Power Management and Distribution Trades Studies for a Deep-space Mission Scientific Spacecraft

[1]Greg L. Kimnach, [2]James V. Soltis
[1]*NASA Glenn Research Center, 21000 Brookpark Rd., MS 301-5 Cleveland, OH 44135, USA*
[2]*NASA Glenn Research Center, 21000 Brookpark Rd., MS 301-5 Cleveland, OH 44135, USA*
216-433-6251, Greg.L.Kimnach@NASA.GOV

Abstract. As part of NASA's Project Prometheus, the Nuclear Systems Program, NASA GRC performed trade studies on the various *Power Management and Distribution* (PMAD) options for a deep-space scientific spacecraft, which would have a nominal electrical power requirement of 100 kWe. These options included AC (1000Hz and 1500Hz) and DC primary distribution at various voltages. The distribution system efficiency, reliability, mass, thermal, corona, space radiation levels, and technology readiness of devices and components were considered. The final proposed system consisted of two independent power distribution channels, sourced by two 3-phase, 110 kVA alternators nominally operating at half-rated power. Each alternator nominally supplies 50 kWe to one-half of the ion thrusters and science modules, but is capable of supplying the total power requirements in the event of loss of one alternator. This paper is an introduction to the methodology for the trades done to arrive at the proposed PMAD architecture. Any opinions expressed are those of the author(s) and do not necessarily reflect the views of Project Prometheus.

INTRODUCTION

Spacecraft historically have had sub-1 kWe electrical requirements for GN&C, science, and communications: Galileo at 600 We, and Cassini at 900 We, for example. These low power level spacecraft are based on a 28 Vdc bus and have very short power distribution lengths. Also, low-power, near-earth missions (communications satellites, for example) rely on solar arrays and batteries to provide all power and to regulate the bus voltage. Because most missions have the same order of magnitude power requirements, the *Power Distribution Systems* (PDS) use existing, space-qualified technology and are very similar. As science payload and mission duration requirements increase, however, the required electrical power increases. Subsequently, this requires a change from a passive energy conversion (solar arrays and batteries) to dynamic (alternator, solar dynamic, etc.), because dynamic conversion has higher thermal and conversion efficiencies, has higher power densities, and scales more readily to higher power levels. Furthermore, increased power requirements necessitate an increased distribution voltage (to maintain distribution efficiency), which requires subsequent component design and space qualification.

A proposed deep-space mission has a 20 kWe science payload and a maximum 100 kWe *Ion Propulsion* (IP) load demand. This mission's power levels are better suited by active power conversion, and a Brayton-cycle driven turbo-alternator has been proposed. This alternator is a 400V *alternating-current* (AC) source and does not require current-limiting devices to keep the bus voltage from collapsing. This is a change in *Power Management and Distribution* (PMAD) design from low voltage DC, and requires the development of space-rated, high-voltage switchgear.

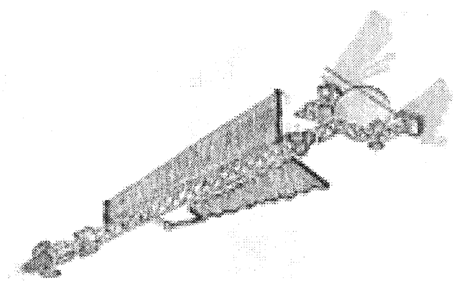
PMAD is defined herein as all power conditioning and controls required to safely, reliably, and efficiently transmit electric power from the source to the spacecraft bus and subsequently the payloads. Safe distribution design has the goal of reducing the possibility of an electrical system failure leading to the loss of the spacecraft or a de-orbit scenario. Reliable distribution is the proper selection and design of components and subsystems to operate in the expected environments, and is the incorporation of contingencies to minimize and recover from fault conditions with minimum interruption of power flow. Efficient distribution is the maximization of electric energy available to the payloads and thrusters.

The trade space criteria of the PMAD system for space missions are: safety, mass minimization and its associated cost impact, and reliability. Safe operation is tantamount for the reasons mentioned above, and is foremost in any design consideration. Cost considerations are primarily launch (i.e., currently $10,000/ kg), hardware development and manufacturing, and so-called *Commercial of the Shelf* (CotS) hardware costs. (It should be noted that CotS can include hardware developed, tested, and space qualified under other NASA, government, or private space missions.)

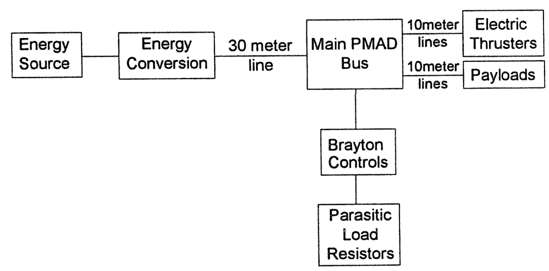
The spacecraft design must fit into the launch vehicle's volume and mass envelope. Reliability of the PMAD system is determined by component MTTF, system stability, power quality, and fault tolerance of the system. Thus, a deep-space mission spacecraft—given a set of launch, payload, and mission requirements—will have its PMAD design based on safety, mass, reliability, and hardware acquisition and development costs. The "Phase A" study herein discussed is the design considerations and resulting system mass for an AC-PDS, and includes some comparisons with the DC-PDS alternative. Both systems are assumed to have an AC source, which is rectified for the DC option.

PMAD SYSTEM OVERVIEW

The electrical power requirement for this conceptual deep-space mission is estimated as a maximum 100 kWe. This high power requirement, compared to previous missions, lends itself to having an alternator, which scales to higher power levels better than passive conversion systems, as the source. A proposed vehicle, Figure 1a, results in the simplified one-line diagram for the proposed alternating current PMAD system as shown in FIGURE 1b. Energy conversion via the alternator, which produces *Alternating Current* (AC), occurs physically distant from the loads: the AC alternator is at the front of the concept vehicle, power is transmitted down the 30 meter boom to the PMAD bus, from which it is distributed to the loads are another 10meters away. Because the primary distribution harness is 30meters and potentially supplies 100 kWe, the transmission voltage and frequency must be judiciously selected.



(a) Vehicle.



(b) One-line diagram.

FIGURE 1. Vehicle Concept and PMAD One-line Diagram.

To facilitate the understanding of the AC PMAD trade studies the reader should be aware that the basic topology of the PMAD system is dependent upon the vehicle concept, as well as the operational and system requirements. A proposed vehicle has 10 *Power Propulsion Units* (PPUs) with two 10 kWe ion thrusters per PPU. (One thruster is redundant backup per PPU.) There is a single *Science and Communications* (S/C) bus rated at 20 kWe, and auxiliary bus rated at 12 kWe. A post star-up mode requirement to operate at full capacity after any single-point failure results in a dual electrical source/dual PMAD bus configuration. Thus, each PMAD bus and source is designed to operate at the full 100 kWe condition, but nominally operates at 50 kWe.

There are four distinct operational modes of the PMAD system: Start-up, propulsion, interplanetary coast, and science mode. During Start-up mod, while it is in NEO, a battery or solar array would be used to power-up the spacecraft; during the propulsion mode the PMAD system must be capable of supplying a maximum 100 kWe to the Ion thrusters, GN&C, communications, and payloads; during the coast mode, the spacecraft requires minimal heating, science, and communications power; during the orbital science mode, the PMAD system must supply a maximum of 20 kWe to the science and communication modules. Further, the propulsion, coast, and science modes have "normal" and "off-normal" modes of operation.

"Normal" mode is defined as both alternators operating. During Normal propulsion mode, the alternators supply 50 kWe at 400 Vrms and 1 kHz. The "off-normal" propulsion mode is defined by the loss of one PMAD channel and the remaining alternator must supply 100 kWe at 600 Vrms and 1.5 kHz. It should be noted that the alternators are assumed to never operate in parallel, therefore there are two PMAD systems rated at 50 kWe, but capable of operating at 100 kWe.

Finally, other factors affecting the PMAD design are the environment and operational life variables. Total gamma dosage levels for the PMAD system during the 12-year deep-space mission, are estimated to be on the order of

4.3Mrad, and the total neutron dosage on the order of $6x10^{12}$ neutrons/cm^2 (Mason, 2003). These numbers are based on having aluminum shielding of 100 mils. The average ambient temperature for the PMAD system is assumed to be 300K.

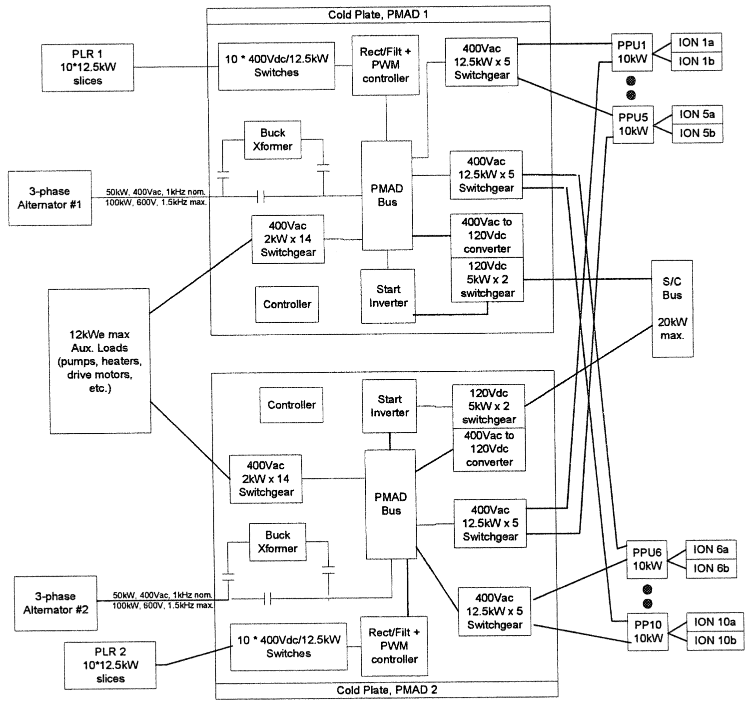


FIGURE 2. Proposed AC PMAD One-line Diagram.

PMAD TRADES

The mass trades of the PMAD system were accomplished by comparing a DC distribution alternative against AC. (The DC distribution system was assumed to have an alternator source, which was immediately rectified, and is very similar to the AC shown in Figure 2.) Specific trades discussed herein, but were not limited to: the alternator rating; harness and protection device mass; distribution voltage level, regulation, frequency, and efficiency; system protection; and component availability. The trades were accomplished with analysis, modeling, and realistic extrapolation of existing space-rated hardware specifications to the system and operational requirements.

Alternator

A power generation scheme for this spacecraft is two independently operating three-phase AC alternators, driven as closed Brayton-cycle turbo-compressor/alternators. (Scalability, efficiency, and development trade studies for other active and passive conversion systems were a separate trade study done outside of the PMAD scope.) A variety of alternator options (i.e., type of machine, control, voltage output level) were considered. The first option considered was whether the machine would be a *Permanent Magnet* (PM) or a wound-field type. The loss of field would result in no counter-torque and a subsequent increase in rotor speed, and is more likely to occur due to a *Single Event Upset* (SEU) in a wound-field machine than in a PM machine. (Although the flux density may decrease over the life of the PM machine, it will not be lost to an SEU.) The next issue was voltage control of the alternator output.

Phase control (load sharing, synchronization, etc.) of the alternators is not required, because the two alternators operate independently on separate busses and are never electrically paralleled. Bus voltage control, however, can be accomplished by varying the field current in a wound-field synchronous alternator, as well as by the rotor speed. A PM alternator generated-voltage, on the other hand, is a function of rotor speed alone. Without a separately excited field, a potential failure mode of the alternator--the loss of field current--is eliminated. However, because the mechanical input torque to the machine is a constant, the speed of the alternator is controlled by maintaining a constant electrical load. This is accomplished with a *Parasitic Load Resistor* (PLR) bank. The 125 kWe PLR is a *Pulse-Width Modulated* (PWM) load, which assures that a rated load, for the given operating mode, is present to the alternators. The PLR is rated 25 kWe more than the 100 kWe required for internal fault tolerance.

As for *Power Factor Correction* (PFC) via the machine, there is no advantage of one alternator type over the other. The *Power Factor* (pf) of a generator cannot be controlled by the field, because it is a function of the load as seen by the source and can be changed only by using a field-wound synchronous machine operating in motor mode (as a load).

A final trade is for the 400 Vrms +/-10% bus regulation during the 50 kWe and 100 kWe modes, and whether to accomplish this with an alternator + autotransformer/relays (see Figure 2) or with a specially wound machine. Because the machine is rotating at 1.5times the speed to supply 100 kWe load, its internally generated voltage and frequency are 1.5times greater than in the 50 kWe mode. An 110 kVA/600$V_{line\text{-}line}$ alternator requires a 600V:400V/37 kVA autotransformer, which has reduced iron mass requirement by directly conducting a portion of the power through the transformer windings. A specially wound machine, which relies soley upon magnetically converting mechanical power, would have a lower efficiency because of the required internal reactive and real voltage drop at the higher speed. Doubling the power to 100 kW at 400 $V_{line\text{-}line}$ would require the phase currents increase two-fold. Thus, the rating of the machine would be approximately 600 V/sqrt(3) * 160 A * 3 = 165 kVA. Thus, the specially wound machine would require an additional 55 kVA compared to the original machine requiring an additional 37 kVA autotransformer and three contactors. There is a significant mass penalty by using the machine to regulate the bus voltage, because the rotor mass (iron and windings) increase and requires a higher current capacity harness.

Based on these control and operational criteria, a PM synchronous machine was chosen as the energy conversion mechanism. It is rated 110 kVA and operates nominally at 55 kVA (400 Vrms/1 kHz). When operating at 100 kVA (600 Vrms/1.5 kHz) it has a 37 kVA autotransformer to buck down the voltage to 400V instead of being wound to internally drop the voltage, because the latter would incur greater mass, thermal, and inertial penalties.

AC versus DC Distribution, Voltage Level, and the Primary Harness

Given the energy conversion process (alternator), a substantial PMAD trade was whether power should be transmitted down the 30meter boom as AC or DC, and at what voltage level. (The DC distribution system assumes rectification and filtering of the alternator output.) While better line regulation and lower ripple over a wider range of load and line levels is possible with a DC-DC converter, the number of components and controls leads to a more complex, and less efficient system. Conversely, the primary advantage of AC distribution is that the voltage level is easily adjusted with a passive and efficient device: a transformer. Thus, the 400Vac can be stepped up to 5kV (required by the PPUs), rectified, and regulated more efficiently.

DC distribution does afford itself, however, to active current-limiting, which can reduce the probability of a bus collapse; however, it also requires more complex circuitry and is relatively slow compared to AC fault clearing for which fast (sub-cycle) initiation and commutation of fault current is possible.

The I^2R line losses decrease with increased distribution voltage: higher is better. Since transmission efficiency increases with increased transmission voltage, the inclination is to raise the voltage, either by rewinding the alternator or by stepping it up with a transformer or DC-DC converter. There are limits, however, upon the distribution voltage due to cable insulation breakdown, Paschen/corona issues, component voltage ratings (without the complexity of series connection of lower voltage-rated devices), mechanical deployment, diminishing returns, etc. Consider the mass savings by increasing the source voltage for a 100 kWe load. At 400 Vrms, the 30 meter primary cable mass is 55 kg per alternator, at 1000 Vrms it is 22 kg, and at 10kV it is 2 kg. Unfortunately, while mass has been significantly reduced with an increased distribution voltage, other performance factors have been affected: switchgear voltage ratings, insulation thickness, cable separation distance, mechanical deployment etc. Because space-rated and qualified power switchgear exists in the 270 Vdc range and could be developed and qualified realistically in the sub-1 kV range, going any higher than 1 kV would not be beneficial. It is for this (and mass) reason that 600 Vrms was selected as the maximum distribution voltage. These considerations resulted in the selection of 400 V nominal and 600 V maximum as the distribution voltage level.

The AC system trades had three lines (no neutral), and the DC system a hot and return line. To determine the required primary cable, it must be sized for a fully-loaded, single alternator scenario, have a maximum voltage drop of 1%, conform to MIL-STD-975, and consist of gages between 6AWG and 18AWG for mechanical deployment considerations. (Cable geometry--flat, co-axial, etc.--were not traded.) Thus, the cable must be sized for a 100 kVA load having a 600 Vrms source, because this will result in the maximum current. (An Excel spreadsheet calculates the required AWG for both the MIL-STD-975 de-rated current capacity and for the 1% drop, and the larger cable is selected.) These constraints, for a 1 kHz alternator, result in a primary AC harness having 12 #6 cables (4 per phase, no neutral). Furthermore, if the alternator output were immediately (passively) rectified, filtered, and transmitted as DC down the 30 meter boom, then the harness would be 18 #6 cables (9 "hot" and 9 "return"). The AC primary harness mass is 55 kg, while the DC harness is 83 kg. Complete harness information for both options are shown in Tables 1 and 2.

TABLE 1. Primary AC Harness Design.

I [A] @ 50kWe	I [A] @ 100kWe	AWG (I)	AWG (ΔV)	No. cables per bundle	Cable mass per Channel	I2R losses [We] at 50kWe	I2R losses [We] at 100kWe
80.2	106.9	6	10	12	55	182	324

TABLE 2. Primary DC Harness Design.

I [A] @ 50kWe	I [A] @ 100kWe	AWG (I)	AWG (ΔV)	No. cables per bundle	Cable mass per Channel	I2R losses [We] at 50kWe	I2R losses [We] at 100kWe
125	250	6	6	18	83	198	783

Voltage Breakdown: Paschen (Corona) Mitigation

For the purposes of this study, the spacecraft would be initially powered up in Low Earth Orbit (LEO) and may operate in celestial orbits of partial-pressure gaseous regions, therefore Paschen breakdown must be considered. Paschen (corona) is a breakdown and ionization of a (typically neutral) gas by a strong electric field, and the minima of the operating voltage versus the pressure-distance product is the maximum voltage which should be present for any given hardware component. Pachen breakdown can be mitigated either by potting and completely out-gassing components and assemblies, or by ensuring that the minimum pressure-distance product for a given curve is not exceeded. These considerations also lead to the conservative approach to not distribute voltage in the multi-kV range.

Distribution Frequency

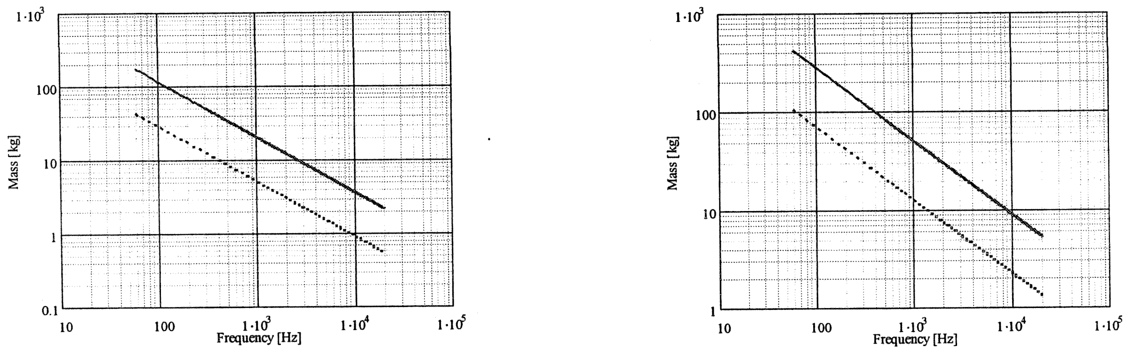
In an AC distribution system, the electrical frequency of the voltage affects the resistance of the distribution lines (due to skin and proximity effects), filters (power quality, EMI and EMC), and magnetics (transformer cores). And, unlike a DC system, there is a power factor which may or may not need to be corrected (see following section). The greatest impact of frequency is on the mass of magnetics: specifically the core of transformers. It has been shown by Schwarze (1984) that the mass of a transformer can be found by:

$$\text{mass [kg]} = \frac{Dw}{kVA^{0.25}} \cdot \left(\frac{10^3}{\alpha \cdot SF \cdot FF \cdot Js \cdot Bm \cdot f} \right)^{0.75}$$

Where, Dw = winding mass density [kg / m^3]
kVA = transformer rating
α = conductor space factor within the transformer window
SF = stacking factor of the core laminations
FF = form factor of the waveform (1.11 for a sine wave)
Js = the maximum current density [Amps / m^2]
Bm = magnetic flux density [T]
f = waveform frequency [Hz]

The above equation assumes a variety of transformer design issues/trades have been made: the efficiency, flux density, maximum current density, thermal dissipation, etc. These transformer optimizations, which are beyond the scope of a Phase A trade study, have to be made to completely trade an AC system against a DC option.

The AC distribution topology requires a number of transformers because the ion thrusters require high DC voltages (on the order of 5k Vdc) and because the alternator output voltage may be 600 Vrms. Stepping down to 400 Vrms from 600 Vrms is most efficiently accomplished via a three-phase autotransformer, since isolation is not required. Autotransformer ratings are significantly lower than a fully isolating transformer, because much of the power is conducted directly instead of magnetically transferred. (Figure 3b graphically depicts the impact of the source frequency upon the core and total mass of a 37 kVA transformer, used on a 110 kVA bus.) The 600:400V autotransformer is designed to operate at a single frequency of 1.5 kHz, and has a resulting mass of approximately 37 kg. Similarly, the 11 kVA PPU transformers are designed to nominally operate at 1 kHz, and the mass (as seen in Figure 3a) is approximately 20 kg.



(a) 11 kVA Transformer

(b) 37 kVA Transformer

Legend Solid line = total transformer mass
Dotted line = core mass

FIGURE 3. Transformer Mass versus Frequency.

LC filters, designed to attain a prescribed ripple at the output of a fully-loaded transformer/rectifier, are also impacted by the line frequency. During interplanetary coast and propulsion mode, either one or both alternators may be operational, and this leads to the four electrical operating points as shown in Table 3.

Table 3. Alternator Operating Points.

Total load [kWe]	Alternator Voltage [Vrms]	Alternator f [Hz]
50	400	1000
100	600	1500
20	368	890
10	356	920

It can be shown that to attain a DC voltage with a given ripple ratio, Fr, the minimum inductor (L) and capacitor (C) values are:

$$\mathrm{Lmin} := \frac{\mathrm{Rload}}{6 \cdot \pi \cdot f} \quad , \quad \mathrm{Cmin} := \frac{1}{3 \cdot (2 \cdot \pi \cdot f)^2 \cdot L \cdot \mathrm{Fr}}$$

Calculating the minimum required values for each mode (see Figure 4) having a ripple ratio of 0.4, the maximum L & C values for the S/C bus are 5mH and 150μF. Similarly, the L and C values at the output of the 5k Vdc rectifier for the PPUs are 3mH and 0.05μF.

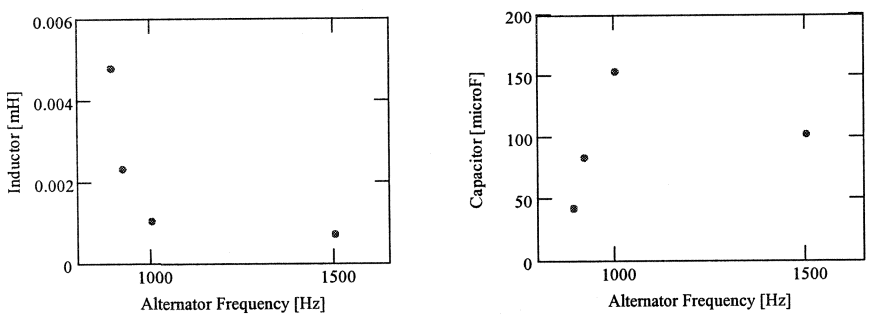


FIGURE 4. LC Values for S/C Bus at Each Operating Point.

Power Factor Correction

Power Factor Correction (PFC) in AC distribution systems reduces line losses by reducing the non-power transferring reactive flow in the lines. While PFC can reduce the mass of transmission lines, for example, by reducing the rms current flow, it requires active monitoring and control of the rectifier bridge of each load. Thus, PFC leads to a reliability versus efficiency—and consequently mass—trade.

As seen in Table 4, the 30meter primary distribution harness mass is 12 kg more for a 100 kWe load having a power factor 0.801-0.907, than for a fully power-factor corrected 100 kWe load: that is, when the power factor is less than 0.907, the mass increases to 55.4 kg from 43.6 kg.

TABLE 4. Power Factor Breakpoints for Cable Mass.

pf	mass [kg]
1	43.556
0.907	55.406
0.801	69.257
0.641	83.108
0.534	96.96

The primary harness make-up as a function of power factor is shown in Figure 5. Therefore the complexity and reliability of active PFC at each load in a space radiation environment is a substantial risk compared to the nominal impact on the mass savings.

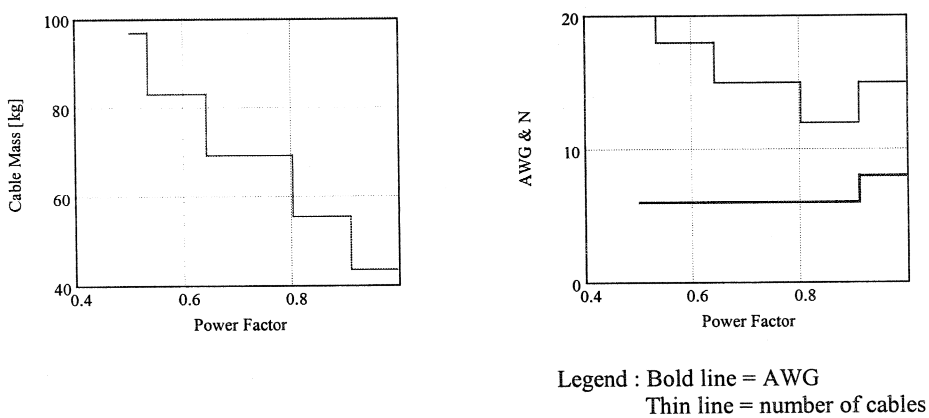


FIGURE 5. Primary Cable Sizing.

The difference for the remaining lines (i.e., auxiliary, S/C, PPU) are less impacted by pf, because the minimum gage size constraint. For example, the 14 Auxiliary Load Channels (shown in Figure 2), rated at 2 kWe each, require 3 #18AWG cables (one per phase) for loads having a pf greater than or equal to 0.418. The PPU 12.5 kWe channels have the maximum current at 400 Vrms and have 9 #16AWG cables (again, three per phase) for power factors as low as 0.925 and is 5.4 kg for pf between 0.69-0.925.

System Protection and Reconfiguration

The dual-channel PMAD distribution architecture, whether AC or DC, requires switchgear to connect the PPUs to one of the two PMAD busses. For the AC system, this requires switchgear rated at 400V/20A. The DC system requires 400V/30A switchgear. All PMAD switchgear has over-current protection. (It should be noted that the PPUs contain PPU self-commutating solid-state switches, which clear a grid-fault within one cycle.) Fuses are not considered as an option for fault clearing within the PMAD box, because fuses are non-resettable and preclude attempts at re-closure on transitory faults or thruster grid shorts, which are self-clearing upon removal of applied voltage

AC switchgear has inverse i^2t trip functions because the relatively stiff alternator can supply sufficient fault current without collapsing the main bus. These PMAD switches are slow relative to the fault-clearing devices within the PPU and are meant only to clear sustained bus or line faults (i.e., not designed to clear transitory fault conditions) or to reconfigure the system upon loss of an alternator channel.
A DC-sourced system (again, assuming the alternator output is rectified and filtered), on the other hand, has active, current-limiting, inverse v^2t trip characteristics to limit the fault current supplied by the source and, consequently, to keep the bus from collapsing. Current-limiting, solid-state switches essentially function by increasing the channel resistance (i.e., drop more voltage across the FET) to reduce the load voltage. Thus, these switchgear have higher thermal dissipation requirements than AC switches.

TOTAL PMAD MASS ESTIMATES

The PMAD system studies include the required gage sizes to meet MIL-STD-975, line losses and operating temperatures, transformer rating (if applicable), switchgear and converter masses, etc. Commercial, off-the-shelf hardware datasheets were used to develop models for switchgear mass approximations. (Note, that 3PDT AC switchgear has less mass than 2PDT DC switchgear for the same voltage and current ratings, since AC switches can interrupt current as it passes through zero.) Transformer masses were not based on optimum designs. These estimates are for the distribution system mass only, and do not include the mass, control complexity, reliability, etc. of the sources or of the devices. The AC and DC system masses are summarized below.

Each 100 kWe AC PMAD system mass is approximately 257 kg, while the 100 kWe DC PMAD system mass is approximately 218 kg. The major mass-contributing components for an AC and DC PMAD system are listed in Tables 5 and 6, respectively. It should be noted that for an AC system the total cable mass per PMAD is 75 kg, and for a DC system it is 105 kg.

TABLE 5. AC PMAD Mass Breakdown of Major Components.

	30meter Primary harness	Autotransformer & relays	PLR & Harness	PPU Switchgear + Harness	Aux. Switchgear + Harness	12kW Start Inverter	10kW AC to 120DC	120Vdc S/C Switchgear + harness	Other	Total
mass [kg]	55	47	35	13	16	25	18	13	35	257

TABLE 6. DC PMAD Mass Breakdown of Major Components.

	30meter Primary harness	PPU Switchgear + Harness	Aux. Switchgear + Harness	12kW Aux. Inverter	10kW 400:120 DC-DC	120Vdc S/C Switchgear + harness	Other	Total
mass [kg]	83	17	20	25	25	13	35	218

Although the AC system has the autotransformer mass penalty compared to the DC system, it has the advantages of lighter distribution hardware (switches and cables) and greater efficiency (lower converter count, and transformer/rectifier/filter boosting from 400V to 5kV for PPUs).

CONCLUSIONS

A closed Brayton-cycle turbo-compressor/alternator concept was selected as the primary power conversion for a conceptual deep-space mission spacecraft, and a Phase-A PMAD trade has been presented. The primary goal of the Phase-A study was to determine the relative masses of AC and DC distribution systems. Two fully independent 100 kWe channels, nominally operating at 50 kWe, were selected to meet fault requirements. While the mass of a DC distribution system channel is approximately 218 kg compared to 257 kg for that of an AC PMAD system, the lower complexity of the passive AC topology would lead to a more efficient system, since less solid-state control and active voltage conversion are required. The proposed AC PMAD system would meet the operational life requirements for the deep-space mission spacecraft.

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