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Power Management and Distribution Considerations for a Lunar Base

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POWER MANAGEMENT AND DISTRIBUTION CONSIDERATIONS FOR A LUNAR BASE

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Abstract

This paper discusses design philosophies and technology needs for the power management and distribution (PMAD) portion of a lunar base power system. A process is described whereby mission planners may proceed from a knowledge of the PMAD functions and mission performance requirements to a definition of design options and technology needs. Current research efforts at the NASA Lewis Research Center to meet the PMAD system needs for a lunar base are described. Based on the requirements, the lunar base PMAD is seen as best being accomplished by a utility like system, although with some additional demands including autonomous operation and scheduling and accurate, predictive modeling during the design process.

INTRODUCTION

The power management and distribution (PMAD) portion of any power system performs critical, yet subtle tasks. It takes the power from the source, conditions it as necessary, and moves it to the load reliably and safely. Its exact form is very much dependent on interfaces with other subsystems. What form is the output source power? How much power is to be transported? What level of reliability and quality is required by the user? These and many other detailed questions must be answered before the PMAD subsystem can be designed.

During the mission planning phase, it is difficult to discuss possible PMAD designs because the detailed requirements and subsystem interfaces are not known. This is the current situation with the lunar base: only general requirements have been developed. These general requirements must be used to define the performance of the lunar PMAD system so possible designs and technology needs can be considered. One way to do this is to first define the functions of the PMAD system, then consider the requirements the system must meet, then determine the implications of the requirements on the PMAD functions. Once the performance of the PMAD functions has been determined, possible designs and associated technology needs can be discussed.

Observations of the Space Station Freedom (SSF) PMAD functions and requirements can be used to help define the PMAD performance for the lunar base. The SSF has a large distributed power system with many users, a long life, and the capacity for future growth. We believe the lunar base power system will have many similar characteristics but with added challenges including: higher power levels, higher launch costs, larger physical size, longer eclipse periods, longer base to ground communication times, and a harsher operating environment.

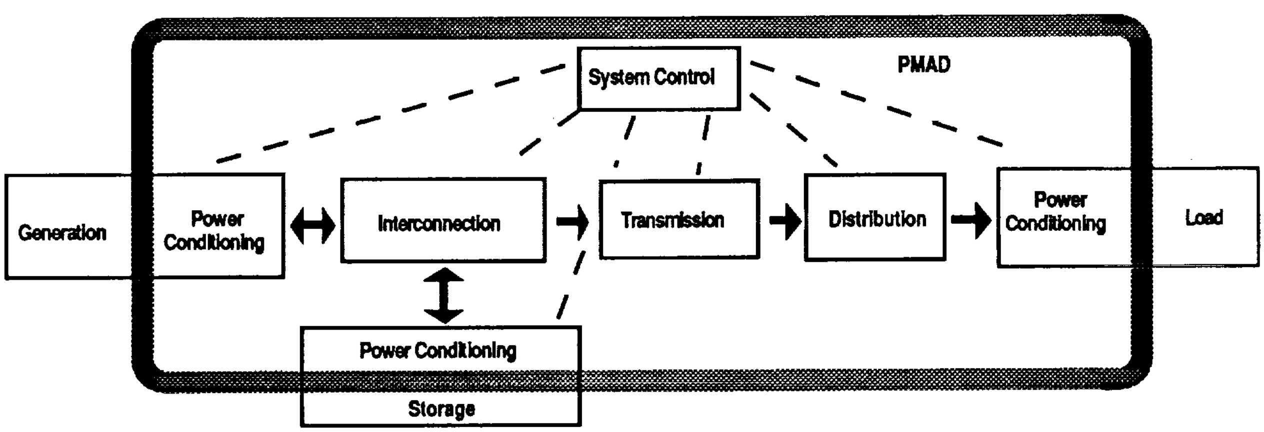

FIGURE 1. Block Diagram of PMAD Functions.

PMAD FUNCTIONS

The PMAD system is responsible for delivering the power from the source and storage devices to the loads. This requires several functions as seen in Figure 1 and explained in Table 1. These functions were previously derived by Kenny et al. (1990) based on a utility-type system such as the Space Station Freedom. However, these functions could be used to describe all space PMAD systems by varying the extent to which each function is performed. For example, in smaller spacecraft, the transmission portion would not be very complex since the source is close to the load and the power being moved is small. On the lunar base, however, there will be a significant transmission function because the source and loads may be separated by kilometers with hundreds of kilowatts to transfer.

TABLE 1. Description of PMAD Functions.

Generic PMAD Functions	Description
Source Power Conditioning and Control	Regulates the source electrical output and converts it into a form desired for transmission
Storage Power Conditioning and Control	Converts and controls the storage electrical input and output to the required values
Interconnections	Allows different source and source/storage combinations to be connected to the main bus or transmission system
Transmission	Transports the power from the source to a "load center". May be at higher voltage
Distribution	Transports the power at a lower voltage from or within a load center to the user interfaces
Load Power Conditioning and Control	Converts the power to a form and quality required by the user (this function is often performed by the user)
System Health Monitoring and Control	Monitors and controls the overall system including fault detection, isolation, recovery, and repair, and may also include load scheduling on larger systems

REQUIREMENTS

There is a minimum set of requirements that must be known before the performance of the PMAD functions can bedefined. When the values of these requirements are known, we believe it is possible to establish the PMAD system performance to the extent that a general discussion of PMAD design possibilities can begin. Table 2 shows the minimum list of requirements and the associated lunar base values.

TABLE 2. PMAD Requirements.

Requirements	Definition	Lunar Base Values
System Reliability	Availability of power to any given load	Man-rated
**Survivability	"Hardness" to deliberate hostile actions	No requirements
Lifetime	Time system must operate	30+ years*
System Safety	Protection of personnel, equipment, experiments, and environment during normal operation and failures	Man-rated
Source Type	Energy source & power generating method	Solar Array for 1st 75 kw, SP-100 with dynamic conversion for rest (Petri et. al. 1990)
Source Size	Amount of electrical power generated by source	Three 25 kw modules of solar array, 100 kw then 450 kw of dynamic nuclear (Petri et. al. 1990)
Source Growth	Growth of generating capacity	Day: 25 kw to 75 kw to 175 kw to 725 kw over 10 to 20 years (Petri et. al. 1990)
Energy Storage	Storage for eclipse, backup, or peaking	Regenerative Fuel Cells for the first 37.5 kw (Petri et al. 1990)
Power Quality	Refers to tolerances of operating parameters: frequency, voltage, harmonics, etc.	Not well defined, probably low EMI, regulated (utility like standards)*
Size of Platform	Distance power must be transferred	Kilometers from nuclear sources to loads, hundreds of meters from solar arrays to loads
Expected Loads	Comparison of power required by loads to power generated	Large number, diverse, total connected load is much greater than source capability*
Flexibility	Adaptability of system to new loads	Loads and load centers will change over life, In-Situ Resource Utilization plant may grow
Environment	Where the system must operate	Must operate and be deployed on the lunar surface (dust, radiation, vacuum)

*Assumed similar requirements to Space Station Freedom

** Typically a Dept of Defense requirement and will not be considered further here

Some of the requirements presented are assumed based on anticipated similarities with the Space Station Freedom (SSF). For the lifetime requirement, the SSF is expected to be capable of operating indefinitely, although 30 years is used as a design life for life cycle cost calculations (Thomas et al. 1990). Plans for the lunar base power growth only extend 10-20 years (Petri et al. 1990) , but it is reasonable to expect an indefinite life for the lunar base also.

It is important to distinguish between requirements and design solutions. Some requirements have led to such standard solutions that the design is confused with the requirement. An example is the reliability requirement. One solution often used is to make a component or function redundant to meet reliability requirements. It is not the redundancy that the system requires, but the reliability. How that reliability is achieved is a design choice; perhaps many designs would satisfy the requirements. Discriminators, such as cost or technology maturity, should determine which design is used.

Certainly, many more details of the requirements must be known to completely design the PMAD system. These requirements, however, are enough to establish the general performance of the PMAD functions. This is described in the next section.

FUNCTION PERFORMANCE

The values of the requirements in Table 2 begin to define the necessary performance of the PMAD system. A summary of the function performances resulting from the requirements is given in Table 3. By looking at the major requirements which impact function performance, one can see some general performance characteristics in each function and can begin to discuss design options. This type of analysis also shows the heavy demands placed on the PMAD functions by the lunar base requirements, more so than in previous space power systems.

Some requirements have a major impact on all the functions, some impact only a few. Lifetime, for example, impacts all the functions mainly through a maintenance or repairability feature. For the lunar base to operate indefinitely, maintenance and repair of all functions must be possible. Maintenance and repairability are new features for space systems (with the exception of the SSF). In previous space systems, where maintenance and repair were not possible, an extended operational life could be achieved by redundancy. Instead of repairing or replacing a failed component, a spare one could be used.

Environment also impacts all the functions: the PMAD system will have to operate in the dust, radiation, temperature extremes and 14 day eclipse period of the lunar surface. In addition, it will have to be constructed or deployed on the lunar surface. For the distribution function, inside one of the habitats or laboratories, construction may not be too difficult because much of the interior wiring could be accomplished prior to launch. But for the functions occurring on the surface, such as the transmission, deployment and construction will have to occur at the site. Any necessary tools to deploy the equipment must be considered as part of a proposed design. Again, this is an unusual requirement for space systems; most are integrated and assembled before being launched.

Other requirements, on the other hand, do not impact all of the functions. The "expected loads" requirement, for example, impacts only the distribution and control functions of the PMAD system. The distribution system must be designed to provide power to a multitude of loads, and the health monitoring and control system must allow the users to efficiently share the available power. Except for Space Station Freedom, a space power system with many more connected loads than available source power is also unusual (Kenny et al. 1990). Typical satellite systems have loads that essentially match the available source power.

Transmission, interconnection, and distribution are functions accomplished through a system architecture. Requirements that impact architecture decisions are system reliability, system growth, and flexibility. For reliability, the architecture must provide alternate means of moving power from the sources to the loads. For growth and flexibility, the architecture must handle new sources coming on line and changes in power requirements of loads and load centers.

There can be many arguments about the details of Table 3 and the extent to which each requirement impacts a given function. We present it as a tool to help define the PMAD system performance at this early stage in planning for lunar mission. Design options and technology challenges can now be discussed in light of the function performances identified.

TABLE 3. Required Function Performances.

Function	Primary Requirements that Determine Performance	Required Function Performance
source power conditioning	Lifetime	Must be maintainable
	System Safety	Protection/ isolation of source and system during fault conditions
	Source Type	Control of source's output: amount and form (voltage, frequency)
	Source Size	Appropriate size of power conditioning equipment
	Power quality	Converts source output power into transmission form within tolerances
	Environment	Must be tolerant of lunar conditions such as dust, radiation, and temperature extremes
Interconnection	System Reliability	Must interconnect sources & storage so if one fails, others are available
	Lifetime	Maintainable and flexible, able to connect to new sources & storage devices
	System Safety	Failure of one interconnected device does not affect other devices or the system
	Source Type	Must connect different sources, or different types of sources, with stability
	Source Size	Appropriate size of switchgear, cables, etc
	Source Growth	Must accomodate additional sources while maintaining stability
	Energy Storage	Fuel cells and electrolyzers must be tied into transmission system
	Flexibility	Must be flexible to handle rerouting of power (if new load center is built)
	Environment	Must be tolerant of lunar conditions such as dust, radiation, and temperature extremes
storage power conditioning	Lifetime	Must be maintainable
	System Safety	Protection/ isolation of fuel cell, electrolyzer, and system during fault conditions
	Energy Storage	Fuel cell output and electrolyzer input interfaced to transmission system
	Power quality	Fuel cell and electrolyzer interfaces do not cause out of tolerance distortions
	Environment	Must be tolerant of lunar conditions such as dust, radiation, and temperature extremes
transmission	System Reliability	Architecture must allow different avenues of routing power
	Lifetime	Ability to reroute power for maintenance or new load centers, maintainable
	System Safety	Must not interfere with surface activities or personnel
	Source Type	Consideration of transmission voltage & frequency depending on source output
	Source Size	Appropriate size of switchgear and cables
	Source Growth	Must be designed to handle extra power
	Power quality	Low noise system, must not radiate or receive outside noise
	Size of Platform	Must transmit power to distribution points
	Flexibility	Must have capability to reroute power
	Environment	Must be tolerant of lunar conditions and not interfere with surface activities
distribution	System Reliability	Architecture must allow different avenues of routing power
	Lifetime	Ability to reroute power for maintenance or new loads, maintainable
	System Safety	Protection of personnel and equipment during fault conditions
	Power quality	Low noise system, must not radiate or receive outside noise
	Expected Loads	Loads must share power
	Flexibility	Ability to deliver to different types & sizes of loads
	Environment	Less impact if located "indoors", but must tolerate possible depressurization
load power conditioning	Lifetime	Must be maintainable
	System Safety	Protection/ isolation of experiments and loads
	Power quality	Must not put noise/harmonics back on the distribution system
	Environment	Less impact if located "indoors", but must tolerate possible depressurization
system health monitoring & control	System Reliability	Must be able to detect faults, possibly incipient ones, & direct rerouting of power
	Lifetime	Fault detection, isolation, recovery & repair, self-healing
	System Safety	Power system continues to operate safely and reliably during control system failure
	Source Type	Monitors source outputs,reacts if out of tolerances (reconfigures or disconnects)
	Source Size	Must monitor available power
	Source Growth	Must monitor increased number of sources & schedule increased available power
	Energy Storage	Fuel cell and electrolyzer monitored, energy storage & release controlled
	Power quality	Measures parameters & flags problems
	Size of Platform	Health monitoring and control distributed over the base
	Expected Loads	Must measure many loads' power usage, must have proirity list of loads
	Flexibility	Must be able to adjust voltage & current out of tolerance trip points
	Environment	Must be tolerant of lunar conditions such as dust, radiation, and temperature extremes

DESIGN OPTIONS

In addition to performing all the functions as described in Table 3, the lunar base PMAD design must provide a low system mass. The cost to launch payload to the lunar surface is currently estimated to be between $80,000/ kg and $100,000/ kg which is approximately ten times the cost to launch to low earth orbit (Brandhorst 1988). The system mass must therefore be an important consideration in the proposed designs. However, the lowest PMAD mass does not necessarily imply the lowest system mass. If more mass in the PMAD subsystem leads to a more efficient delivery and use of power, that means less power must be generated at the source, and less energy must be radiated away as heat. Thus the PMAD design with the lowest system mass may not be the PMAD design with the lowest PMAD mass.

With the exception of low mass, the terrestrial utility system has been successfully meeting many similar requirements for almost one hundred years. The terrestrial electric utility system is a good analog for an initial design of a lunar PMAD system (Bercaw 1989). It is very reliable; it moves large amounts of power; it accommodates growth; power is available at many locations; and there are many loads on the system.

The terrestrial utility system meets its requirements through a grid of paralleled sources and loads. By paralleling the sources, the system pools its resources onto a power grid. This power can then be used wherever needed. The amount of power taken from the grid is not limited by the size of any one generating station, only by the size of the conductors and switchgear moving the power to the load. The loads can change and grow to the limit of the conductors and switchgear provided. Also, this system makes a reliable network: if one generator fails, others are on line continuing to provide power to the grid.

On the lunar surface, paralleling the sources would provide similar benefits. All of the available power can be used in whatever increments are necessary, limited only by the size of conductors and switchgear to the loads. As long as the choice of the initial conductor and switchgear size is reasonable, a paralleled philosophy of PMAD design can provide a flexible backbone for later expansion and growth. Reliability can be ensured by providing alternate paths for the power through proper system architecture design.

The architecture alternative to a paralleled system is a channelized one. In this case, the power is moved in separate channels from the sources to individual groups of loads. Channelization provides the benefit that the power ratings of the protective switchgear are reduced to the maximum power surge available in the channel, not in the entire system as would be the case in a paralleled architecture. However, there are many disadvantages. Non-critical loads would need to be hard-wired onto a particular channel and would not have the flexibility of using power available on a different channel. If the load mix isn't selected correctly, one channel may be operating near capacity all the time with loads having to wait for power, while another operates at only partial capacity. Even if the load mix is selected properly, there may still be power wasted through the inability to use "left-over" power on each channel. For example, channel A may have 300 watts available and channel B may have 300 watts available, but a 500 watt load would not be able to operate. It is also more difficult to provide efficient load scheduling on several channels than on one. For these reasons, a channelized system would not allow as efficient use of power as a paralleled one.

A less efficient system will be a heavier system for the same number of loads operating and power used. The source will need to be bigger, the PMAD components will need to be sized to handle the greater amount of power being moved, and the thermal control system may be larger. With the high transportation costs to the lunar surface, every efficiency point is important to reduce system mass.

A paralleled system has some design/technology challenges, however. In the terrestrial case, a new generator coming on line joins a "stiff" system (many sources spread throughout the grid, some in "spinning reserve" status to be available for any sudden system load changes, providing essentially constant frequency and voltage) Stability is not usually an issue. This would not be accomplished as easily on the lunar surface. Various types of sources and storage devices would need to be connected together, each providing a substantial portion of the total power. Spinning reserve would be an unaffordable luxury. The interactions between the sources and storage devices would need to be studied carefully, especially with the system operating under full load. This will require close cooperation between source and storage experts and PMAD designers to design the control and interconnection functions properly.

Although the terrestrial utility system is a good starting point, the lunar base power system faces more difficult challenges. Load scheduling, and fault detection, isolation, recovery and repair must be predominantly performed locally and autonomously. The amount of information to send and the transmission time to send it will preclude operation by a terrestrial operator. To achieve autonomous operation, operating decisions must be made at the lowest level possible in the computer hierarchy (Nurre et al. 1991). This allows many decisions to be made simultaneously (parallel processing) instead of sequentially (as would be the case if the decisions were made centrally). This "distributed intelligence" concept requires smart components such as programmable Remote Power Controllers (RPCs) and devices with built-in test and health monitoring capability.

Autonomous load scheduling will be required to insure the most efficient use of the available power. Based on similarities with SSF, the total power requirement of the loads will exceed the capability of the source if all loads are operated at once. Some loads will be critical and must be operated all the time or whenever needed; others can be operated intermittently, as power becomes available. All the loads must share resources to maximize the use of the available power. This can be accomplished through a scheduling program. The scheduling program takes power being used by the loads throughout the system, determines what additional power is available, then commands additional loads to come on line based on their priority and required power usage.

Accurate system modeling will be required for the lunar base power system. The impact of sudden load changes and new loads on the power system must be known before reliable system operation can be ensured. This can be accomplished either through hardware, duplicating every part of the power system on a testbed, or through software, by modeling all system components, or a combination of the two. In the case of the Space Transportation System, (the Space Shuttle) there exists an exact duplicate of the electrical power system. The duplicate tests the effect of new loads on the power system. This approach would not be feasible with the lunar base because of the number of anticipated loads, sources and storage devices, and the anticipated growth and change of the base. Therefore, there must be an accurate power system model, designed and tested along with hardware development, that can predict the system effects of load switching, faults, and transients.

There are many more design implications of the required function performances of Table 3 which warrant further discussion. Some, such as high voltage transmission of power, are being considered (Schwarze 1988 and Gordon 1990). Design approaches for other issues such as operation in the hostile lunar environment, maintenance over the long life, and insurance of ultimate system reliability, need to be discussed and considered in future studies. Low mass and life cycle costs must continue to be important parameters in design decisions.

Current Work

Currently, the Electrical Component and Systems Branch at Lewis Research Center is investigating some of the issues raised in the preceding discussion. We are investigating autonomous power system operation, including fault detection, isolation, recovery and repair, and scheduling, using a testbed with a brassboard and software (Ringer et al. 1991). Built-in test capability is being researched and applied in our work with advanced motor controls (Sundberg 1990). We are in the process of setting up a small facility with distributed high frequency power to investigate different system architecture options and benefits. Differences between a channelized and paralleled architecture will be studied and quantified. Some preliminary high frequency power system modeling work is being carried out by P.C. Krause and Associates (Wasynczuk and Krause 1990). Finally, two other areas with lunar base applications are being researched: development of high temperature (200^{o} C) components and devices (Hammoud et al. 1991), and the complex relationship between system cost and reliability (Suich et al. 1990).

CONCLUSIONS

Power management and distribution design options should be considered as early as possible for a new mission so necessary technologies can be defined and appropriate research implemented. This is difficult to do, however, because of the integrating nature of the PMAD subsystem in the overall electrical power system and its dependance on detailed requirements. This paper addresses some very preliminary lunar base power system requirements and derives general function performances for the PMAD system. Design options based on a terrestrial utility system were suggested. Paralleled sources and loads, autonomous scheduling, distributed intelligence and accurate system modeling were discussed as design solutions that could meet the required function performances.

Research work at Lewis is focused on making some of the lunar base design options feasible. Important areas such as autonomous control, modeling, architecture selection, high temperature tolerance, and reliability are being researched. When specific requirements are finally known, our goal is to have the technology base to implement the necessary PMAD design with the lowest system mass and life-cycle cost.

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