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Wide Bandgap Semiconductor-Based Power Electronics for Aviation

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There is a growing trend in aircraft electrification, which can reduce green-house gas emissions, reduce audible noise, reduce maintenance needs, lower cost, and improve safety. Moving from mechanical, pneumatic, and hydraulic power to electric power requires architecture changes, more electric power, and improvements in electric power generation, distribution, and conversion. There are two main categories of aircraft electrification in aviation industry: the more-electric aircraft (MEA), which replaces secondary aircraft systems traditionally supplied by pneumatic, hydraulic, or mechanical power with electrical systems; and the electrified aircraft propulsion (EAP), which includes turbo-electric, hybrid-electric, and all-electric architectures.

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Power electronics play a crucial role for aircraft electrification. At the heart of power electronics are power semiconductor devices. The emergence of wide bandgap (WBG) semiconductor devices are profoundly changing power electronics. The superior performance of WBG devices over silicon (Si) devices can improve efficiency, power density, specific power, and reliability of power electronics, the characteristics that are particularly important for aviation applications. Authors have been involved in the development of several power electronics equipment prototypes utilizing WBG devices for aircraft applications. All of them have achieved significantly improved efficiency and specific power over the comparable, state-of-the-art Si-based commercial equipment. On the other hand, the fast switching WBG devices and the aviation environment also pose unique challenges for the design and application of power electronics. Fast switching speed can cause high *dv/dt* and *di/dt* slew rates, leading to increased electromagnetic interference (EMI), and higher parasitics induced overvoltage and power loss. Aviation environment includes low pressure, strong cosmic ray radiation, and wide temperature range associated with the flight environmental conditions. Addressing these issues and requirements in design and application is critical to the successful utilization and maximizing the benefits of WBG-based power electronics in aviation.

I. Benefits of WBG-Based Power Electronics

Generally, the physical properties including bandgap energy, breakdown electric field, saturation drift velocity, and thermal conductivity are all significantly higher for WBG semiconductors, as compared to Si. Therefore, WBG devices can achieve lower specific ON-resistance, faster switching speed, higher operating temperature, and better radiation hardening capability. Additionally, certain WBG devices exhibit superior performance at cryogenic temperatures. For example, GaN high electron mobility transistors (HEMTs) show significantly reduced specific ON-resistance (>4X) at cryogenic temperatures [1]. Therefore, WBG devices are advantageous for aviation applications, where cosmic radiation and extreme temperature can be a concern. Also, for aviation applications, high efficiency, high power density, and high specific power of power electronics are essential.

The benefits of utilizing WBG devices in power electronics can be realized in four ways. 1) Direct substitution of Si devices with WBG devices. Lower ON-state resistance, faster switching speed, and less diode reverse recovery of WBG devices can lead to lower power loss and therefore higher efficiency. Together with higher operating temperature of WBG devices, cooling needs can be reduced. Moreover, with higher switching frequency of WBG devices, passive components can be reduced. As a result, power electronics equipment efficiency, power density, specific power, and/or temperature capability can be improved. 2) Topology simplification due to lower power loss, higher voltage, and higher switching frequency capability of WBG devices. For example, complex Si-based soft switching topologies to avoid high switching loss can be replaced with simpler WBG-based hard switching topologies. Higher voltage and faster switching WBG devices offer an opportunity to replace the Si-based multilevel topologies with the simple two-level or other topologies with reduced levels, which can still achieve the needed performance, such as low harmonics and fast dynamics. Therefore, the converter design, control, and operation can be greatly simplified, resulting in higher density, higher reliability, and lower cost. 3) Enabling system-level benefits. WBG-based power electronics can have better dynamic performance and more system-level functionalities as a result of higher switching frequency and higher control bandwidth, which can lead to system-level benefits. For example, high control bandwidth can enhance the stability and power quality, and reduce the design margin and filter needs in a system, which can directly translate into weight reduction in an aircraft electrical system. 4) Enabling new applications. With lower loss and faster switching capabilities of WBG devices, some of the mechanical or other nonelectrical functions can be replaced by electrical ones. Examples include solid-state transformers (SSTs), solid-state circuit breakers (SSCBs), and high-speed motor drives. There are Si-based SSTs and SSCBs in the market but their efficiency and related performance are generally inferior to their mechanical counterparts. To improve their efficiency, hybrid solutions with both mechanical and electrical portions have been introduced for high power applications, which will add weight and complexity, and therefore not ideal for aviation applications. With WBG devices, the power loss can be significantly reduced. In addition, SSTs and SSCBs will introduce valuable system-level benefits. For example, SSCBs can interrupt fault currents at least an order of magnitude faster, in less than hundreds of microseconds instead of milliseconds or

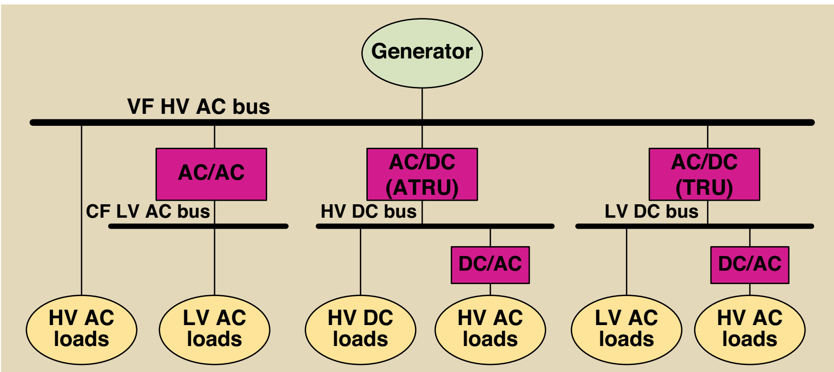

FIG 1 MEA architecture.

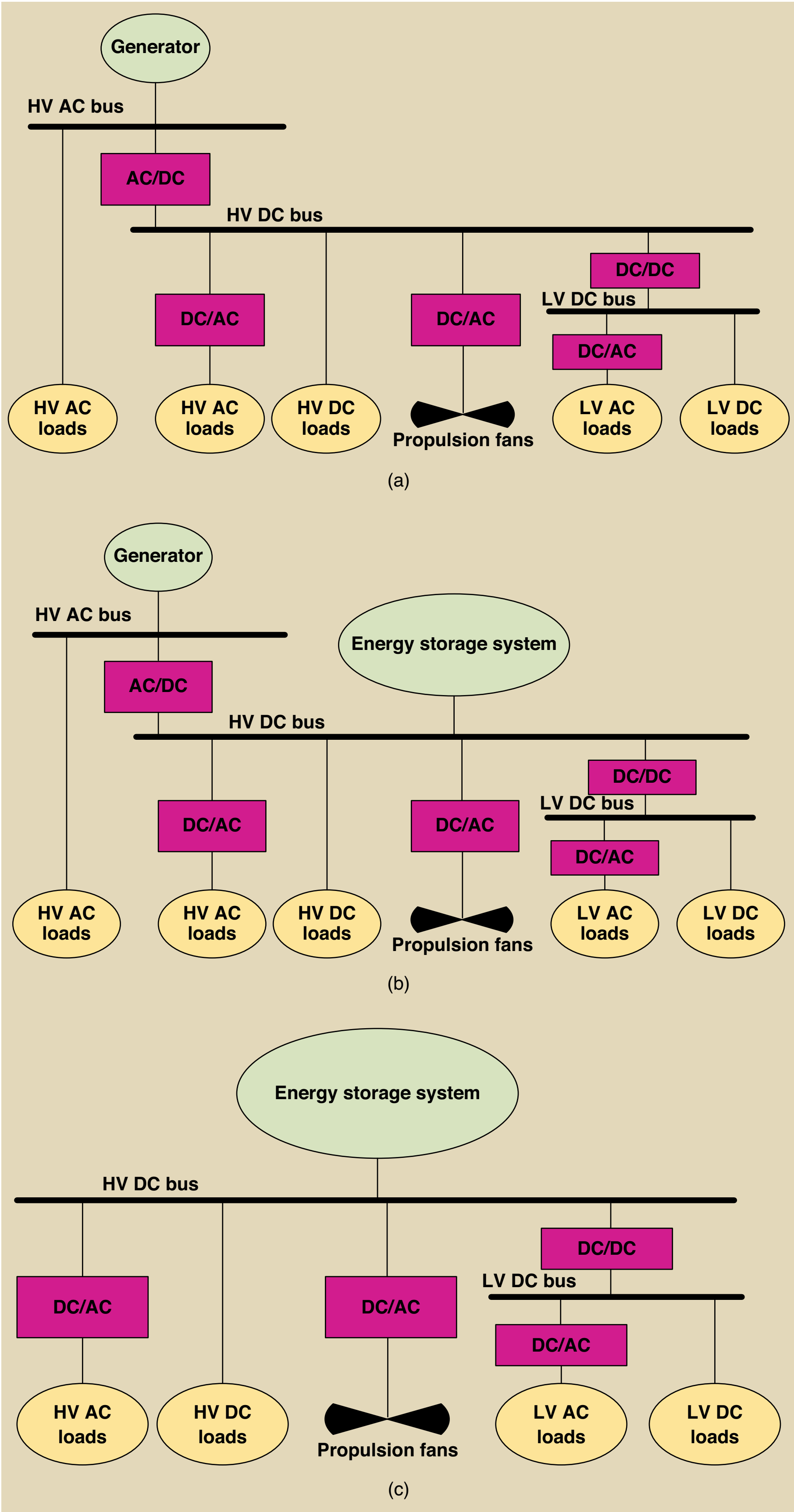

FIG 2 Examples of EAP-based electrical architecture. (a) Turbo-electric architecture. (b) Series hybrid-electric architecture. (c) All-electric architecture.

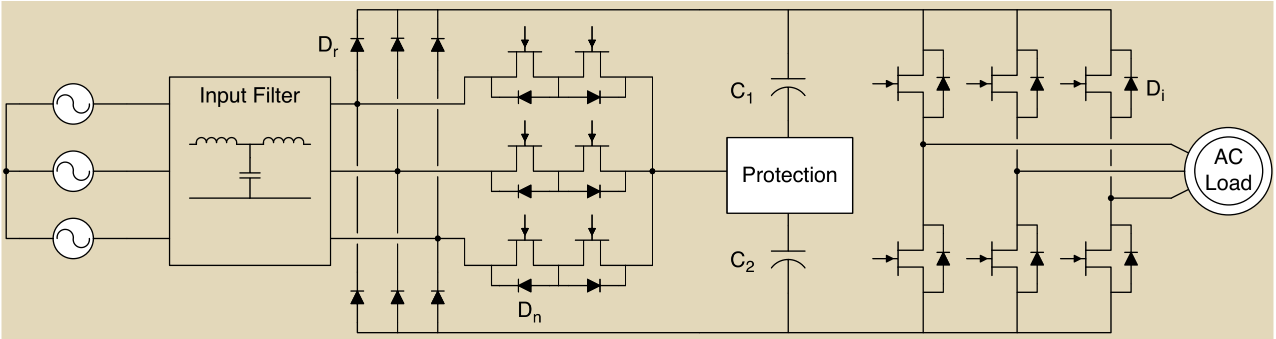

FIG 3 AC–AC converter system diagram.

longer needed for mechanical breakers, which will lead to reduced design margins needed for aircraft electrical system components like cables, capacitors, and inductors. These system-level benefits, together with much reduced power loss, will justify the applications of WBG-based SSTs and SSCBs, especially for aviation applications. The high-speed motor drive will be a key enabler for aviation electrification, where the fundamental frequency is high and the high-speed motor is preferred for smaller size and lower weight. It would be challenging to realize a Si-based high-power high-speed motor drive without incurring high switching loss and/or using some complex multilevel topologies.

Clearly, WBG-based power electronics can be a critical enabling technology for aviation electrification, with their benefits both at the equipment level and the system level.

II. Examples of WBG-Based Power Electronics for Aviation

Clearly, WBG-based power electronics can be a critical enabling technology for aviation electrification, with their benefits both at the equipment level and the system level. This section overviews power electronics in MEA and EAP applications, and presents several WBG-based power electronics development examples for these applications, mainly from the authors' experience.

A. Power Electronics in Aviation

MEA technologies have been implemented in large commercial aircraft, including Boeing 787 and Airbus A380. Figure 1 shows a typical electrical architecture of the MEA [2]. The variable frequency (VF) high voltage ac (HVAC) bus is rated at 115 V and 360–800 Hz (A380 case), or 230 V ac and 360–800 Hz (B787 case). The constant frequency (CF) low voltage ac (LVAC) bus is rated at 115 V and 400 Hz. The high voltage dc (HVDC) bus is rated at 270 VDC (A380 case) or 540 VDC (B787 case). The low voltage dc (LVDC) bus is rated at 28 V.

EAP is the next step for aviation electrification and is gaining much research and development interest. Turbo-electric, hybrid-electric, and all-electric are the three main electric propulsion architectures. Figure 2 shows examples of the electrical architectures for EAP [2]. Several ac–dc, ac–ac, dc–ac, and dc–dc converters are required depending on the main bus configuration and the propulsion technology. Note that for EAP, distributed propulsion can be easily achieved with multiple fans distributed on the aircraft for a more effective propulsion, and each fan is driven by its own dc/ac inverter motor drive. Some large EAP aircraft are under investigation. For example, NASA's single-aisle STARC-ABL and N3X airplane projects aim for dc/ac inverters rated at a minimum of 1 MW with a dc bus level between 1000 and 3000 V [3].

Various types of faults can occur in the aircraft electrical system, such as short circuit, overload, and arcing. Protection devices are required to isolate and clear faults, and to ensure safe flying conditions. Mechanical circuit breakers are still predominantly used in conventional aircraft. However, they are not suitable for systems with high dc voltages. On the other

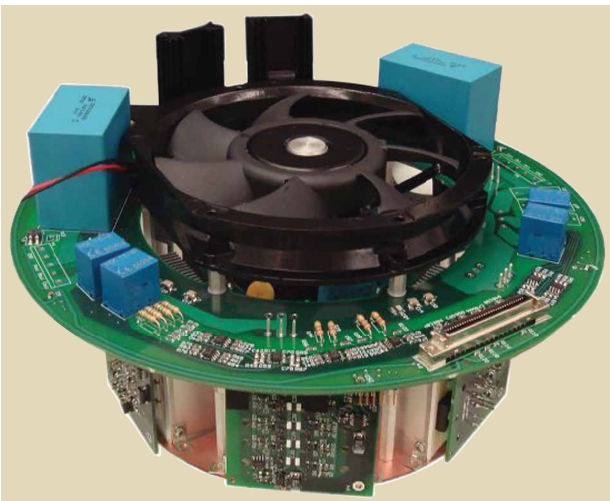

FIG 4 10 kW SiC JFET-based ac-dc-ac converter prototype.

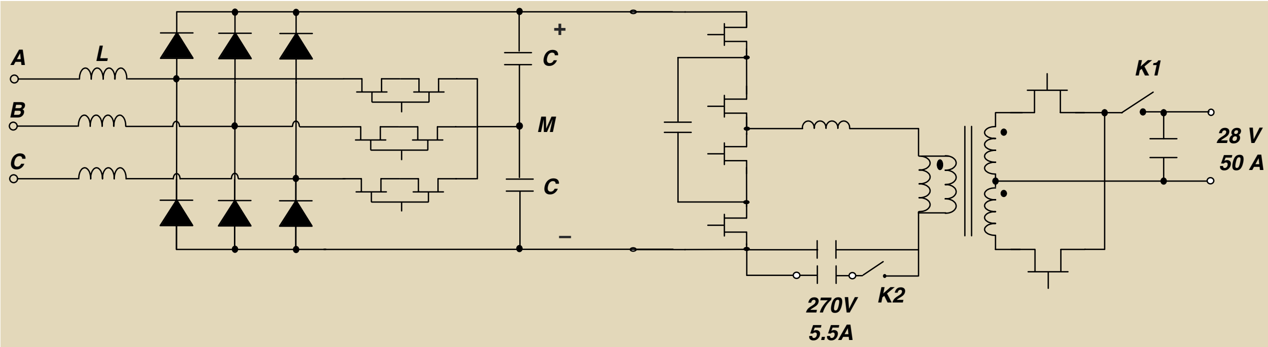

FIG 5 AC–DC converter system diagram.

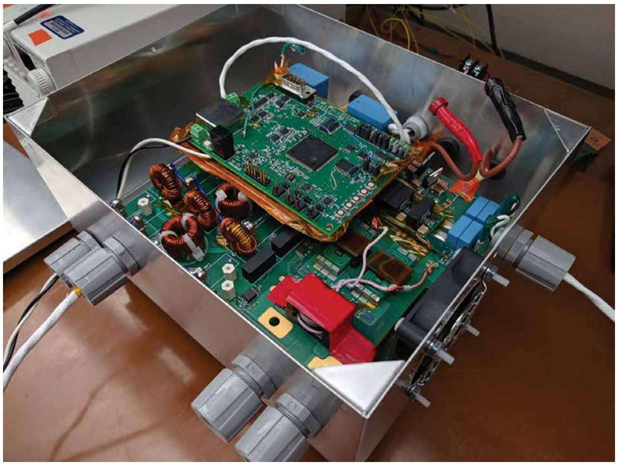

FIG 6 1.5 kW GaN-based ac–dc converter prototype.

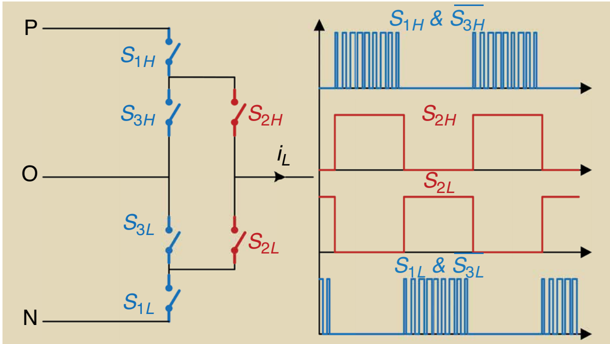

FIG 7 Phase-leg of the 3L-ANPC converter and corresponding modulation.

hand, SSCBs can provide fast protection and be adapted to protect either ac or dc circuits. Traditionally, SSCBs available are mostly rated at 28 V dc and several hundred amperes, or 270–540 V dc and several tens of amperes with limited efficiencies. With the huge increase in power and voltage ratings, especially in the case of EAP, higher current capabilities and corresponding breakers at high dc voltage are needed.

B. Examples of WBG-Based Power Electronics for MEA and EAP

1) 10 kW SiC-based high power density ac-fed motor drive for MEA.

A 10 kW high density three-phase ac–dc–ac converter was developed more than a decade ago using the first available SiC devices at the time, the 1.2 kV normally-on SiC junction-gate field-effect transistors (JFETs) and SiC Schottky diodes [4]. As shown in Figure 3, the converter topology consists of a three-level Vienna-type rectifier as an active front-end with a two-level voltage source inverter. Note that a protection circuit was added on the dc link to take care of the potential failures of the normally-on JFETs. This topology was selected as it can lead to a higher specific power. The ac phase voltage was 235 V rms with 360–800 Hz frequency, similar to that of Boeing 787. The switching frequency was selected to be 70 kHz as it is the optimal point for the overall weight, in particular, considering the EMI filter weight reduction. The 70 kHz switching frequency was enabled by the SiC devices.

Figure 4 shows the converter hardware. One innovation of this converter is the SiC JFET modules that were custom packaged with planar structure and are capable of operating at 250 °C junction temperature. The prototype was tested verifying key performance requirements including compliance with the power quality and EMI standards. With the ambient temperature designed for 65 °C, the prototype achieved > 95% efficiency and 3.59 kW/kg specific power, which was about an order of magnitude lighter than the commercially available Si-based ac-fed motor drives at the time.

2) 1.5 kW GaN-based high power density ac–dc universal charger for MEA.

A 1.5 kW high density ac/dc converter utilizing 650 V GaN HEMTs was designed as a universal battery charger for potential aircraft applications. As shown in Figure 5, the topology is based on a three-level Vienna-type rectifier and a three-level dual output dc–dc converter. The ac voltage is 115 or 235 V rms with 360–800 Hz frequency. The dual dc output are 28 V/50 A (range 20–33.6 V) and 270 V/5.5 A (range 180–302 V).

The prototype of the hardware with both power stage and EMI filters, shown in Figure 6, was tested under full power operation. The hard switching ac–dc stage achieved

97.9% efficiency at 112.5 kHz switching frequency and 95.3% efficiency at 450 kHz switching frequency. The *LLC* and buck modes of dc/dc stage achieved 95.1% efficiency and 97.8% efficiency, respectively. The specific power is 2 kW/kg.

3) 1 MW SiC-based high power density cryogenically-cooled dc–ac converter for EAP.

A 1 MW inverter was developed for future EAP applications utilizing cryogenic cooling [5]. This inverter is dc-fed from ±500 V bus and capable of three-phase output up to a fundamental frequency of 3 kHz. The inverter utilizes a three-level active neutral point clamped (3L-ANPC) topology, with one of its three phase-legs and corresponding low-loss modulation scheme shown in Figure 7. Two 500 kW inverters are paralleled through coupled inductors to achieve 1 MW power while reducing harmonic ripples and EMI noise. Dc and ac side EMI filters are employed to meet DO-160 standards on both sides. Figure 8 shows the system configuration of the 1 MW inverter.

As mentioned above, GaN HEMTs exhibit excellent performance at cryogenic temperatures. However, in order to build a MW-level inverter, too many discrete GaN HEMT devices need to be paralleled since there were no commercial GaN modules available. Even with the commercial modules, their package is not built to operate at cryogenic temperatures. As a result of these practical limitations, the 900 V/800 A SiC MOSFET power module was adopted.

Figure 9 illustrates the 1 MW inverter system layout and Figure 10 shows the actual hardware. The EMI filters

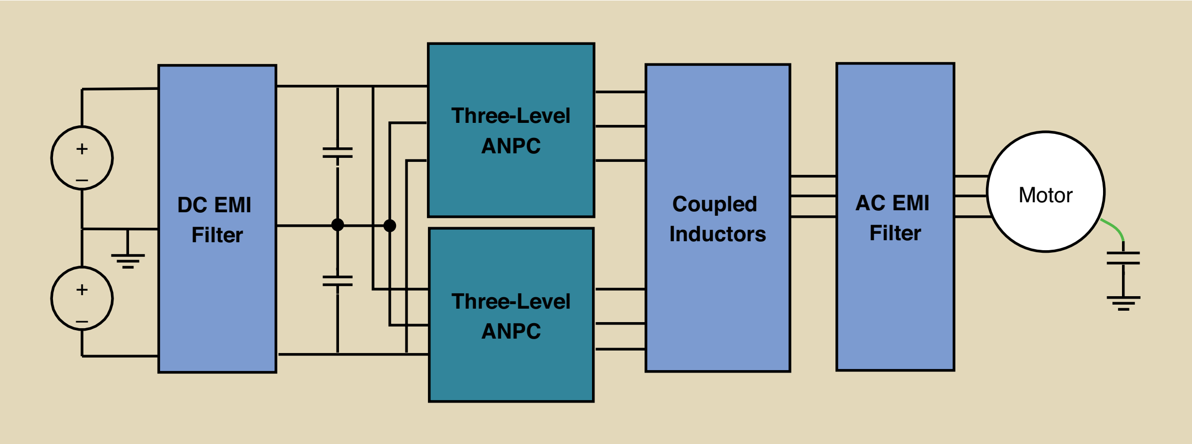

FIG 8 1 MW inverter system configuration.

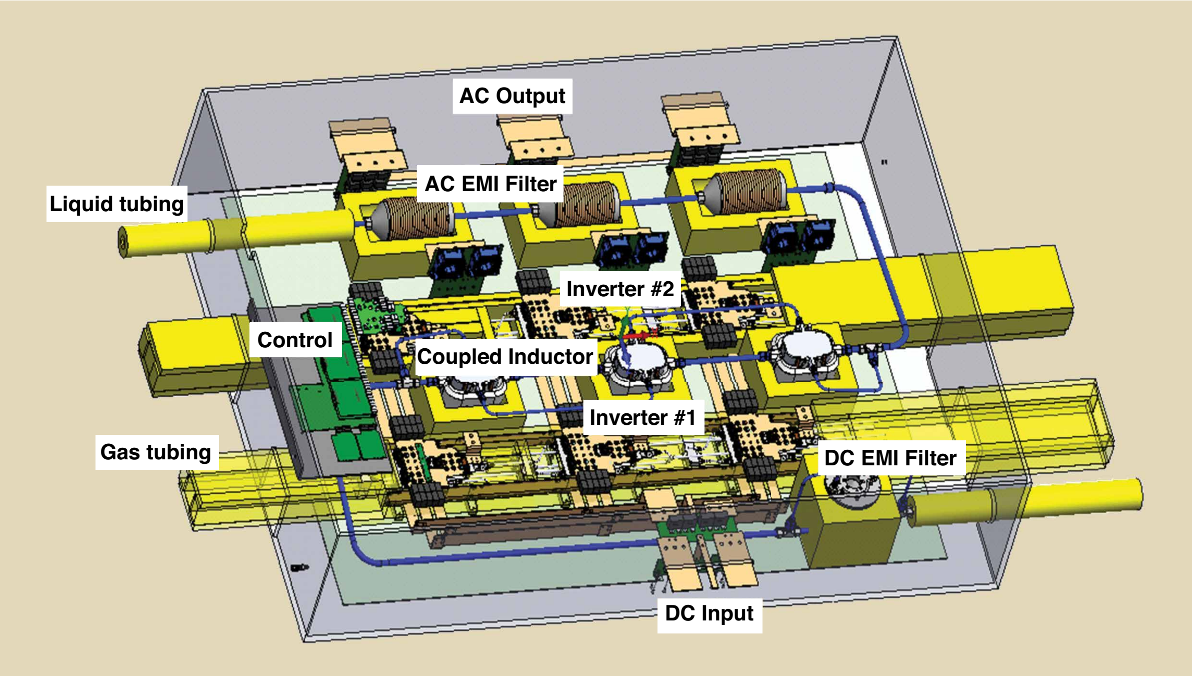

FIG 9 Integrated cryogenically cooled 1 MW inverter.

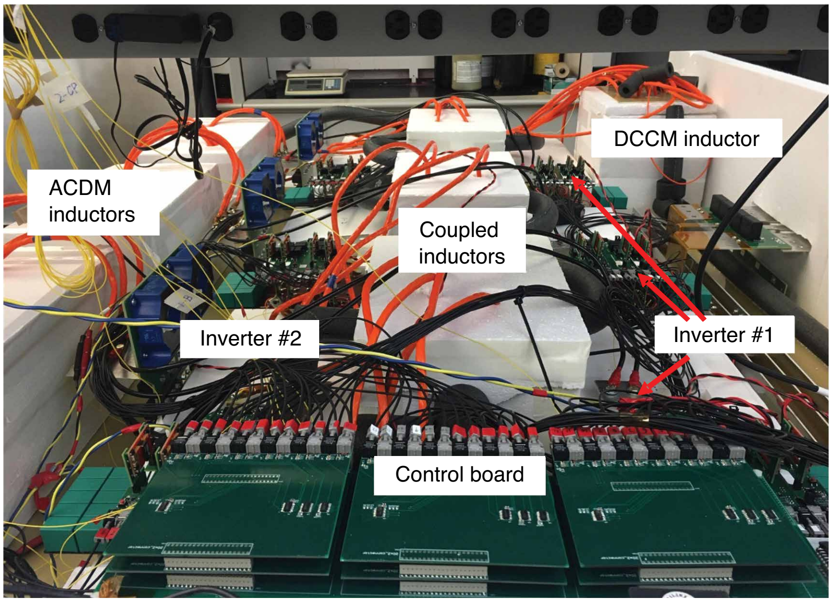

FIG 10 1 MW SiC-based cryogenically cooled inverter prototype.

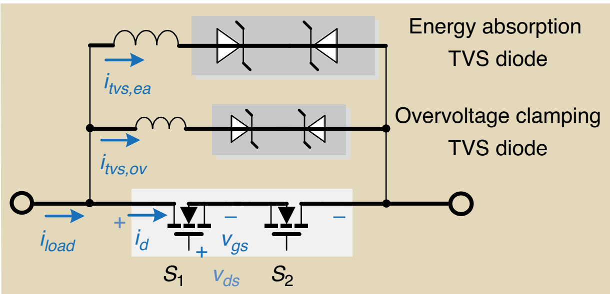

FIG 11 Bi-directional dc SSPC topology.

are directly cooled with liquid nitrogen while the inverter power stage is cooled with cold gaseous nitrogen. The gaseous nitrogen is used to regulate the SiC MOSFET junction temperature to be around room temperature at full load for better loss performance, and also to avoid the SiC MOSFET module temperature to be too low due to the packaging limitations.

The 1 MW prototype was tested at full load operation. The inverter half load efficiency is above 99% and the weight is 55.6 kg corresponding to a specific power of 18 kW/kg, which provides a promising solution to achieve high specific power and high efficiency for future EAP applications.

4) 1 kV/500 A SiC-based high power density solid-state power controller (SSPC) for EAP.

The SSPC is a SSCB plus intelligence for fault detection, diagnostics, and management. A 1 kV/500 A dc SSPC for future EAP utilizing 1.2 kV SiC MOSFET was developed [6]. The common source SiC module HT3220 from Wolfspeed intended for bidirectional applications was selected as the main switch. The main circuit topology for the SSPC is shown in Figure 11. Two SiC modules are paralleled for the 500 A rated operation condition.

The SSPC prototype as shown in Figure 12 was fully tested at rated conditions with protection functions verified. The overall loss is 2400 W, which corresponds to an efficiency of 99.52%. The total weight with and without enclosure are 4.45 and 3.16 kg, respectively, corresponding to specific power of 112.4 and 158.2 kW/kg. The power rating and the specific power are both significantly higher than the previously reported SSPCs.

III. Challenges and Solutions of WBG-Based Power Electronics for Aviation

While WBG devices can significantly improve power electronics, to fully utilize their superior characteristics poses unique challenges and, in many cases, requires comprehensive new design approaches. In particular, these characteristics include high switching frequency, high *dv/dt*, high *di/dt*, and high/low temperatures. Aviation applications certainly desire to fully utilize WBG capabilities and also need to consider special operation requirements, including EMI standard compliance and high altitude environment. Special considerations are needed for power electronics design with WBG devices in order to apply them effectively and reliably for aviation. Several key aspects on WBG-based power electronics design challenges and potential solutions are discussed in this section.

A. Cross-Talk and Short Circuit Protection

High *dv/dt* during a fast switching transient of a WBG device will affect its complementary device in the same phase-leg and this interaction between two switches is termed cross-talk. Cross-talk is a clear hazard for the safe operation of WBG devices, with their lower threshold voltage, lower negative gate breakdown voltage, and faster switching speed.

To suppress cross-talk without sacrificing fast switching, gate assist circuits including gate impedance control and gate voltage control were developed [7]. In general, *dv/dt* can be reduced through intelligent gate control or soft switching circuits. For example, the gate driving voltage can be programmed to a specific pattern that results in a smoothed drain–source voltage of the switching device. This requires a programmable gate driving voltage or impedance, e.g., by switching on/off multiple gate resistors, multilevel gate voltage or current source-based gate drivers.

Compared with Si devices, the short circuit protection of WBG devices is more challenging. Because of smaller chip area and higher current density, SiC MOSFETs and GaN HEMTs have poorer short circuit withstand capability compared with Si devices. Si devices usually have a >10 μs short circuit withstand time, while the typical short circuit withstand time of SiC MOSFETs is several microseconds [8] and for GaN HEMTs it is several hundreds of nanoseconds [9], [10]. As a result, WBG devices require faster response of their protection circuits. Under high *dv/dt* and *di/dt* of WBG devices, it is challenging for a short circuit protection scheme to achieve fast response time and strong noise immunity simultaneously. One robust scheme is desaturation-based protection with optimized circuit scheme and parameters were proposed for SiC MOSFET short-circuit protection [11]. A three-step short-circuit protection strategy was developed for GaN HEMTs [12]. First, an ultrafast detection circuit detects the sudden phase-leg voltage dip when short circuit occurs. Then an active gate voltage clamping circuit lowers the gate voltage to limit short-circuit current. Finally, the desaturation-based protection circuit turns-off the device.

B. Overvoltage

Overvoltage on a switching device occurs during its turn-off transient or the turn-on transient of its complementary device in a phase-leg configuration. High voltage spikes during switching transients can lead to device breakdown or failure. WBG devices with high switching speed capability and small ON-state resistance will exacerbate the issue. Good device and module packaging techniques and optimal layout design to minimize loop parasitics are general approaches to reduce the overvoltage.

Three-level converters, such as the Vienna-type rectifier (Figure 3) and 3L-ANPC (Figure 7) converter, can be preferred topologies for high power aviation applications, due to their lower device rating, lower power loss, and lower harmonics and EMI. However, these converters can have multiple switching commutation loops, which can make the overvoltage issue more severe and complicated. Considering the 3L-ANPC inverter as an example, both short loop (consisting of two switches, e.g., S_{3L} and S_{1L} in Figure 7) and long loop (consisting of four switches, e.g., S_{3H}, S_{2H}, S_{2L} and S_{1L}) exist. For the modulation scheme shown in Figure 7, some devices (e.g., S_{1L} and S_{3L}) switch at high frequency and some (e.g., S_{2L} and S_{2H}) switch at line frequency. The switching commutation between two high switching frequency devices in the short loop (e.g., S_{1L} and S_{3L}) will also induce overvoltage on the OFF-state nonactive line switching frequency device in the long loop (e.g., S_{2H}). The line switching frequency device usually experiences higher overvoltage than the high switching frequency device as the long loop usually has larger loop inductance than the short loop. The nonlinearity of the device output capacitance has significant influence on the overvoltage level. The modulation shown in Figure 7, which keeps the nonactive high switching devices (e.g., S_{1H} and S_{3H}) in the negative half line cycle off, will build some initial voltage on the OFF-state line switching frequency device (e.g., S_{2H} in Figure 7) before the switching transient, reducing the device output capacitance nonlinearity and thus reducing its overvoltage. Laminated busbar and vertical loop layout are preferred in the 3L-ANPC inverter to fully utilize the magnetic cancelling effect to reduce both the short loop and long loop parasitic inductances [13].

C. Converter Interactions With Load and Source

Pulse-width-modulated (PWM) voltages can cause harmful interactions between converters and their sources/loads, such as generators, motors, cables, and transformers. For example, in the case of an inverter driving a motor through a cable, it is well known that PWM voltages can lead to voltage doubling at the motor terminals due to the cable transmission line effect. High *dv/dt* and high switching frequency

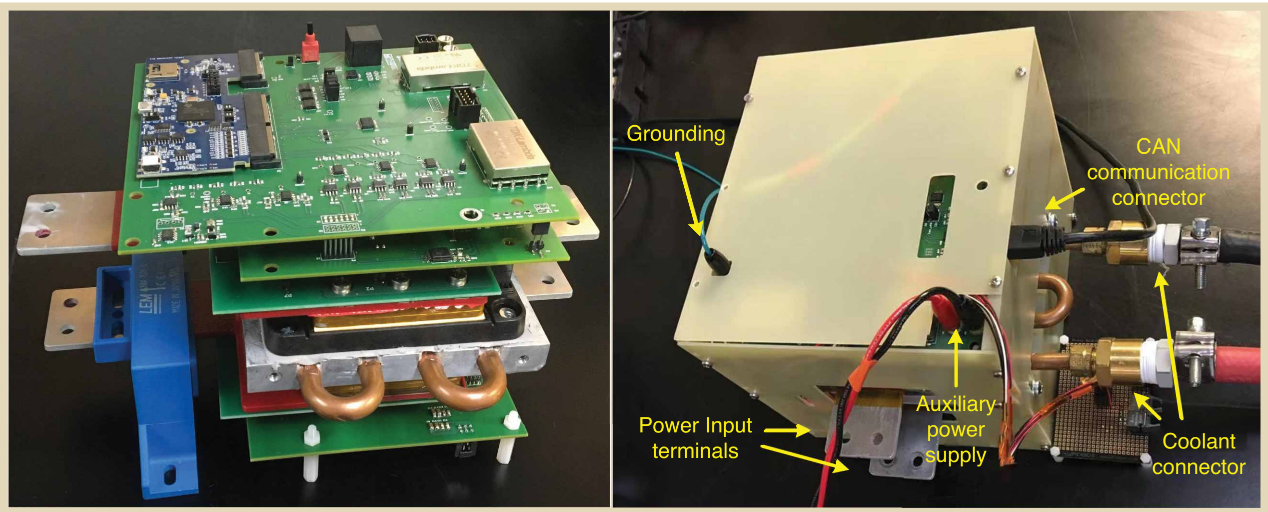

FIG 12 1 kV/500 A dc SSPC prototype. (a) Without enclosure. (b) With enclosure.

of the WBG-based converters will exacerbate interactions between converters and their loads/sources. The critical cable length for voltage doubling depends on *dv/dt*, and will decrease from tens of meters for Si-based inverters to only several meters for WBG-based inverters. PWM voltages can also produce common mode (CM) voltages on motor shaft, which in turn can induce detrimental bearing current through parasitic capacitance and bearing lubricant breakdown. The high *dv/dt* and high switching frequency of WBG-based motor drives will increase the capacitive bearing current and accelerate bearing degradation. The issue can be mitigated through specially designed motor to electrically insulate bearings from the motor frame, which will add cost. The charging and discharging of the cable and load/source parasitic capacitances during switching will introduce extra switching loss, which will be exacerbated with high switching frequency.

Commonly used solutions to mitigate converter and load/source interactions due to high *dv/dt* include: the intelligent gate control techniques for *dv/dt* reduction as discussed previously, and the *dv/dt* filter at the ac terminals of the WBG converters to limit the *dv/dt* seen by the load or source [14]. The motor terminal filter to eliminate voltage reflection is also effective but less flexible. Note that the *dv/dt* filter will not help with high *dv/dt* induced converter internal issues such as the cross-talk. Additionally, multilevel converters, which have lower output harmonics and lower *dv/dt* due to more levels in the output voltage, can be utilized to reduce converter output *dv/dt* and CM voltage, albeit at the cost of increasing the number of components.

D. EMI Filter

In aviation applications, EMI filters are generally required for power electronics equipment to attenuate EMI noise and to meet stringent EMI standards such as DO-160. Since EMI filters are commonly made of passive inductors and capacitors, they can be bulky, heavy, and lossy, and often contribute to 50% or more of the total equipment weight. For a converter with given power and voltage, the size of the EMI filter is generally determined by its cutoff frequency. WBG-based converters with high switching frequency capabilities are generally beneficial to EMI filters with their increased switching frequencies and corresponding increased EMI filter cutoff frequencies. In fact, both the ac-fed motor drive in Figure 4 and the universal charger in Figure 6 took advantage of the high switching frequency capabilities of SiC and GaN devices for reduced EMI filters.

Even with much reduced EMI filters in WBG-based converters, they are still main contributors to overall converter weight, size and power loss. To further reduce the EMI filters, an effective approach is the EMI noise source reduction, which refers to techniques of directly reducing the converter input/output EMI emission. PWM technologies, such as the active zero state PWM [15] for two-level converters, and CM elimination PWM [16] for three-level converters, can be utilized to reduce the CM voltage, which is an important EMI noise source. Four-leg converter topology can also be used for CM EMI noise elimination [17], [18]. The variable switching frequency PWM, which spreads the narrow band harmonics to a wide frequency range and thus reduces the EMI noise peak, is also a potential solution. For paralleled converters, the interleaving angle can be optimized to minimize EMI [19]. In fact, the 1 MW inverter in Figures 8–10 adopted two paralleled and interleaved 500 kW inverters for reduced EMI filters.

For a given attenuation requirement, techniques are also available to reduce size, weight, and power loss of EMI filters. Multistage filter topology can be utilized to achieve higher-order attenuation than single-stage topology. The hybrid active–passive filter can attenuate low frequency noise via an active filter with small size and light weight, such that a much smaller and lighter passive filter can be designed only for high frequency noise attenuation [20]. Advanced materials, cooling, and geometry can be used for EMI filter size and weight reduction. For example, the filter inductor for the 1 MW inverter in Figure 12 utilized a 3-D printed housing to realize cryogenically cooled inductor windings for overall filter weight reduction.

E. High Altitude Impact

Power electronics must be designed to work under their intended environmental conditions. For aviation applications, they need to be designed for high altitude environment, considering low pressure, low temperature, and high cosmic ray radiation. Low pressure will adversely affect the health of electrical insulation materials used in power electronics. Partial discharge (PD) phenomenon is a primary aging mechanism in dielectrics. A study of power module PD in [21] demonstrates that a void that is harmless at sea level can turn into an additional source of aging and couple with other voids to escalate PD intensity by a factor of two or more. WBG devices with higher *dv/dt* may suffer more severe PD issues compared to Si devices as PD behavior is influenced by *dv/dt* of the excitations. A study in [22] shows that, under square pulses with ultra-fast *dv/dt* (>100 V/ns), SiC power module PD inception voltage decreases with decreasing rise times if the pulses are short (e.g., <300 μs).

Low pressure thin air at high altitude will reduce the air heat dissipation capability and impact the cooling system of power electronics. Cosmic ray at high altitude can increase failure-in-times (FITs) of devices, which calls for significant voltage derating for Si devices. As mentioned earlier, one superior characteristic of WBG devices is their better radiation hardening capability against cosmic rays due to their wide energy bandgap. In this regard, the WBG-based power electronics are ideal for aviation applications.

F. High and Low Temperatures

WBG semiconductor materials are capable of operating at much higher temperatures (>500 °C) compared to Si materials, which can be very valuable for aviation applications. With high temperature capability, power electronics can be placed in the harsh environment, e.g., near the jet engine with an ambient temperature range between –55 °C and 225 °C, which is desirable in some cases. Another benefit to operate power electronics at high temperature is to reduce the cooling need, as in the case of the high-density motor drive in Figure 4, which employed a custom packaged module operating at 250 °C junction temperature. However, it is difficult to find low cost commercial power devices with junction temperature capability >175 °C. High temperature power electronics are limited by device packaging, gate drive ICs, and passive components [23]. With these limitations, the maximum ambient temperature capability of power electronics today is in the range of 210 °C–240 °C.

As presented earlier, certain WBG devices such as GaN HEMTs exhibit improved performance as temperature decreases. The low temperature capability and superior characteristics of WBG-based power electronics can also be valuable for aviation applications. They can be used in low temperature environments, including high altitude and cryogenically cooled environments. On the other hand, low temperature power electronics are even less mature than high temperature power electronics. Commercially available power semiconductor modules often employ silicone gel as encapsulant. These device modules cannot be used at cryogenic temperatures as the mechanical integrity and electrical insulation performance of silicone gel will deteriorate significantly once the temperature is below –60 °C [24]. Epoxy could be a promising candidate of encapsulant material as most epoxies can work properly at cryogenic temperature. Magnetic materials such as ferrite and nanocrystalline materials will survive but exhibit significant performance degradation at cryogenic temperature [25]. Other auxiliary components such as commercially available gate driver ICs, isolated power supplies, and sensors are not designed for extremely low temperature and their functionality at cryogenic temperature need further investigation. As in the case of high temperature WBG power electronics, much research and development work are needed for low temperature WBG power electronics as well.

IV. Future Perspectives

With their compelling benefits at both the equipment and system level, WBG-based power electronics are expected to dominate future aviation electrification applications. While SiC and GaN devices are still being developed and evolving rapidly, the low voltage (1200 V or below for SiC and 650 V or below for GaN) devices are already quite mature in terms of performance, cost, and reliability. These commercially available devices have been successfully employed in many terrestrial applications, including relatively high-power applications, such as electric vehicles, photovoltaic inverters, battery energy storage systems, datacenter power supplies., and more. For aviation, SiC-based motor drives have been developed and tested in battery-powered EAP systems for small aircraft, such as electric vertical take-off and landing (eVTOL) aircraft and unmanned aerial vehicles (UAVs).

For large commercial aircraft, WBG-based power electronics will likely be first adopted in MEA with HVDC bus voltage at several hundreds of volts and converter power around tens to hundreds of kilowatts, similar to the Boeing 787 case. As the next step of aircraft electrification moves from MEA to EAP, the required electric power will be increased to megawatt and tens of megawatt level. To reduce the electrical system weight, especially, the cable weight, the system voltage needs to be increased from hundreds of volts to several kilovolts. As a result, power electronics must be capable of handling kilovolts and kiloamperes for aviation operating conditions. High-voltage and high-power power electronics with consideration for electrical insulation, thermal, and radiation performance at high altitude will need to be developed. High-voltage WBG devices, e.g., the 10 kV SiC MOSFET power modules currently available only as engineering prototypes, can help to enable the high-voltage EAP system.

With the help of WBG devices, the specific power of MW-level motor drives for EAP applications is approaching 20 kW/kg and the peak efficiency can be above 99%. Cryogenic cooling, which can be realized by using liquid hydrogen fuel and liquefied natural gas as the coolant, has great potential to further reduce the weight and power loss of the WBG-based power electronics by taking advantage of the superior performance of WBG semiconductors at cryogenic temperature. On the other hand, high temperature capability of WBG semiconductors can also be utilized for harsh environment and reduced cooling needs. Materials, components, packaging, data, models, and standards will need to be developed for low and high temperature power electronics.

The EAP in large aircraft will likely adopt distributed propulsion architecture. Integrated power electronic inverters with electric motors can help to further increase system power density and specific power. The integrated motor drive system can have shared mechanical structure and cooling for the inverter and motor, and reduced connections to enable overall weight and volume savings. The superior temperature capability of the WBG devices will help such integration. For both the regular motor and the cryogenically cooled superconducting motor, the high or low temperature capability of the WBG semiconductors can be utilized in the converter and motor integration.

With the fast dynamics enabled by fast switching speed and high switching frequency, WBG-based power electronics are also expected to be designed and utilized for system-level functions and benefits in future aviation applications. The benefit of the SSCB or SSPC to quickly interrupt a fault is already explained. The other functions and benefits include but not limited to stability enhancement, power quality improvement, transient ride through, and coordinated protection. All these can translate to reduced design margin needs and reduced system weight.

This article has focused on aviation applications. Conceivably, many of the same WBG-based power electronics technologies can also be applied to future electrified spacecraft applications, where the requirements on power density, specific power, efficiency, reliability, and the operating environment for power electronics will be even more challenging. WBG-based power electronics can also play an important role for satellites, future space stations, lunar-based electric power systems, and other space exploration applications.

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