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Enabling Universal Access to Power on the Lunar Surface

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Abstract

The National Aeronautics and Space Administration (NASA) Artemis Missions will return human astronauts to the lunar surface, demonstrate technologies that establish a sustained presence on the lunar surface and enable human missions to Mars, and help create a lunar commercial economy. Creating a sustained permanent presence on the lunar surface will require access to continuous and highly reliable power to support mission needs. During Artemis, lunar surface operations will evolve and grow over time (years), requiring an increase in the amount of power needed (100s of kW) and distance that the power must be transmitted (up to 10 km during early Artemis missions). A lunar commercial economy is likely to exceed this power demand to the MW level and distance in the 100s of km. This increased distance and demand for highly reliable power drives the need to create an electric power grid by connecting localized lunar power systems (e.g., habitats, in-situ resource utilization plants, etc.), each containing one or more loads and/or sources. Developing a lunar surface power grid will allow lunar surface operations to resemble electrical utility operations on Earth; it allows power to be generated where it is convenient and allows power to be consumed where it is convenient and required. A lunar surface electric power grid will facilitate the growth of a lunar commercial economy because it provides a means to connect new loads to an existing electrical power system. A common standardized interface to the grid and a set of standardized voltages is required to take full advantage of the benefits of an electric power grid, similar to the terrestrial power grid. NASA Glenn Research Center is leading an effort to create universal access to power through the development of the Universal Modular Interface Converter (UMIC). The UMIC is designed to have a common interface that connects sources and loads compliant with the International Space Power System Interoperability Standard (ISPSIS) to a higher voltage AC transmission system or power grid. This presentation will further discuss the evolution of power during the Artemis missions, challenges associated with creating a sustained presence on the lunar surface, progress made on the UMIC, and future opportunities for technology development and standards.
Keywords: space power systems, lunar power grid

Acronyms/Abbreviations

ADD Architecture Definition Document
DARPA Defense Advanced Research Projects Agency
ISPSIS International Space Power System Interoperability Standard
LOGIC Lunar Operating Guidelines for Infrastructure Consortium
LunA-10 10-Year Lunar Architecture Capability Study
M2M Moon to Mars
NASA National Aeronautics and Space Administration
UMIC Universal Modular Interface Converter

1. Introduction

The National Aeronautics and Space Administration (NASA) is engaged in a long-term mission that will develop technologies and systems to return human astronauts to the lunar surface, establish the first ever permanent presence on the lunar surface, and prepare for manned missions to Mars. The Artemis Campaign[1,2] focuses on these objectives to get the first humans to Mars and conduct further lunar science. The execution of this plan is documented in the Moon to Mars Architecture Definition Document (ADD),[3] which gets updated each year based on feedback from industry. The ADD defines 5 segments as part of the Moon to Mars Architecture Framework:

- Human Lunar Return – Re-establish human presence and initial utilization on and around the Moon.
- Foundational Exploration – Expansion of lunar capabilities and Mars forward precursor missions.
- Sustained Lunar Evolution – Establish a steady cadence of human presence on and around the Moon.
- Human to Mars – Establish human presence on and around Mars.
- Future Segments – Additional segments can be added to enable continued exploration for the Moon, Mars, or beyond.

In addition to the Artemis Missions, the Agency has published the Moon to Mars (M2M) Objectives[4] that provides an objectives-based approach to human deep space exploration and focuses on the big picture. This document provides the framework for NASA's exploration goals, including near- and long-term lunar objectives and objectives aimed at human, Mars exploration. The M2M Objectives contains an objective regarding lunar surface power that envisions a larger system than may be initially required for Artemis:

> *Lunar Infrastructure LI-1: Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.*

Expansion of the Artemis lunar power system beyond the needs of the Artemis missions is a highly advantageous step towards this goal. Such an expansion will enable other future lunar elements to gain access to electric power on the lunar surface. Having access to power on the lunar surface is critical for larger systems that may not have mass margin for power generation equipment, especially at industrial levels, and for growing a lunar economy.

This paper focuses on enabling lunar systems to access electric power on the lunar surface. Section 2 focuses on the concept of universal power and addresses key aspects. Section 3 discusses long-distance power transmission on the lunar surface. Section 4 presents the Universal Modular Interface Converter that enables access to universal power, while Section 5 discusses future standards that will be required and how to address them.

2. Universal Power

All space assets require electric power to operate. The actual power demand level of the systems may vary based on the time of the lunar day and desired operations, but continuous power is required for the systems to survive. This means that electrical power must have high reliability and availability. In addition, if many systems need to access power, it must have a common interface that can connect the power sources to the power loads. This concept of all systems having access to electric power that is always accessible and available is commonly referred to as universal power. The universal power concept resembles the terrestrial power system. Universal power allows for larger systems to be deployed since they may not have to carry their own power generation and energy storage systems to the lunar surface.

The universal power concept requires a known common interface and a power strategy that can provide the required power even in the presence of faults and failures and is independent of environmental conditions. To help address the common interface concern and enable the integration of dissimilar power sources to help address the power reliability and availability considerations, the NASA Glenn Research Center is developing the Universal Modular Interface Converter (UMIC). This UMIC is a modular, bi-directional converter that is designed to interface space power sources with loads, which would also include secondary power distribution systems. The "Load/Source" side of the UMIC connects to the sources and loads that operate at 120 VDC and conform to the International Space Power System Interoperability Standard (ISPSIS).[5] The "Grid" side of the UMIC connects to one or more other UMICs via a long-distance cable or network/grid. The UMIC is designed to process 10 kW of power nominally and has a peak of 12 kW but is also parallelable to be connected to sources/loads that require higher power ratings. Based on current lunar surface power trade studies, which are discussed in Section 3, it is envisioned that AC power maybe used for power transmission distances beyond what is capable with 120 VDC. Therefore, the UMIC contains grid forming and grid syncing inverters.

3. Power Transmission on the Lunar Surface

Over time, lunar surface operations will grow and expand, increasing the power demand to a level requiring power from external sources. If the additional power sources are in proximity (less than 100 m), then power can be provided at the standard space power voltage of 120 VDC according to ISPSIS. For distances beyond 100 m, the voltage needs to be increased to reduce the transmission losses.

The concept of a lunar base and its power system has a long history that dates to when Astronauts first walked on the Moon. [6] Over the years, power transmission [7] and cable deployment has been studied. [8] A more recent trade study comparing DC, single-phase AC, and three-phase AC with AC frequencies in the range from 100 to 1000 Hz and voltages from 600 to 6000 Volts was conducted. [9] The trade study reported in [9] also compared power system networks including a radial, ring, and mesh for a power system that generated/consumed about 150 kW of total power and contained a total power transmission line distance of 10 km. For a system this size, [9] found that the mass trends are roughly the same regardless of the system architecture. Typically, DC had the lowest overall mass at any voltage above 100 VDC, three-phase AC was slightly heavier than DC, and single-phase AC was the heaviest. In addition, the higher the frequency the lower the mass but this mass savings was marginal. The data indicates that increasing voltage is in most cases, the most effective way to reduce mass. However, at some point, [10] reducing the conductor size does not have a positive impact on mass and the insulation mass increases due to the higher voltages, resulting in higher mass. Ref. [9] notes that no space rated switches currently exist (when used with proper derating) that could enable a DC-DC converter for a high voltage DC transmission system without requiring additional series stacking stages. It claims that with about 5 series stages composed of switches derated to 300 V (the best available voltage rating), the maximum realistic DC voltage would be 1.5 kV, and that further series stages would imply compromised reliability. Comparing the mass of a 1.5 kV DC system against higher AC voltages shows that an AC lunar system does provide significant mass savings. In addition, as power level and distance increase, an AC system would more easily be adapted to even higher voltages via a change in transformer design. This level of extensibility resembles the terrestrial power system. Based on this analysis, the UMIC grid voltage is being designed for 3000 VAC, 3-phase and 1000 Hz.

4. Creating a Lunar Power Grid

This section will discuss a potential growth of power on the lunar surface, from self-sufficient microgrids to support Artemis science missions to a power system that is *evolvable* and *capable of scaling to global power utilization and industrial power levels*.

4.1 Initial Artemis Power System / No Grid

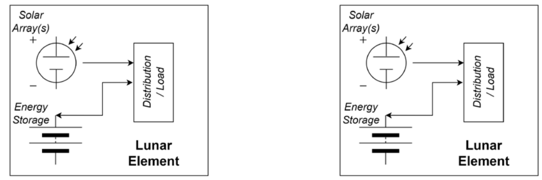

Fig. 1. Self-sufficient Artemis Power System

During the human lunar return and foundational exploration segments of the Artemis missions, most operations will occur near the lander or will be robotically deployed. Mobile assets used by the Astronauts may include a lunar terrain vehicle and pressurized rover.

At this phase, each lunar element will be designed to be self-sufficient and will have to bring all the power it will need to survive the lunar year. This type of system is shown in Fig. 1. All power generation and energy storage is contained within the element.

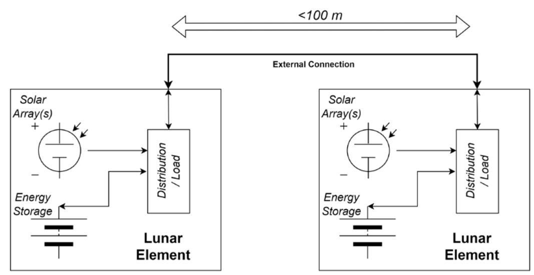

Fig. 2. Self-sufficient Artemis Power System with the Capability to Exchange (share) Power between Lunar Elements

As part of the self-sufficient power concept, it is possible for elements to exchange power in emergency or contingency operations. If one lunar element requires power, another lunar element many provide power if the two elements are in proximity to each other (less than 100 m) at the standard operating voltage. This power system architecture is shown in Fig. 2.

4.2 Localized Power Grid

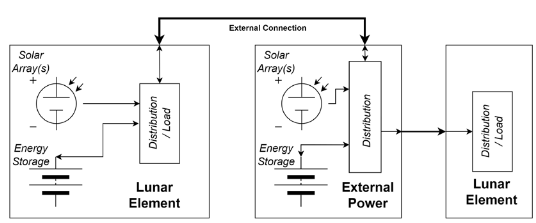

Fig. 3. Localized Power Grid where two or more lunar elements receive power from an external power source.

As the Artemis Campaign advances from the foundational exploration segment to the sustained lunar evolution segment, lunar operations and systems will expand and become more complex, increasing the power demand. This power demand may require the elements to receive power from an external power source. This concept is often referred to as external power augmentation. This external power source or external power augmentation device may be able to provide power to one or more lunar elements, creating a localized power grid as shown in Fig. 3. The localized power grid still may operate at the standard ISPSIS voltage of 120 VDC. This could be envisioned as the first lunar grid.

4.3 Lunar Regional Power Grid

As the Artemis mission and lunar systems continue to grow and power is required over longer distances, the voltage for which power is needed to be transmitted must be increased. This may be accomplished by connecting one power source to a single power load, or by connecting one or more sources to one or more loads, creating the first regional power grid on the Moon, as shown in Fig. 4. This type of system can also integrate dissimilar power sources, which can increase the power availability and reliability. One way to increase power availability and reliability on the lunar surface is by offering a nuclear power source that can generate power without the sun.

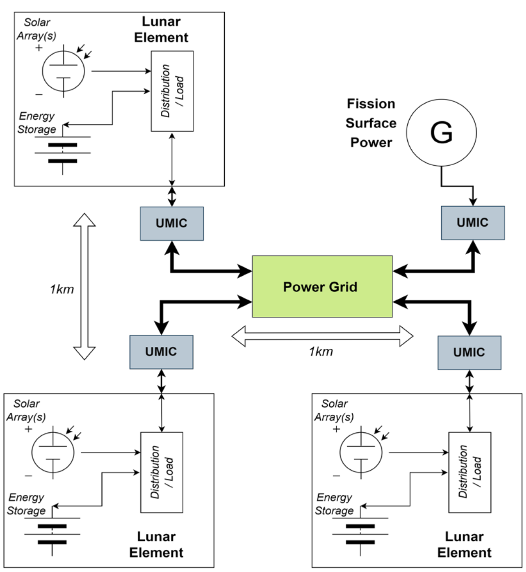

Fig. 4. Lunar Regional Power Grid

In this architecture, the grid connections will resemble a standard power source (when the lunar element is receiving power from the grid) or power load (when the lunar element is providing power to the grid) as defined by ISPSIS. A grid controller or grid manager would regulate the power distribution over the power grid network. During the Artemis missions, the power grid would attempt to deliver power to as many high priority systems as possible to ensure systems stay alive and meet high level science objectives. For a post Artemis grid that has industry systems/loads, the power grid may operate as a small-scale utility and mimic the terrestrial power grid where the power grid buys and sells power from lunar elements.

4.4 A Full Power Grid /Power Utility

The NASA Space Technology Mission Directorate's Envisioned Future Priorities for Power and Energy Storage [11] suggests that there will be a transition point where commercial industry will begin to lead (or assume ownership) of lunar surface power operations and NASA will transition to a customer. This transition point will likely occur once operations expand beyond the initial lunar south pole Artemis location. The total power demand is likely to be in the megawatts (vs the 100 kW-200 kW Artemis power demand) and will cover distances approaching 100 km (vs the 10 km distance through Artemis) and require a full power grid or power utility.

The design of a lunar power utility has many options and may change based on priorities and optimization strategies. One option is to adopt the approach of the terrestrial power utility and have different operating voltages/grid sizes. Expanding from the likely first lunar microgrid, a lunar regional power grid at the lunar south pole, other regional power grids can be built at other locations at the lunar south pole or towards the equatorial region. These regional lunar grids would be analogous to the street-level neighbourhood power grid. The regional power grids would then be integrated and interconnected through the larger/higher voltage power utility grid, which would be analogous to the terrestrial transmission grid. The power utility could manage power sharing between regional grids and integrate power sources from large solar array fields or other power sources. An example power utility is shown in Fig. 5. The grid operations would once again mimic the terrestrial power utility where the grid operator would buy and sell power to the different lunar elements or regions.

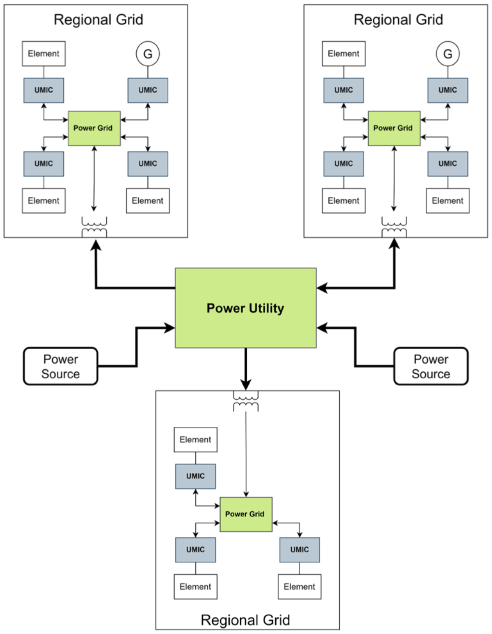

Fig. 5. Example Power Utility

5. Power Standards

A major focus of the larger technical community is related to standards, especially power standards. This is evident through the recent Defense Advanced Research Projects Agency (DARPA) 10-Year Lunar Architecture Capability Study (LunA-10)[12] and the Lunar Operating Guidelines for Infrastructure Consortium (LOGIC)[13] announcements. The current LOGIC effort will provide NASA with a set of recommended standards that they believe are required to enable commercial operations on the lunar surface.

The ISPSIS power quality standard provides the requirements for the power systems for lunar elements to operate at 28 VDC or 120 VDC and allows these systems to integrate with common characteristics. Power providers may not generate power at 120 VDC, but 120 VDC will be required at the user interfaces. Additional technical details specific to vehicles or programs can be contained in a power specification, but an additional standard is not required to build lunar elements for the Artemis Campaign. As surface operations expand to greater distances requiring higher transmission voltages and the use of a power grid, no additional power standards will be needed for power providers or consumers due to the design of the UMIC. The design of the UMIC will allow power providers and consumers to connect to long-distance transmission lines and the power grid and adhere to ISPSIS.

The operation of a lunar power grid will require additional power standards to be developed. This includes a power quality standard for the power grid, a grid architecture document that guides development of potential grid architectures, and finally a lunar grid operation document that contains the concept of operations regarding power management and includes contingency operations (load shedding), stability, and fault protection. Additionally, there needs to be consideration if a regulatory body is required to oversee power transmission on the lunar surface or if lunar power will truly be a free market.

Even though some of the lunar surface power grid architectures and policies may be derived from the terrestrial grid, there are some differences that need to be accounted for. The ionizing radiation in space and on the lunar surface poses a significant challenge towards developing high reliability power system components, especially those required for high voltage DC grids (i.e., DC to DC converters). With this challenge towards development of a lunar high voltage DC power system, AC power is being considered for long-distance transmission to reduce the transmission losses and overall mass of the power transmission system. There has been no AC power transmission on the lunar surface and therefore the interaction between power cables and lunar regolith is unknown. Use of high frequency AC power on the lunar surface (i.e., thousands of Hz or higher) decreases the mass and volume of transformers required for the AC grid, however it poses challenges such as higher reactance, which may cause power quality issues on longer cable lines such as Ferranti effect, higher losses, and will require sizing up the power system for the larger reactive power. Analytical models and terrestrial "dirty" thermal vacuum chambers that contain a chemically equivalent lunar simulant may provide insight on regolith interaction, but lunar surface testing/demonstrations maybe required. Therefore, it may not be possible to formalize power quality standards until verification and validation of those standards have occurred on the lunar surface. Attempting to write and draft standards prior to having sufficient data to support the basic power/voltage may unnecessarily limit alternate and perhaps superior options. It is best not to prematurely make decisions until sufficient data is obtained. Additionally, partnerships between industry and the government can be very beneficial to moving forward with testing/verifying long-distance power transmission as well as writing lunar power grid standards.

6. Conclusion

The lunar surface power system is a blank canvas and offers electrical power engineers the opportunity to design and implement a superior power grid to offer highly reliable and available power to electrical power consumers in a relatively unknown planetary surface environment. However, there are significant challenges to overcome which include the classical power transmission discussion of AC vs. DC, standardized interfaces, power quality standards and specifications, regulatory discussions, and how to grow from a small self-sufficient power system to a global power utility. It is attractive to consider the final end-state or system and derive requirements early-on that guide the development efforts towards the desired end-state. However, this does not guarantee that other goals/objectives/milestones will be appropriately met. In regard to the NASA and the Moon to Mars objectives, this may not help achieve the NASA objective of developing technology to deliver a human Astronaut to Mars. Careful considerations must be made to prioritize nearer term goals and objectives that can still lead to the desired end-state and development of standards when and where appropriate. In the case of lunar power standards related to a grid, analytical tests, Earth based environmental tests and perhaps a lunar demonstration should be completed before finalizing standards that will guide operations beyond the initial implementation and help ensure a successful lunar economy.

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References

[1] NASA, "Artemis Program," [Online]. Available: https://www.nasa.gov/specials/artemis/index.html. [Accessed July 2, 2024].

[2] NASA, "NASA's Lunar Exploration Program Overview," September 2020, [Online]. Available: https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf?emrc=f43185. [Accessed on July 2, 2024].

[3] NASA, "Moon to Mars Architecture Definition Document," NASA/TP – 20230017458, ESDMD-001 Revision A, January 2024.

[4] NASA, "Moon to Mars Architecture," [Online]. Available: https://www.nasa.gov/moontomarsarchitecture/. [Accessed on July 2, 2024].

[5] D.J. Sadey and N.A. Carbone, "International Space power System Interoperability Standards," 20220009953, NASA, July 26, 2022.

[6] J. Boretz, M. Koslover, "Synthesis of an Electrical Power System for a Manned Lunar Base," Electrical Power Laboratory, Redondo Beach, CA, IEEE Transactions on Aerospace and Electronics Systems, Vol 5, No. 5, Sept 1969.

[7] T. Kerslake, "Lunar Surface-to-Surface Power Transfer," NASA, NASA Technical Memorandum, NASA/TM—2007-21504, 2007.

[8] L. B. Gordon, "Electrical Transmission on the Lunar Surface," NASA Contractor Report, NASA/CR-2001-210759/PT1,2001

[9] G. Thomas, M. Granger, and J. Csank, "Lunar Microgrid Trade Studies to Define Interface Converter Requirements," AIAA 2023-4784, AIAA ASCEND 2023, Las Vegas, NV, October 23-25, 2023.

[10] T. McNichol, "AC/DC The Savage Tale of the First Standards War," Jossey-Bass, A Wiley Imprint, San Francisco, CA, 2006.

[11] J. Scott, "Envisioned Future Priorities for: "LIVE: Power and Energy Storage"" NASA, June 20, 2023.

[12] M. Nayak, "10-Year Lunar Architecture Capability Study," [Online]. Available: https://www.darpa.mil/program/ten-year-lunar-architecture-luna-10-capability-study. [Accessed July 2, 2024]

[13] DARPA, "Accelerating Interoperability Standards for Commercial Lunar Infrastructure," [Online]. Available: https://www.darpa.mil/news-events/2023-10-11. [Accessed July 2, 2024]