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Spinning-in Terrestrial Technologies

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Design of Space Microgrid for Manned Lunar Base: Spinning-in Terrestrial Technologies

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***Abstract*— The present study analyses the design of the power system of a manned lunar base, in Shackleton crater, using well-established terrestrial technologies deriving from DC microgrids with increased fault-tolerance needs. Expected luminance data from 2020 is used in order to select the ideal base location in terms of mean annual solar irradiance, according to which, the sizing of the power generation and storage units is performed. The proposed grid topology is meshed in order to satisfy the high reliability requirements of a manned space mission and, at the same time, to reduce the mass/ volume budgets of the mission. The load profile is constructed using a set of notional loads. Furthermore, a novel solar array configuration is proposed under the scope of maximizing the energy production under the specific irradiance of the base siting. After preliminary sizing is performed, a series of microgrid-related technologies is suggested, covering all levels of grid design, control and protection.**

Keywords—microgrid, lunar manned base, spin-in

I. Introduction

The current state-of-the-art in space power systems (SPS) architectures follows radial schemes, with additional redundancies, a best practice usually being N+1 for power modules [1]. Such approaches, however, lead to increased mass budget and pre-set fault tolerance (max two-points-of-failure). Furthermore, up until now, power systems are not designed in a scalable manner. Thus, these established good practices may not be sufficient for the future exploration missions, which may demand gradual module-wise deployment. New approaches however need to satisfy the already-standardized reliability because, the relative contribution of the power system, including distribution, batteries to spacecraft failure is quite high, mean value ~22% [2]. Thus, there is a need for majorly improved SPS.

In order to speed up procedures, collect more expert critical mass around this topic and capitalize on the developments on those, one should recognize the inherit similarities between smart grid related technologies and the requirements deriving from the vitality of the SPS. By nature, this subsystem is a typically stand-alone, remote energy network, which, in grid terminology, is called islanded microgrid [3]. A microgrid is controllable entity, consisting of Distributed Energy Sources (DERs) and loads that is able to operate both interconnected and disconnected ("islanded") from the grid [4]. Microgrid design principles have been applied in high-reliability applications, such as avionics, automotive, marine or rural areas [5]. For the past 10 years,

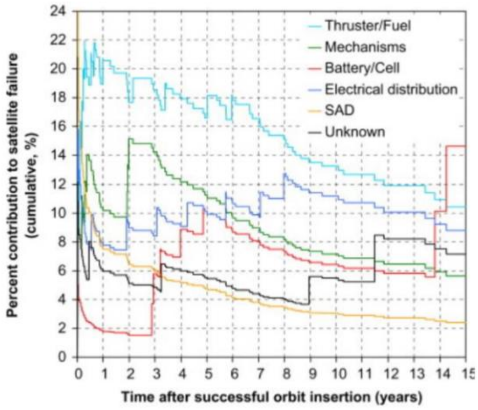

Fig. 1. Relative contributions of various subsystems to failures [2]

microgrid-related research includes a plethora of references, in which authors characterize spacecrafts and space bases as natural DC microgrids, e.g. [6]. However, research related to holistic power system design based on microgrids is particularly sparse [7], [8]. Systematic design, development and implementation methodologies in regards to SPS based on DC microgrids principles are still missing. Such spin-in approach has been pursued for other subsystems, e.g. Robotics [9], however not the SPS [10].

Looking towards the future steps in human space exploration, a first step can be the deployment of a permanently manned Moon base, an endeavour that is fully dependent on a lightweight, efficient, scalable, resilient power system. A possible design for its power subsystem is the meshed microgrid, i.e. multi-looped architectures that enhance system reliability through their multi-point of failure endurance and zonal protection schemes and are characterized by high-power transfer capability [11]. These topologies have been successfully applied in military bases, offshore bases, telecommunication stations and all-electric ships [5]. There is no standardized meshed microgrid formation because the design depends solemnly on the number of additional interconnections between the grid nodes. Nonetheless, meshed networks also present issues, such as protection and stability challenges [12]. This paper will address the later issue. The goal of this paper is to present a preliminary study for the design of a lunar base power system as a meshed bipolar DC microgrid, under the scope of proposing set terrestrial technologies applicable on future exploration activities on near-earth objects.

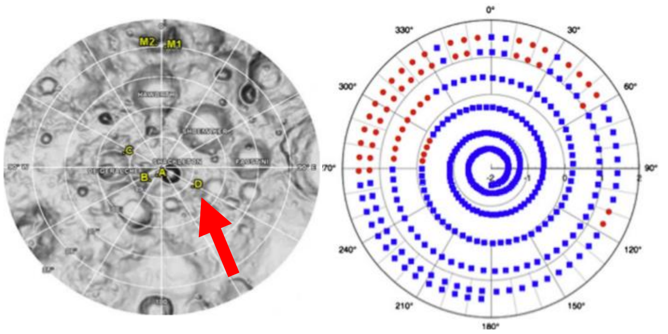

Fig. 2. Base Installation Candidates at Lunar South Pole (Left) - Illumination Profile of Point D (right) [13]

II. Lunar Microgrid Sizing

A. Installation site

Solar irradiance conditions is the main criteria for the selection of the installation site, since the lunar base is powered by photovoltaic (PV) arrays. In 2007, "Kaguya" mission collected data and estimated the total solar irradiance at various locations on the Moon for the year 2020. Point D (99.79˚S, 124.5˚E) at the rim of Shackleton crater, which is located on the Moon South Pole, was identified as the most illuminated point for 2020, with an annual mean irradiance of 86% and the longest eclipse period of approximately 11.5 Earth days during lunar mid-winter [13]. Fig. 2 presents the illumination profile at point D for the year 2020. Each dot corresponds to a time duration of 12 hours and characterizes the area as lit or dark. Due to solar symmetry only 6 months' worth of data are plotted, as the same illumination pattern is repeated for the remaining months of the year. To be noted that within the context of this study, it is assumed that the microgrid is already in place and thus, the year requirements are defined for the total duration of the year 2020.

B. Load Profiling

According to [14] a set of thirty notional loads for deep space missions is used. Each load is assigned power consumption for "on" and "idle states". In order to scale-up the studied lunar base to a realistic crew number, the loads were adjusted to a ten-member crew and additional loads such as greenhouse, solar array lunar dust cleaner and lunar roving vehicle were added, using consumptions from terrestrial equivalents. The loads are divided in ten categories as shown in Table 1. The scheduling is done - on an hourly step - trying to equally share the loads among the (Earth) days of the week assuming 8 working hours per day. During eclipses, the lunar base goes into power saving mode, leaving only the critical loads to an operational state. The scientific experiments are interrupted during that period. The weekly load scheduling of the scientific experiments conducted on the lunar base is shown in Table 2.

Table 1 - Load Scheduling based on illumination

Load Category	Always Operating	Operating only during sunlight
Communications	✓	
Crew Health Care	✓	
Crew Support	✓	
Data Handling		✓
EVA		✓
Crew Off-Duty	✓	
Solar Array Dust Cleaner	✓	
Greenhouse	✓	
Mechanical		✓
Science		✓

In Fig. 4, the distribution of the various categories loads is shown based on the operational status of the lunar base, i.e. on the left, normal/ sunlight and on the right, eclipse operations. In addition, the overall installed power is presented. Based on these considerations, Fig. 3 demonstrates the produced load profile during two weeks of full illumination (bottom) and one week of eclipse, followed by a week of illumination.

Table 2 - Load scheduling within an Earth week

Loading Conditions	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
EVA	✓						
Terraforming	✓	✓	✓	✓	✓		
Experiment 1		✓	✓				
Experiment 2			✓	✓			
Experiment 3				✓	✓		
Experiment 4					✓	✓	
Experiment 5						✓	✓

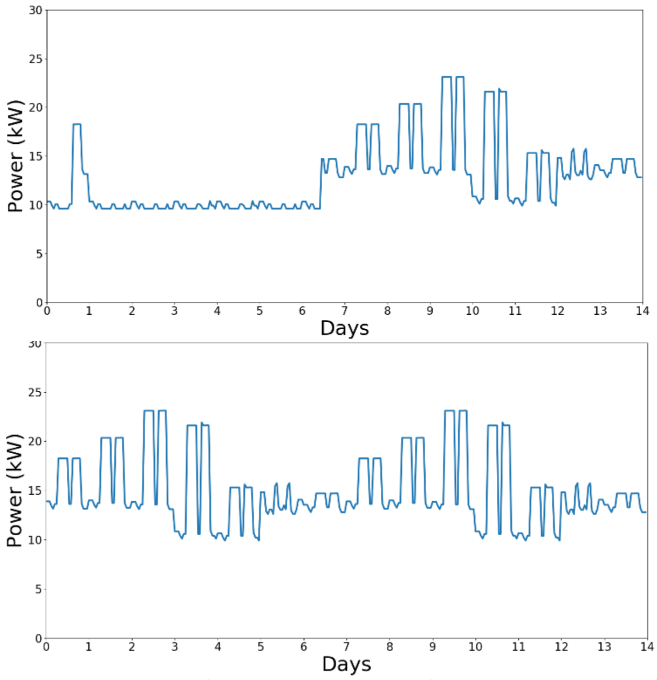

Fig. 3. Load Profiles during a) one week of sunshine and one week of eclipse (top) and b) two weeks of continuous sunshine (bottom)

C. PV Sizing & Configuration

The need for high efficiency space solar cells with increased energy density and radiation hardness has led to constructing multiple junction solar cells surpassing the 30% efficiency level [15]. Triple junction solar cells, consisting of three levels of semiconductor materials, are selected as they have been successfully used at space missions over the years. Each material's *p-n* junction produces electric current in response to different wavelengths of light.

Taking into account the particularity of the irradiance time series Point D, a novel PV configuration is designed in order to maximize the produced energy (see Fig. 5). At the Moon's South Pole, the sun will always appear low in the horizon. In addition to that, the Moon only tilts on its axis at an angle of 1.54˚. Thus, it is assumed that during a lunar year, solar elevation angle remains approximately stable at 0˚. This means that the sun is constantly at the position of sunrise. In order to maximize PV generation, modules are placed vertically to the ground, in order to form a 90˚ angle with the sun's rays. Panel orientation is defined via analysis of annual

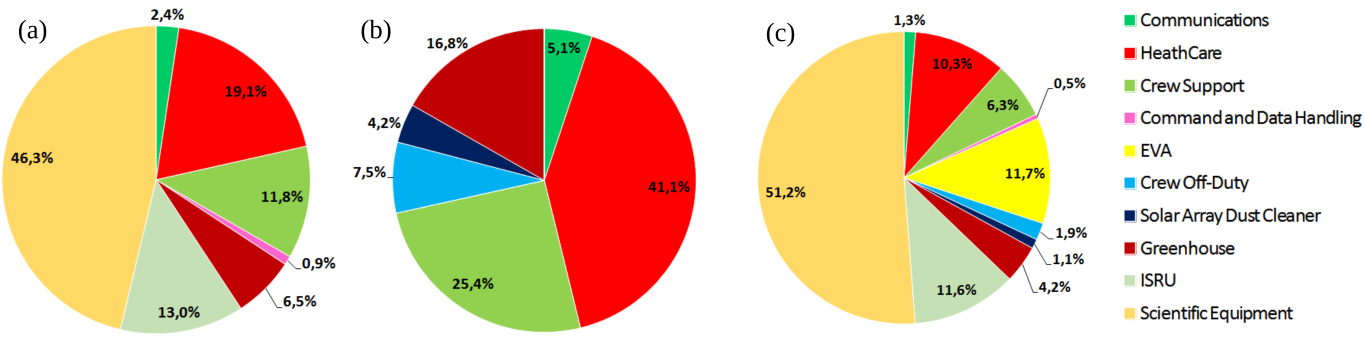

Fig. 4. Consumption percentages per load category during (a) maximum loading and (b) eclipse operation. In (c), the installed load power.

lunar orbits. Lunar month -i.e. period of time for Earth's Moon to complete one rotation on its axis with respect to the Sun - is ~29.5 Earth days. For uninterrupted power generation, the sunrays must constantly face at least one PV panel. The suggested PV configuration is consisted of three PV modules, consisting of three PV panels each, forming an equilateral triangle, placed vertically to the ground (see Fig. 5). The sizing of the PV installation is performed by considering the maximum power consumed by the lunar base for the year 2020, as defined in the previous subparagraph:

$$P_{max} = 23.11kW \quad (1)$$

Assuming modules of 8 kW rated power per panel, each module consists of a total installed of 24 kW_p power, and thus, the total installed power of the PV plant is equal to 72kW. However, this is never reached. In order to ensure that at all given orbit times the necessary 24 kW_p are provided, the proposed PV plant formation is set as demonstrated in Fig. 5. In order to provide an overview of the PV sizing, in the following paragraphs, a proper sizing study is presented, assuming that the PV cells are provided by Azur Space (model: TJ Solar Cell 3G30C). From the cell datasheet, the needed information such as nominal cell power, maximum power point cell voltage/ current etc., are taken. The necessary number of cells per panel is found with the help of cell maximum power point (MPP), given that the designed PV plant is destined to operate with MPP tracking. Throughout operation, there is a ~10% degradation compared to the MPP

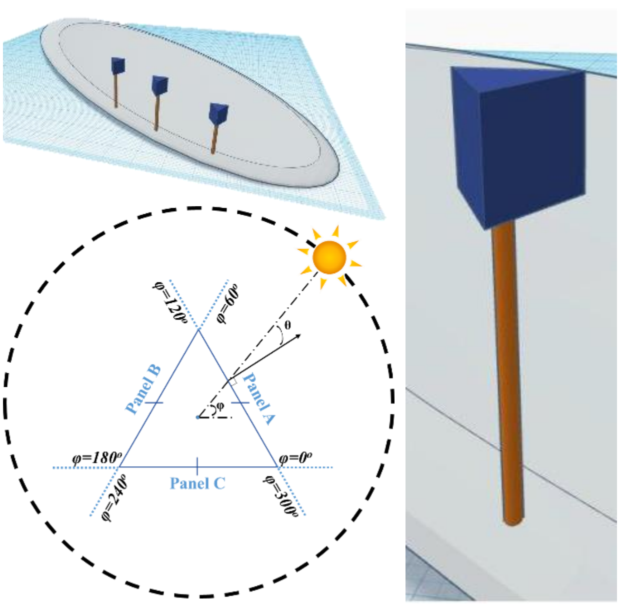

Fig. 5. Proposed lunar module configuration

voltage and current values. Consequently, sizing should be performed with End of Life (EOL):

$$P_{max}^{cell\_EOL} = V_{mpp}^{EOL} \cdot I_{mpp}^{EOL} = 2.246V \cdot 0.4866A = 1.092W \quad (2)$$

$$n_{panel} = \frac{8000W}{1.092W} = 7326 \rightarrow 7400\ cells \quad (3)$$

A common configuration is the in series connection of 100 cells. In order to reach the desired panel MPP, it is found that 74 cell strings must be connected in parallel. Indeed:

$$P_{max}^{panel} = n_{string} \cdot V_{mpp}^{EOL} \cdot n_{parallel} \cdot I_{mpp}^{EOL} = 8.087kW \quad (4)$$

The aforementioned sizing has been performed assuming cell temperature equal to 28°C. However, extreme temperature conditions on the lunar surface may increase temperature up to 95°C, due to the lack of atmosphere and bad thermal conductivity of surficial lunar regolith [16]. According to the PV manufacturer, the voltage on the maximum point of efficiency drops by $6.7 \cdot 10^{-3}$ V for each degree above 28°. The estimated string of 100 cells is expected to have the following decrease on its voltage:

$$\Delta V_{string} = 6.7 \cdot 10^{-3} V \cdot (95 - 28) \cdot 100 = 44.9V \quad (5)$$

Based on this, it becomes apparent that the number of cells per string increases by:

$$\Delta n_{string} = {\Delta V_{string}}/{V_{mpp}^{EOL}} = {44.9V}/{2.246} \rightarrow 20 \quad (6)$$

Consequently, taking into consideration the extreme temperature conditions, the necessary cells per panel are:

$$n_{panel} = \left(n_{string} + \Delta n_{string}\right) \cdot n_{parallel} = 8880 \quad (7)$$

The following calculations of the PV sizing take into account only one of the three PV modules, since the other two modules are identical. If φ is the sun angle as seen from each PV axis and θ is the sun incidence angle with respect to the normalized panel vector (see Fig. 5), then the production of each PV panel is defined by the Kelly cosine [17]:

- Panel A: $P_A(\varphi) = 8 \cdot \cos(\varphi - 30^\circ),\ -60^\circ \leq \varphi \leq 120^\circ$
- Panel B: $P_B(\varphi) = 8 \cdot \cos(\varphi - 120^\circ),\ 60^\circ \leq \varphi \leq 240^\circ$
- Panel C: $P_C(\varphi) = 8 \cdot \cos(\varphi - 240^\circ),\ 180^\circ \leq \varphi \leq 360^\circ$

Fig. 6 presents the power production for one PV module during a lunar month, namely a complete rotation of the Moon around its axis (~29.5 Earth days), assuming irradiance conditions as given in [13].

D. Battery Sizing

Space missions require rechargeable batteries with specific characteristics such as high energy density, operation

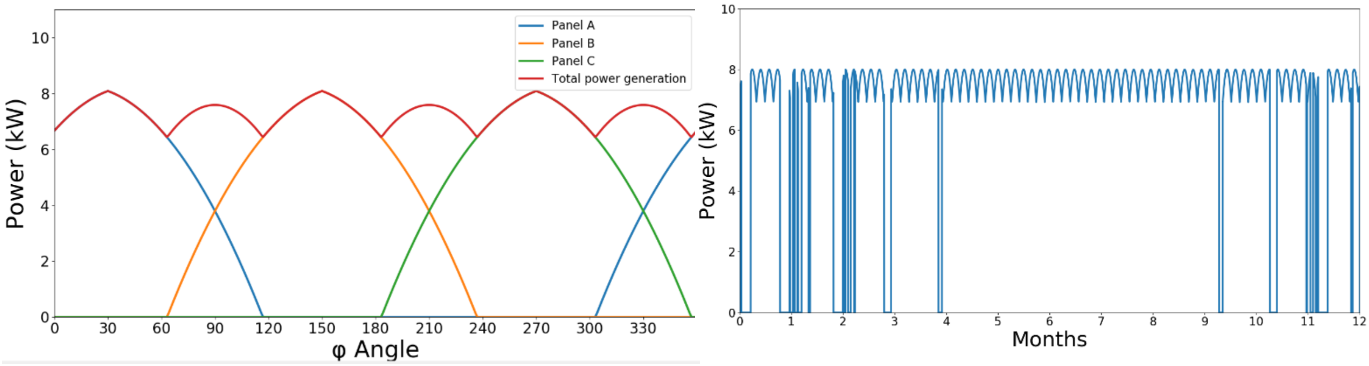

Fig. 6. PV production per module within one lunar month (left) and the examined year 2020 (right)

at a large temperature range, lightweight, reliability and tolerance to high intensity radiation environment, even during extreme events such as sun storms [18]. Space-qualified lithium-ion batteries meet those technological requirements. The detailed irradiance profile of the installation site for 2020 defines the size of the batteries, which are designed to cover the worst-case scenario, namely the $T_{eclipse} = 11.5$ days of eclipse when the Moon is shadowed by the Earth. As explained, during this time, only the critical loads are on, consuming a total power: $P_{min} = 9.6kW$. Hence, the energy storage system (ESS) should cover:

$$Cap_{req\_tot} = T_{eclipse} \cdot 24 \cdot P_{min} = 2.65MWh \qquad (8)$$

This capacity is the required one. In order to size properly an energy storage system, the depth-of-discharge (DoD) must be included in the calculations. In order to perform an indicative sizing of the batteries, the Li-ion battery cells from Saft (VES 180) are selected. According to the manufacturer's datasheet, the allowed DoD is equal to 80%. Thus, the total capacity of the energy storage system must be:

$$Cap_{ESS} = (2 - DoD) \cdot Cap_{req_{tot}} = 3.18MWh$$

In order to calculate an indicative setup of the ESS, the next step is to define the necessary modules. Each module contains multiple battery cells connected in proper configuration. The manufacturer suggests a 12S12P setup, meaning that 12 cells are connected in series and 12 in parallel. Each cell has a capacity equal to $Cap_{cell} = 50Ah$, with a mean voltage $V_{cell} = 3.6V$, leading to a $Cap_{cell} = 180Wh$. Thus, each 12S12P module has an equivalent capacity equal to $Cap_{module} = 12 \cdot 12 \cdot Cap_{cell} = 25.92kWh$. In order to cover the lunar base needs, ~123 modules are mandatory. Following the same logic as with the PVs, three storage units, comprised of 41 modules each is proposed, reaching a total capacity $Cap_{unit} = 1.06MWh$. In Fig. 7, the fluctuation of the stored energy within each unit is presented throughout the year 2020. It should be noted that the configuration of the

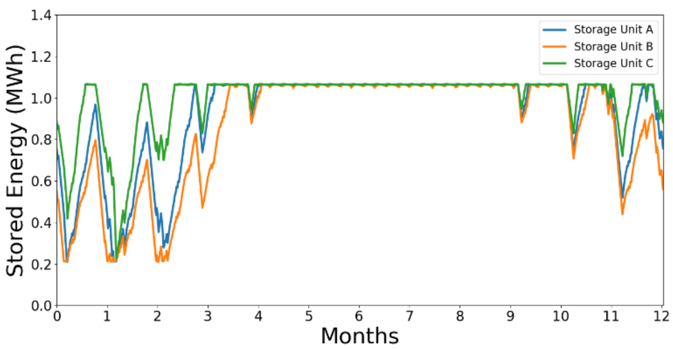

Fig. 7. Stored energy within the batteries within the year 2020.

modules within each unit (i.e. how many modules are connected in series/ parallel, with how many DC-DC converters the modules interfaced etc.) is a trade study that must be performed, with the objective of minimizing the overall ESS mass.

III. Spin-In Microgrid Technology Candidates

After defining the requirements of the examined lunar microgrid, the next step is to select which technologies in general should be selected for the formation of the microgrid. This paper advocates for the application of well-known terrestrial microgrid-related technologies and thus, in the following paragraphs, suitable microgrid technologies regarding grid design, control and protection are presented.

A. AC vs DC Distribution

Spacecrafts use at their vast majority DC architectures because production and storage means are DC-based and thus, inefficient conversion stages can be omitted in case of a DC distribution system. Even though there is currently no AC-based operational spacecraft, trade studies regarding AC and DC transmission for a lunar outpost have been carried out by most major space agencies. In preliminary design phase, the main objective is the minimization of mass in order to reduce the launch costs. Though typically DC transmission is more efficient compared to AC (more efficient DC transmission lines, easier to parallel DC lines, no need for reactive power management, simpler design and manufacturing, no reactance nor harmonics or skin effect upon lines), high frequency AC systems are still valid candidates due to the simpler voltage transformations and power conditioning units design [19]. For example, in [20], taking expertise from high frequency AC aircraft power systems, a 3φ\5kV\400Hz AC distribution system was designed and tested. The stated reason for selecting such AC system was the limited expandability of similar DC systems. Nonetheless, since this approach was found in very limited studies, within the context of this work, the selected microgrid architecture is fully based upon DC systems. This claim is further enhanced by the fact that during the last decade, the developments in DC microgrid technologies has been considerable, thus it is interesting to assess their applicability upon a lunar DC microgrid.

B. Bus Voltage

From related terrestrial experience, high voltage (i.e. greater than 300V DC) transmission should be pursued due to its lower overall system mass, lower power losses and low maintenance needs [19]. Thanks to the extremely low atmospheric pressure ($\sim 3 \cdot 10^{-15}$ atm) on lunar surface, according to Paschen's high vacuum curve [21], any DC voltage level below 10kV can be considered safe.

Consequently, high-voltage distribution is possible for lunar microgrids. In addition, deploying such a high DC voltage system is expected to be relatively cheaper since, compared to lower voltage systems, high voltage systems have lower overall mass and volume. As proven in [22], bus voltage level of 400Vdc are identified as optimal for terrestrial DC microgrids based upon conversion stages efficiencies. Furthermore, 400Vdc are used in military more-electric aircrafts as standardized in MIL-STD-704F [23]. Thus, there is extensive know-how on such DC distribution systems. Though higher voltages could be pursued for power transmission on the Moon, within the context of this study, which concerns a manned mission, 400Vdc are selected by also taking into consideration human safety levels.

C. Grid Topology

The space microgrid's network should be designed in a way that ensures that loads are powered reliably since fault recovery is not always feasible in space missions. In general, radial architectures consist the standardized practice when it comes to the design of power management and distribution systems (PMAD) of spacecrafts, with additional bus redundancies. The reason is its simplicity. This practice is not limited to satellites; the International Space Station is power by such a grid [24]. However, such approach comes with predefined fault tolerance. In order to overcome this shortcoming, one approach could be the incorporation of fault-resilient microgrid architectures in future PMAD. Expertise could derive from many successful paradigms in more electric aircrafts and ships, which are designed as meshed microgrids, which are essentially multi-looped architectures. As in any kind of network, meshed configurations enhance the system reliability significantly [25]. Furthermore, such topologies bring the additional advantages of high-power transfer ability as well as zonal protection schemes [11][26]. In general, there is no standardized methodology to mesh a microgrid network. Such microgrids can comprise of one or more DC bus rings with few or more interconnections between its nodes. A subcategory of meshed configurations are the Zonal Electrical Distribution Systems (ZEDS). These are essentially meshed microgrids following internally within an outer loop, radial architectures forming zones, i.e. logical and physical grouping of generation, storage and loads arranged in a common "neighbourhood" [27]. ZEDS are destined to be applied in the future all-electric ships [28] , which share several common characteristics with SPS. A meshed microgrid has been suggested for a deep space habitat in [29], where a triple ring bus architecture is proposed in a conceptual level. The advantage of this configuration lies on the smart placement of sources and critical loads upon nodes that are fed from multiple possible lines.

Another selection that must be determined during the design phase of DC microgrids concerns voltage polarity. The options are: a) unipolar (2-wire system), b) bipolar (3-wire system) [30]. The selection depends on the number of available voltage levels, two in unipolar systems ($+V_{dc}$, $-V_{dc}$) and three in bipolar ($+V_{dc}$,$-V_{dc}$, $2V_{dc}$) [31]. Though unipolar systems are simple to implement and operate, they are characterised by reduced fault tolerance compared to bipolar [32]. Further, if needed it is easy to generate single phase ac voltage from a simple half-bridge topology. Nonetheless, bipolar DC microgrids may suffer from unequal load distribution [33]. Consequently, proper controllers for dynamic voltage balancing must be included. Within the context of this paper, bipolar ZEDS architecture is suggested for further analysis as it appears to be the most fitting with respect to the lunar base technical requirements.

The issues that arise from meshing an electrical network mainly derive from the fluctuating voltage levels throughout the network [34] and they can be grouped into stability issues and protection [31], with the latter analysed in the next Subsection. [12]. Thus, it is imperative to assess the microgrid stability in all possible loading cases. There are multiple methodologies regarding its assessment, both for small and large signal analysis. For example, in [35] two meshed microgrids (double and triple ring) with constant power loads and droop-controlled sources are analysed regarding their stability by employing probabilistic analysis for deterministic systems. Stability assessment of a generic droop-controlled meshed microgrid is realised using graph theory [36], whereas another approach based on Lyapunov techniques [37] examines stability during transient phenomena.

D. Microgrid Control

Since the first spacecrafts were launched in the 1950's, SPS needed to be managed [38]. The first energy management system consisted only of a very simple current-limiting controller on a primary battery. Soon afterward, PV systems were developed, which gave spacecraft much longer useful lives. For most orbits, relying on solar insolation for primary power also meant having an energy storage system, usually containing secondary batteries. As spacecrafts evolved in complexity, so did the complexity of managing the SPS. More payloads and multiple mission goals necessitated careful planning of power consumption and demands. Through the urgency of efficient SPS energy management is already here, there is still room for significant improvements. There are several publications related to the simulation environment setups of PMAD coupled with some sort of energy management software. For instance, in [39], a management approach is presented aiming towards minimizing the State-of-Health of Li-ion batteries, however, many simplifications were made, the most prominent of which being the disregard of the network topology. The work done in [40] is particularly noteworthy because the designed energy management was loaded in Software-in-the-Loop (SIL) and applied on a testbed SPS (corresponding to future Orion Multi-Purpose Crew Vehicle) in Hardware-in-the-Loop (HIL). Though the configuration is very flexible and produces accurate results, the energy management system algorithm is still rule-based and it relies periodically on external settings sent via telemetry. Though not directly applicable to SPS, there is considerable research work regarding energy management upon More Electrical Aircrafts (MEA). For example, in [41] a fuzzy logic-based energy management was developed for a fuel cell and battery-based auxiliary power unit with the fuel cell supplying average load power and the battery handling load transients and overload situation. The scheme was tested on a HIL-based testbed, demonstrating very good performance especially during overload events.

Recognizing the similarities between DC microgrids and SPS, there are several potentially applicable control schemes deriving from the sector of isolated/ islanded DC microgrids. In general, they all follow the three-level hierarchical control architecture as proposed in [5]. In summary, the primary level is responsible for power sharing among the sources; the secondary takes care of power management, while the tertiary concerns energy management. In the following paragraphs, prominent promising technologies are briefly discussed, as they appear to be applicable on a lunar microgrid.

1) Primary Control Level

The examined lunar microgrid is formed by multiple converter-interfaced units working in parallel. In general, power sharing can be achieved in a centralised (active power sharing), distributed (circular chain control, DC bus signalling) or decentralised way (linear or nonlinear droop control) [42]. Centralised approaches, though very effective in accuracy and power quality suffer from the peril of single point of failure. On the other end, fully decentralised droop-based approaches exhibit poor performance when supporting nonlinear loads and, dependent behaviour upon the network lines. Finally, distributed control is characterised by increased complexity and limited proven application. These statements though accurate, they are not absolute since there are hybrid primary control approaches categories that overcome the fundamental drawbacks of each. Given the fact that a lunar microgrid must exhibit high reliability and at the same time, provide high power quality to its loads, the following primary controls should be considered. In [43], a communication ring is formed in order to realise the so-called circular chain control (3C), where the output of each unit is based upon the measured output of the neighbouring units. In [44], Chul has proposed a distributed droop control for an isolated DC microgrid to keep an optimal, semi-constant State of Charge (SOC) the microgrid ESSs. This was achieved by modifying dynamically the voltage droop reference on the point of connection between the ESS and the DC bus. In [45], an enhanced droop-based controller is proposed specifically for meshed DC microgrids. In [33], a simple voltage balancer based on simple analogue controller, is proposed to be added critical load buses. Recognizing the importance of droop control (i.e. the elimination of the need for centralised controllers for the fundamental operation of proper power sharing), nonlinear and adaptive droop controllers have been proposed. The basis of most is the adaptation of the droop inclination and/ or its dynamic vertical shifting (e.g. [46]). However, the logic behind this decision-making is an objective of secondary and tertiary control levels, thus, it is analysed in the following paragraph. Finally, the method of DC bus signalling appears promising since in [47] it was applied experimentally upon a DC microgrid with the objective of increasing the system reliability and flexibility. It should be noted that all the aforementioned studies follow the principle of "*simple is faster/ cheaper/ better*" [48], which should dictate the design of an SPS.

2) Secondary Control Level

The main objectives of this control level are: a) voltage restorative control and b) power sharing management. With respect to space microgrids, since sources and loads are all converter-interfaces, the importance of the first objective diminishes. However, the need for proper power management remains. In general, secondary controllers are implemented in a centralised [49] or a distributed manner. Distributed secondary control is an active, promising field of research since it raises the single point of failure vulnerability and at the same time, it reduces communication and computational burden. The authors of [50] suggest an improved distributed secondary control scheme, which is a hybrid scheme of voltage shifting and slope adjusting. The proposed method was successfully validated on a prototype DC microgrid during various operating conditions. In [51], the distributed secondary controller is implemented in the local controllers, and the information used in the local secondary control scheme is exchanged via a low bandwidth communication (LBC) network. The effectiveness of the scheme is validated by a simulation study, while its viability is verified by experimental studies on a laboratory prototype. Finally, in [52] LBC and local controllers are employed again for the configuration of a distributed secondary control, with the objectives of simultaneous voltage restoration and current sharing accuracy enhancement. The demonstration of the proposed method suggests that even though communication delays exist, the system stability is guaranteed.

3) Tertiary Control Level

The highest control level aims towards optimizing one or several objectives, such as energy scheduling of both loads and sources, power flow, balancing ESSs, minimizing losses or operating cost [42]. The vast majority of tertiary controllers is implemented in a centralized manner; however, distributed approaches can be applied in case of microgrid clusters. Within the context of small DC microgrids, like the examined lunar base, a centralized controller is more suitable.

Considering the special technical requirements of a space microgrid, a tertiary controller should firstly perform power flow analysis in order to schedule accordingly the units and adjust -if needed- the configuration of the protection system [53]. For example, in [54], power flow analysis assists in the identification of potentially overloaded lines and consequently, a set of preventive measures are suggested in order to avoid this situation. Power flow can also be part of the objective function of a tertiary controller; for instance, the objective can be optimizing power flow via SoC balancing [55], minimization of converter switching/ conduction losses [56], optimized management of hybrid ESS [57]. Finally, the optimized yet seamless operation between generation and storage is ensured by tertiary level control by employing various methods. To that end, the work in [58] is noteworthy since a fuzzy-based energy management system for MEA aims towards maximizing efficiency whilst maintaining voltage stability and ensuring storage availability.

E. Microgrid Fault Management & Protection Schemes

While meshed grids provide higher reliability, protection of meshed grids is challenging because protection systems will have to be adaptive to topology changes [12]. The recent work by Tan *et al.* stands out [1], since protection for a space-based microgrid in proposed. In this work, various engineering models of a DC microgrid were developed in order to test a spacecrafts' autonomous recovery of major critical functionalities, securing the systems' resiliency. The system was equipped with built-in resiliency via the technique of "triple majority voting circuitry" and also, with a hard-wired isolation and restoration scheme including an overcurrent limiter, an overvoltage limiter, and a constant power limiter to protect the circuit from short-circuit failure and to provide the ability to survive one failure.

There is a respectable amount of research regarding protection and fault identification solutions for terrestrial DC meshed microgrids, however none has been applied to space-based microgrids. For example, in [59] Ibrahim uses an artificial neural network (ANN) to represent a NAND logical gate and determine whether a possible fault would exist taking real time current measurements in many points of a ring bus configuration. Two main drawbacks could be seen in this protection proposal: a) three circuit breakers are needed for each connection in the DC bus and 2) the thresholds need to be previously established by the user, therefore, the protection scheme is not dynamic. On the other hand, in [60] two ANN are used to identify whether a phenomenon is a fault or not and if so, locate the place of fault. This approximation performs well in simulation, even though a wide architecture is necessary in order to take current samples of the entire microgrid system, representing an increase in the architecture cost and weight. Furthermore, that proposed system demands an offline training of the ANN, a fact that would decrease the spacecraft autonomy. In [61], Ali uses a multi-layer perceptron trained offline to determine a fault and its location in any part of the microgrid, but, just like latter proposals, a high number of sensors located in each end of each line is mandatory, a fact that demands significant communication infrastructure with high cost and a high probability to failure. In [62] and [63], similar methods are proposed for fault identification and isolation destined for dc microgrids with specifically ring configuration. In this case instead of an ANN, Intelligent Electric Devices (IED) are employed, though it is not stated anywhere that ANNs and IEDs are incompatible with each other. The method of detection is based on thresholds regarding overcurrent or low resistance faults and differential current levels for high resistance faults. The location of fault is pinpointed by analysing the dynamics of the grid segment, which is calculated via a probe considering an equivalent circuit. An important consideration could be the use of algorithms for training ANN online just like is used in [64], where it applied the Least Mean Square Error Algorithm to get the minimum possible error to follow a signal and consequently getting a constant power to the main grid. This online training implies that ANN could be completely independent of targets pre-determined gaining more robustness.

IV. Conclusions & Future Work

This work has presented a preliminary analysis regarding the positioning and sizing of a lunar manned based on Moon South Pole. The definition of these basic technical requirements serves as the corner stone for the suggestion of suitable technologies that derive from the growing sector of terrestrial DC microgrids. The motivation spinning-in these technologies is justified by the inherent similarities between SPS and DC microgrids such as MEA, all-electric ships. First, proper synergies between aerospace and microgrid industries should be encouraged. Second, in order to qualify for space applications each of these technologies, suitable standardization practices should be established, the outline of which should be the following: the technology candidates are first identified and then, prioritized based on the imperative nature of the shortcomings exhibited by the current state-of-art SPSs. The next step is the qualification of each technology candidate separately in a loop: adjusting the technology to the needs of the specific application, e.g. lunar base, implementing adjustments, testing and evaluating the performance of the various prototypes based on the relevant space industry standards (ECSS-E-HB-10-02A, ECSS-E-ST-20-20C, ECSS-E-ST-20-08C, ECSS-E-ST-20C31). It should be noted that since some of the suggested concepts derive directly from smart grid sector, consulting standards such as the IEEE2030 series, IEEE 1547, IEC 61850, IEC TS 62898-1:2017, is advised.

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