipment. The RAMS are experiment modules and will all be different. On-board maintenance and repair of every module will be a design objective where possible. All equipment required for crew safety will be triply redundant or back-up modes will be available to achieve Fail Ops/Fail Safe capability.

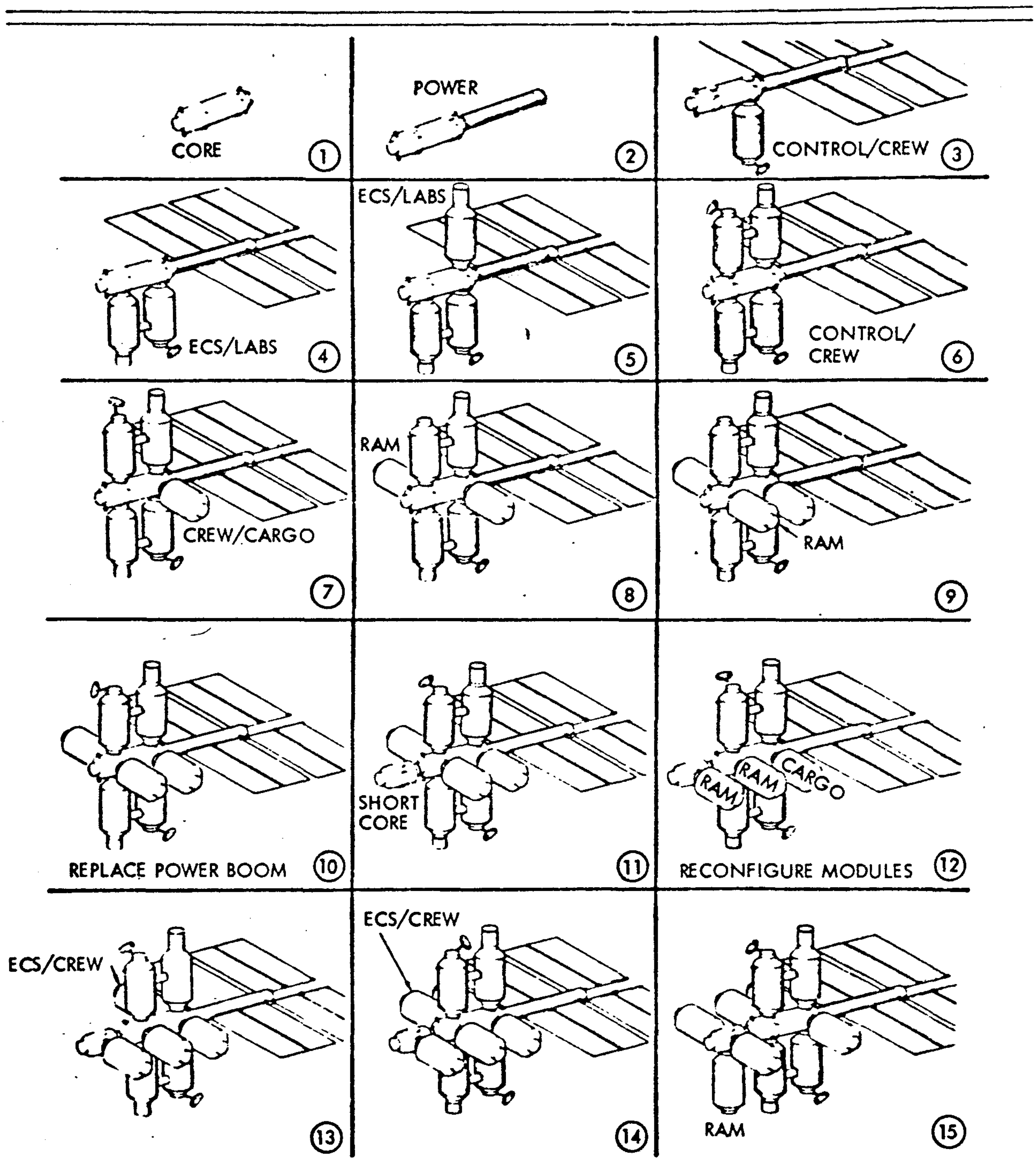
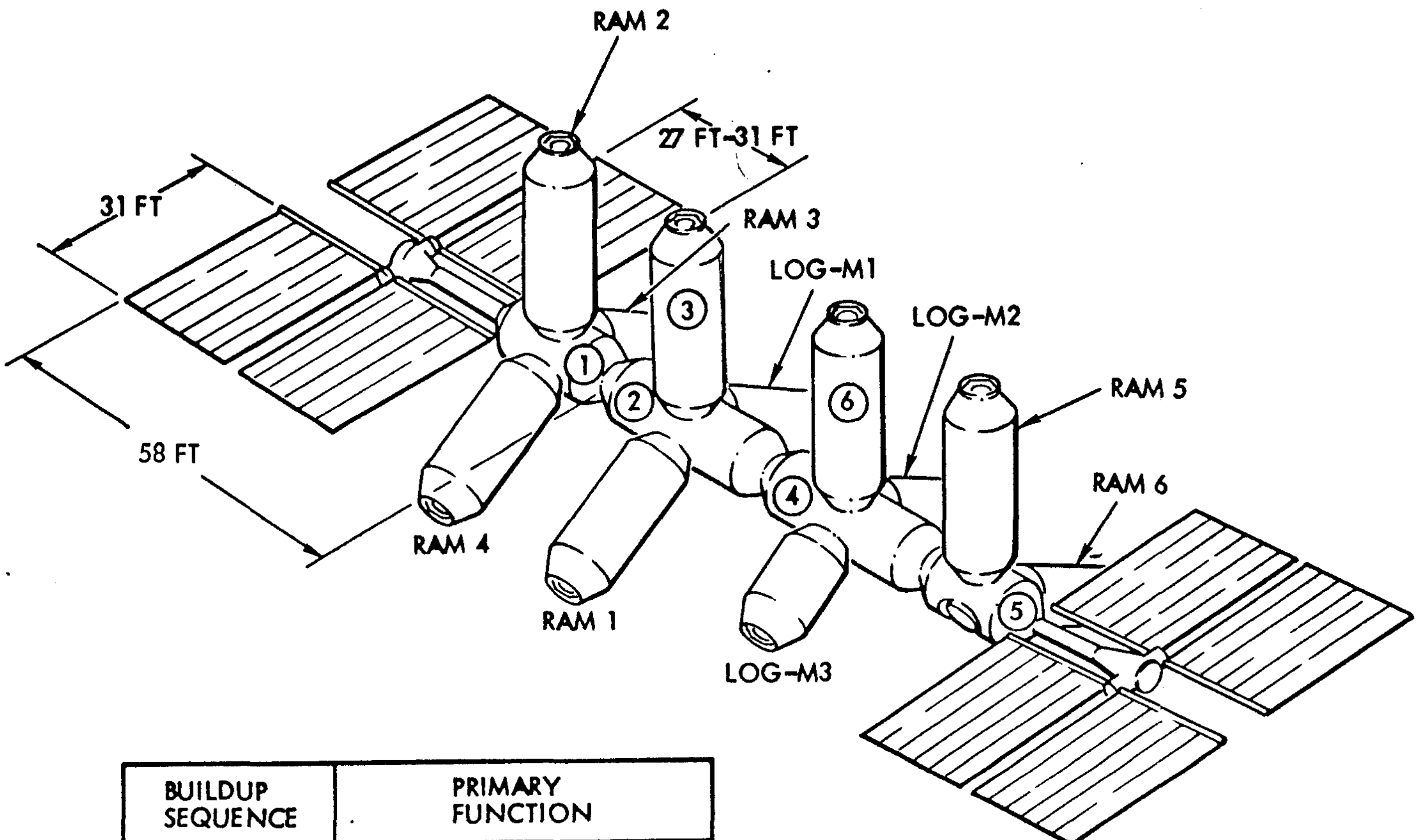


Figure 2.9. Modular Space Station Buildup - NAR Concept



BUILDUP SEQUENCE	PRIMARY FUNCTION
1	POWER/SUBSYSTEMS
2	CREW/OPERATIONS
3	GPL
4	CREW/OPERATIONS
5	POWER/SUBSYSTEMS
6	LABS

Figure 2.10. MDAC 12-man Modular Space Station

2.3.1.2 Power Requirements

Electric power requirements have been estimated by the Space Station Phase B contractors by adding up individual equipment requirements for each module and each subsystem. 24 hour average power requirements as seen by the main load bus in each module are listed in Table 2.5. In each instance the total installed load may be 2-3 times larger than the average power to be supplied by the bus because many loads operate intermittently or are on inactive standby. The peak power to be supplied by each bus can be found only from an analysis of the detailed power profile which has not yet been generated, but will lie within the range of 120-160% of average power for any module (Reference 11). The sustained peak power determines the heat rejection requirements and must be known to size the cabling system.

Table 2.5. 24 Hour Average Power Requirements at Load Bus

MDAC		NAR	
Module	KW	Module	KW
Power/Subsystem	2.8	Core	1.8
Crew/Ops	5.1	Power	0.1
Gen. Purpose Lab (GPL)	5.2	Control/Crew	3.8
RAM (2)	3.7	ECS/Labs	4.7
Total for ISS	16.8	ECS/Labs	1.4
Crew/Ops	3.6	Control/Crew	2.7
Power/Subsystem	1.9	RAM (2)	3.7
Labs	3.4	Total ISS	18.2
RAM (3)	5.1		
Total for GSS	30.8		

The daily average power reuirements by subsystem are compared in Table 2.6 for the MDAC and NAR 12-man configurations. Note that except for the large ECLS power requirement for CO_2 reduction in the NAR Space Station, the subsystem power requirements are quite similar. Table 2.7 gives the equipment count by type based on a computer printout of equipment weight and average power requirement obtained from MDAC. Although not explicitly shown in the computer run, we have included redundant loads in the inventory. About 1,000 separate loads must be served by the PDC subsystem. Electric power system equipment is not included in this table. Although no detailed load lists were obtained from NAR, there are about 2,000 power using components in their MSS version, approximately one half of which are part of the EPS (Reference 12). This means that both modular Space Station designs have about the same power distribution requirements.

Table 2.6. 24 Hour Average Power Requirement by Vehicle Subsystem (KW) for 12-Man GSS at Load Bus

	NAR	MDAC
Environ. Control/Life Support	13.7 (1)	3.8 (2)
Guidance and Control	0.7	0.8
Communications	1.7	0.6
Data Management and Instrumentation	4.2	6.8
Lighting	3.2	2.0
Crew	0.7	0.6
Cargo	0.1	0.5
Propulsion	-	0.7
Power Distribution	1.0	1.1
Contingency	2.5	1.4
Total for Subsystems	27.8	18.3
Experiments	6.0	12.0
Exper. Power Distribution	.2	0.5
TOTAL Load Power	34.0	30.8

(1) Includes 9.6 KW FOR CO_2 management and thermal control power.

(2) Based on chemical absorbtion of CO_2 and O_2 resupply

Table 2.7. Load Equipment Inventory (No. of Units) (MDAC Baseline Configuration

Load Type	Module Designation						Total MSS
	1-Pwr	2-Crew	3-GPL	4-Crew	5-Pwr	6-GPL	
Electronic Equipment-Analog	40	68	18	31	33	10	201
Electronic Equipment-Digital	59	22	38	20	18	16	173
Motors	12	10	8	10	10	4	54
Valve Drivers	74	100	4	20	74	4	276
Lights	25	60	50	50	25	50	260
Heaters	2	14	10	14	2	2	44
Experiments	-	-	20	-	-	20	40
Energy Storage	2	2	2	2	2	1	11
Total	215	276	150	147	164	107	1059

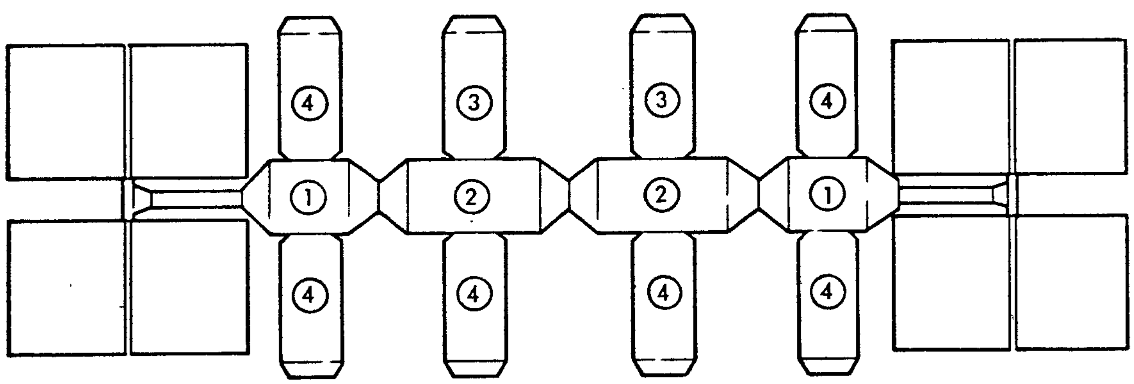
Notes: Does not include elec. power processing, distribution and control equipment.

Table 2.8 lists some of the experiments which are contemplated for the station attached RAMs (Reference 13). Note that in some instances it will be necessary to operate the RAM experiments one at a time in order to stay within the average power capability of the MSS given in Table 2.5.

Table 2.8. Station Attached RAM Loads

Designation	Payload Name	Desired Lifetime	Experiment Power	
			Ave.(W)	Peak (W)
P6A3A	Combined Physics (1983, 1988)	3 Yrs.	3900	5900 (2 Hr.)
P3A3A	Cosmic Ray (1988)	2-5 Yrs.	690	750 (24 Hr.)
E1A2B	Intermed. Earth Obs. (1981)	2-3 Yrs.	4800	5700 (10 Min.)
E1A3B	Complete Earth Obs. (1984)	2-5 Yrs.	4800	5700 (1 Hr.)
C1A2B	Intermediate Comm/Nav. (1983)	2 Yrs.	1500	2500 (1.5 Hr.)
C1A3B	Complete Comm/Nav. (1990)	5 Yrs.	1500	2500 (1.5 Hr.)
M1A3B	Materials Science (Con F-2)	2-5 Yrs.	500	100,000 (Sec.)
T1A3A	Complete Contam. Meas.	2 Yrs.	825	1185 (.5 Hr.)
T4A1A	Medium Duration Adv. S/C Test	4 Mos.	500	-
L8A1B	Life Sciences Lab (Midi) (1981)	2-5 Yrs.	3600	-
L8A2B	Life Sciences Lab (Maxi/Nom.) (1985)	2-5 Yrs.	3600	-

In order to select the best PDC concept, we must know how much power is required by each type of load in addition to knowing the total number of loads to be supplied. We may assume that in spite of the different distribution of load equipment among the various station modules, both the NAR and MDAC configurations will carry approximately the same equipment if the CO_2 management method proposed by NAR is abandoned. We may further simplify our analysis without compromising the objectives of the study by considering the PDC problem for each of the four types of modules and separately consider power transmission from the EPGS in the power modules to the load bus of every module. For purposes of this study, we will therefore define a "model" Space Station which is representative of the maximum loads and transmission distances for either design and has the configuration shown in Figure 2.11.



TYPE	FUNCTION
1	POWER/SUPPORT MODULE
2	CREW/OPERATION MODULE
3	SERVICE/LABS MODULE
4	RAM

Figure 2.11. Model MSS Configuration

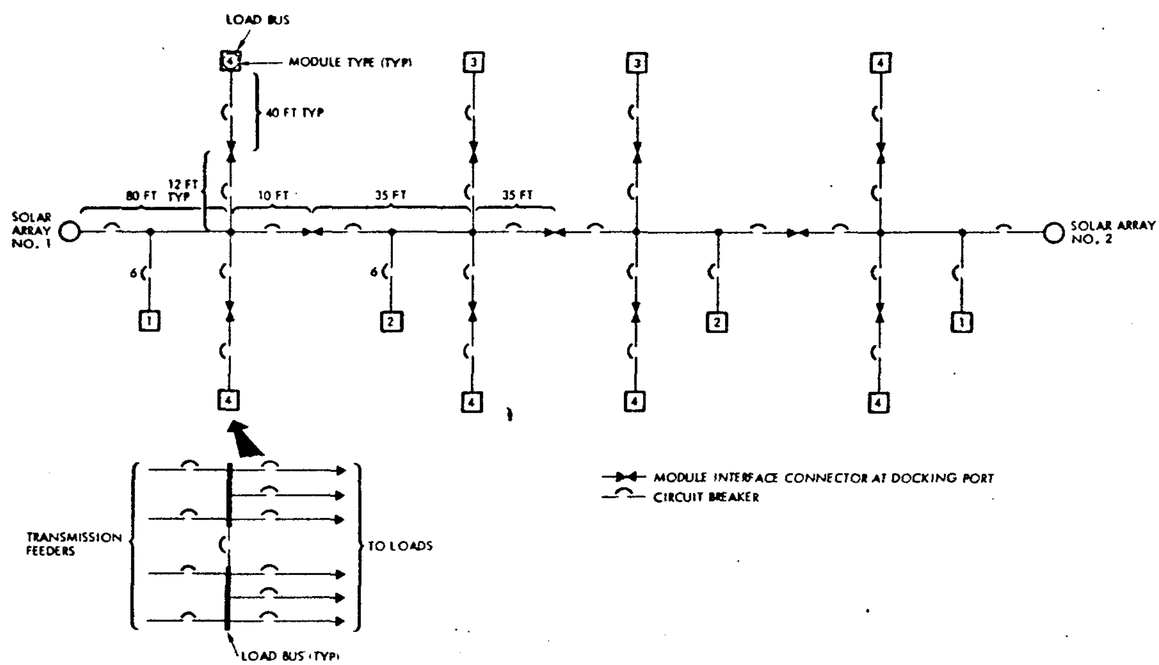


Figure 2.12. Power Transmission for Model Space Station

2.3.2 Load Requirements for Space Shuttle

2.3.2.1 Vehicle Description

The Space Shuttle will consist of a two-stage vehicle for transporting large payloads into low earth orbits. Phase B program definition studies were conducted by three contractor teams headed by MDAC, NAR, and GAEC (Grumman Aircraft Engineering Corp.). These studies resulted in detailed conceptual designs for a manned Orbiter and a manned flyback booster with maximum commonality of equipment for each stage. The flyback booster carries a crew of two and has 12 liquid fuel rocket engines which fire for approximately 200 seconds to boost the Orbiter to an altitude above 110,000 feet. Ten conventional aircraft jet engines are used during landing and for ferry missions. The Orbiter has two large boost engines, smaller orbit maneuvering engines, and four jet engines for landing and atmospheric ferry flights. Since the electric power requirements of the booster are determined primarily by its engines and since present program plans assume use of a recoverable unmanned booster with solid rocket engines, we will not consider detailed requirements for a manned flyback booster.

Requirements for the Shuttle Orbiter were obtained from preliminary equipment lists and briefing charts obtained from NASA/MSFC and from discussions with NAR and MDAC personnel. In addition, draft copies of Phase B study reports (References 14 to 17) became available in July 1971 after completion of our initial requirements studies. The objective of our effort was to determine the key features of a Shuttle Orbiter which have primary influence on the selection of the PDC configuration. We therefore compared all available design information from the MDAC and NAR Phase B studies and defined model requirements which were intended to reflect the worst case requirements as seen by the PDC subsystem for any probable Shuttle Orbiter design. Our requirements model is based on the Orbiter configuration assumptions presented herein.

The Shuttle Orbiter will carry an unspecified payload weighing up to 25,000 lbs. into low earth orbit and may have to remain in orbit for a maximum of 7 days. The payload must fit within a 15 ft. by 60 ft. cargo space and be provided with 500W of electric power from the Shuttle. The Shuttle will return to earth, land like an aircraft, and be ready for its next space flight in 2 weeks. A traffic model of 445 flights over a 10 year period has been postulated.

The Orbiter is a delta wing vehicle about 160 ft. long with internal fuel tanks and payload space. Launch weight is about 850,000 lbs. Crew safety is a primary design requirement and FO/FO/FS operation shall be achieved. Physical separation of redundant equipment prevents loss of the crew in case of fire or local structural damage.

2.3.2.2 Subsystems

Every Orbiter vehicle subsystem interfaces with the on-board electrical power system (EPS). Subsystems may be grouped according to basic functions as follows:

- Structural/Mechanical Subsystems
- Avionics
- Propulsion
- Environmental Control and Life Support (ECLS)
- Power Group

The basic design features of each group of subsystems (or systems) and their requirements for electrical power are as follows:

- <u>Structural/Mechanical Group</u>

This group contains the basic airframe structure, the thermal protection subsystem, aerodynamic surfaces, landing gear, deployment mechanisms for airbreathing engines (ABES), payload handling, and docking provisions. In agreement with Phase B baseline designs, we have assumed that all required mechanical energy is supplied from the hydraulic system. The only electrical power required from the PDC subsystem is intermittent current to actuate hydraulic or pneumatic valve drivers which however have been included in the Power Group for convenience. All electronic sensing, control, and display circuits required for proper operation of the structural/mechanical subsystems are part of the Avionics Group.

- <u>Avionics</u>

This group of subsystems contains all the electronic equipment for guidance, navigation, data management, flight control, communication, display, and control. Table 2.10 lists the LRUs of the NAR and MDAC Phase B Shuttle baseline configurations (References 14 and 15) which are connected to the power distribution bus. In each case, operational instrumentation is not part of the load utilization equipment since all instrumentation sensors and displays are fed from specific electronic LRUs and not the power distribution bus. Instrumentation power requirements therefore are included in the LRU power requirements. Power requirements for pilot and indicator lights are included in panel and display power requirements and are not part of the vehicle's lighting load. The major difference in the number of separate loads is due to the digital interface units which form part of the data bus equipment. The total power requirement for the NAR baseline is smaller primarily because the active redundancy level of the NAR configuration is lower than that of the MDAC baseline design.

Table 2.10. Avionic Load Utilization Equipment

MDAC					NAR				
Qty	Active	LRU Designation	Watts per Unit	Max Load (W)	Qty	Active	LRU Designation	W/Unit	Max Load (W)
Guidance & Navigation									
4	4	IMU	150	600	3	3	IMU	160	480
3	3	Star Tracker	23	(69)					
4	4	Horizon Sensor	15	(60)	2	2	Star Tracker	21	(42)
11	11	Total		600	5	5	Total		480
Flight Control									
8	8	Thruster Elec.	30	(240)	3	1	ATR Data Pkg.	34	34
4	4	Actuator Elec.	90	360	22	22	ACPS Drivers Various	2-7	-
4	4	Rate Gyro Pkg.	15	60	4	4	Aero Surf/TVC Drivers	25-50	190
8	8	Temp & Press. Sense	5	40	1	1	ABES Throttle	5	5
4	4	Accelerometer	3	12	3	2	Rate Sensor Pkg.	12	24
28	28	Total		472	33	30	Total		253
Data Management									
4	4	Computer	450	1800	4	2	CPU	128	256
1	1	Syst-Contr-Unit	52	52	12	10	Main Memory	43-68	480
4	4	IOCU	20	80	3	2	Mass Memory	160	320
52	52	Data Bus Equipment	15-20	640	150	150	Data Bus	1-5	270
2	1	Maint. Recorder	250	250					
2	1	Mass Memory	60	(60)					
65	63	Total		2822	169	164	Total		1326
Comm.									
3	2	S-Band Equ.	75	(150)	1	1	S-Band Equ.	90	90
					2	1	UHF	200	200
2	2	UHF	100	200	4	2	VHF/FM	20/250	250
3	3	DME	75	225	1	1	USBE	20	20
3	3	Glide Slope	6	18	3	3	Inter Veh. Comm.	20	(60)
3	3	VOR/LOC	80	240	3	2	Interrogation	140	280
					3	2	Sig. Proc	13	26
					10	5	Antenna Selector	5	25
					2	2	Decoder	12	24
					2	1	ATC Transp.	54	54
3	3	Radar Altim	100	300	2	1	Radar Altim.	200	200
					1	1	Recorder	15	15
3	3	Audio	20	60	2	1	Audio	20	20
20	19	Total		1043	36	23	Total		1154
Control & Display									
3	3	CRT	127	380	4	4	CRT	106	424
3	3	Symb. Gen	168	504	3	3	Display Elec.	100/205	510
3	3	Micro Viewer	16	48	2	2	Readout	7	14
3	3	Ctr Panels	86E	258	2	2	Alpha Num. Disp.	45	90
4	4	Pilot Panels	120E	480	2	2	Manual Contr.	19	38
					2	2	Keyboard	51	102
					2	2	Mode Contr.	55	110
					4	4	Panels	50/75	250
16	16	Total		1670	21	21	Total		1538
140	137	Total Avionics		6607	264	243	Total Avionics		4751

- Propulsion

All Shuttle Orbiter configurations resulting from Phase B studies contain three separate propulsion subsystems, namely a main propulsion subsystem (MPS), an auxiliary propulsion subsystem (APS) which provides thrust for orbit maneuvering and vehicle attitude control, and an air-breathing engine subsystem (ABES) which is used during powered descent and landing. The MPS uses two 630,000 lb. pump fed H_2/O_2 engines. The engines are gimbal mounted to provide thrust vector control. Phase B Shuttle design studies were based on a power requirement of 1,800 watts ac (400Hz) plus 850 watts dc for each engine. In addition, it was assumed that nozzle extension prior to engine firing would require 4,500W of ac power plus 500W of dc. These MPS electric power requirements probably are not realistic since each engine when finally developed will require somewhat less than 1 KW of power from the vehicle EPS (Reference 18). In addition to the engine proper, the MPS requires electrical power for the propellant handling and monitoring equipment. A list of MPS equipment items based on Reference 15 which require vehicle electric power forms part of Table 2.11.

Table 2.11. Propulsion Group Electrical Load Utilization Equipment

Item	Qty	Active	Watts/Unit	Max Load (W)
Main Propulsion				
Engine Control Elec.	4	4	200	800
Gimbal Drive	4	4	225	900
Type 1 Valve	20	3	42	126
Servo Valves	8	8	50	400
Total MPS	36	19		2226
Aux Propulsion				
Engine Control Electronics	3	3	210	630
Type 1 Valve	40	20	42	840
Type 2 Valve	30	6	75	450
Motor Driven Actuator	2	1	200	200
Gas Generator	8	2	224	448
Igniters	31	2	266	532
Total APS	114	34		3100
ABES				
Booster Pump	3	2	700	1400
Thermal Control	4	4	150	(600)
Fuel Iso. Valves	9	4	60	240
Air Valve	4	4	30	120
Thrust Cont. Syst	4	4	150	600
Ignition	4	2	120	(240)
Fire Detection & Control	4	4	10	40
Oil Tank Iso. Valve	8	8	150	(1200)
Total ABES	40	32		2436

The auxiliary propulsion subsystem contains three pump fed liquid H_2/O_2 engines each rated at 10,000 lbs. thrust for the orbit maneuver subsystem (OMS) and 31 attitude control propulsion subsystem (ACPS) thrustors using gaseous H_2 and O_2 propellant. The propellant handling and conditioning system requires electrical power for gas generators, igniters, and valves as shown in Table 2.11.

The ABES employs four aircraft type jet engines which burn JP4 fuel. They are deployed by the structural/mechanical system after re-entry.

- Environmental Control

The environmental control and crew subsystems group contains the cabin atmosphere controls, equipment heat transfer provisions, food handling, and waste management subsystems. Interior lighting has also been included as part of this subsystem group. ECLS and crew provisions are different for the MDAC and NAR Phase B baseline configurations, but the power requirements are comparable. Electric power using equipment which is part of the ECLS group is listed in Table 2.12 and was obtained from Appendix H of Reference 16, and from Reference 15.

Table 2.12. ECLS & Crew Subsystems Electrical Power Utilization Equipment

Item	Qty	Active	Watts/Unit	Max Load (W)
MDAC				
Equipment Cool Pump	4	2	180	360
Cabin H_2O Pump	4	2	40	80
Compressor	3	1	400	400
Condensate Sep.	2	1	15	15
Waste Mgmt.	1	1	62	62
Oven	3	1	500	500
Spot Light	15	5	13	65
Flood Light	4	2	50	100
Total	36	15		1582
NAR				
Freon Pump	3	1	115	115
Water Pump	3	1	110	110
Temp Contr. Fans	6	2	70	140
Cabin Fans	3	3	40	120
Humidity Control	2	1	55	55
Waste Mgmt.	1	1	200	200
Ovens	3	1	500	500
H_2O Mgmt.	1	1	1000	(1000)
Misc. Htrs	5	4	10	40
Incand. Lights	8	2	10-100	110
Fluor. Lights	14	6	13-100	150
Total	49	23		1530

- Power Group

The remaining electrical power users which must be served by the PDC subsystem fall within the power group which includes the hydraulic power generation and distribution subsystem, controls for the electric power generation subsystem (EPGS) and exterior lights. Table 2.13 lists the individual electrical loads of the power subsystems group based on Reference 15.

Table 2.13. Power Group Electrical Power Utilization Equipment

Item	Qty	Active	W/Unit	Max Load (W)
APU Control Pkg.	4	3	300	900
FC Parasitic Load	4	4	100	400
Heaters	4	2	16	32
O_2 Tank Htr	2	1	1258	(1258)
Backup Pump	2	1	40	40
Valves (Latching)	38	4	6.5	26
Generator Controls	4	4	50	200
Aux Hyd. Pump	4	2	500	1000
Hydro Subsystem Cont. Valves	10	3	30	90
Servo Valves	16	2	115	230
Ext. Running Lights	8	8	5	40
FAA Ldg-Lights	3	3	1000	3000
FAA Exter. Lights	5	5	40	200
Total	104	42		6158

2.3.2.3 Reference Load Requirements

In order to inject realism into our PDCS trade studies, we have defined a baseline or "model" set of load power requirements for Shuttle type vehicles based on the equipment lists of Tables 2.10 through 2.13 and the schematic layout of Figure 2.13.

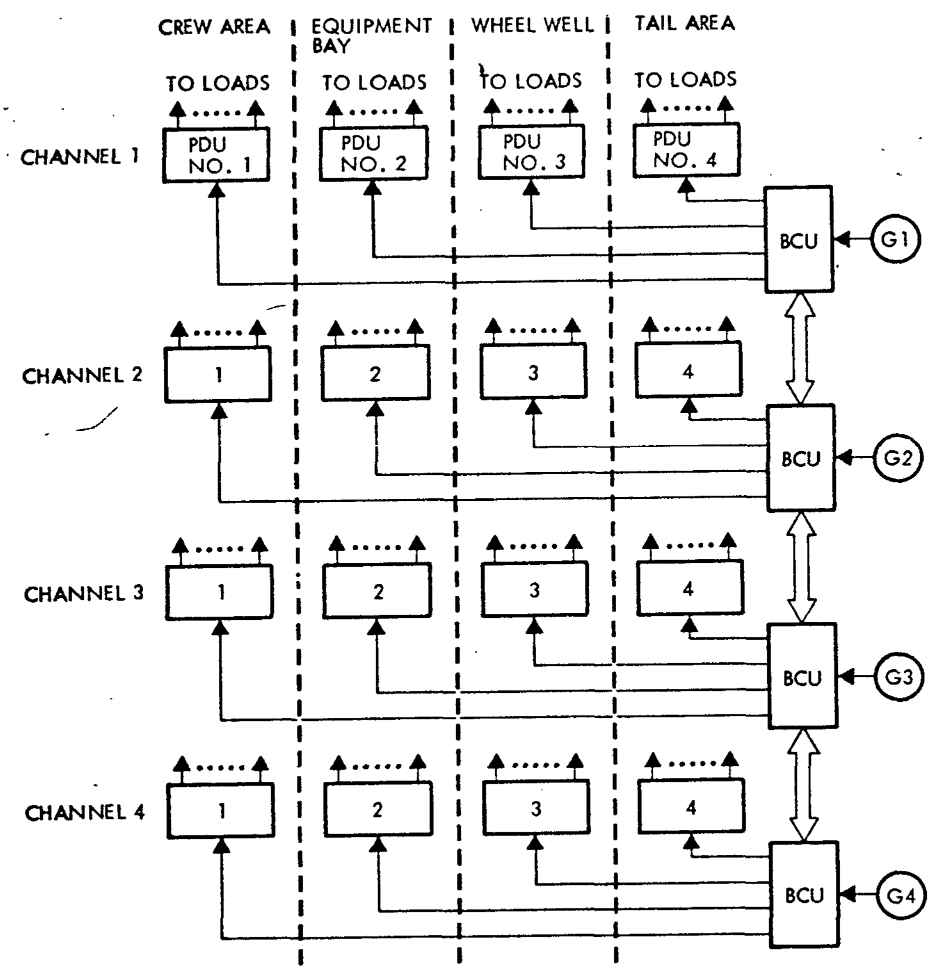


Figure 2.13. Power Transmission and Distribution Model

This requirements model defines the power requirement of each load, its location relative to its power source (in terms of transmission distance l_t and distribution distance l_d) and the operating time per flight. It is used for calculating performance of candidate PDCS configurations and was chosen to contain the representative set of loads as listed in Table 2.14.

Figure 2.14. Load List of Shuttle Orbiter Model

PDU	Item	l_d ft	Pwr/Unit Watts	No. of Units					Max Pwr/Ch (w)			Time On (hrs)	KWH/Ch
				Ch 1	Ch 2	Ch 3	Ch 4	Total	Boost	Orbit	Land		
#1 (Crew Area) l_t=250 ft	Electronics (Analog)												
	CRT	5	127	1	1	1	-	3	127	127	127	168	21.4
	UHF	5	100	1	-	1	-	2	-	-	100	1.2	.1
	VOR/LOC	5	80	1	1	1	-	3	-	-	80	0.5	-
	DME	5	75	1	1	1	-	3	-	-	75	0.5	-
	S Band	5	75	1	1	1		3	-	75	-	165	12.6
	Audio	10	20	1	1	1		3	20	20	20	168	3.3
	Glide Slope Revr.	5	6	1	1	1		3	-	-	6	0.5	-
	Total			7	6	7	-	20	147	222	408		37.4
	Electronics (Digital)												
	Computer	6	450	1	1	1	1	4	450	450	450	168	
	Symbol Gen	6	168	1	1	1	-	3	168	168	168	168	
	C/D Panel	10	120	1	1	1	1	4	120	120	120	168	
	OH Panel	15	86	1	1	1	-	3	86	86	86	168	
	SCU	6	52	1	-	-	-	1	52	52	52	168	
	LOCU	6	20	1	1	1	1	4	20	20	20	168	
	Micro Viewer	8	16	1	1	1	-	3	16	16	16	168	
	DIU	10	12	5	5	5	5	20	60	60	60	168	
	Total			12	11	11	8	42	972	972	972		164
	Motors												
	Fans	15	40	1	1	1	-	3	40	40	40	10	.4
	Waste Mgmt.	20	50	1	1	-	-	2	-	50	-	5	.2
	Total			2	2	1	-	5	40	90	40		.6
	Heaters												
	Waste Mgmt	20	150	1	1	-	-	2	-	150	-	5	.7
	Oven	10	500	1	1	1	-	3	-	500	-	6	3
	Misc	12	50	3	3	3	-	9	100	100	100	10	1
	Total			5	5	4	-	14	100	750	100		4.7
	Lights												
	Spot Lights	12	15	4	4	-	-	8	120	120	120	98	
	Flood Lights	12	40	2	2	2	2	8	160	160	160	98	
	Total			6	6	2	2	16	280	280	280		28
	Total from PDU #1			32	30	25	10	97	1539	2314	1800		234.7
#2 (Equip Bay) l_t=150 ft	Electronics (Analog)												
	IMU	5	150	1	1	1	1	4	150	150	150	168	25
	Star Tracker	15	23	1	1	1	-	3	-	23	-	30	1.5
	Hor. Sensor	20	15	1	1	1	1	4	-	15	-	30	
	Gyro Pkg.	6	15	1	1	1	1	4	15	15	15	2.5	-
	Misc. Sensors	15	5	3	3	3	3	12	15	15	15	2.5	-
	Recorder	6	50/250	1	-	1	-	2	250	250	250	168	42
	Mass Memory	6	60	1	-	1	-	2	60	60	60	-	
	Radar Altim.	20	100	1	1	1	-	3	-	-	100	0.5	-
	Total			10	8	10	6	34	490	528	590		68.5
	Electronics (Digital)												
	DIU	6	15	2	2	2	2	8	30	30	30	168	5
	Motors												
	Fans	12	70	2	2	2	-	6	140	140	140	168	23.5
	Total from PDU #2			14	12	14	8	48	698	698	760		97
#3 (Wheel Well) l_t=100 ft	Electronics (Analog)												
	ABES Thrust Ctr	20	150	1	1	1	1	4	-	-	150	.3	-
	Ignition	50	120	1	1	1	1	4	-	-	120	-	-
	Fire Detection	50	10	1	1	1	1	4	-	-	10	.3	-
	Total			3	3	3	3	12	-	-	280		-

Table 2.14. Load List of Shuttle Orbiter Model (Continued)

PDU	Item	l_d ft	Pwr/Unit (Watts)	No. of Units					Max Pwr/Ch (w)			Time On (hrs)	KWH/ Ch
				Ch 1	Ch 2	Ch 3	Ch 4	Total	Boost	Orbit	Land		
#3 (Contd.)	Electronics (Digital)												
	DIU	30	12	3	3	3	3	12	36	36	36	168	6.0
	Thruster Ctr	6	30	2	2	2	2	8	-	60	-	5	-
	FCS Act.	6	90	1	1	1	1	4	-	-	90	1.2	.1
	APS Ctr.	8	210	1	1	1	-	3	-	210	-	165	33
	Temp. Ctr	10	150	1	1	1	1	4	-	150	-	168	25
	Total			8	8	8	7	31	36	456	126		64.1
	Motors												
	ABES Boost Pump	40	700	1	1	1	-	3	-	-	700	1.2	.8
	Coolant Pump	20	180	1	1	1	1	4	180	180	180	168	30
	Water Pump	20	110	1	-	1	-	2	110	110	-	168	18.5
	Compressor	15	400	1	1	1	-	3	400	400	400	168	68
	Fan	10	70	1	1	1	-	3	70	70	70	168	12
	Total			5	4	5	1	15	760	760	1350		129.3
	Actuators												
	Fuel Iso Valve	30	60	3	2	2	2	9	-	-	120	-	
	Air Valve	20	30	1	1	1	1	4	-	-	(30)	-	
	Tank Iso Valve	30	150	2	2	2	2	8	-	300	-	-	
	Misc. Latch. Valves	20	6	5	5	4	4	18	-	(18)	(18)	-	
	APS Valves	30	42	10	10	10	10	40	-	(168)	-	-	
	Total			21	20	19	19	79	-	300	120		
	Heaters												
	Humid Ctr.	10	55	1	-	1	-	2	55	55	55	168	9.2
	Lights												
	Ext. Warning	50	40	5	-	5	-	10	-	-	200	0.5	.3
	Landing Lts.	40	1000	1	1	1	-	6	-	-	1000	0.2	.2
	Flood Lts.	15	40	3	-	3	-	6	-	120	-	1.0	.1
	Total			9	1	8	-	22	-	120	1200		.6
	Total from PDU #3			47	36	45	30	161	851	1691	3131		139.2
#4 Tail Area l_t=50 ft	Electronics Analog)												
	APU Ctr.	6	300	1	1	1	1	4	300	-	300	1.5	.5
	Gen Ctr.	12	50	1	1	1	1	4	50	-	50	1.5	-
	Igniters	50	50	8	8	8	8	32	-	100	-	-	
	Total			10	10	10	10	40	350	100	350		.5
	Electronics (Digital)												
	DIU	20	15	3	3	3	3	12	45	45	45	168	7.5
	MPS Ctr.	5	200	1	1	1	1	4	200	-	-	0.25	
	Total			4	4	4	4	16	245	45	45		7.5
	Motors												
	MPS Gimbal Dr	20	225	1	1	1	1	4	225	-	-	0.25	
	APS Act.	15	200	1	-	1	-	2	-	200	-	-	
	Aux. Hyd. Pump	10	500	1	1	1	1	4	500	500	500	20	10
	Backup Pump	20	40	1	-	1	-	2	40	40	40	168	6.7
	Total			4	2	4	2	12	765	740	540		16.7
	Actuators												
	MPS Valves	15	42	5	5	5	5	20	128	-	-	-	
	MPS Servo	15	50	2	2	2	2	8	100	-	-	-	
	APS Valves	50	75	8	7	8	7	30	-	300	-	-	
	Latching Valves	20	6	5	5	5	5	20	12	18	6	-	
	Hydr. Ctr. Valves	15	30	3	2	3	2	10	60	30	60	-	
	Misc Servo Valves	12	115	4	4	4	4	16	230	-	230	-	
	Total			27	25	27	25	104	530	348	296		-
	Heaters												
	Gas Gener	15	224	2	2	2	2	8	-	(224)	-	-	
	Total from PDU #4			47	43	47	43	180	1890	1297	1231		94.7

In order to meet the FO/FO/FS failure criterion for the Shuttle, all flight safety equipment; i.e., loads which are required for safe return of the crew, must be quad redundant. We therefore have four power "channels" for essential equipment and have further assumed, as indicated in Figure 2.13, that in case of EPGS failure the affected main bus can be switched to an unfailed generator. As shown in Figure 2.1, this results in a reduction of system failure probability by as much as an order of magnitude depending on the ratio of generator to load channel failure probability. Switchgear to provide for feeder protection and cross strapping or paralleling of generators is contained in bus control units (BCU) as shown in Figure 2.13 and described in Section 3.3 of this report along with switchgear and central conversion equipment associated with each PDU.

Table 2.15 summarizes the peak power requirements by equipment type. It shows that about 2/3 of the energy goes to electronic equipment and less than 1/3 of the power is used for motors.

Table 2.15. Power Utilization for Shuttle Model (Channel 1)

	Max Power (Watts)				
End Use	No. of Loads	Boost	Orbit	Landing	KWH per Flight
Electronics	56	2270	2253	1801	
Analog	(30)	(987)	(750)	(628)	106
Digital	(26)	(1283)	(1503)	(1173)	240
Motors	13	1705	1730	2070	170
Actuators	49	530	648	416	-
Heaters	8	155	805	155	14
Lights	15	280	400	1480	28
Total for Ch. 1	141	4960	5836	5922	558

2.3.3 Reference Load Model for Aircraft

On-board load utilization equipment for aircraft received much less study effort than determination of typical load equipment inventories for manned space vehicles. Utilization of electric power on high performance aircraft depends on the aircraft's mission and its design characteristics. Rather than speculating on the configuration of possible future aircraft we have briefly examined the requirements of a typical present day commercial transport aircraft and of the B-1 military aircraft which is currently under development. The power requirements of these two types of aircraft are very different and hence should provide further insight into the range of applicability of a given candidate PDC concept.

Electric power requirements for transport aircraft including supersonic transports have recently been studied by AiResearch under NASA contract NAS12-659. We have used their results as reported in Reference 2 to define the reference requirements model given in Table 2.16 for purposes of the present study contract. A four engine aircraft similar in size to current jumbo jets is implied with one electric power generator mounted to the accessory pad of each engine. Major load centers are located in each wing, the cockpit, the passenger compartment, and in the rear wheel well area. The average length of main power feeders is 120 ft.

Table 2.16. Typical Power Requirements - Transport Aircraft

Type of Load	Qty	Power per Unit	Max Bus Power Required KW
Electronic Equipment			
Analog	60	5-150 W	8
Digital	60	5-500 W	7
Total	120		15
Motors			
Pumps	2	15 KW	30
Envir. Control	4	2 KW	8
Fans & Misc	54	100-500 W	7
Total	60		45
Actuators			
Valve Drivers	40	40-200 W	4.7
Misc.	12	5-50 W	0.3
Total	52		5
Heaters			
Galley	5	5-110 KW	25
Envir. Control	5	0.5-2 KW	5
Misc.	60	150-300 W	10
	70		40
Lights			
Interior	300	40-200 W	15
Exterior	12	0.5-2 KW	5
	312		20
Total	614		125

Typical load requirements for the B-1 class military aircraft were obtained informally from North American Rockwell personnel (Reference 19). The basic B-1 aircraft will have four 105/115 KVA constant speed 400 Hz alternators which can provide 300% of rated current under low impedance fault conditions. The load utilization equipment which is installed depends on the mission but always will include a large number of electronic loads. During the strike phase of some missions the peak power requirement for avionic and special payload equipment may go as high as 150 KW. Since detailed load lists are not available and in any case will probably change before the B-1 goes into production, we have used the equipment complement listed in Table 2.17 for PDCS trade studies. We believe that this adequately represents the basic character of the B-1 type aircraft electric power requirements for purposes of this study program.

Table 2.17. Reference Power Requirements for Military Aircraft

Type of Load	Qty	Power per Unit	Max Bus Power Required KW
Electronic Equipment			
Analog	50	5W-1KW	5
Digital	120	5W-1KW	10
	170		15
Payload Equipment	14	.5-50KW	140
Motors & Actuators			
Fuel Pump	24	2-3KW	14
Envir. Control	4	4-7KW	10
Fans and Misc.	16	50-500W	2
Valve Drivers	50	15-200W	1
	94		27
Heaters			
Envir. Control	10	50W-2KW	6
Misc.	15	50W-2KW	6
	25		12
Lights			
Exterior	12	0.1-2KW	5
Interior	10	20-200W	1
	22		6
Total	325		196

2.4 ELECTRIC POWER GENERATION

The influence of the power processing and distribution subsystem configuration on the power generation subsystem and the output characteristics of various types of generators must be considered in sufficient detail to enable comparison at the power system level. For this purpose all power generation subsystems (EPGS) may be divided into two groups: one based on static energy conversion, and the other utilizing dynamic energy conversion to provide electric power. Power generation subsystems with static energy conversion always provide dc power. They include subsystems which contain photovoltaic solar arrays, electrochemical batteries, fuel cells, thermoelectric and thermionic converters. In power generation subsystems with dynamic energy conversion ac power always exists somewhere in the subsystem although the subsystem output may be dc. Dynamic conversion power generation subsystems include jet engine driven aircraft alternators, Brayton cycle power units, open cycle turbo alternators, and MHD generators. For purposes of this program only the following types of power generation subsystems were considered:

Static Energy Conversion
- Solar Array with NiCd-Battery
- Solar Array with Rechargeable Fuel Cell
- Fuel Cell

Dynamic Energy Conversion
- Brayton Cycle Generator
- Constant Speed Engine Driven Generator (IDG)
- Variable Speed Engine Driven Generator
- Open Cycle Turbo Alternator (APU)

We are not interested in the complete power generation subsystem but only in the impact of system voltage, frequency, and control/protection methods on the EPGS. This section therefore is concerned only with the incremental weight, heat dissipation, cost, and failure probability of the various EPGS configurations considered due to the power requirements of the PDC subsystem. In addition since the quality of output power during steady state and transient conditions strongly affects the PDCS design it will also be considered herein.

The impact of different PDCS configurations on the EPGS can be expressed as the incremental generator weight ΔM_G and cooling requirement ΔQ_G due the PDCS losses P_d. If

$$m_G = \frac{dM_G}{dP_o} = \text{generator specific weight}$$

$$q_G = \frac{dQ_G}{dP_o} = \text{generator specific thermal output}$$

$$P_o = \text{useful generator electrical power output}$$

then the reflected generator weight and cooling requirement due to power distribution, processing and control equipment losses are

$$\Delta M_G = m_G P_d \tag{2.7}$$

$$\Delta Q_G = q_G P_d \tag{2.8}$$

in which m_G and q_G may be functions of P_o. These relations give the required increase in generator weight and generator cooling due to the operation of the PDC subsystem. Typical values of the specific weight and thermal dissipation for various EPGS configurations will be provided.

2.4.1 Solar Array/Battery Power Generation Subsystem

A solar array/battery power source has been selected for the baseline EPGS for the Space Station. The complete EPGS consists of the following:

- Solar Cell Panels
- Solar Array Structure and Deployment Mechanism
- Orientation Drive and Power Transfer Assembly (ODAPT)
- Solar Array Shunt Regulator
- Rechargeable Batteries (NiCd)
- Battery Charge/Discharge Control Units

Batteries and associated charge/discharge control units are located in each station module and are sized to supply module power during eclipse. The solar array and the shunt regulator which limits the array output voltage are located in the power module. Since we are only interested in changes in EPGS weight, cost or electrical performance due to changes in PDCS configuration and since the power used by the PDCS (i.e. the PDCS losses) for the Space Station amounts to approximately 10% of the useful load power, we may make the assumption that except for the number of solar cells which must be provided and the nominal array and battery output voltage the entire power source subsystem is independent of the PDCS configuration. Thus for small changes in rated power output capacity of the EPGS only the weight of the solar panels and supporting structure need to be considered. A reasonable specific weight figure for a large oriented solar array panel in earth orbit is 50 lb/KW. This allows for a 20% degradation of electrical output during the design life of the array due to radiation damage, and micrometeorite impact and is consistent with design studies performed by TRW, Lockheed, and others (see References 20 and 21). The incremental cost of the solar cell panels depends on manufacturing techniques, inspection requirements, and the detailed design configuration. Assuming that large scale production economies are realized the cost is approximately $200 per watt. This does not include development or first unit costs. Since each solar panel contains many cells in series and in parallel, individual cell or interconnection failures have a negligible effect on array output regardless of output voltage within the range considered.

The solar array shunt regulator consists of high power switching transistors which are operated either at cut-off or in the saturated collector mode thereby short circuiting a portion of the array to maintain the array output voltage within a specified regulation range at all array temperatures and for all load conditions. Since the shunt regulators may be assumed to have their own radiators and since the PDC losses are small compared to the power regulation range, the same regulator can be used for all candidate PDCS configurations. We therefore can dismiss the solar array output voltage regulator from all further tradeoff considerations.

In addition to providing load power and PDC losses the solar array must recharge the batteries. The maximum solar array power P_{ch} required for recharge is given by

$$P_{ch} = \frac{t_d}{t_{ch}} \frac{P_L + P_d}{\eta_B \eta_C} \qquad (2.9)$$

where t_d = maximum discharge time = 36 minutes per orbit

t_{ch} = minimum charging time = 58 minutes per orbit

P_L = useful load power during discharge

P_d = PDCS power loss

η_B = battery recharge efficiency $\frac{WH_{out}}{WH_{in}}$

η_C = efficiency of battery charge/discharge control unit

For a 72% watt hour efficiency of the battery and a charge/discharge unit efficiency of 87% we get

$$P_{ch} = P_L + P_d \quad \text{and} \quad \frac{\partial P_{ch}}{\partial P_d} = 1$$

The weight of the solar array panels M_{SA} which must be provided just to supply PDCS losses P_d is therefore given by

$$\Delta M_{SA} = w_{SA} \left(P_d + \frac{\partial P_{ch}}{\partial P_d} P_d \right) = 2\ P_d\ w_{SA}$$

where w_{SA} is the incremental specific weight of the solar array in lb/KW.

The specific weight of reliable long life NiCd batteries is 100 lb/KWH based on 100% depth of discharge. Since the usable capacity decreases with increasing number of charge/discharge cycles the depth of discharge must be limited from 10% to 40% of initial rated capacity in order to obtain at least 3 years of orbital operation or 16,500 cycles. The cycle life depends strongly on battery temperature, charge method, and in orbit reconditioning procedures. Assuming a maximum depth of discharge of 33% the installed battery weight would be 300 lb/KWH or 180 lbs. per KW of power to be delivered during eclipse. The PDCS loss as mentioned amounts to about 10% of the useful power hence it accounts for 10% of the installed battery weight or 10% of the depth of discharge. Because battery cells are manufactured in discrete sizes and because the battery depth of discharge is relatively low we may reason that the installed battery size and weight will not change for different PDCS configurations supplying the same useful load.

Next, consider battery reliability for different PDCS configurations requiring different battery output voltages. Intuitively one may reach the conclusion that battery reliability decreases with increasing battery voltage because more battery cells must be connected in series. Further consideration, however, shows that for a given size cell, the total number of cells is approximately the same regardless of system voltage as long as the power and discharge energy requirement is held constant. Since future high reliability batteries will use simple electronic means to insure that single cell failures cannot cause complete battery failures (Reference 22) the reliability of a multicell battery installation is approximately the same for all output voltages considered. The same conclusion was also reached during a previous battery study program conducted by TRW under contract to NASA (Reference 23).

Battery charge/discharge units regulate battery current and voltage to optimize recharge efficiency and enable parallel connection of battery modules. No detailed consideration of their performance was necessary for comparative analysis of PDCS configurations.

The power quality available from a solar array and battery power source is generally determined by the voltage regulation and impedance characteristics of the battery since the battery acts as a clamping device for voltage excursions. This also means that the magnitude of fault currents is only limited by battery internal impedance and the fault resistance. If the battery is disconnected, static and dynamic output voltage variations are determined by the solar array shunt regulator.

2.4.2 Fuel Cell Generators

The electric power generation subsystem for the Shuttle Orbiter will contain fuel cells using propulsion grade gaseous H_2 and O_2. Two types of fuel cells were considered during Space Shuttle Phase B studies, namely an acid electrolyte matrix fuel cell proposed by Pratt & Whitney and the ion exchange fuel cell under development by General Electric. Descriptions of each of these fuel cell power plants as configured for the Shuttle Orbiter are contained in Reference 16. The complete EPGS contains the fuel cell stack, valves and plumbing for reactant control, a coolant pump, water separator, and heat exchanger. Design and performance characteristics of both types are summarized in Table 2.18.

Table 2.18. Fuel Cell Performance

	Matrix	Ion Exchange
Vendor	P & W	GE
Electrolyte	KOH	Solid polymer
V_{oc} (per cell)	1.10 V	1.23 V
V_o at rated load (per cell)	0.97 V	0.93 V
Cooling Method	Pumped liqu. coolant plus open cycle H_2O boiling as backup	Pumped liquid coolant
Rated Output Power	7 KW	7 KW
Max. Output Power	14 KW (With open cycle cooling)	14 KW (short duration)
Nominal current density	120 amp/ft^2	130 amp/ft^2
Stack Temperature	190°F	180°F
Reactant Inlet Pressure	60 psia max	50 psia max
Heat generated at rated load	4.4 KW	4.35 KW
Efficiency	61%	62%
Inherent Voltage Regulation (0.5 to 7.0 KW)	±5%	±5%
Short circuit current	3000 amp	800 amp
Weight	245 lb	325 lb
Specific Weight	35 lb/KW	46 lb/KW
Spec. Reactant Consumption	0.9 lb/KWH	0.9 lb/KWH

Because of the increased complexity of the plumbing as the number of individual cells in the stack increases, the EPGS reliability may decrease as the output voltage increases. Preliminary and unofficial estimates for the matrix fuel cell indicate the following failure rates per 10^6 hours (Reference 24):

Output Voltage	28 Vdc	120 Vdc
Stack Failures	7.0	14.7
Power Plant Failures	29.8	37.5

If provisions are made, however, to bypass failed cells in a stack as has been assumed for Space Station batteries, the reliability would be the same for any reasonable output voltage.

Current Shuttle fuel cell developments are aimed at obtaining a power plant with a useful life of 5,000 hours. The development cost has been estimated at $5M to $20M. Production cost may be in the range of $150K to $300K per power plant.

Fuel cells may be considered for use on the Space Station instead of batteries to obtain a potential reduction in weight. If the product water is electrolyzed during illuminated portions of each orbit, the resultant H_2 and O_2 can be used to provide power during eclipses. A separate electrolysis unit is required or the fuel cells must be redesigned to provide a rechargeable fuel cell source. Since the performance and design of the PDC subsystem are not significantly different whether rechargeable batteries or fuel cells form part of the EPGS, rechargeable fuel cells were not included in this study program.

2.4.3 Rotating Generators

In order to determine the characteristics of electric power generation subsystems which affect the design of the PDC subsystem, both the prime mover and the rotating generator must be considered. The source of mechanical power for the electric generator may be a main propulsion engine, a separate gas turbine which is part of an auxiliary power unit (APU), or a closed cycle heat engine. Much effort has been expended in the past by NASA, the Air Force, and various contractors to develop reliable lightweight equipment for aircraft and space electric power systems including each of these generator drive methods.

The main engines provide generator drive power on almost all modern aircraft. If the generator must supply constant frequency electrical output and since the engine speed normally varies over a 2:1 range, a constant speed transmission must be used between the engine gear box to which the generator is connected and the alternator drive shaft. Alternatively the generator output may be converted to constant frequency ac by electronic means. APUs are used for relatively short duty cycles where their high specific fuel consumption can be tolerated and main engine power is not available. For long duration missions a closed cycle system using a nuclear or solar heat source is required whenever the total fuel consumption becomes excessive. The most highly developed such system uses the Brayton cycle and high speed turbo alternators.

A detailed analysis of each type of dynamic EPGS is clearly beyond the scope of the present study and is not necessary to determine the effect of the PDCS configuration on EPGS requirements and characteristics. In the case of aircraft engine driven generators only the weight of the generator itself and the need for speed and voltage regulation equipment is affected by the choice of system voltage and frequency. The constant speed transmission or frequency converter which must be provided for constant frequency ac transmission represents a penalty due to the choice of PDCS configuration. If electric power is obtained from an APU, speed control can be obtained by pressure or time modulation of turbine throughflow and by using parasitic loads. Since the APU generally provides hydraulic or pneumatic power in addition to electrical power, its weight and reliability are approximately the same for all electrical output voltages and frequencies considered. The fuel consumption, however, is a function of total output power and efficiency and therefore increases when PDCS losses require an increase in APU electrical power output. For typical high performance spacecraft APUs burning hydrogen and oxygen the specific reactant consumption ranges from 2.2 to 4.0 lb/KWH which is more than twice as large as the corresponding requirement for fuel cells. The fixed equipment weight of an APU exclusive of hydraulic or pneumatic generators may be significantly less than the fixed weight of a fuel cell. Because of their high specific reactant consumption however, we have not included turbine driven generators or APUs in our PDCS tradeoff studies for space vehicle applications.

Closed cycle dynamic energy conversion has been considered as an alternate to the solar array/battery power generation subsystem. Conceptual designs for Brayton cycle power systems using radioisotope or nuclear reactor heat sources were developed during Space Station Phase A and Phase B studies by the prime contractors and their subcontractors (see References 6, 7, 8, and 9). When shielding and nuclear safety equipment were included these power systems proved to be heavier and considerably more expensive than solar array systems and hence are not planned for future near term Space Stations.

Figure 2.14 shows block diagrams of different EPGS arrangements for both dc and ac distribution. Because of reliability and life requirements brushless ac generator configurations as shown in Figure 2.15 are implied.

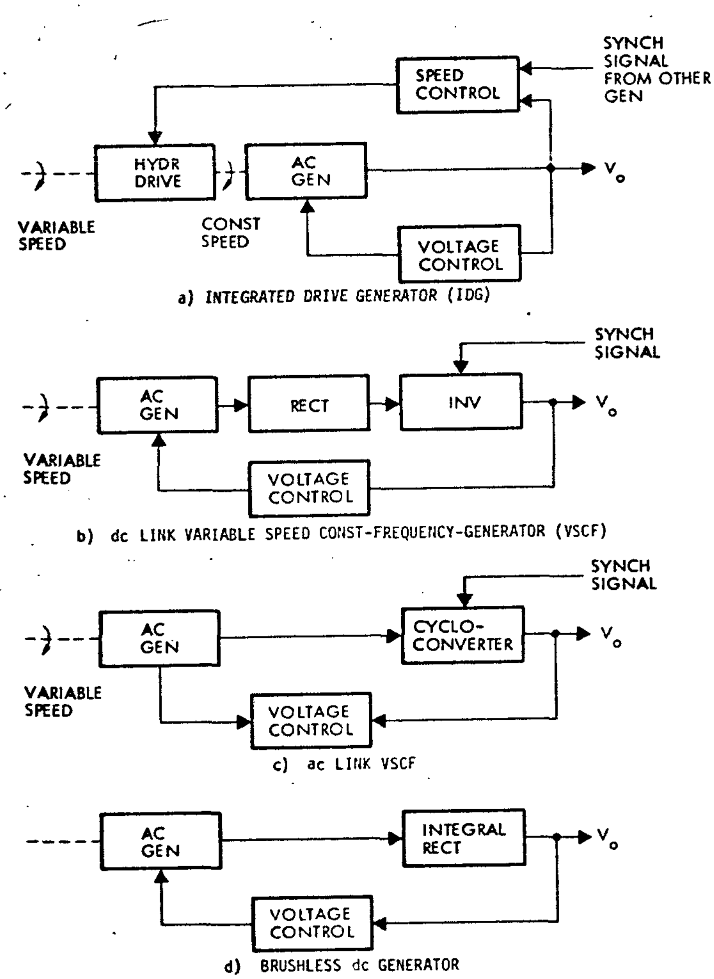


Figure 2.14. Rotating Generator EPGS

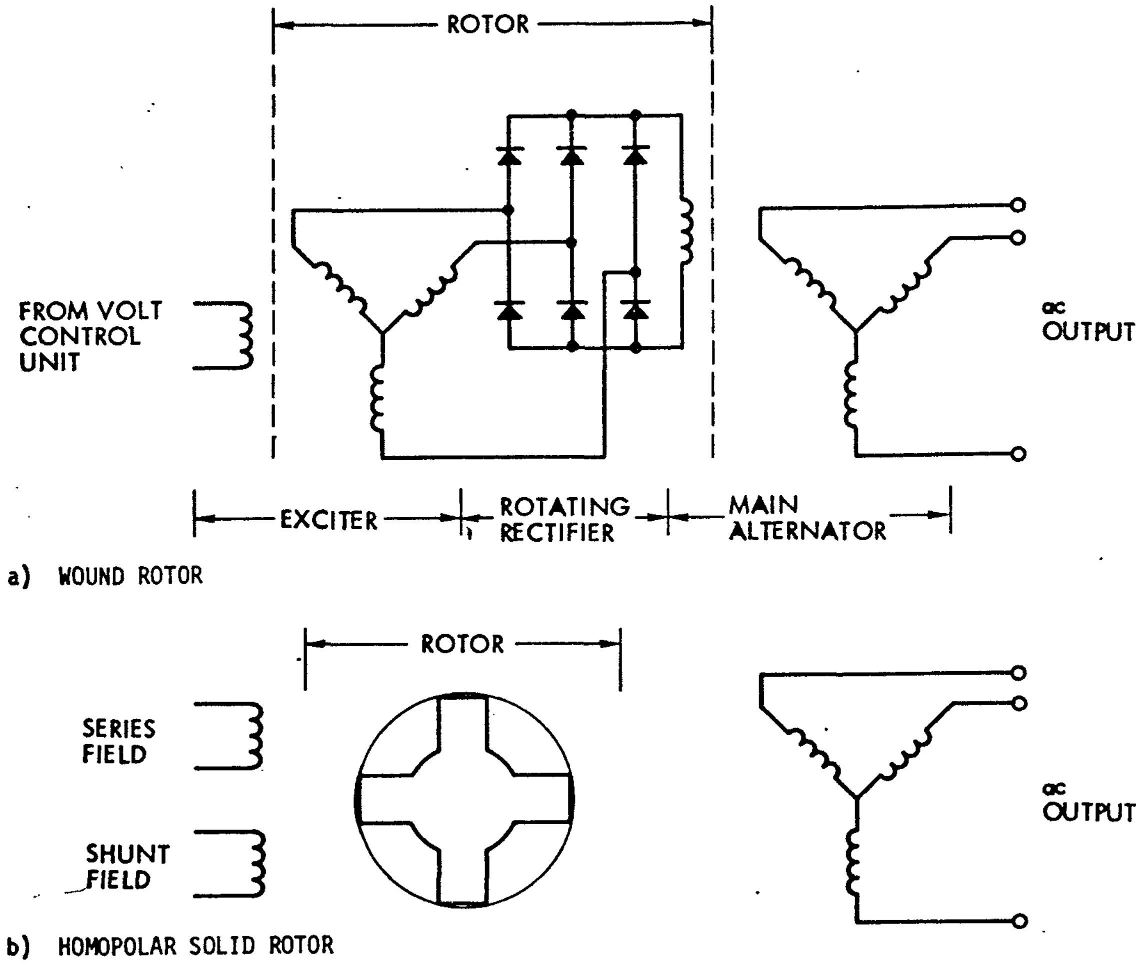


Figure 2.15. Brushless Alternator Configurations

If essential loads are supplied with ac power the EPGS must include provisions for frequency synchronization so that generators can be connected in parallel to avoid power interruption in case one generator fails. This is not required for dc output EPGS since blockind diodes may be used to avoid circulating currents when two generators feed the same load. Table 2.19 lists typical performance figures for different types of generators. Weight and reliability depend strongly on operating speed and cooling method. The costs listed represent best guesses of recurring unit production costs using space vehicle quality assurance procedures. Output voltage characteristics are shown in Table 2.20. The waveform is a function of the load on the machine and depends strongly on generator design. Filters may be required to suppress undesirable harmonics. Design of such filters, however, requires complete specification of load characteristics and generator design parameters.

Table 2.19. Performance Characteristics of Rotating Generators

Output Rating	Type	Weight lb	ΔM_G lb/KW	Effic. %	MTBF hrs	Cost $000	Notes
115/200 Vrms 400 Hz, 3Ø 60 KVA, .85 pf	Aircraft IDG, 12,000 rpm	100	1.5	75	10,000	30-50	Oil spray cooled
	AC link VSCF	100	1.3	~60	15,000	50-80	1200-2400 Hz gen. freq.
	DC link VSCF	90	1.3	70	15,000	50-80	Not developed
115/200 Vrms 1200 Hz, 14 KVA, 0.8 pf	Solid Rotor Research Unit	51	-	75	10,000	-	Brayton cycle development unit
120/240 Vdc 60 KW	Brushless alternator with integral rectifier	80	0.8	83	20,000	10-20	Oil cooled, 10-21,000 rpm

Table 2.20. Electrical Characteristics of Rotating Generators

	Aircraft IDG	AC Link VSCF	Brayton Research Unit	Brushless DC Gener.
Nominal Voltage & Freq.	115/200 Vrms 400 Hz, 3Ø	115/200 Vrms 400 Hz, 3Ø	115/200 Vac 1200 Hz, 3Ø	120 or 240 Vdc
Voltage Regulation	±2.0%	±1%	±2%	±3.3%
Freq. Regulation	±5%	±.00025%	±1%	-
Transient Voltage Limits				
Load Switching	80-140 Vrms	±1%	98-148 Vrms	60-260 Vdc (120 V nom)
Fault Conditions	0-180 Vrms	0-115 Vrms	No data	0-340 Vdc (120 V nom)
Max. Fault Current	300%	200%	300%	>200%
Total Harmonic Content or Ripple Voltage	8%	4% plus 0.6 Vdc	10-15%	±6 V peak
Reference	MIL-STD-704A and MIL-G-21480	MIL-E-23001	NASA TMX-52813	Gen Elec. Spec. GE 700617 (Proposal)

2.5 HEAT REJECTION INTERFACE

Rational selection of a power processing, distribution and control subsystem from a group of candidate concepts must include an analysis of the impact of the PDCS on other vehicle systems and subsystems. Since in general different PDCS configurations will have different power losses and hence different heat rejection requirements, we have examined the resultant cooling system weight impact for the typical vehicles of concern to this program as described in the following paragraphs.

2.5.1 Space Station Characteristics

In order to maintain the energy balance for the vehicle, all electrical power which is converted to heat losses must ultimately be radiated to space. In addition waste heat must be transported from its source inside the vehicle to a radiator which forms part of the external structure. Although one may reason that since the differences in PDCS heat rejection requirements for different PDCS configurations are negligibly small compared to the total heat rejection capability of all the radiators so that radiator sizes in practice will be unaffected by the PDCS configuration selection, it will nevertheless be valuable to compute the portion of the total thermal control system weight which is needed to reject the PDCS losses. The radiator forms part of the vehicle's external structure and will have an average temperature of approximately 60^{o}F. The weight of the radiator is about 0.5 lb/ft^2 greater than a structure which does not also serve as a radiator. In addition heat must be transported from the PDC equipment where it is generated to the radiator from which it is rejected. A combination of heat transfer methods consisting of conduction through structure, convection, pumped liquid heat transfer, and use of heat pipes will be used with an estimated average weight of 2.5 lb. per KW of heat transferred to the radiator. The average heat rejection capability of the radiator is about 8 watts per ft^2 so that the total incremental heat rejection weight penalty m_q in lb. per KW of heat becomes

$$m_q = \frac{0.5}{8} \times 1000 + 2.5 = 65 \text{ lb/KW}$$

This figure will be used for PDCS configuration trade studies.

2.5.2 Shuttle Orbiter Heat Rejection

The Shuttle Orbiter will have one or more radiators which are deployed during the orbit phase and retracted during the re-entry phase to prevent damage due to re-entry heating. They must be sized for worst case heat rejection requirements during the orbiting phase. If the assumption is made that the weight of the radiators and heat transfer components is a linear function of heat rate, analysis of the Shuttle Phase B baseline designs (Reference 14) gives an incremental specific weight for the deployable radiator, liquid heat transfer loop, and heat exchangers of 146 lb. per KW of heat to be rejected. This figure is based on an average radiator temperature of $60^{o}F$. During boost and re-entry the environmental control method involves heat storage and energy interchange with the atmosphere but may be ignored for purposes of power system design studies.

2.5.3 Thermal Control for Aircraft

Temperature control methods for aircraft equipment are different from those for space vehicles because of heat exchange with the atmosphere and because of the large thermal capacity of the fuel carried aboard. Since there is no radiator and since the fuel tanks are normally used as a heat sink for electrically generated waste heat, the design of the environmental and temperature control system is not affected by the PDCS concept selected. Individual power system components such as generators and secondary power supplies require spray oil or blast air cooling. The incremental specific weight and power requirements of the oil pumps or fans per KW of cooling capacity are sufficiently low so that the heat rejection weight does not affect the choice of aircraft PDCS configurations and hence will be ignored.

3.0 COMPONENT ANALYSES

The electric power processing, distribution and control subsystem may be partitioned into functional equipment categories as follows:

- Load Power Processing Equipment Units (PPUs)
- Transmission and Distribution Equipment (Wires and Cables)
- Control and Protection Equipment (Switchgear)
- Central Power Conversion Equipment (CPUs)

In order to put the synthesis of PDC subsystems on a rational and generalized basis, each of these PDCS elements were studied separately to determine critical performance characteristics as functions of input voltage, frequency, and output power rating. When possible, parametric curves were derived which provide weight, efficiency, and failure rate for a wide range of input voltage and output power at several input frequencies. Cost was estimated on the basis of part count or complexity. Procedures and results are described below.

3.1 LOAD POWER PROCESSING EQUIPMENT

The basic function of load power processing equipment is to convert power available from the power generation subsystem (or power distribution substation) to the voltages and/or frequencies required at the load or utilization equipment interface. Typically, such a load power processing unit (PPU) is packaged with the individual load which is served. For electronic loads, which primarily require dc at various levels, these local PPUs are electronic secondary power supplies which provide the necessary dc to dc (or ac to dc) conversion and regulation.

A fuller listing of the basic electrical requirements placed on local or single load PPUs follows:

- Convert input line voltage to load voltages
- Provide required load power quality (regulation and ripple)
- Control conducted and radiated electromagnetic interference
- Attenuate input line transients and ripple

- Limit input power during equipment turn-on, load fault conditions or internal PPU failure (optional)
- Provide on/off control (optional)
- Monitor input and output currents and voltages (optional)

To determine individual load PPU performance capability for typical equipments required in the various PPDC configurations, detailed design studies and calculations were performed on several commonly encountered circuits to obtain parametric data on PPU weight, power dissipation (efficiency), failure rate (reliability), and comparative cost. Standardized specifications were established for the basic PPU circuits selected and a number of designs, under various input and loading conditions were executed to obtain the desired parametric data. The effects of various local PPU design requirements were quantitatively evaluated so as to determine the variation in PPU weight, efficiency, and reliability as functions of variations in:

- Output power rating
- Output voltage levels
- Distribution of load at various output voltage levels
- Output voltage regulation
- Input voltage amplitude and frequency
- Input voltage regulation
- Electromagnetic interference requirements

The parametric curves developed were used to estimate the weight, power dissipation, reliability, and cost parameters of the PPU complement in the different PDC configurations under study.

3.1.1 Standardized Requirements

A standardized set of electrical input and output specifications were established to evaluate the performance of multiple output, secondary dc power supplies. For the two basic classes of electronic loads, analog and digital, a representative set of output voltage and power requirements, based on the power utilization equipment study, Section 2.2.1, was selected and is presented in Table 3.1. Also given in the table is the total power range examined for each load class.

Table 3.1. Standard PPU Loads

Load Type	Description	Total Power Rating (Watts)	Voltage Requirements & Regulation	Fraction of Total Power Required At Each Voltage	Duty Cycle
I	Analog	10-100W	+28VDC, ±3%	80%	Cont.
			+15VDC, ±3%	15%	Cont.
			-15VDC, ±3%	5%	Cont.
II	Digital	15-450W	+5VDC, ±5%	60%	Cont.
			-5VDC, ±3%	10%	Cont.
			+15VDC, ±3%	15%	Cont.
			-15VDC, ±3%	15%	Cont.

The standard input voltage levels and ranges selected as alternatives for the detailed converter design calculations are listed in Table 3.2. Included are high and low dc input voltage levels, bipolar dc, and single and three-phase ac inputs. The three-phase ac input case is used for load PPU ratings in excess of 400 watts.

Table 3.2 Load PPU Input Parameters

Nominal Input Voltage/Frequency	Voltage and Frequency Variation
28 Vdc	24 to 36 Vdc
±28 Vdc	±24 to ±36 Vdc
115 Vdc	100 to 125 Vdc
115V RMS, 1Ø, 400 Hz	100 to 122V RMS, 380 to 420 Hz
115V RMS, 1Ø, 1200 Hz	100 to 122V RMS, 1140 to 1260 Hz
115/200V RMS, 3Ø, 400 Hz	100/173 to 122/211V RMS, 380 to 420 Hz

The selection of input operating ranges is generally based on MIL-STD-704A electric power quality requirements, taking into account line drops from power source to load for MIL-STD-704A Category B utilization equipment. For 115 Vac systems, this drop amounts to 4 volts; for 28 Vdc systems, 2 volts. For 115 Vdc systems, a 3 volt line drop was assumed. The ranges for both the 115 Vdc and ac systems reflect approximately a $\pm$10 percent variation in source voltage, corresponding, roughly, in the ac case, to the Mil-Spec "abnormal steady state limits". For 28 Vdc battery (or fuel cell) sources, a $\pm$20 percent variation was assumed, corresponding, in percentage, to the Mil-Spec variation designated "emergency steady state limits".

3.1.2 Circuit Configurations

3.1.2.1 Basic Switching-Type Power Conditioning Circuit Approaches

Switching-type dc-dc and ac-dc power conditioning systems generally include an ac inversion step for converting input voltage to the desired output level(s). There are two basic power inversion techniques: parallel inversion and series inversion. In the former case, with equivalent circuit as shown in Figure 3.1, the output load is reflected back to the transformer primary and is essentially connected in parallel with the source through the power switch. Figure 3.2 illustrates the equivalent circuit of the series inversion technique in which the output load is reflected back to the source through an added passive energy storage network. The series passive network in effect provides a current limiting function for the power stage, which maintains control of the current flow during circuit turn-on and overload conditions, thereby protecting the power source from current surges and the power switch from overstress.

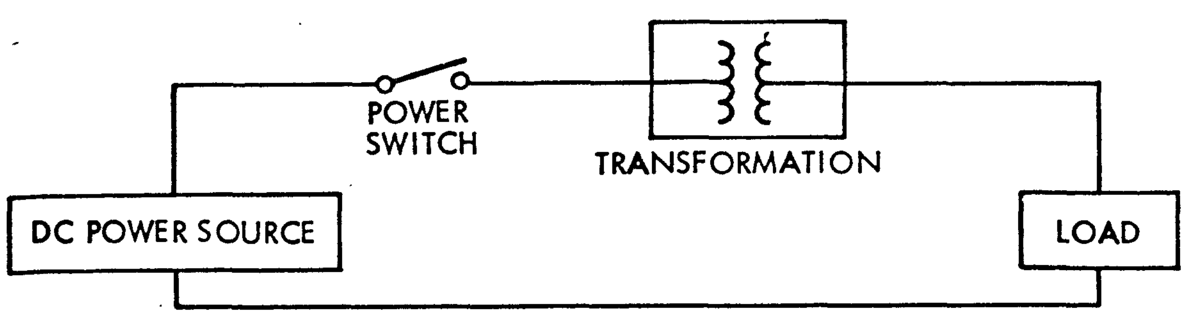


Figure 3.1. Equivalent Circuit of Parallel Inverter

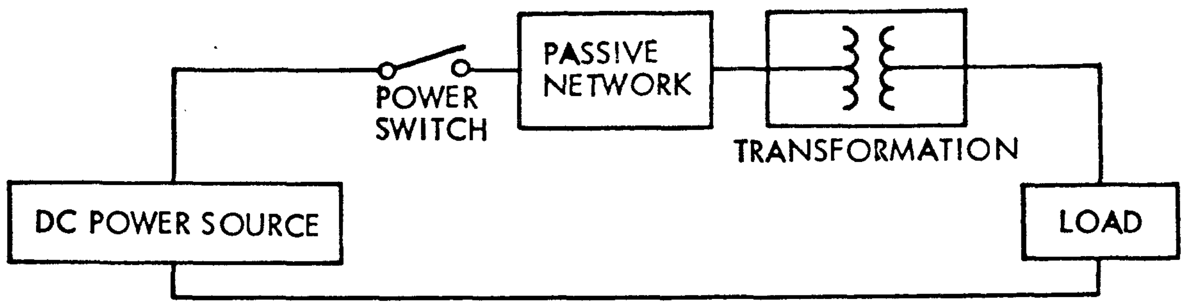


Figure 3.2. Equivalent Circuit of Series Inverter

A simplified schematic diagràm of a parallel inverter-type power conditioning circuit frequently used is shown in Figure 3.3. This system includes a switching pre-regulator (transistor Q_A, diode D_A, and filter L_A, C_A) followed by a parallel squarewave inverter to obtain the ac inversion and multiple outputs. Output voltage regulation is accomplished by duty cycle control of power switch, Q_A.

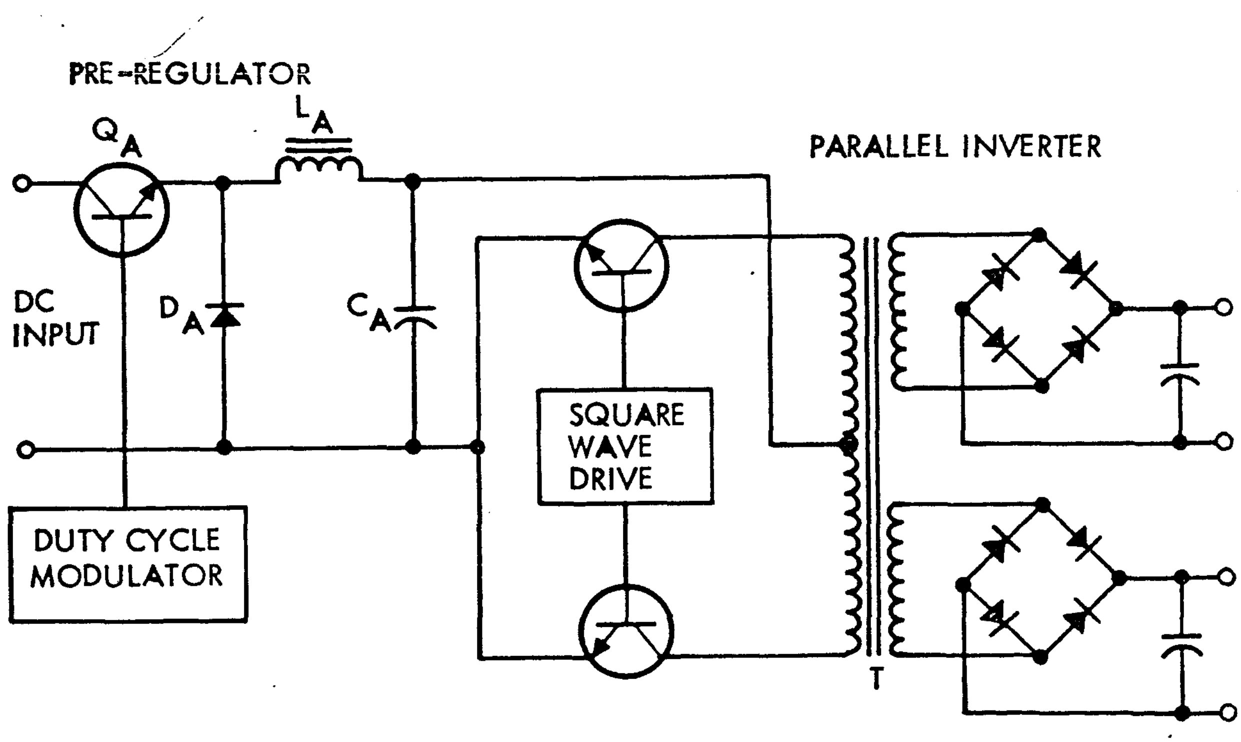


Figure 3.3. Pre-Regulator - Parallel Inverter

A commonly encountered circuit of the series inverter class is the quasi-squarewave inverter. The basic circuit is illustrated in Figure 3.4. The power switches, Q_1 and Q_2, alternately connect the primary winding (N_1) of the transformer, T, to the input power source. The output voltage of the transformer has a quasi-squarewave waveform with the time periods of zero voltage corresponding to the "off" time of the transistors. The latter are duty cycle controlled to maintain output voltage regulation. The output inductor, L, and the modulator can be designed to limit current flow during start-up and overload conditions to protect the power source and power switches from current transients, and hence constitute the series passive network of Figure 3.2.

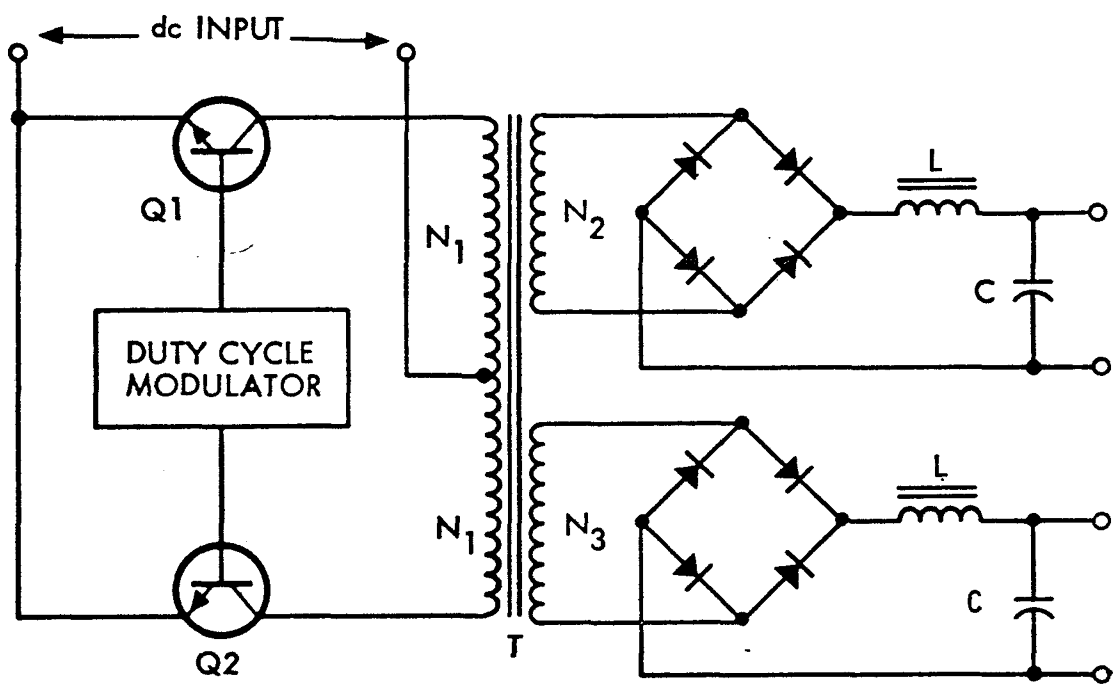


Figure 3.4. Quasi-Squarewave Series Inverter

Other series inversion-type power conditioning circuits are the series resonant tank circuit and the series inductor inverter shown in Figures 3.5 and 3.6. For load control applications, use of the former is generally constrained to special load applications where adverse loading and high power are involved. The resonant network, in conjunction with the power switches, force sinusoidal current flow through a conducting switch and the converter power transformer. Application of the series inductor approach is relatively recent. In this technique, an inductor, usually serving also as a transformer, stores energy during the conduction period of a primary power switch and discharges the energy into the load during switch "off" periods. Output voltage is controlled by adjusting the power switch on/off time ratio.

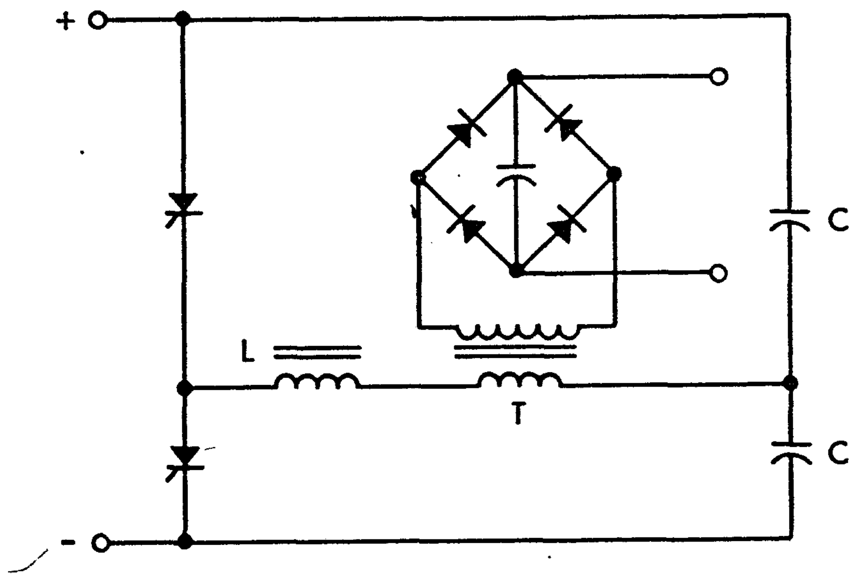


Figure 3.5. Series Resonant Inverter

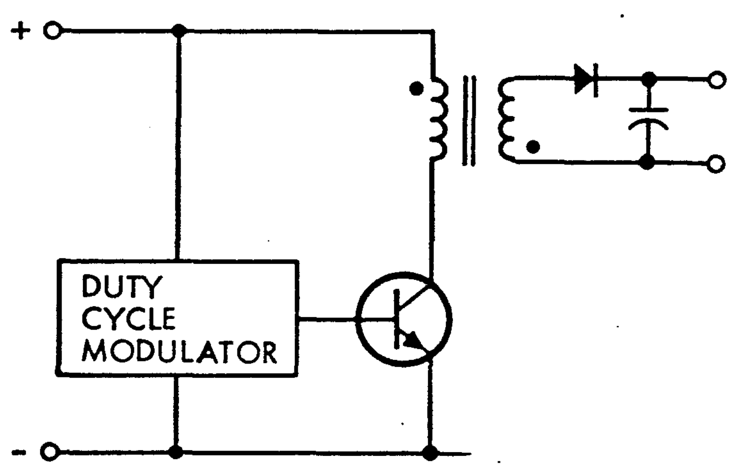


Figure 3.6. Series Inductor Inverter

For high efficiency ac to dc power conversion and regulation, several basic approaches can be implemented. One consists of transformation of the input voltage, either single-phase or three-phase, with phase controlled rectification, in either transformer primary or secondary circuits, for output control (Figure 3.7). Another approach utilizes conventional input transformation and rectification techniques followed by multiple switching-type dc output regulators, as shown in Figure 3.8. A third approach entails direct rectification and filtering of the ac input, with the dc obtained powering a high frequency switching-type dc to dc converter of any of the forms previously described (Figure 3.9).

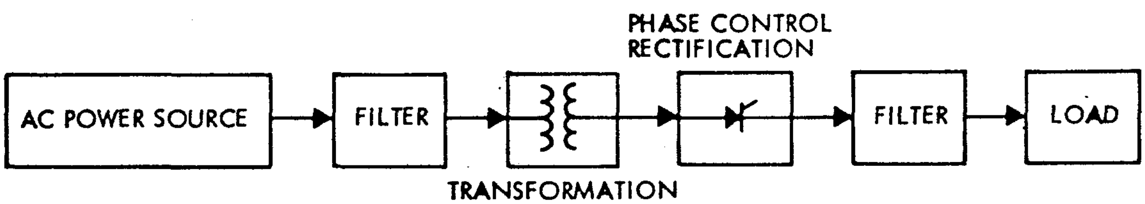


Figure 3.7. Ac to Dc Conversion - Phase Control

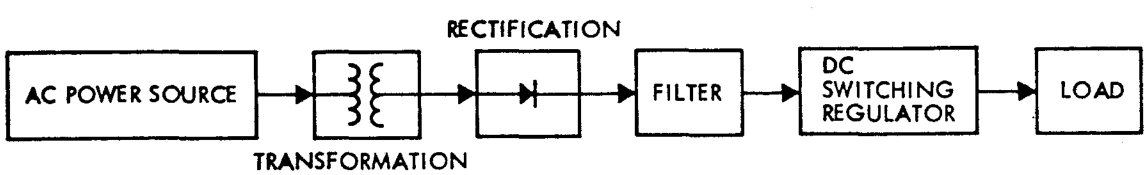


Figure 3.8. Ac to Dc Conversion - Transformer/Rectificer/Output Regulator

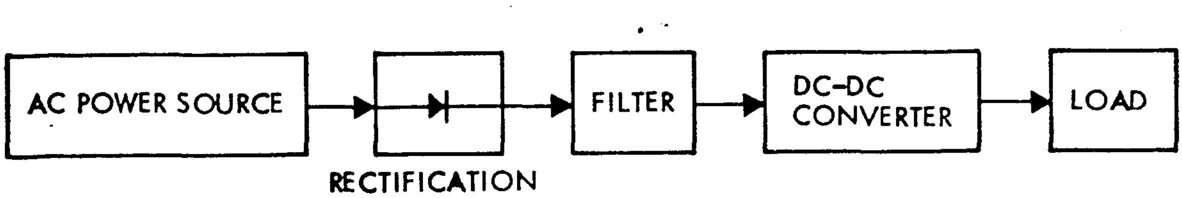


Figure 3.9. Ac to Dc Conversion - Direct Rectifier/
High Frequency Dc-Dc Conversion

3.1.2.2 Selected Circuits

Table 3.3 lists the load PPU circuit configurations, providing the standardized output voltages, selected for the development of parametric data on PPU performance characteristics.

Table 3.3. Selected Load PPU Circuit Configurations

Dc to Dc Conversion	
Type 1	Quasi-Squarewave Inversion or Pulse Width Modulated (PWM) Type
Type 2	Pre-regulator-Squarewave Inversion (SWI) Type
Ac to Dc Conversion	
Type 3	Direct rectification to Type 1 (PWM) dc to dc Converter
Type 4	Direct rectification to Type 2 (SWI) dc to dc Converter
Type 5	Transformer-rectifier to dc Output Switching Regulators (REG.T-R)

The Type 1 PPU is one of the most commonly used circuits for dc to dc conversion. It is characterized by high efficiency and low weight due to the combination of regulation and inversion functions within one power switching stage.

The Type 2 PPU is inherently less efficient than the Type 1 circuit since input power is passed through two power switches (pre-regulator and inverter). It is included for calculation because of its common usage in computer applications, providing low output impedance at the high load switching frequencies.

The Types 3 and 4 PPU configurations represent ac to dc conversion approaches yielding lower weight than is obtained in the commonly used Type 5 PPU because of the elimination of the power line frequency, input transformer. Input/output isolation is provided via the high frequency, dc-dc converter transformer.

The Type 5 regulated ac-dc converter selected, utilizes dc output switching regulation to eliminate the problem of undesired harmonics in the input supply lines, a problem that must be faced when using phase control regulation techniques for regulation.

Table 3.4 relates the selected load PPU configurations by type to the input voltage alternatives identified in Table 3.2. These comprise the individual cases for which detailed design calculations were performed.

Table 3.4. Standard Load PPU Design Cases

Load Type (See Table 3.1)	Input Voltage/Frequency	Circuit Type (See Table 3.3)	Output Power Range (Watts)
I (Analog)	A 28 Vdc, $\pm$ 28 Vdc	1, 2	10-100
	B 115 Vdc	1, 2	10-100
	C 115 Vac, 1Ø, 400 Hz	3, 4, 5	10-100
II (Digital)	A 28 Vdc, $\pm$28 Vdc	1, 2	15-450
	B 115 Vdc	1, 2	15-450
	C 115 Vac, 1Ø, 400 Hz	3, 4, 5	15-450
	D 115/199 Vac, 3Ø, 400 Hz	4, 5	15-450
	E 115 Vac, 1Ø, 1200 Hz	5	15-450

Simplified circuit diagrams of each of the selected PPU types are illustrated in Figures 3.10, 3.11, and 3.12. Figure 3.10, showing the basic Type 1 circuit implemented for the standard analog load case, illustrates three, source-dependent input configurations. Input circuit (a) is used for standard unipolar dc inputs, (b) for bipolar dc inputs, and (c) for single-phase ac inputs. With use of the last, a Type 3 PPU is formed.

Figure 3.11, in a similar fashion, illustrates a Type 2 (or 4, with ac input) PPU, implemented for the standard digital load case. Figure 3.12 illustrates the Type 5 PPU, implemented for the standard analog load case. As noted previously, for output powers in excess of 400 watts, three-phase transformer-rectifier (or three-phase rectifier only for Types 3 and 4) configurations are used.

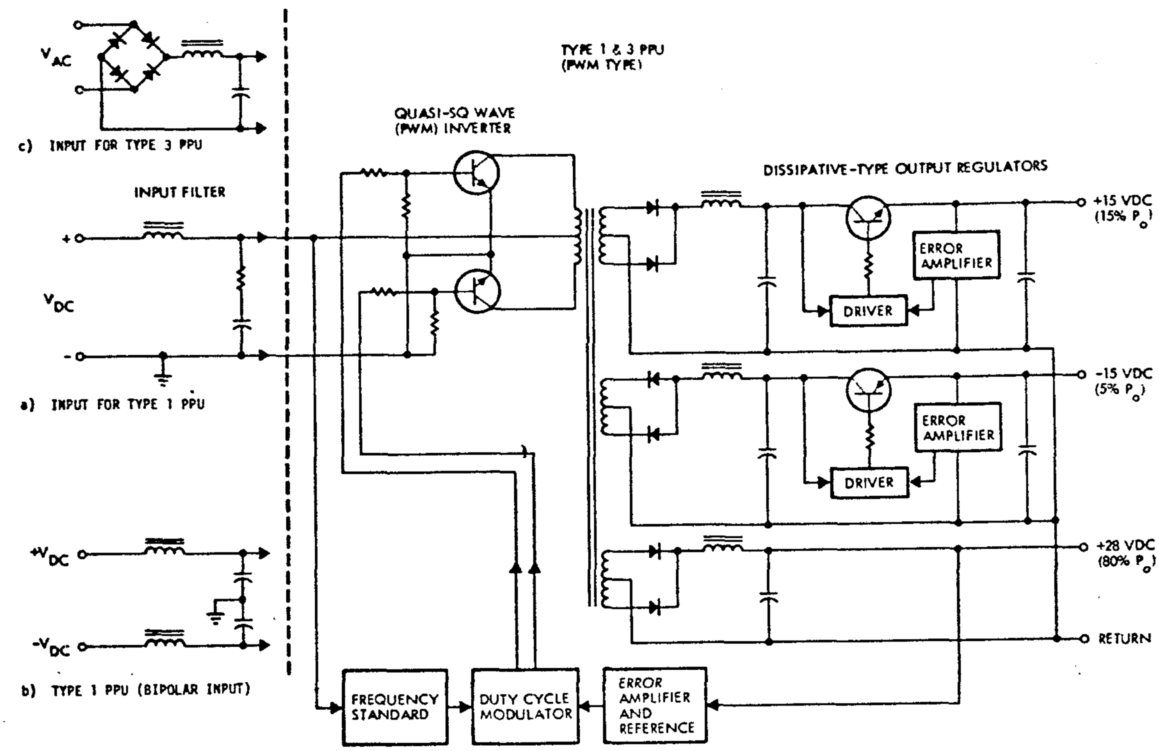


Figure 3.10. PWM Type Power Processing Unit (Type 1 or 3)

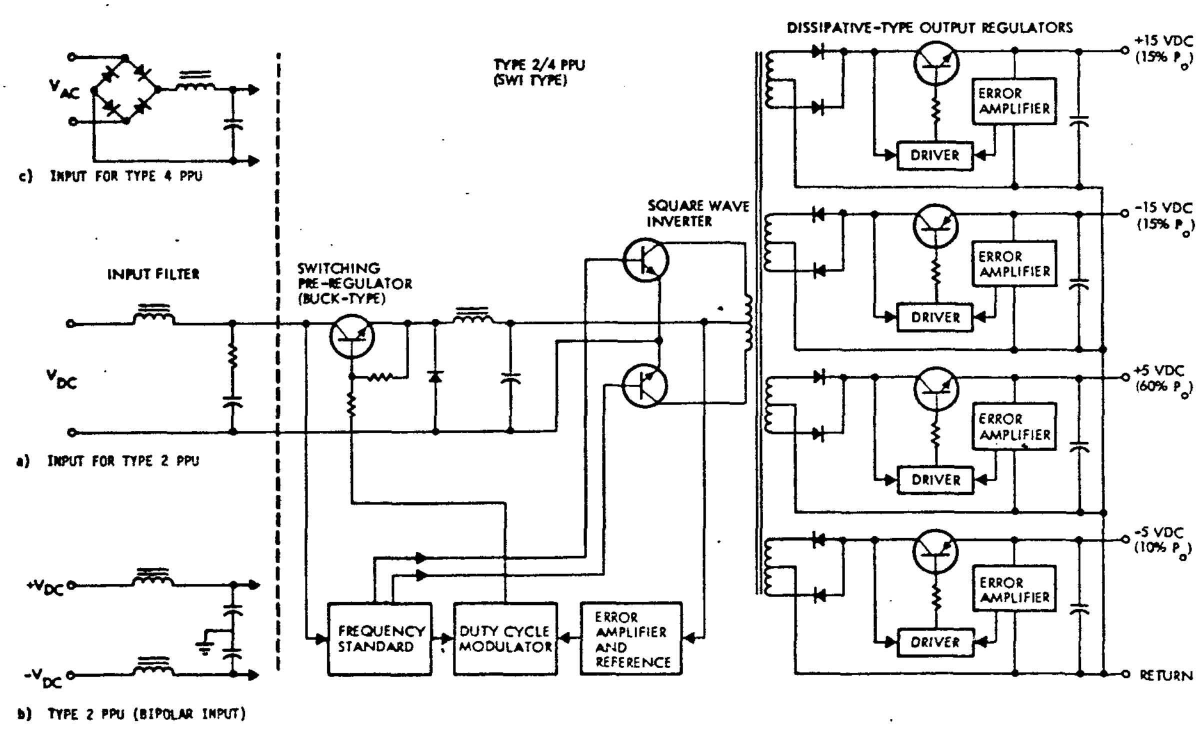


Figure 3.11. SWI Type PPU (Type 2 or 4)

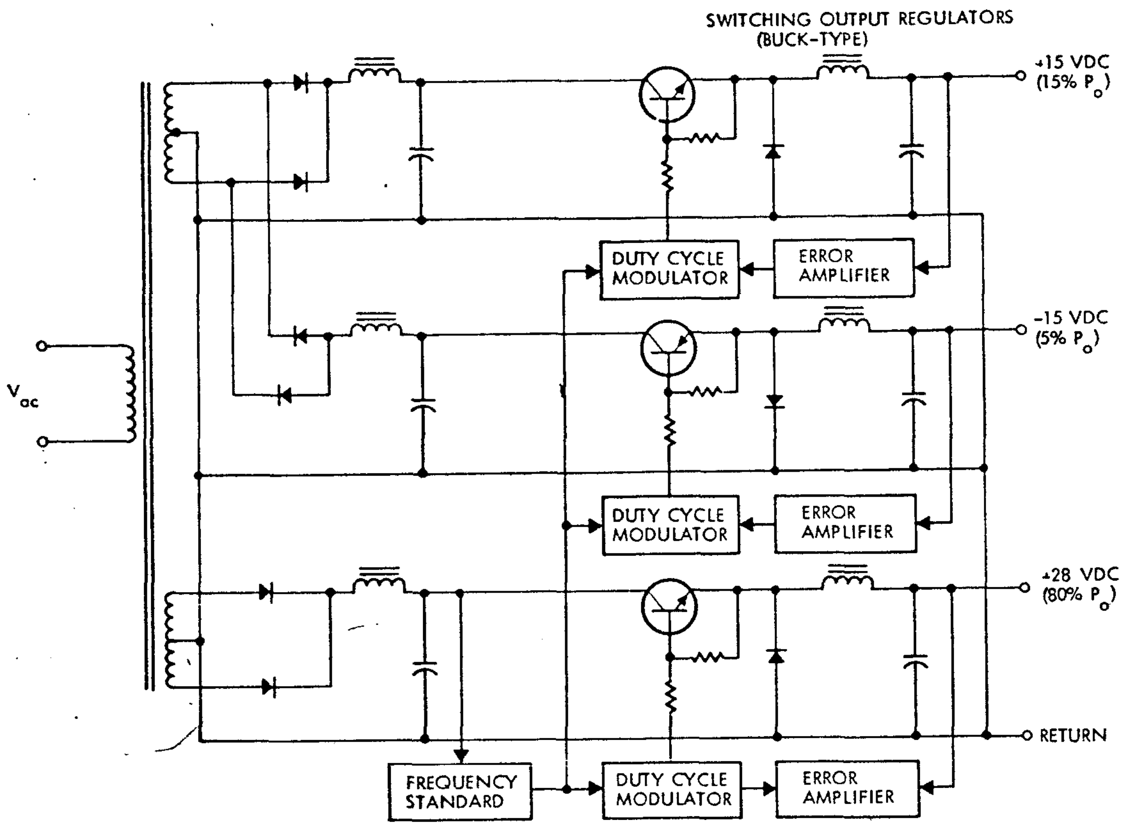


Figure 3.12. Regulated Transformer-Rectifier (Type 5 PPU)

Dissipative output regulators are utilized in the configurations of Figures 3.10 and 3.11, as required, to obtain the desired output voltage regulation characteristics. In the Type 1 or 3 PPU, no output regulator is required on the +28 Vdc output since this is the major load about which the converter feedback loop is closed. In the Type 2 or 4 PPU, output regulators are provided on all outputs since the switching pre-regulator feedback signal is derived from the inverter dc input.

3.1.3 Design Procedure and Assumptions

The method of generating PPU parametric data follows the approach and utilizes the results of two previous studies (References 23 and 25). Briefly, analytical models of standardized subcircuit functions comprising the building blocks of typical power conditioning circuits are established and designs of these functions are performed over a variety of operating ranges and conditions, spanning the output and input requirements given in Tables 3.1 and 3.2. The function weight, power loss, and failure rate data for those functions common to a particular power processing unit can then be combined to yield overall power processor parametric data.

Basic assumptions followed in the development of the data are outlined below:

- Function design constraints and component derating policy follow that outlined in Reference 25 and summarized in Appendix A. The derating reflects that required for long-life space application.
- The summation of function component weights (including semiconductor heat sinking) is multiplied by a power-sensitive factor to yield PPU packaged weight. This factor, presented in Figure 3.13, was developed in a previous NASA study (Reference 23).

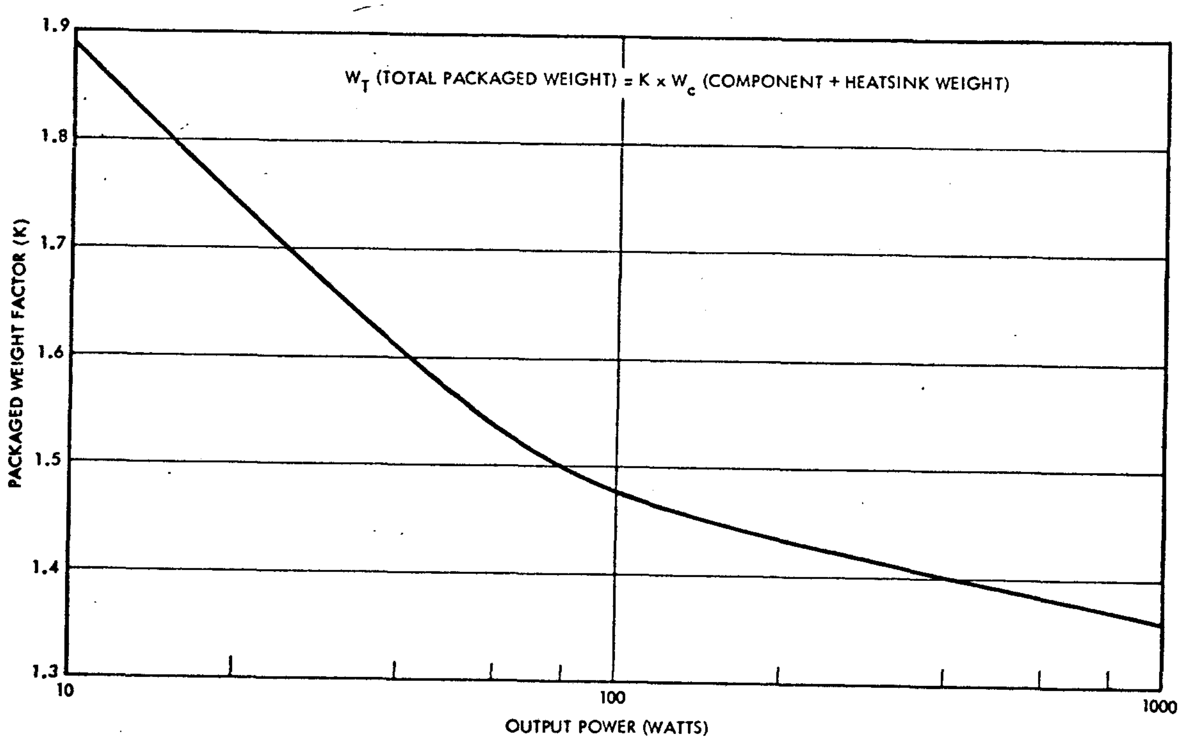


Figure 3.13. Packaging Weight Factor

- Part failure rates used in function design are those given in Reference 23 and Appendix A and reflect actual unmanned spacecraft operating experience.
- PPU mounting to a 55°C maximum cold plate is assumed.
- Function power losses are calculated worst case losses obtained generally at maximum input line conditions and with maximum component voltage drops.
- A fixed converter switching frequency of 10 KHz is assumed throughout.
- No circuit redundancy or built in test (BIT) circuitry is included in the PPU designs. The latter is limited to means for sensing PPU input current and provision of critical test points for bench testing. The primary BIT function would be associated with the specific load output.
- Internal PPU (oscillator) turn-on/off control is assumed, having negligible effect on PPU performance calculations.
- Overload protection is provided by automatic oscillator turn-off when input current exceeds twice rated current. This has negligible effect on PPU performance.
- For ac input designs, a 50 to 100 percent load variation is assumed for sizing the input rectifier-filter inductor.
- For dc input designs, input power line filter design is based on limiting conducted interference to 1 percent (RMS) of the dc input current, at nominal input voltage. A single-stage, passive filter design is assumed which must also meet an audio frequency conducted susceptibility requirement of 3 percent (RMS) of the nominal input voltage (30 Hz to 15 KHz) and a transient susceptibility requirement of the lesser of twice nominal input voltage or 100 volts, for 10 μsec.
- PPU cost is based on component count.
- Hybrid microcircuits are used in signal level function designs.

Appendix A contains details on function design including:

- Definition of power conditioning functions
- Function block diagrams of the selected load PPUs
- Identification of new function classes examined
- Function design procedure, design constraints, and component derating policy

- Part failure rates
- General notes on the presentation and use of function parametric data
- New function descriptions and analytical models
- Special function design assumptions and constraints
- Function parametric data curves

3.1.4 Parametric Performance Results

3.1.4.1 Baseline PPU Designs

The secondary power supply (load PPU) parametric performance data developed are presented in Figures 3.14, 3.15, and 3.16. These curves show, respectively, the specific weight (pounds per watt output), efficiency, and total failure rate for the various selected circuit types as functions of total PPU output power rating, and the previously defined source voltage/frequency alternatives (Table 3.2) and standardized output requirements (Table 3.1). As noted previously, converter switching frequency (and Type 5 output switching regulator frequency) is assumed constant at 10 KHz.

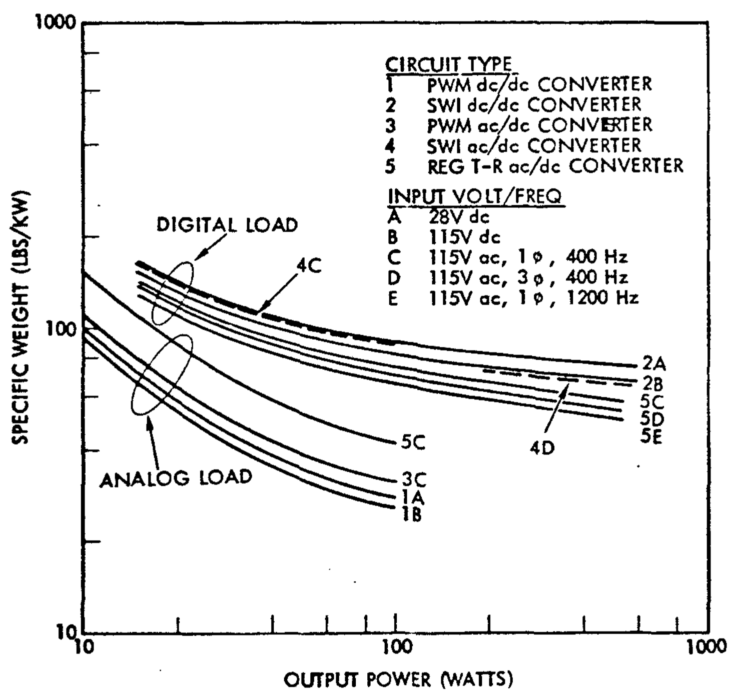


Figure 3.14. Specific Weight of Dc Output PPU

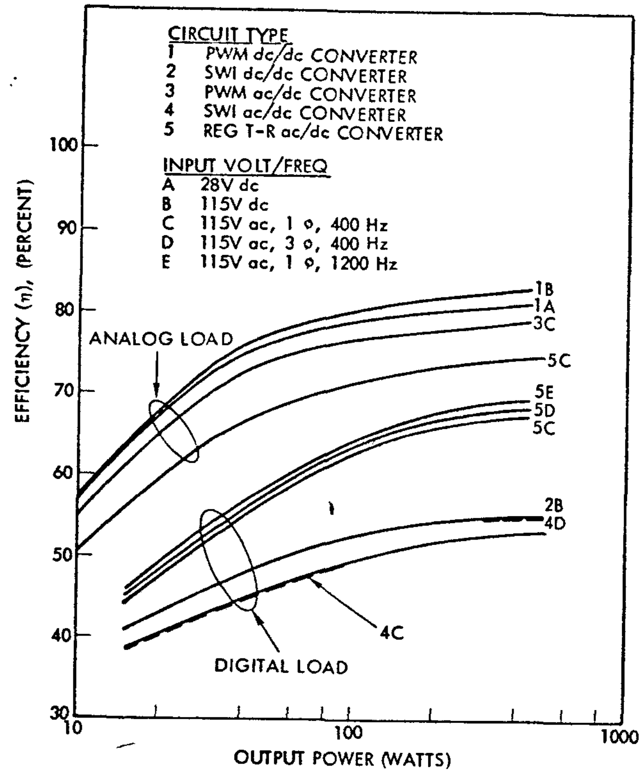


Figure 3.15. Efficiency of Dc Output PPUs.

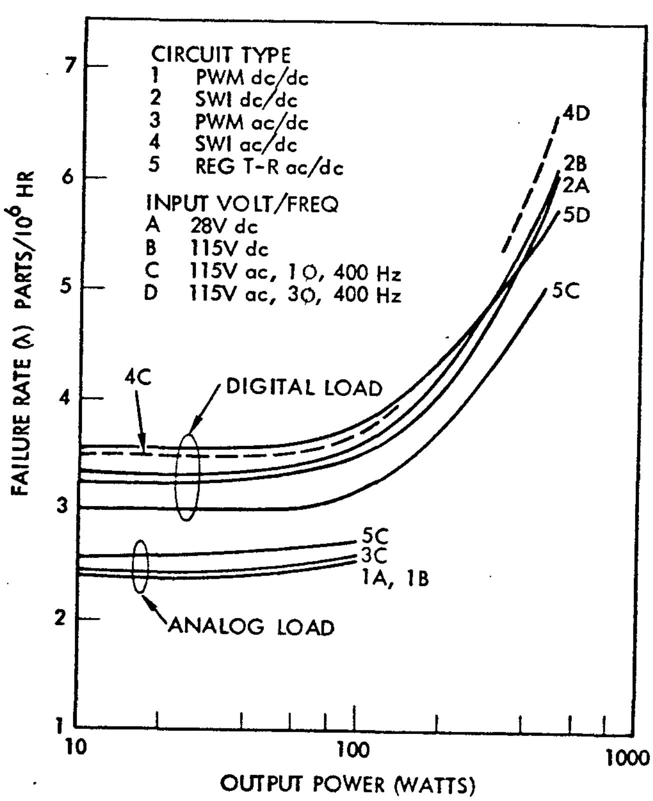


Figure 3.16. Failure Rates of Typical Converters

A bipolar input case, ± 28 Vdc, was calculated for the Types 1 and 2 PPU configurations. This input is effectively equivalent to an input voltage of 56 Vdc and corresponding weight, efficiency, and failure rate figures (not plotted) fall between the rather close values derived for the 28 and 115 Vdc input cases. With a bipolar input, a reliability advantage can be obtained, at the expense of efficiency and weight, by using a redundant PPU configuration. Figure 3.17 illustrates a modified Type 1 PPU, consisting of dual input line filters and a PWM bridge inverter. In the event of loss of power on either side of the input, operation can be sustained by disabling the appropriate side of the bridge inverter (upper or lower pair), converting it to the standard center-tapped push-pull circuit configuration.

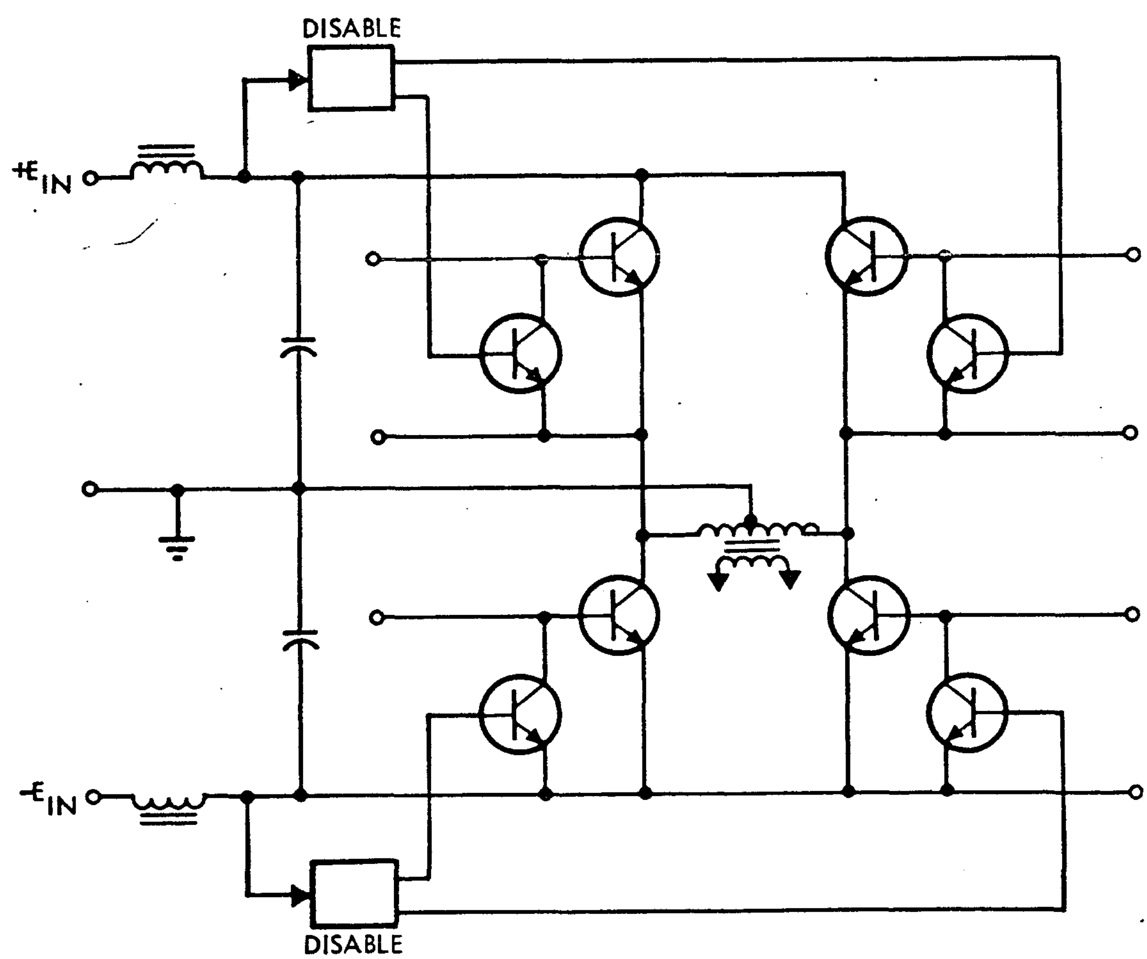


Figure 3.17. Bipolar PPU Configuration for Increased Reliability

Table 3.5 summarizes the performance data calculated for a 100 watt PPU of each configuration considered. The data show that for a given circuit configuration and load type, the variation in PPU specific weight, efficiency, and failure rate is less than 25 percent for the dc and ac input levels and ranges examined. The reduction in PPU weight and losses with increasing input voltage is also evidenced as are the relative advantages of dc over ac input power and the Types 1 and 3 PPU approach over that embodied in the Types 2, 4, and 5.

Table 3.5. Performance of 100W PPU for Electronic Loads

Circuit Type	Input Voltage	Weight (lb.)		Efficiency (%)		Failure Rate (per 10^6 hrs)		Cost ($000)	
		(1)	(2)	(1)	(2)	(1)	(2)	Devel.	Prod.
PWM INV.	28 VDC	2.8	4.86	79	65.1	2.55	2.32	0-100	1-5
	115 VDC	2.6	4.44	80	65.6	2.55	2.32	50-150	1-5
	115V, 400Hz	3.2	5.2	76.2	63	2.72	2.51	0-150	1-5
LINE REG.	28 VDC	4.22	9.4	71.6	49.5	2.65	3.5	0-100	1-5
	115 VDC	3.3	8.1	75.4	52.2	2.69	3.6	50-150	1-5
	115V, 400Hz	4.0	9.1	72	49.8	2.84	3.7	0-100	1-5
REG. TR	115V, 400Hz	4.2	7.45	71.5	62	2.57	3.17	0-50	0.5-3
	115V, 1200Hz	3.4	6.7	72.9	63.2	2.6	3.2	50-100	0.5-3
	115V, 400Hz, 3Ø	4.1	7.1	72.5	62.7	3.2	3.8	0-50	0.5-3

(1) Standard analog load per Table 3.1
(2) Standard digital load per Table 3.1

The following comments on the relatively low efficiency characteristics as calculated should be noted. Type II loading, applied to any circuit configuration yields much lower efficiency than the Type I load case because 70 percent of the total delivered power is at +5 Vdc or -5 Vdc. At this low voltage level, output rectifier and output regulator transistor voltage drops constitute the major loss components. With Type I loading, the minimum output voltage is $\pm$15 Vdc, supplying 20 percent of the total rated power and, therefore, the efficiency penalty in output semiconductors is much less. The effect of output voltage level on efficiency and weight characteristics will be more fully discussed in paragraph 3.1.4.2(c).

The Type 2 or 4 PPU inherently yields poorer efficiency characteristics due to the switching of power in two semiconductors; pre-regulator and inverter transistors. The disparity in efficiency between the Types 1 or 3 and 2 or 4 PPUs is further enhanced because of the absence of a +5 Vdc output regulator in the former.

Calculated values of efficiency in all cases are based, in part, on worst case semiconductor element voltage drops (1 volt-output rectifier, 1 volt-output regulator transistor) and, therefore, are very conservative. A 450 watt Type 2 PPU, operating from an input of 28 Vdc yields a calculated efficiency of 54 percent using the assumed element voltage drops. Using typical values of 0.8 volt and 0.4 volt, respectively, for the output semiconductors, the calculated PPU efficiency would approximate 74 percent, a value typically realized.

Also indicated in Table 3.5 are estimated development and production costs of spacecraft quality PPUs of the types evaluated. These costs, estimated on the basis of prior program experience, do not reflect defensible dollar values since development and production costs are strongly influenced by program management requirements and ground rules. In this study, relative cost or cost differences are the primary consideration.

3.1.4.2 Effect of Load PPU Design Requirements

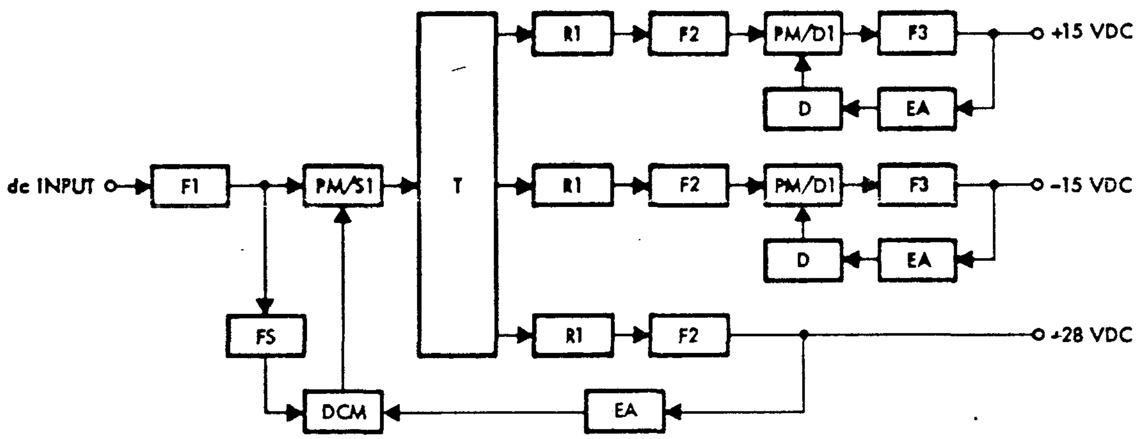
In this section, the effect of the following variations in load PPU electrical design requirements are quantitatively described:

- Output voltage regulation
- Input voltage regulation
- Load distribution and output voltage level

The impact of electromagnetic interference requirements will be presented in Section 4.3.

a. <u>Output Voltage Regulation</u>

Figure 3.18 and Table 3.6, respectively, illustrate the function block diagram of a Type 1 PPU and the corresponding breakdown of function losses, weights, and failure rates for the conditions of 28 Vdc input and Type I loading. (Appendix A contains all function block diagrams used in developing parametric performance data). An examination of Table 3.6 shows the impact of the output regulation requirement in the ±15 volt outputs. Functions 2(a) through 2(d) and 3(a) through 3(d), the functions comprising the ±15V output regulators, contribute approximately 18 percent of the total weight, 20 percent of the total power loss, and 40 percent of the total failure rate in this particular example.



FUNCTION CODE

POWER FUNCTIONS
- F1 PASSIVE FILTER (L-C TYPE - ac CURRENT)
- F2 PASSIVE FILTER (L-C TYPE - ac VOLTAGE)
- F3 PASSIVE FILTER (C TYPE - NO ac)
- PM/S1 POWER MODULATION, SWITCHING (PWM INVERSION TYPE)
- PM/D1 POWER MODULATION, DISSIPATIVE (SERIES-TYPE)
- T TRANSFORMATION
- R1 RECTIFICATION, (PWM SQ WAVE)

SIGNAL LEVEL FUNCTIONS
- D DRIVER
- EA ERROR AMPLIFIER
- FS FREQUENCY STANDARD
- DCM DUTY CYCLE MODULATOR

Figure 3.18. Function Block Diagram - Type 1 PPU

Table 3.6. Breakdown of Function Power Loss, Weight & Failure Rate

Type 1 PPU

P_o (total)=100 W
E(in)=24-36 Vdc

Output 1 +28 Vdc $\pm$3%, 80W
Output 2 +15 Vdc $\mp$3%, 15W
Output 3 -15 Vdc $\mp$3%, 5W

Converter Switching Frequency 10 kHz

Item Function	Loss (Watts)	Weight (LBS)	Fail. Rate (pts/10^6 hrs)
1(a) +28 V output-output filter (F2)	1.0	0.156	.075
1(b) +28 V output-rectifier (R1)	2.9	0.205	.080
2(a) +15 V output-output filter (F3)	0	0.022	.011
2(b) +15 V output-regulator transistor (PM/D1)	2.1	0.105	.126
2(c) +15 V output-error amplifier (EA)	1.0	0.070	.370
2(d) +15 V output-driver (D)	0.3	0.016	.019
2(e) +15 V output-rectifier filter (F2)	0.2	0.030	.061
2(f) +15 V output-rectifier (R1)	1.4	0.081	.080
3(a) -15 V output-output filter (F3)	0	0.007	.011
3(b) -15 V output-regulator transistor (PM/D1)	0.7	0.036	.126
3(c) -15 V output-error amplifier (EA)	1.0	0.070	.370
3(d) -15 V output-driver (D)	0.1	0.005	.019
3(e) -15 V output-rectifier filter (F2)	0.2	0.013	.056
3(f) -15 V output-rectifier (R1)	0.5	0.030	.040
4 Transformer (T)	5.0	0.153	.010
5 PWM Inverter (PM/S1)	5.0	0.390	.080
6 Error Amplifier (main loop) (EA)	1.0	0.078	.390
7 Duty Cycle Modulator (DCM)	2.0	0.099	.143
8 Frequency Standard (FS)	1.0	0.078	.390
9 Input Filter (F1)	0.8	0.211	.093
Totals	26.2	1.855	2.55

$$\text{Eff.} = \frac{100}{100 + 26} = 79.1\%$$

Pkg. factor (at P_o = 100 W) = 1.48
Weight = 1.48 x 1.855 = 2.74 lb

The percentages for output regulator weight, power loss, and failure rates for 100W power processing units of various circuit types examined are listed in Table 3.7. Tighter output regulation requirements than those assumed in this study essentially impact only on cost (cost of output regulator reference element and, if required, additional driver gain stages).

Table 3.7. Cost of Output Voltage Regulation (Typical)

PPU Type	Input Voltage	Load Type	% of Total Loss	% of Total Weight	% of Total Failure Rate
1	28 Vdc	I	20	18	40
2	28 Vdc	II	33	34	55
5	115 Vac	I	35	38	85
5	115 Vac	II	35	40	83

b. Input Voltage Regulation

Figure 3.19 illustrates the effect of PPU input voltage regulation on the efficiency, weight, and failure rate of a Type 1 PPU at two output power levels: 10 and 100 watts. (Input voltage regulation is defined herein as

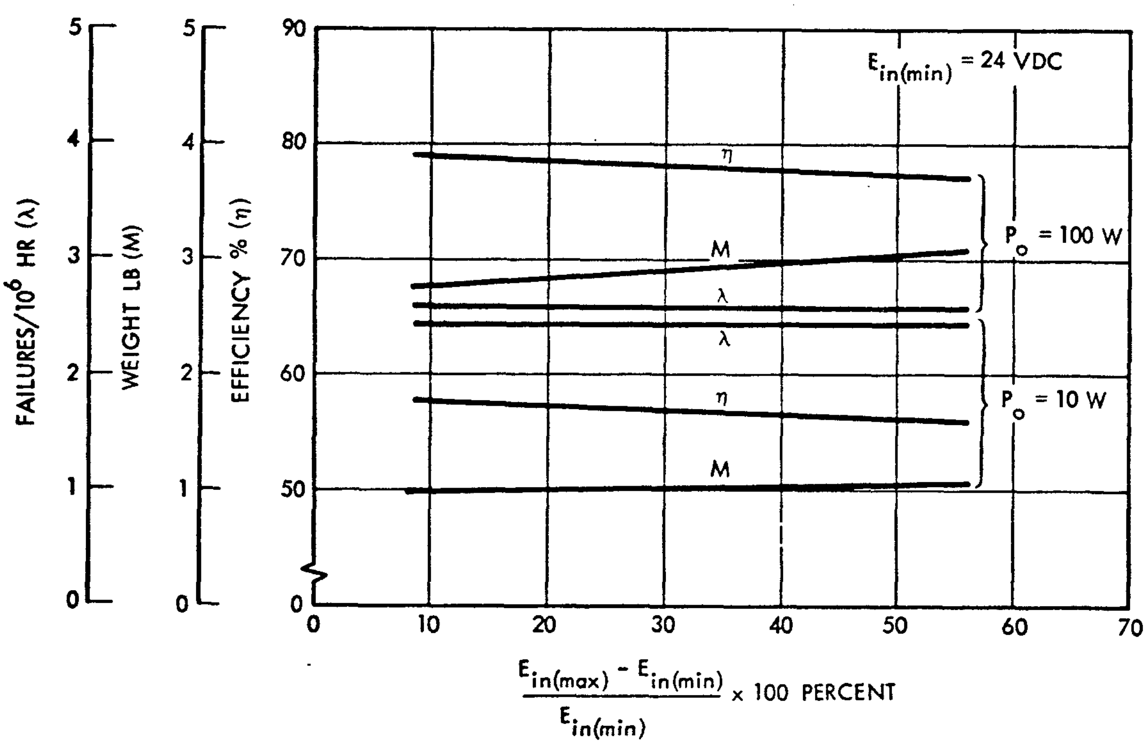


Figure 3.19. Effect of Input Voltage Regulation (Type 1 PPU)

100 times the difference of steady state maximum and minimum input voltages divided by the minimum input voltage value.) Values of regulation examined ranged from 8.33 to 50 percent, corresponding to 24 to 26 Vdc and 24 to 36 Vdc, respectively, in the selected design cases. The curves of Figure 3.19 demonstrate the relatively small effect on PPU performance over the specified regulation range. In the 100 watt case, for example, weight increases by 11 percent (2.75 to 3.04 pounds), efficiency drops from 79 to 77.5 percent and failure rate is unchanged as input regulation is increased between the selected limits. The small changes result because variations in input voltage regulation, with the limits establishing maximum power switch duty cycle, influence the design of only three of the basic Type 1 PPU power level functions; input filter, output filters, and the pulse width modulated inverter. Of these, the impact on filter design, both input and output, dominates, with filter weight and losses increasing with wider input regulation limits. Table 3.8 shows a breakdown of weight and losses in the affected functions of a 100 watt Type 1 PPU at the two limits of input voltage regulation evaluated. Also indicated are the percentage of function weight (and losses) to the total PPU function weight (or loss).

Table 3.8. Function Weight & Loss Breakdown as Function of Input Voltage Regulation for 100 Watt Type 1 PPU

	Weight (lbs)		Losses (watts)	
Input Voltage Limits→	24-26 Vdc	24-36 Vdc	24-26 Vdc	24-36 Vdc
Output Filters	0.131 (7%)	0.219 (11%)	0.5 (0.4%)	1.6 (1.2%)
PWM Inverter	0.378 (20%)	0.398 (16.5%)	5.1 (4%)	5.0 (4%)
Input Filter	0.268 (14%)	0.339 (19.5%)	1.2 (1%)	2.0 (1.5%)

The influence of tighter input voltage regulation limits (such as $\pm 1\%$) on the performance characteristics of PPUs supplying power to the selected standard loads is strongly dependent on circuit approach. If input/output isolation is a requirement in a particular application, a PPU inverter function must be implemented. Also, output regulators may be required to

...on must be implemented. Also, output regulators may be required to ... the effects of load changes. For circuits implemented to provide ... functions, PPU weight and efficiency can suffer in comparison to ... obtainable in the standard (unregulated input) configurations previously ...ed. In the absence of a circuit isolation requirement, considerable ...t modification can be implemented, yielding much improved overall ...mance characteristics.

Performance figures for various modifications of 10 and 100 watt Type 1 PPUs and 15 watt Type 2 PPUs (supplying, respectively, Type I and Type II standard loads) operating from a 28 Vdc ±1 percent bus are presented in Table 3.9. Figures for the basic Type 1 and 2 PPUs, with the baseline unregulated input (24-36 Vdc) are given for comparison.

Table 3.9. PPU Performance with Regulated Input

PPU Type	Input Voltage (VDC)	Load Type	P_o (watts)	Input-Output Isolation	Efficiency (%)	Weight (lbs)	Failure Rate (pts/10^6 hrs)
1	24-36	I	100	Yes	79.1	2.78	2.55
1	24-36	I	10	Yes	57.1	0.99	2.42
1A	28±1%	I	100	Yes	74.4	3.38	2.55
1B	28±1%	I	100	No	88.7	1.41	1.86
2	24-36	II	15	Yes	38.7	2.6	3.24
2A	28±1%	II	15	Yes	44.3	1.98	2.62

The Type 1A PPU consists basically of a square-wave, rather than PWM-type, dc-dc converter with dissipative regulators provided on all outputs. In the Type 1B configuration, 28 volt power is supplied directly, via the input filter, and a small, square-wave type dc-dc converter and output dissipative regulators supply the ±15 Vdc requirements. The Type 2A PPU is similar to the Type 2 except that the pre-regulator is omitted. Table ... shows the significant improvement obtained in the Type 2A case over the Type 2 while the Type 1A, providing isolation, yields poorer performance when compared to the Type 1 PPU. The Type 1B, providing no input/output isolation, offers much improved performance over the Type 1 due to circuit simplification and reduced inverter power rating.

c. Load Distribution and Output Voltage Level

The amount of power supplied at low voltage in multiple output PPUs has a major impact on PPU efficiency and weight characteristics. Table 3.10 illustrates, for a specific case, the effect of output requirement change. Calculated PPU parameters for a standard Type 2 design (load Type II) are compared with a Type 2 dc-dc converter modeled for a particular load application, a computer core memory. Total load is identical in both cases. This load requires approximately 35 percent of the total power supplied at ±5 Vdc. In the standard design, 70 percent of total power is supplied at ±5 Vdc, significantly penalizing PPU weight and efficiency. Higher failure rate obtains in the former case due to the increased number of outputs.

Table 3.10. Effect of Output Requirement Change (Type 2 PPU)

	Standard Load	Core Memory Load
Converter Outputs	+5V, 146W -5V, 24W +15V, 37W -15V, 37W	+40V, 28W +20V, 130W +5V, 61W +5V, 15W -5V, 10W
Total Output Power	244W	244W
Input Voltage	28VDC	28VDC
Calculated Weight (lbs)	19.3	16.4
Calculated Efficiency (%)	52.4	58.6
Calculated Failure Rate	$4.17/10^6$ hrs	$4.64/10^6$ hrs

The effect of relative low voltage output power is graphically illustrated in Figure 3.20 which shows, for a standard 28 Vdc input, 100 watt Type 2 PPU, the change in unit weight and efficiency as the percentage of output power supplied at ±5 Vdc is varied from 0 to 100 percent. As indicated, an 80 percent increase in weight and a 20 percent drop in efficiency results as ±5 Vdc power is increased from 0 to 100 percent.

By sensing the proper output for major loop feedback control as a function of load distribution, multiple output PPU efficiency can be maximized in individual design cases, as illustrated in the following group of figures (Figures 3.21 to 3.25).

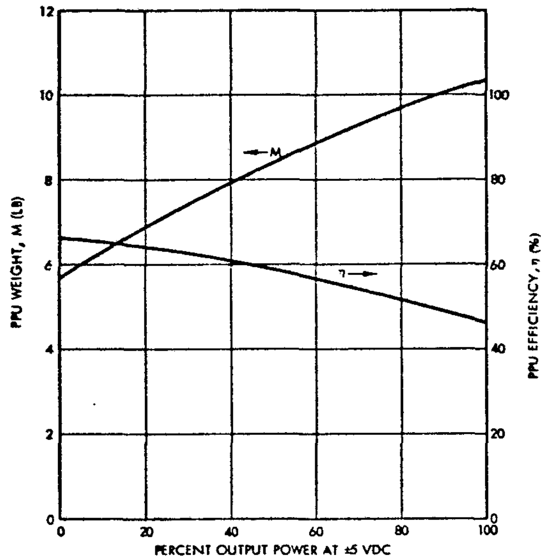


Figure 3.20. Effect of Relative Low Voltage Output Power (Type 2 PPU)

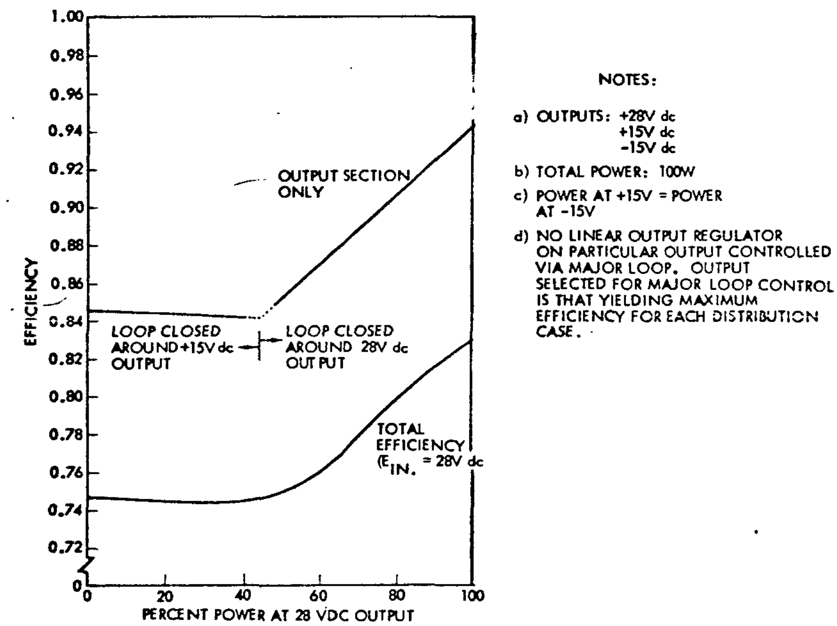


Figure 3.21. Type 1 PPU Efficiency Versus Load Distribution

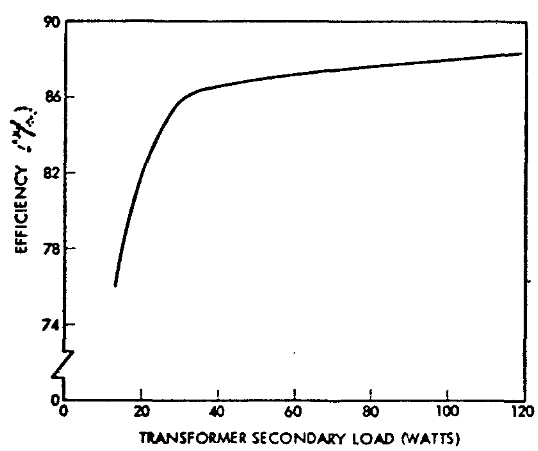


Figure 3.22. Type 1 PPU Front-End Efficiency; Ein = 28 Vdc

For a 100 watt Type 1 PPU (with modified Type I load) operating from a 28 Vdc bus, the top curve of Figure 3.21 shows PPU output section efficiency as a function of percentage output power at 28 Vdc, with the balance divided equally between +15 and -15 volt outputs. The output section consists of all output rectifiers and post regulators. From approximately 44 percent power at 28 Vdc to 100 percent, the PPU major feedback loop closed around the 28 volt output yields maximum output section efficiency. Below this level, maximum output section efficiency is obtained by closing the major loop about either the +15 or -15 volt output, post regulators being utilized on the two remaining outputs. Combining data from this plot with that obtained from Figure 3.22, Type 1 PPU front-end circuit efficiency, total PPU efficiency can be plotted and is presented in the lower curve of Figure 3.21. Front-end circuitry includes all input functions through the high frequency converter transformer. Figure 3.23 illustrates, for a fixed load distribution, the independence of PPU output section efficiency with total PPU power rating. Above approximately 20 watts, the efficiency is constant.

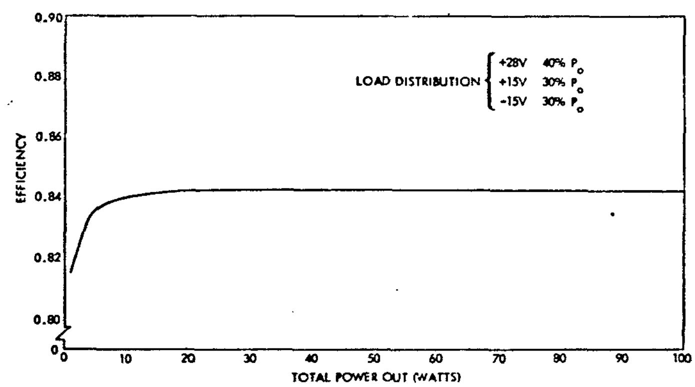
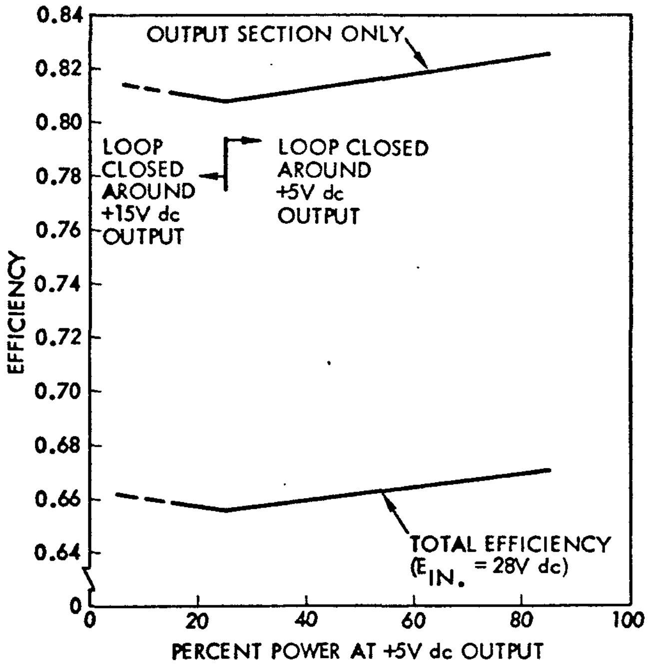


Figure 3.23. Type 1 PPU Output Section Efficiency Versus Total Output Power with Fixed Load Distribution

Figures 3.24 and 3.25 show similar results for the Type 2 (Squarewave Inverter) PPU.



NOTES:

a) OUTPUTS: +15V dc
-15V dc
+5 V dc
-5 V dc

b) TOTAL POWER: 100W

c) POWER AT +15V = POWER AT -15V

d) POWER AT -5V = 5.0W

e) NO LINEAR OUTPUT REGULATOR ON PARTICULAR OUTPUT CONTROLLED VIA MAJOR LOOP. OUTPUT SELECTED FOR MAJOR LOOP CONTROL IS THAT YIELDING MAXIMUM EFFICIENCY FOR EACH DISTRIBUTION CASE.

Figure 3.24. Type 2 PPU Efficiency Versus Load Distribution

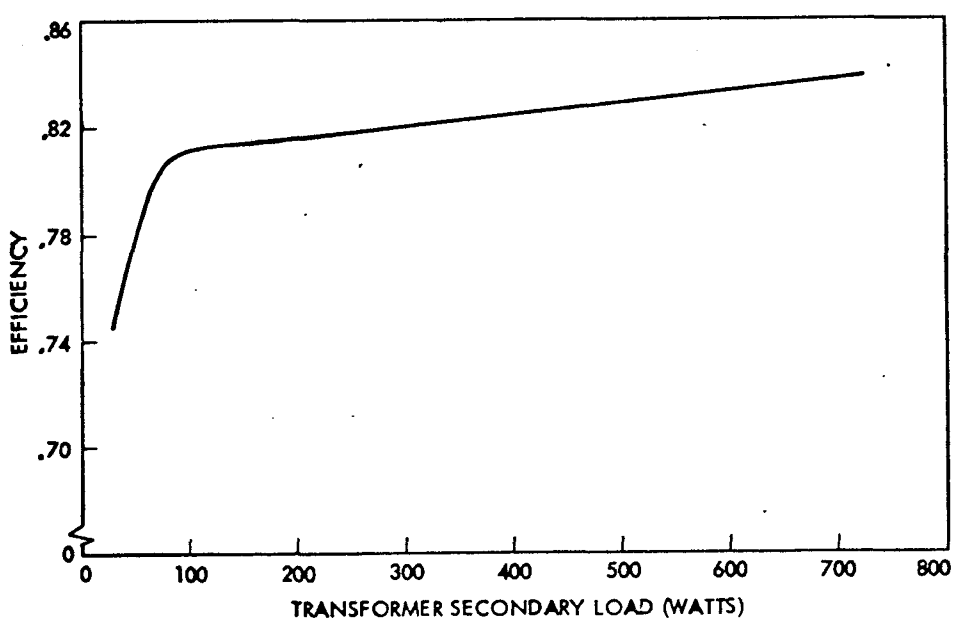


Figure 3.25. Type 2 PPU Front-end Efficiency; Ein = 28 Vdc

3.2 TRANSMISSION AND DISTRIBUTION

This section describes the affect of transmission voltage and frequency and other PDCS configuration variables on the design and performance of cables and connectors.

3.2.1 Circuit Considerations

For purposes of this study program we have assumed that transmission always refers to the delivery of power from the EPGS source or generator bus to a local power distribution unit (PDU) or load bus by means of feeder cables. Distribution refers to delivery of power to individual load utilization equipment (LRUs) from a load bus by means of distribution wires and cables. The transmission/distribution equipment consists of cabling and connectors of various physical configurations. Our study is concerned with the choice of voltage and frequency as well as the transmission/distribution circuit design to minimize cable weight, power losses, and interference consistent with reliability and safety requirements.

Figure 3.26 shows the basic transmission or distribution circuits for delivering power from a generator or bus G to a load Z. Configuration 1 has the lowest weight because vehicle structure is used for the return path. This is acceptable if the structure impedance is small and the transmission frequency is sufficiently low so that the voltage induced in nearby circuits due to the transmission current is negligible.

For configuration 2 twice as much wire is required but electromagnetic interference can be greatly reduced by tightly twisting the two wires to minimize the external magnetic field. Since three-phase generators and motors are lighter and more efficient than single-phase machines, balanced three-phase ac power is provided. Configurations 3 and 4 imply balanced loads under normal unfaulted conditions. The neutral current under these conditions is zero and the external magnetic field from the three closely spaced transmission wires is negligibly small. Under unbalanced or fault conditions a neutral (zero sequence) current must flow giving rise to an external field which is somewhat larger for the three-wire case. The bipolar configuration consists of two actively redundant single line links when the voltages to ground are equal and is equivalent to configuration 2 when the voltages between lines are equal. In the latter case, it has the same weight as configuration 2 but half the voltage to ground. The homopolar link has been used for high voltage dc transmission of utility power where it has some slight advantage over the bipolar link when switching of terminal equipment is required. It will not be considered further.

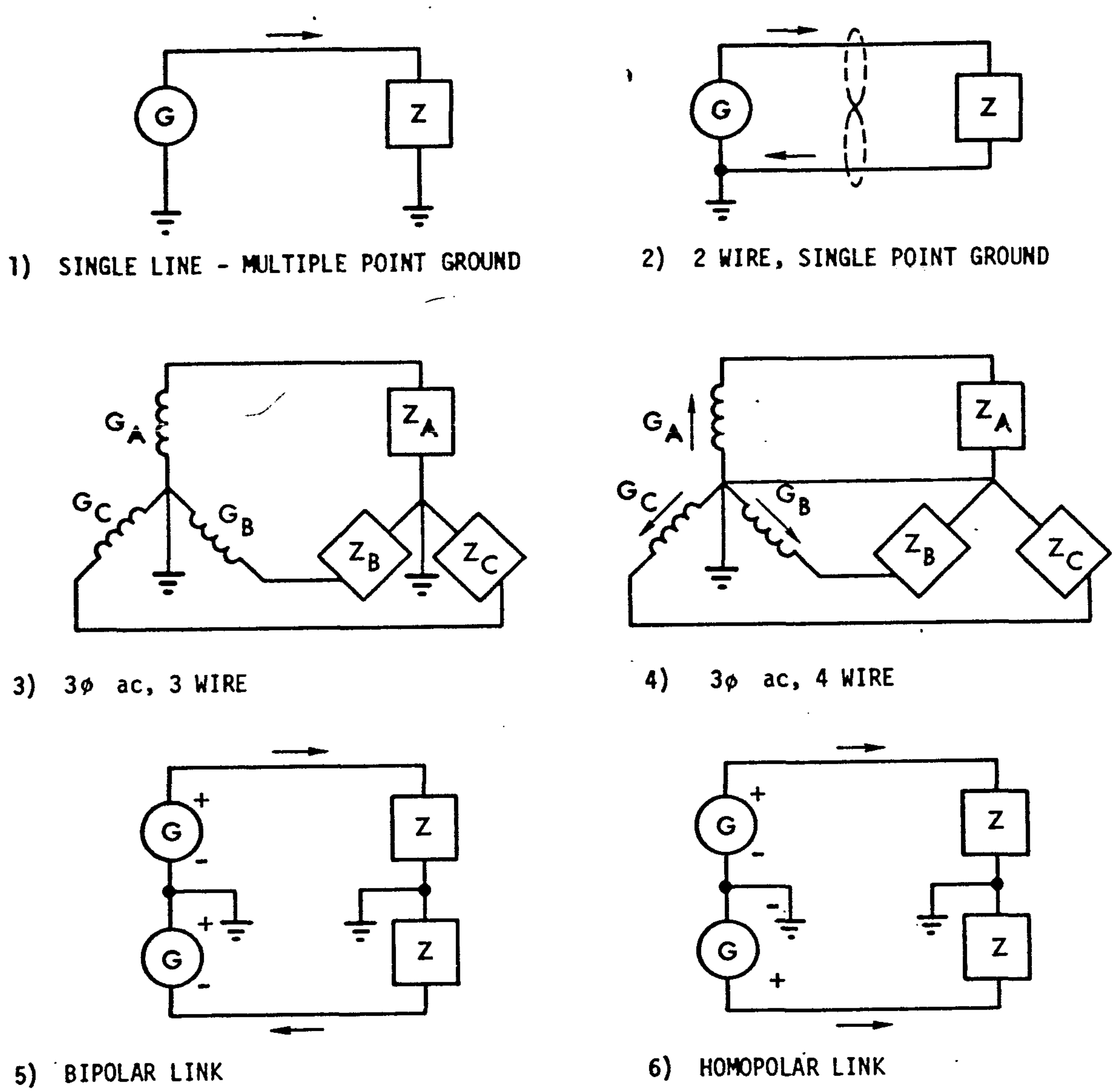


Figure 3.26. Transmission Configurations

3.2.2 Cabling Configurations

Several different cabling configurations are used in aerospace equipment. The types are described below:

- Round bundled wire cables

  Round wire bundled cable is, as its name implies, a round bundle of cables packed closely together and tied at intervals along its length to form a coherent bundle of wires. Individual wires or groups of wires may enter or leave the main harness at any point along its length. This is the most common method of cabling. It forms a strong, relatively rigid harness which is shaped prior to installation. It is the most adaptable method of harness formation, accommodating all sizes and types of wire in a single bundle, subject only to the possibility of capacitive or magnetic coupling between wires.

- Collated and flat moulded cable

  Because of the relative rigidity of bundled cables, collated and flat moulded cables were developed. In this form, round wires of all types are laid parallel in a single plane, and are sewn together or moulded together inside a single insulation film. This type of cable is relatively flexible in a plane normal to that in which the wires are laid. The sewn, collated cable is relatively expensive because of the high labor costs, but has a short lead time, since ordinary wire is used in its formation. The moulded cable has a long lead time and high setup charges, but is less expensive than the collated sewn cable in large runs. Individually shielded wires, coaxial cables, twisted pairs, etc. can all be accommodated in the sewn or moulded collated cable form.

- Flat-conductor cable

  In this cable, relatively flat, rectangular cross-section conductors are bonded between sheets of plastic insulation to form a type of collated cable. The thin conductor layers result in greater flexibility of bending of the strip than is possible with the collated cables. Setup charges are high, lead time is long, and there are limitations in the type and mix of conductors which can be incorporated into a flat conductor assembly.

Twisted pair conductors may be simulated by use of a quasi-twist pattern, and a three-layer (of insulation) assembly technique. Coaxial cables and individual shielded cables cannot be made by this technique, although all of the wires within a single flat-conductor cable can be enclosed within an outer shield.

Hand-assembled cables, such as the bundled and sewn collated cables, share the advantage of being able to accommodate last minute design changes more readily than the pre-fabricated cables, such as the moulded collated cable or the flat-conductor cable.

The round bundled cable has the advantage of having already flight-qualified connectors and terminations available, whereas the flat-conductor type connectors have not yet been flight qualifed.

Table 3.11 shows the qualitative advantages and disadvantages of the several types of cable.

Table 3.11. Cabling Configurations

	BUNDLED CABLE	COLLATED CABLE (sewn)	COLLATED CABLE (molded)	FLAT CONDUCTOR CABLE
Costs				
Setup costs	Low	Low	High	High
Manufacturing costs	High	High	Low	Low
Properties				
Flexibility	Poor	Good (1 direction)	Good (1 direction)	Good (1 direction)
Weight	Moderate	Moderate	Moderate	Low (variable)
Lead Time	Short	Moderate	Long	Long
Adaptability to design change	Good	Good	Poor	Poor
Accommodates twisted pair	Yes	Yes	Yes	Quasi-twist-weight penalty
Accommodates shielded wire	Yes	Yes	Yes	Shielding in groups only
Accommodates coaxial cable	Yes	Yes	Yes	No
Connectors	Qualified	Qualified	Qualified	No qualified connectors
Cross-talk	Good	Good	Good	Fair

3.2.3 Effect of Frequency

In addition to the ohmic resistance which causes I^2R losses, transmission lines have distributed series inductance and shunt capacitance which produce reactive voltage drops. When the transmission distance is large or the frequency exceeds the usual power frequencies, the voltage amplitude and phase angle are functions of the line length as well as the load impedance. The affect of frequency above 400 Hz on transmission lines and frequency sensitive loads such as motors and transformers has been studied by AiResearch under NASA contract (Reference 3). Neglecting the shunt capacity and using theoretical formulas as found in standard texts (Reference 26) for self inductance, they calculated cable impedance as a fucntion of frequency and wire size obtaining the curves of Figure 3.27.

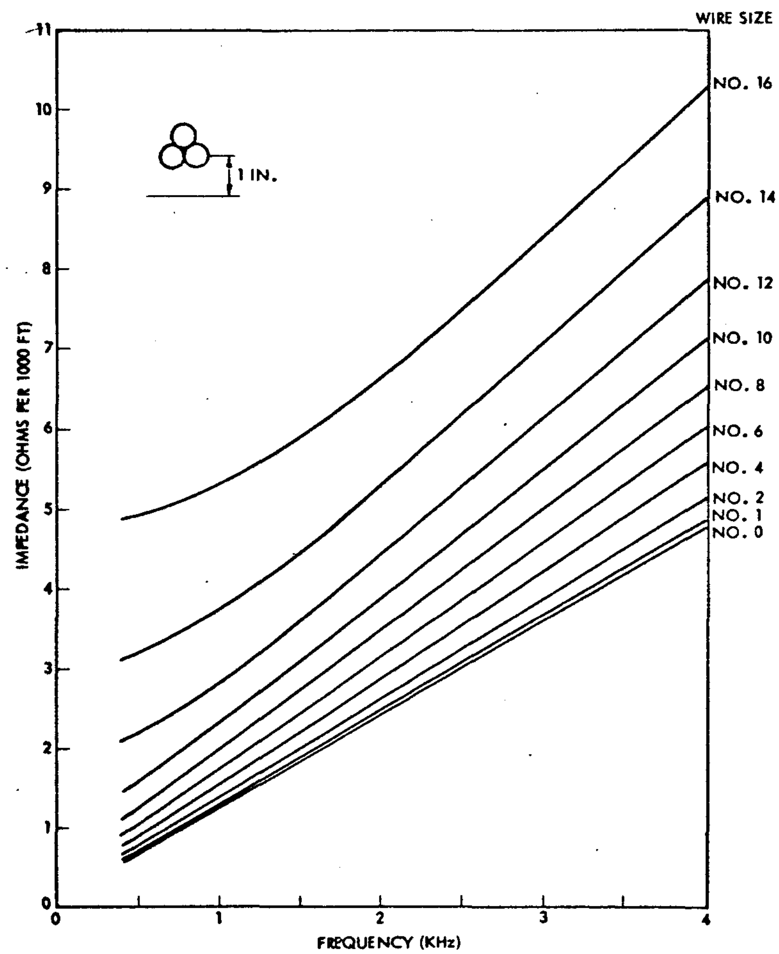


Figure 3.27. Cable Impedance Per Wire Versus Frequency

For a constant transmission voltage drop of 4% at any frequency and for a specific set of frequency sensitive loads as might be found on a large transport aircraft, AiResearch calculated the relative cable plus motor and transformer weight as a function of frequency and voltage. The results show that since the motor and transformer weight decreases with increasing frequency while the cable weight must increase to maintain the cable voltage drop constant, an optimum frequency at which the total weight is minimum exists. The optimum frequency depends strongly on the load power, feeder length and voltage, and the assumption of constant cable voltage drop. Since the purpose of our study is to develop generalized power processing, distribution and control configurations, no attempt has been made to determine an optimum frequency for each of the requirements models developed in Section 2.3. Since induction motors represent a relatively small portion of total spacecraft power requirements and since the amplitude of induced voltage due to mutual inductance between wires increases linearly with frequency, only the standard 400 Hz frequency was selected as a candidate transmission/distribution frequency.

3.2.4 Transmission Voltage

The weight of the transmission and distribution wires depends on the power to be delivered, the circuit configuration, system voltage, and cable voltage drop ΔV. Since in many spacecraft the EPGS weight must increase to supply the cable power loss, an optimum value of ΔV exists for which the net transmission weight given by

$$M' = M + \Delta M_G \tag{3.1}$$

where

M = weight of wires

ΔM_G = generator weight penalty due to ΔV

is minimized. In addition the cross section and hence the weight of the cable must be such that the maximum allowable current rating is not exceeded and the cable has adequate mechanical strength characteristics.

The cable weight M may be calculated as follows for round wire insulated cable. Let

ρ = density of conductor in gm/cm^3

ρ_i = density of insulation in gm/cm^3

σ = resistivity in ohm-cm

ℓ = cable length in cm

d = diameter of conductor in cm

δ = thickness of insulation in cm

I = current in amperes

M_c = weight of conductor

M_i = weight of insulation in gm

V = transmission voltage

P = transmitted power

Then

$$M = M_c + M_i = \frac{\pi}{4} d^2 \rho \ell + \pi d \delta \rho_i \ell \qquad (3.2)$$

But since $\rho_i \leq \frac{1}{3} \rho$ and $\delta \leq \frac{1}{4} d$ for wires larger than 20 gage assuming .005 in. insulation, we get $M_c > 3M_i$ so that the weight of the insulation may be neglected for wires larger than AN size 20.

Then $$M \approx \frac{\pi}{4} d^2 \rho \ell \qquad (3.3)$$

Also $$\Delta V = \frac{4}{\pi} \frac{\sigma}{d^2} \ell I \qquad (3.4)$$

from which $$M \approx \rho \ell^2 \sigma I/\Delta V \doteq \rho \ell^2 \sigma \frac{P}{V(\Delta V)} \qquad (3.5)$$

which shows that for any given current or power to the load the cable weight per unit length is inversely proportional to the voltage drop per unit length.

The generator weight penalty is given by

$$\Delta M_G = m_G I \Delta V \qquad (3.6)$$

where m_G is the incremental specific weight of the EPGS (see Section 2.4).

Substitution of (3.5) and (3.6) in (3.1) yields

$$M' \approx \rho \ell^2 \sigma I/\Delta V + m_G I \Delta V \tag{3.7}$$

which has a minimum value when

$$\frac{\Delta V}{\ell} \approx \sqrt{\frac{\rho\sigma}{m_G}} \tag{3.8}$$

and $M = \Delta M_G$. The minimum transmission weight per unit length of cable is therefore

$$\left.\frac{M'}{\ell}\right)_{min} \approx 2 \frac{P}{V} \sqrt{m_G \rho \sigma} \tag{3.9}$$

Note that a minimum is obtained only for non-zero values of generator incremental weight m_G and that M' varies directly with load power P and inversely with transmission voltage V.

The transmission weight as obtained from equation (3.9) and assuming a solar cell generator with m_G = 100 lb/KW is plotted in Figure 3.28.

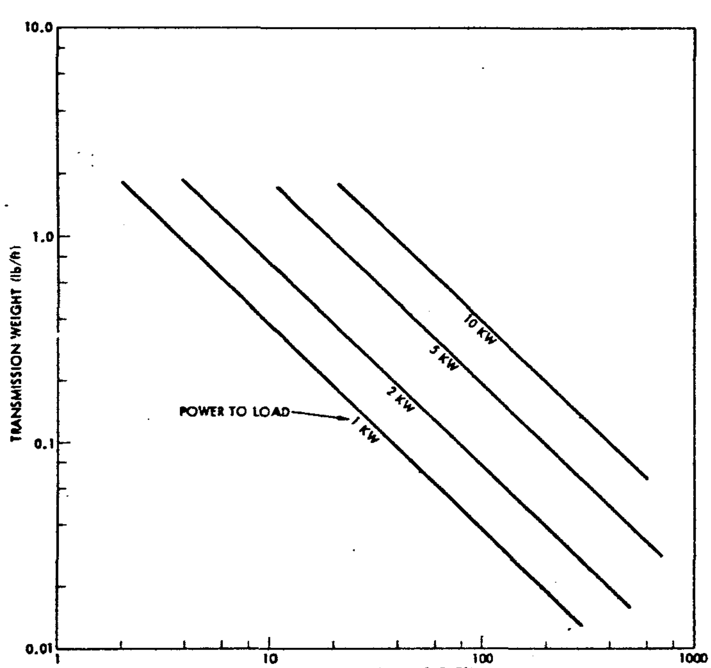


Figure 3.28. Optimized Space Station Transmission Weight

The current carrying capacity depends on the cable configuration and the maximum allowable temperature rise. Excessive current may cause charring of the insulation, loss of strength, and finally fusing of the wire. Current as a function of temperature rise for single wire cable in air, assuming an insulation thickness of less than .025 inches, is shown in Figure 3.29. Starting from this point, derating factors must be applied to compensate for three environmental factors:

- Bundled wires must be derated to avoid accumulation of heat within a bundle.
- Wires must be derated to compensate for operation in an ambient temperature different from that at which the recommended rating was formulated.
- Wires must be derated to compensate for differences between the heat transfer coefficients at which the wire was rated (still air, with convection) and the operating environment (space, or low pressure atmospheres).

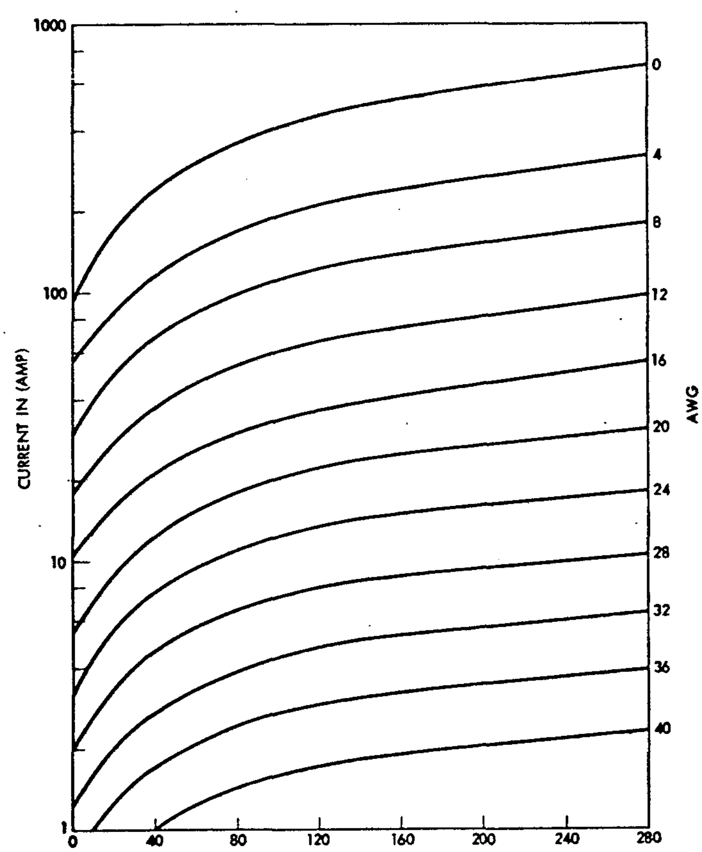


Figure 3.29. Current Carrying Capacity of Insulated Wire

Typical wire bundling derating factors vary with wire size between 0.53 and 0.63 as derived by calculating the fraction of current allowable in a bundle of more than 15 wires over that allowed in a single wire in free air. The data show no logical trend with changing wire gauge sizes.

Derating for ambient temperature may be achieved by use of the following relationship:

$$f_t = \frac{I}{I_r} = \sqrt{\frac{t_c - t}{t_c - t_r}} \qquad (3.10)$$

where

I = current rating for ambient temperature t

I_r = current rating at rated ambient temperature t_r

t_c = maximum temperature rating of insulated wire or cable

Derating for altitude requires that for altitudes above 60,000 ft., the allowable current capacity is approximately 80% of the sea level rating and changes linearly between sea level and 60,000 ft.

Figure 3.30 gives the weight per unit length as a function of current carrying capacity of single conductor aircraft wire per MIL-W-5088 above 60,000 ft. assuming a temperature rise of about 50°C. Note that for small sizes, the weight is approximately 0.83 lbs/1,000 ft. per ampere of rated current capacity. If higher temperature rise is allowed, the weight can be reduced accordingly. By use of equation (3.9) and since the wire weight comprises one half of the transmission weight, it can be shown that cables designed for optimum voltage drop will not exceed the maximum allowable current rating for 50°C temperature rise whenever the EPGS specific weight m_G is larger than 20 lb/kw.

Figure 3.31 compares the transmission weights per 100 ft-kw, as obtained from equation (3.9), for the Space Station and Shuttle when using optimized cable sizes with cables conforming to conventional voltage drops referenced to MIL-STD-704A category B equipment tolerances. Note that at 115 Vdc, and for a load of 10 KW, 56 lb/100 ft. can be saved on the Shuttle and 18 lb/100 ft. can be saved on the Space Station when cables are designed for optimum voltage drop.

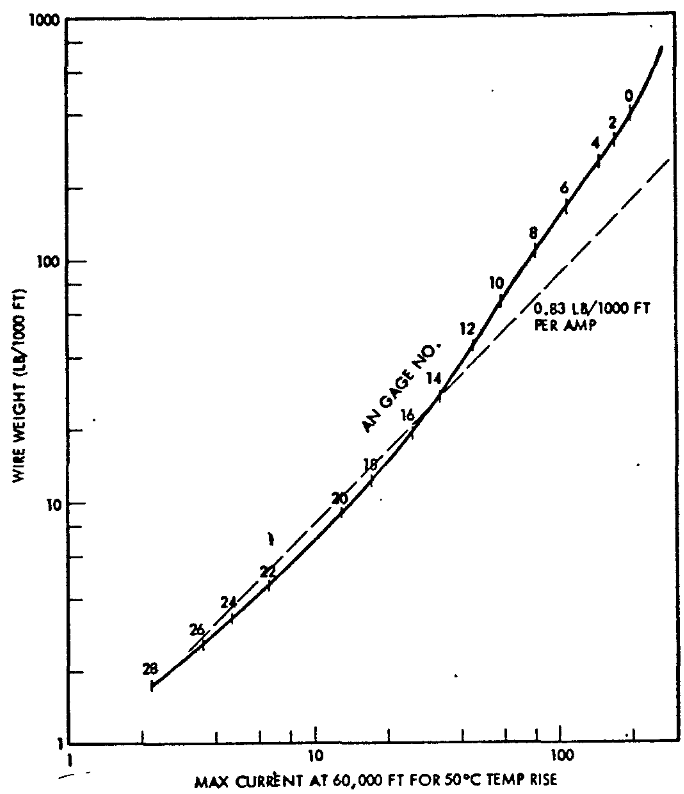


Figure 3.30. Wire Weight as Function of Maximum Current

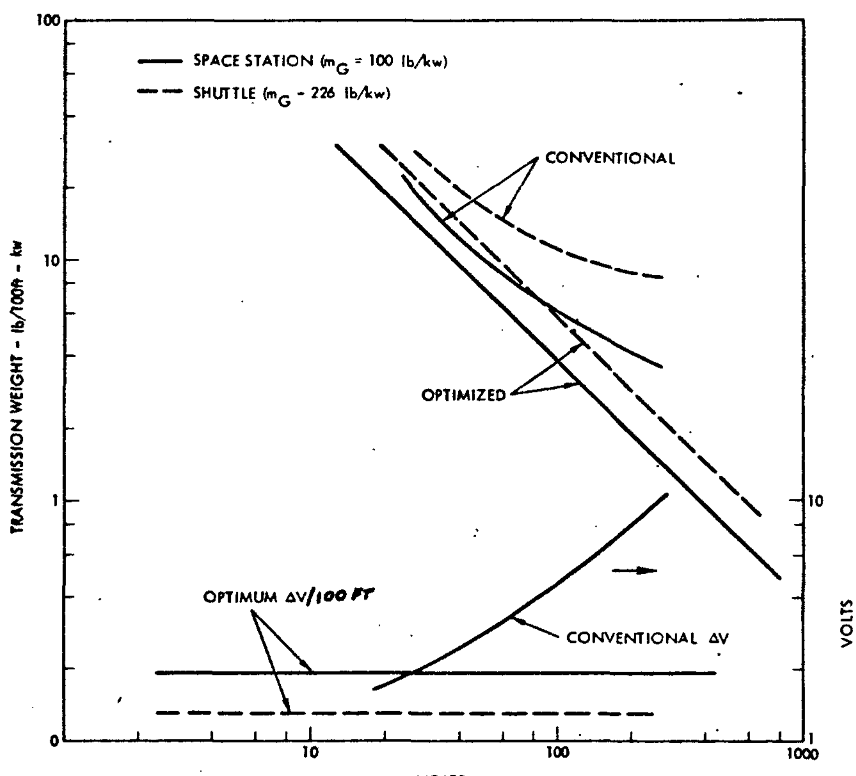


Figure 3.31. Weight to Transmit 1 KW for 100 Ft.

3.2.5 Reliability and Safety

Considerations of safety and reliability do not significantly affect the choice of transmission voltage, frequency, and grounding methods because of the following:

a. Transmission and distribution failures are due to open circuits and short circuits to ground or between wires. They are more likely to occur at the connector than in the wire runs except as a result of physical damage. It can be argued that multiple point grounding is more reliable than the single point ground system because there is less wire and the wire damage probability is reduced, but this does not take into account the requirement for a low impedance path through structure. The failure probability of connectors depends on the design and installation. For small space-qualified connectors a failure rate of 10 per 10^9 hr per active pin has been used in making system reliability assessments. Connectors are currently available with voltage ratings up to 3,000 volts between adjacent pins at sea level and minimum breakdown in excess of 300 volts at critical pressure.

b. Dielectric breakdown does not limit the transmission voltage except in the KV range. Corona can appear at relatively low voltages (below 100V) under special circumstances but is easily prevented by using potted connectors and normal precautions in harness design. In general, corona on-set voltage is higher for dc than ac but in either case presents no significant problem if the peak voltage is below 500 volts.

c. Electric shock hazard to personnel is roughly proportional to body current and hence increases with increasing voltage. A current of about 1 ma is perceptible and can cause involuntary reactions in the average man while currents in excess of 150 ma will cause heart fillibration which often is fatal (Reference 27). Since the impedance of the human body varies greatly as a function of skin condition, location of electrodes, etc., it is difficult to establish a maximum allowable voltage. Using 500 ohms as the minimum body resistance between extremities would indicate that all voltages in excess of 75 volts are potentially lethal and hence require insulation. The effect of power frequency on shock hazard is such that at frequencies below 10Hz and above 1,000Hz the maximum current which allows use of the muscles (the let-go current) increases sharply above the let-go current at normal power frequencies.

3.3 CONTROL AND PROTECTION EQUIPMENT

The ultimate purpose of the complex of control and protection equipment is to provide effective management of on-board electrical power and energy. The equipment consists primarily of switchgear for application or removal of input power from individual loads or power lines and for interconnecting redundant PDCS components. Switchgear may respond to crew initiated signals, computer generated commands, or operate automatically when predetermined overload conditions exist. Several types of load control switches and remote power controllers (RPC) have been studied but all can be classified as electromechanical relays, solid state power controllers or hybrids of electromechanical and solid state switches.

Various terms have been used in the aerospace industry to designate different types of switchgear. A relay generally is any switching device which can be opened or closed by means of a magnetic actuator although solid state switches are often also called relays. A contactor is a switch designed to open and close repeatedly under normal conditions while a circuit breaker interrupts current automatically under abnormal conditions and can be closed under normal conditions. As used in this report swithces, relays, and RPCs may perform any or all of these functions.

Since through the use of on-board computers many concepts of power management, supervision and checkout become feasible (References 28 and 29), and since an evaluation of these concepts can only be based on detailed mission requirements and economic tradeoffs which are beyond the scope of this study program, we have purposely limited our investigations to the least complicated implementations which will meet vehicle safety requirements. Design of software for providing power management to minimize reactant utilization, to meet load priority requirements and to conduct on-board checkout and maintainance was not included as part of this study.

In this section basic control and protection logic requirements are outlined, the effect of system voltage, frequency, and power level on switchgear performance are discussed and use of multiplexing is described for a specific application.

3.3.1 Requirements Analysis

The basic subsystem functional requirements which must be implemented by the control and protection equipment may be summarized as follows:

- Switch power to loads on or off at proper time
- Isolate single point faults to prevent propagation of failure
- Limit sustained current and voltage to protect wiring and load equipment
- Monitor PDC equipment and identify failed LRU or component
- Log failures and indicate emergency conditions requiring mission abort
- Switch buses and loads to activate alternate or backup modes
- Initiate start-up and shut-down of power sources.

Clearly these requirements imply existence of a command and display (C/D) subsystem which provides for supervision of the PDCS by the crew and allows the crew to initiate certain switching and control functions.

Fault protection must be provided for crew safety and has a number of fundamental design implications. In order to prevent mission failure, fault currents must be interrupted by means of a fuse or circuit breaker or be limited by saturation of the generator output to a value which cannot cause fault propagation. To insure availability of redundant equipment supplied from a single source, the fault must be isolated by a fuse or circuit breaker. If normal vehicle operation is required while the fault exists, critical loads must be redundant, active and connected to isolated power channels. As an alternate method the transients existing on the power line to the unfaulted load during fault removal shall be suppressed. Finally in order to facilitate fault location and repair, instrumentation must be provided and the circuit protectors must be resettable or easily replaced.

Figure 3.32 schematically illustrates how electrical power flows from the EPGS to typical load units and shows the control and protection equipment required to mechanize the above requirements. In order to provide reasonable bounds for subsequent tradeoff analyses, we have assumed for purposes of this study that interconnections between redundant equipment

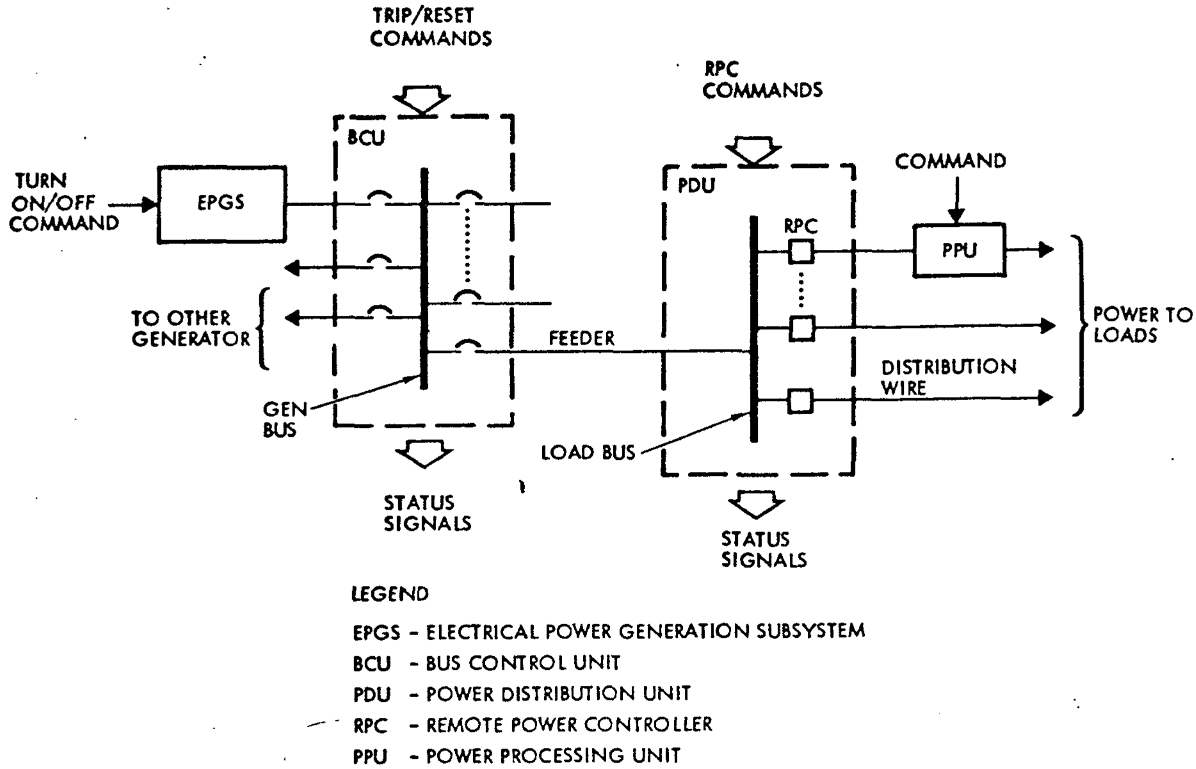


Figure 3.32. Control and Protection Equipment

can only be made at the main bus and each load or load bus can be supplied from only one distribution wire or feeder cable. This satisfies the reliability and safety criteria established in Section 2.1 because we have assumed that each generator can be connected to any one of the three or four main buses whose generator has failed and can also be paralleled with any other generator within the BCU. Referring to Figure 3.32 we may define three categories of switchgear or circuit breakers, namely load controllers, feeder controllers, and main bus or generator controllers. They have typical ratings to cover the baseline vehicle load requirements developed in Section 2.3 as shown in Table 3.12. All circuit breakers must also have provisions for intentional trip and reset and for status monitoring. The role of each category of switch in the PDC subsystem is discussed below. Design configurations for various PDCS concepts are described in paragraphs 3.3.2 and 3.3.3.

Table 3.12. Switchgear Classification

	1 Load Control Switch	2 Feeder Control Switch	3 Main Bus Control Switch
Functions	Connect load Disconnect load Protect dist. wires	Connect PDU Disconnect PDU Protect main feeders	Connect bus to gen Protect generator Parallel generators Parallel buses
Rated Power	5 W to 5 KW	1 to 15 KW	10-100 KW
Max inrush current (120 V)	200 amp	1200 amp	2000 amp
Immediate trip current (typical)	150% of load inrush	150% of inrush	Less than gen. short circuit current
Rupture capacity	Less than transient current rating of wire	10 times rated (typ)	Greater than gen. short circuit current

3.3.1.1 Load Control

The switches which provide on/off control for individual loads are shown as part of the PDU in Figure 3.32 and identified as remote power controllers. They must interrupt current automatically in case of a low impedance fault in the power distribution line or the load and hence are circuit breakers. If the load unit is supplied from a power processing unit (PPU) instead of directly from the load bus, two methods of load control are possible as shown in Figure 3.33. The preferred method is to use internal control of the PPU to control the PPU output voltages which are applied to the load circuits as shown. This requires a fuse in the PDU to protect the load bus in case the power line to the PPU or the PPU input circuits develop a low impedance to ground. Advantages of this method are that inrush current during turn-on is minimized because the PPU filter remains charged and the fact that most circuit elements to provide on/off control of the PPU are already present in the regulating loop of the PPU. Note that with external control by means of an RPC, fuses are also required in the PDU or must be included in each RPC. For either method, command and status indication signals are required as shown. This includes monitoring of the load bus to determine if normal

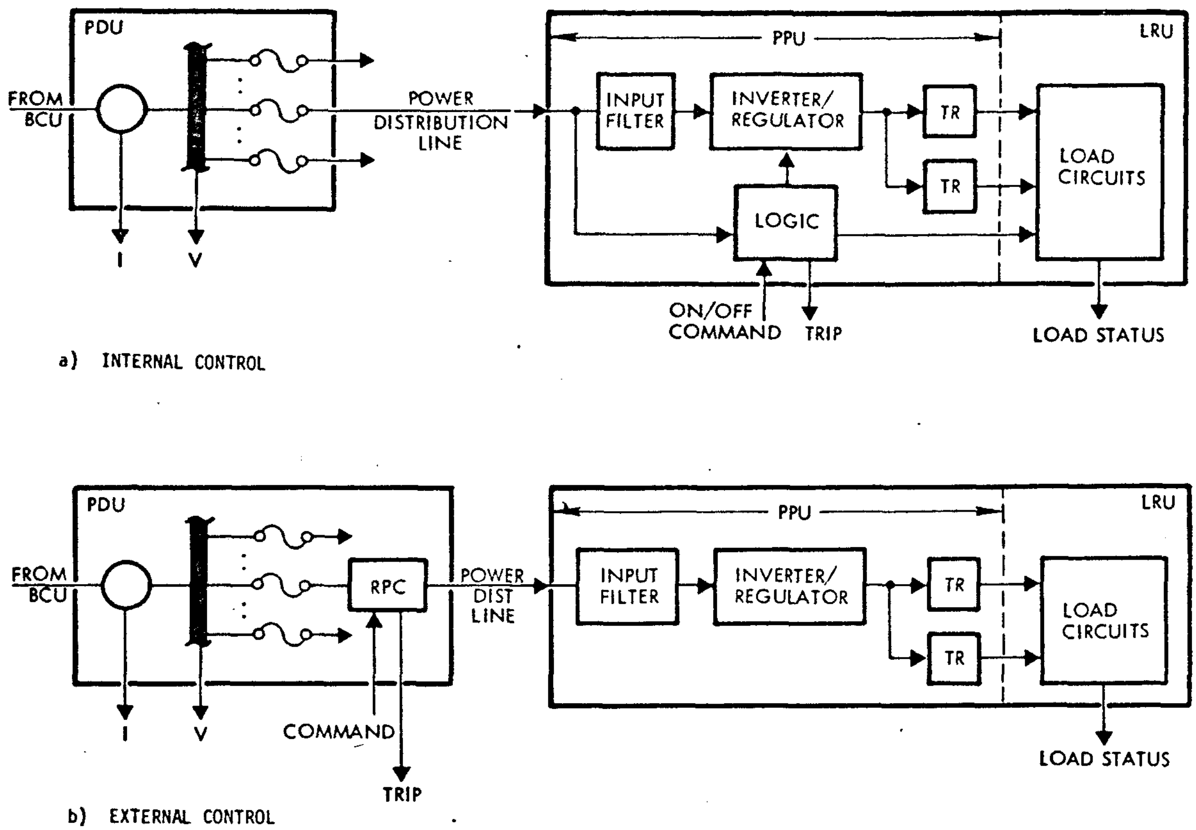


Figure 3.33. Load Control Methods

voltage V and feeder current I exist. To meet the control and protection requirements listed in the previous paragraph the load control switch (RPC) or PPU control circuits must have the capabilities as listed in Table 3.13 which also gives the related control and display subsystem requirement.

Table 3.13. Load Control and Protection Logic

Requirement	Implementation	Backup	C/D Requirement
ON/OFF CONTROL	Discrete Command	None	Generate Command
FAULT ISOLATION	Automatic trip if input current exceeds preset I^2t limit	Fuse	None
OVERLOAD PROTECTION	Limit steady current to 125±5% of rated current	Fuse	None
FAULT INDICATION	Continuous bilevel trip signal	Load Status Signal	Read and display or store
TRIP FREE	Automatic trip has priority over ON command	Not Required	None
CHECKOUT	Send command and read load status	Trip Signal	No fault when (ON $\overline{TRIP}$ V_{Load} = 1) or (OFF $\overline{V}_{Load}$ = 1)

3.3.1.2 Bus and Feeder Control

As mentioned previously we have limited our studies to the case where paralleling or cross-strapping is possible only at the main generator buses which means that complete PDCS channels are switched after a critical failure. The bus control and protection method which has been chosen allows any one generator to feed any main bus and is illustrated in Figure 3.34 for a three channel system. The arrangement of generator control and bus tie relays required to allow connection of any generator to any and all buses with or without paralleling is shown in Figure 3.35. Switch commands and status indication signals which are required for supervision and control are indicated in Figure 3.34. Table 3.14 describes how the various control and protection requirements are implemented by the basic control configuration of Figure 3.34.

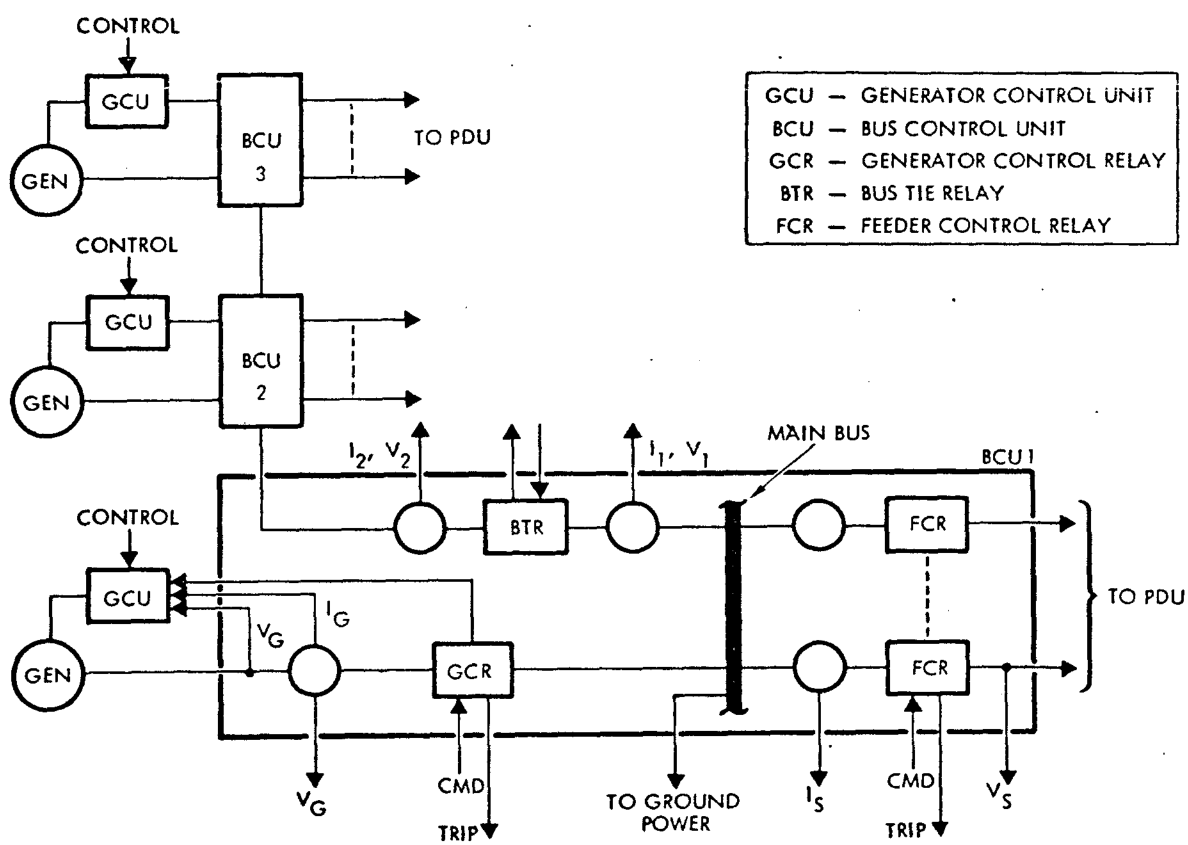


Figure 3.34. Bus Control and Protection Method

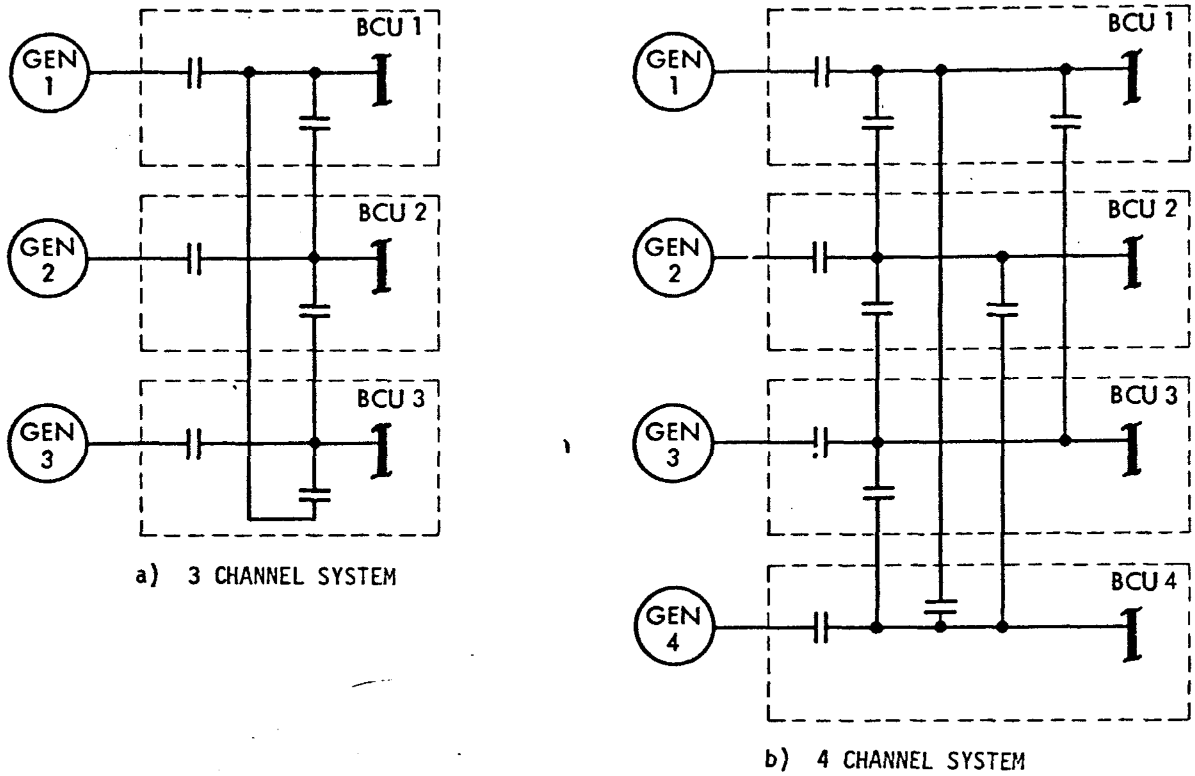


Figure 3.35. Main Bus Switching Configuration

Table 3.14. Bus Control and Protection Logic

Requirement	Implementation	Backup	C/D Requirement
<u>Power ON/OFF Cont.</u>	Gen. Control Unit (GCU)	GCR Command	GCU Sequencing Read & Store GCR trip sig.
<u>Overload Protection</u>			
Feeder	Monitor I_S and send OFF cmd. to FCR	1) Automatic FCR trip 2) Automatic GCR trip	Read I_S, compare to limit and generate cmd.
Generator	GCU	1) Monitor I_G, send GCR trip cmd. 2) Gen temp. limit	None for GCU Monitor and cmd. for backup
<u>Short Circuit Isolation</u>			
Feeder Fault	Automatic trip of FCR	1) Feeder Fuse	None
Main Bus Fault	Inst. trip of GCR	2) Automatic GCR trip gen. shut down thru GCU	None
Generator	Trip GCR	Trip BTR	None
<u>Trip Indication</u>	Continuous bi-level signal	Output voltage signal	Read and display

3.3.1.3 Failure Location

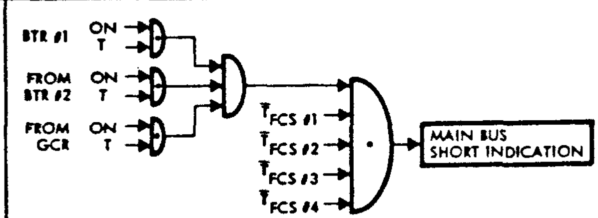
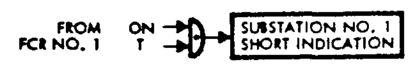
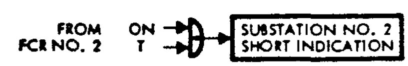
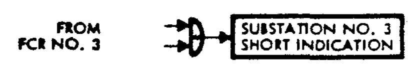
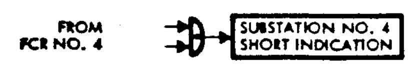
Since the power system must be able to withstand more than one failure it is necessary to locate and identify failures quickly so that alternate or emergency load utilization procedures can be implemented by the crew. Table 3.15 lists various power line and switchgear failures and how they may be detected.

Table 3.15. Failure Identification

Type of Failure	Detection Method	Backup	C/D Requirement
Open Feeder	Monitor V_s, FCR trip in BCU and PDU voltage V_{ss}	$I_s = 0$	Compute $(\overline{Trip}\ V_s\ \overline{V}_{ss}) = 1$
Shorted Feeder	FCR trip cmd.	Cmd ON, check $V_s = 0$	Read and record
Open FCR	Monitor V_1 and V_s	$I_s = 0$	Check $V_{Bus}\ \overline{Trip}\ \overline{V}_s = 1$
Shorted FCR	With BTR open, send OFF cmd.	None	Check V
Main Bus Fault	Monitor all V_s	All I_s	Check $V_{s1} + V_{s2} -- V_n = 0$
Command Failure	Trip Ind.	V or I monitor	Display V or I
Sensing Failure	Compare with upstream and downstream indication	None	Pilot readout
Open GCR	Monitor V_G and V_1 when BTR is open	$I_G = 0$	Check $\overline{Trip}\ V_G = 1$ $V_{Bus} = 0$
Open BTR	Open GCR1 and check V_1	Open GCR2 and check V_2	Check $\overline{Trip}\ V_2 = 1$, $V_1 = 0$

Examples of display and computation requirements for fault indication and location in the bus control configuration of Figure 3.34 assuming each main bus supplies four substation buses (PDUs) through four feeders are given in Table 3.16 which also shows that by feeding command and status signals to a number of gates as illustrated the location of the fault can easily be determined.

Table 3.16. Failure Location Mechanization

FAILURE MECHANISM	LOGIC EQUATION	IMPLEMENTATION	BACK-UP INDICATION
SHORT AT MAIN BUS	MAIN BUS SHORT = $\left[ON_{BTR} \cdot T_{BTR} + ON_{GCR} \cdot T_{GCR}\right]$ $\left[\bar{T}_{FCR\#1} \cdot \bar{T}_{FCR\#2} \cdot \bar{T}_{FCR\#3} \cdot \bar{T}_{FCR\#4}\right]$		$I_G > 130\%\ I_{RATED}$ $I_{BTR} > 130\%\ I_{RATED}$
SHORT AT SUBSTATION NO. 1 BUS	SS NO. 1 SHORT = $ON_{FCR\#1} \cdot T_{FCR\#1}$		$I_{S1} > 130\%\ I_{RATED}$
SHORT AT SUBSTATION NO. 2 BUS	SS NO. 2 SHORT = $ON_{FCR\#2} \cdot T_{FCR\#2}$		$I_{S2} > 130\%\ I_{RATED}$
SHORT AT SUBSTATION NO. 3 BUS	SS NO. 3 SHORT = $ON_{FCR\#3} \cdot T_{FCR\#3}$		$I_{S3} > 130\%\ I_{RATED}$
SHORT AT SUBSTATION NO. 4 BUS	SS NO. 4 SHORT = $ON_{FCR\#4} \cdot T_{FCR\#4}$		$I_{S4} > 130\%\ I_{RATED}$

3.3.2 Electromechanical Switchgear

Electromechanical relays and circuit breakers have been used almost exclusively in the past for all three categories of switchgear defined in Table 3.12. Current flows through metallic contacts which can be physically separated by an electromagnetic actuator or other mechanical means to interrupt the current. Auxiliary contacts and solenoid windings are generally used to provide remote electrical on/off (or reset and trip) capability and to generate status indication signals. Circuit breakers are distinguished from relays or contactors by the fact that the main contacts separate automatically when a predetermined overload current flows for a specified period of time. The current-time characteristic of the trip point depends on the design of the breaker. Two types of breakers are in common use, thermal breakers and magnetic trip breakers. The former uses a bimetallic element which is heated by the load current to actuate the trip mechanism and separate the contacts. In the magnetic breaker the load current flows through a low impedance solenoid which actuates the trip mechanism when the current becomes excessive. Mechanical damping may be used to obtain a desired current versus time function. Electronic current sensing and time delay circuits which activate the trip coil are also available.

The switchgear characteristics of interest for this study program are steady state power dissipation, weight, failure rate, cost and availability. In addition the dynamic or electrical interference characteristics during switching must be considered. Tables 3.17 and 3.18 present data for typical relays and circuit breakers which are available or have been proposed for use on manned aerospace vehicles. All switches rated at 28 Vdc can also be used at 115 or 230 Vac.

Table 3.17. Electromechanical Relays and Circuit Breakers for Low Voltage dc Loads

	Load Power - KW					
	24	2.8	2.8	1.4	1.0	1.0
Rated Voltage - Vdc	28	28	28	28	50	50
Rated current - amp	800	100	100	50	20	20
Interrupt capacity - amp	4000	3500	1000	1500	500	500
Overload Sensing	None	Thermal	None	Electronic	Magnetic	None
Reset	28 Vdc	Manual	28 Vdc	28 Vdc	24 Vdc	Manual
Trip time - msec	-	1000	-	5-10	30	30
Voltage drop - Vdc	Neg	<0.3	<0.2	0.2	<0.2	<0.2
Design Config.	Sealed MDS	Sealed	Sealed	Sealed	Sealed	Sealed
Design life - cycles	50,000	5000	50,000	50,000	5000	10,000
Weight - lb	3.5	0.25	0.65	0.41	0.7	<0.2
Cost (estimated)	$900	$100	$150	$300	$50	$16
Availability	Developed	Prod	Prod.	Devel.	Prod.	Prod.
Vendor	Teledyne	Several	Hartman	Bendix	Airpax	Airpax
Model No.	Mod 1244	MS 25361	N-419	L-109	Bull 16E-11	Bull B-97

Table 3.18. High Voltage dc Electromechanical Switchgear

	Load Power - KW							
	45	30	30	25	24	24	18	12
Rated Voltage - Vdc	9000	120	120	250	120	120	120	120
Rated Current - amp	50	250	250	100	200	200	150	100
Interrupt cap.- amp	5	2500	5000	10,000	1000	1000	5000	1000
Overload Sensing	None	None	Thermal	Thermal	None	None	None	None
Reset	28 Vdc	28 Vdc	Manual	Manual	28 Vdc	28 Vdc	28 Vdc	28 Vdc
Trip time - msec	10	-	32	30-50	-	-	-	-
Voltage drop - Vdc	<0.2	<0.2	0.2	<0.2	<0.5	0.6	<0.5	<0.2
Design Config.	Vacuum Switch	Vented, arcing contacts	De-ion low press.	Vented	Sealed MDS, 4 gaps	6 gaps	Oil filled	Vented Magnetic blowout
Design Life - cycles	500,000	?	?	10,000	50,000	50,000	10,000	?
Weight - lb	1.0	5.9	4.5	6.0	3.5	6.0	6.7	2.75
Cost (est.)	$50	$300	$100	$70	$900	$200	$500	$100
Availability	Prod.	Prod.	Proto.	Prod.	Proposal	Proposal	Devel.	Proto.
Vendor	ITT-Jennings	Hartman	None	Westigh.	Teledyne	Cuter Hammer	None	Hartman
Model No. or Ref.	RF10B	A-751B	Ref. 30	AQB-A101	Mod 1245	Ref. 31	Ref. 32	A-754P6

An important difference between contactors for high and low dc voltages is the fact that when the supply voltage exceeds about 50 Vdc the possibility exists that the arc which forms as the contacts separate may continue to burn as long as the circuit can provide sufficient energy unless special means are provided to extinguish the arc. Without going into details of arc theory this may be explained as follows. An arc always will form between metallic contacts as they separate provided that the initial current exceeds about one ampere and there is sufficient voltage to establish the ionized plasma or to initiate transfer of conducting metal vapor. The voltage between the contacts during arcing is a complicated function of current, contact material, contact spacing, temperature and the medium in which the arc burns. In air at atmospheric pressure the voltage versus current characteristic for different contact spacings can be approximated by Airton's equation (Reference 33)

$$V_A = \alpha + \beta d + \frac{\gamma}{I} \qquad (3.11)$$

where

V_A is the voltage between the contacts

I is the arc current

α is the voltage drop at the electrode

β is the voltage gradient in the plasma

d is the contact spacing

γ is a linear function of d

Equation (3.11) has the general characteristics shown in Figure 3.36. For the simple case illustrated note that with a resistance corresponding to the typical load line shown, the current I is initially about 7 amps dropping to less than 6 amps at point 1 as soon as the contacts separate and will suddenly drop from 2 amps at point 3 to zero when the contacts have separated about 3 cm. If the contact spacing never exceeds 1 cm a stable operating point at 2 is established. If current starts to decrease from this point a voltage ΔV_1 which tends to increase the current becomes available. Since the opposite happens due to voltage ΔV_2 as arc current increases, point 2 is a stable operating point and the arc will not extinguish under these conditions.

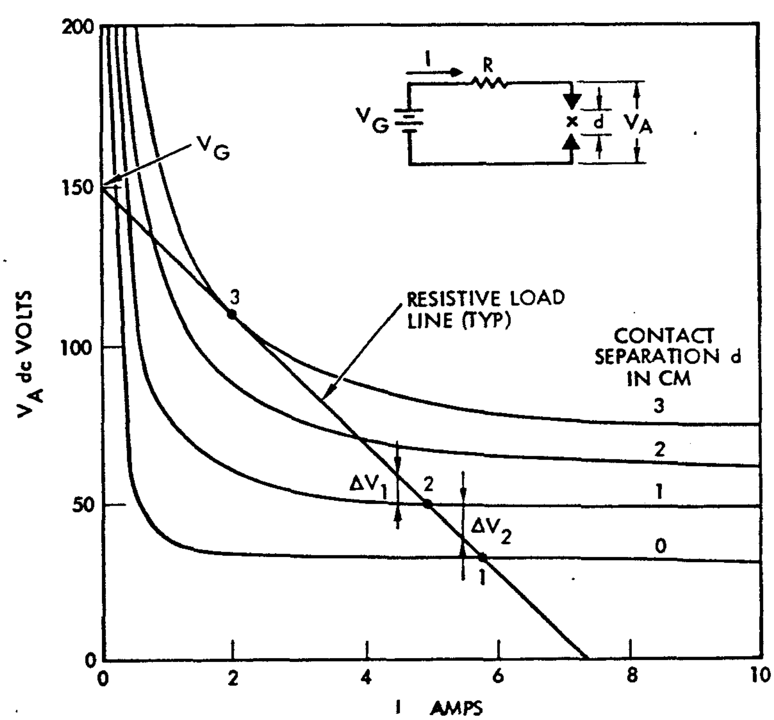


Figure 3.36. Typical Arc Voltage Characteristic

There are several methods available to guarantee that the arc will be interrupted as follows:

1. Force the current to zero. This happens automatically in ac circuits every half cycle.

2. Separate contacts until point 3 of Figure 3.36 is reached. This is generally not possible for high supply voltage V_G or low circuit resistance.

3. Reduce the temperature of the arc plasma to increase its resistivity. This can be accomplished in a variety of ways.

4. Maintain the voltage between contacts below the asymptote of V_A at zero separation (see point 1 in Figure 3.36)

Introduction of insulating barriers between the contacts to interrupt the arc is not feasible because of the high arc temperature. The third and fourth method are used in practice. Temperature reduction is obtained through gas blast cooling, magnetic blowout or introduction of elements to deionize the plasma and render it non-conducting. Method 4 can be implemented by using several gaps in series.

High voltage dc circuit breakers designed for sea level operation will not provide arc interruption at altitudes above about 60,000 ft. since they rely on the airblast due to the large temperature gradient to extinguish the arc. Oscillograms of arc voltage during interruption at several ambient pressures are shown in Figures 3.37 and 3.38 and were obtained as part of this study program on two types of vented circuit interruptors. A battery supply and resistance load were used throughout. Note that the time until arc interruption progressively increases as the ambient pressure is reduced. Circuit breakers which can operate at any pressure are currently not available but can be designed to meet voltage requirements of at least 250 Vdc by use of multiple gaps, operation in oil, blast cooling or other means. Although new design and development work must be performed to meet requirements for spacecraft bus controllers as shown in Table 3.12, it appears to be entirely feasible to achieve the required performance within reasonable weight and size limits.

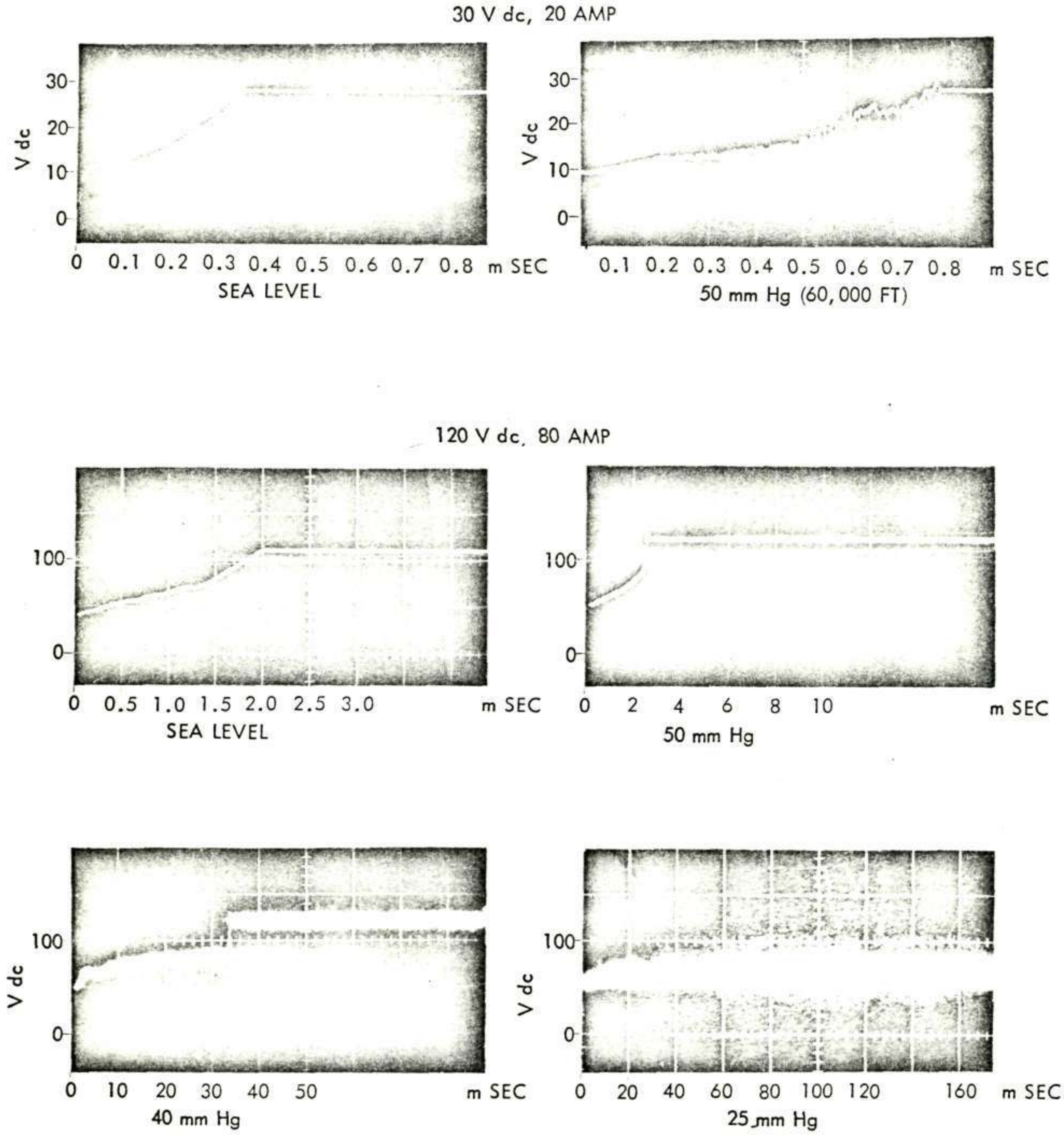


Figure 3.37. Oscillograms Showing Voltage Across ALB-1 Thermal Circuit Breaker During Current Interruption

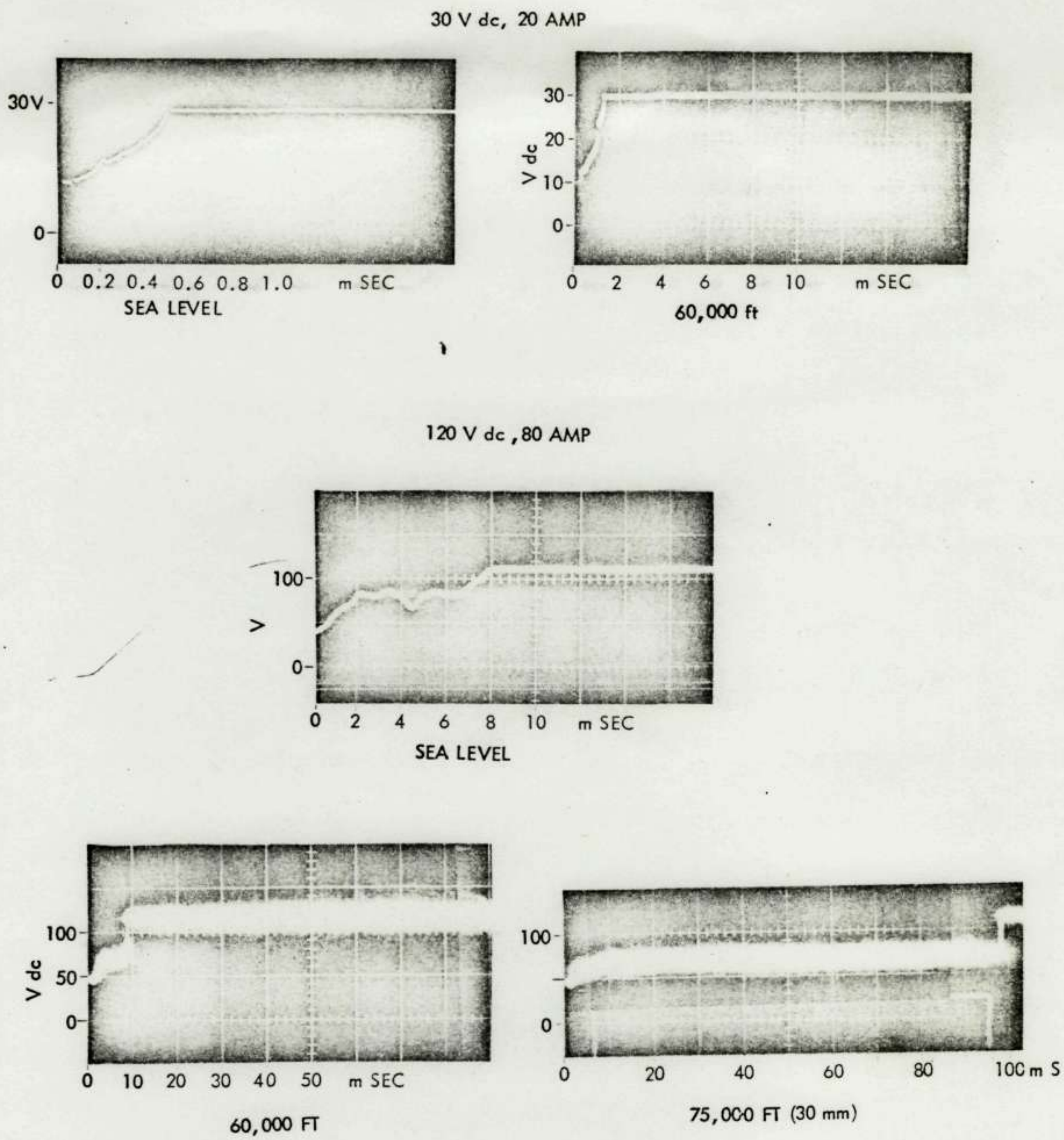


Figure 3.38. Oscillograms Showing Voltage Across Hartman Magnetic Blowout Contactor

Conclusions reached regarding electromechanical switchgear which affects selection of the PDCS configuration may be summarized as follows:

- Power dissipation is very small, independent of system voltage and depends primarily on the current sensing method and the number of contact gaps in series.
- Weight increases with increasing dc voltage because auxiliary arc interruption means are required.
- Reliability depends on design configurations and probably decreases with increasing voltage if the number of contact gaps increases. Since circuit breakers operate only during abnormal conditions the usual measures of failure rate do not have much meaning. Endurance tests indicate that cycle life exceeds requirements for all voltage ratings of interest.
- Cost depends on the overload sensing and reset method but can be expected to be somewhat higher for higher voltage ratings.
- Dynamic performance is determined by the arc characteristics and the rate of change of current in the operate coils. High voltage reduces coupled interference because currents are lower.

3.3.3 Solid State Switchgear

Use of semiconductors in place of the moving contacts of electromechanical switchgear avoids problems due to arcing but introduces a higher series voltage drop and does not provide galvanic isolation during the off state. Because there are no moving contacts solid state relays can be expected to be more reliable than conventional switchgear provided they are properly designed and used within their steady state and dynamic voltage and current ratings. The performance characteristics of solid state circuit breakers or RPCs depends strongly on the switching device and design tradeoffs involving current versus time trip characteristics, forward voltage drop, control logic, and heat transfer design.
Since many design options are possible we shall be concerned only with fundamental limitations as they affect selection of power distribution voltage and frequency.

The three basic types of solid state RPCs which have been considered are shown schematically in Figure 3.39. Either transistors or thyristors may be used as the switching element. A fuse is used in the power line to meet the "fail safe" requirement; i.e., provide for current interruption in case the switching element fails in its usual short circuit failure mode.

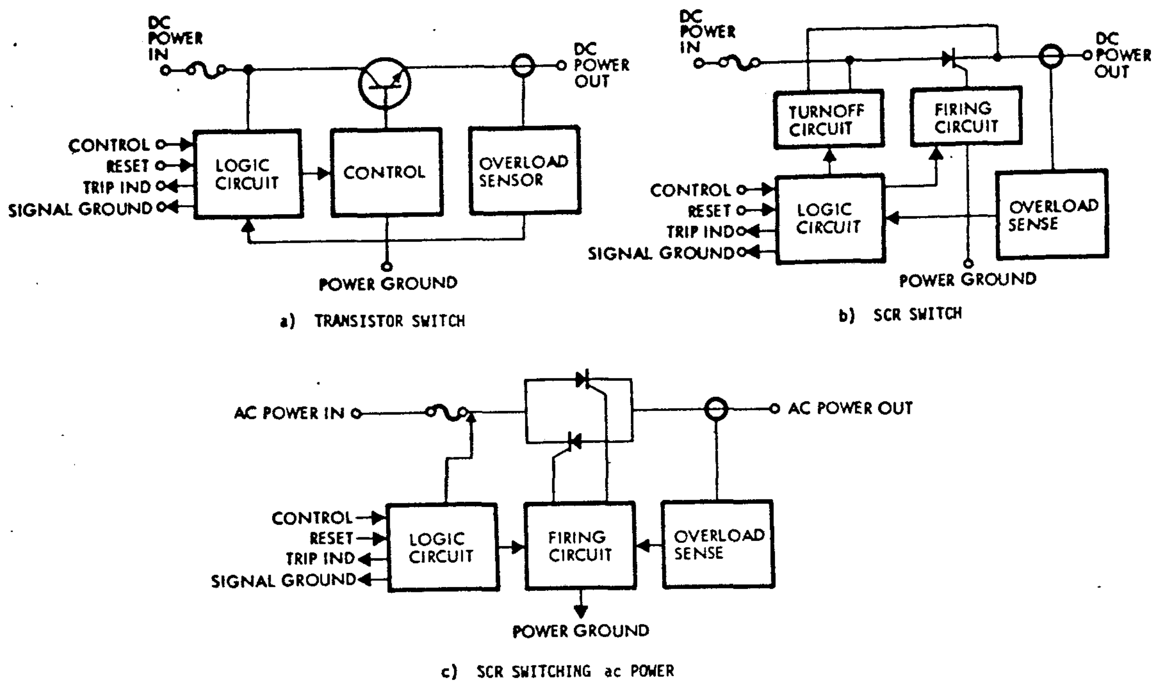


Figure 3.39. Solid State Remote Power Controllers

The transistor switch is turned off by maintaining a reverse bias across the BE junction and hence requires a few milliwatts of power during the off state. If an SCR is used to switch dc power the current through the SCR must be forced to zero by the turn off circuit which contains an energy storage capacitor to achieve current interruption. The back-to-back SCR switch requires no such turn-off circuit when switching ac power because current goes to zero every half cycle and a pulse from the firing circuit must be applied to the gate of each SCR during every cycle when conduction is required.

The power dissipation P_d in the switch during the closed state is approximately

$$P_d = I_c \left(1 + \frac{1}{\beta}\right) V_{CE_{sat}} \tag{3.12}$$

where

I_c = collector current

$V_{CE_{sat}}$ = saturated forward voltage drop

β = collector to base current gain

The maximum load power which can be supplied is

$$P_L = I_c V_{CE_o} \tag{3.13}$$

where V_{CE_o} is the maximum collector voltage with reverse biased base so that

$$P_d/P_L = (1 + 1/\beta) V_{CE_{sat}}/V_{CE_o} \tag{3.14}$$

The SCR effectively has two emitter junctions in series and hence has at least twice the $V_{CE_{sat}}$ of an equivalent transistor. The forward loss is correspondingly larger even though current gain β approaches infinity.

RPCs using transistors as the series switching element are limited in power handling capability by the switching speed during turn off and the heat storage capability since during the turn off interval

$$P_L \max = I_c V_{CE_o} = I_c V_{Load} \tag{3.15}$$

Although various schemes for paralleling transistors and limiting the peak power are possible, the maximum load power which can be interrupted by transistor switches is a few KW.

Operation of a typical SCR switch with forced commutation is illustrated in Figure 3.40. The size of the energy storage capacitor C_c and inductor L_c are calculated for a supply voltage of 100 Vdc and a maximum current interruption capability of 200 amps as 30 μf and 10 μh respectively. The estimated weight of the capacitor is 1.6 lbs. and that of the inductor 4.5 lbs. This means that the weight of the complete RPC is more than 6 lbs for a rated load power (100 Vdc, 20 amps) of only 2 KW. SCR switches for ac power require no commutation circuits and are currently available for industrial applications. A summary of solid state RPCs and their salient design characteristics is presented in Table 3.19. Estimated weight of

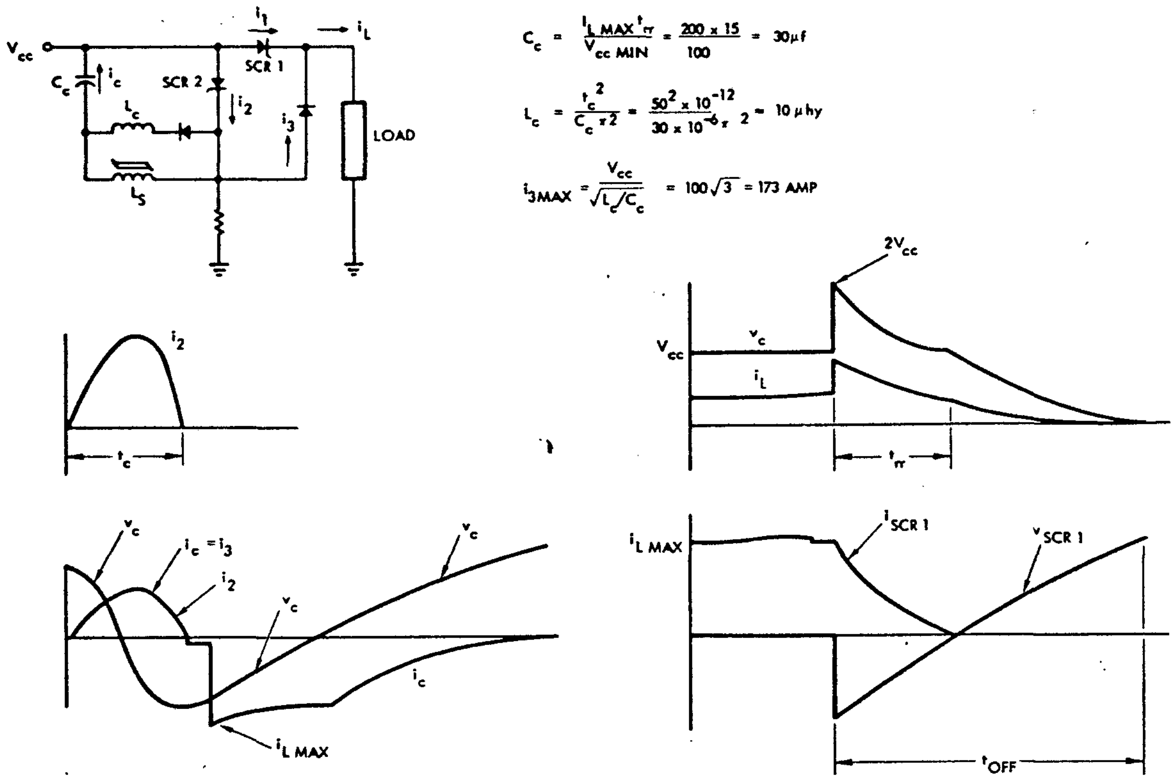


Figure 3.40. Design of SCR Type dc Circuit Breaker

Table 3.19. Characteristics of Solid State RPCs

	Load Power - KW						
	6	4	4	2.4	0.25	0.16	0.15
Rated Voltage/Frequency	240V,60Hz	115V,400Hz	270 Vdc	120 Vdc	115V,400Hz	80 Vdc	30 Vdc
Rated Current - amp	25	35	15	20	2	2	5
Power Loss P_d - watts	45	62	40	30	3.3	6.3	4.5
Design Configuration	SCR	SCR	SCR	Transistor	SCR	Transistor	Transistor
Weight[(1)] - lb	0.25	0.31	6.0	0.5	0.125	0.15	0.15
Cost (Est.)	$33	$300	$500	$300	$200	$200	$200
Availability	Prod.	AF Devel.	NASA Devel.	Concept	AF Devel.	NASA Devel.	Devel.
Vendor	Crydom Controls	Wstgh.	Martin	-	Wstgh.	Wstgh.	Various
Reference	Mod 2425	MIL-P-81653A	NASA Contr. NAS3-15824	TRW Design Calculation	MIL-P-81653A	NAS8-26425	MIL-P-81653A

(1) Without heat sink.

solid state and electromechanical RPCs is plotted as a function of load power in Figure 3.41. The following conclusions are reached regarding performance of solid state RPCs as a function of line voltage and frequency:

- Efficiency increases with increasing power line voltage.
- Weight is larger for dc power systems because the control circuits are more complex.
- Reliability depends on part count and circuit design techniques. A minimum operating life of 10^6 operations is specified in MIL-P-81653A. All types can be designed to meet this requirement.
- Dynamic performance characteristics are a function of circuit design. Soft turn-on can be provided at the cost of increased weight and cooling requirements. Peak inrush currents must be known since transient overload capacity is very small.
- Cost depends primarily on quality assurance requirements. Cost should generally be lower for ac RPCs.

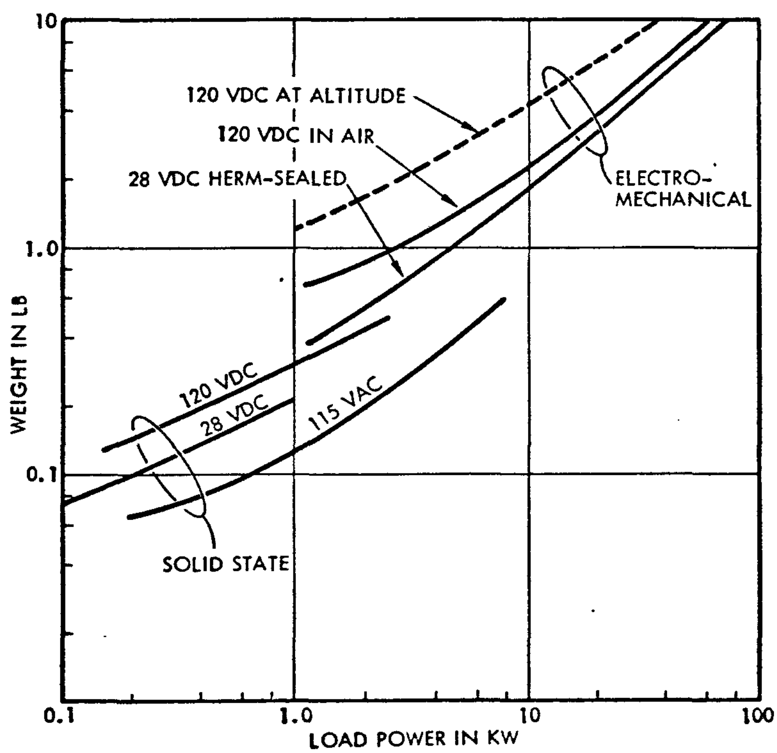


Figure 3.41. Switchgear Weight Comparison

3.3.4 Command and Display

Two different command and display (C/D) methods can be used for supervision and control of the electric power system. The first is the "conventional" C/D method which uses illuminated toggle switches and meters for remote control of switchgear and PPUs and for monitoring of PDCS status. The second method uses a digital computer to develop commands and decode status signals which are transmitted to and from each PDCS component over a data bus. For simplicity we refer to this method as "multiplexed" command and display. The C/D method actually does not influence the selection of power system voltage and frequency or the type of switchgear, electromechanical or solid state, which can be used. But since use of a data bus for EPS command and signal distribution has been proposed for the Shuttle and Space Station during Phase B studies and is under development for aircraft which use solid state switchgear (Reference 35) we performed a simple tradeoff analysis to compare conventional and multiplexed PDCS command and supervision.

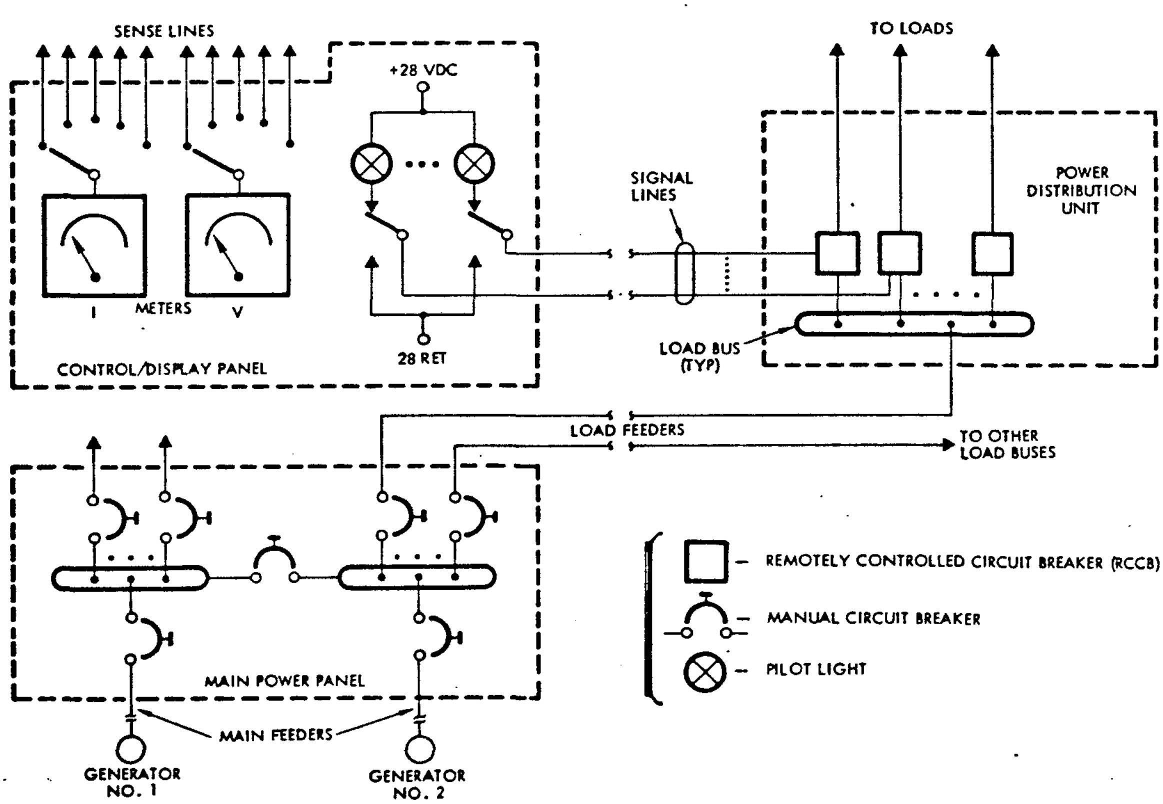


Figure 3.42. Conventional C/D Method

Figure 3.42 illustrates a typical conventional scheme for command and supervision of the PDCS. We have assumed remotely controlled electromechanical circuit breakers (RCCB) for load control and manually reset circuit breakers for bus and feeder protection. A significant reduction in main feeder length, however, can be obtained by also using RCCBs for bus and feeder control so that the main power panel or BCU can be located near the generators or a large load center instead of in the cockpit. As indicated in Figure 3.42 all commands and status signals are carried through separate small wires (AWG 24 or 26) to the C/D panel in the cockpit. Table 3.21 lists the signals and commands which flow between each PDCS component and the C/D panel to provide control and supervision.

Table 3.21. Commands and Status Monitoring Signals

PDCU Component	Command	Signal
Bus Control Unit (BCU)	BTR close BTR trip GCR close GCR trip Feeder CB close Feeder CB trip	Main bus voltage Gen. voltage Gen. current Feeder current BTR tripped GCR tripped
Power Distribution Unit (PDU)	RPC on RPC off RPC reset	RPC tripped Load voltage Load current PDU input current
Power Processing Unit (PPU)	Turn on Turn off	Input current Temperature
Central Processing Unit (CPU)	Turn on Turn off	Input current Output voltage Temperature

Figure 3.43 shows our method of providing control and status indication for a typical remote circuit breaker which also serves as a power controller using only one command and signal line between the cockpit and RCCB. Note that this control method is fail safe because the power contactor cannot be closed if the signal line is open or shorted to the 28 Vdc return line. Also, failure of the signal source does not prevent tripping under overload. A similar hardwired command and sensing method can be used with solid state RPCs.

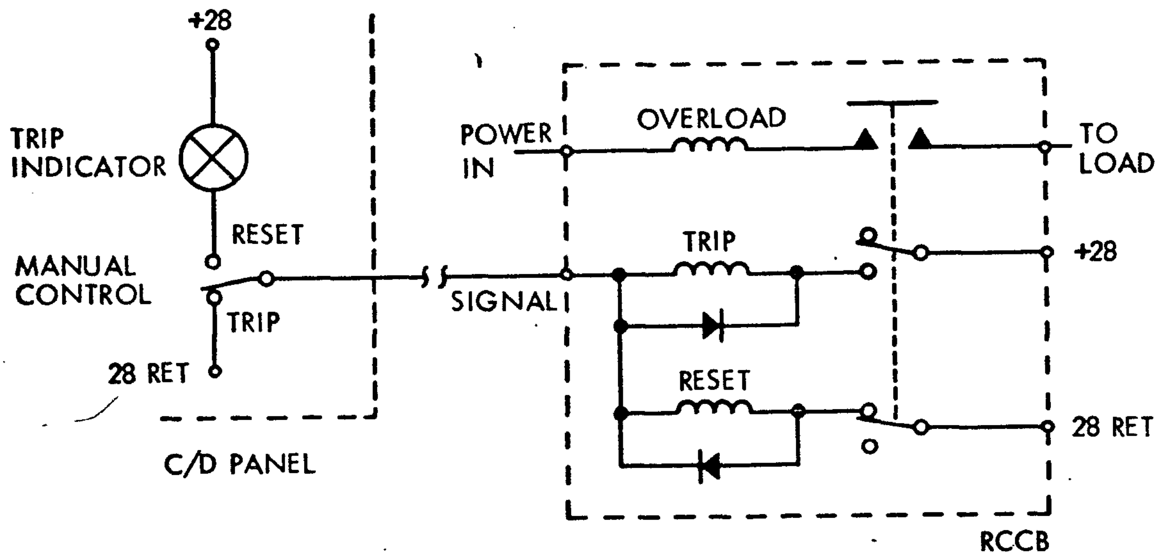


Figure 3.43. Remote Control of Circuit Breaker (Typ.)

The multiplex C/D method is shown schematically in Figure 3.44. Solid state RPCs and electromechanical RCCBs are used for load, bus and feeder control. The RCCBs contain buffer amplifiers which operate the trip and reset coils in response to the low level output signals obtained from a digital interface unit (DIU). The solid state RPCs can interface directly with the DIU if the logic voltage and impedance levels are compatible. Commands transmitted over the data bus are decoded by a DIU and converted to a bilevel signal on the proper DIU output line which serves the RPC that must be commanded. Status monitoring signals received by a DIU from a sensor or switch are converted to digital form by the DIU and transmitted over the data bus to the computer. The crew has access through the Input/

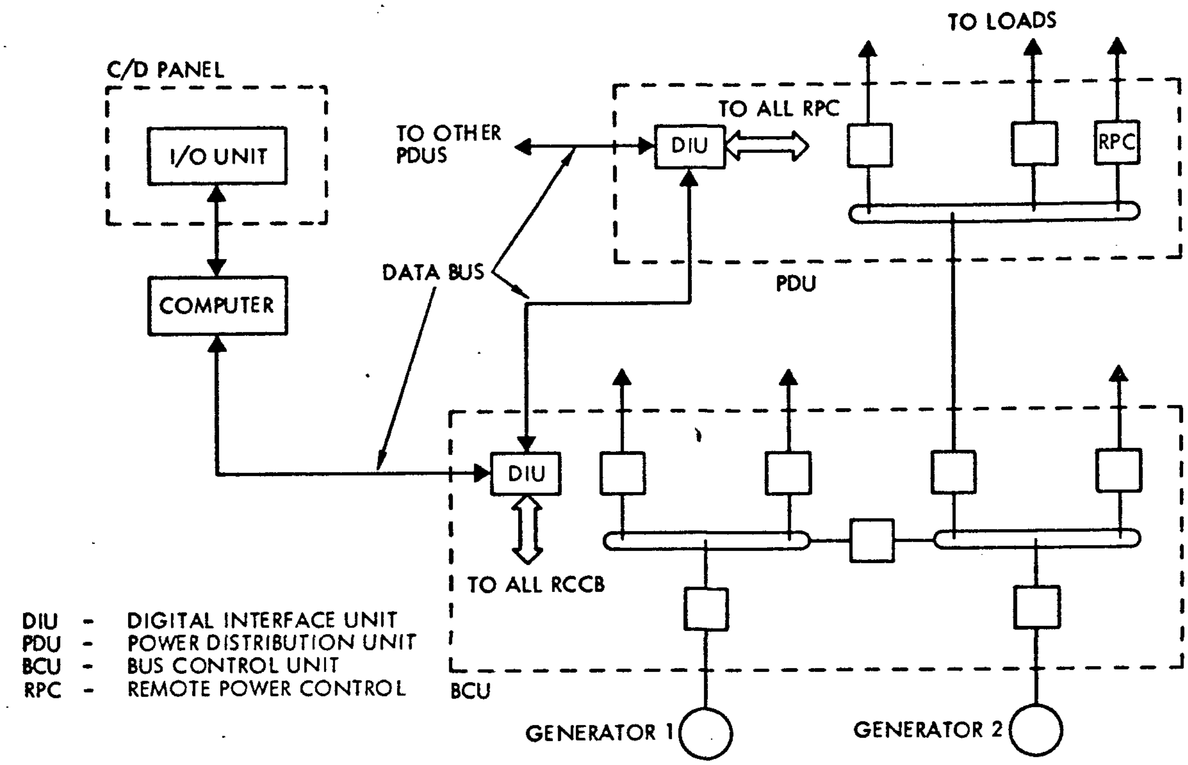


Figure 3.44. Multiplexed Command and Display

Output unit on the C/D panel which contains a keyboard, alpha numeric readout, printer, and other control and display devices if necessary. The computer can be programmed to switch loads in a predetermined sequence in response to particular kinds of trip indications, recycle switchgear, start up generators, and initiate any kind of action within the capability of the electric power system. In addition it can be used to program inflight checkout routines. Since such uses of the computer do not affect the design of the PDCS equipment or selection of the power distribution voltage they need not be considered herein. Estimated unit weight, failure rate, cost, and power input for the equipment required for conventional and multiplexed command and display are listed in Table 3.22. Cost and failure rate are based on space vehicle type equipment. The CDC 469 computer has a 4,000 bit memory and is typical of a small space-qualified computer which could provide all power management, checkout and EPS failure location computations for the typical vehicles considered during this study. A quantitative comparison between conventional and multiplexed command and display can only be obtained by considering a specific PDCS in which all loads and the complete distribution and protection network are defined. We have estimated C/D weight, power requirements, failure rate, and cost for the conventional and multiplex method for the Space Shuttle reference requirements and for aircraft under the assumption that a central digital computer is available to solve failure location and checkout logic equations. Results are included in the comparative PDCS analyses contained in Section 5.0.

Table 3.22. C/D Equipment Characteristics

Component	Power (watt)	Weight (lb)	λ (Fail. per 10^6 hrs)	Cost $
Conventional				
Wire (per ft)	-	0.0042	-	0.5
Connector (50 pins)	-	0.15	4	60
Command Switch (Lighted Push Button)	-	0.2	5	150
Selector Switch (50 pos.)	-	0.2	4	150
Panel Meter	-	0.4	-	100
28 Vdc Power Supply	20	0.5	5	200
Misc. Hardware & Structure	-	20	-	2000
Multiplexed				
Data Bus Cable (per ft)	-	.01	-	1
I/O Unit	6	2	50	15,000
DIU	3	3	30	3,000
Computer (CDC 469)	30	7	100	40,000

3.4 CENTRAL POWER CONVERSION

The basic function of a central power conversion unit (CPU) is to process power as available from the generation subsystem (EPGS) or power distribution substation to the voltage level and form required at local substation distribution terminals and/or the utilization equipment interface. The central power processing units, as defined herein, are basically those supplying multiple loads such as (1) large dc-ac inverters which process all source power, (2) large transformer-rectifier units which process the bulk of the source power in ac systems, and (3) motor drive inverters which feed several ac motors. The inverter or electronic commutator used in brushless dc motors is, broadly, a PPU but, herein, is considered as part of the motor and, therefore, is not included in the last category.

The following list summarizes the basic electrical requirements placed on the equipments described above:

Substation PPUs

- Convert transmission voltage to distribution voltage
- Control conducted and radiated interference
- Provide regulation of distribution voltage (optional)
- Limit input current (optional)
- Provide output current and voltage instrumentation

Source PPUs

- Rectify ac generator output
- Invert dc generator output
- Control interference
- Provide for load sharing
- Limit fault current
- Provide output current, voltage and frequency signals

Performance capability for typical equipments required in the various PDC configurations was determined by performing detailed design studies and calculations on inverter and transformer-rectifier circuits suitable for use in central power processing applications. As in the development of load PPU parametric data, standardized specifications were established for these circuit configurations and designs performed to obtain unit weight, efficiency and failure rate characteristics as functions of power level. The effect of input or output voltage level and frequency variation was also quantitatively examined in particular design cases.

The parametric curves developed were used in the estimation of weight, power dissipation, and reliability parameters for the source and substation PPU complement in the various PDC configurations studied. Comparisons between the calculated data and published figures for similar higher power equipments were drawn where possible although the information available in this area is limited.

3.4.1 Standardized Requirements

The standardized electrical input/output requirements established for evaluating central power processing units are presented in Tables 3.23 and 3.24. The former indicates the input voltage/frequency level and ranges selected for each central PPU class while the latter identifies the output voltage levels and power range examined in each case. The output parameters were chosen, in part, to be compatible with the input requirements of load PPUs as previously set forth in Paragraph 3.1.

Table 3.23. CPU Input Parameters

CPU Type	Nominal Input Voltage & Freq.	Input Voltage/ Freq. Ranges
Motor Driver Inverter	28 Vdc 115 Vdc	24 to 36 Vdc 100 to 115 Vdc
Transformer-Rectifier	115/200 Vac, 3Ø, 400Hz 115/200 Vac, 3Ø, 1200Hz 115/200 Vac, 3Ø, 4000Hz	100/173 to 122/211 Vac, 3Ø, 400 ± 20Hz 100/173 to 122/211 Vac, 3Ø, 1200 ± 60Hz 100/173 to 122/211 Vac, 3Ø, 4000 ± 200Hz
Source Inverter	115 Vdc	100 to 125 Vac

Table 3.24. Standard CPU Load Parameters

CPU Type	Output Power Range (KVA)	Output Voltage	Regulation	Waveform
Motor Drive Inverter	0.1 to 2.5	115/200 Vac, 3Ø, 400Hz	Unregulated	Quasi-Square
Transformer Rectifier	0.3 to 3.0	+28 Vdc +115 Vdc	Unregulated	Filtered dc
Source Inverter	2.5 to 25.0	115/200 Vac, 3Ø, 400Hz	Regulated: Voltage $\pm 2\%$ Frequency $\pm 5\%$	Sinewave THD, 5%

3.4.2 Circuit Configurations

Table 3.25 lists the central PPU circuit configurations, providing the standardized output parameters, selected in the development of parametric data on central PPU performance characteristics.

Table 3.25. Selected CPU Circuit Configurations

CPU Type	Circuit Configuration
Motor Drive Inverter	Transistor Switch Type, 3Ø, Quasi-Squarewave
Transformer-Rectifier	6Ø Parallel Bridge Rectifier with Interphase Transformer
Central Inverter	a) SCR Switch Type, 3Ø, Sinewave b) High Frequency Series Inverter Driving a Cycloconverter

Simplified circuit diagrams of each of the selected central PPU circuit configurations are illustrated in Figures 3.45, 3.46, and 3.47.

The motor drive inverter circuit is characterized by its simplicity, high efficiency, and low weight. No regulation is provided and motor inrush current must either be accommodated in the design of the inverter or controlled in an externally connected output RPC. The parametric data generated herein for this class of PPU assumes the latter case; the inverter designs being rated only for running load conditions.

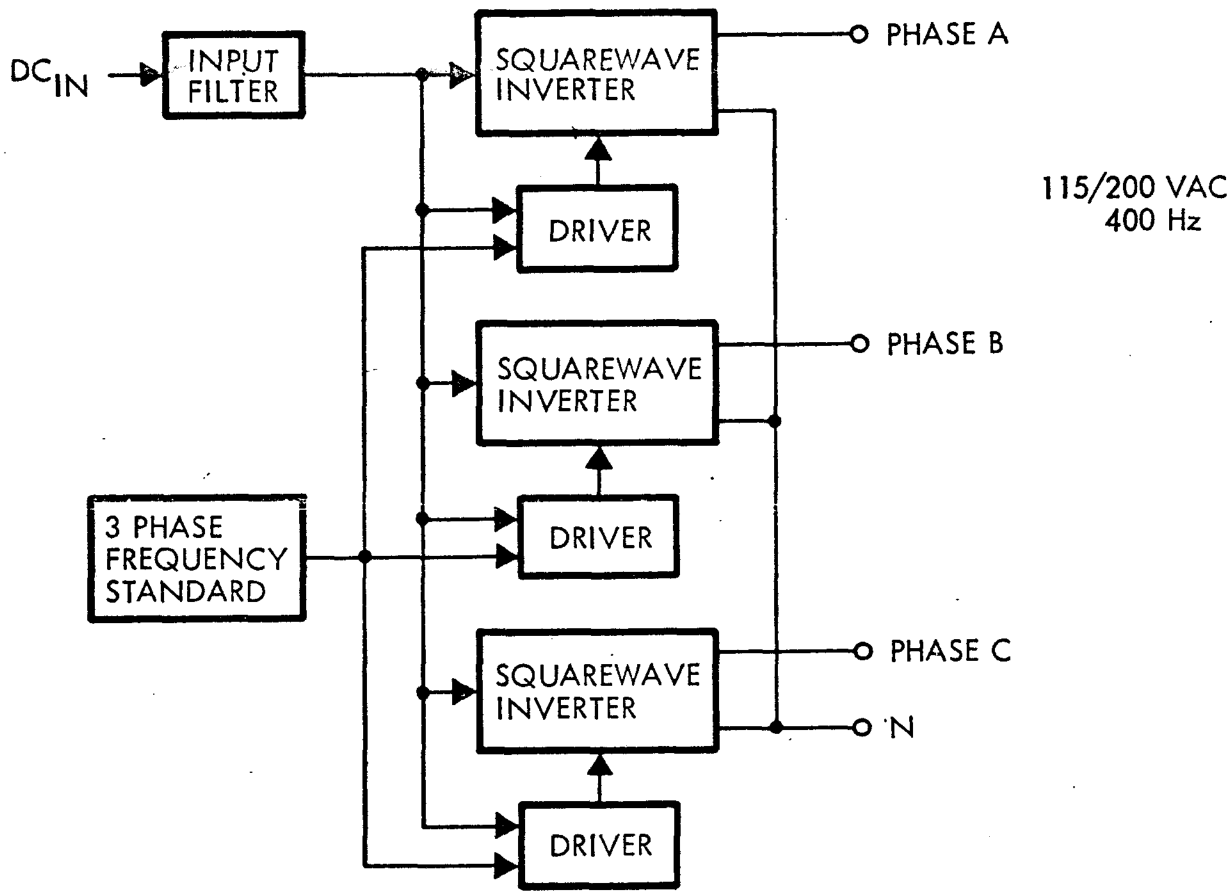


Figure 3.45. Motor Drive Inverter (3 Phase, Quasi-Square Wave)

The selected unregulated transformer-rectifier configuration is commonly used in high power applications. It features a very low output ripple voltage (approximately 1 percent) without added filtering and also presents a very high input line power factor.

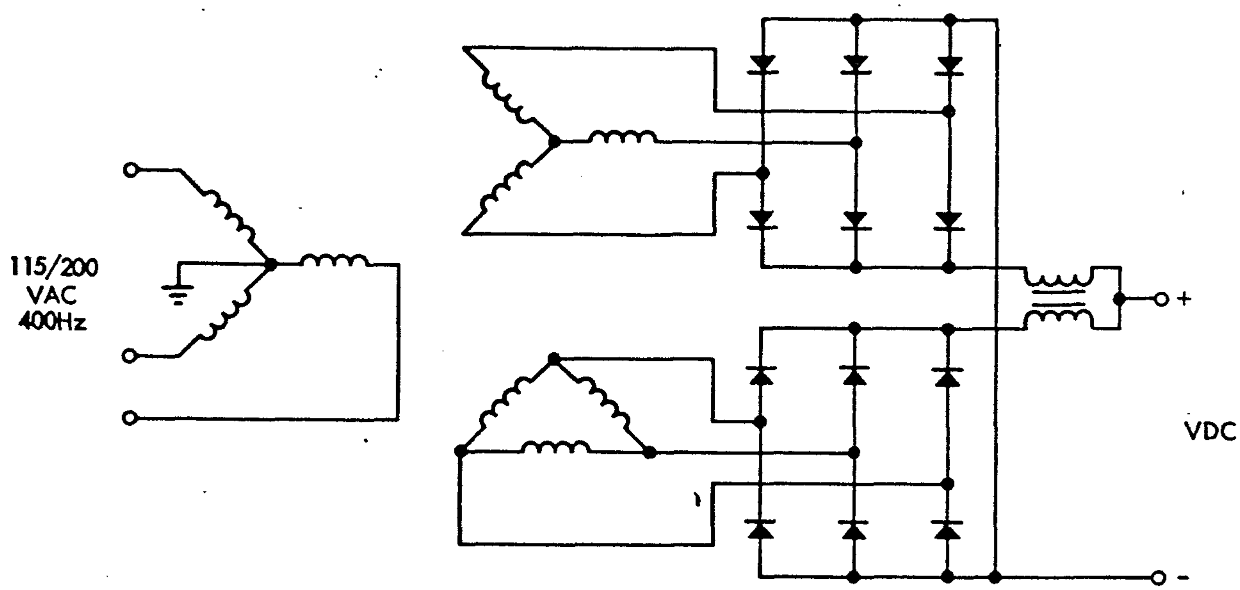


Figure 3.46. Transformer-Rectifier (Unregulated)

A variety of central inverter configurations have been developed in recent years to provide large sinewave ac power requirements at low weight and high efficiency. Included are such basic approaches as those utilizing fundamental frequency conversion, either directly from the dc bus or from an elevated dc link and those accomplishing conversion through pulse frequency modulation techniques operating upon a high frequency waveform generated from the dc bus or again, an elevated dc link. Waveform synthesis is typically implemented by open loop techniques and output voltage control achieved by either varying the inverter dc input or utilizing some form of pulse width modulation.

The configuration selected herein for a central inverter is based on a recent series inverter development effort funded by NASA (Reference 41). A high frequency SCR series inverter is used in conjunction with a cycloconverter to provide a 3 phase, regulated sinewave output from a high voltage bus (115 Vdc). The combination, properly a cycloinverter, offers the advantages of high efficiency, low weight and an inherent output current limiting, by virtue of the current source nature of the series inverter.

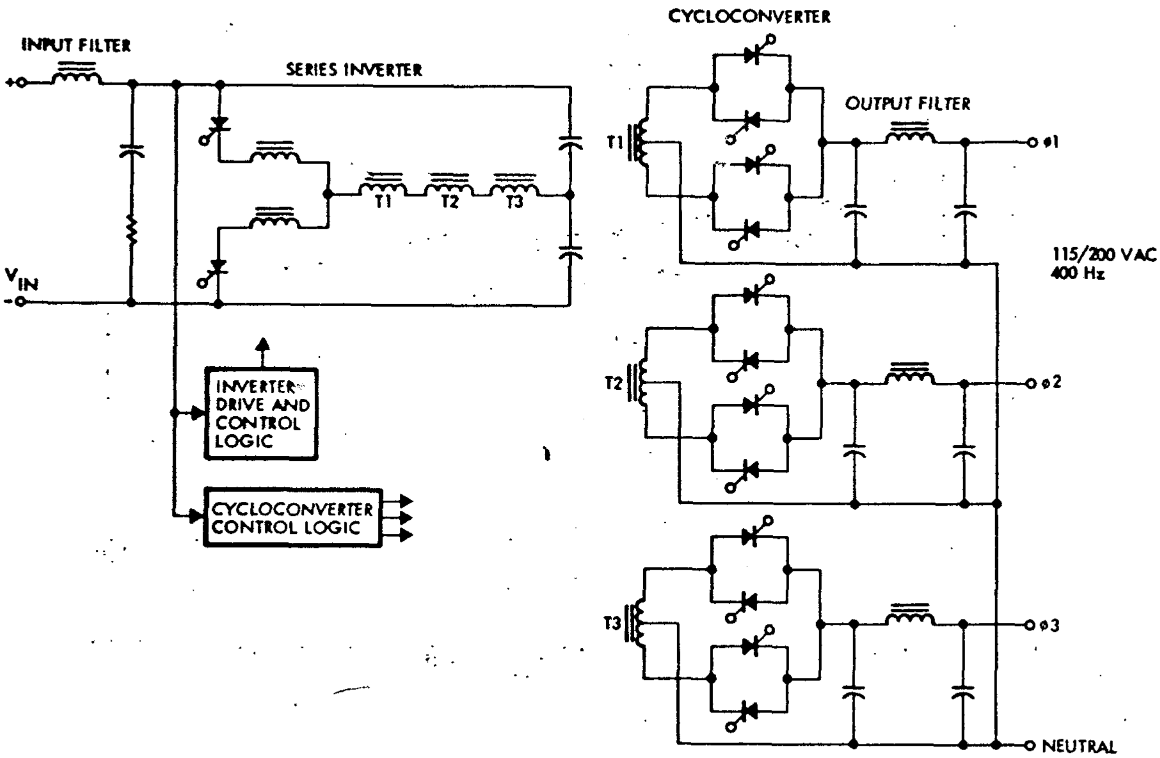


Figure 3.47. Central Inverter (AC Link)

3.4.3 Performance Analysis

Parametric data for the CPU performance analysis was generated under the basic procedure and assumptions outlined for load power processing equipments in Paragraph 3.1. Again, a switching frequency of 10 KHz was assumed where appropriate. The data developed for the selected CPUs are presented in the curves of Figures 3.48, 3.49, and 3.50. These show, respectively, specific weight, efficiency and total failure rate as functions of output power rating and the source and load voltage/frequency parameters defined in Tables 3.23 and 3.24.

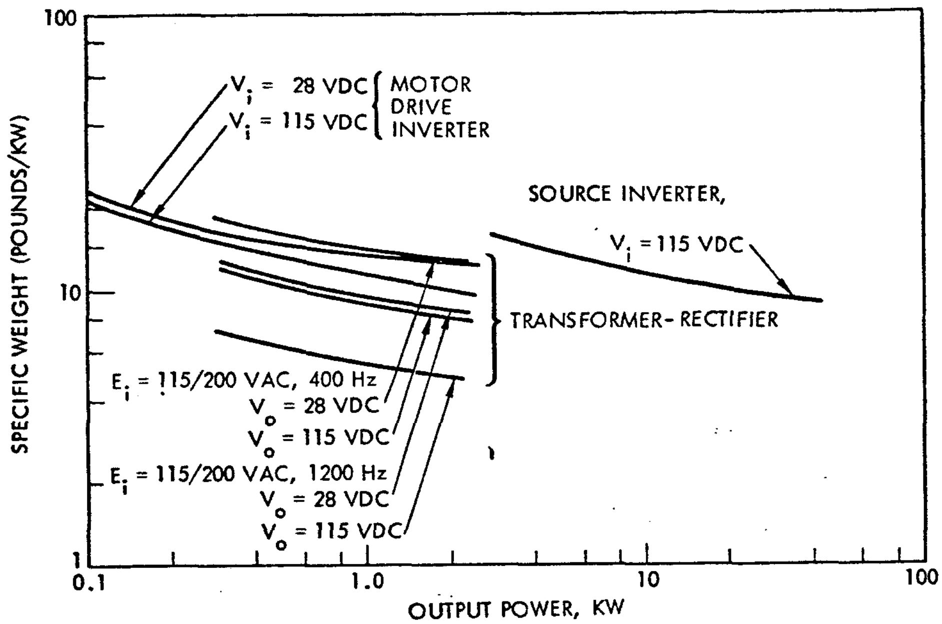


Figure 3.48. Central Power Processing Unit Specific Weight

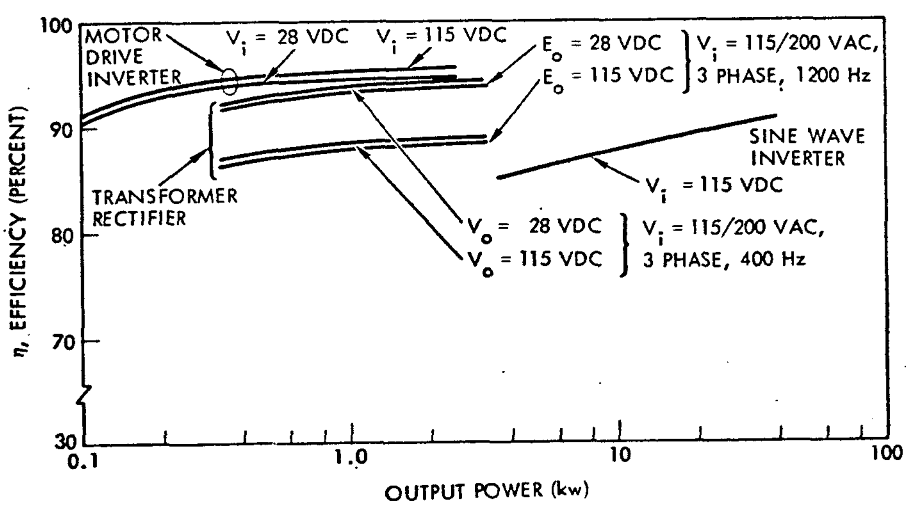


Figure 3.49. Central Power Processing Unit Efficiency

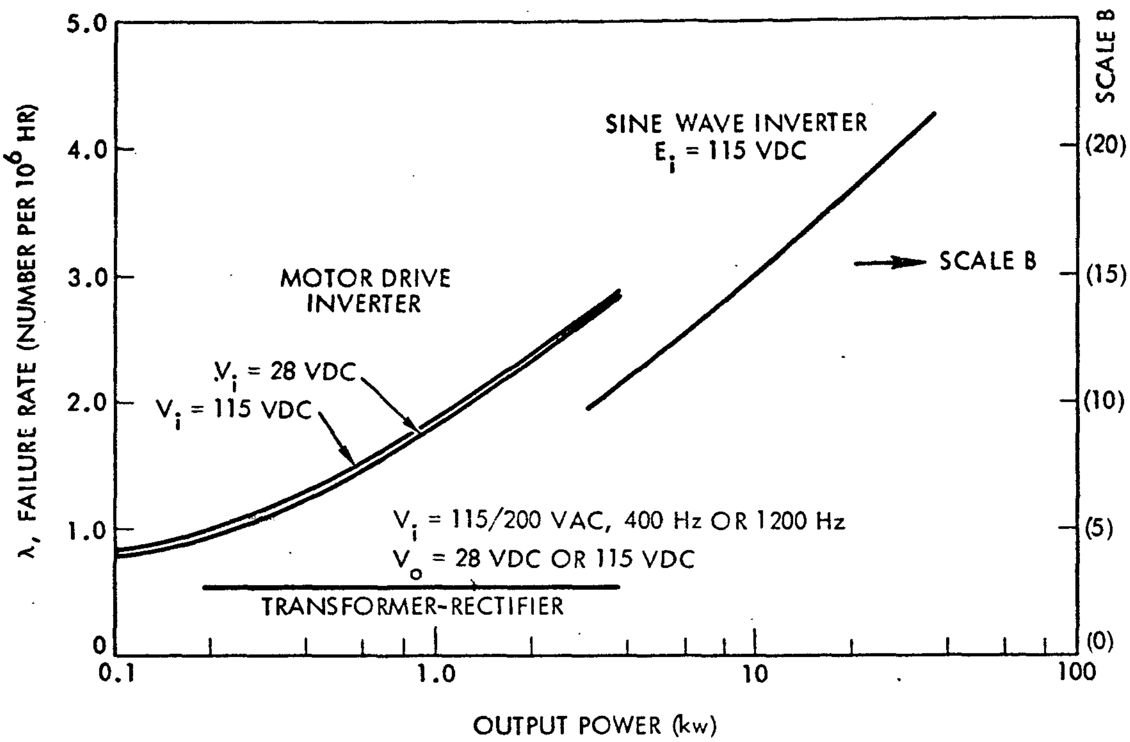


Figure 3.50. Central Power Processing Unit Failure Rates

The motor drive inverter configuration assumed yields a specific weight figure, at 1 KW and with a 28 Vdc input, of 13.5 pounds per KW. With a 115 Vdc, the weight decreases by approximately 15 percent. As noted previously, the inverter rating is based on motor running load only. Providing a 5 per unit inrush capability would almost double inverter weight and increase failure rate by 50 percent since the inverter switching components and associated heat sinking would have to be designed to accommodate inrush conditions.

Output voltage level of the assumed transformer-rectifier configuration significantly affects the specific weight and efficiency characteristics. At 1 KW, a 115 Vdc output unit would weigh approximately 9 pounds under the assumed cooling conditions (mounting to a 55°C maximum cold plate). This represents a specific weight improvement of 36 percent over that achievable in a 28 volt unit. An efficiency increase of 5 percent is also realized in 115 Vdc case.

The effect of input frequency on the specific weight of a similarly configured transformer-rectifier unit is illustrated in Figure 3.51. The weight of a 28 Vdc, 1 KW unit, for example, decreases by 30 percent (9.6 lbs versus 14 lbs) with a tenfold increase in supply frequency (4 KHz versus 400 Hz) since the required transformer weight reduces by the 3/4 power of supply frequency.

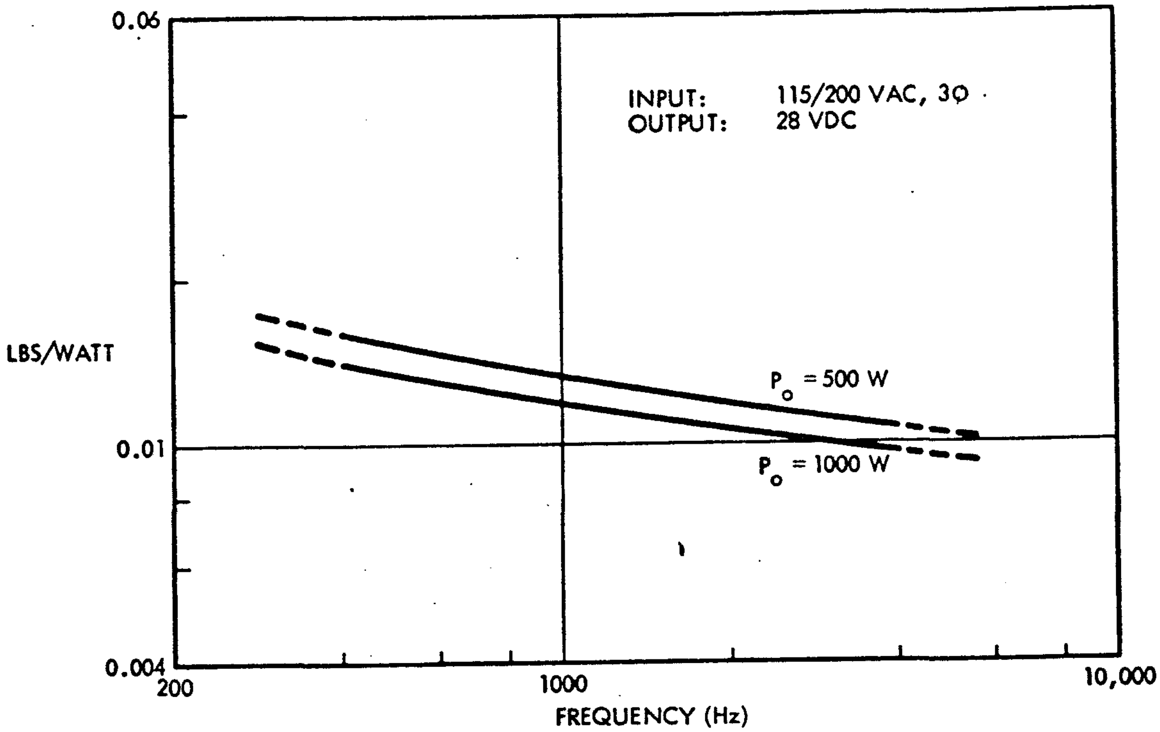


Figure 3.51. Effect of Supply Frequency on Transformer-Rectifier

The selected sinewave inverter configuration, operating from a 115 Vdc input, yields, in the 5 to 10 KVA range, specific weight and efficiency figures of approximately 12 pounds per KW and 88 percent. The input filter, in this instance required to attenuate sinusoidal high frequency series inverter switching currents, constitutes approximately 10 percent of the total central power processor weight. Recent investigations on high power inverter systems which indicate the feasibility of obtaining specific weight and efficiency figures approaching, respectively, 8 pounds per KW and 95 percent, are based on operating at dc input voltage levels in the 200 to 400 Vdc range.

3.4.4 Summary

The quantitative analysis on typical central power processing equipments has shown the benefit of increased operating voltage levels and, in the case of transformer-rectifier units, the weight saving achievable with increased supply frequency level. In PDCS utilizing source inverters to generate ac power, a significant weight, loss, and failure rate penalty is developed despite the use of a circuit configuration embodying advanced state-of-the-art technology.

4.0 DYNAMIC PERFORMANCE AND FILTERING

The power processing, distribution and control subsystem consists of a complicated electrical network which interconnects a small number of generally identical generators and a large number of loads of various types and with different power requirements. Selection and design of the PDC subsystem involves both its static and dynamic electrical characteristics.

The instantaneous voltage at an arbitrary point in the PDC subsystem may be written as

$$v = V_o + \Delta V + v_t + v_r \tag{4.1}$$

where

- V_o is the steady state voltage at the fundamental power frequency (which may be dc)
- ΔV is the variation due to voltage regulation
- v_t is the transient or surge voltage due to load switching, bus switching, power interruption, etc.
- v_r is the ripple voltage or voltage modulation due to periodic switching actions, noise, spikes, internal load and generator operation.

The sum of the first two components $V_o + \Delta V$ expresses the static performance, while the quantity $(v_t + v_r)$ may be referred to as the dynamic component of voltage v_d. The sum $\Delta V + v_t + v_r$ is a measure of power quality. For simplicity, the dynamic component $v_d = v_t + v_r$ will be called the interference voltage, although this is not always consistent with the usual connotation of electromagnetic interference (EMI) which sometimes omits the transient term.

The PDC subsystem must be designed to meet the power quality requirements imposed by the loads in the most effective and economical manner. In addition, it must not generate interference which can be coupled to sensitive loads through electromagnetic radiation. Normally, the power quality requirements of electronic loads are satisfied by providing secondary power supplies (load PPUs) which contain regulators and filters for that purpose. The power quality at the input to load PPUs and at all loads which do not have PPUs as well as the radiated interference are caused by the generators and the distribution and control equipment. Actual determination of power quality and interference is a network analysis problem which requires a detailed knowledge of the generation subsystem and the PDC network for each candidate configuration and therefore was not feasible during this study program. In order to make a comparative evaluation of different PDC configurations, however, it is sufficient to examine the major sources of interference and to calculate approximate transfer functions between each source and critical load equipment terminals to show how the dynamic performance depends on transmission/distribution voltage and frequency. The impact of switchgear characteristics and design of power supply filters will also be considered in detail in this section.

4.1 POWER QUALITY REQUIREMENTS

The maximum allowable voltage regulation ΔV, transient surge voltage v_t and ripple or modulation voltage v_r which a load utilization unit can withstand at the power line input terminals is a function of the load unit design. The allowable values of v_t and v_r represent the transient and steady state susceptibility limits. In addition the load units must be designed to limit the transient current i_t and ripple current i_r in the power line due to operation of the load unit. This represents the conducted interference. Requirements for susceptibility and conducted interference characteristics of electronic, electrical and electromagnetic equipment including PDCS components are contained in MIL-STD-461A, TOR-1001(2307)-4, and similar EMC specifications. Characteristics of the voltage supplied by the PDCS to utilization equipment are specified by MIL-STD-704A for aircraft. No comparable specification exists for space vehicles.

An examination of the various aerospace power quality and EMI requirements documents reveals considerable variation in dynamic performance specification limits. Figures 4.1 and 4.2 illustrate the continuous ripple limits, expressed in terms of i_r, input current (conducted emission or interference) and v_r, input voltage (conducted susceptibility), as defined in the applicable paragraphs of MIL-STD-461A, TOR-1001(2307)-4, and MIL-STD-704A, the specifications most commonly applied in aerospace electrical systems and/or equipment design. The first two documents define equipment EMC requirements, while the last defines electric power quality supplied to airborne equipment.

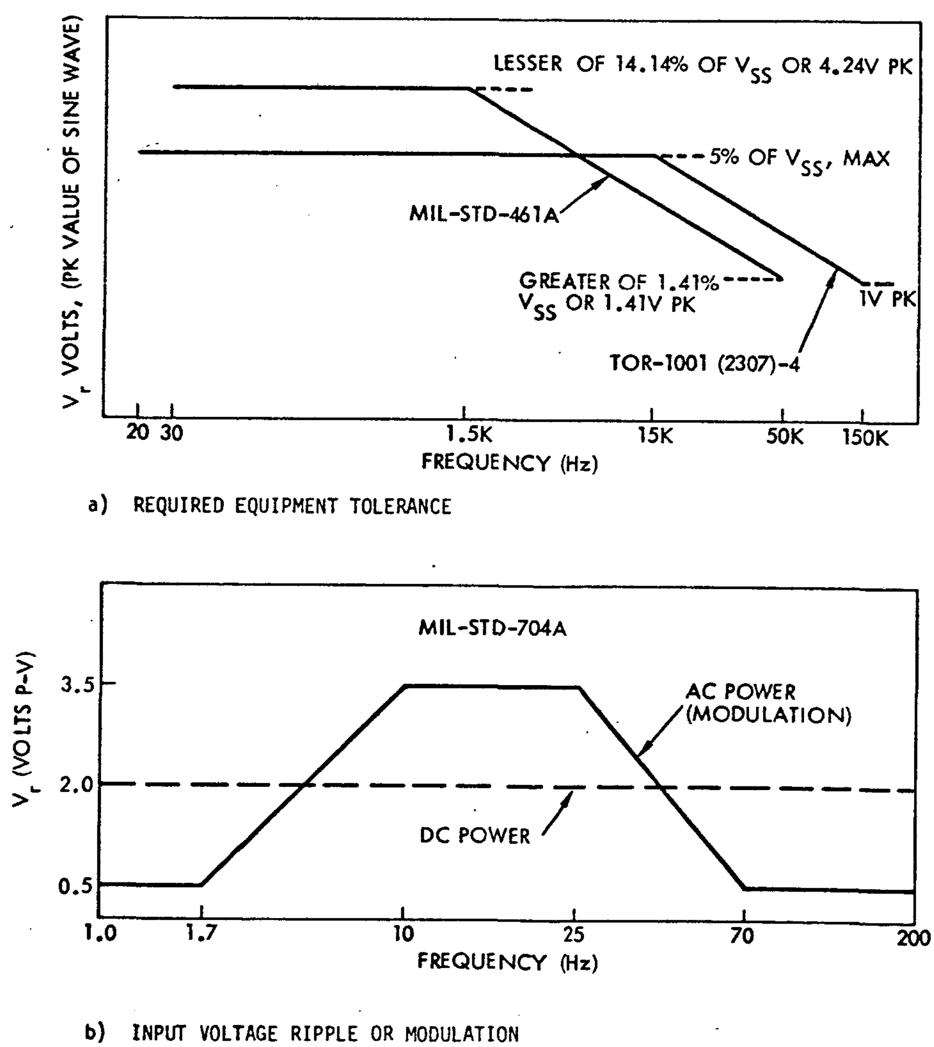


Figure 4.1. Continuous Ripple Limits - Conducted Susceptibility

Allowable conducted interference values, which are independent of equipment power rating, vary quite widely in the individual EMI specifications and, as will be shown in a subsequent section, the variations can significantly impact PPU power line filter design. At 10 KHz, for example, allowable peak ripple current values are 56 ma for MIL-STD-461A, Notice 3 (Air Force equipment), 7 ma for TOR-1001-4 (Air Force Space Systems), and 1.26 ma for MIL-STD-461A (original issue). In the TOR document, a reflected ripple voltage specification is also placed on equipments operating from a dc souce, limiting such interference to 1 mv peak per watt of consumed power over a frequency range of dc-10MHz.

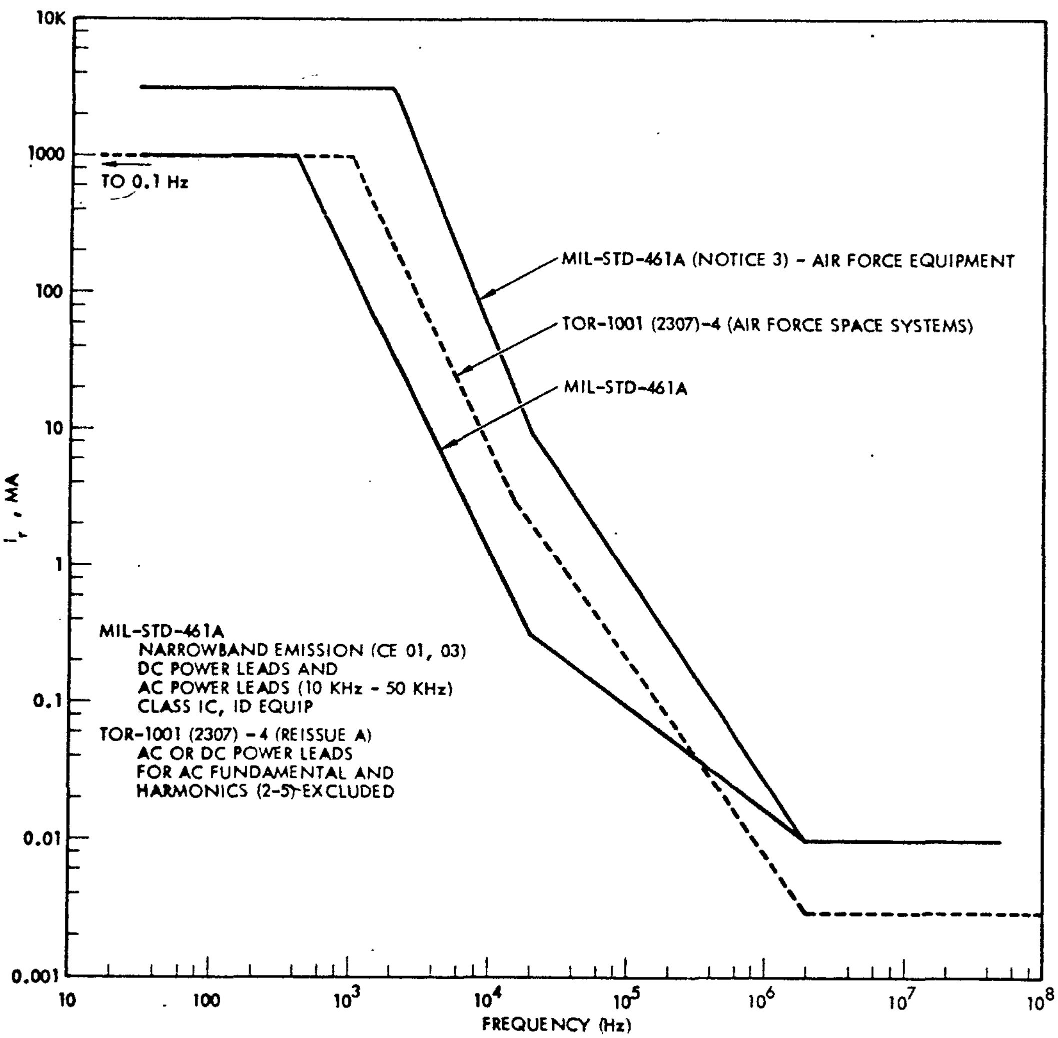


Figure 4.2. Continuous Ripple Limits - Conducted Interference

Considerable variation in specified conducted susceptibility limits are also exhibited in these documents. In the low audio frequency range, for example, specified ripple voltage limits for MIL-STD-704A, Category B equipment operating from a 22.5 to 30 Vdc bus are 3.96, 1.5, and 2.0 volts peak in, MIL-STD-461A, TOR-1001-4, and MIL-STD-704A, respectively. In addition, the TOR document specifies a continuous ripple voltage limit of 3 percent peak-to-peak of maximum line voltage over the range of dc to 10 MHz for vehicle power sources. In the example above, this is equivalent to 0.45 volts peak.

Similar disparities in the specification of transient performance are also evidenced in the cited documents. Ac or dc powerline conducted interference due to single event switching, e.g., equipment turn-on/off, is specified in terms of pulse voltage (v_t) in both the TOR document and in MIL-STD-461A. In the former, a curve defines the maximum allowable pulse voltage as a function of pulse width. Typical values are 200% maximum line voltage for pulse widths of 0.1 μsec and less, decaying to a pulse magnitude of the lesser of 32 volts or 1/3 maximum line voltage for durations of 2 to 60 μsec. In the original issue of MIL-STD-461A, short duration interference was not exempt from requirements of the standard, hence requiring compliance with continuous interference limits. In the latest issue of this standard (Notice 4), applicable only to Army procurements, allowable pulse interference voltage is specified in terms of a pulse voltage-time product, $2\ A\ d \leq 10$, where A is the pulse amplitude in volts and d is the pulse duration in μsec. Application of these criteria to an equipment powered by a 24-32 Vdc bus yields, for a 0.1 μsec pulse, allowable amplitudes of 64 and 50 volts, respectively, for the TOR and MIL-STD-461A (Notice 4) limits.

In the EMI documents, transient susceptibility specifications, for ac or dc powered equipment, are described in terms of a superimposed power line pulse of prescribed amplitude and duration. For equivalent amplitudes, the TOR specification provides for a longer duration pulse. In a 24-32 volt dc system, for example, MIL-STD-461A establishes a 64 volt, 10 μsec pulse while TOR-1001-4 specifies a 64 volt, 62.5 μsec pulse. These values can be compared with the abnormal ac and dc power system performance limits of

MIL-STD-704A, given in Table 4.1. This table summarizes the transient limits in the various specifications. As seen, there is essentially no correlation between MIL-STD-704A limits and the EMI specifications.

Table 4.1. Transient Limits

	MIL-STD-461A	TOR-1001(2307)-4	MIL-STD-704A (Abnormal System Operation)
Transient Susceptibility (positive transient)	Lesser of $2xV_{Line}$ or 100 volts, 10 μsec Pulse Width: dc or ac	Lesser of $2xV_{Line}$ (max) or 100 volts, 4 volt-msec Pulse Width; dc or ac	DC 80 volts (28V system) to 50 msec and +600V max to 10 μsec-spike AC 180 volts rms (115/200 Vac system) to 100 msec
Transient Susceptibility (negative transient)	"	"	DC 0 volts to 7 sec and -600 volts max to 10 μsec-spike AC 0 volts to 7 sec
Transient Input Current Generation	Not specified	Not specified	Not specified
Input Voltage Spike Generation	$2Ad \leq 10$ A=peak volts d=pulse width in μsec (dc or ac)	Figure 3 of Reissue A Pulse Amplitude vs Duration	Not applicable

In summary, power quality specifications, including EMI, require further definition and standardization to assure compatibility in the design of power processing, distribution and control systems.

4.2 GENERATION OF INTERFERENCE

The dynamic or interference component of voltage at equipment input terminals is due to one or more of the following:

- Dynamic component of generator output voltage
- Current transients in the power line feeding the equipment
- Current or voltage transient on nearby power lines
- Transient and repetitive load equipment operation including secondary power supplies
- Operation of switchgear including arcing between contacts
- Interference generated by source power converters due to commutation, load changes, etc.

The dynamic component of the primary generated voltage depends on the design of the generator and its electrical loading. Batteries and fuel cells have the lowest source impedance and hence the lowest interference voltage output. As mentioned in Section 2.4 rotating generators of all types have higher source impedance and produce harmonics of the power frequency which are part of the interference voltage. In addition, the dynamic performance of a rotating generator is determined by the frequency response of the drive mechanism and the provisions for sharing real and reactive loads between generators. A detailed analysis of inherent generator dynamic characteristics and waveform as a function of output voltage, frequency, and load are outside the scope of this program.

Current transients in power lines are due to changes in connected load or generators. The resulting voltage changes depend on the source impedance, line impedances, and mutual impedances. Interference caused by PDC equipment due to its internal operation also affects the power quality and may radiate to susceptible load equipment.

A start has been made during this study in obtaining dynamic performance data on typical hardware units suitable for possible use on future manned aircraft and space vehicles. These data have been gathered on such items as power relays, secondary power supplies (PPUs), and susceptibility of a data bus using remote multiplexing. The findings were therefore not tied directly to the selection of any one particular power subsystem scheme, and were also intended to assist in evaluating the adequacy of existing EMC specifications.

More detailed analysis of the interference generation characteristics of PDC equipment must be deferred to future studies since detailed configuration parameters such as cable layout, grounding, switchgear design, load characteristics and power profile and generator dynamic characteristics must be known for EMI compatibility analysis. Mathematical techniques such as SEMCAP which use digital computer simulation techniques are available to perform this analysis (References 36 and 37).

4.2.1 Relay Switching Transients

EMI measurements during current interruption were made on typical electromechanical relays rated for 28 Vdc and 120 Vdc power circuits. One of the more interesting results of the relay switching tests was the generally lower level of interference produced by the high voltage relay when compared to a Leach 28V aircraft relay. It is believed that this performance is directly attributable to the magnetic blowout feature of the high voltage relay, which tends to rapidly quench the arc formed during load power disconnects. Figures 4.3, 4.4, and 4.5 show this comparison.

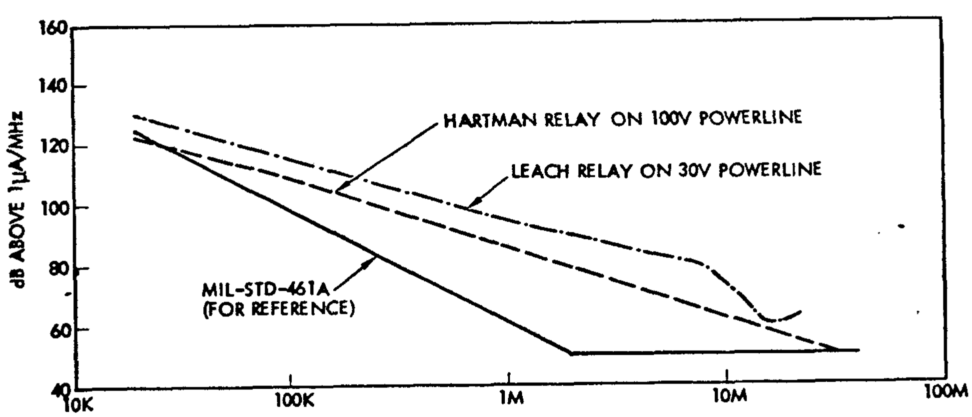


Figure 4.3. Measured Broadband Conducted Emissions During Interruption of 10 Ampere Load Current

The performance comparison under conditions of equal 10 ampere current interruptions showed that the magnetic blowout feature leads to significantly lower levels of high frequency noise. This reduction appears in the range from 1 to 30 MHz, where noise cross-coupling is most often encountered. Digital interface lines, for instance, are most susceptible over this band due to the drop in shielding efficiency caused by long pigtails on shields and the resultant exposure of unshielded center-conductors at connectors.

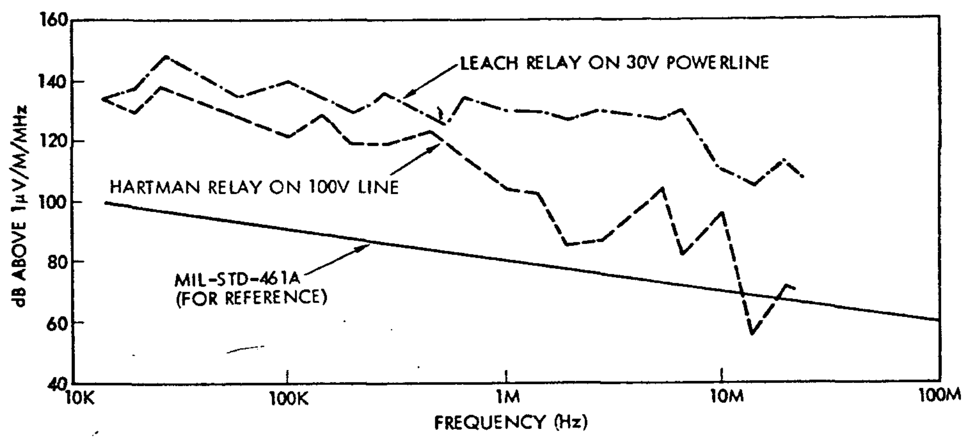


Figure 4.4. Broadband Radiated Emissions During Interruption of 10 Ampere Load Current

As an example, the 10 db difference in conducted current noise levels means an interference reduction in adjacent low impedance circuits by a factor of about 3. In the case of higher impedance circuits, such as digital signal lines, the difference in powerline conducted voltage levels may mean a reduction of 100 to 1 in interference on adjacent lines.

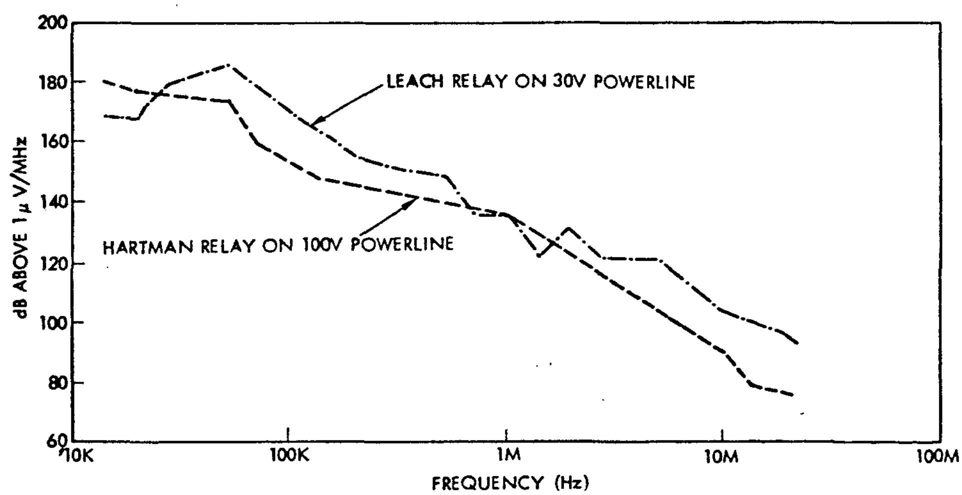


Figure 4.5. Broadband Conducted Emissions During Interruption of 10 Ampere Load Current

Care must of course be taken in interpreting these results. Given enough spacing between the wires, powerlines and even unshielded analog lines can be used in the same vehicle. The main factor working against their compatibility is the fact that "black boxes" normally interface with many types of wiring, powerlines among them. Problems thus occur where these wires are routed in close proximity, such as at connectors, bulkheads, and sliprings. The problems may be compounded even further by poor design practices, but issuance of a rationally developed EMC control plan and strict enforcement of its provisions from program start can do much to ensure ultimate system compatibility.

4.2.2 Interference From Power Processing Units

Power processing units such as central inverters must contain an input filter to attenuate ripple currents in the input power line and output filters to control output voltage harmonics and commutation spikes. The magnitude of the input current ripple and the output harmonics and spikes depend on the power rating of the inverter and the design of the filters. The interference amplitude is also a strong function of the load on the unit. Although total harmonic distortion is usually kept below 8% by filtering and waveform synthesis methods, the interference on input and output lines during turn-on or load switching may be much greater.

4.2.2.1 DC Input PWM Inverter

The inrush current characteristics for a typical load power processor using a pulse width modulated inverter circuit switching at 10 KHz was analyzed to illustrate the generation of interference currents in the power line due to PPU action. Figure 4.6 illustrates the salient portions of the power processor and the transient response characteristics. Inrush current is determined primarily by the input line filter which in our example has been designed to obtain 40 db attenuation of inverter switching current at 10 KHz giving a steady state ripple current of 40 ma pp in the input power line.

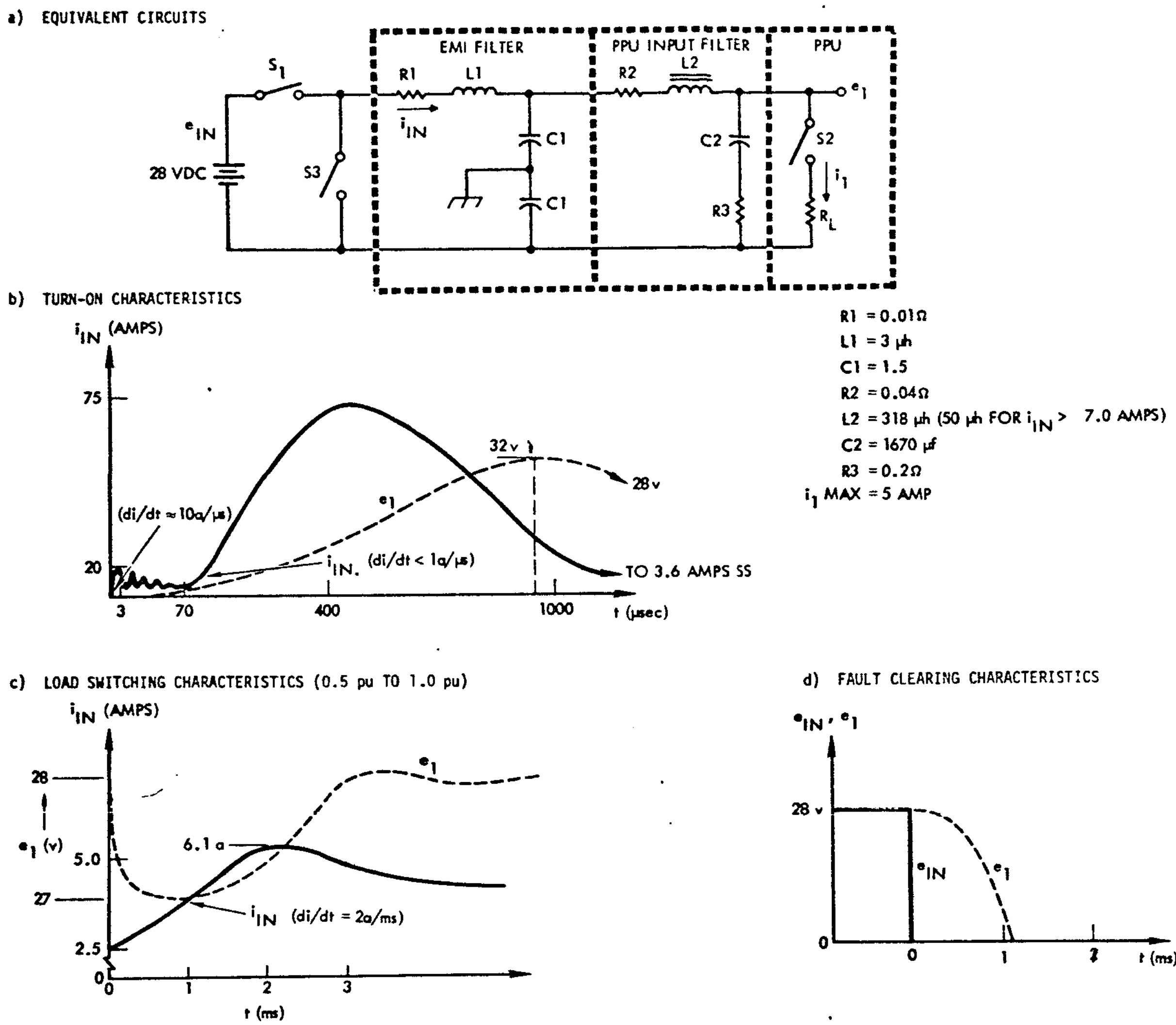


Figure 4.6. Typical Transient Characteristics of 100W PPU

Added to the basic line filter circuit are typical element values for an EMI feedthrough filter, a component generally added to control megahertz range, PPU-generated switching spikes. Switches S1, S2, and S3 provide, respectively, the means for initiating turn-on, load switching and fault clearing actions. The voltage and current response characteristics shown were calculated using the appropriate time functions for the circuit variables of interest and the listed filter element values.

a. Turn-On

Circuit turn-on is accomplished by closing switch, S1. The input filter inductor, L2, is designed to saturate when input current exceeds approximately 7 amps, dropping to an air core inductance value of 50 μh. The inrush or input current and filter output voltage characteristics are illustrated for this "hard" turn-on case, with the filter previously in a fully discharged condition. An initial inrush current oscillation, peaking at 20 amps at 3 μsec. results from the charge-up of the EMI filter. This oscillatory current is superimposed on the relatively slow rise of input current as controlled by inductor, L2. When L2 saturates (at 70 μsec.), the rapid charge-up of output capacitor, C2 (and PPU output filter capacitors), results in a peak current of approximately 74 amps at 400 μsec. after turn-on is accomplished. The input current then decays to its average value of 3.6 amps at about 1 msec. Filter output voltage, e_1, reaches its peak overshoot value (32V) at this time and then decays to 28 volts. The rate of rise of input current, initially and after saturation of L2, are, respectively, 9.6 and 0.45 amps per μsec. As seen, "hard" turn-on results in a large surge, in this case, 20 times the average, steady-state value. Implicit here, of course, is the capability of the power source to provide this surge. Equipment turn-on via internal PPU clock oscillator control can greatly reduce the turn-on surge (typically, by a factor of 5) since the input filter can be in a pre-charged condition, leaving only the requirement for charge-up of PPU output filter capacitors after turn-on.

b. Load Switching

In the example shown, load switching is accomplished by connecting switch, S2, from a half to full load condition (2.5 amp to 5.0 amps max). The characteristics plotted are filter input current and output voltage. The input current rises to a peak value of 6.1 amps in approximately 2 msec. then decays to its final value. The rate of rise is approximately 2 amps per msec, a rather benign value.

The filter output voltage drops instantaneously due to the influence of damping resistance, C3, then decays to 27 volts before rising to a slight peak and ringing to 28 volts.

c. Fault Clearing

Closure of switch, S3, simulates a fault clearing condition. Illustrated is the typical decay in filter output voltage, which for this design is accomplished in slightly more than one msec. The filter energy storage characteristics can influence the fault clearing requirements placed on RPCs in power system utilizing external on/off control of PPUs.

4.2.2.2 AC Input PWM Inverter

As a second example of the input line interference generated by a power processor consider an ac to dc converter which uses an input rectifier followed by a 10 KHz PWM inverter to provide voltage level changes and circuit isolation as illustrated in Figure 3.10c. The input rectifier and filter are shown in Figure 4.7 along with the switches which symbolize turn-on/off, fault removal and inverter action. Also shown in Figure 4.7 are the waveforms of the line current i_{IN} and output voltage e_1 following switching transients. Results are qualitative since no detailed calculations were performed.

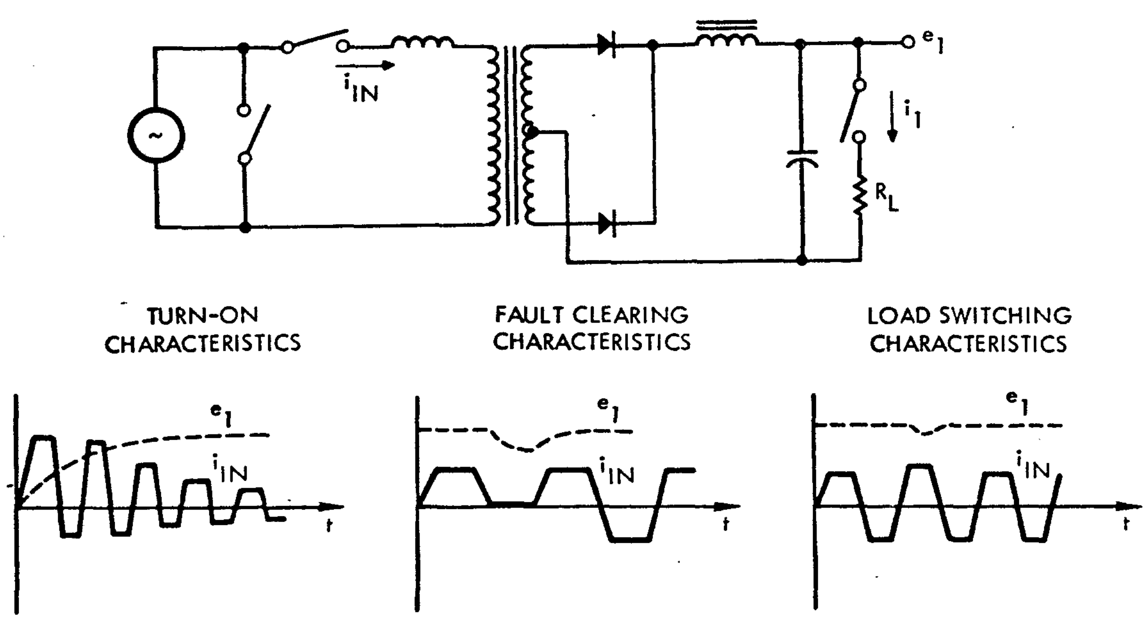


Figure 4.7. Typical Transient Characteristics of ac Input PPU

4.2.3 Power Source Interference Voltage

The dynamic component v_d of the EPGS output voltage is specified for aircraft electrical systems by the power quality specification MIL-STD-704A as discussed previously. Limits on the transient voltage surge v_t and the recurring ripple voltage or voltage modulation component v_r are called out and are shown in Table 4.1 and Figure 4.1, respectively. These limits are based on the use of rotating machinery employing slip rings and mechanical commutators. Static dc power sources do not exhibit the large transient voltage excursions but may produce ripple currents if switching type series or shunt regulators are employed. Typical transient and ripple voltage amplitudes for the rotating generators considered in this study program were listed in Table 2.19. These voltages can be reduced by improved generator field control methods and by use of output filters at the expense of increased weight and power dissipation.

4.3 INTERFERENCE COUPLING

Dynamic voltage or current variations generated at one point in the PDC network are coupled into load or PDCS equipment through common impedances or by electromagnetic radiation. In order to evaluate the relative magnitude of the interference at the affected loads the transfer functions of the coupling paths are given below.

4.3.1 Interference Transfer Via Common Impedances

Figure 4.8 shows one of the most often encountered modes of common impedance coupling - sharing of a common power return line. Note that the common return path has both a resistive and an inductive term, with the inductive term rapidly becoming the overriding factor at increasing frequency. The inductance for low frequencies is given by (Reference 38)

$$L = .00508\, \ell \left(2.303 \log_{10} \frac{4\ell}{d} - .75\right) \qquad (4.2)$$

where

L = inductance in microhenries

ℓ = wire length in inches

d = wire diameter in inches

For a 1 meter length of common return, the crossover frequency where L = R occurs at 615 Hz for AWG 12 gauge wire and at 3.5 KHz for AWG 20 wire.

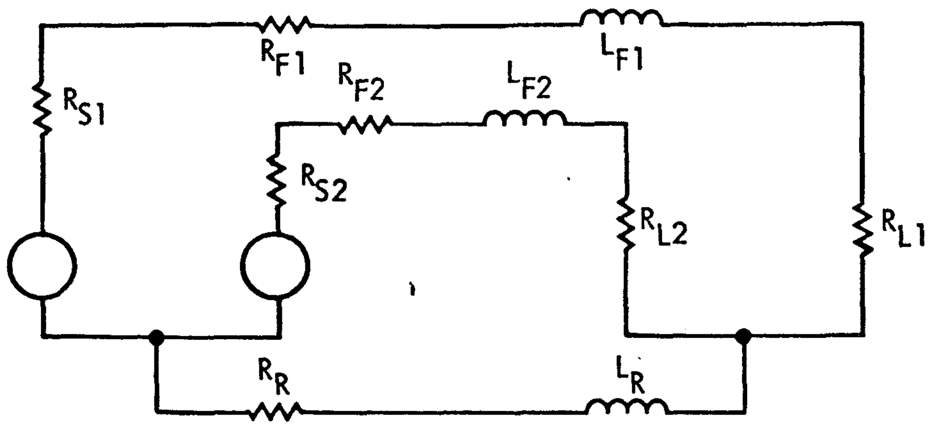


Figure 4.8. Common Ground Return

Figure 4.9 illustrates the case of parallel load circuits. This is a potentially more severe case of common impedance coupling since any noise resulting from the operation of one load will be coupled directly into the parallel load also. This cross-coupling will again increase as a function of frequency, partly due to the inductance of the wires, and partly also because the damping effect of the low impedance power source will be isolated from the load due to the increased wiring impedance. Two factors thus have to be considered for parallel loads, namely, how much noise will be cross-coupled due to the common wiring impedance, and how much will this noise level increase due to diminished power supply damping.

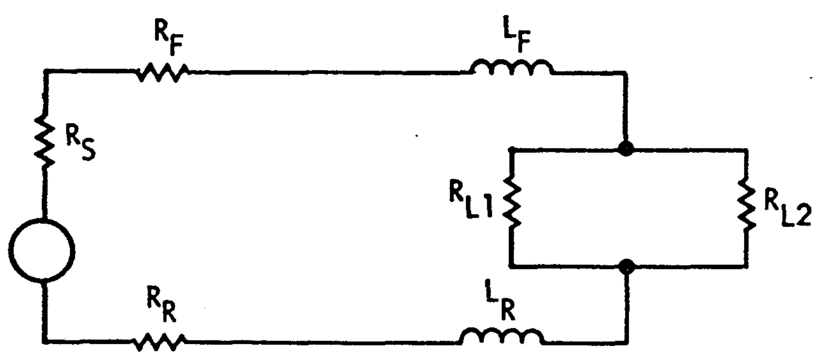


Figure 4.9. Common Feeder Impedance

Figure 4.10 illustrates the case which is often encountered in so-called "single-point ground" configurations. Here, even though all feeder lines are assigned to one single load each, and each load has its own return line, the loads may still interact via the power supply internal (source) impedance. At low frequencies, this impedance may be higher than the wiring impedance, and thus become the main coupling mechanism.

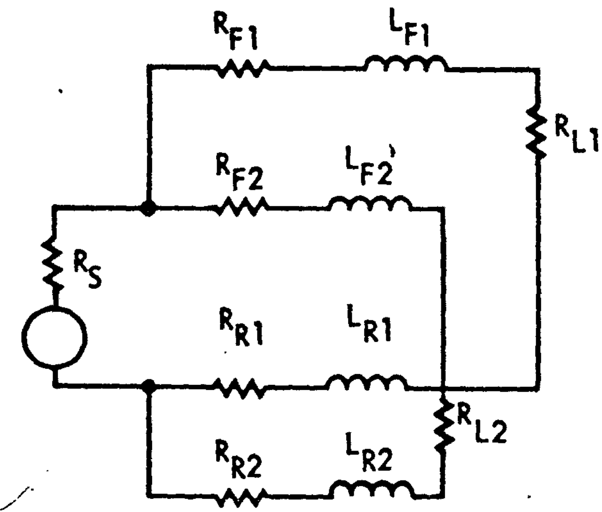


Figure 4.10. Common Source Impedance

4.3.2 Interference Transfer Via Mutual Inductance

The voltage induced in circuit 2 due to a current in a nearby circuit 1 is given by

$$e_2 = M_{12} \frac{di_1}{dt} \tag{4.3}$$

where M_{12} is a term whose value is fixed by the permeability of the material linking the two circuits and their respective geometries. M is defined by the equation

$$M = \frac{1}{I_2} \int_{S_1} \overline{B_2} \cdot dS_1 \tag{4.4}$$

where $\overline{B_2}$ is the average magnetic field due to circuit 2 existing over the cross-sectional area S_1 of circuit 1.

Figure 4.11 illustrates one such typical situation for unshielded parallel wires which are routed fairly closely together.

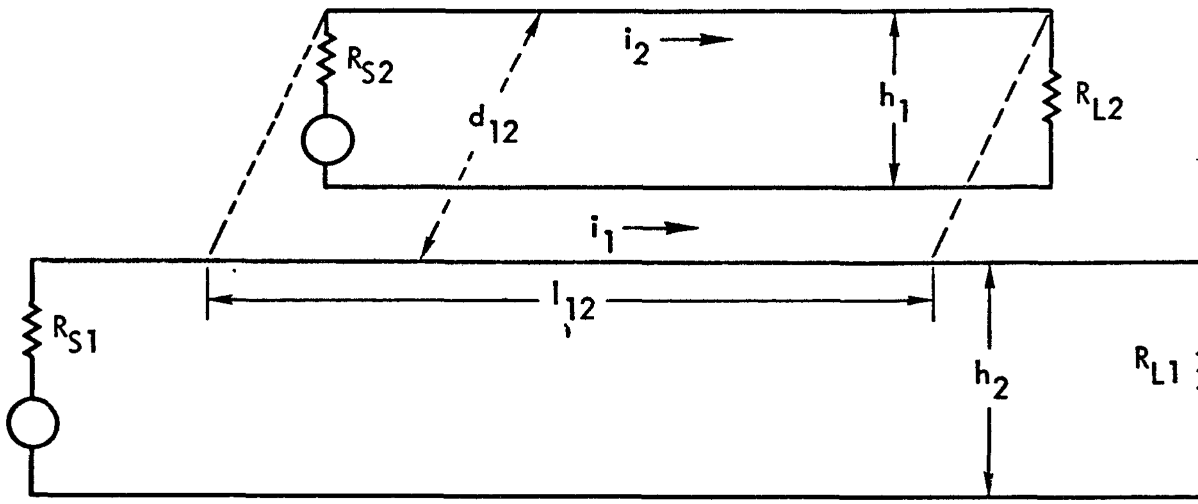


Figure 4.11. Mutual Inductance Coupling

For the given geometry, the mutual inductance is

$$M \approx 1 \times 10^{-7}\, l_{12} \ln_e \left[\frac{(h_1 + h_2)^2 + d^2_{12}}{(h_1 - h_2)^2 + d^2_{12}}\right] \tag{4.5}$$

where l_{12} is the length of the common run for the two circuits
The voltage induced across R_{L1} is then calculated from the formula

$$V_1 = M \left(\frac{R_{L1}}{R_{S1} + R_{L1}}\right) \frac{di_2}{dt} = 2\pi f I_2 M \left(\frac{R_{L1}}{R_{S1} + R_{L1}}\right) \tag{4.6}$$

For closely coupled wires, where circuit 2 carries 1 ampere at 10 KHz, V_1 equals about $.04\left(\frac{R_{L1}}{R_{S1} + R_{L1}}\right)$ volts per meter of common run.

4.3.3 Capacitive Coupling

The process whereby interference is capacitively coupled from one circuit to a second circuit is schematically shown in Figure 4.12.

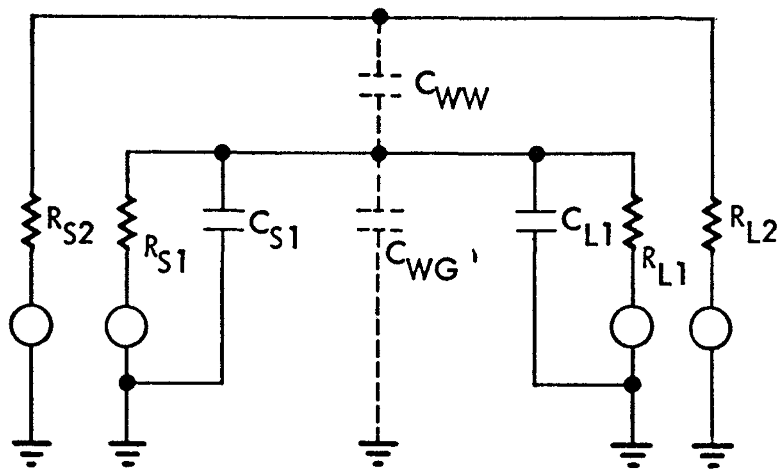


Figure 4.12. Capacitive Coupling

For ease of analysis, the sketch has been redrawn in Figure 4.13 where

$$R_L = R_{S1} R_{L1}/(R_{S1} + R_{L1})$$

and

$$C_L = C_{S1} + C_{WG} + C_{L1}$$

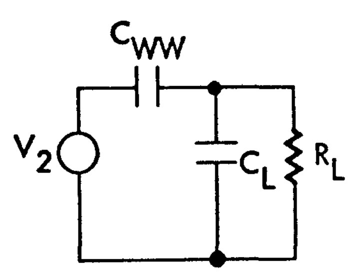


Figure 4.13. Equivalent Circuit

The voltage across the load, R_L, can thus be described in terms of the voltage existing on an adjacent wire.

$$V_L = V_2 \frac{2 f R_L C_{WW}}{2\pi f R_L C_{WW} + 2\pi f R_L C_L + 1} \quad . \qquad (4.7)$$

For high frequencies ($f >> \frac{1}{2\pi R_L C_L}$), the equation reduces to the form for a voltage divider:

$$V_L = V_2 \frac{C_{WW}}{C_{WW} + C_L} \quad . \qquad (4.8)$$

4.3.4 Electric and Magnetic Field Coupling Via Radiation

Electric and magnetic field coupling of interference via radiation is usually not a major consideration in electric power subsystem design. The near field terms, which have already been evaluated for the inductive (H-field) and capacitive (E-field) components, are thus the main factors of concern. Since the radiation resistance R_r is given by

$$R_r = 20\pi^2 \left(\frac{\pi f d}{c} \right)^4 \qquad (4.9)$$

where

d = Loop diameter

c = Velocity of light ($\approx 3 \times 10^8$ m/sec)

The radiation resistance of a loop of wire, 1 m^2 in area, at 10 KHz, is equal to only 4×10^{-14} ohms. Such low values indicate that, over the frequency range of interest to the power subsystem designer, the physical dimensions of the wiring preclude it from being either a good source of far field interference or a good receiving antenna. This statement assumes, of course, that at least a minimum amount of filtering, such as feedthrough capacitors, has been provided for high frequency (500 KHz and above) interference reduction.

4.4 FILTER DESIGN

The input power line filter is a major element in the design of high efficiency, aerospace power processing equipment. It's primary function in dc operated equipments is to attenuate the high frequency alternating current components, generated by internal PPU switching action, to within specified limits of conducted interference or ripple current (i_r) at the equipment input terminals. To prevent degradation of PPU performance, the filter, consisting generally of a low frequency, passive (L-C) network, must also exhibit sufficient damping to audio frequency line disturbances (ripple voltage, v_r) so that resonant peaking at the filter output is properly controlled, and suppress input voltage transients (v_t). When properly designed for the specified degree of electromagnetic interference (EMI) control, the input filter can account for a large portion of total circuit weight in switching-type power processing units (>30% for 100 watt, 28 Vdc filter) since the series-connected filter inductance(s) must be rated for maximum input current and the shunt-connected output capacitance requires high ac current handling capability.

Input filter transient response under PPU turn-on, load switching, and fault clearing conditions not only impacts on unit performance but also affects EMI characteristics and overall power system component compatibility. The current inrush during equipment turn-on is especially significant. High values of current are typically drawn by a PPU due to the charge-up of input filter capacitances including the high frequency input line feedthrough filters, the latter provided for control of mega-hertz range, PPU generated switching spikes. The resulting high charging rates developed in input lines can induce interference in adjacent conductors.

The method for effecting PPU on/off control, either by external RPC action or by internal PPU oscillator control, greatly influences the circuit inrush characteristic. With the latter approach, the PPU input filter is pre-charged, considerably reducing the turn-on current transient. In systems utilizing external on/off control of load PPUs, the PPU input filter energy storage characteristics will also affect RPC fault clearing requirements.

In this section, the effect of EMI requirements on power processing unit characteristics, both static and dynamic, are examined. A procedure for PPU input filter design (presented in Appendix B) was developed and calculations performed to obtain:

- Input filter weight as a function of conducted interference (attenuation) requirements and power level, holding continuous and transient susceptibility requirements fixed under typically specified conditions, and
- Typical input filter transient characteristics under turn-on, load switching, and fault clearing conditions.

In the development of parametric weight data, the effect of dc input voltage levels was assessed as was the improvement achievable utilizing two-section rather than single-section filter designs. The parametric weight curves generated are related to typical EMI requirements as given in military specifications (MIL-STD-461A and TOR-1001(2307)-4).

For the ac input PPU configurations examined in this study, in which conversion and/or regulation functions are provided after input transformation and rectification (or rectification only), parametric function data for the input filter (or, properly, rectifier filter) were generated for both single and three-phase input cases. In the former, the rectifier filter is sized so as to present a specified circuit power factor to the ac source (0.85 lagging at full load) and, so designed, provides sufficient attenuation to high frequency switching components generated by output switching converter and/or regulator action. In the three-phase input case, the rectifier filter design was based on providing the specified degree of attenuation to high frequency switching currents and, so designed, in the selected three-phase PPU configurations, a high source utilization factor is inherently afforded.

A proper comparison of ac versus dc input filter impact on PPU characteristics requires an examination of ac input PPU configurations other than the essentially harmonic-free type considered in this study; i.e., circuit configurations in which harmonics are not generated and fed back into the ac power system. Typical circuits are those utilizing time modulation of the ac input or phase controlled rectification. These circuits act as non-linear loads, generating undesired harmonic currents which when fed back into the power system introduce waveform distortion in the distribution network. Passive input filter networks providing the requisite power factor correction for such circuits will, in general, be heavier than their counterparts in the PPU configurations considered in this study. Further work in this area is required to obtain quantitative comparisons of the filter weight impact. Additional discussion of ac input filter design is presented in Paragraph 4.4.2.

4.4.1 DC Input Filter Design and Performance Characteristics

To obtain parametric weight information on PPU input filter networks, as functions of both conducted interference requirements and power level, a function design procedure, applicable to switching regulator-type filter loads, was developed using fundamental network equations and simplifying (but practical) design assumptions. The procedure yields, for given values of input current attenuation, filter load and dc input voltage level, the element values for a single section L-C network and the information necessary for inductor design and capacitor selection so as to obtain total filter (component) weight. Included is an equation with which accurate estimations of inductor weight can be obtained without laborious iterative calculations (Reference 39). Constant values of filter network efficiency and load switching frequency are assumed and susceptibility requirements, both conducted and transient, are fixed at typically specified levels. The detailed procedure, including assumptions, is presented in Appendix B along with a similar development for a two-section filter network. The latter offers weight and performance advantages over a single section network when high input current attenuation is required.

Single section input filter specific weight data are presented in Figure 4.14 for both 28 and 115 Vdc input designs. The curves, plotted for three discrete input current attenuation values, 0.1, 0.01, and 0.001 (-20, -40, and -60 db), cover a filter load range of 30 to 300 watts. Fixed values of load switching frequency and filter efficiency, 10 KHz and 98%, respectively, were assumed.

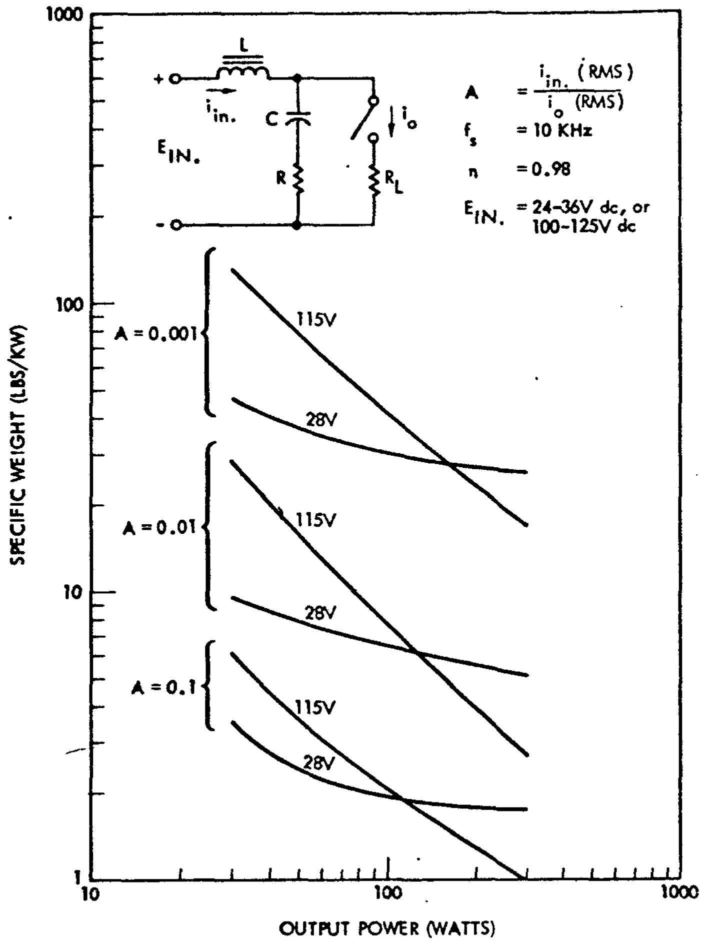


Figure 4.14. Single Section Filter Weight

In presenting input filter weight data in this manner, it should be noted that input voltage level is compared at a constant attenuation value and, therefore, at a given power level, the ac input ripple current in 115 Vdc cases is considerably lower than that obtained when considering 28 Vdc filters. As an example, consider a 100 watt filter with an attenuation of 0.01. Reference to the appropriate curves yields figures of 6.5 and 8 lbs. per kw, respectively, for the 28 and 115 Vdc designs. In the former, the input ripple current is approximately 18 ma, rms (based on design equations - Appendix B); the latter 1.8 ma, rms. To reduce input ripple in the 28 Vdc filter to that obtained in the 115 Vdc case, a value within the narrowband conducted ripple limits of MIL-STD-461A, Notice 4, and TOR-1001(2307)-4, an attenuation factor of 0.001 is required. The specific weight of a 28 Vdc filter, so designed (see Figure 4.14), is 30 lbs. per kw, almost four times the weight of the 115 Vdc filter.

As power level is increased, the weight difference between 28 and 115V designs is even more pronounced. Comparing 300 watt designs with equivalent input ripple current values; e.g., a 115 Vdc filter with A = 0.01 and a 28 Vdc design with A = 0.001, results in respective specific weights of 2.7 and 26 lbs. per kw, almost a factor of ten difference.

Narrowband conducted interference limits in all EMI specifications are independent of equipment power rating, a crucial point that impacts greatly on input filter weight in high power regulator or converter equipments. To illustrate the effect on filter weight of this type of characterization, filter designs were calculated for 100, 300, and 1,000 watts, +28 Vdc, PWM inverter type PPUs, providing identical input ripple current values of one-half the allowable MIL-STD-461A, Notice 3, value at 10 KHz. The respective filter current attenuation values required are -40, -50, and -60 db and the computed corresponding filter weights are 0.77, 4.35, and 28.7 pounds. These filter weights, comprise, respectively, 32, 48, and 68 percent of total part weight in the three Type 1 PPU designs. It should also be noted that the MIL-STD-461A, Notice 3 specification reflects the least required attenuation requirements of those evaluated in this study.

To relate the data presented in the curves of Figure 4.14 to various military specification requirements on narrowband conducted interference at 10 KHz, the maximum filter power levels, beyond which individual specification limits are exceeded, were calculated for the three attenuation values of Figure 4.14. The results given in Table 4.2 for the individual requirements of different issues of MIL-STD-461A and for TOR-1001(2307)-4, demonstrate the wide variation encompassed in currently applied EMI specifications. For example, a 28 Vdc filter providing 60 db of attenuation will meet the specification requirements of Notice 1, MIL-STD-461A for filter loads up to 50 watts, while the designs for loads up to 2.28 KW will be within the Notice 3 requirement of the same specification.

Table 4.2. Maximum Filter Power Versus Attenuation

	Maximum Filter Load, Watts						Allowable Input Ripple Current at 10 KHz ma, RMS (I_{in}, ac)
	28 Vdc			115V			
	0.1	0.01	0.001	0.1	0.01	0.001	
MIL-STD-461A, Notice 1	0.5	5	50	5	50	500	0.89
" , Notice 3	23	228	2280	223	2230	22300	40
" , Notice 4	2.3	23	228	22	223	2230	4
TOR-100(2307)-4	2.8	28	280	27	273	2730	4.9

Two-section L-C input filter designs, also examined in this study, can offer significant weight advantage in applications requiring a high degree of ac ripple current attenuation. Calculations for a 28 Vdc, 100 watt, two-section filter, based on the design procedure outlined in Appendix B, show a weight advantage over a single-section design for values of attenuation in excess of -55 db. The two-section filter offers further advantages in providing:

- A controlled resonant peaking in the filter output voltage (important in maintaining voltage swing within component and circuit tolerances)
- Reduced PPU inrush current and startup transient
- High filter efficiency.

Figure 4.15 presents filter specific weight data for several design cases plotted as a function of conducted interference level. The latter is expressed as the percentage value of rms input ripple current to the peak current, Io, drawn by the switching load. The specific weight variation for the following cases are illustrated:

- 28 Vdc, 100W - single-section filter with efficiency of 98%
- 28 Vdc, 100W - single-section filter with efficiency of 97%
- 28 Vdc, 30W - single-section filter with efficiency of 98%
- 115 Vdc, 100W- single-section filter with efficiency of 98%
- 28 Vdc, 100W - two-section filter with efficiency greater than 98%

The weight advantage of a two-section design for high attenuation requirements is readily seen.

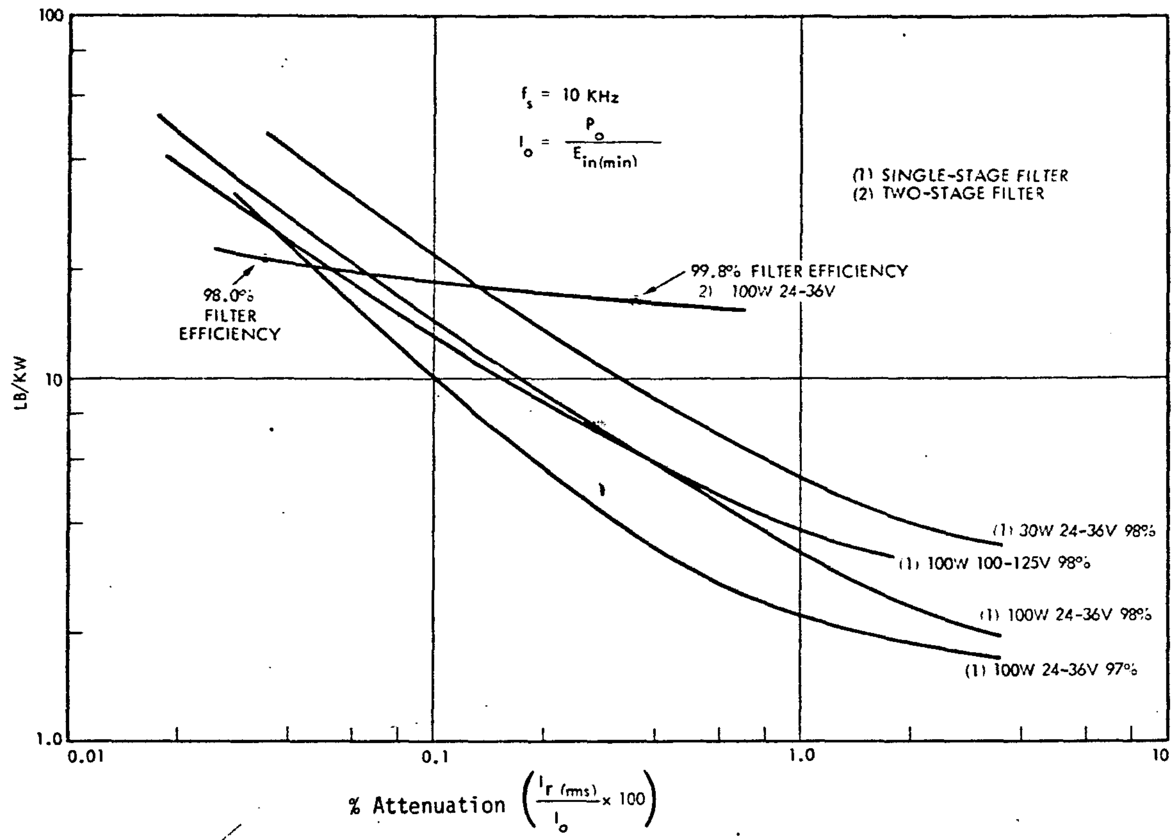


Figure 4.15. Filter Weight

In comparing the 115 Vdc filter with the 28 Vdc cases, it must be noted that equivalent attenuation values yield different values of input ripple current and, therefore, different values of Ir/Io. For example, for Ir/Io = .001, the attenuation and ripple current in the 28 Vdc cases are, respectively -51 db and 5 ma. In the 115 Vdc case, an attenuation of -51 db yields a ripple current of 0.5 ma and a corresponding Ir/Io value of 0.0005.

All dc input filters calculated in this study, as previously noted, were also designed to meet identical conducted and transient susceptibility requirements. The MIL-STD-461A limits were selected, as follows:

- Conducted susceptibility - lesser of 10% of E_{in} (DC) or 3 volts, rms, 30 Hz to 1.5 KHz; decreasing to greater of 1% E_{in} DC or 1 volt, rms at 50 KHz
- Transient susceptibility - lesser of 2 E_{in} or 100 volts for 10 µsec.

Also reflected in all designs are typical space-use, component derating factors for filter elements. For example, filter output capacitors are derated 60 percent in voltage and 50 percent in ac current at 85^{o}C.

It should be noted here that the baseline input filter function data utilized in generating PPU performance characteristics (Section 3.1) was based on attenuating to an ac input ripple current level of 1 percent of the full load dc input current. The corresponding 10 KHz attenuation afforded amounts to -31 db and -25 db, respectively, in 28 and 115 Vdc cases.

4.4.2 AC Input Filters

As noted in the introductory paragraphs of this section, the ac input, PPU circuit configurations evaluated in this study are those involving rectification (or transformation-rectification) of the ac input waveform, followed by high frequency conversion and/or regulation. In this approach, the design of the input filter function becomes one of the proper design of the ripple filter (input rectifier filter), such that specified requirements on both input current ripple reduction (i.e., conducted interference resulting from converter and/or regulator high frequency switching action) and circuit input power factor are met. When compared with configurations utilizing either time modulation of the input ac waveform or phase controlled rectification for output control, the selected approach yields the lowest input filter weight and, for this reason, represented the preferred ac input, PPU configuration in this study.

AC input time modulation circuits have seen limited usage, to date, in aerospace power systems, these being primarily in aircraft and missile applications. An accurate assessment of ac input filter weight impact in this class of PPU circuit configurations requires knowledge of the source impedance spectrum and harmonic modeling of the ac source and distribution system, a highly involved task, especially in power systems utilizing central inversion. An approximate design procedure for input filter design in such circuit configurations has been developed and is given in Reference 40. Further work is required in this area to obtain the parametric data necessary for quantitative assessments.

5.0 CANDIDATE SYSTEMS EVALUATION

In accordance with the study procedure outlined in Section 1.0, we are now ready to use the results of the component analyses presented in Section 3.0 to define and evaluate candidate power processing, distribution and control subsystems which meet the vehicle and electric power generation subsystem interface requirements derived in Section 2.0. Our evaluation will be based on estimates and analyses of reliability and safety features, dynamic performance characteristics, total effective weight, and estimated development and acquisition cost.

5.1 CANDIDATE CONFIGURATIONS

Candidate configurations are defined in terms of the following configuration input variables:

- Equipment redundancy
- Transmission voltage and frequency
- Distribution voltage and frequency
- Control, display and protection (CDP) method
- Checkout and maintenance procedures

The checkout and maintainance procedure is intimately related to the CDP method and the equipment redundancy. It has only minor effects on system weight, cost, and dynamic performance. For purposes of this study program we have assumed that equipment required for control and display is also sufficient for checkout and maintainance and that the calculated reliability is unaffected by the type of checkout and maintainance procedure which is finally selected for a specific vehicle system. We therefore have omitted checkout and maintainance from all configuration trade studies.

The remaining configuration variables are basically independent of each other except for the fact that central power conditioning equipment is required if the distribution voltage and frequency is not the same as the transmission voltage and frequency. Because of this independence, subsystem configuration trade studies may be conducted for one variable at a time.

This does not mean that the weight and cost of the CDP equipment for example will be the same regardless of the redundancy level or transmission and distribution voltage which are used, but merely that each of the configuration variables may be selected individually without regard to the selected value of the other variables. In other words, a given transmission/distribution voltage will be best no matter what redundancy or CDP method is chosen, a given CDP tradeoff applies to all redundancies and voltage levels, etc.

The candidate PDC subsystem configurations for the four requirements models defined in Section 2.3 are listed in Table 5.1. For each, only one redundancy level which meets the vehicle requirements was considered. Other redundancy levels require proportionate changes in equipment quantities. Dual redundancy for Space Station modules has been assumed because the crew can move to an unfailed module for survival. Power transmission to each module is quad redundant. The difference between the conventional CDP method which uses toggle switches and wiring and a multiplex data bus system was evaluated only for the Shuttle model because of the clear advantage of the data bus system over hard wiring as vehicle dimensions and equipment count increase making a data bus the clear choice for the Space Station.

Table 5.1. Candidate PDC Configurations

Config. No.	Application: Station	Application: Shuttle	Application: Aircraft	Redundancy (Note 1)	Transmission Voltage (Note 2)	Distribution Voltage (Note 2)	CDP Method
1	x	x		4	28 Vdc	28 Vdc	Mux.
2	x	x	x	4	115 Vdc	115 Vdc	Mux.
3	x	x	x	4	115/200 Vac	115/200 Vac	Mux.
4	x	x	x	4	115/200 Vac	28 Vdc	Mux.
5		x		4	28 Vdc	28 Vdc	Convent.
6		x		4	±28 Vdc	±28 Vdc	Convent.
7			x	4	270 Vdc	270 Vdc	Mux.

Notes: 1 - Except for dual redundance within Space Station modules.
2 - All ac is 400 Hz sinewave.

Basic single channel block diagrams for the candidate configurations are shown in Figures 5.1, 5.2, and 5.3. The power processing, distribution and control equipment which is required for each candidate PDC configuration depends on the generator output voltage and the complete set of load utilization equipment which must be supplied. We have limited our study to the four load sets derived in Section 2.3 representing Space Station, Shuttle Orbiter, commercial and military aircraft installations. In each case we have selected the simplest possible mechanization of the PDCS which will deliver power at the desired voltage to each load unit of the respective load requirements model. In order to highlight the differences due to the basic configuration variables, we have made a number of design decisions and assumptions which apply to all candidate PDC configurations for all reference load requirements models. They may be summarized as follows:

- All electronic loads have individual PPUs which are used for load turn on/off and provide input current limiting.
- All distribution wires are protected by RPCs or fuses.
- Fractional horsepower motors are supplied from the ac transmission lines or a central 3Ø inverter through solid state RPCs.
- All loads are grounded at the nearest power distribution bus.
- The vehicle structure is used as ground return path for transmission.
- Fuses are assumed to have negligible failure rates and weight and hence are not included in the equipment list.
- No separate computer or display panel is required for configurations using a data bus.
- For each DIU, input power is supplied from every channel through a protected OR network.
- Except for motors, all loads requiring less than 500W input power use dc or single-phase ac power.

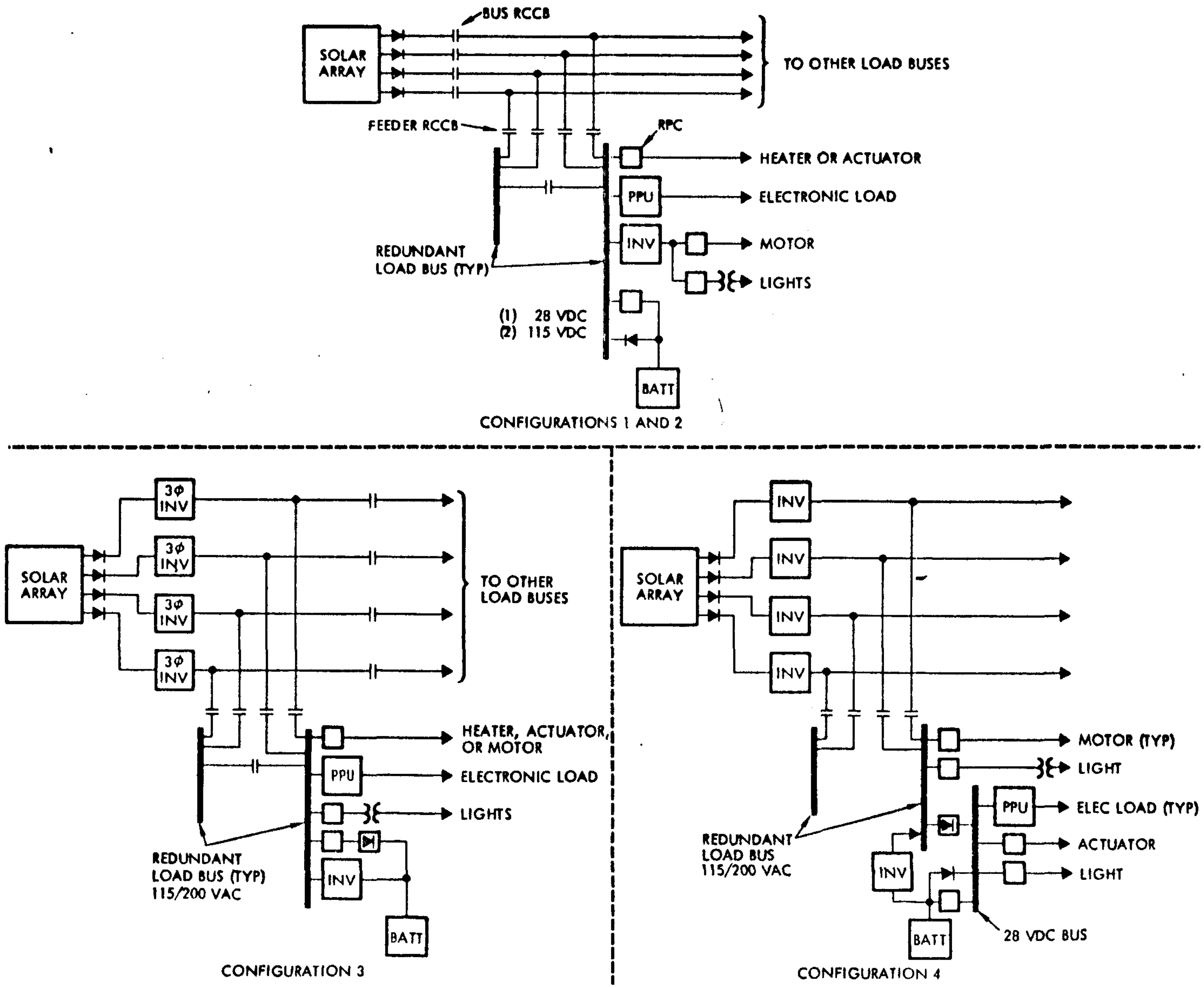


Figure 5.1. Candidate Configurations - Space Station

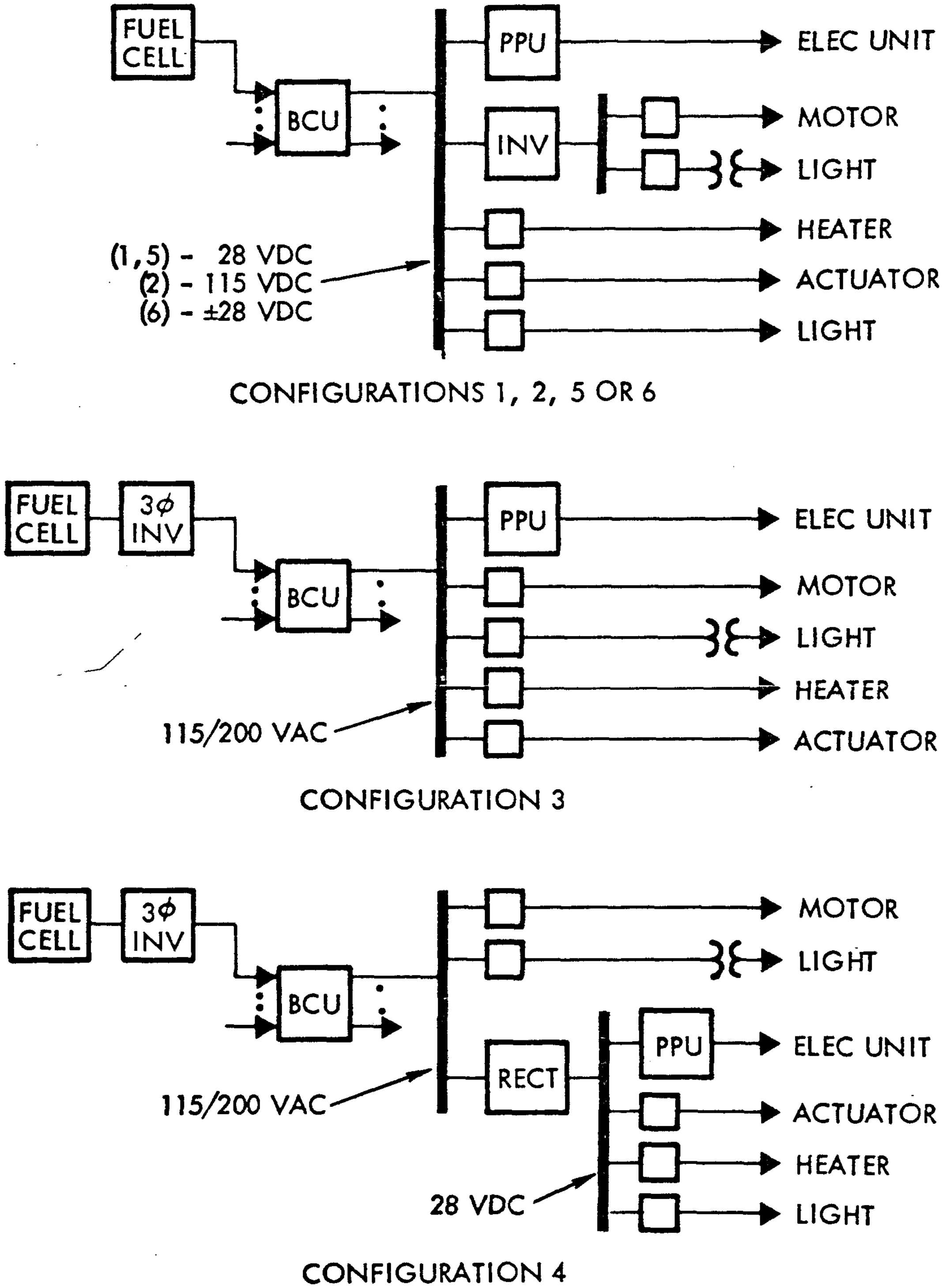


Figure 5.2. Candidate Configurations - Shuttle Orbiter

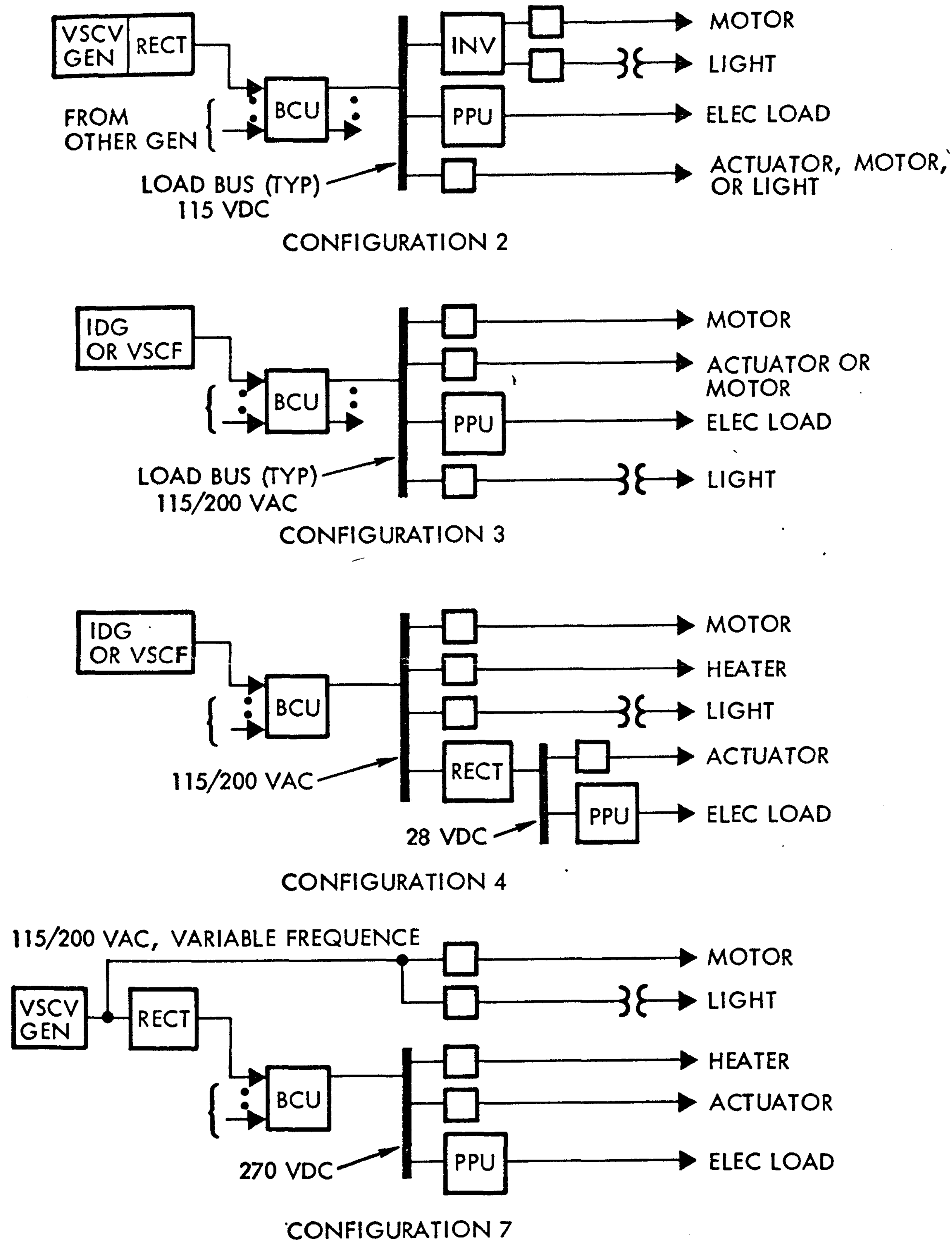


Figure 5.3. Candidate Configurations - Aircraft

The PDC equipment required to implement the four candidate PDC configurations considered for the Space Station is listed in Table 5.2 for each type of Station module. We have assumed that power is generated by two solar arrays on opposite ends of the string of modules and is transmitted to dual redundant load buses in each module as shown in Figure 2.12. Each of the four transmission lines can carry 1/2 of the maximum current output of one solar array.

Table 5.2. PDCS Equipment List - Space Station Requirements

Item	Quantity		
	Conf. 1 & 2	Conf. 3	Conf. 4
Power Module			
Transmission Lines (120 ft ea)	4	12	12
Bus Contr. RCCB	8	4 (3Φ)	4 (3Φ)
Feeder RCCB	13	13 (3Φ)	13 (3Φ)
Inverter - 3Φ	2	6	6
Rectifier	-	2	2
PPU - Analog Load	40	40	40
PPU - Digital Load	50	50	50
RPC - DC	78	-	78
1Φ AC	25	100	25
3Φ AC	12	14	14
Crew Module			
Transmission Line (80 ft ea)	4	12	12
Bus Contr. RCCB	8	8 (3Φ)	8 (3Φ)
Feeder RCCB	13	13 (3Φ)	13 (3Φ)
Inverter	2	2	2
Rectifier	-	2	2
PPU - Analog Load	68	68	68
PPU - Digital Load	22	22	22
RPC - DC	174	-	174
1Φ AC	-	174	-
3Φ AC	10	10	10
Lab Module			
Feeder (50 ft ea)	4	12	12
Feeder RCCB	5	5 (3Φ)	5 (3Φ)
Inverter	2	2	2
Rectifier	-	2	2
PPU - Analog Load	20	20	20
PPU - Digital Load	40	40	40
RPC - DC	36	-	84
1Φ AC	58	82	-
3Φ AC	-	10	10
Research Appl. Module (RAM)			
Feeders (50 ft ea)	4	12	12
Feeder RCCB	5	5 (3Φ)	5 (3Φ)
Inverter - (3Φ, Sq. Wave)	2	-	-
Rectifier	-	-	2
PPU - Analog Load	8	8	8
PPU - Digital Load	4	4	4
RPC - DC	33	-	33
1Φ AC	-	26	-
3Φ AC	4	11	4

The PDCS equipment to mechanize the six candidate configurations for the Shuttle Orbiter is listed in Table 5.3 which also gives typical maximum power ratings for each PDC unit. The equipment quantities and power ratings are consistent with the load model of Table 2.14 and the above PDCS design assumptions.

Table 5.3. PDCS Equipment List - Shuttle Orbiter

Function	Item	Quantity	Typ. Rating (per unit)	Configuration 1	2	3	4	5	6
Central Conv. and Transmission	Cable (1 or 3 wires)	16	2KW	x	x	x	x	x	x
	Bus Control Unit	4	-	x	x	x	x	x	x
	Main Bus RCCB	10	10KW	x	x	x	x	x	x
	Feeder RCCB	16	2KW					x	x
	Solid State RPC	16	2KW	x	x	x	x		
	Central Inverter	4	10KW			x	x		
Distribution and Local Power Conv.	Cable (two-wires)	5K ft	#22	x	x	x	x	x	x
	Analog Load PPU	106	100W	x	x	x	x	x	x
	Digital Load PPU	97	50W	x	x	x	x	x	x
	Inverter	14	1KW	x	x			x	x
	Transformer-Rectifier	16	2KW				x		
	Power Distribution Unit	16	-	x	x	x	x	x	x
	Solid State RPC	287	50W	x	x	x	x		
	RCCB	287	50W					x	
	RCCB	574	25W						x
Control and Display	Digital Interface Unit	16	3W	x	x	x	x		
	I/O Cont. Unit	4	3W	x	x	x	x		
	C/D Panel	2	-					x	x
	Power Supply	4	150W					x	x
	Meters	8	-					x	x
	Manual Control Switch	516	-					x	x
	Control & Sense Wires	80K ft	#24					x	
	Control & Sense Wires	120K ft	#24						x

The list of PDC equipment required for the typical commercial transport and B-1 type military aircraft is given by Tables 5.4 and 5.5. We have assumed that power is transmitted to a main bus control unit (BCU) (located near the center of the aircraft) from each of the four engine pad mounted generators. The generators may be paralleled or cross strapped within the BCU,but faults within the BCU which can fail all four main buses are considered not possible because of the physical design of the bus structure. Feeder lines go from each of the four main buses to local load buses or individual loads throughout the vehicle. All relays and circuit breakers are remotely reset. Common protective features such as differential current protection, reverse current protection, over and undervoltage protection have been ignored because they do not significantly influence the selection of the PDC configuration.

Table 5.4. PDC Equipment List - Commercial Aircraft

Function	Item	Qty	Typ. Rating per Unit	Notes
Transmission	BCU			
	Gen. Relay	4	90 Kw	Config. 3 & 4 only
	Bus Tie Relay	6	90 Kw	
	Feeder CB	20	20 Kw	
	Gen. Cable	4	90 Kw	50 ft ave. length
	Main Feeder Cables	20	20 Kw	100 ft ave. length
Distribution & Local Conversion	Pwr Dist. Unit			
	RCCB	16	5 Kw	Config. 1 & 2 only
	Solid State RPC	466	100 w	
	Solid State RPC	16	5 Kw	Config. 3 & 4 only
	Cables (two-wire)	7,000 ft	#22	
	Inverter	4	15 Kw	Config. 1 & 2 only
	Transf.-Rect.	4	20 Kw	Config. 4 only
	PPU - Analog Loads	60	100 w	
	PPU - Digital Loads	60	50 w	
Cont. & Display	Digital Proc. Units	24	3 w	
	Digital I/O Unit	2	5 w	
	Illum. Toggle Switch	46	2 amp	
	Wiring	10,000 ft	#26	
	Meters	4	-	

Table 5.5. PDC Equipment List - Military Aircraft

Function	Item	Qty	Typ. Rating per Unit	Notes
Transmission	BCU			
	Gen. Relay	4	100 Kw	Config. 3 & 4 only
	Bus Tie Relay	6	100 Kw	
	Feeder CB	20	20 Kw	
	Gen. Cable	4	100 Kw	
	Main Feeder Cables	20	20 Kw	
Dist. & Local Pwr. Conversion	Pwr Dist. Unit			
	Solid State RPC	8	2 Kw	
	Solid State RPC	190	200 w	
	Inverter	12	4 Kw	Config. 1 & 2 only
	Transf.-Rect.	12	15 Kw	Config. 4 only
	PPU - Analog Load	42	100 w	
	PPU - Digital Load	120	100 w	
	PPU - Special	8	20 Kw	
	Pwr. Dist. Lines	10,000ft	-	
Cont. & Display	Digital Proc. Unit	20	3 w	
	Digital I/O Unit	4	5 w	
	Illum. Switches	30	2 amp	
	Meters	8	-	
	Wiring	5,000ft	#26	

5.2 SUBSYSTEM RELIABILITY AND SAFETY

As pointed out in Section 2.1 there are three basic reliability and safety requirements for the power processing, distribution and control subsystem of manned spacecraft, namely:

1. The PDCS reliability must be commensurate with the reliability of the load equipment and the EPGS.
2. The vehicle must be operational or safe after one or more PDCS failures as specified.
3. There shall be no hazard to personnel due to electric shock, fire or localized structural damage.

To meet these requirements every candidate PDC configuration incorporates the following:

1. Equipment redundancy
2. Automatic failure isolation and overload protection
3. Physical isolation of redundant equipment to prevent failure propagation due to fire or mechanical damage
4. Adequate insulation of all wiring, terminals, etc. to avoid corona and shock hazard to personnel.

After the vehicle design and the power distribution network are completely defined, the vehicle failure probability S_s can be computed from the single channel PDCS and load failure probability S_L and the EPGS failure probability S_G as outlined in Section 2.1. In practice simplifying assumptions must be made to obtain the PDCS failure probability S_p from component failure rate assessments. Since the failure probability of any one component or element of a subsystem must be small compared to subsystem failure probability the component failure rates λ_i or failure probabilities S_i are simply added to get subsystem failure probability.

During this study program failure rates were calculated for typical load power processing units based strictly on component count. Reliability data for switchgear and power generation equipment was obtained from life test requirements in specifications or from vendor catalogs. The failure probabilities obtained in this manner may admittedly be far from what will ultimately be achieved for actual vehicles. The numerical values, however, are not especially significant for this generalized study since the objective to compare alternate PDCS configurations can be achieved as long as the same failure rates are used for like components in different PDCS configurations. We therefore will restrict all further consideration to possible major differences in system safety and reliability with the understanding that where failure rates or probability figures are given only relative magnitudes when compared to other configurations have any significance.

5.2.1 Personnel Hazard

High voltage power distribution is potentially more dangerous than low voltage because it can produce larger currents through the human body. Since a current of 1 ma is perceptible and 150 ma may be lethal, all wiring and exposed terminals must be insulated even in 28 volt systems. The impedance of the human body may be as low as 500 ohms. Thus there is no real disadvantage in high voltage distribution since insulation must be provided in every instance.

Corona can damage insulation and should be prevented. Since corona can appear at lower voltages in ac circuits, dc distribution provides some extra margin.

5.2.2 Space Station PDCS Reliability

A qualitative comparison of PDCS reliability for different candidate configurations can be obtained by comparing the PDCS components required for each candidate. Figure 5.4 gives simplified single channel reliability block diagrams for each configuration. Since the reliability of the solar array and the digital interface and data bus equipment for multiplexing are the same for all configurations they are omitted from the analysis. The major differences between configurations which affect their reliability are the type of switchgear which is used and whether central inverters and motor drive inverters are required. Table 5.6 gives relative values of component failure rate based on a failure rate of 1 for solid state remote power controllers since they have a mean-time-to-failure

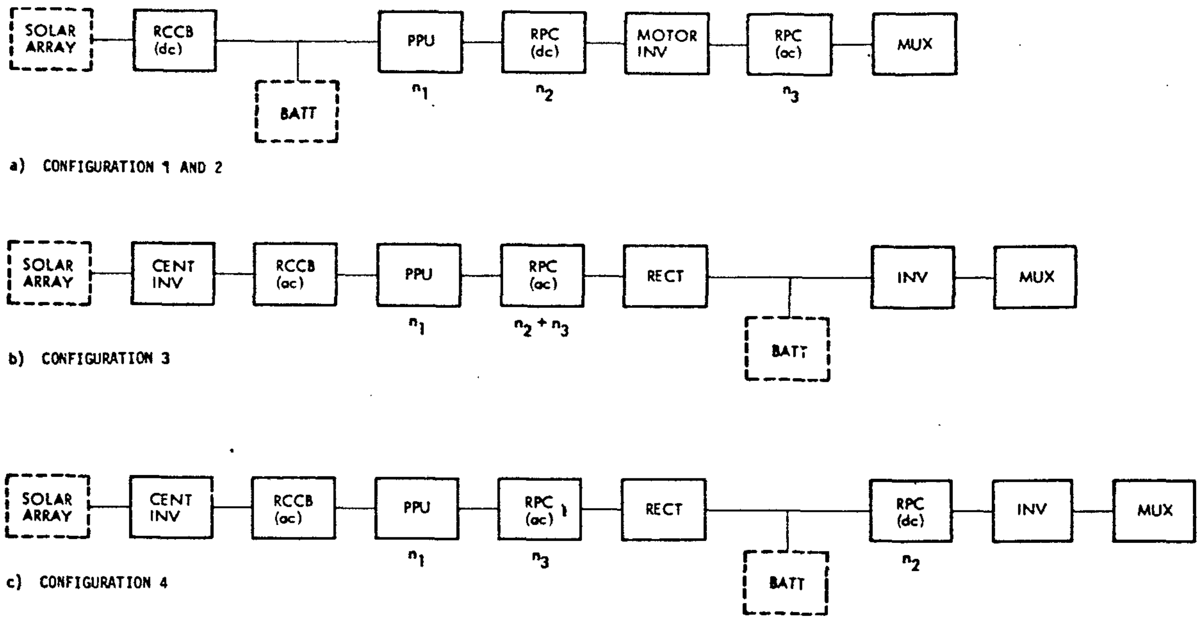


Figure 5.4. Reliability Block Diagrams for Space Station PDCS

design goal of 10^6 operations corresponding to a failure rate λ of 1 per 10^6 operations. The figures of Table 5.6 are gross estimates but agree with the rough calculations of Section 3.0. The subsystem failure probability per channel is determined largely by the power processor reliabilities because of the large number of separate units.

Table 5.6. Space Station PDCS Failure Rate - Power Module

	PDCS Configuration (Table 5.1)			
	1 28 Vdc	2 115 Vdc	3 100/ 200 Vac	4 Hybrid
No. of Units per Channel				
Central Inverter	-	-	1	1
Motor Inverter	1	1	-	-
RCCB	2	2	6	6
PPU	45	45	45	45
RPC - dc	39	39	-	39
ac	30	30	86	30
Component Failure Rate				
Central Inverter	-	-	20	20
Motor Inverter	2	2	-	-
RCCB	10	15	5	5
PPU	3	3	4	3
RPC - dc	1	1	1	1
ac	1	1	1	1
Channel Failure Rate	226	236	316	254

Note: Failure rate in parts per 10^6 hours.

5.2.3 Space Shuttle PDCS Reliability

Reliability block diagrams for the Shuttle Orbiter are identical to those for the Space Station except for the type of power source and the use of illuminated toggles instead of the multiplex data bus in configurations 5 and 6. Equipment count and component failure rates used to obtain comparative single channel PDCS failure estimates are given in Table 5.7. Note that the data bus or hard wired control functions have been included. Failure rates are expressed as relative value but can also be interpreted as failures per 10^6 hours of operation.

Table 5.7. Shuttle Failure Rates per PDCS Channel

	PDCS Configuration (Table 5.1)					
	1	2	3	4	5	6
Component Fail. Rate						
Main Circuit Breaker	10	15	10	10	10	10
Feeder Circuit Breaker	10	15	10	10	10	10
PPU	3	3	4	3	3	3
Sine Wave Inv.	-	-	20	20	-	-
Squ. Wave Inv.	2	2	-	-	2	2
Rectifier	1	1	-	1	1	2
RPC - dc	1	1	-	1	1	1
ac	1	1	1	1	1	1
Data Bus Unit	20	20	20	20	-	-
Pwr Supply	-	-	-	-	10	10
Toggle Switch	-	-	-	-	5	6
No. of Units per Channel						
Main CB	2	2	6	6	2	4
Feeder CB	4	4	12	12	4	8
PPU	50	50	50	50	50	50
Sine Wave Inv.	-	-	1	1	-	-
Squ. Wave Inv.	2	2	-	-	2	2
Rectifier	4	4	-	4	4	4
RPC - dc	70	70	-	69	70	140
ac	12	12	84	15	12	24
Data Bus Unit	4	4	4	4	-	-
Pwr. Supply	-	-	-	-	1	1
Toggle Switch	-	-	-	-	140	140
PDCS Channel Fail. Rate	362	410	564	518	930	870
Fuel Cell (for Ref.)	30	37	37	37	30	35

Note: Failure rate in parts per 10^6 hours.

5.2.4 Aircraft Power System Reliability

Actual airline experience indicates that the failure rate of power generation subsystem components lies between 0.1 and 0.5 failures per 1,000 hours. Since the EPGS equipment differs for the four candidate configurations we will include the EPGS equipment in our reliability comparison. We will only consider commercial transport aircraft since such a large part of the power used aboard military aircraft supplies payloads whose power processing requirements are undefined. Table 5.8 lists the equipment failure rates which we have chosen for the comparative estimate of single channel power system failure rate. Failure rates

Table 5.8. Aircraft Power System Failure Rate

	PDCS Configuration (Table 5.1)			
	2 115 Vdc	3 115 Vac	4 115 Vac/28 Vdc	7 270 Vdc
Component Fail. Rate				
CSD	-	370	370	-
Generator	200	270	270	200
Generator Controls	100	300	300	100
Rectifier	5	-	5	5
RCCB - dc	15	5	5	15
RPC - dc	1	1	1	2
ac	1	1	1	1
Inverter	4	-	-	4
PPU	3	4	3	3
Data Bus Unit	20	20	20	20
Toggle Switch	5	5	5	5
No. of Units per Channel				
CSD	-	1	1	-
Generator	1	1	1	1
Rectifier	1	-	2	1
RCCB	7	21	21	7
RPC - dc	50	-	42	50
ac	12	62	20	12
Inverter	1	-	-	1
PPU	20	20	20	20
Data Bus Unit	5	5	5	5
Toggle Switch	12	12	12	12
Subsystem Fail. Rate/Channel				
EPGS	305	940	940	305
PDCS	391	407	397	391
EPS Fail Rate/Channel	696	1335	1337	696

Note - Failure Rate = Failures per 10^6 hrs of operation.

for the alternator and constant speed drive (CSD) were obtained from reference (2) which is based on Eastern Airlines Fleet Reliability Report for January 1969 and hence may be somewhat conservative. Subsystem and electric power system (EPS) failure rates do not include internal redundancies and back-up modes and hence should be used only for comparison of alternative system configurations.

5.3 DYNAMIC PERFORMANCE COMPARISON

Dynamic performance characteristics represent a significant criterion for evaluation of candidate PDCS configurations since they affect the electromagnetic compatibility of the PDCS with critical load equipment, influence the required transient voltage rating of electronic components, and determine equipment requirements to enable paralleling or substitution of redundant power distribution channels. Various aspects of the transient and steady state interference voltages and currents at equipment input terminals were discussed in Section 4.0. Using this material as background we shall now consider how dynamic performance differs for the various candidate PDCS configurations. Comparisons will be based on the following:

- PPU filter weights for specified conducted interference levels
- Transient voltage at equipment input terminals due to line current transients
- Equipment and power requirements to enable paralleling of redundant channels

Our analysis is kept sufficiently simple to yield generally applicable results and is not aimed at predicting interference voltage or current magnitudes throughout any of our baseline electric power systems.

5.3.1 Effect of Voltage and Frequency on PPU Filters

As discussed in Section 4.1, EMI specifications require that the steady state power line interference current due to PPU action not exceed specified values over the frequency range from 30 Hz to more than 10 MHz. The maximum allowable value of interference current is independent of distribution voltage and power drawn by the load equipment since the effect on sensitive load equipment or signal lines depends only on interference current magnitude and frequency and not on the power frequency current which may be orders of magnitude larger than the interference component i_r.

Calculated weights of single section line filters for power processors switching at 10 KHz are plotted as a function of the 10 KHz ripple current drawn from the power line in Figure 5.5. For ac input the filter must be designed to also provide a power factor of 0.85 at the power frequency of 400 Hz which solely determines the filter weight. Note that for all levels of power line interference the filter weight is significantly less for a line voltage of 115 Vdc.

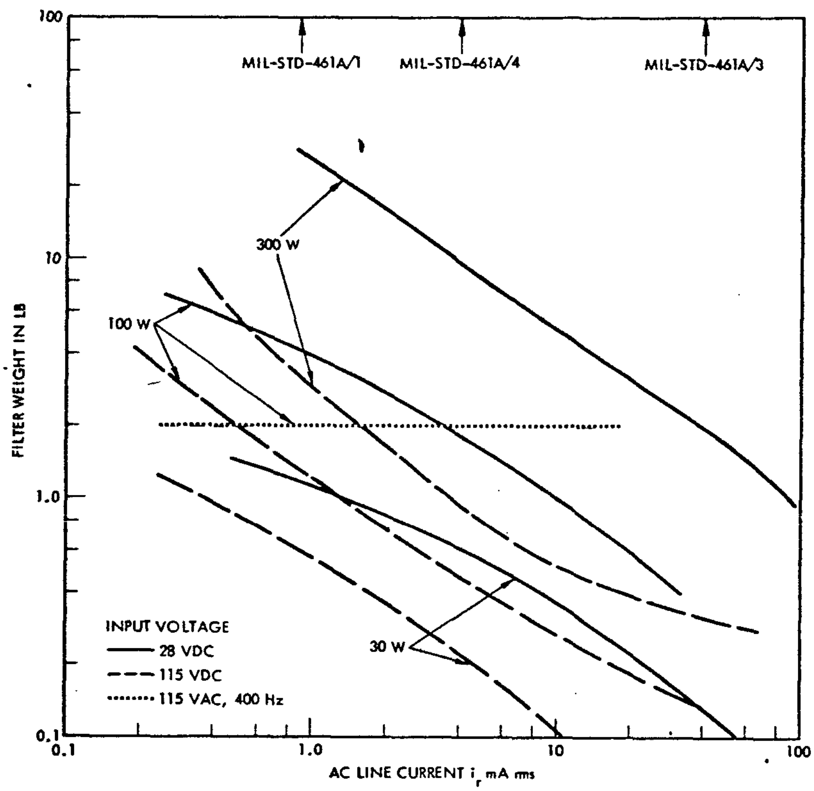


Figure 5.5. Weight of Single Section Power Line Interference Filters

5.3.2 Coupling of Transients

Sudden changes in current in a power line will cause a transient voltage to appear in nearby circuits due to H-field or E-field coupling. This situation was analyzed in Section 4.3 where it was shown that the voltage in circuit 1 due to a current of amplitude i_{d2} and frequency f_2 in circuit 2 is

$$v_{d1} = M \frac{di_{d2}}{dt} \left(\frac{R_{L1}}{R_{S1} + R_{L1}} \right) \tag{4.6}$$

Likewise the capacitively coupled voltage v_{c1} across an impedance in circuit 1 due to a voltage v_{d2} in circuit 2 is given by

$$v_{c1} \approx v_{d2} \frac{C_{ww}}{C_{ww} + C_L} \tag{4.8}$$

Consider the case where circuit 1 represents a signal line feeding a low power load and circuit 2 contains a power cable which delivers power P_G from a generator at voltage E_G. Let the maximum value of the transient or interference current i_{d2} be a step change in current

$$\left.\Delta i_{d2}\right)_{max} = \frac{P_G}{E_G} = I_{20} \tag{5.1}$$

Since P_G, M and $\frac{R_{L1}}{R_{S1} + R_{L1}}$ are independent of E_G the induced interference voltage is

$$\left.v_{d1}\right)_{max} = \text{const.} \frac{1}{E_G \Delta t} \tag{5.2}$$

But $\frac{1}{\Delta t}$ is the frequency of the interference current i_{d2} or the duration of the current transient which is also independent of line voltage E_G so that for equal power transients or steady state interference, the induced voltage amplitude varies inversely with line voltage E_G. Thus the higher the system voltage the lower the interference voltage due to transient, ripple or harmonic currents, which constitutes an important conclusion for selection of transmission or distribution voltage magnitude.

Based on (4.8) the effect of system voltage E_G is different for capacitive coupling. Since the capacitance ratio is generally independent of E_G, an interference voltage in circuit 1 will cause the same effect in circuit 2 regardless of transmission voltage E_G. Since the coupling capacitance C_{ww}, however, is generally very low capacitive coupling can usually be ignored entirely in power circuits.

Next consider the case where two loads are supplied from the same feeder cable and load is switched causing a transient current i_{t1} in the feeder. The voltage v_{t2} at the input terminals to load 2 due i_{t1} is given by

$$v_{t2} = (R_G + R_F)\, i_{t1} + L_F \frac{di_{t1}}{dt} \qquad (5.3)$$

where R_F and L_F are the resistance and inductance of the feeder cable which has a length ℓ and R_G is the resistance of the generator. As before we are interested in the magnitude of the induced interference voltage v_{t2} as a function of source voltage E_G. Since power is constant for all E_G we may assume that the amplitude of the interference current is

$$|i_{t1}| = K_1 I_{10} = K_1 \frac{P_{10}}{E_G} \qquad (5.4)$$

where I_{10} is the rated steady state current to load 1 and K_1 is a constant. Also

$$R_G = K_G E_G, \quad L_F = \ell K_L, \quad R_F = \frac{K_F}{E_G} \qquad (5.5)$$

where K_G, K_L and K_F are constants. Substitution of (5.4) and (5.5) in (5.3) gives

$$|v_{t2}| = \left(K_G + \frac{K_F}{E_G^2}\right) K_1 P_{10} + K_L \ell \frac{\Delta i_{t1}}{\Delta t} \qquad (5.6)$$

We may reason as before that Δt is independent of supply voltage E_G and $\Delta i_{t1\ max} = K_1 I_{10}$ so that

$$|v_{t2}| = \left(K_G + \frac{K_F}{E_G^2}\right) K_1 P_{10} + \text{const.} \times \frac{P_{10}}{E_G} \qquad (5.7)$$

which shows that the interference voltage due to feeder line current transients decreases with increasing supply voltage E_G.

To summarize we have shown that for equivalent power levels interference due to transient or ripple currents and voltage decreases with increasing system voltage. This was fully expected because all currents decrease as voltage increases while rates of change of currents remain relatively constant.

5.3.3 Parallel Operation

In order to meet the safety requirements of manned vehicles the electric power system must be designed to allow two or more generators to run in parallel or to automatically connect an unfailed generator and transmission channel to a critical load channel in case of fault. In either case dynamic interactions which lead to excessive transients or tripping of circuit breakers must be avoided.

In dc systems critical loads can be supplied from more than one source simultaneously when blocking diodes are used to prevent circulating currents between sources. Load sharing can be provided if the generator voltages are adjustable in response to unbalanced current signals. Since the voltage drop across a blocking diode is relatively constant regardless of current, the power loss due to the blocking diodes varies inversely with transmission voltage thus favoring high voltage systems.

In ac power distribution systems paralleling of generators requires automatic control of amplitude, frequency and phase of each generator. This means that both real and reactive line currents must be sensed and used to correct generator field excitation and generator speed. Although electronic control circuits for synchronization of paralleled generators in 400 Hz aircraft electrical systems are commonplace, low frequency oscillations due to load swapping can occur when APUs are operated in parallel due to torque noise in the gas turbine or mechanical oscillations in the drive shaft. Such low frequency oscillations can under certain circumstances cause dangerous interactions with the flight control subsystem. If the distributed ac power is obtained from electronic inverters or cycloconverters, synchronization is still required for parallel operation to prevent commutation failures.

If ac sources are not operated in parallel, large transients can occur when a bus or feeder is switched from one generator to another. In addition power dropouts during switchover are more severe than for parallel operation.

5.4 WEIGHT ANALYSIS

Since weight is a critical parameter for most space vehicles and aircraft it constitutes one of the primary criteria for power system trade off analysis. In this section the results of PDCS equipment weight calculations are presented and the increases in power generation and heat rejection subsystem weights due to inefficiency or losses in the power distribution, processing and control equipment will be derived. Selection of the preferred PDCS concepts thus includes consideration of reflected weights as well as actual equipment weight.

5.4.1 Space Station Weight Analysis

From the PDCS equipment list of Table 5.2 and the parametric data of Section 3.0, the weight and power losses of the PDC equipments have been calculated. Results are shown in Tables 5.9 and 5.10 for the reference set of load utilization equipments developed in Section 2.3.1. The weight and loss of command and display equipment was not calculated since we assumed that a central data bus system will be available to serve the EPS and because the portion attributable to the EPS has the same weight and complexity for all four candidate PDCS configurations which were considered. Losses were computed for maximum sustained load during solar array illumination and with three RAMs active. The reflected weight of the solar array and radiators chargeable to the PDCS losses and the resulting effective weight are shown in Table 5.11.

Table 5.9. Space Station PDC Weight Analysis (Lb)

	Configuration			
	(1) 28 Vdc	(2) 115 Vdc	(3) 115/200 Vac	(4) 115Vac/28Vdc
Power Module				
Transmission				
Cables	225	55	55	55
Switchgear	83	167	94	86
Inverters	-	-	820	850
Total	308	222	969	991
Distribution & Processing				
Cables	75	16	16	75
RPCs	10	12	8	10
PPUs Analog	68	64	76	68
PPUs Digital	194	182	189	194
CPUs	50	47	152	215
Total	397	321	441	562
Total Power Module	705	543	1410	1553
Crew Module				
Transmission				
Cables	150	37	37	37
Switchgear	81	158	103	103
Total	231	195	140	140
Distribution & Processing				
Cables	132	26	26	132
RPCs	14	15	12	14
PPUs Analog	89	77	95	89
PPUs Digital	110	91	105	110
CPUs	21	18	188	309
Total	366	226	426	654
Total Crew Module	597	421	566	794

Table 5.9. Space Station PDC Weight Analysis (Lb) (Continued)

	Configuration			
	(1) 28 Vdc	(2) 115 Vdc	(3) 115/200 Vac	(4) 115Vac/28Vdc
Lab Module				
Transmission				
Cables	102	21	21	21
Switchgear	12	26	11	11
Total	114	47	32	32
Distribution & Processing				
Cables	78	15	15	78
RPCs	8	11	7	8
PPUs-Analog	29	26	42	29
PPUs-Digital	224	202	219	224
CPUs	26	24	238	335
Total	365	288	521	674
Total Module	479	337	553	706
RAM				
Transmission				
Cables	104	23	23	23
Switchgear	9	22	9	9
Total	113	45	32	32
Distribution & Processing				
Cables	353	76	76	353
RPCs	6	9	3	6
PPUs-Analog	10	9	14	10
PPUs-Digital	9	8	8	9
CPUs	17	15	110	205
Total	395	117	211	583
Total Module	508	162	243	615
Space Station Total				
Cables	4266	940	940	3052
Switchgear	506	964	542	554
Processing Units	1838	1654	3400	4490
Source Inverter	-	-	1640	1700
Total	6610	3558	6522	9796

Table 5.10. Space Station PDCS Losses (watts)

	PDC Configuration			
	1 (28 Vdc)	2 (115 Vdc)	3 (115/200 Vac)	4 (115 Vac/28 Vdc)
POWER MODULE				
Cables	2400	700	700	700
Switchgear	215	54	54	54
Inverters	-	-	4400	4400
Tot. Transmission	2615	754	5154	5154
Dist. Wires	40	10	10	40
Switchgear	90	48	48	48
Analog PPUs	133	127	132	133
Digital PPUs	540	525	590	540
CPUs	100	90	185	320
Tot. Dist. & Proc'g.	903	800	965	1071
Total per Module	3518	1554	6119	6225
CREW MODULE				
Cables	2000	500	500	500
Switchgear	300	75	75	75
Tot. Transmission	2300	575	575	575
Dist. Wires	15	4	4	15
Switchgear	141	36	36	36
Analog PPUs	200	190	220	200
Digital PPUs	860	840	940	860
CPUs	100	90	305	560
Tot. Dist. & Proc'g.	1316	1160	1505	1671
Total per Module	3616	1735	2080	2246
LAB MODULE				
Cables	320	80	80	80
Switchgear	45	12	12	12
Tot. Transmission	365	92	92	92
Dist. Wires	100	25	25	100
Switchgear	54	14	14	14
Analog PPUs	146	138	174	146
Digital PPUs	885	872	970	885
CPUs	100	90	380	550
Tot. Dist. & Proc'g.	1285	1139	1563	1695
Total per Module	1650	1231	1655	1787

Table 5.10. Space Station PDCS Losses (watts)
(Continued)

	PDC Configuration			
	1 (28 Vdc)	2 (115 Vdc)	3 (115/200 Vac)	4 (115 Vac/28 Vdc)
RAM				
Cables	320	80	80	80
Switchgear	45	12	12	12
Tot. Transmission	365	92	92	92
Dist. Wires	100	25	25	100
Analog PPUs(1)	50	45	55	50
Digital PPUs(1)	40	35	35	40
CPUs	55	50	380	400
Tot. Dist. & Proc'g.	245	155	495	590
Total per Module	610	247	587	682
SPACE STATION TOTALS(2)				
Cables & Dist. Wires	11010	2955	2955	3350
Switchgear	1825	515	515	515
PPUs	5800	5600	6320	5790
CPUs	765	690	2880	4060
Source Inverter	-	-	8800	8800
Total	19400	9760	21470	22515

Notes:

(1) Does not include equipment PPUs

(2) Space station consists of 12 modules. 3 RAMS are not powered.

Table 5.11. Effective PDCS Weight for Space Station (lbs)

	PDC Configuration			
	1 (28 Vdc)	2 (115 Vdc)	3 (115/200 Vac)	4 (115 Vac/28 Vdc)
POWER MODULE				
PDCS Equipment	705	543	1410	1553
Solar Array Increase	352	155	612	623
Heat Rej. Increase	230	102	398	404
Total	1,287	800	2,420	2,580
CREW MODULE				
PDCS Equipment	597	421	566	794
Solar Array Increase	362	174	208	225
Heat Rej. Increase	255	113	136	147
Total	1,214	708	910	1,166
LAB MODULE				
PDCS Equipment	479	337	553	706
Solar Array Increase	165	123	166	179
Heat Rej. Increase	107	80	108	117
Total	751	540	827	1,002
RAM				
PDCS Equipment	508	162	243	715
Solar Array Increase	61	25	59	68
Heat Rej. Increase	40	16	38	44
Total	609	203	340	827
SPACE STATION TOTAL				
PDCS Equipment	6,610	3,558	6,522	9,796
Solar Array Increase	1,940	976	2,147	2,252
Heat Rej. Increase	1,270	640	1,400	1,470
Total	9,820	5,174	10,069	13,518

5.4.2 Shuttle Weight Analysis

The load utilization equipment inventory for the typical Shuttle Orbiter which is used as model for PDC trade studies was derived in Section 2.3 and is listed in Table 2.14. The PDCS equipment required to supply these loads is given in Table 5.3. In order to compare the candidate configurations on the basis of weight we must add the increase in fuel cell and radiator weight and the weight of fuel cell reactants required to supply PDC power losses to the PDC equipment weight to obtain the effective weight as discussed previously. Since the objective is to determine differences between candidate PDC configurations rather than accurate weights for any one configuration, we have used the following simplifying procedures for the calculations without compromising the validity of the results:

- Equipment weight and power losses are calculated by assuming that all units of a given type have the "typical" power ratings given in Table 5.3.

- Each fuel cell is sized to provide the maximum useful power of Table 2.15 plus associated PDCS losses for one channel. The generator weight penalty ΔM_G reflects these losses and assumes a fuel cell specific weight of 35 lb/KW.

- The heat rejection weight penalty ΔM_Q is obtained by assuming that the radiator must be sized to reject all the losses of the PDC equipment including the cabling and the increase in generator thermal output chargeable to the generated power to supply maximum PDC losses which are assumed to be double the maximum PDC losses occurring in one channel. Radiator specific weight is 146 lb/KW.

- The fuel cell reactant weight penalty ΔM_R is obtained by assuming that the mission average power consumed by the entire EPS equals 2.0 times the average power of channel 1.

- Cables are sized to minimize effective transmission weight; i.e., including generation and heat rejection weight penalties.

Results of the comparative loss and weight analyses are given in Tables 5.12 and 5.13.

Table 5.12. PDCS Power Loss - Shuttle Orbiter

	Configuration											
	1		2		3		4		5		6	
	P_1	W_m	P_1	W_m	P_1	W_m	P_1	W_m	P_1	W_m	P_1	W_m
Central Conv. & Transmission												
Central Inv.	-	-	-	-	950	174	950	174	-	-	-	-
Cables	435	70	111	17	115	18	115	18	435	70	435	70
BCU	310	62	215	39	215	39	215	39	200	37	200	37
Total	745	132	326	56	1280	231	1280	231	635	107	635	107
Dist. & Local Conv.												
PDU	100		100		100		100		24		48	
Wiring	100	20	25	5	25	5	100	20	100	20	50	10
Analog Load PPU	200	56	188	53	238	67	200	56	200	56	200	56
Digital Load PPU	800	254	775	248	880	280	800	254	800	254	790	250
Inverters	130	25	94	16	-	-	-	-	130	25	130	25
Total	1330	355	1182	322	1243	352	1200	330	1254	355	1218	341
Cont. & Display												
C/D Panel									27	5	27	5
Digital Equipment	15	3	15	3	15	3	15	3				
Total	15	3	15	3	15	3	15	3	27	5	27	5
PDCS Total	2090	490	1523	381	2538	586	2495	564	1916	467	1880	453

Notes: P_1 = Max loss per channel in watts for requirements of Table 2.15
W_m = Loss per mission for all channels in KwH

Table 5.13. PDCS Weight Analysis (lbs) - Shuttle Orbiter

	Configuration					
	1	2	3	4	5	6
Central Conv. & Transmission						
Central Inverters	-	-	480	480	-	-
Cables	600	156	160	160	600	600
Bus Control Units	38	72	38	38	38	49
Sub Total	638	228	678	678	638	649
Loss Penalty	585	255	1010	1010	493	493
Effect. Weight	1320	483	1688	1688	1131	1142
Distribution & Local Conv.						
Pwr. Dist. Unit	22	29	19	22	29	43
Wiring	47	47	47	47	47	47
Analog Load PPU	296	275	340	296	296	285
Digital Load PPU	490	440	520	490	490	470
Inverter or TR	200	168	-	416	200	185
Sub Total	1055	959	926	1271	1062	1030
Loss Penalty	1156	1029	1095	1051	1103	1068
Effect. Weight	2393	1988	2021	2322	2165	2098
Cont. & Display						
C/D Panel Equipment	-	-	-	-	140	150
Wiring	-	-	-	-	270	400
Digital Equipment	52	52	52	52	-	-
Sub Total	52	52	52	52	410	550
Loss Penalty	12	12	12	12	22	22
Effect. Weight	64	64	64	64	432	572
PDCS Totals						
Equipment	1745	1239	1656	2001	2110	2229
Loss Penalty	1753	1296	2117	2073	1618	1573
Total Effective Weight	3498	2535	3773	4074	3728	3902

5.4.3 Aircraft Weight Analysis

Since the electric power system represents a very small load on the propulsion engines and since the EPS equipment is cooled by oil or blast air which are available for other purposes, we have ignored all weight penalties due to PDCS power losses. Cables are sized to meet MIL-STD-704A voltage drop requirements for category B equipment in configurations 2, 3, and 4 but a voltage drop of 9 Vdc is allowed for the 270 Vdc power lines of configuration 1. We have assumed that all switchgear is remotely controlled and that main bus and feeder RCCBs are hardwired to cockpit toggle switches while all RPCs and PPUs are controlled and monitored by means of a power system data bus which interfaces with a central aircraft digital computer. Estimated weights for each of the four candidate configurations for the reference load requirements of Tables 2.16 and 2.17 are given in Tables 5.14 and 5.15. The large weight savings achievable by changing from the conventional 400 Hz power distribution system to 270 Vdc are noteworthy.

Table 5.14. Commercial Aircraft EPS Equipment Weight (lb)

	Configuration			
	2 (115 Vdc)	3 (115 Vac)	4 (115 Vac/ 28 Vdc)	7 (270 Vdc)
Transmission				
Generator Cables	304	300	300	122
Feeder Cables	490	800	800	176
BCU	224	176	176	254
Subtotal	1018	1276	1276	552
Dist. & Local Conv.				
CPUs	700	-	336	-
PPUs-Analog Loads	162	213	175	155
PPUs-Digital Loads	265	313	292	253
RPCs & RCCBs	75	35	50	72
Dist. Wires	46	68	66	34
Subtotal	1248	629	919	514
Command & Display				
DIUs	24	24	24	24
I/O Control Units	4	4	4	4
Toggle Switches	9	9	9	9
Meters & Hardware	18	18	18	18
Wiring	12	12	12	12
Subtotal	67	67	67	67
PDCS Total	2333	1972	2262	1133
EPGS Total (Ref)	340	400	420	320
Total EPS	2673	2372	2682	1453

Table 5.15. Military Aircraft EPS Equipment Weight

	Configuration			
	2 (115 Vdc)	3 (115 Vac)	4 (115 Vac/ 28 Vdc)	7 (270 Vdc)
Transmission				
Generator Cables	304	300	300	160
Feeder Lines	610	1000	1000	220
BCU	250	190	190	280
Subtotal	1164	1490	1490	660
Dist. & Local Conv.				
CPUs	480	-	340	-
PPUs-Analog Loads*	130	170	140	124
PPUs-Digital Loads	530	626	585	505
RPCs & RCCBs	21	12	12	20
Dist. Wires	66	98	94	49
Subtotal	1227	906	1171	698
Command & Display				
DIUs	20	20	20	20
I/O Control Units	8	8	8	8
Toggle Switches	6	6	6	6
Meters & Hardware	20	20	20	20
Wiring	12	12	12	12
Subtotal	66	66	66	66
PDCS Total	2457	2462	2727	1424
EPGS	510	600	630	480
Total EPS	2967	3062	3357	1904

* Does not include payload PPUs.

5.5 COST ANALYSIS

In general the ultimate criterion for selection of one system design approach from a group of candidate concepts is the total effective cost in terms of dollars. An economic tradeoff analysis can only be performed if it is possible to assign realistic dollar values to differences in weight, reliability, efficiency, and the development or schedule risk involved in deviating from existing and usable equipment or design approaches. The true economic cost of the PDCS is the sum of the following costs:

- Recurring PDCS equipment cost
- Non-recurring (development) cost of PDCS equipment including test and vehicle integration
- Reflected power generation cost
- Reflected load utilization equipment cost
- Weight cost
- Economic value of increased reliability or life
- Cost overrun due to development and schedule risk

Any estimate of the true cost of candidate PDCS for future aerospace vehicles must reckon with the uncertainty of the scope and start date of vehicle development programs, the competitive environment, and the total market for similar PDC equipment in addition to aerospace applications. This makes it very difficult to arrive at defensible cost estimates unless all aspects of each application are defined in detail. This would have to include schedules, production rates, detailed quality assurance requirements, standby costs, weight margins, etc. Since it was not possible to do this for the reference vehicle requirements utilized for this study, the cost estimates described herein are based on typical unmanned and manned spacecraft experience for similar equipment and should only be used to compare different PDCS concepts against each other.

5.5.1 PDC Equipment Cost

Both the non-recurring development cost and the recurring unit production cost of PDCS equipment items depends strongly on equipment design complexity and quality assurance requirements. Since the number of individual units is so large and since there is considerable uncertainty regarding actual requirements we have used the typical costs listed in Table 5.16 for all units of a given type regardless of power rating or design configuration. Approximate PDC subsystem costs can then be obtained for the reference Space Station, Shuttle, and aircraft by applying these costs to the equipment lists of Tables 5.2, 5.3, 5.4, and 5.5. Results are given in Tables 5.17, 5.18, and 5.19.

Table 5.16. Typical PDCS Equipment Cost ($000)

	Non-Recurring Cost			Recurring Cost Per Unit		
	Station	Shuttle	Aircraft	Station	Shuttle	Aircraft
Cabling (per 1,000 ft.)						
Transmission	-	-	-	1.0	1.0	1.0
Distribution	-	-	-	0.5	0.5	0.5
Power Processing						
Load PPUs	150	100	50	10	5	0.5
Source Inverter	600	500	-	150	100	-
Motor Drive Inverter	300	250	100	50	30	10
Transformer Rectifier	100	80	50	10	10	2
Switchgear						
RCCB - 28 Vdc	50	50	-	0.2	0.2	0.1
115 Vdc	200	200	150	0.3	0.3	0.2
115 Vac (3Ø)	50	50	-	0.2	0.2	0.1
RPC - 28 Vdc	100	100	50	0.2	0.2	0.2
115 Vdc	120	120	60	0.2	0.2	0.2
115 Vac	80	80	-	0.2	0.2	0.05
C/D Equipment						
DIU	-	50	30	-	3	0.2
I/O Unit	-	100	50	-	15	3.0
Command Switch - 28 Vdc	-	-	-	-	0.15	0.02
115 Vdc	-	30	20	-	0.15	0.03

Table 5.17. Space Station PDCS Equipment Cost ($000)

	PDC Configuration							
	1 (28 Vdc)		2 (115 Vdc)		3 (115 Vac)		4 (115 Vac/ 28 Vdc)	
	NR	R	NR	R	NR	R	NR	R
Cables								
Transmission	-	3.2	-	3.2	-	9.2	-	9.6
Distribution	-	27.2	-	27.2	-	42.2	-	26.9
Subtotal	-	30.4	-	30.4	-	51.8	-	36.5
Power Processors								
PPU	6000	5500	6000	5500	6000	5500	6000	5500
Sinewave Inverter	-	-	-	-	3000	3600	1800	1200
Squarewave Inverter	600	1200	600	1200	-	-	600	1200
Transf. Rect.	-	-	-	-	100	240	200	240
Subtotal	6600	6700	6600	6700	9100	9340	8600	8140
Switchgear								
RCCB	100	23	400	34	100	24	100	24
RPC - dc	200	155	240	155	-	-	200	155
RPC - ac	160	46	160	46	160	200	160	48
Subtotal	460	224	800	235	260	224	460	227
Total	7060	6954	7400	6965	9360	9616	9060	9403

Notes:
Does not include C/D equipment and experiment PPUs cost
NR - Non-recurring cost
R - Recurring cost per ship set

Table 5.18. Space Shuttle PDC Equipment Cost ($000)

	Configuration											
	1 (28 Vdc)		2 (115 Vdc)		3 (115 Vac)		4 (115 Vac/ 28 Vdc)		5 (28 Vdc, Conv.)		6 (+28 Vdc, Conv.)	
	NR	R	NR	R	NR	R	NR	R	NR	R	NR	R
Power Processors												
Load PPUs	2000	1000	2000	1000	2000	1020	2000	1000	2000	1000	2000	1030
Motor Drive Inverter	300	420	300	420	-	-	-	-	300	420	300	420
Transf. Rect.	-	-	-	-	-	-	80	160	-	-	-	-
Source Inverter	-	-	-	-	500	400	500	400	-	-	-	-
Subtotal	2300	1420	2300	1420	2500	1420	2580	1560	2300	1420	2300	1450
Switchgear												
RCCBs	100	5	400	8	100	5	100	5	100	11	100	22
RPCs - dc	200	48	240	48	-	-	200	45	-	-	-	-
RPCs - ac	80	2	80	2	160	67	160	22	-	-	-	-
Subtotal	380	55	720	58	260	72	460	72	100	11	100	22
Cabling	-	6	-	6	-	12	-	8	-	6	-	8
C/D Equipment												
Digital Units	-	108	-	108	-	108	-	108	-	-	-	-
Meters and Switches	-	-	-	-	-	-	-	-	-	80	-	80
Wiring	-	-	-	-	-	-	-	-	-	40	-	60
Subtotal	-	108	-	108	-	108	-	108	-	120	-	140
Total PDCS	2680	1589	3020	1592	2760	1612	3040	1748	2400	1556	2400	1618

Table 5.19. PDCS Equipment Cost ($000) For Transport Aircraft

	Configuration							
	2 (115Vdc)		3 (115Vac)		4 (115Vac/ 28 Vdc)		7 (270Vdc)	
	NR	R	NR	R	NR	R	NR	R
Power Processors								
Load PPUs	200	60	100	60	100	60	200	60
Motor Inverter	200	40	-	-	-	-	-	-
Transf. Rect.	-	-	-	-	50	8	-	-
Subtotal	400	100	100	60	150	68	200	60
Switchgear								
RCCBs	300	9	-	5	-	5	300	10
RPCs - dc	120	93	-	-	100	45	120	93
RPCs - ac	-	6	-	72	-	33	-	-
Subtotal	420	108	-	77	100	83	420	103
Cables								
Transmission	-	2	-	6	-	6	-	2
Distribution	-	7	-	14	-	8	-	7
Subtotal	-	9	-	20	-	14	-	9
C/D Equipment								
Digital Units	80	11	80	11	80	11	80	11
Command Switch	20	1.4	-	1.0	-	1.0	20	1.5
Meters, etc.	-	2	-	2	-	2	-	2
Subtotal	100	14	80	14	80	14	100	14
Total	920	231	180	171	330	179	720	186

5.5.2 Indirect Costs

Indirect costs are cost variations in other subsystems or in overall program costs due to the choice of PDCS concept. As mentioned previously, they include a number of cost items which can be treated individually as described in this section.

The reflected generator cost is due to the fact that the generator must be sized to supply PDCS losses in addition to useful load power. The cost of solar arrays varies linearly with power output at a rate of $200 per watt so that PDCS losses have a significant influence on array cost. Batteries, fuel cells, and rotating generators of a given size and cost are capable of providing power output over a fairly broad tolerance range if the temperature does not approach critical values. We may therefore reason that since EPGS output ratings have to vary less than $\pm 5\%$ to accommodate the candidate PDC configurations considered herein, the reflected EPGS cost does not change except for solar array generators. The same is basically correct for changes in generator voltage as long as power rating is not affected.

The cost of load utilization equipment has been used by some as the chief criterion for selecting 28 Vdc or 115 Vac power distribution systems. To estimate the reflected load equipment cost each type of load must be considered separately. For electronic equipment we have established the groundrule that every separate load unit has its own power processing unit. Since the cost of PPUs is included in PDCS cost and PPU outputs are the same for all PDCS configurations, there is no cost variation in electronic load equipment. The only type of motor which has been considered during this study is the brushless ac induction motor. This motor can operate directly from the main bus in configurations 3 and 4 and is supplied from a squarewave inverter whose cost has been included as part of PDCS equipment cost in all configurations except configuration 7. For this configuration we have postulated that the cost impact of using a somewhat larger motor in order to tolerate the frequency variation is negligible. Thus, motor cost is not affected by PDCS configuration.

Heaters and actuators are easily designed for any dc voltage. Although actuators can be designed to operate on ac power, it may be simpler to use an inexpensive rectifier for each actuator to provide dc coil current in the case of PDC configuration 4. The cost of heaters and actuators should therefore also be independent of PDC configuration although it is recognized some cost associated with qualification of actuators with rewired solenoids will be incurred. Electric lights typically are available for several low ac or dc input voltages. Since the average lighting load is relatively small, we have assumed that squarewave inverters or transformer rectifiers available for other loads will be used to supply lights as shown in the candidate configuration schematic diagrams of Section 5.1. The cost impact on lighting loads is not significant.

To summarize we have shown that the cost of all load equipment which is supplied with raw power as distributed is independent of distribution voltage. Loads receiving power from power processing units are also unaffected by the distribution voltage since the PPU output voltages are made the same for all distribution voltages.

The major indirect cost is the PDCS weight cost; i.e., the cost of transporting the PDCS equipment and the weight of PDCS support items. Weight cost can also be interpreted as the economic benefit derived from saving weight aboard the vehicle. It is a function of vehicle design, utilization of available payload weight, weight margin and booster cost. Since transportation cost is generally used as a basic figure of merit for the overall vehicle system, we may also use it to compare PDCS configurations. Although a final figure will not be available until the development program is complete, a reasonable estimate of Shuttle transportation cost is $100/lb. This figure is used to determine the weight cost of Space Station equipment since the Space Station is launched by the Shuttle. For Shuttle PDCS equipment we shall use a weight cost of $6,000/lb. assuming each Shuttle vehicle will make 60 flights during its lifetime. During Shuttle Phase B studies, however, weight costs of $9,000 to $28,000 per lb. have been used for various trade studies. The weight cost for aircraft equipment can be obtained from the anticipated revenue per passenger mile and the aircraft life. We shall use $50,000/lb. which is slightly less than the figure used by Boeing for economic analysis of the Super Sonic Transport.

Although a dollar cost for reliability and the economic risk to the overall program due to PDCS development requirements could also be considered as part of the tradeoff analysis, we have chosen not to do this because the cost of failure is so high that it would mask all other costs. It can also be argued that all candidate configurations have sufficiently high reliability to merit their consideration without including a cost risk or cost penalty.

Total direct and indirect cost including PDCS equipment, generator cost penalty due to PDCS losses and weight costs are provided in Table 5.20.

Table 5.20. Cost Summary ($M)

	Equip. Cost per Vehicle	Devel. Cost	Weight Cost	Total Eff. Cost
Space Station				
28 Vdc	10.83	7.06	0.98	18.87
115 Vdc	8.90	7.40	0.52	16.82
115 Vac, 3Ø	13.90	9.36	1.00	24.26
115 Vac/28 Vdc	13.90	9.06	1.35	24.31
Space Shuttle				
28 Vdc	1.59	2.68	21.0	25.3
115 Vdc	1.59	3.02	15.1	19.7
115 Vac, 3Ø	1.61	2.76	22.5	26.9
115 Vac/28 Vdc	1.75	3.04	24.4	29.1
28 Vdc Convent. C/D	1.56	2.40	22.4	26.4
±28 Vdc Convent. C/D	1.62	2.40	23.4	27.4
Transport Aircraft				
115 Vdc	.27	.92	98.6	99.8
115 Vac, 3Ø	.33	.18	118.6	119.1
115 Vac/28 Vdc	.36	.33	134.1	134.8
270 Vdc	.27	.72	72.6	73.6

5.6 SUMMARY

Selection of the best power processing, distribution and control subsystem (PDCS) configurations for advanced future aerospace vehicles involves three basic items for tradeoff analysis. They are

a. the command and display method

b. the type of switchgear

c. the transmission and distribution voltage and frequency

We have shown that multiplexing of commands and status signals and use of a small on-board digital computer greatly simplifies the crew/power system interface, saves weight, and improves reliability. It therefore is the clear choice over more conventional C/D methods. Selection of the type of switchgear is not quite so obvious since the lower weight and better reliability of solid state RPCs is counterbalanced by the better efficiency and lower cost of electromechanical relays for equal power switching capability. We have considered subsystem configurations using both types and recognize that more detailed analysis is required for specific applications to arrive at the optimum balance and accurate evaluation of the differences in dynamic performance between the two types of switchgear.

The transmission/distribution voltage is the most important configuration variable determining PDCS performance. Results of voltage tradeoff analyses which were performed are contained in the tables presented previously in this section and in the figures and charts of Section 3.0.

They can be summarized by means of the normalized bar graphs shown in Figures 1, 2, and 3 of Volume I and lead to the following major conclusions:

1. Transmission and distribution at 115 Vdc results in the lowest weight and power loss among the candidate configurations which were considered. When compared to conventional 28 Vdc power systems, this gives a 47% reduction in weight for the Space Station and 28% for the Shuttle including the weight to support PDCS power losses.

2. For commercial transport aircraft a 39% reduction in weight compared to the conventional 115/200V, 400Hz electrical system is obtained by using a hybrid system which provides variable frequency 115 Vac to motors and 270 Vdc to all other loads.

3. Power transmission at voltages higher than 115 Vdc would result in still lower weight due to further reduction in I^2R losses but requires semiconductors with higher reverse voltage ratings than currently available.

4. For the Shuttle and aircraft the true PDCS life cycle cost consists mainly of the cost to transport the PDCS equipment and support weight. A 22% cost savings can be realized for the Shuttle by changing from 28 Vdc to 115 Vdc power distribution.

5. Power processing equipment comprising secondary power supplies associated with load utilization equipment, central inverters and transformer rectifiers accounts for more than 90% of the equipment cost and 50% of the PDCS weight and power loss except in 28 Vdc systems when the cables and switchgear become the dominant items.

Additional conclusions were presented in Volume I.

6.0 TECHNOLOGY REQUIREMENTS

Design of power processing, distribution and control subsystems for advanced future spacecraft and airplanes involves a number of technical challenges which are not usually encountered in unmanned spacecraft and existing transport aircraft. Even when contrasted with the requirements of the Apollo spacecraft the future PDCS designs must reckon with the following:

- The highest possible efficiency must be achieved because of the high cost of heat rejection.
- The quantity, variety and sensitivity of electronic sensing, communication and data processing equipment will increase steadily which requires that the PDCS must be more flexible, noise free and adaptable than in the past.
- Efficient use of redundancy to meet the longer lifetime and greater reliability requirements of future aerospace vehicles demands a better understanding of switchgear and fault recovery methods than necessary in the past.

The component and subsystem studies presented herein have shown that PDCS efficiency can be raised, weight can be lowered, dynamic performance improved, and redundant units can easily be paralleled when higher than normal dc voltage rather than the usual 28 Vdc or 115 Vac is used for power transmission and distribution. Since the use of high voltage dc (HVDC) represents a departure from currently established practice, specifications must be prepared which govern the use and performance of HVDC electrical systems. In addition development and laboratory demonstration of electromechanical and solid state switchgear compatible with HVDC power distribution must be completed before such a system can be committed to flight. A brief outline of the suggested technology programs and recommendations for development of a PDCS integration breadboard are described below.

6.1 DEVELOPMENT OF HIGH VOLTAGE SWITCHGEAR

As discussed in Section 3.3 remotely controlled circuit breakers (RCCB) are required for bus and feeder protection while remote power controllers (RPC) are needed for on/off control and input current limiting to all loads other than those having internal PPUs. In general an RPC will also function as a circuit breaker and hence may be used wherever an RCCB is required. The current and voltage ratings of presently available solid state RPCs are not adequate for most bus and feeder control requirements. The parallel development of both solid state and electromechanical circuit breakers for such service is therefore recommended. The solid state breakers are inherently more reliable and generate less EMI than electromechanical breakers if properly designed but they will always introduce a larger voltage drop in the power line than mechanical contacts and hence require more extensive cooling provisions.

The basic objective is the development of a line of reliable RCCBs for the 10 to 100 KW power range. They must interrupt currents in resistive and inductive circuits fed from a stiff source at 120 Vdc or higher. Size, weight, cost and power loss during the ON state must be minimized and operation must be possible at any pressure from sea level to vacuum. The recommended technology program to meet this objective should include the following theoretical and laboratory investigations:

- Evaluation of existing deion, magnetic blowout and multiple break contactors at 150 Vdc and reduced ambient pressure.
- Evaluation of sealed oil and gas filled electromechanical contactors.
- Design and test of 4, 6, and 8 break solenoid operated and motor driven switches over the required ambient temperature and pressure range.
- Feasibility study of a 150-200 Vdc, 50 amp gate turn-off thyristor.
- Develop a simple method for shunting solid state switchgear with mechanical contactors to reduce the line drop.
- Perform EMI measurements on selected high power electromechanical and solid state switches while changing switch position.
- Develop improved noise suppression means based on careful analyses of oscillograms and EMI measurements during switchgear operation.
- Study the feasibility of using a self healing fuse in series with a solid state or mechanical circuit breaker to guarantee interruption and enhance reliability.

The following active research and development programs are too limited in scope to provide an adequate technology base for high voltage dc circuit breakers but are expected to furnish useful information. They are a feasibility study of a 15 amp, 300 Vdc circuit breaker performed by The Martin Co. (Denver Division) under contract to NASA Lewis Research Center and two programs by the General Electric Research Laboratories aimed at development of a self-healing fuse also sponsored by NASA/LeRC and design of a 200 amp turn-off switch under contract to the Air Force AeroPropulsion Laboratory. In addition the work being performed by the Naval Research and Development Center at Annapolis, Maryland, on high pressure oil filled circuit breakers is noteworthy.

The listed development tasks are aimed at screening all the off-the-shelf circuit breaker types as well as proposed concepts to allow selection of the approach most likely to meet the HVDC system requirements at minimum cost. Detailed prototype design, fabrication and flight certification tests should be undertaken after the configuration and design approach are selected.

6.2 HIGH VOLTAGE DC POWER PROCESSING, DISTRIBUTION AND CONTROL TECHNOLOGY BREADBOARD

Although all components required for high voltage dc PDCS are state-of-the-art devices, with the possible exception of high power switchgear, confident application of any new electrical system requires prior demonstration of the reliability, safety, flexibility, and capability of such a system in the laboratory. An "EPS Technology Test and Evaluation Facility" which for convenience may simply be called a "Technology Breadboard" is required to serve as a test bed for the various components as they become available and to conduct a variety of PDCS integration and performance tests. The subsystem technology development tests should be designed to accomplish the following:

- Measure Interference Thresholds Due to
  - Feeder line pulse currents
  - Main bus pulse voltage
  - Control voltage pulse
  - Switchgear operation

- Develop PDCS Checkout Techniques
  - Establish checkout sequence
  - Develop computer software
  - Determine stimulus requirements
- Study Abnormal Subsystem Behavior Due to
  - Line to ground faults
  - Load switching
  - Bus switching
  - Open feeder line
  - Line to line faults
  - Motor overload
  - Internal PPU fault
  - Command errors
  - Fault application/removal from control lines

The basic block diagram of such a technology breadboard is shown in Figure 6.1. A full-scale mockup of the PDCS cabling and switchgear network

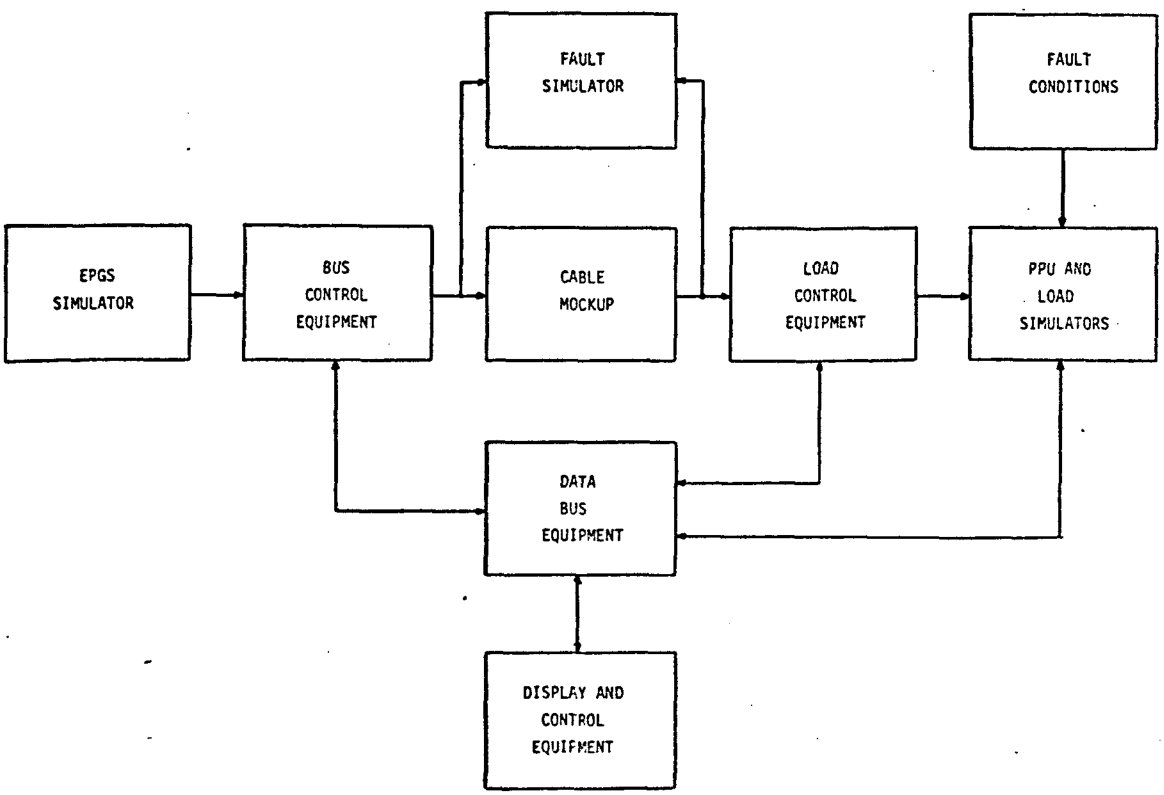


Figure 6.1. Proposed EPS Technology Test and Evaluation Facility

is envisioned. Actual load utilization equipment including its power processors (PPUs) should be used whenever available or full power simulators must be provided. A simulator is shown in place of an actual EPGS because batteries or low impedance laboratory power supplies can adequately simulate the source characteristics of the fuel cell or solar array/battery electric power generation subsystem.

Provisions for measurement and display of breadboard performance are not indicated. Since the dynamic performance of the PDCS technology breadboard is of primary interest most current measurements should be performed by means of current probes which have flat response from dc to at least 1 MHz if possible. Dual beam storage oscilloscopes are available to record current and voltage transients during switchgear operation. It may also be desirable to conduct certain critical component level dynamic interaction and EMI tests in a suitably screened environment.

Preliminary requirements for each major element of the technology breadboard of Figure 6.1 are listed below:

<u>Power Source Simulator</u>

Description	Rechargeable battery or filtered and regulated transformer rectifier unit
No. of Units Required	Four (4)
Output Power/Unit	15 KW Continuous
Output Voltage	28 to 120 Vdc Nominal
Output Voltage Regulation	$\pm 5\%$ (0 to 150% Load)
Rated Current/Unit	120 Amps
Maximum Current	$\geq$240 Amps for 5 Sec.
Short Circuit Current	$\geq$1500 Amps for 1 Sec.
Ripple Voltage	<1% pp
Instrumentation	Output voltage (steady state and transient) Output current (steady state and transient) RMS ripple voltage versus frequency at no load and full load

Bus Control Equipment

Description	Hermetically sealed thermal or magnetic circuit breaker
No. Required	14
Voltage Rating	120 Vdc
Current Rating	120 Amps Continuous, 240 Amps for 5 Sec.
Interrupt Capacity	1500 Amps Min.
Instrumentation	Line Current (steady state and transient) Contact Voltage (transient) Control Current (if required)

Load Control Equipment

Description	Solid State RPCs
No. Required	Approximately 100 at 0-5 Amps Approximately 20 at 5-50 Amps
Voltage Rating	120 Vdc
Instrumentation	Load Current (steady state and transient) Voltage Drop (steady state and transient) Control Current (transient) Temperature

Cable Mockup

Description	Cables in simulated raceways between physical mockups of main bus, PDU buses, and LRU input connectors
No. Required	Actual wire length to 250 ft.
Instrumentation	Fixed current probes for all main feeders Movable current probes on 3 distribution wires Bus voltage (steady state and transient) Cable voltage drop (transient only) Radiated interference per MIL-STD-461 Procedures RE01 and RE02

Fault Simulator

Description	Shorting bars and variable resistance elements connectable to bus and connector terminals
No. Required	Three (3)
Instrumentation	Current Probes

PPU/Load Simulator

Description	Avco Dynamic Load Simulator consisting of lumped constant equivalent circuits with switchable and variable resistance elements. Needs redesign to handle load power greater than 250W and 115 Vdc input.
No. Required	At least 6 but 1 for each load desirable
Voltage Rating	120 Vdc and 115 Vac, 400 Hz
Power Rating	3 KW Max.
Instrumentation	Voltage (steady state and transient)
	Input current (steady state only)

Data Bus Equipment

Description	Computer and Digital Interface Units (DIU) for generation of control and supervision signals
No. Required	1 Computer, 4 Buses, 10 DIUs (min.)
Instrumentation	Current probe to measure bus current or DIU output
	Pulse generator (current and voltage drive)

Display and Control Equipment

Description	Configuration determined by specific vehicle application and computer I/O equipment

6.3 ELECTRIC POWER SYSTEM STANDARDIZATION

Although MIL-STD-704 which specifies the type of electrical power to be used on military and commercial aircraft has been in existence for more than 25 years, no similar specification applicable to manned space vehicles exists. Selection of the voltage and frequency at which power is transmitted and/or distributed and definition of the power quality is crucial for orderly development of all future manned spacecraft. This is due to the fact that the PDCS interfaces with every other subsystem and affects the design and performance of the power utilization equipment. Our recommendation to develop new power system specifications and standards outlined below is based on the following considerations:

- When space vehicles are docked in orbit their electrical power distribution systems should be compatible so that certain experiments and life support equipment can be "plugged in" in either spacecraft. This is especially important if rescue missions are to be performed.
- Cost savings are obviously possible if utilization equipment is designed for a single input voltage level and power quality existing on all future aerospace vehicles.
- PDCS components such as switchgear and load power processors should not be custom engineered for each new vehicle but selected from a list of fully qualified standardized hardware.
- Simple adaptation of existing specifications (MIL-STD-704A, MIL-STD-461, etc.) to the proposed 115 Vdc distribution system is not feasible because existing specifications contain conflicting requirements and do not adequately define dynamic compatibility requirements and characteristics.
- Power quality standards of existing specifications do not reflect the characteristics of the power sources and utilization equipment of manned spacecraft and future airplanes.

In order to facilitate the development and utilization of high voltage dc power systems for all future aerospace vehicles the following specifications should be prepared and coordinated with all affected agencies and major vehicle manufacturers:

- A basic power quality and power utilization specification similar to MIL-STD-704 which defines the voltage level and frequency (nominally 115 Vdc) which shall be distributed to all power using equipment aboard manned space vehicles and certain types of future aircraft.

- A specification and supporting design criteria documents for secondary power supplies (PPUs) which convert electric power as distributed to secondary power as required by electronic load utilization equipment. Requirements for current limiting, on/off control, status monitoring, checkout procedures and logic levels should be standardized even for secondary power supplies which are physically and electrically integrated with the load equipment.

- A specification which defines requirements and procedures for analytical or experimental determination of electrical interference and interference margins due to operation of the power processing, distribution and control subsystem when installed in the vehicle. This document shall provide a means for ensuring electromagnetic compatibility of the PDCS with the power generation subsystem and all susceptible user subsystems.

- A specification related to MIL-STD-461 which defines dynamic performance and EMI characteristics of all PDCS components including secondary power supplies physically integrated with load equipment.

The current study program has disclosed the need for well designed and properly interrelated specifications and has furnished part of the analytical tradeoff results which are necessary to set numerical limits on power quality parameters which are practical and generally applicable. Further analysis and development of the technology breadboard are required to complete the recommended set of specifications.

6.4 COMPONENT IMPROVEMENTS

This power processing, distribution and control study has provided quantitative assessments of PDCS performance as a function of the performance capabilities of individual components which make up the subsystem. It has been shown that for manned spacecraft the largest portion of subsystem weight, cost and use of power is attributable to the power processing equipment consisting of secondary power supplies for electronic loads, motor controls and source power converters. It is therefore highly recommended that advanced circuit development work on all types of PPUs be more vigorously pursued than in the past. Some areas where the potential payoff is especially significant in terms of impact on the complete PDCS are:

- Improvements in dc to ac inverters to supply induction motors.

- Development of hybrid integrated circuit versions for digital control and stabilization of PPUs.

- Reduction of rectification and I^2R losses in secondary power supplies for low output voltage and low output impedance.
- Development of new filter design techniques which do not depend on large values of capacitance and inductance or invention of new types of capacitors and inductors which have greatly reduced size, weight and respectively larger ac or dc current carrying capability.

Recent developments indicate that major improvements are possible in each of these areas. The SCR series inverter mentioned in Section 3.4 is a strong candidate for major improvement of motor drive inverters. It appears to be ideally suited to furnish the current source characteristics which provide inherent fault protection and limit inrush current. This minimizes dynamic interactions with other loads by reducing the transients in the feeder lines.

Development of digital control and stabilization of power processors is also well along and deserves wider application and further component standardization (Reference 42).

The need for improvements in low output voltage PPUs is evidenced by the parametric data for type 2 (digital load) PPUs. The saturated forward drop of silicon rectifiers is too large for the typical 5 volt requirement of digital TTL logic circuits. Other rectification means should be explored or bipolar TTL logic circuits should be avoided. Use of other logic families such as high voltage and COS/MOS logic should be encouraged.

Requirements for PPU input filters to meet present conducted interference specifications were described in Section 4.4. Use of two-stage filters and determination of the optimum tradeoff between filter weight, dissipation and inrush current due to inductor saturation is desirable. Methods for providing different turn-on logic which allows the filter capacitor to charge during non-critical periods of operation should be investigated.

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42. Vincent Lalli and A. D. Schoenfeld, "ASDTIC Duty Cycle Control for Power Converters," Presented at 3rd IEEE Power Processing and Electronics Specialists Conference, Atlantic City, New Jersey, 22 May 1972.

APPENDICES

A - Power Processing Unit Design Data

B - Input Filter Design

C - Calculation of Wire Size

A - POWER PROCESSING DESIGN DATA

A simplified method for the development of parametric data for the selected power processors and discussion of the method is herein presented. The method and the bulk of the parametric data utilized are derived from two previous NASA-sponsored studies (References 23 and 25). Briefly, design information on a series of power conditioning subcircuit functions is generated and then merged in a specific order to obtain parametric weight, power loss and failure rate data for the various types of power processing equipments under evaluation. Contained in this appendix are:

1. Definition of circuit functions and listing of function classes.
2. Function block diagrams of selected PPUs.
3. Function design procedure, design constraints and assumptions, component derating policy, and function parametric data.
4. Supplementary function parametric data.

A1. POWER PROCESSING CIRCUIT FUNCTIONS

The formulation of analytical power conditioner models and the determination of their adaptability to other than the specified requirements and ranges can be greatly enhanced by standardizing various subcircuit functions because of the commonality displayed by such functions in power conditioning equipment. Various subcircuit functions have been formulated and are shown in Table A-1. The functions are divided into power level and signal level categories. The definitions of the power level functions are given in Table A-2.

Table A-1. Circuit Functions

POWER	SIGNAL
Basic	**Basic**
Power modulation (7 classes)	Sensing
Inversion (5 classes)	Voltage
Transformation (2 classes)	Current
Rectification (3 classes)	References
Passive filtering (11 classes)	Frequency standard
	Pulse generator
	Operational amplifier
	Voltage gain
	Current gain
Auxiliary	**Auxiliary**
RFI filtering	Time delay
Transmission	Logic
Power control	OR gate
Overcurrent protection	AND gate
Overvoltage protection	Digital
	Flip-flop
	Multivibrator
	Schmitt trigger
	Relay driver
	Telemetry conditioning

Table A-2. Power Function Definitions

Power Modulation

- Switching. The process of controlling power from a source such that the output is maintained within desired limits. The control is accomplished by varying the ON/OFF time ratio of a power switch either by pulse width modulation (PWM) or by pulse rate modulation (PRM). Either process, herein, is referred to as pulse modulation (PM).
- Dissipative. The process of controlling power from a source such that the output is maintained within desired limits. The control involves dissipation of excess energy.

Inversion

The process of converting dc voltage to ac voltage.

Transformation

The process of converting ac voltage from one level to another, either step-up or step-down, and working as an isolation transformer or as an auto-transformer.

Rectification

The process of converting ac voltage to an unfiltered dc voltage.

Passive Filtering

The process of suppressing or minimizing frequency components in power lines with passive components. The two types considered in this study are the dc filter (those used in either dc power lines, input, or output) and the ac-type (used primarily for harmonic filtering in ac output power lines or waveshaping of currents drawn from the power source).

Active Filtering

The process of suppressing or minimizing frequency components in power lines with active elements. This process is effectively equivalent to the dissipative power modulation process.

a. Basic Power Functions

Most of the basic power functions are characterized by differing design constraints on the critical components, depending on the particular type of power conditioner involved. These variations or classes are listed in Table A-3. Suborders of these classes, such as polyphase rectification, polyphase transformation and dc filters with rectified sinusoidal inputs, though not indicated, will be discussed later.

Table A-3. Power Function Classes

Power Modulation

- Switching
  - PWM-inversion
  - PWM-rectification
  - PM-buck
  - PM-boost
  - PM-buck/boost
- Dissipative
  - Series
  - Shunt

Inversion

- Squarewave - Transistor Type
  - Resistive load
  - Rectifier-LC filter load
  - Rectifier-C filter load
- Squarewave with fixed dwell
- Sinewave - SCR Type

Transformation

- Low power
- High power (500W)

Rectification

- Square
- PWM-squarewave
- Sinewave

Passive Filtering

- dc filters
  - LC-no ac requirement
  - LC-high ac current
  - LC-high ac voltage
  - LC-high ac voltage and current
  - LC-high ac voltage with transformation
  - LC-high ac voltage and current with transformation
  - C-no ac requirement
  - C-high ac current, low frequency
  - C-high ac current, high frequency
- ac filters
  - LC-high ac voltage and current
  - C-high ac current

b. Auxiliary Power Functions

The following auxiliary functions, while not identified in the power processing units studied, are necessary in actual system design:

- RFI filtering - the process of suppressing or minimizing the above audio range frequency components in power lines with passive components.
- Transmission - the means of distributing power (includes connectors and cabling).
- Power control - the means of connecting or disconnecting power (includes relays, contactors, and static devices).
- Overcurrent protection - the process of providing protection in the event of fault conditions, either by current interruption or by current limiting.
- Overvoltage protection - the process of protecting load equipment against overvoltages during a power conditioner fault.

c. Basic Signal Functions

The basic signal functions used in the selected power conditioners are defined below. Auxiliary signal functions, not defined, are listed in Table A-1.

- Reference - a voltage or current level established as a standard of comparison for feedback control purposes.
- Frequency standard - a self-oscillating source used to develop power conditioner operating frequency and required low-level timing signals.
- Duty cycle modulator - an active network for converting variable analog signal levels to a pulse-type digital signal having either variable pulsewidth or variable pulse frequency.
- Operational amplifier - an active network for obtaining a controlled voltage (or current) gain versus frequency characteristic. This function is taken to include both error amplifier and power stage driver amplifier types.

A2. POWER PROCESSING UNIT BLOCK DIAGRAMS

Function block diagrams of the selected power processing units identified in Section 3, in terms of the function classes listed in Table A-3, are illustrated in Figures A-1 through A-6.

Figure A-1 illustrates the functional breakdown of the Types 1 and 3 PPUs shown in Figure 3.10 of Section 3. The required functions are defined in Figure A-1 along with those necessary to implement the Type 3 PPU (the modified Type 1 PPU for ac input power).

Figures A-2 and A-3 show, respectively, the diagrams for the Types 2 and 4 PPUs and the Type 5 PPU (Figures 3.11 and 3.12 of Section 3).

Figures A-4 to A-6 show, respectively, the functional diagrams for the central power processing units described in Table 3.25 and Figures 3.45 to 3.47 of Section 3.

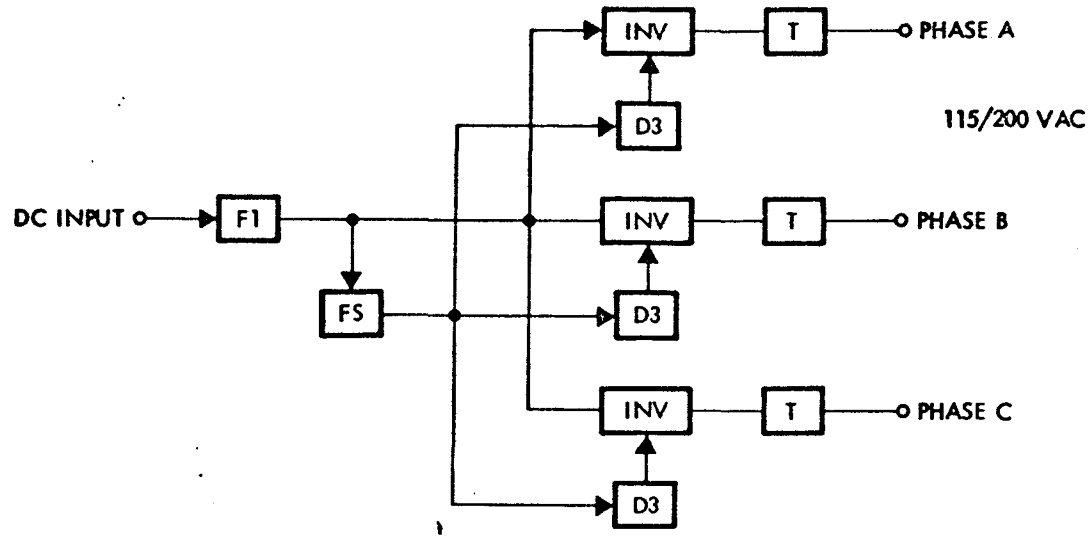
A3. FUNCTION DESIGN

a. Function Circuit Design

In the generation of parametric data (weight, power loss and failure rates) for the various power processing subcircuit functions defined herein, the voltage and power ranges of interest are rearranged into a set of discrete function design points that effectively cover the applicable ranges of the load and central power processing designs covered in this study. These design points are:

Operating voltage	3, 10, 30, 100 and 300 Vdc
Switching frequency	10 KHz
Power	10, 100, 300, 1000, 3000 and 10,000 watts

The design procedure entails the selection of one set of voltage design points and the performance of a design, as based on an analytical model or set of design equations, at several of the design point power levels. This procedure is then completely repeated at other voltage design points. The design goal, in all cases, is to achieve minimum weight utilizing state-of-the-art components and techniques.



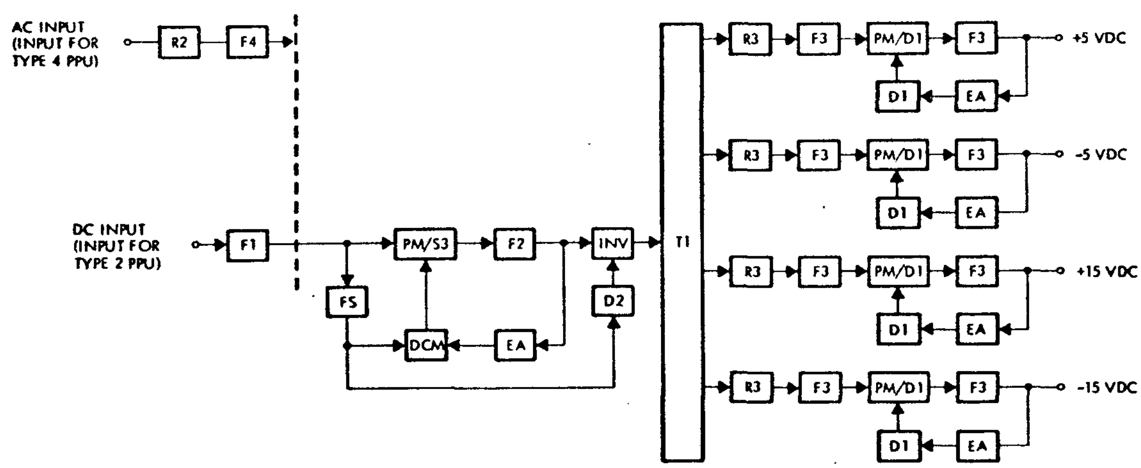
POWER FUNCTIONS

- F1 — PASSIVE FILTER (L-C, AC CURRENT)
- INV — INVERSION (SQUARE WAVE)
- T1 — TRANSFORMATION

SIGNAL FUNCTIONS

- D3 — DRIVER AMPLIFIER (SWITCHING INVERSION)
- FS — FREQUENCY STANDARD (3 PHASE)

Figure A-1. Function Block Diagram - Types 1 and 3 PPU



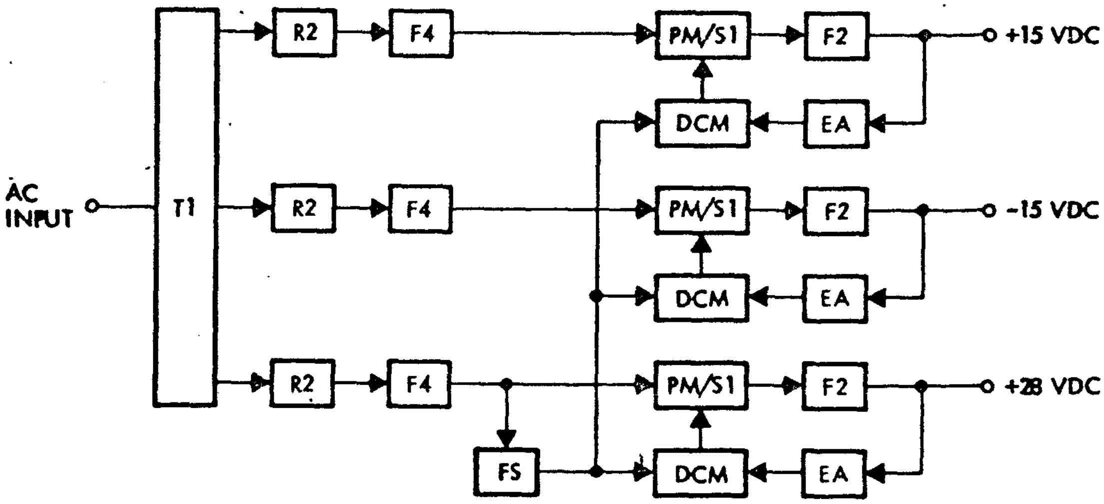
POWER FUNCTIONS

- F1 — PASSIVE FILTER (L-C, AC CURRENT)
- F2 — PASSIVE FILTER (L-C, AC VOLTAGE)
- F3 — PASSIVE FILTER (C, NO AC)
- F4 — PASSIVE FILTER (L-C, 1 PHASE RECTIFIER-FILTER)
- PM/S3 — POWER MODULATION, SWITCHING (BUCK)
- PM/D1 — POWER MODULATION, DISSIPATIVE (SERIES)
- INV — INVERSION (SQUARE WAVE-LC FILTER LOAD)
- T1 — TRANSFORMATION (LOW POWER, < 500W)
- R2 — RECTIFICATION (1 PHASE SINE WAVE)
- R3 — RECTIFICATION (SQUARE WAVE)

SIGNAL FUNCTIONS

- D1 — DRIVER AMPLIFIER (LINEAR SERIES)
- D2 — DRIVER AMPLIFIER (SWITCHING INVERSION)
- EA — ERROR AMPLIFIER
- FS — FREQUENCY STANDARD
- DCM — DUTY CYCLE MODULATOR

Figure A-2. Function Block Diagram - Types 2 and 4 PPU



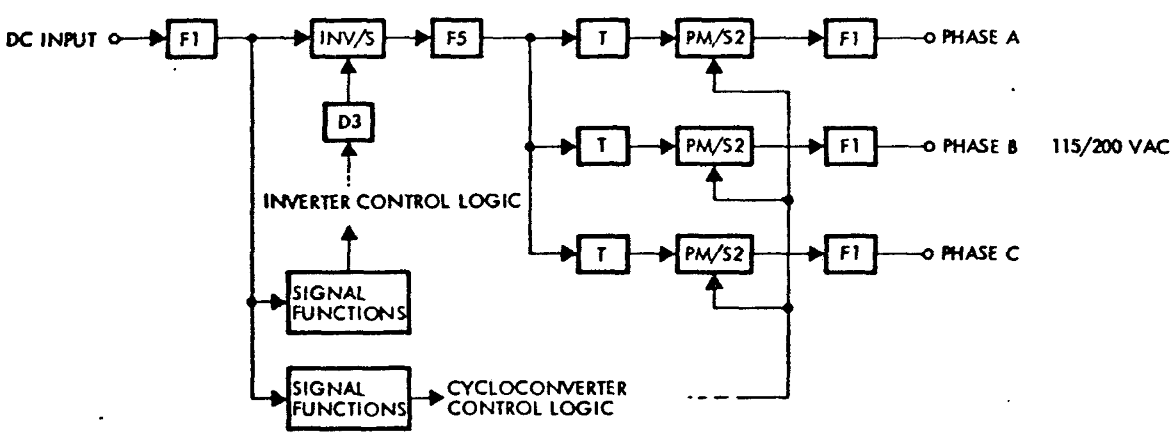
POWER FUNCTIONS

F4 PASSIVE FILTER (L-C, 1 PHASE RECTIFIER-FILTER)
F2 PASSIVE FILTER (L-C, AC VOLTAGE)
PM/S1 POWER MODULATION, SWITCHING (BUCK)
T TRANSFORMATION (LOW POWER)
R2 RECTIFICATION (1 PHASE SINE WAVE)

SIGNAL FUNCTIONS

EA ERROR AMPLIFIER
FS FREQUENCY STANDARD
DCM DUTY CYCLE MODULATOR

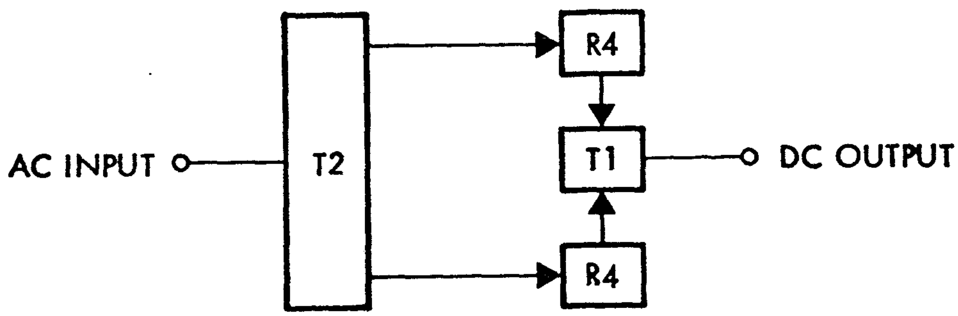
Figure A-3. Function Block Diagram - Type 5 PPU



FUNCTION CODE

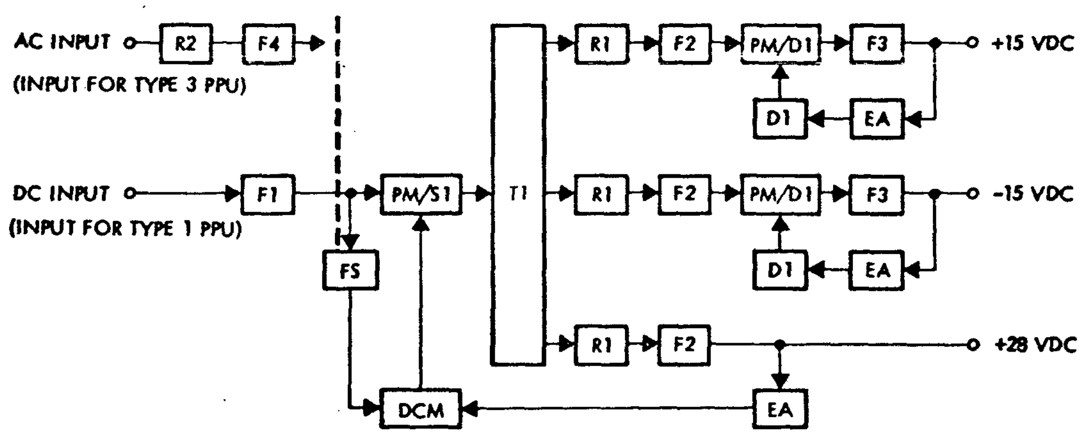
F1 PASSIVE FILTER (L-C, AC CURRENT)
F5 PASSIVE (AC) FILTER (L-C, AC VOLTAGE AND CURRENT)
INV/S INVERSION, SINE WAVE (SERIES RESONANT, SCR TYPE)
T TRANSFORMATION
PM/S2 POWER MODULATION, SWITCHING (PWM RECTIFICATION)

Figure A-4. Function Block Diagram - Motor Drive Inverter CPU



T2 TRANSFORMATION (HIGH POWER, POLYPHASE)
T1 TRANSFORMATION (LOW POWER)
R4 RECTIFICATION (POLYPHASE SINE WAVE)

Figure A-5. Function Block Diagram - Transformer/Rectifier CPU



POWER FUNCTIONS

F1	PASIVE FILTER (L-C, AC CURRENT)
F2	PASSIVE FILTER (L-C, AC VOLTAGE)
F3	PASSIVE FILTER (C, NO AC)
F4	PASSIVE FILTER (L-C, 1 PHASE RECTIFIER-FILTER)
PM/S1	POWER MODULATION, SWITCHING (PWM INVERSION)
PM/D1	POWER MODULATION, DISSIPATIVE (SERIES)
T1	TRANSFORMATION (LOW POWER)
R1	RECTIFICATION (PWM SQ WAVE)
R2	RECTIFICATION (1 PHASE SINE WAVE)

SIGNAL LEVEL FUNCTIONS

D1	DRIVER AMPLIFIER (LINEAR SERIES)
EA	ERROR AMPLIFIER
FS	FREQUENCY STANDARD
DCM	DUTY CYCLE MODULATOR

Figure A-6. Function Block Diagram - Central Inverter CPU

The general design constraints applied in the design of all functions are listed below:

- Thermal vacuum environment is assumed with maximum allowable component temperatures as follows:

Silicon semiconductors	100°C case temperature
Magnetics	30°C rise to hot spot
All others	85°C case temperature

- Minimum temperature is -35°C
- Capacitor derating factors are 60 percent on dc voltage at 85°C case temperature and 50 percent or less on ac current rating. Ceramic capacitor ac current ratings are based on simplified thermal calculations.
- Resistor derating is 25 percent on power at 85°C case temperature.
- Diode derating factors are 50 percent at 85°C case temperature for both forward current and peak reverse voltage. When paralleling of fast-recovery rectifiers is required, units matched for both recovery time and forward drop are selected. When series connected diodes are required, shunt-connected zener diodes are used across each diode to protect against the effects of unequal diode switching times and unequal voltages.
- Transistor derating factors are 80 percent on V_{CEO} and 50 percent on I_C both at 100°C case temperature. These are applied, as follows, in the selection of a particular device for switching application. The forward bias "safe area" curve, which requires inputs for pulsewidth, duty cycle, and collector-emitter voltage, is utilized. As an approximation, the transistor switching time intervals can be converted to an equivalent single pulsewidth and the duty cycle determined. This approximation is used because available safe area data are very limited. (A more valid approximation would entail the use of both forward and reverse bias safe area curves.) The peak collector-emitter voltage during the switching interval (with the above 80 percent derating factor applied) is used to enter the safe area curve along with the pulsewidth and duty cycle factors. The collector current capability, applying the given 50 percent current derating factor, is thus determined. Devices are placed in series or parallel, if required.

In paralleling power transistors, beta matched units are assumed with individual drive resistances (R_B). In connecting transistors in series, collector-base connected zener diodes are used to protect against the effects of unequal switching times and unequal voltage across the transistors.

- It is assumed that semiconductors are mounted directly to an aluminum heat sink, which is insulated from a baseplate having a maximum temperature of 71°C. Heat transfer is by conduction only. Heat sink weight is added to component weight in computing total function weight. It is determined by multiplying semiconductor losses by a factor equal to 0.05 lb/w loss. This figure is based on an assumed heat conduction of 0.5 w/in^2 to the baseplate.

- In magnetic design, the following general considerations apply.

  Peak core-flux density is limited as follows:

Oriented silicon steel	10,000 gauss
Powdered permalloy	4,000 gauss
Ferrite	3,000 gauss
Grain oriented 50 percent NiFe	11,000 gauss
Grain oriented 80 percent NiFe	5,000 gauss

  Current density is initially set at 500 circular mils per ampere in "filled window" designs.

  Gapped cores for inductor designs are limited to a gap length, one-tenth or less, of the smallest cross sectional dimension.

  To account for potting or hardware in magnetic designs, the following weight-scaling factors are used:

Conformally coated units	
Toroids	1.15 x (core weight + copper weight)
Pot cores	1.2 x (core weight + copper weight)
Gapped tape-wound cores (less than 1 lb)	1.25 x (core weight + copper weight)
Gapped tape-wound cores (1 to 10 lbs)	1.2 x (core weight + copper weight)

- Generic parts failure rates used for calculation of failure rates of each electronic function and complete PPUs are shown in Table A-4 which is based on TRW's unmanned spacecraft experience. The data assume 30°C ambient temperature and operation at 25% of initial rated part stress.

Table A-4. Generic Part Failure Rates for Spacecraft Applications

Part Type	Failure Rate (Failures/10^9 hrs) at 25 Percent Rated Stress and 30°C Amb. Temp.
Capacitors	
Ceramic	6*
Ceramic, feed-thru filter	10
Glass	3*
MICA	4*
Mylar	20*
Polystyrene	1
Tantalum, solid	9*
Tantalum, foil	20
Variable	40
Connectors	
General	40*
Coaxial	10*
Connector pins (active)	0.1*
Diodes	
Silicon, general purpose	2*
Silicon, power rectifier	44*
Tunnel	100
Varactor	40
Zener	23
4-level device (SCR, etc.)	136*
Inductive Devices	
Inductors (per coil)	10*
Transformers	
(<0.5 w)	14*
(0.5-1 w)	14*
(10-1000 w)	14*
Integrated Circuits	
Analog amplifier	150
RTL	35
DTL	25
TTL	50
MOS	100
Hybrid (Nonmicrowave)	65

Part Type	Failure Rate (Failures/10^9 hrs) at 25 Percent Rated Stress and 30°C Amb. Temp.
Resistors	
Compsition, carbon	2*
Metal film	1*
Wirewound allurate	10
Wirewound power	10
Wirewound variable	50*
Relays	
Magnetic latching	64*
General purpose	106*
Microwave Components	
Diplexer	131
Filters (low pass)	5
Omnimode transducer	3
Hybrid	23
Coupler	13
Variable attenuator	80
Waveguide	1
Waveguide tuning screw	0.5
Ferrite junction	5
Microwave diode	50
Stripline structure	1
Transistors	
Silicon (high power > 10 w)	40*
Silicon (low power <10 w)	10*
Field effect	60
Mechanical Components	
Squib pin puller	300,000/cyc.
Separation nut, explosive	48,000/cyc.
Hold down spring	110
Hold down arm	100
Hold down latch	100
Torsional spring	220
Compression spring	110
Pin puller device	48,000/cyc.
Shear pin	6
Hinge joint	100
Ratchet latch	100
Paddle hinge assembly	662
Boom hinge assembly	600,000/cyc.

Part Type	Failure Rate (Failures/10^9 hrs) at 25 Percent Rated Stress and 30°C Amb. Temp.
Other Components	
Antenna	90
Azimuth motor	200
Bearings	11
Bolometer	620
Compression spring	110
Crystals, quartz	20
Fill	70
Fuse	200
Heater, blanket	14
Heater, strip, flexible	10
Holding latch mechanism	100
Hydraulic damper, viscous	500
Interconnections	
Solar array	1
Soldered	0.5
Welded	0.5
Magnetic amplifier	14
Nozzle, hot gas	166/cyc.
Cold gas	16/cyc.
Pressure transducer	540
Pressure switch	320/hr + 80/cycle
Resolver	100
Slip rings and brushes	860 per brush per slip ring contact
Shuttle or mechanical switch	461
Solar cell	1
Solenoid	347
Squib	300,000/cyc.
Tank (per inch of weld)	0.6
Tanks (propellant)	120
Tank bladder	330
Thermistor	35
Thermostat	70
Thermostat switch	9
TWT (0-5 w)	500
(5-20 w)	2500
(>20 w)	7250

*Based entirely on orbital operating data

b. Function Parametric Data

Parametric data for each functional element of a PPU are plotted as

- Power loss in percent versus operating voltage at 1 KW
- Weight versus voltage for 1 KW output
- Failure rate versus voltage at 1 KW
- Relative change in percent power loss, weight and failure rate as a function of power level with respect to 1 KW

A switching frequency of 10 KHz has been assumed throughout. Results for two of the 30 functions which were analyzed are shown in Figures A-7 and A-8. Data for other function blocks are contained in Reference 25.

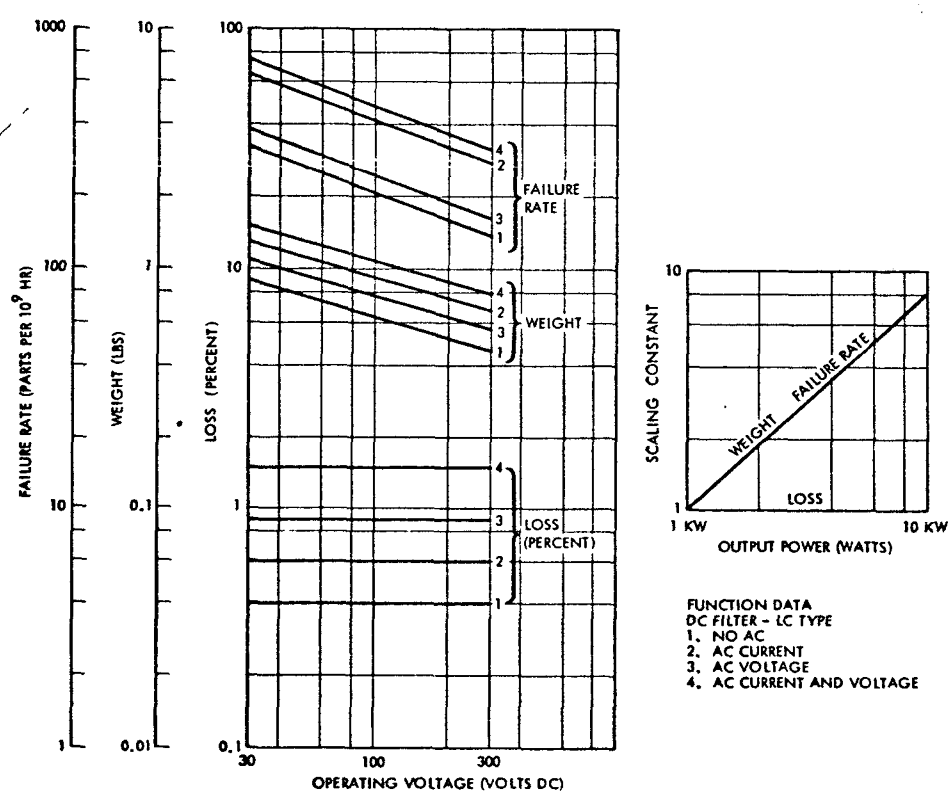


Figure A-7. Function Data, dc Filter - LC Type

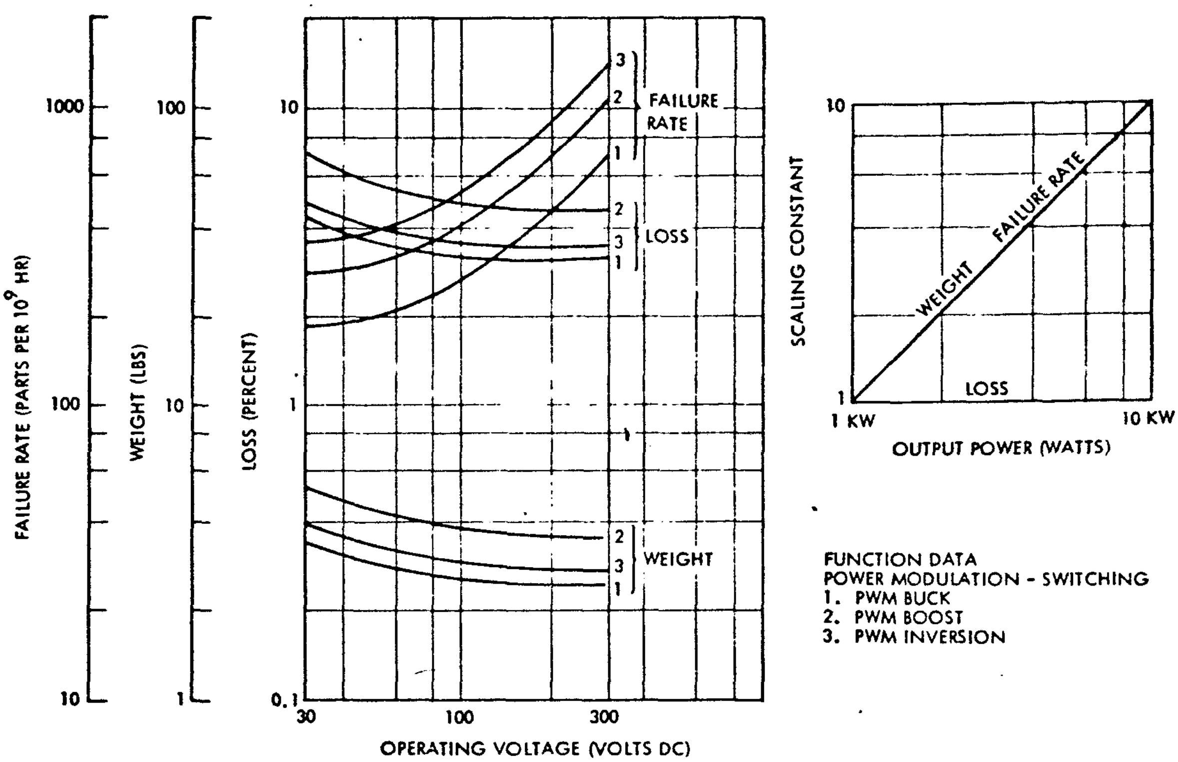


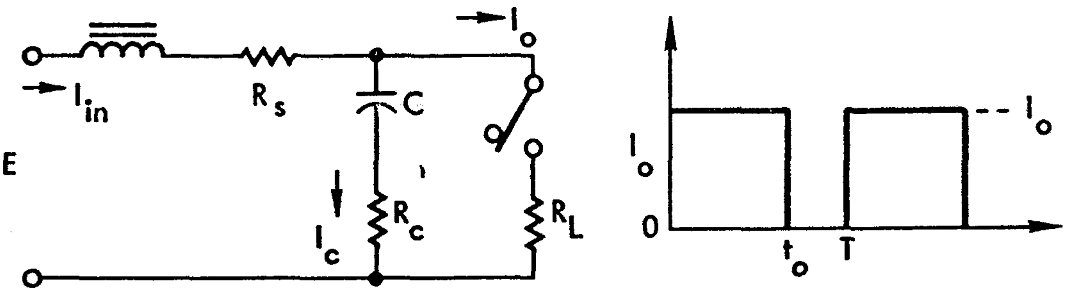
Figure A-8. Function Data, Power Modulation - Switching

B - PPU INPUT FILTER DESIGN

Single Section Filter Design Procedure

Filter weight determination for specified rms input current ripple, $I_{in(ac)}$ and a given load switching frequency fs are based on the following:

Circuit



Given

P_o	filter load in watts
f_s	load switching frequency in Hz
η	filter efficiency
E_{nom}	nominal input voltage
E_{min}	minimum input voltage
E_{max}	maximum input voltage
$I_{in(ac)}$	allowable rms input ripple current

Symbols

I_o	peak load current in amps
d	load duty cycle, $\frac{t_o}{T}$
t_o	load "on" time, μsec
T	switching period, $\frac{1}{f_s}$, μsec
V_r	audio susceptibility input voltage level, volts rms
P_ℓ	filter losses, watts
I_c	capacitor current, amps rms

δ	filter damping ratio
K	ratio of series to shunt resistance $\frac{R_s}{R_c}$
P	allowable filter peaking at filter resonant frequency
f_o	filter resonant frequency, Hz
f_n	filter natural frequency, Hz
$I_{o(ac)}$	fundamental component of load current, amps rms
ΔV_c	allowable peak-peak ripple voltage across C, volts
I_p	peak inductor current, amps
ΔI	inductor current increment during transient susceptibility test, amps
ΔE	input voltage increase during transient susceptibility test, volts
t_1	input transient voltage duration, μsec
A	required attenuation $= \frac{I_{in(ac)}}{I_{o(ac)}}$

Assumptions

$P = 2$ (6 db peaking)

Series loss = shunt loss $(I_c^2 R_c = I_o^2 R_s)$

$R_c + R_s << R_L$

Procedure

1. $I_o = \frac{P_o}{E_{min}}$

2. $d_2 = \left(\frac{t_o}{T}\right)_{min} = \frac{E_{min}}{E_{max}}$, $d_1 = \left(\frac{t_o}{T}\right)_{nom} = \frac{E_{min}}{E_{nom}}$

if $t_o = T$ at $E = E_{min}$

3. $P = \dfrac{E_{nom} - E_{min}}{\sqrt{2}\ V_r(rms)}$ (for $f_o \leq 1500$ Hz)

where $V_r(rms) = 0.1\ E_{nom}$ or 3 volts, whichever is less

4. $P_\ell = P_o \dfrac{(1 - \eta)}{\eta}$

5. $I_c = I_o \sqrt{d_1(1 - d_1)}$, rms

6. $I_c^2 R_c = \frac{1}{2} P_\ell$ or $R_c = \dfrac{P_\ell}{2 I_c^2}$

7. $K = \dfrac{R_s}{R_c} = \left(\dfrac{I_c}{I_o}\right)^2$

8. $R_s = K R_c$

9. Check that $R_c + R_s << R_L$ where $R_L = \dfrac{E_{nom}}{d_1 I_o}$

10. $\delta = \frac{1}{2}(K + 1) \dfrac{1}{[P^2(K + 1)^2 - 1]^{1/2}}$

11. $f_n \approx \dfrac{(K + 1)}{28} A f_s$ where $A = \dfrac{I_{in(ac)}}{I_{o(ac)}}$

12. $I_{o(ac)} = \dfrac{\sqrt{2}}{\pi} \sin(\pi d_1) I_o$

13. $f_o = f_n \sqrt{1 - \delta^2}$

14. $C = \dfrac{\delta}{\pi f_n (R_s + R_c)}$ which must $> C_{min}$

15. $C_{min} = \dfrac{I_o\, t_o\,(1 - d_2)}{\Delta V_c}$ where $t_o = \dfrac{d_1}{f_s}$

16. $L = C\, \dfrac{(R_s + R_c)^2}{4\delta^2}$

17. Select C and determine capacitor weight, W_c

Current Rating $= 2\, I_{c(max)}$ at f_s, 85°C

where $I_{c(max)} = I_o \sqrt{d_2\,(1 - d_2)}$

Voltage Derating $\simeq \dfrac{E_{max}}{0.6}$ at 85°C

18. $I_p = I_o + \Delta I$ where $\Delta I = \dfrac{\Delta E\, t_1}{2\,L}$

19. Calculate inductor weight, W_L, assuming gapped toroid, Hipersil core using (Reference 39)

$$W_L = (1.15)\, \frac{2\pi\, D_c}{\sqrt{3}} \left(\frac{L\, I_p\, A_c}{B_o\, \pi\, F_w}\right)^{3/4} \delta^{-1/2} \left[6\, F_c\, F_w + \left(\frac{D_i}{D_o}\right)\left(S + \frac{S^2}{6}\right)\right]$$

where $S = \sqrt{1 + \dfrac{12\, F_c\, F_w\, D_c}{D_i}} - 1$

D_c = 8.9×10^3 kgm/meter^3, density of copper

D_i = 7.65×10^3 kgm/meter^3, density of iron

F_w = .4, window fill factor

F_c = 2, ratio of mean length per turn of copper conductor to circumference of core cross-section

B_o = 1.5 weber/sq. meter, core operating flux density

A_c = 2.71×10^{-6} sq. meter, copper area per turn

W_L = kgm, inductor weight

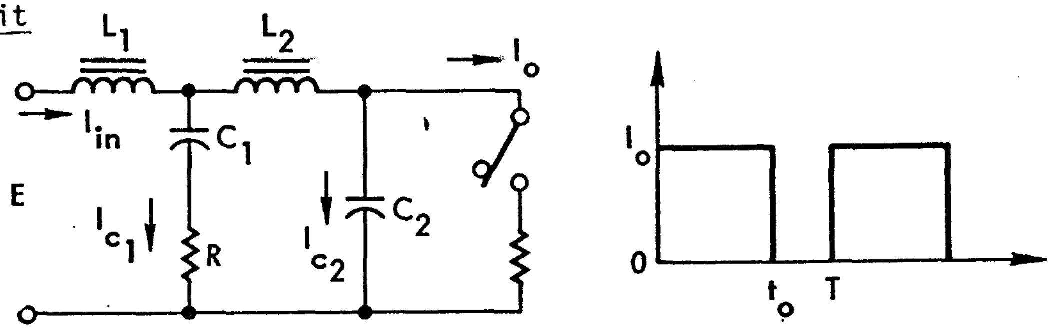
S = dimensionless factor

20. Determine power rating and weight of R_C

21. Sum W_L, W_C and W_R for total filter weight.

Two Section Filter Design Procedure

Circuit



Given

P_o	filter load in watts
f_s	load switching frequency in Hz
$E_{nom, min, max}$	input voltage - nominal, minimum, maximum
$I_{in(ac)}$	allowable RMS input ripple current

Symbols

I_o	peak load current in amps
d	duty cycle, $\frac{t_o}{T}$
t_o	load "on" time in μsec
T	switching period, $\frac{1}{f_s}$, μsec
I_{c_2}	capacitor current in C2, amp rms
P_1	allowable filter peaking in first section
δ_1	first section damping ratio

$I_{o(ac)}$	fundamental component of load current, amp rms
A	required attenuation
f_1	first section resonant frequency, Hz
f_2	second section resonant frequency, Hz
ΔV_c	allowable peak-peak ripple voltage across C2, volts

Assumptions

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}} << f_2 = \frac{1}{2\pi\sqrt{L_2 C_2}}$$

R of inductors is negligible

$$R\,L >> \sqrt{\frac{L}{C}}$$

$$P_1 = \sqrt{2} \quad \text{(3 db peaking)}$$

Procedure

1. $$I_o = \frac{P_o}{E_{min}}$$

2. $$d_1 = \left(\frac{t_o}{T}\right)_{nom} = \frac{E_{min}}{E_{nom}} \cdot , \quad d_2 = \left(\frac{t_o}{T}\right)_{min} = \frac{E_{min}}{E_{max}}$$

3. $$I_{c2(max)} = I_o \sqrt{d_2 (1 - d_2)}$$

4. Select C_2 such that $C_2 > \dfrac{I_o\, t_o\, (1 - d_2)}{\Delta V_c}$

   with current rating $= 2\, I_{c2(max)}$ at f_s, 85°C

   and voltage rating $\simeq \dfrac{E_{max}}{0.6}$ at 85°C

   and determine weight

5. $I_{o(ac)} = \frac{\sqrt{2}}{\pi} \sin (\pi d_1) I_o$, rms

6. $A = \frac{I_{in(ac)}}{I_{o(ac)}}$

7. Select L_2/L_1, C_2/C_1, and $\left(f_1/f_2\right)^2$ ratios as follows

A (db)	L_2/L_1	C_2/C_1	$\left(f_1/f_2\right)^2$
-40	1/2	1/10	1/20
-60	1/3	1/12	1/36
-80	1/4	1/15	1/60
-100	1/4	1/20	1/80

8. $C_1 = \frac{C_2}{C_2/C_1}$; select for proper voltage derating and determine weight.

9. $$\delta = \left[\frac{1 - P_1^2 \left(\frac{C_2}{C_1}\right)^2}{P_1^2 \left[1 - \frac{C_2}{C_1}\left(1 + \frac{L_2}{L_1}\right)\right]^2 - 1} \right]^{-1/2}$$

10. Calculate f_1 from

$$\frac{f_s}{f_1} \simeq \sqrt[3]{\frac{1}{\left(\frac{f_1}{f_2}\right)^2 \left(\frac{1}{\delta}\right)^A}} + \frac{\delta \frac{C_2}{C_1}}{3\left(\frac{f_1}{f_2}\right)^2}$$

11. $L_1 = \frac{1}{2\pi f_1^2 C_1}$

12. $L_2 = L_2/L_1 (L_1)$

13. $R = \delta\sqrt{\frac{L_1}{C_1}}$

14. I_{p_1} (peak current in L_1) $= I_o + \Delta I$

where $\Delta I = \dfrac{\Delta E \, t_1}{2 \, L_1}$

15. I_{p_2} (peak current in L_2) $= I_o$

16. Calculate inductor weights

L_1 use same equation as for single section filter

L_2 use powder toroid

$D_i = 8.4 \times 10^3$ kgm/meter^3

$B_o = 0.35$ weber/sq. meter

17. Select R and sum all weights for total filter weight.

C - CALCULATION OF WIRE SIZE

A computer program was designed to optimize the electric power distribution system for minimum weight. It selects the smallest number of smallest size wires from a listing of available standard AWG sizes and calculates the losses and voltage drops to be expected in each of the wires. Single-wire with structural return or two-wire systems are both handled by this program. When a structural return is assumed, the resistance of the structure is assumed to be negligible.

The program can handle up to 250 different loads supplied from each of ten distribution substations. Each load is assumed to be supplied from a single central distribution point within the substation. The voltage at all substations is assumed to be equal to a single-valued subsystem voltage.

Wire data are inherent in the program in the form of data statements. Up to 11 wire sizes are used in this program, although an expansion to a larger number of wire sizes is a simple modification. Wire data are in the form of lists of gauge numbers, resistances per 1,000 ft., weight per 1,000 ft., and maximum allowable current of a single wire in air.

The program uses as its input the system voltage, a listing of the peak power and the distance over which the power must be conducted for each of the loads in each of the substations. Additional data, such as wire derating factors for altitude and bundling, number of substations, and whether or not the structure is used as a return are input from the terminal.

For each of the loads in each substation, the program goes through the following basic calculations:

- An optimum voltage drop is calculated using equation (3.8) as derived in Section 3.2.4 and given by

$$\Delta V = \ell \sqrt{\frac{\rho \sigma}{m_G}}$$

where ℓ = cable length (ft.)

σ = specific resistance of copper (ohm-ft)

ρ = density of copper, lb/ft^3

m_G = specific weight of generator, lb/watt

- Upper and lower limits are set on the optimum voltage drop.
- The resistance required to produce the optimum voltage drop is calculated, after compensating for an assumed 50°C temperature rise, using Figure 3.29.
- The required resistance per 1,000 ft. of wire is calculated.
- The resistances of each of the wires in the data listing are compared with the required resistance, and the smallest wire capable of producing an equal or smaller resistance is selected.
- Should the program be unable to find a single wire which is capable of producing the optimum voltage drop, it will increment the number of wires (up to a maximum of 20) and continue its search.

Having selected the optimum wire size from the standpoint of weight and voltage drop, the program then tests to determine whether or not the current rating of the wires is exceeded. If not, the program continues; otherwise, the size and number of wires is increased until the current falls within the allowable limit, and a flag is set which prints an asterisk in the output list to indicate that the wire size is determined by the current rating rather than by the optimum voltage drop.

The final selection having been made, the losses, actual voltage drop in the wire, and weight of the wires is calculated, and the program goes on to the next load. If a value of zero is found for power (peak), it assumes that there are no further listings for the current substation, and it proceeds to the output routine, where it sums the weight, losses and output power of each of the wires in the substation, writes the results on a file, and goes on to the next substation.

Additional features of the program are as follows:

- If a negative value of power is input, and the program is not instructed to ignore that fact, it then changes the input assumptions, assuming instead that a 3 phase ac distribution system is used in place of the dc or single phase ac.
- All output data are clearly presented, and page-formatted, with headers on each page.
- A 70-character line is reserved for descriptive material to be input from the terminal for each run.

- All output data are written on a disc file, which may be copied at a high speed printer at the computer facility.

- All input data are printed on the output file to serve as a check when the data are being examined.

A typical output printout is shown below.

28 V DC 2-WIRE SYSTEM,NO AC

STATION NO. 2

POWER WATTS	DIST. FEET	NO.OF WIRES	GAUGE (AWG)	WEIGHT POUNDS	HEAT WATTS	VOLTAGE DROP	VOLTAGE LIMIT	CURRENT AMPS.
150.00	5.00	1	10	.30	.333	.062	.079	5.37
23.00	15.00	1	20	.11	.184	.222	.238	.83
15.00	20.00	1	22	.09	.168	.310	.317	.54
15.00	6.00	1	22	.03	.050	.092	.095	.54
5.00	15.00	1	24	.04	.025	.138	.238	.18
5.00	15.00	1	24	.04	.025	.138	.238	.18
5.00	15.00	1	24	.04	.025	.138	.238	.18
250.00	6.00	1	8	.66	.606	.068	.095	8.95
60.00	6.00	1	14	.14	.156	.073	.095	2.15
100.00	20.00	1	12	.75	.957	.266	.317	3.61
15.00	6.00	1	22	.03	.050	.092	.095	.54
15.00	6.00	1	22	.03	.050	.092	.095	.54
70.00	12.00	1	14	.28	.429	.170	.190	2.52
70.00	12.00	1	14	.28	.429	.170	.190	2.52

TOTAL POWER= 798.0000
TOTAL HEAT = 3.4851
TOTAL WT. = 2.8271