

Review

Autonomous Isolated Power Conversion Architecture for Lunar and Mars Resource Extraction Robots

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Abstract

Autonomous robotic systems designed for extraterrestrial in situ resource utilization (ISRU) will play a central role in enabling a sustained human presence on the Moon and Mars. These robots are expected to perform tasks such as regolith excavation, water extraction, oxygen production, and propellant generation under extremely harsh environmental conditions, including large temperature variations, abrasive dust, high radiation levels, and significant communication delays with Earth. Consequently, their onboard electrical systems must operate with high reliability, autonomy, and fault tolerance. A critical enabling technology for these systems is the isolated power conversion architecture, which distributes energy from primary power sources to multiple robotic subsystems, including mobility actuators, drilling systems, sensors, computing units, and thermal management modules. Future lunar and Martian missions are expected to rely on a combination of alternative energy sources, including solar photovoltaic arrays with energy storage, fuel cells, radioisotope power systems, and nuclear surface power reactors, which can provide continuous and high-density energy independent of sunlight availability. These diverse power sources require flexible and highly efficient isolated DC–DC power conversion architectures capable of managing wide input voltage ranges while ensuring electrical isolation, safety, and system stability across distributed robotic platforms. This literature review surveys recent developments in autonomous isolated power conversion architectures suitable for lunar and Martian resource extraction robots. The review examines advanced converter topologies such as resonant converters, phase-shifted full-bridge converters, dual-active bridge converters, and modular multiport power converters designed for high efficiency, high power density, and scalable power distribution. Emphasis is placed on converter architectures capable of interfacing with nuclear-powered systems and other high-energy-density sources while supporting distributed loads in robotic mining and processing systems. In addition, the paper reviews emerging autonomous control strategies, including adaptive digital control, intelligent power management, fault detection and self-recovery mechanisms, and distributed power architectures capable of maintaining stable operation under dynamic load conditions. The role of wide-bandgap semiconductor technologies, including silicon carbide (SiC) and gallium nitride (GaN), is also examined, highlighting their potential to enable higher switching frequencies, improved efficiency, reduced system mass, and enhanced thermal performance in vacuum environments. Finally, system-level considerations for integrating isolated power conversion within robotic ISRU platforms are discussed, including redundancy strategies, power bus architectures, electromagnetic compatibility, thermal management, and long-duration reliability requirements. By consolidating advances across power electronics, autonomous control, and space



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power systems, this review identifies key research gaps and outlines design directions for next-generation autonomous power conversion systems capable of supporting scalable lunar and Martian resource extraction infrastructures powered by both renewable and nuclear energy sources.

Keywords: autonomous power systems; in situ resource utilization (ISRU); DC–DC converters; power electronics; wide-bandgap semiconductors; GaN; SiC; digital twins; lunar robotics; Mars exploration

1. Introduction

NASA's Moon-to-Mars (M2M) exploration initiative has identified in situ resource utilization (ISRU) as a key technology for establishing a sustainable human presence on the Moon and enabling future crewed missions to Mars [1–6]. ISRU involves extracting, processing, and utilizing locally available planetary resources to reduce dependence on Earth-based resupply while significantly lowering launch mass, mission cost, and logistical complexity [3,4]. Within NASA's Artemis program, ISRU technologies are being developed for oxygen extraction from lunar regolith, water recovery from permanently shadowed regions, propellant production, energy storage, and construction material manufacturing. Future Mars missions are expected to expand these capabilities to include atmospheric carbon dioxide processing, methane production, autonomous excavation, and large-scale resource processing [5,6].

Achieving these objectives requires autonomous robotic systems capable of performing excavation, transportation, processing, construction, and infrastructure maintenance under extreme environmental conditions. Unlike terrestrial mining operations, extraterrestrial robotic platforms must operate in environments characterized by extreme temperature cycling, abrasive dust, radiation exposure, vacuum or low-pressure conditions, and significant communication latency with Earth [1,5,7]. These challenges necessitate highly reliable, energy-efficient, and fault-tolerant electrical power systems capable of autonomous operation with minimal human intervention.

Recent advances in power electronics have identified isolated power conversion systems as a critical enabling technology for extraterrestrial robotic platforms. Isolated DC–DC converters provide galvanic isolation, voltage regulation, bidirectional power transfer, and distributed power management between primary energy sources and robotic subsystems, including mobility actuators, drilling mechanisms, sensing units, onboard computers, communication systems, and thermal management equipment [8,9]. Numerous converter topologies have been investigated for space applications, including half-bridge and full-bridge converters, phase-shifted full-bridge (PSFB) converters, resonant converters, dual-active-bridge (DAB) converters, and modular multiport converter architectures designed to achieve high efficiency, high power density, and scalable system integration [9–11].

Future lunar and Martian missions will likely employ hybrid power systems combining solar photovoltaic arrays, regenerative fuel cells, radioisotope power systems, and nuclear fission surface reactors capable of supplying continuous electrical power independent of solar illumination (see Figure 1) [6,12]. These heterogeneous energy sources require intelligent isolated power conversion architectures capable of operating over wide input voltage ranges while maintaining electrical isolation, efficient energy coordination, and stable operation under highly dynamic loading conditions.

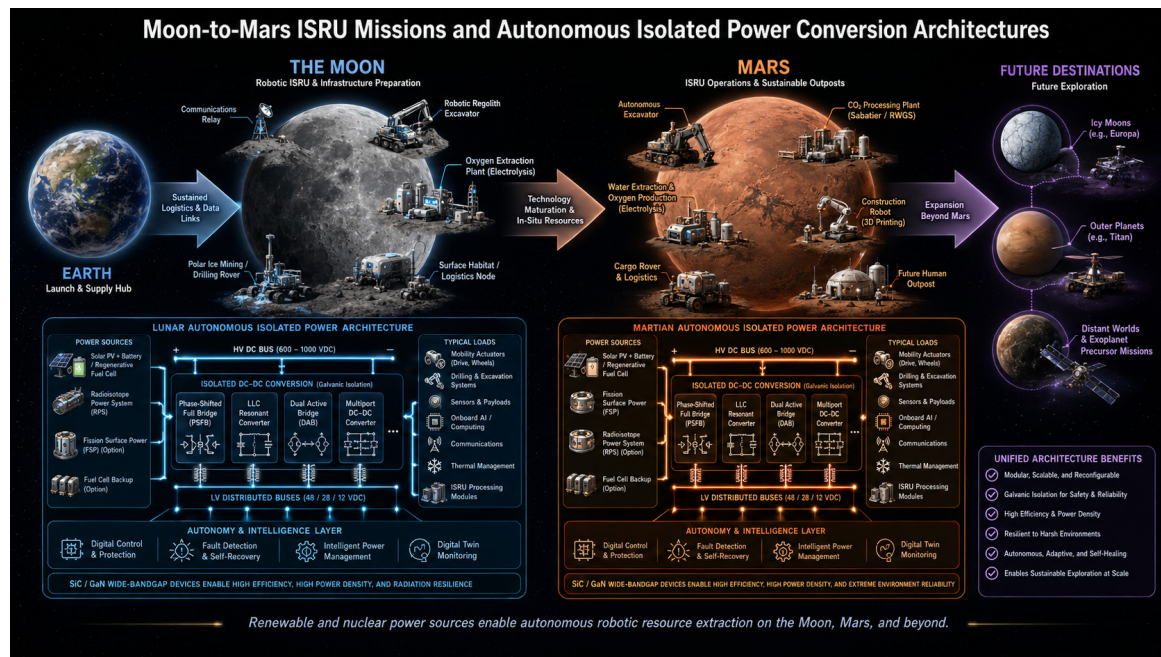


Figure 1. AI-generated illustrations based on Moon to Mars scope developed by NASA [13].

Significant advances have also been made in adaptive digital control, intelligent power management, distributed energy coordination, fault diagnosis, digital twins, and artificial intelligence for autonomous power electronics [14,15]. Furthermore, the rapid development of silicon carbide (SiC) and gallium nitride (GaN) semiconductor technologies has enabled substantially higher switching frequencies, increased power density, reduced converter mass, and improved thermal performance, making these devices highly attractive for extraterrestrial robotic applications [16]. Together, these developments provide the technological foundation for next-generation intelligent power conversion systems capable of supporting long-duration ISRU operations.

Although considerable research has been conducted on individual aspects of power electronics, autonomous robotics, space power systems, and intelligent energy management, the existing literature remains fragmented across these disciplines. Comprehensive reviews specifically addressing autonomous isolated power conversion architectures for lunar and Martian resource extraction robots remain limited. Therefore, this paper presents a comprehensive review of recent advances in isolated converter topologies, autonomous control strategies, intelligent power management, wide-bandgap semiconductor technologies, digital twins, fault-tolerant architectures, and system-level integration for renewable- and nuclear-powered extraterrestrial robotic systems. The paper also identifies current research gaps and discusses future research directions toward scalable, resilient, and intelligent power conversion systems capable of supporting sustainable ISRU infrastructure on the Moon and Mars.

The principal contributions of this review are summarized as follows. First, it establishes the mission-level context for autonomous power conversion by linking the electrical power requirements of representative lunar and Martian ISRU robots and processing systems with candidate renewable and nuclear surface power sources and the environmental constraints of extraterrestrial operation. Second, it synthesizes and comparatively evaluates major isolated converter topologies, including wide-bandgap half-bridge and full-bridge converters, dual-active-bridge converters, phase-shifted full-bridge converters, LLC and CLLC resonant converters, and modular multipoint architectures, with particular attention to efficiency, power density, soft-switching capability, bidirectional operation, scalability,

and radiation-related reliability. Third, it integrates power-converter hardware with autonomous operation by reviewing adaptive digital control, intelligent power and energy management, fault detection and self-recovery, digital twins, artificial intelligence-enabled predictive maintenance, and SiC and GaN semiconductor technologies. Fourth, it identifies unresolved system-level challenges and future research directions involving high-voltage DC distribution, thermal management in vacuum, electromagnetic compatibility, radiation tolerance, modular redundancy, and long-duration reliability.

The remainder of this paper is organized as follows. Section 2 reviews the electrical power demands of representative ISRU robotic platforms, candidate renewable and nuclear energy sources, and the environmental challenges associated with lunar and Martian operations. Section 3 examines isolated power-conversion architectures, including wide-bandgap bridge converters, DAB, PSFB, LLC and CLLC resonant converters, comparative topology characteristics, and radiation-tolerant and redundant converter designs. Section 4 discusses adaptive digital control, intelligent power management and energy coordination, fault diagnosis, digital twins, AI-enabled predictive maintenance, and autonomous self-recovery. Section 5 identifies major research gaps and future development directions in power-bus architecture and system integration, thermal management in vacuum, electromagnetic compatibility, reliability, redundancy, and long-duration autonomous operation.

2. Extraterrestrial ISRU Robotic Systems and Power System Requirements

Extraterrestrial ISRU systems encompass a diverse range of robotic platforms and resource processing facilities designed to support long-duration lunar and Martian exploration. These systems perform tasks including regolith excavation, material transportation, oxygen and water production, propellant generation, construction material manufacturing, and infrastructure maintenance. Because these operations involve highly dynamic electrical loads and operate under harsh environmental conditions, their power systems must provide high efficiency, fault tolerance, autonomous operation, and long-term reliability. This section reviews the electrical power requirements of representative ISRU robotic systems, available renewable and nuclear energy sources, and the environmental challenges that influence the design of autonomous isolated power conversion architectures.

2.1. Electrical Power Demands of ISRU Robotic Platforms

The electrical power demand of in situ resource utilization robotic platforms is a critical design consideration for sustained lunar and Martian exploration missions. Robotic ISRU systems must be capable of supporting energy-intensive activities including regolith excavation, material transport, oxygen production, and autonomous construction, requiring power architectures that balance mobility, processing throughput, and operational longevity. Based on the number of different tasks ISRU platforms are designed to accomplish, the power required for each system can vary significantly. Table 1 shows various ISRU architectures and its estimated required power.

Table 1. Representative Electrical Power Requirements of Lunar and Martian ISRU Systems.

Equipment	Primary Function	Estimated Power Requirement
Miniature Thermal Emission Spectrometer [17]	Mineralogical and thermal imaging	5.6 W—Operation 0.3 W—Standby
Mars Environmental Dynamics Analyzer (MEDA) [16]	Atmospheric and environmental monitoring	17 W

Table 1. *Cont.*

Equipment	Primary Function	Estimated Power Requirement
Mars Oxygen ISRU Experiment (MOXIE) [17]	Oxygen production from atmospheric CO ₂	300 W
Radar Imager for Mars' Subsurface Experiment (RIMFAX) [16]	Ground-penetrating radar	5–10 W
Drilling and Sample Collection Systems [18]	Regolith excavation and sample acquisition	50–250 W
Sample Analysis at Mars (SAM) [19]	On-site chemical and organic analysis	~200 W peak ~average 100 W
Chemistry and Mineralogy (CheMin) Instruments [20]	Mineralogical analysis	46 W peak
Dynamic Albedo of Neutrons(DAN) [21]	Subsurface hydrogen detection	13 W
Regolith Excavator (RASSOR for Comparison) [22,23]	Autonomous regolith excavation operations	4 W per kg of regolith excavated
Molten Regolith Electrolysis (MRE) Reactor [24,25]	Large-scale oxygen and metal production	14,000–56,000 W
Mars Atmosphere and Regolith Collector/Processor (MARCO POLO) Atmospheric Processing Module (APM) [26]	Atmospheric CO ₂ collection and processing	Day operation ~850 W Night operation ~50 W
Hydrogen Reduction Reactors [27]	Oxygen extraction from lunar regolith	3300 W
Proton Exchange Membrane (PEM) Electrolyzers [28]	Water electrolysis and oxygen generation	1500 W
Laser-Based Road Construction System [29]	Regolith sintering and infrastructure construction	23,000 W—Assume heated over 10 h

2.2. Renewable and Nuclear Energy Sources for Surface Missions

Reliable electrical power generation is one of the fundamental requirements for sustained lunar and Martian exploration. Future extraterrestrial missions are expected to rely on a combination of renewable and nuclear energy systems capable of supplying both primary and auxiliary electrical loads while supporting autonomous robotic operations, ISRU facilities, habitats, communication infrastructure, and scientific payloads [30]. Candidate power technologies differ significantly in power density, operational lifetime, environmental resilience, scalability, and electrical distribution characteristics, making the selection of an appropriate energy source highly dependent on mission duration, geographical location, and surface operating conditions.

Solar photovoltaic (PV) systems remain the most mature renewable energy technology for robotic planetary exploration because of their modularity, low maintenance requirements, and proven flight heritage [31]. Photovoltaic arrays directly convert solar radiation into electrical energy and have successfully powered numerous lunar and Mars missions. Recent studies suggest that solar power can continue to play a major role in supporting future human exploration of Mars, particularly in equatorial regions where solar irradiance remains relatively high [32]. Compared with nuclear systems, photovoltaic power plants may require lower transported mass during early mission phases and offer greater deployment flexibility for modular surface installations. However, solar energy production is highly dependent on illumination conditions and is significantly affected by seasonal variations, eclipse periods, and dust accumulation on solar panels. Consequently, hybrid

renewable energy systems combining photovoltaic arrays with batteries, regenerative fuel cells, wind turbines, or other energy storage technologies have been proposed to improve system resilience and ensure continuous operation during extended dust storms or prolonged periods of low solar irradiance [33].

For long-duration lunar and Martian missions, nuclear power remains the most attractive option for providing continuous baseload electrical power independent of environmental conditions. Two primary nuclear technologies have been developed for space exploration: radioisotope power systems (RPSs), which convert the decay heat of plutonium-238 into electricity for low-power applications, and fission power systems (FPSs), which employ controlled uranium-235 fission reactions to generate electrical power ranging from several kilowatts to megawatts. Radioisotope power systems have successfully supported numerous NASA missions, including Apollo, Pioneer, Viking, Voyager, Cassini, New Horizons, and the Mars Curiosity and Perseverance rovers, demonstrating exceptional operational reliability over several decades.

To satisfy the substantially higher power requirements of future ISRU facilities and human habitats, NASA and the U.S. Department of Energy have jointly developed the Kilopower and Fission Surface Power (FSP) programs. These systems utilize compact heat-pipe-cooled reactors coupled with Stirling power converters to provide continuous electrical power for oxygen production, water extraction, propellant manufacturing, habitat operations, and robotic mining independent of solar illumination [34]. Nuclear surface power significantly reduces dependence on large battery storage systems and enables continuous operation in permanently shadowed lunar regions and during global Martian dust storms. Nevertheless, the deployment of nuclear power systems introduces additional engineering challenges, including radiation shielding, reactor startup and control, heat rejection in vacuum environments, launch safety, and long-term reliability. Consequently, future extraterrestrial power architectures are expected to integrate both renewable and nuclear energy sources within intelligent hybrid power management systems to maximize efficiency, resilience, and mission flexibility.

2.3. Environmental Challenges in Lunar and Martian Operations

The harsh environments of the Moon and Mars present significant challenges for the design and long-term operation of autonomous robotic systems and their associated power electronics. These challenges directly influence the reliability, efficiency, and lifetime of power generation, energy storage, and power conversion systems, making environmental resilience a primary design consideration for future ISRU missions.

One of the most severe environmental hazards on the lunar surface is the accumulation of highly abrasive and electrostatically charged lunar regolith. Fine dust particles readily adhere to solar panels, optical instruments, thermal radiators, mechanical seals, bearings, and electrical connectors, degrading their performance and accelerating mechanical wear [7,35]. Unlike Earth, the Moon lacks both a substantial atmosphere and a global magnetic field, exposing its surface directly to solar wind plasma, ultraviolet radiation, and continuous micrometeoroid bombardment. These conditions cause fine regolith particles to become electrostatically charged and levitated above the surface, allowing dust to adhere to exposed equipment and interfere with robotic mobility, scientific instruments, communication hardware, and photovoltaic power generation [36].

Extreme thermal cycling further complicates lunar surface operations. Surface temperatures fluctuate from approximately $-173\text{ }^{\circ}\text{C}$ during the lunar night to more than $120\text{ }^{\circ}\text{C}$ during the lunar day, producing severe thermal stresses on batteries, power electronic modules, semiconductor devices, solar arrays, thermal control systems, structural materials, and electrical interconnections [37]. Repeated thermal expansion and contraction can

accelerate solder fatigue, insulation degradation, packaging failure, and material aging, significantly reducing the operational lifetime of electronic systems. Consequently, future lunar power systems must incorporate robust thermal management, dust mitigation technologies, radiation-hardened electronics, and fault-tolerant power conversion architectures capable of maintaining reliable operation throughout extended mission durations.

The Martian environment presents a different but equally demanding set of engineering challenges. Frequent regional and global dust storms suspend large quantities of fine electrostatic dust within the atmosphere, allowing particles to infiltrate mechanical joints, optical sensors, electrical connectors, cooling systems, and power electronics [38]. Dust accumulation significantly reduces photovoltaic power generation, degrades optical system performance, and increases mechanical wear, while suspended atmospheric dust attenuates both optical and radio-frequency communication signals between surface assets, orbiters, and Earth [39]. In addition, the thin CO₂ atmosphere provides only limited convective cooling, placing greater demands on thermal management systems for high-power electronic equipment. These environmental constraints require future autonomous robotic platforms to employ advanced dust mitigation strategies, intelligent power management, fault-tolerant converter architectures, autonomous health monitoring, and predictive maintenance technologies to ensure reliable long-duration operation on the Martian surface.

3. Isolated Power Conversion Architectures for Lunar and Martian Robotic Platforms

3.1. Wide-Bandgap Half-Bridge and Full-Bridge Converter Topologies

Wide-bandgap (WBG) semiconductor devices, particularly gallium nitride (GaN) high-electron-mobility transistors (HEMTs) and silicon carbide (SiC) MOSFETs, have emerged as enabling technologies for next-generation high-power-density power conversion systems intended for lunar and Martian surface missions [40]. Compared with conventional silicon devices, WBG semiconductors exhibit higher breakdown voltage, lower switching losses, faster switching speeds, higher junction-temperature capability, and superior power density, making them well suited for the stringent mass, volume, and efficiency requirements of extraterrestrial robotic systems [41]. These characteristics enable converter switching frequencies from several hundred kilohertz to the megahertz range, significantly reducing the size and weight of transformers, inductors, and filtering components while improving overall converter efficiency [42].

Half-bridge and full-bridge converter topologies constitute the fundamental building blocks of many isolated DC–DC converter architectures used in distributed power systems [43]. Half-bridge configurations are widely employed in compact point-of-load converters, motor drives, auxiliary power supplies, and medium-power isolated converters because of their relatively simple structure and high efficiency. In contrast, full-bridge topologies provide greater power handling capability, bidirectional power flow, and improved transformer utilization, making them particularly suitable for high-power ISRU applications, including excavation systems, drilling platforms, thermal processing units, and autonomous construction equipment [44]. These bridge topologies also serve as the basis for more advanced isolated converters, including phase-shifted full-bridge (PSFB), LLC resonant, and dual-active-bridge (DAB) converters (see Section 3.2).

Despite their superior electrical performance, WBG-based converters must operate under the harsh environmental conditions encountered on the Moon and Mars. Extreme thermal cycling, vacuum or low-pressure environments, radiation exposure, abrasive dust contamination, and prolonged autonomous operation impose significant challenges on semiconductor packaging, gate-drive circuitry, magnetic components, and insulation sys-

tems. Although numerous studies have demonstrated that GaN devices exhibit excellent tolerance to total ionizing dose (TID), concerns remain regarding single-event effects (SEE), threshold-voltage drift, leakage-current degradation, and long-term gate reliability under high-radiation environments. Consequently, future extraterrestrial converter designs should integrate radiation-aware device selection, fault-tolerant gate drivers, optimized thermal paths, EMI suppression techniques, autonomous health monitoring, and intelligent protection strategies. These design considerations enable WBG half-bridge and full-bridge converter topologies to provide compact, efficient, and highly reliable isolated power conversion for distributed robotic platforms and future lunar and Martian surface infrastructure.

3.2. Dual-Active-Bridge (DAB) Converters

The Dual-Active Bridge (DAB) converter has emerged as a preferred topology for spacecraft electrical power systems due to its symmetrical isolated full-bridge architecture, which utilizes two active bridges on either side of a high-frequency transformer. This structure employs the transformer's leakage inductance as the primary energy-transfer element, enabling seamless bidirectional power flow by modulating the phase shift between the two bridges. Such bidirectionality is critical for lunar and Martian missions, allowing a single converter to function as both a battery charger during solar periods and a boost regulator during eclipse phases. Furthermore, DAB converters provide essential galvanic isolation, which protects sensitive onboard avionics from high-voltage transients generated by dynamic loads like electric propulsion thrusters [45–47].

A defining advantage of the DAB topology is its inherent ability to achieve Zero-Voltage switching for all semiconductor devices, which significantly reduces switching losses and electromagnetic interference. When integrated with WBG devices (such as SiC or GaN), DAB converters can achieve peak efficiencies approaching 99% while operating at frequencies that dramatically reduce the mass and volume of magnetic components. NASA-funded research has successfully demonstrated interleaved GaN-based DAB modules capable of operating in cryogenic environments, making them suitable for extreme planetary surface conditions [48–50].

To maintain high efficiency across the volatile input/output voltage ranges characteristic of spaceborne energy storage, advanced modulation strategies beyond standard Single-Phase Shift (SPS) are often required. Schemes such as Triple-Phase Shift (TPS) provide additional degrees of freedom to minimize circulating currents and backflow power, ensuring ZVS across the entire operational envelope even under mismatched voltage conditions. For systems with multiple voltage domains—such as the International Space Station's mix of 160 V solar, 120 V distribution, and 28 V battery buses—the DAB topology can be extended into the Triple-Active-Bridge (TAB) configuration. This multi-port evolution allows for omnidirectional power flow between three or more buses using a single magnetic core, achieving up to a 40% reduction in system volume compared to traditional multi-converter baselines [51,52].

3.3. Phase-Shifted Full-Bridge Converters

Phase-shifted full-bridge (PSFB) converters are among the most widely adopted isolated DC–DC converter topologies for medium- and high-power applications because they combine transformer-based galvanic isolation, fixed-frequency operation, high efficiency, and soft-switching capability. Power transfer is regulated by introducing a phase shift between the two bridge legs, while transformer leakage inductance and device output capacitance enable zero-voltage switching (ZVS), thereby minimizing switching losses, reducing electromagnetic interference, and increasing converter power density. Com-

pared with conventional hard-switched full-bridge converters, PSFB converters provide improved efficiency over a wide operating range and are well suited for high-voltage, high-power applications.

The inherent advantages of PSFB converters make them attractive candidates for lunar and Martian power distribution systems, where isolated conversion is required between high-voltage DC buses supplied by nuclear reactors or photovoltaic arrays and distributed robotic loads, including excavation actuators, drilling systems, thermal processing equipment, sensors, communication modules, and onboard computing platforms. Furthermore, PSFB converters can readily interface with SiC MOSFETs and GaN HEMTs, enabling higher switching frequencies, reduced transformer size, lower conduction losses, and improved overall converter efficiency [53].

Although PSFB converters have demonstrated excellent performance in terrestrial applications, their deployment in extraterrestrial environments presents additional challenges. Under light-load conditions, the loss of zero-voltage switching can increase switching losses and reduce converter efficiency. Additional concerns include circulating current, transformer volt-second imbalance, parasitic oscillations, electromagnetic interference, radiation-induced degradation, and thermal management under vacuum conditions [54]. Recent research has therefore focused on adaptive dead-time optimization, synchronous rectification, digital control, radiation-aware gate-driver design, and autonomous fault detection to improve converter robustness and long-term reliability. These advances position PSFB converters as one of the most promising isolated converter architectures for future nuclear-powered and renewable-powered ISRU systems operating on the lunar and Martian surfaces.

3.4. Resonant Converter Architectures for Space Applications

Resonant converter architectures have become an integral component of advanced space power systems because they offer high conversion efficiency, high power density, reduced electromagnetic interference (EMI), and soft-switching operation [10]. Unlike conventional pulse-width modulation (PWM) converters, resonant converters employ inductive-capacitive (LC) resonant networks to shape voltage and current waveforms, enabling zero-voltage switching (ZVS) and/or zero-current switching (ZCS). These soft-switching mechanisms substantially reduce switching losses, minimize semiconductor stress, and permit significantly higher switching frequencies, thereby reducing the size and mass of transformers, inductors, and filter components. Such characteristics are particularly advantageous for spacecraft, lunar bases, Mars habitats, and autonomous in situ resource utilization (ISRU) systems, where mass, volume, thermal management, and long-term reliability are critical design constraints.

Among the various resonant topologies, the LLC resonant converter has emerged as one of the most widely adopted solutions for isolated high-frequency power conversion because of its wide input-voltage operating range, excellent efficiency, and ability to maintain soft-switching over a broad load range [55]. Bidirectional CLLC resonant converters further extend these capabilities by enabling efficient energy exchange between batteries, fuel cells, and distributed DC buses, making them attractive for energy storage systems, electric mobility platforms, and modular surface power architectures [56]. In addition, series resonant converters (SRCs), parallel resonant converters (PRCs), and hybrid resonant switched-capacitor converters continue to be investigated for high-voltage and high-reliability space applications due to their potential for increased power density and reduced magnetic component size [57].

Recent advances in wide-bandgap semiconductor devices, particularly SiC MOSFETs and GaN HEMTs, have significantly enhanced the performance of resonant converters by

enabling switching frequencies from several hundred kilohertz to the megahertz range while maintaining high conversion efficiency [58]. The resulting reductions in transformer size, filter volume, cooling requirements, and overall system mass are particularly beneficial for extraterrestrial missions where payload weight directly impacts launch cost. Furthermore, resonant converters are increasingly being considered for integration with NASA's Fission Surface Power (FSP) systems, photovoltaic arrays, regenerative fuel cells, and future high-voltage DC distribution networks envisioned for long-duration lunar and Martian surface infrastructure.

Despite these advantages, resonant converters continue to present several design challenges for extraterrestrial deployment. Performance may deteriorate under light-load operation because of reduced soft-switching capability, while converter characteristics remain sensitive to resonant component tolerances, magnetic parameter variations, and frequency-dependent control. In addition, prolonged exposure to radiation, vacuum environments, abrasive dust, and extreme thermal cycling can adversely affect semiconductor devices, magnetic components, insulation systems, and passive elements. Consequently, current research is increasingly focused on adaptive frequency control, digital twin-assisted converter monitoring, radiation-tolerant magnetic materials, fault-tolerant control strategies, and autonomous health management systems capable of supporting long-duration planetary missions. These advances position resonant converter architectures as one of the most promising isolated power conversion technologies for future robotic mining systems, ISRU facilities, habitat power distribution networks, and nuclear-powered lunar and Martian surface operations.

3.5. Comparative Analysis of DAB, PSFB, LLC, and CLLC Converter Topologies

Selection of an isolated DC–DC converter for lunar and Martian ISRU systems should not be based solely on peak conversion efficiency. The selected topology must also satisfy mission-specific requirements related to rated power, input- and output-voltage variation, direction of power flow, load-transient response, soft-switching range, power density, electromagnetic compatibility, control complexity, radiation exposure, fault isolation, and modular scalability. The relative importance of these criteria varies considerably among mobile robots, drilling systems, energy-storage interfaces, scientific payloads, thermal-processing equipment, and centralized ISRU plants.

Table 2 provides a comparative assessment of the dual-active-bridge, phase-shifted full-bridge, LLC resonant, and bidirectional CLLC resonant converters. Because converter power rating, efficiency, and power density depend strongly on semiconductor technology, switching frequency, voltage ratio, magnetic-component design, cooling method, packaging, and control strategy, the quantitative values shown in the table represent selected hardware demonstrations rather than fundamental limits of the topologies.

The comparison indicates that no single converter topology is optimal for every extraterrestrial power-conversion function. The PSFB converter represents a mature and robust option for predominantly unidirectional conversion from a high-voltage nuclear or photovoltaic bus to relatively stable, high-power loads. The LLC converter is particularly attractive when maximum power density, low EMI, and high efficiency are required within a reasonably controlled voltage-conversion range. In contrast, the DAB converter is generally preferable when inherent bidirectional power transfer, modularity, and flexible interconnection among batteries, fuel cells, and distributed DC buses are primary requirements. The CLLC converter combines the bidirectional capability of an active-bridge architecture with the reduced switching losses of resonant conversion, but it requires more complex resonant design, control, and parameter management.

Table 2. Concise comparison of isolated converter topologies for extraterrestrial ISRU systems.

Criterion	DAB	PSFB	LLC	CLLC
Power level	Medium–high; modular	Medium–high	Low–medium; scalable	Medium–high
Efficiency/ power density	Very high/high	High/high	Very high/very high	Very high/high
Soft switching	ZVS; broad with advanced modulation	ZVS mainly at medium–high load	ZVS/ZCS near resonance	ZVS/ZCS in both directions
Bidirectional capability	Inherent	Not inherent	Generally unidirectional	Inherent
Voltage range and control	Wide range; complex control	Moderate range; simpler control	Frequency-dependent; component-sensitive	Wide range; most complex control
Radiation-related considerations	More active switches; good modular fault isolation	Fewer switches, but sensitive to voltage overshoot	Low switching stress; sensitive to passive-component drift	More devices and passives; supports modular recovery
Best suited for	Batteries, fuel cells, DC-bus interties	High-power unidirectional loads	Avionics and compact point-of-load supplies	Bidirectional storage and regenerative loads
Main limitation	Circulating current and control complexity	Light-load loss of ZVS	Limited reverse power and frequency variation	High component count and control complexity

3.6. High-Power-Density and Radiation-Tolerant Converter Designs

High-power-density and radiation-tolerant converter designs are essential for future space power systems because spacecraft, lunar surface assets, and Martian ISRU platforms must operate under stringent constraints on mass, volume, efficiency, thermal management, and long-term reliability [45]. Modern converter architectures increasingly leverage wide-bandgap SiC and GaN semiconductor devices, high-frequency magnetic components, soft-switching techniques, advanced packaging technologies, and integrated thermal management to maximize efficiency while minimizing passive component size and overall system mass [59]. Compared with conventional silicon-based converters, these technologies enable significantly higher switching frequencies, lower switching losses, and improved power density, making them particularly attractive for extraterrestrial applications.

Unlike terrestrial power electronics, space-qualified converters must also withstand radiation-induced degradation resulting from total ionizing dose (TID), displacement damage, and single-event effects (SEE), including single-event burnout, gate rupture, threshold-voltage drift, and leakage-current degradation [60]. Consequently, radiation-tolerant converter designs employ device derating, radiation-characterized semiconductor components, fault-tolerant gate drivers, redundant converter modules, and reconfigurable power architectures to improve operational robustness and mission lifetime [61]. These approaches are especially important for isolated DC–DC converters interfacing high-voltage nuclear or photovoltaic power sources with robotic actuators, drilling systems, thermal processing equipment, sensing instruments, communication payloads, and onboard computing systems.

$N + 1$ modularization does not reduce the intrinsic SEB susceptibility of an individual semiconductor. Instead, it converts a properly contained single-module failure into a recoverable system-level event. Its effectiveness therefore depends on conservative voltage derating, radiation-characterized SiC or GaN devices, transient suppression, rapid fault detection, bidirectional module isolation, autonomous reconfiguration, and the elimination of common-mode failure mechanisms. The combination of radiation-aware topology selection and modular redundancy provides a practical foundation for long-duration, self-recovering

power conversion systems supporting lunar and Martian robotic resource extraction. Future converter architectures are expected to integrate high-power-density topologies with intelligent thermal management, EMI suppression, autonomous protection, modular redundancy, digital health monitoring, and predictive maintenance. Such integrated designs will significantly improve converter resilience while supporting long-duration autonomous operation in the extreme thermal, radiation, and dust environments encountered on the Moon and Mars. Collectively, these technologies represent a critical foundation for next-generation extraterrestrial power systems supporting sustainable robotic resource extraction, surface infrastructure development, and future human exploration.

4. Autonomous Control, Intelligent Power Management, and Wide-Bandgap Technologies

4.1. Adaptive Digital Control Strategies

Adaptive digital control has become a cornerstone of modern high-power-density power converters because it provides superior dynamic response, robustness, flexibility, and autonomous operation compared with conventional analog control techniques. Advances in digital signal processors (DSPs), field-programmable gate arrays (FPGAs), and system-on-chip (SoC) platforms have enabled the real-time implementation of sophisticated control algorithms for isolated DC–DC converters, resonant converters, and bidirectional power conversion systems [62]. Unlike fixed-gain proportional-integral (PI) controllers, adaptive digital controllers continuously update control parameters in response to input-voltage variations, load transients, component aging, and thermal drift, thereby maintaining high conversion efficiency and stable operation over a wide operating range [63].

A variety of adaptive control techniques have been proposed for switching converters, including model predictive control (MPC), sliding-mode control (SMC), adaptive PI/PID control, deadbeat control, fuzzy logic, artificial neural networks (ANNs), reinforcement learning (RL), and hybrid intelligent control strategies. Among these approaches, MPC offers excellent transient response and constraint handling, while sliding-mode control provides strong robustness against parameter uncertainties and external disturbances. Artificial intelligence-based controllers further improve nonlinear compensation and adaptive decision-making without requiring highly accurate mathematical models.

The adoption of SiC and GaN power devices further increases the need for adaptive digital control because these devices operate at significantly higher switching frequencies than conventional silicon technologies. Consequently, precise timing, adaptive dead-time compensation, digital gate-drive optimization, and high-speed sampling become essential for minimizing switching losses and electromagnetic interference while maximizing converter efficiency. For lunar and Martian surface missions, adaptive digital controllers also enable autonomous operation under radiation exposure, extreme temperature cycling, communication latency, and rapidly changing robotic loads. Emerging technologies such as digital twins, edge computing, artificial intelligence, and prognostics and health management (PHM) are expected to become integral components of future adaptive control systems, enabling intelligent, resilient, and self-healing power converters for long-duration extraterrestrial exploration.

No single control strategy is optimal for every ISRU operating condition. A practical mission-oriented architecture should therefore employ multiple control layers, with each layer assigned functions that match its response speed, computational requirements, and reliability needs. As shown in Figure 2, adaptive PI/PID or sliding-mode control can be implemented at the local converter level to provide fast and deterministic voltage and current regulation, reject abrupt disturbances from drilling, excavation, and robotic-actuation loads, and initiate immediate protection during abnormal conditions. Fast local current

and voltage loops may employ adaptive PI/PID, deadbeat control, or appropriately designed SMC to provide deterministic regulation and immediate protection. MPC may operate at the converter or power-distribution level to coordinate DAB, CLLC, multiport, and redundant converter modules while enforcing electrical and thermal constraints. AI, digital twins, and prognostics and health management may operate at a slower supervisory level to predict load demand, identify degradation, optimize energy allocation, and recommend reconfiguration.

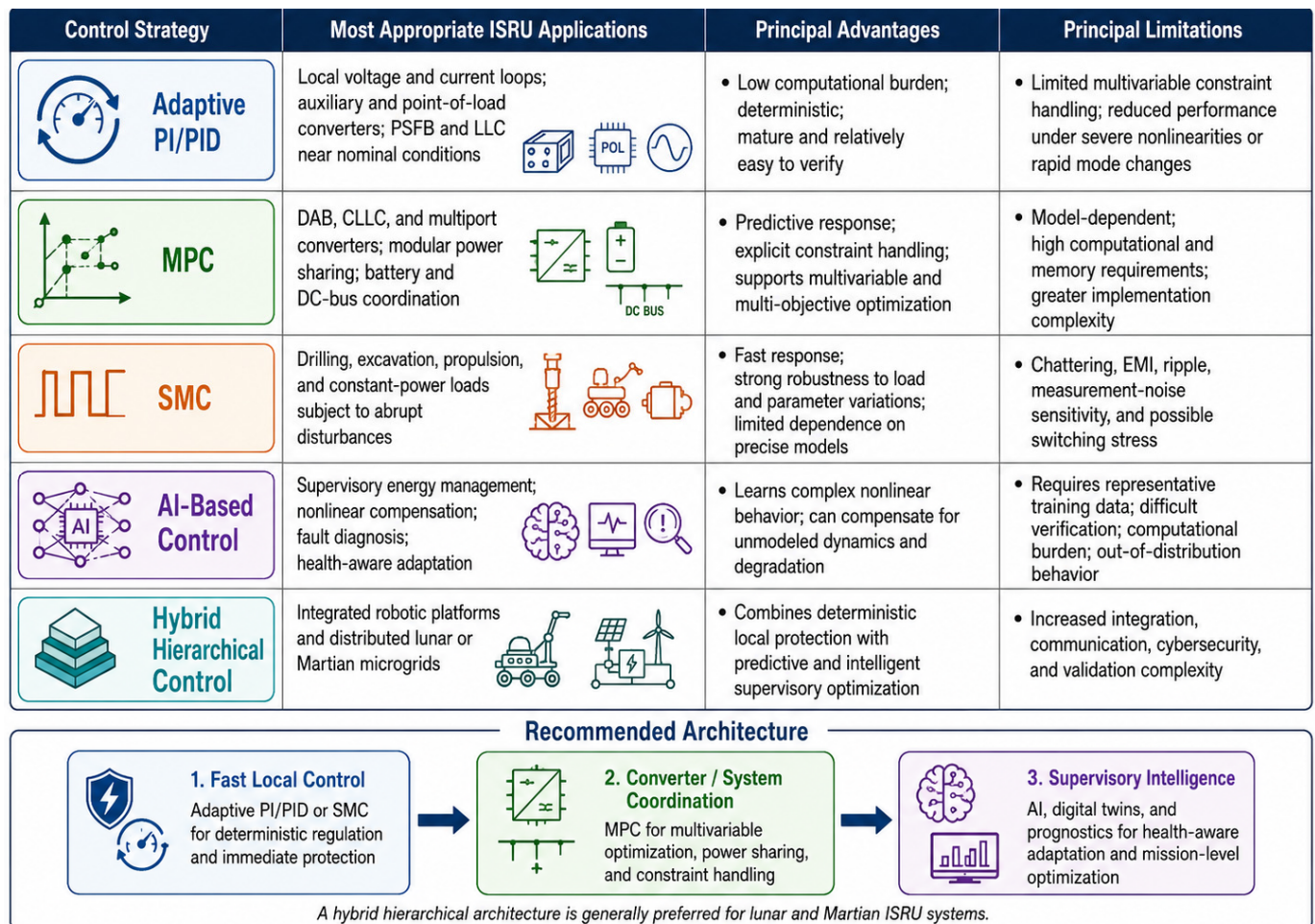


Figure 2. Applicability of Adaptive Control Strategies to Lunar and Martin ISRU Power Systems (AI-Generated).

4.2. Intelligent Power Management and Energy Coordination

Intelligent power management and energy coordination constitute the supervisory layer of future extraterrestrial power systems, enabling multiple power sources, energy storage units, robotic platforms, and ISRU processing facilities to operate as an integrated autonomous energy network. Unlike conventional spacecraft power systems that primarily regulate power generation and distribution, future lunar and Martian infrastructures must dynamically coordinate nuclear reactors, photovoltaic arrays, batteries, fuel cells, mobile robots, excavation equipment, communication systems, and habitat loads under highly uncertain and time-varying operating conditions [64].

Modern intelligent energy management systems employ predictive control, optimization-based scheduling, distributed control, machine learning, and multi-agent coordination to optimize energy utilization while satisfying constraints related to efficiency, reliability, battery state-of-charge, thermal limits, and mission priorities. These capabilities are par-

ticularly important for ISRU operations, where excavation, material transport, oxygen production, propellant manufacturing, and thermal processing generate highly variable electrical loads. Intelligent coordination also enables cooperative energy sharing among large excavation rovers, small scouting robots, swappable tools, and centralized ISRU hubs through dynamic power allocation based on mission objectives, terrain conditions, equipment health, communication delays, and available generation capacity [65].

Future planetary energy management systems are expected to integrate digital twins, artificial intelligence, and prognostics and health management to continuously assess system health, predict energy demand, optimize resource allocation, and autonomously reconfigure power distribution following component degradation or unexpected disturbances. Consequently, intelligent power management should be regarded as a fundamental architectural layer for autonomous isolated power conversion systems, providing the resilience, scalability, and energy awareness required for sustainable robotic resource extraction and long-duration human exploration of the Moon and Mars.

4.3. Fault Detection, Diagnostics, and Self-Recovery Mechanisms: Digital Twins and AI-Enabled Predictive Maintenance

Fault detection, diagnostics, and self-recovery are essential capabilities for next-generation autonomous power conversion systems supporting lunar and Martian exploration, where maintenance opportunities are extremely limited and communication delays prevent continuous human supervision. Unlike conventional protection systems that respond only after catastrophic failures, intelligent converter architectures continuously monitor electrical, thermal, and mechanical parameters to identify incipient faults before they propagate into system-level failures [66]. Common failure modes in isolated DC–DC converters include semiconductor degradation, transformer insulation aging, capacitor wear-out, gate-driver malfunction, thermal overstress, radiation-induced single-event effects, and sensor or connector failures [67]. Modern fault diagnosis combines model-based observers, state estimation, signal processing, and machine learning algorithms to detect abnormal operating conditions using voltage, current, temperature, vibration, and switching waveform signatures.

Digital twin technology has emerged as a powerful framework for intelligent diagnostics by maintaining a real-time virtual representation of the physical power conversion system synchronized with operational telemetry [68]. By continuously comparing predicted and measured system behavior, digital twins enable early detection of parameter drift, thermal imbalance, magnetic component degradation, and semiconductor aging while providing accurate estimates of remaining useful life (RUL) and supporting autonomous fault isolation [69].

A concrete digital-twin architecture for an autonomous space power converter can be organized into six coordinated layers. The physical converter and sensing layer monitors voltages, currents, temperatures, switching states, and environmental conditions, while the embedded data-acquisition layer filters, timestamps, and processes these signals in real time. The multi-fidelity virtual-model layer combines reduced-order electrical, control, thermal, and degradation models for onboard operation with higher-fidelity models for detailed analysis. The online synchronization and parameter-estimation layer continuously update model states and health-sensitive parameters using measured telemetry. The fault-diagnosis and prognostics layer compares measured and predicted behavior to detect anomalies, isolate likely component faults, and estimate remaining useful life. Finally, the autonomous decision and recovery layer uses these results to derate or isolate failed modules, activate redundant converters, reroute power, adjust operating conditions, or shed noncritical loads while maintaining mission-critical ISRU functions.

Artificial intelligence further extends these capabilities through machine learning, deep learning, reinforcement learning, and prognostics and health management (PHM) techniques that enable predictive maintenance and autonomous decision-making [70]. AI-enabled maintenance systems can forecast component degradation, optimize maintenance schedules, prioritize mission-critical loads, and automatically reconfigure converter operation to maximize system availability and reliability. Following fault diagnosis, autonomous self-recovery mechanisms can isolate failed converter modules, activate redundant hardware, reroute power through alternative distribution paths, adjust converter operating conditions, and safely shed nonessential loads while maintaining critical mission functions [71]. The integration of digital twins, edge computing, AI-enabled predictive maintenance, and self-healing control establishes a resilient power management framework capable of supporting long-duration robotic resource extraction and sustainable human exploration on the Moon and Mars.

5. Research Gaps and Future Development Directions

5.1. Power Bus Architectures and System Integration Switching

Future lunar and Martian missions will require scalable, fault-tolerant power architectures capable of integrating diverse power generation, energy storage, and utilization systems within a unified electrical network [72]. High-voltage DC (HVDC) distribution, typically operating between 300 and 1000 V, is emerging as the preferred architecture because it minimizes transmission losses, reduces cable mass, and enables efficient long-distance power delivery across planetary surface infrastructure [73]. These HVDC buses interface with isolated DC–DC converters that supply regulated power to robotic excavators, ISRU processing facilities, habitats, communication systems, and scientific payloads [74]. Distributed Power Management and Distribution (PMAD) systems employing intelligent solid-state power controllers (SSPCs) further improve system resilience through autonomous load prioritization, fault isolation, reliabilities, and dynamic power routing [75]. NASA's Fission Surface Power (FSP) architecture envisions modular plug-and-play power buses that can accommodate future expansion of habitats, robotic fleets, and ISRU facilities without significant modifications to the primary electrical network [76]. Coupled with distributed communication networks and intelligent energy management, these architectures establish the foundation for autonomous planetary microgrids capable of supporting long-duration exploration missions [77].

In addition, the above mentioned HVDC distribution for lunar and Martian infrastructure may introduce significant risks related to electrical arcing and insulation breakdown, governed by Paschen's Law, which dictates that the breakdown voltage of a gas is a function of the product of pressure and the distance between conductors. To ensure the reliability a few design mitigation strategies such as rigorous mandate to maintain minimum spacing to prevent arcing between high-voltage pins, advanced insulation and sealing that utilize hermetic sealing to prevent insulation aging (caused by the combined effects of vacuum exposure and ionizing radiation), corona mitigation via geometry by avoiding sharp edges and utilizing rounded geometries must be implemented [78].

5.2. Thermal Management in Vacuum Environments

Thermal management remains one of the most significant challenges for high-power-density power converters operating on the Moon and Mars because heat dissipation relies primarily on conduction and radiation, with little or no convective cooling available [79,80]. The widespread adoption of SiC MOSFETs and GaN HEMTs has increased converter switching frequencies and localized heat fluxes, requiring more effective thermal management strategies to maintain semiconductor junction temperatures within safe operating limits.

Current space-qualified solutions employ high-conductivity baseplates, vapor chambers, heat pipes, loop heat pipes, phase-change materials, and high-emissivity radiators to reject waste heat efficiently into the surrounding environment [81]. In addition, repeated thermal cycling between extreme lunar day and night temperatures accelerates solder fatigue, bond-wire degradation, insulation aging, and thermal interface material deterioration, reducing converter lifetime [82]. Consequently, recent research has emphasized integrated electro-thermal design, lightweight thermal structures, additive manufacturing, and digital twin-based thermal monitoring to optimize heat dissipation while reducing system mass. These technologies are expected to play a critical role in improving converter efficiency, reliability, and operational lifetime for autonomous robotic systems supporting long-duration lunar and Martian missions.

5.3. Electromagnetic Compatibility, Reliability, and Long-Duration Operation

Electromagnetic compatibility (EMC), reliability, redundancy, and long-duration operation are fundamental design requirements for autonomous power conversion systems supporting future lunar and Martian exploration. High-frequency switching converters based on wide-bandgap SiC and GaN devices offer substantial improvements in efficiency and power density; however, their fast-switching transitions and high voltage slew rates (dv/dt) and current slew rates (di/dt) significantly increase conducted and radiated electromagnetic interference (EMI), potentially degrading communication systems, navigation sensors, scientific instruments, and autonomous control electronics [83]. Effective EMI mitigation therefore requires a system-level design approach incorporating optimized printed circuit board (PCB) layout, minimized parasitic inductance, common-mode and differential-mode filtering, shielded cables, controlled gate-drive switching, soft-switching converter topologies, spread-spectrum modulation, and electromagnetic shielding to ensure compliance with spacecraft EMC requirements [84].

Beyond EMC considerations, planetary power converters must maintain continuous operation for many years while withstanding radiation exposure, extreme thermal cycling, abrasive dust contamination, vacuum environments, and progressive component aging. These harsh operating conditions demand converter architectures with exceptionally high reliability and fault tolerance [85]. Modern space power systems increasingly employ modular redundancy, intelligent solid-state power controllers (SSPCs), fault-tolerant converter topologies, redundant communication networks, and reconfigurable high-voltage DC distribution buses capable of autonomously isolating failed components while maintaining uninterrupted operation of mission-critical loads [86]. Such self-reconfigurable architecture significantly improve system availability and mission resilience by preventing localized failures from propagating throughout the power network.

Emerging digital technologies are further transforming the reliability of autonomous extraterrestrial power systems. Digital twins, artificial intelligence (AI), edge computing, and prognostics and health management (PHM) enable continuous monitoring of converter health, thermal behavior, switching characteristics, insulation degradation, and remaining useful life (RUL) estimation. AI-enabled diagnostic algorithms can detect abnormal operating conditions, predict impending failures, optimize maintenance schedules, and autonomously initiate corrective actions before catastrophic failures occur. Combined with intelligent energy management and autonomous fault recovery, these technologies establish self-healing power conversion architectures capable of adapting to changing mission conditions without human intervention.

Future lunar and Martian surface infrastructure will likely consist of interconnected nuclear reactors, renewable energy sources, robotic mining systems, ISRU processing plants, habitats, communication nodes, and autonomous transportation networks operating as

distributed planetary microgrids. Consequently, next-generation power conversion systems must integrate high-efficiency converter topologies with EMC-aware design, radiation-hardened components, modular redundancy, intelligent fault management, and AI-assisted predictive maintenance. Such architecture will provide the resilience, scalability, and long-term reliability required to support sustained robotic resource extraction and future human exploration on the Moon and Mars.

6. Conclusions

This review examined the space mission requirements, isolated converter topologies, autonomous control strategies, wide bandgap semiconductor technologies, and system integration challenges associated with power conversion for lunar and Martian ISRU robots. Future ISRU platforms must interface heterogeneous energy sources, including solar photovoltaic systems, batteries, regenerative fuel cells, radioisotope power systems, and fission surface power with loads ranging from low-power sensing and onboard computing to high-power excavation, drilling, electrolysis, thermal processing, and construction equipment. Consequently, galvanic isolation, wide input-voltage capability, high efficiency and power density, bidirectional power transfer, fault tolerance, and autonomous operation are fundamental requirements for extraterrestrial power-conversion architectures.

The comparative analysis indicates that no single converter topology is optimal for all ISRU applications. PSFB converters provide a mature, fixed-frequency solution for medium- and high-power unidirectional loads, although their soft-switching range may narrow under light-load conditions. LLC converters offer high efficiency, low electromagnetic interference, and high-power density near their designed operating range, but their performance is sensitive to resonant-component tolerances and wide frequency variation. DAB converters provide inherent bidirectional power transfer, modularity, and flexible energy coordination, making them particularly suitable for batteries, fuel cells, regenerative robotic loads, and DC-bus interconnections; however, circulating current and control complexity may increase under large voltage-ratio mismatches. CLLC converters combine bidirectional operation with resonant soft switching but require more complex resonant-network design and control. A heterogeneous architecture that assigns different topologies to mission functions according to their electrical and operational requirements is therefore preferable to a single universal converter solution. SiC and GaN devices can enable higher switching frequencies, reduce magnetic-component size, improved efficiency, and increased power density. Nevertheless, these benefits do not eliminate the challenges associated with radiation-induced degradation, thermal cycling, vacuum heat rejection, electromagnetic interference, packaging reliability, and long-duration component aging. Mission-ready converters should therefore combine radiation-characterized devices, conservative electrical derating, fault-tolerant gate drivers, effective thermal and EMI management, modular redundancy, and autonomous health monitoring. Hierarchical control architectures that integrate deterministic local regulation and protection with predictive system coordination, digital twins, fault diagnosis, prognostics, and supervisory intelligence provide a practical path toward resilient and self-recovering operation.

Future research should prioritize the experimental validation of integrated converter systems under representative combinations of radiation, vacuum or low-pressure operation, abrasive dust, extreme thermal cycling, and highly dynamic robotic loads. Additional priorities include standardized high-voltage DC distribution architectures, interoperable modular converter interfaces, $N + 1$ redundancy, autonomous fault isolation and power rerouting, digital-twin validation, and long-duration hardware-in-the-loop and fault-injection testing. Overall, autonomous isolated power conversion is a foundational enabling technology for scalable lunar and Martian ISRU infrastructure. Its successful development will re-

quire the coordinated integration of advanced converter topologies, wide-bandgap power devices, intelligent control, fault-tolerant system design, and mission-level power and energy management.

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References

1. NASA. *Moon to Mars Architecture Definition Document*; NASA Headquarters: Washington, DC, USA, 2023. Available online: <https://www.nasa.gov/moontomarsarchitecture/> (accessed on 27 July 2026).
2. NASA. *NASA Technology Taxonomy: In-Situ Resource Utilization (ISRU) Technologies*; Space Technology Mission Directorate: Washington, DC, USA, 2020. Available online: <https://www.nasa.gov/mission/in-situ-resource-utilization-isru/> (accessed on 27 July 2026).
3. Sanders, G.B.; Larson, W.E. Progress Made in Lunar In Situ Resource Utilization Under NASA's Exploration Technology and Development Program. In Proceedings of the AIAA SPACE Conference & Exposition, Long Beach, CA, USA, 27–29 September 2011.
4. Anand, M.; Crawford, I.A.; Balat-Pichelin, M.; Abanades, S.; van Westrenen, W.; Péraudeau, G.; Jaumann, R.; Seboldt, W. A Brief Review of Chemical and Mineralogical Resources on the Moon and Likely Initial In Situ Resource Utilization (ISRU) Applications. *Planet. Space Sci.* **2012**, *74*, 42–48. [CrossRef]
5. Mueller, R.P.; King, R.H.; Schreiner, S.S. *Trade Study of Excavation Tools and Equipment for Lunar Outpost Development and ISRU*; NASA Kennedy Space Center: Merritt Island, FL, USA, 2010.
6. Muscatello, A.C.; Santiago-Maldonado, E. *Mars In Situ Resource Utilization Technology Evaluation*; NASA Kennedy Space Center: Merritt Island, FL, USA, 2012. Available online: <https://ntrs.nasa.gov/citations/20120001775/> (accessed on 27 July 2026).
7. Horányi, M.; Szalay, J.R.; Wang, X. The Lunar Dust Environment: Concerns for Moon-Based Astronomy. *Philos. Trans. R. Soc. A* **2024**, *382*, 20230075. [CrossRef] [PubMed]
8. Erickson, R.W.; Maksimović, D. *Fundamentals of Power Electronics*, 3rd ed.; Springer: Cham, Switzerland, 2020.
9. Mohan, N.; Undeland, T.M.; Robbins, W.P. *Power Electronics: Converters, Applications, and Design*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2003.
10. Shahsevani, J.; Beiranvand, R. Application-Oriented Review of LLC Resonant Converters. *IEEE Access* **2024**, *12*, 52687–52726. [CrossRef]
11. Jung, J.-H.; Kim, H.-S.; Ryu, M.-H.; Baek, J.-W. Design Methodology of Bidirectional CLLC Resonant Converter for High-Frequency Isolation of DC Distribution Systems. *IEEE Trans. Power Electron.* **2013**, *28*, 1741–1755. [CrossRef]
12. Mason, L.S. *Comparison of Energy Conversion Technologies for Space Nuclear Power Systems*; NASA/TM-2019-220935; NASA Glenn Research Center: Cleveland, OH, USA, 2019.
13. NASA. *NASA's Moon to Mars Strategy and Objectives Development*; Technical Report; NASA: Washington, DC, USA, 2023.
14. Buso, S.; Mattavelli, P. *Digital Control in Power Electronics*, 2nd ed.; Morgan & Claypool: San Rafael, CA, USA, 2015.
15. NASA. *Autonomous Systems and Robotics Roadmap and Investments*; NASA Technology Roadmaps; NASA Headquarters: Washington, DC, USA, 2023. Available online: <https://ntrs.nasa.gov/api/citations/20210023502/downloads/lisic-intro-to-ASR.pdf> (accessed on 27 July 2026).
16. Lidow, A.; Strydom, J.; de Rooij, M.; Reusch, D. *GaN Transistors for Efficient Power Conversion*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2019.
17. NASA. *Mars Exploration Rovers: Science Instruments*; NASA: Washington, DC, USA, 2025. Available online: <https://science.nasa.gov/mission/mars-exploration-rovers-spirit-and-opportunity/science-instruments/> (accessed on 21 July 2026).

18. Zacny, K.; Chu, P.; Vendiola, V.; Bywaters, K.; Goldman, S.; Creekmore, P.; Ng, P.; Seto, E.P.; Quinn, J.; Eichenbaum, A.; et al. TRIDENT Drill for VIPER and PRIME-1 Missions to the Moon. In Proceedings of the 53rd Lunar and Planetary Science Conference, The Woodlands, TX, USA, 7–11 March 2022; Abstract No. 1068.
19. Mahaffy, P.R.; Webster, C.R.; Cabane, M.; Conrad, P.G.; Coll, P.; Atreya, S.K.; Arvey, R.; Barciniak, M.; Benna, M.; Bleacher, L.; et al. The Sample Analysis at Mars Investigation and Instrument Suite. *Space Sci. Rev.* **2012**, *170*, 401–478. [\[CrossRef\]](#)
20. Johnson, D.L.; Carroll, B.C.; Leland, R.S. *MSL/CheMin Cryocooler System Requirements and Characterization Tests*; Jet Propulsion Laboratory, California Institute of Technology: Pasadena, CA, USA.
21. Space Research Institute of the Russian Academy of Sciences (IKI RAS). Dynamic Albedo of Neutrons (DAN) Instrument Department of Nuclear Planetology. Available online: <https://np.cosmos.ru/en-us/instruments/dan> (accessed on 21 July 2026).
22. Mueller, R.P.; Cox, J.L.; Mantovani, J.G. *Regolith Advanced Surface Systems Operations Robot (RASSOR)*; NASA Kennedy Space Center: Merritt Island, FL, USA, 2013.
23. Tan, J.; Melkounian, N.; Harvey, D.; Akmeliawati, R. Lunarminer, Framework for Nature-Inspired Swarm Robotics in Lunar Water Ice Extraction. *Biomimetics* **2024**, *9*, 680. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Yu, K.; West, W.; Stokes, J.; Harder, B.; Reidy, L.; Dominguez, J.; Faber, K.T. Improving Molten Regolith Electrolysis with Zirconia-Based Hollow Anode Technology. *Acta Astronaut.* **2025**, *235*, 723–735. [\[CrossRef\]](#)
25. Harper, C. Molten Regolith Electrolysis Processing for Lunar ISRU: Financial and Physics Analysis of SpaceX Starship Transportation. Bachelor's Thesis, University of Central Florida, Orlando, FL, USA, 2021.
26. Muscatello, A.; Devor, R.; Captain, J. *Atmospheric Processing Module for Mars Propellant Production*; NASA: Washington, DC, USA, 2012.
27. Colozza, A.J.; Wong, W.A. *Evaluation of a Stirling Solar Dynamic System for Lunar Oxygen Production*; NASA Glenn Research Center: Cleveland, OH, USA, 2006.
28. Chow, R.; Nelson, G.; Perry, J. Electrolyzer Exergy Analysis for an Environmental Control and Life Support System. In Proceedings of the ASME 2018 International Mechanical Engineering Congress and Exposition, Pittsburgh, PA, USA, 9–15 November 2018; Paper IMECE2018-88119.
29. Chen, J.; Li, R. Advances in Solidification Technologies of Lunar Regolith-Based Building Materials under Extreme Lunar Environments. *Buildings* **2025**, *15*, 2543. [\[CrossRef\]](#)
30. NASA. *Fission Surface Power Project Overview*; NASA Glenn Research Center: Cleveland, OH, USA, 2023. Available online: <https://www.nasa.gov/exploration-systems-development-mission-directorate/fission-surface-power/> (accessed on 21 July 2026).
31. Drabczyk, A.; Uss, P.; Bucka, K.; Bulowski, W.; Kasza, P.; Putynkowski, G.; Socha, R.P. Space Photovoltaics: Materials, Device Concepts and Operational Challenges. *Electronics* **2026**, *15*, 1978. [\[CrossRef\]](#)
32. Chowdhury, B.H.; Hossain, S.A.; Lawrence, J.T.; Barave, S. AC/DC Power Systems with Applications in Future Human Habitat on Lunar and Mars Bases. *AIP Conf. Proc.* **2006**, *813*, 193–200. [\[CrossRef\]](#)
33. Darya, A.M.; Bansal, R.C.; Jarndal, O.A. Seasonal Performance Evaluation of a Hybrid PV–Wind–Battery Power System for a Mars Base. In Proceedings of the 2024 7th International Conference on Electric Power and Energy Conversion Systems (EPECS), Sharjah, United Arab Emirates, 12–14 November 2024.
34. NASA. *Kilopower*; NASA Space Technology Mission Directorate: Washington, DC, USA, 2017. Available online: <https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/kilopower-hmqzw/> (accessed on 21 July 2026).
35. Li, J.; Xu, W.; Yang, J.; Xue, H.; Yuan, J.; Wei, T. Key Technological Challenges and Systemic Solutions for Lunar Base Energy Systems Designed for Long-Term Deployment Needs. *npj Space Explor.* **2026**, *2*, 12. [\[CrossRef\]](#)
36. Gaier, J.R. *The Effects of Lunar Dust on EVA Systems During the Apollo Missions*; NASA/TM-2005-213610; NASA Glenn Research Center: Cleveland, OH, USA, 2005.
37. NASA. *Weather on the Moon*; NASA Science: Washington, DC, USA, 2024. Available online: <https://science.nasa.gov/moon/weather-on-the-moon/> (accessed on 21 July 2026).
38. He, F.; Rong, Z.; Wu, Z.; Gao, J.; Fan, K.; Zhou, X.; Yan, L.; Wang, Y.; Wei, Y. Martian Dust Storms: Reviews and Perspective for the Tianwen-3 Mars Sample Return Mission. *Remote Sens.* **2024**, *16*, 2613. [\[CrossRef\]](#)
39. NASA. *The Fact and Fiction of Martian Dust Storms*; ASA: Washington, DC, USA, 2015. Available online: <https://www.nasa.gov/solar-system/the-fact-and-fiction-of-martian-dust-storms/> (accessed on 21 July 2026).
40. Millán, J.; Godignon, P. Wide Band Gap Power Semiconductor Devices. In Proceedings of the Spanish Conference on Electron Devices, Valladolid, Spain, 12–14 February 2013.
41. Ding, X.; Zhou, Y.; Cheng, J. A Review of Gallium Nitride Power Devices and Their Applications in Motor Drives. *CES Trans. Electr. Mach. Syst.* **2019**, *3*, 54–64. [\[CrossRef\]](#)
42. Bi, J.; Shen, L.; Mei, B.; Cao, S.; Sun, Y.; Yu, Q. GaN power devices and their radiation effects for space applications. *J. Natl. Univ. Def. Technol.* **2024**, *46*, 149–159. [\[CrossRef\]](#)
43. Texas Instruments. *Phase-Shifted Full-Bridge Converter Fundamentals*; Power Supply Design Seminar SLUP414; Texas Instruments: Dallas, TX, USA, 2024.

44. Lemmon, A.N.; Mazzola, M.S.; Gafford, J.R.; Parker, C. Ensuring Volt-Second Balance in High-Power-Density Phase-Shifted Full-Bridge Converters Design. In *2014 IEEE Applied Power Electronics Conference and Exposition*; IEEE: New York, NY, USA, 2014.
45. Ravindran, R.; Massoud, A.M. State-of-the-Art DC-DC Converters for Satellite Applications: A Comprehensive Review. *Aerospace* **2025**, *12*, 97. [\[CrossRef\]](#)
46. Talebzadeh, S.; Beik, O. Spacecraft Medium Voltage Direct-Current (MVDC) Power and Propulsion System. *Electronics* **2024**, *13*, 1810. [\[CrossRef\]](#)
47. Dual Active Bridge Control: Modulation & Simulation | Impedyme. Available online: <https://impedyme.com/resource-center/dual-active-bridge/> (accessed on 28 June 2026).
48. NASA TechPort—Project. Available online: <https://techport.nasa.gov/projects/90266> (accessed on 28 June 2026).
49. Esteve, V.; Jordán, J.; Pomar, A.; Pérez, V. Bidirectional Dual Active Bridge Converter with Extended Voltage Range for HEMS Applications. *Electronics* **2026**, *15*, 1391. [\[CrossRef\]](#)
50. Krishnan, S.; Giardine, F.; Zou, J.; Abramson, R.A.; Pilawa-Podgurski, R.C. Design and Implementation of a GaN-Based, Cascaded Isolated DC-DC Converter for Satellite Applications. In *2025 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC + EATS)*; IEEE: New York, NY, USA, 2025; pp. 1–6.
51. Design Guide: TIDM-02002 Bidirectional CLLC Resonant Dual Active Bridge (DAB) Reference Design for HEV/EV Onboard Charger, 2019. Available online: www.ti.com (accessed on 28 June 2026).
52. Henao-Muñoz, A.C.; Debbat, M.B.; Pepiciello, A.; Domínguez-García, J.L. Triple Active Bridge Modeling and Decoupling Control. *Electronics* **2025**, *14*, 4224. [\[CrossRef\]](#)
53. Gögen, F.E.; Ozturk, S.B.; Aksit, M.H.; Dugan, G.; Cakmak, B.; Demir, C. Design and implementation of a full SiC-based phase-shifted full-bridge DC-DC converter with nanocrystalline-cored magnetics for railway battery charging applications. *Energies* **2025**, *18*, 3945. [\[CrossRef\]](#)
54. Pastor, M.; Gordan, D.; Maxwell, C.L. From IGBT to GaN Implementation in Phase-Shifted Full-Bridge Converter. *Electr. Eng.* **2025**, *107*, 11831–11845. [\[CrossRef\]](#)
55. Patel, M.R. *Spacecraft Power Systems*; CRC Press: Boca Raton, FL, USA, 2005.
56. Ramya, K.; Sundaramoorthi, R. Bidirectional Power Flow Control using CLLC Resonant Converter for DC Distribution System. *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.* **2014**, *3*, 8716–8725.
57. Kazimierczuk, M.K. *Resonant Power Converters*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2011.
58. Lei, Y.; Pilawa-Podgurski, R.; Perreault, D. Analysis and Design of Resonant Switched-Capacitor Converters. *IEEE Trans. Power Electron.* **2016**, *31*, 7450–7462. [\[CrossRef\]](#)
59. NASA. *Wide Bandgap Reliability and Application Guidelines*; NASA Glenn Research Center: Cleveland, OH, USA, 2020. Available online: <https://ntrs.nasa.gov/citations/20205002797> (accessed on 21 July 2026).
60. Maksimović, D.; Zane, R.; Erickson, R.W. Impact of Digital Control in Power Electronics. *IEEE Trans. Power Electron.* **2004**, *19*, 15–22. [\[CrossRef\]](#)
61. Mattavelli, P. Digital Control of DC–DC Boost Converters with Improved Dynamic Response. *IEEE Trans. Power Electron.* **2005**, *20*, 1203–1210.
62. Rodríguez, J.; Cortés, P. *Predictive Control of Power Converters and Electrical Drives*; Wiley-IEEE Press: Hoboken, NJ, USA, 2012.
63. Kim, N.; An, D.; Choi, J.-H. *Prognostics and Health Management of Engineering Systems*; Springer International Publishing: Cham, Switzerland, 2017. [\[CrossRef\]](#)
64. Soeder, J.; Raitano, P.; McNelis, A. NASA Glenn Research Center. Intelligent (Autonomous) Power Controller Development for Human Deep Space Exploration. NASA Technical Reports Server, 2017. Available online: <https://ntrs.nasa.gov/citations/20170000018> (accessed on 21 July 2026).
65. Shahzad, S.; Abbasi, M.A.; Chaudhry, M.A.; Hussain, M.M. Model Predictive Control Strategies in Microgrids: A Concise Review. *IEEE Access* **2022**, *10*, 122211–122225. [\[CrossRef\]](#)
66. Khan, S.; Wen, H. A Comprehensive Review of Fault Diagnosis and Tolerant Control in DC-DC Converters for DC Microgrids. *IEEE Access* **2021**, *9*, 80100–80127. [\[CrossRef\]](#)
67. Malik, J.A.; Amir, M.; Haque, A.; Bakhsh, F.I. A Comprehensive Review of Fault Detection and Diagnosis Techniques for DC–DC Power Converters in Smart Grid Applications. In *2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*; IEEE: New York, NY, USA, 2024.
68. Tao, F.; Zhang, M. *Digital Twin Driven Smart Manufacturing*; Academic Press: London, UK, 2019.
69. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems*; Springer: Cham, Switzerland, 2017.
70. Michael, G. *Pecht, Prognostics and Health Management of Electronics*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2008.
71. Muhammad, S.; Waqar, M.; Umar, H.B.; Ali, M. Digital Twin-Based Predictive Monitoring and Intelligent Fault Diagnostics for High-Reliability Electrical Machines and Power Infrastructure. *Glob. Res. J. Nat. Sci. Technol.* **2026**, *4*, 519–546. [\[CrossRef\]](#)

72. NASA. Power Systems for Human Exploration Missions; NASA Technical Reports Server. 2021. Available online: <https://ntrs.nasa.gov/api/citations/19990025828/downloads/19990025828.pdf> (accessed on 21 July 2026).
73. NASA Headquarters. *NASA Technology Roadmaps. TA03: Space Power and Energy Storage*; NASA Headquarters: Washington, DC, USA, 2015. Available online: https://www.lpi.usra.edu/sbag/goals/capability_inputs/2015_Tech_3_space_power_energy_storage.pdf (accessed on 21 July 2026).
74. *IEEE Std 2030.10-2020; Interoperability of DC Microgrids*. IEEE Standards Association: Piscataway, NJ, USA, 2020.
75. Csank, J.T.; Soeder, J.; Follo, J.; Muscatello, M.; Hau, Y.H.; Carbone, M. An Autonomous Power Controller for the NASA Human Deep Space Gateway. In Proceedings of the International Energy Conversion Engineering Conference, Cincinnati, OH, USA, 9–11 July 2018; NASA Technical Reports Server 2018. Available online: <https://ntrs.nasa.gov/citations/20180005241> (accessed on 31 July 2026).
76. Nuclear Newswire, Nuclear Power on the Moon: What We’re Watching NASA Glenn Research Center. Available online: <https://www.ans.org/news/2025-09-02/article-7336/nuclear-power-on-the-moon-what-were-watching/> (accessed on 21 July 2026).
77. Saha, D.; Bazmohammadi, N.; Lashab, A.; Vasquez, J.C.; Guerrero, J.M. Power and Energy Management System of a Lunar Microgrid—Part I: Modeling Power Demand of ISRU. *IEEE Trans. Aerosp. Electron. Syst.* **2023**, *60*, 1364–1375. [CrossRef]
78. Dong, M.; Li, H.; Yin, S.; Tian, B.; Yang, S.; Chen, Y. An Overview of DC-DC Power Converters for Electric Propulsion. *Aerospace* **2026**, *13*, 36. [CrossRef]
79. Gilmore, D.G. *Spacecraft Thermal Control Handbook*; Aerospace Press: El Segundo, CA, USA, 2002.
80. NASA. *Thermal Control Handbook*; NASA Glenn Research Center: Cleveland, OH, USA, 2002.
81. Ku, J. Introduction to Loop Heat Pipes. NASA Technical Reports Server. Available online: <https://ntrs.nasa.gov/citations/20150018090/> (accessed on 21 July 2026).
82. Lau, J.H. *Thermal Stress and Strain in Microelectronics Packaging*; Springer: Berlin/Heidelberg, Germany, 1993.
83. Ott, H.W. *Electromagnetic Compatibility Engineering*; Wiley: Hoboken, NJ, USA, 2009.
84. Paul, C.R. *Introduction to Electromagnetic Compatibility*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2006.
85. Wang, Y.; Lucia, O.; Zhang, Z.; Gao, S.; Guan, Y.; Xu, D. A Review of High Frequency Power Converters and Related Technologies. *IEEE Open J. Ind. Electron. Soc.* **2020**, *1*, 247–260. [CrossRef]
86. NASA. State-of-the-Art of Small Spacecraft Technology, 3.6 State-of-the-Art—Power Management and Distribution. Available online: <https://www.nasa.gov/smallsat-institute/sst-soa/power-subsystems/> (accessed on 21 July 2026).

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