Centralized, Distributed, and Module-Integrated Electric Power System Schemes in CubeSats: Performance Assessment

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ABSTRACT Pico-satellites, also called CubeSats, have gained significant attention in recent years because they offer a low-cost and low-power solution with low latency communication and high data rates compared to larger satellites. The most critical subsystem in a CubeSat is the Electrical Power Subsystem (EPS) that provides the needed power to operate the remaining subsystems. The EPS mainly incorporates solar panels (generation), power electronic converters (shaping and distribution), and battery cells (storage). One of the main factors in EPS design is the system's reliability. This work proposes a module-integrated (MI) scheme for EPS architectures to increase the reliability through modularity and redundancy. Furthermore, a comparison between different EPS architectures (centralized, distributed, and module-integrated EPS topologies) based on Direct Energy Transfer (DET) and Peak Power Transfer (PPT) is presented. A performance evaluation is conducted considering different factors, such as reliability, fault ride-through capability, efficiency, re-usability, and scalability. The results confirm that MI architectures have higher reliability than centralized and distributed architectures.

INDEX TERMS CubeSats, DC-DC converters, Electric Power System (EPS), LEO (Low Earth Orbit) satellites, Modularity, Solar Panels

I. INTRODUCTION

CubeSats are small satellites built in a standard dimension of 1U (10 × 10 × 10 cm³), weighing around 1.33 kg/U and can be extended to multiple units: 1U, 2U, 3U, and 6U [1]. They are deployed in the Low Earth Orbit (LEO) at altitudes less than 2000 km, with 90-120 minutes orbital period and 0-90° inclination angle [2]. They gained significant popularity within the last few years due to their lower cost, lower latency communication (0.02 seconds versus 0.5 seconds in geostationary satellites), and lower power consumption while providing wireless access with improved data rates [3]. The cubic structure (hence the name CubeSat) optimizes the surface area, thus enhancing solar power generation and thermal stability [4]. It also provides a standardized shape, enabling batch launching as a secondary load to launching vehicles, significantly reducing launching costs.

The Electric Power Subsystem (EPS) is considered an essential subsystem of a CubeSat. This subsystem uses solar energy to generate the required power to operate the remaining subsystems in the CubeSat, including the communication system (COM), the attitude determination and control system (ADCS), the on-board computer (OBC), and the payload. As shown in Fig. 1, a general EPS includes power generation, power conditioning, power conversion, power storage, and power distribution modules [5]. Additionally, an EPS is equipped with protections for overcurrent, overvoltage, overcharge, and over-discharge [6]. The EPS design considers many factors, such as the altitude of the orbit, the mission and its duration, the arrangement and size of the photovoltaic (PV) panels, the high-speed movement of the CubeSat, the load profile, the weight, and volume restrictions [7].

The idea of integrating multiple functionalities into a single module for CubeSat designs goes beyond modules related to the same subsystem. For example, in [8] and [9], novel configurations were proposed for the design and integration of circularly polarized (CP) antennas on the surface of the PV panels to minimize the shadowing effect and maximize the absorbed solar radiation by the PV panels and as a result, maximize the power generation.
Since the EPS provides the power for the whole CubeSat, the design process requires knowledge of the power consumption of each subsystem in the CubeSat. Generally, the payload depends on the mission of the CubeSat. A general estimation for CubeSat’s power budgeting is presented in Table I [10].

This work aims to present a review of the different EPS architectures based on Direct Energy Transfer (DET) and Peak-Power Transfer (PPT) with regulated, unregulated, and partially-regulated DC busses. Furthermore, we propose a new Module-Integrated (MI) scheme for EPS architectures to increase reliability and fault ride-through capabilities and reduce the failure probability of the EPS and mission. A reliability assessment of the different architectures confirms that MI schemes outperform conventional architectures.

This paper is organized as follows: in Section II, a general overview of the EPS components (generation, conditioning, storage, and distribution) is presented. Also, the literature review is conducted to identify the gaps. Section III discusses the specifications and ratings of CubeSat’s components and modules. Section IV elaborates on the MI schemes and compares their reliability with conventional architectures. Then, Section V presents a discussion about the manufacturability of MI schemes. Lastly, Section VI concludes the paper.

II. EPS Architecture and Classification

A. Power Generation

The primary source of electric power generation in a CubeSat is solar power. The PV panels are either attached to the faces of the CubeSat, deployed in the wings, or both. The deployable panels are advantageous because they can be oriented in the direction of the Sun and harvest the maximum power [11], unlike the fixed panels. In [12], a multi-array lens system was proposed to increase the solar energy concentration on the PV panels for efficient power generation. The incidence angle, revolution, and rotation of the CubeSat were all considered. CubeSats generally may not receive the same irradiation amount in all positions along their orbits, resulting in eclipse conditions. Typically, the panels attached to opposite sides are connected in parallel because only one of them is exposed to solar irradiation at an instance [10].

The power generation can be affected by many factors, including temperature rise, weak illumination of the cell, distance from the Sun, and the CubeSat’s orbital mechanics. Modeling of the orbit analytically and numerically using different techniques was discussed in [24]. In [25], an analytic model for the solar power of LEO satellites was developed considering the geometric representation of the orbit. The model considered the Keplerian elements that described the orbit with reference to the equator and the angle between the Sun radiations vector and the orbit plane. The incidence angle, eclipsing, and power values were calculated for an orbiting satellite. In [26], the characteristics of deployable solar panels and solar radiation torque were investigated using software algorithms to simulate different orbit scenarios. In [27], a simulation model for solar power generation optimization is presented considering the PV array modeling, illumination level, calculation of the Sun’s position, the orbital parameters, and the panel’s generated power and energy. The total generated power is represented by [27],

$$P_{total} = \sum_{i=1}^{6} P_i$$  (1)
where \( P_i = S_0 \eta A \cos \gamma \)  

\( (2) \)

where \( S_0 \) is the solar index of the orbit, \( \eta \) and \( A \) are the efficiency and area of the PV panel, respectively, \( \gamma \) is the incident angle of the Sun with the PV panel, and \( i = 1, 2, \ldots, 6 \) identifies the different faces of the CubeSat.

Multi-junction (MJ) solar cells are made up of many layers of materials that can efficiently absorb light and convert it into electrical energy. Triple-junction (TJ) PV panels (particularly GaInP/GaAs/Ge cells) are frequently used in the aerospace industry as they are significantly efficient for their cost compared to other cells and can absorb longer wavelength [28]. Modeling TJ solar cells through a detailed three-diode equivalent circuit based on the used materials in the TJ solar panel was presented in [29]. A market overview is conducted in Table II, showing the well-known CubeSat vendors and the associated PV panels they offer. Based on the CubeSat PV panels market study, around 87.5% of today’s market is based on MJ panels whereas 12.5% use monocrystalline PV modules.

\[ \text{EPS System Configurations Proposed in the Literature} \]

| Contribution & Limitations | CubeSat / Mission | EPS Architecture | SAR (DET or MPPT) | No. of DC-DC converters | Harvested Power (W) | Efficiency |
|-----------------------------|-------------------|------------------|-------------------|-------------------------|---------------------|------------|
| [32] DET in extreme low voltage cases (+) Reliability was compromised at eclipse instances since the PV panels were incapable of feeding the system (-) | NutSat / Collect broadcast data from aircrafts with ADS-B sensor | Centralized | MPPT, SEPIC/ Perturb & observe | 4 SEPIC for MPPT, 3 Buck for loads Total: 7 | 19.457 | Circuit efficiency: 85% |
| [33] Modulated the PV panels and MPPT converters (+) No modularization in the storage system (-) | Ten-Koh | Distributed | MPPT Boost/ N/A | N/A | 10.98 | MPPT tracking efficiency: 99% |
| [34] Modulated the PV panels and MPPT converters (+) No modularization in the storage system (-) | N/A | Distributed | MPPT Buck/ Perturb & observe | 4 Buck for MPPT 3 Regulators for loads Total: 7 | 75 | Circuit efficiency: 88.49% |
| [35] Modulated the PV panels and storage systems (+) No MPPT operation to optimize power extraction (-) | N/A | Distributed | DET | N/A | 4.76 | MPPT tracking efficiency: N/A |
| [36] A topology using half-bridges at the PV output terminals based on single inductors (+) Half-bridges experience more switching and conduction losses and low efficiency (-) | 1U Lab-based CubeSat | Centralized | MPPT Boost/ Perturb & observe | 1 Boost for MPPT 3 Half Bridges 2 for loads Total: 6 | 2.25-3.1 | MPPT tracking efficiency: 96% |
| [37] EPS design considering latency & power requirements (+) Analyzing the nadir orientation scenario only (-) | 1U CubeSat for 5G Mission | Centralized | MPPT Boost/ Perturb & observe | N/A | 20 | MPPT tracking efficiency: N/A |

\[ \text{B. Power Conditioning} \]

The power conditioning unit delivers the voltage to the DC bus. However, the power produced from the PV panel depends on many environmental conditions. Even at the instances of maximum irradiance, the mismatch in the load can cause the extracted power from the PV panels to drop. The maximum possible power is generated from a solar panel when the load impedance matches the panel’s internal resistance, calculated from the panel’s I-V curve. To mitigate this issue, Solar Array Regulators (SARs) are inserted after the PV Panel. SARs are required for two main tasks: load matching and prevention of batteries’ overcharging. They generally have two approaches, Direct Energy Transfer (DET) and Peak-Power-Transfer (PPT). In DET-based topologies, the energy is transferred directly through the diodes that connect the panel to the DC bus. A parallel regulator can be added to bypass the extra power when batteries are fully charged. The load dictates the operating point of the panel, which may not be the maximum power point [30]. In contrast, PPT-based topologies have a series-connected DC-DC converter between the panel and the bus. This unit sets the operating point of the PV panel such that the load is matched to the characteristic resistance of the panel to draw the maximum power. PPT topologies include fixed-power-point-tracking (FPPT) and maximum-power-point-tracking (MPPT). The isolation provided by the DC-DC converter in MPPT-based topologies allows the connection of multiple PV panels to a single DC bus. Mostly, MPPT
TABLE IV
LITERATURE WORKS THAT CONDUCTING COMPARATIVE ASSESSMENTS OF EPS ARCHITECTURES

| Publication Year | Contribution | Metrics | Compared Architectures and their number, N | Used Techniques | Proposed |
|------------------|--------------|---------|-------------------------------------------|----------------|----------|
| 2011             | Comparison of architectures | Reliability | PPT/DET + Regulation Method | Failure Mode and Effect Analysis (FMEA) | Extensive comparison of architectures |
| 2013             | Comparison of architectures | - Efficiency - Reliability - Cost | PPT/DET/Hybrid + Regulation Method | Series/Parallel Connection | Proposing module-integrated (MI) concept in EPS + Comparison of architectures |
| 2021             | Comparison of architectures | - Orbit Efficiency - Battery Sizing - Component Count - Reliability | PPT + Regulation Method | Single-point-of-failure (SPOF) | |
| 2021             |                      |                      | Conversion Stages + Location of converters N=17 | Qualitative Discussion | |
| 2022             |                      |                      | Centralized/decentralized/MI + PPT/DET/Hybrid + Regulation Method |                      | |
|                  |                      |                      | + Conversion Stages + Location of converters N=17 |                      | |
|                  |                      |                      | N=21 - Series/Parallel Connection - Single-point-of-failure (SPOF) |                      | |
|                  |                      |                      | + Conversion Stages + Location of converters N=17 |                      | |
|                  |                      |                      | N=21 - Series/Parallel Connection - Single-point-of-failure (SPOF) |                      | |
|                  |                      |                      | + Conversion Stages + Location of converters N=17 |                      | |
|                  |                      |                      | N=21 - Series/Parallel Connection - Single-point-of-failure (SPOF) |                      | |

FIGURE 2. Classification of EPS architectures

topologies are preferred for CubeSats to maximize power harvesting. In [31], a combination of DET and PPT concepts was proposed, where DET-based PV panels fed Lithium-Ion (Li-ion) batteries, and PPT-based PV panels fed supercapacitors.

Generally, the categorization of EPS architectures, as illustrated in Fig. 2, can be in terms of the energy transfer method (DET or PPT) or the voltage regulation of the DC bus, where it can be unregulated, partially-regulated or fully regulated. The unit, or the lack thereof, interfacing the DC bus and the load dictates the topology.

C. Storage System

The significance of an energy storage system is for cases where the power from the source is unavailable or insufficient, like eclipse cases or increased data rate requirements cases, respectively. The storage system, typically rechargeable batteries, can be connected to the DC bus either directly or via a power electronic unit that acts as a battery charger regulation (BCR) or a voltage regulator (VR). When the storage system is connected to the bus directly, the bus is unregulated. In regulated DC bus topologies, the storage units are connected through a BCR or a VR, both of which stabilize the bus voltage at a pre-defined value. Generally, loads in the CubeSat can be source-fed, battery-fed, or both. That is, if the power generation does not meet the load demand, the storage system provides the needed power. Otherwise, the excess power is stored in the storage system. Li-ion batteries are commonly used in CubeSats because of their ability to withstand intensive radiation. They are characterized by high energy density (>120 Wh/kg) and a long life-cycle [32]. However, due to the charging and discharging performances of the on-board Li-ion cell, high heat is dissipated, negatively affecting its life cycle and causing complications in the thermal management of the system. Supercapacitors or ultracapacitors (SC or UC, respectively) have been introduced recently in the design of CubeSats due to their broader operating temperature range and extremely high life cycle. Combining the Li-ion and supercapacitor technologies can result in a system that meets the requirements with increased reliability and performance [33].

D. Voltage Regulation and Power Distribution

DC-DC converters are employed to regulate the voltage levels from the DC bus to the required voltage levels for the remaining subsystems. The power distribution system allocates the power to CubeSat’s remaining subsystems through the Power Distribution Module (PDM) that consists of multiple switches rated at different voltages to deliver power to the loads.

Table III summarizes the recent works proposing and developing novel EPS for CubeSat [34]-[39]. The table organizes them based on the contribution of the work, the mission of the CubeSat, the architecture of the EPS, the employed SAR technique, the used DC-DC converter, and the employed algorithm for PPT-based architectures. While some contributions in the literature presented details about proposed EPS, other contributions included comparisons between different EPS architectures for performance evaluation, as summarized in Table IV. In [40], an approach to estimate the reliability of DET and PPT-based EPS was presented, considering the EPS elements’ redundancy. DET architectures
were found to be more reliable than the PPT-based ones. In [41], ten different DET- and PPT-based topologies with different DC bus regulation methods were compared in terms of reliability, efficiency, and cost-effectiveness. Among ten topologies, it was found that semi-regulated DET-based EPS architecture has the highest performance. In [42], the authors compared the efficiency of four different architectures, where the prime difference was the interfacing unit between the panel and DC bus. They concluded that the very-low-drop-out (VLDO) architecture had the highest efficiency but not the maximum harvested energy. In [43], the work focused on PPT-based architectures with different DC bus regulation methods. The comparison concluded that unregulated voltage regulation has an optimal performance in terms of reliability, number of components, battery sizing, and orbital efficiency. In [44], a comprehensive review of seventeen different DET and PPT architectures was presented. The classification of the architecture was in terms of four different categories: the regulation of the DC bus, the number of conversion stages, the energy transfer method, and the location of the DC-DC converter. The review concluded that DET-based architectures with unregulated bus had the least number of components, which consequently enhanced the overall efficiency of the EPS.

However, among the literature that discussed modularity, none has considered modularity in the overall design of the EPS, which can further boost the reliability of the EPS. Thus, the contribution of this work can be highlighted as:

1- Since the success or failure of CubeSat’s mission depends solely on the EPS performance, a modified Module-Integrated (MI) scheme for the EPS is required, where the EPS is integrated into the back of the PV panel. MI architectures mainly enhance reliability by increasing the redundancy of the elements. It allows designing smaller modules at low-power levels and utilizing them in a plug-and-play approach, making it easier to reduce or alleviate power levels based on the mission requirements. MI EPS architectures offer redundancy, re-usability, scalability, and reduction of development time.

2- To evaluate the performance, a comparison is carried out between MI and centralized EPS architectures. The comparison of EPS architecture should consider the size and component count of the system, the overall efficiency, reliability, scalability, and re-usability of the EPS.

III. CubeSat Specifications

CubeSats are comprised of different modules, including PV panels, EPS module, battery module, and PDM, as shown in Fig. 3. They have maximum ratings of 0.89 W power, 196 mA current, and 4.5 V voltage. The open-circuit voltage is 5.178 V, whereas the short-circuit current is 0.205 A. The output of the two-cell solar panel is connected to the EPS module shown in Fig. 3(b) through four BCRs. All BCRs have 10 V input voltage and 750 mA input current. The EPS can operate at temperatures -40 °C to 85 °C and has three busses: 3.3 V, 5 V, and 12 V. The maximum output current for each is 4.5 A, 4.5 A, and 1.5 A, respectively. The output of the BCR is connected to the DC bus, which has a Lithium polymer battery connected to it. The battery module shown in Fig. 3(c), has maximum and minimum voltages of 8.27 V and 6.2 V, respectively. The maximum output current from the battery bus is 4.5 A at voltages of 8.26 V. Lastly, the PDM in Fig. 3(d) has 13 switches to distribute the voltage to the loads. The ratings of the switches are distinguishable at 3.3 V, 5 V, 12 V, and 8.3 V for the battery voltage. The PDM is equipped with overcurrent protection and an I2C communication node at 0x50 address and 10 MHz operating frequency to access all telemetry on the switchboard.

IV. Module-integrated Schemes

Modularity in the EPS design can be added on different levels. In this work, redundancy is added to the architecture at a cell level, and the concept can then be extended to a group-of-cells level. The proposed idea is to modularize all components of the EPS—including the DC-DC converters
and battery storage system and integrate each module at the back of the solar cell, as illustrated in Fig. 4. Instead of having the EPS occupying the limited space inside the CubeSat, the integration within the PV panel will provide more spatial area to add mission-related components while complying with the weight and volume restrictions. Module-integrated (MI) schemes allow the development and optimization of minimized EPS within a single solar cell for a given power level. Then, a plug-and-play approach can be employed to control the total generated power level from the solar panel, based on the requirements. The merits of this design can be stated as the following:

1. The system’s reliability and fault ride-through capabilities are increased because of modularity. A failure of a single cell or a single EPS component does not severely impact the operation of the satellite as other modules will override it.
2. The scalability of the system is increased because of the plug-and-play approach. The total power generated by the EPS can be changed based on the used number of cells in the PV panel.
3. The fabrication and development time is reduced because re-sizing the elements (including DC-DC converters and battery storage systems) for a given power level is not an issue.

**A. MI EPS Topologies**

The modularity aspect can be added to the EPS design at a cell level or a group-of-cells level. Either way, the reliability is increased. Based on the MI concept, both DET and PPT architectures with different voltage regulation methods are analyzed. This section studies cell-modulearized MI EPS schemes. MI DET-based architectures with different voltage regulation methods are shown in Fig. 5. The architecture presented in Fig. 5(a) is simplistic and has a low component count. Despite having high efficiency, connecting the battery unit directly to the DC bus is not a recommended practice since the operating point of the solar cell will be fixed, and thus the maximum power cannot be extracted. In Fig. 5(b), a BCR is added between the battery and the bus to control the battery voltage and current through multi-loop control. Fig. 5(c) shows the architecture for a MI DET-based sun-regulated DC bus. The BCR regulates the battery voltage and current throughout the sunlit instances and is disabled during eclipse, where the battery supplies the load with the required demand. MI PPT-based architectures with different voltage regulations are illustrated in Fig. 6. The MPPT unit in these architectures extracts the maximum power from the solar panel and provides it to the DC bus. In Fig. 6(a), the battery is floating, whereas, in Fig. 6(b), it is interfaced with a BCR. In Fig. 6(a), the MPPT operates as VR when the battery is fully charged. Fig. 6(c) shows the sun-regulated PPT-based architecture, where the BCR regulates the battery charging process in sunlit instances and gets disabled during eclipse periods. The architecture in Fig. 6(c) offers flexibility in battery sizing because the BCR unit regulates the bus voltage based on the battery voltage.
However, in this architecture, Fig. 7-9 are all DET-based architectures. In Fig. 7, the DC bus is unregulated, where the panel's voltage is dedicated by the battery voltage, and the current of the PV panel depends on its I-V curve. This means that the PV may be operating at a point other than the MPP. During eclipse periods, the battery feeds the loads. Fig. 8, presents DET-based architectures with a regulated bus. In Fig. 8(a), a BCR is added before the battery to control the charging current. In Fig. 8(b), the DC bus is regulated by a VR unit connected in series with the load converters. Arch-7 and Arch-8 have more component count and thus experience more losses. In Fig. 8(c), the VR is connected to the battery rather than the load-side converters to balance the power between the generation side and the load demand [33].

In Fig. 9, the DET sun-regulated EPS is shown. During the sunlight periods, the BCR operates and regulates the charging process. During the eclipse instances, the BCR is blocked, and the battery supplies the load through the diode only, reducing the conversion losses compared to the previous architectures employing BCR units.

B. Comparison with existing architectures

This section discusses architectures with different energy transfer methods (DET and PPT) using unregulated, fully-regulated, and partially-regulated DC buses.

- DET-based Architectures

The architectures shown in Fig. 7-9 are all DET-based architectures. In Fig. 7, the DC bus is unregulated, where the panel's voltage is dedicated by the battery voltage, and the current of the PV panel depends on its I-V curve. This means that the PV may be operating at a point other than the MPP. During eclipse periods, the battery feeds the loads. Fig. 8 presents DET-based architectures with a regulated bus. In Fig. 8(a), a BCR is added before the battery to control the charging current. In Fig. 8(b), the DC bus is regulated by a VR unit connected in series with the load converters. Arch-7 and Arch-8 have more component count and thus experience more losses. In Fig. 8(c), the VR is connected to the battery rather than the load-side converters to balance the power between the generation side and the load demand [33].

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- PPT-based Architectures

Most CubeSats employ PPT-based architectures to retrieve the maximum power from the Sun [32]. Fig. 10-12 present architectures that employ MPPTs with different regulation methods for the DC bus. In Fig. 10, PPT-based unregulated bus schemes are illustrated. In Fig. 10(a), each group of panels is connected to a designated MPPT unit so that each group extracts its maximum power based on its irradiation levels. The DC bus is kept unregulated by connecting the battery directly to the DC bus. However, unlike DET-based unregulated architecture, the MPPT unit is controlled to optimize power extraction of the PV panel regardless of the output voltage. Thus, the battery no longer dictates the operating point of the PV. In this architecture, the MPPT unit operates like a VR if the battery voltage is at its peak to maintain that level, and the PV panel supplies the load. In Fig. 10(b), parallel-connected panels are interfaced with the remaining EPS through a single unit of MPPT. Although this reduces the component count, it degrades the overall performance because it assumes that all PV panels are exposed to the same irradiation level, which may not be the case. In Fig. 10(c), a hybrid storage system is employed using Ultra-Capacitors (UC) in addition to the typical battery
TABLE V
SPOF ANALYSIS FOR EPS ARCHITECTURES

| Architecture | SR | MPPT | BCR | Battery | VR | DC/DC | Total |
|--------------|----|------|-----|---------|----|-------|-------|
| Arch-1       | Yes| Yes  | Yes | Yes | Yes | No | 2 |
| Arch-2       | No | No   | No  | Yes | No  | No | 0 |
| Arch-3       | No | No   | No  | No  | No  | No | 0 |
| Arch-4       | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-5       | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-6       | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-7       | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-8       | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-9       | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-10      | No | No   | Yes | Yes | Yes | No | 0 |
| Arch-11      | No | No   | Yes | Yes | Yes | No | 0 |

*The BCR in Arch-16 acts like BCR and VR units.

FIGURE 12. Arch-19: PPT-based sun-regulated DC-bus

pack to increase efficiency and reliability [34]. A regulator for battery discharge is added between the two units to control the current from the battery to the loads and UC.

In Fig. 11, PPT-based regulated DC bus EPS is presented. In Fig. 11(a), a VR unit is added before the load converters to keep the voltage of the bus at a pre-defined value. In Fig. 11(b), the topology allows a wide range of battery choices because the DC-DC converter unit can operate as a BCR or a VR. This, with the MPPT unit, allows using higher voltages at DC bus and hence reduce the conduction losses. In Fig. 11(c), MPPT and VR units are connected to the output of the parallel-connected panels. In Fig. 11(d), a parallel MPPT unit is connected to each group to maximize power generation from the PV panel. This output is fed to a VR unit to regulate the DC bus. In Fig. 12, a sun-regulated PPT-based architecture is shown. The VR unit maintains the voltage of the DC bus during the sunlit period and gets blocked by the diode during the eclipse. At fully charged batteries, the VR is blocked, and the MPPT maintains the bus voltage. In Fig. 13, DET-and-PPT hybrid architectures are illustrated. In Fig. 13(a), the MPPT unit ensures maximum power extraction. When the battery's voltage is at its maximum, the architecture becomes like the DET-based regulated bus architecture, where the bus is regulated at maximum voltage battery. In Fig. 13(b), a similar scheme is presented with a diode added parallel with the MPPT unit. This allows the MPPT unit to operate during sunlit periods and maintains the voltage of the bus at the battery’s peak. During the eclipse, the battery discharges through the diode to feed the loads.

FIGURE 13. Hybrid architecture (a) Arch-20: hybrid unregulated (b) Arch-21: hybrid sun-regulated

and the MPPT is disabled. In this topology, the maximum battery voltage should be lower than the PV’s MPP to avoid diode conduction during sunlit periods.

C. Reliability Calculations

The reliability of the EPS is of utmost importance. Thus, redundancy is ensured in MI-EPS architectures to improve the system's reliability. To further study and assess the reliability of each architecture, this section considers two techniques: the single-point-of-failure (SPOF) and the series/parallel connection of the components.

- Single-point-of-failure (SPOF)

SPOF are points in an architecture that, if failed, would cause the complete system to fail. Architectures with the least number of SPOF are considered the most reliable. In Table V, a SPOF analysis is given for each architecture. It should be noted that module-integrated architectures do not have any SPOF because of the components' redundancy and fault ride-through capabilities. The results show that they are considered the most reliable architectures among all of them.

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In the SPOF analysis, the shunt regulators (SR) are not considered SPOF since they are connected in parallel with the PV panels, and their failure does not stop supplying the energy to the load. A single MPPT is not considered a SPOF because the remaining MPPT units can still supply energy to the loads. However, in architectures 13 and 17, MPPT is considered a SPOF because it is a single unit rather than a modularized one. Furthermore, both the BCR and the battery are considered SPOF because the first failure will cause the energy storage system to be disconnected from the loads, whereas the second failure would stop the mission immediately if the panels are not supplying sufficient power. The VR units are considered SPOF only if they disconnect the loads or the battery from the panels. Lastly, the DC-DC converters on the load side are all considered as SPOF as they disconnect the load from both sources of energy: the PV panels and the battery. The results of this method confirm that MI architectures have higher reliabilities than the others due to redundancy and no SPOFs.

- Series/parallel connection

In this method, the overall reliability of each architecture considers the series or parallel connection of the unit. Given the reliability of the two units, \( R_1 \) and \( R_2 \), the reliability of their series connection is calculated through [23]

\[
R_s = R_1 R_2
\]  

(3)

whereas the reliability of their parallel connection is calculated through [23]

\[
R_p = 1 - (1 - R_1)(1 - R_2)
\]

(4)

Following this convention, the overall reliability of each architecture is calculated, and the bar chart in Fig. 14 summarizes the calculations and confirms that MI architectures are the most reliable among the 21 discussed architectures. It is also noticed that Arch-14 has high reliability due to the UC employed along with the battery storage system. In general, DET-based architectures are more reliable than PPT architectures, but this comes with the cost of losing the MPPT operation. A compromise is to employ MPPT in MI architectures to have higher reliability and a better power extraction scheme.

### Table VI

|          | Centralized | Distributed | MI |
|----------|-------------|-------------|----|
| Organization | Single unit combining all components | Multiple units, each combining related components | Cells are integrated with their PEC and batteries |
| Component Count | Low | Medium | High |
| Occupied Volume | Large | Medium | Small |
| Efficiency | High | High | Highest |
| Reliability | Low | Medium | High |
| Cost | Low | Medium | High |

V. Discussion

Recent reported EPS in the literature could be classified into centralized EPS architectures or distributed EPS architectures. This work proposes a new scheme for EPS architectures, module-integrated EPS architectures. A comparison is conducted between the centralized, distributed, and module-integrated (MI) architectures in terms of the architecture organization, the component count, the occupied volume, the anticipated efficiency, and the reliability. The results are shown in Table VI. Centralized EPS architectures have all components connected to a central unit summoning all power electronic converters (PEC) and a common DC bus that feeds the respective loads. These architectures are simple, size-efficient, and inexpensive, but they have low reliability because a single fault can destruct the whole system, consequently affecting the mission of the CubeSat. In contrast, each PEC is placed with its respective component in distributed EPS architectures. The MPPT converter is placed near the PV panel, the BCR is placed near the battery, and the DC-DC converter is placed near the loads, each in a distributed manner on separate units. These architectures have increased reliability due to redundancy. They are also characterized by re-usability and reduced noise levels due to placing each PEC near its subsystem. Lastly, module-integrated architectures work by cell-level modularity, where each solar cell has its own PEC and storage cells attached at the back. The EPS is designed such that the overall power is divided into modules. This allows employing components with lower ratings, further reducing the EPS size and giving room for other subsystems in the CubeSat. Although the component count and the cost are increased, these architectures have increased reliability compared to the others, which is confirmed in the previous section using two techniques. Moreover, MI architectures achieve scalability and allow a plug-and-play approach to alleviating power levels as needed. They have increased performance in addition to reduced development time. The performance is enhanced because each cell has its own PEC instead of a single MPPT for many cells with different characteristics and temperatures. As identical modules are fabricated, the time associated with EPS development is reduced because the testing and verification processes are
conducted once. Furthermore, using low-power rated components reduces the overall cost.

The manufacturing process of module-integrated architectures includes manufacturing integrated solar panels with PEC attached to their back. This will also reduce the weight and size of the EPS since smaller components are employed. To discuss the manufacturability of module-integrated architectures, the modular-integration concept is further divided into two designs:

- Semi-module-integrated, where the components of the EPS are all modularized, but batteries are centralized. These architectures are similar to distributed EPS architectures, but the modularity is implemented at a cell level, and the EPS components are integrated at the back of the cell itself.
- Fully module-integrated, where the components of the EPS are all modularized, including the batteries.

In semi-module-integrated architectures, the reliability of the overall system is compromised (because the battery is centralized rather than distributed) with the manufacturability.

Typical batteries can be employed with specific energy and voltage ratings for the EPS design. On the other hand, fully module-integrated architectures require manufacturing special batteries that have to be smaller to fit the cell with the remaining PEC, complicating the manufacturing process. Furthermore, the testing process is simpler for semi-module-integrated because an experimental prototype can readily be constructed with commercial off-the-shelf (COTS) batteries.

To sum up, semi-module-integrated architectures have higher reliability than distributed and centralized architectures, and it is more feasible and manufacturable than fully-module-integrated architectures.

VI. Conclusion

In this work, a performance assessment has been conducted between different EPS architectures, namely the centralized, distributed, and MI architectures. The main advantage of MI architectures is the added redundancy which further improves the reliability of the EPS. Two main categories were reviewed: DET and PPT architectures. Unregulated, regulated, and sun-regulated methods were investigated. The concept of MI was extended to these architectures, and a comparison in terms of reliability was conducted. The two techniques (SPOF and series/parallel connection) used to study the reliability confirmed that MI architectures are highly reliable. Among MI architectures, DET-based EPS had higher reliability. In addition to that, MI architecture offers a plug-and-play approach where the overall power of the EPS can be changed according to the needs of the CubeSat. This, in turn, is expected to reduce the development time and cost and simplify the production process. MI architectures essentially offer scalability, re-usability, and high reliability. MI architectures can be further divided into semi-module-integrated and fully-module-integrated architectures. The main difference between these two is the connection of the battery storage system: centralized for the first and distributed for the second. The impact of this differentiation is mainly in the testing and manufacturing processes, where semi-module-integrated architectures allow employing typical COTS batteries instead of manufacturing special batteries with particular specifications.

ACKNOWLEDGMENT

The work of B. Hussein in this publication was made possible by award number GSRRA8-L-2-0524-21054 from Qatar National Research Fund, QNRF (a member of Qatar Foundation, QF). The work of A. Massoud and T. Khattab is supported by grant number AICCO3-0530-200033 from QNRF. Open Access Funding provided by the Qatar National Library, QNL. The contents herein are solely the responsibility of the authors.

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