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Power Electronics

A critical enabler of future hydrogen–electric systems for aviation.

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IN FUTURE HYDROGEN-POWERED ELECTRIC aircraft, electric energy generated from hydrogen through turbine generators or fuel cells needs to be converted to suitable voltages and frequencies for propulsion motors and other loads. This conversion of electric power and energy is best realized through power electronics converters based on semiconductor technology. In other words, power electronics are a key enabler for hydrogen–electric systems for aviation. In addition to power conversion, power electronics can be used to control the power flow and for protection. Compared with the traditional electrical, mechanical, and pneumatic devices in aircraft, power electronics-based equipment is extremely flexible, easy to control, and fast, and it has built-in intelligence.

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Power electronics are already revolutionizing the electrical system design, operation, and control of today's aircraft. It is expected that power electronics will play a much greater role in future electrified aircraft, including hydrogen-powered electric planes. Obviously, power electronics for aviation must be reliable, efficient, compact, and lightweight. These stringent requirements are difficult to meet for traditional power electronics using silicon (Si)-based power semiconductors. Emerging power electronics technologies based on wide-bandgap (WBG) semiconductors, including Si carbide (SiC) and gallium nitride (GaN), promise to significantly enhance the performance of power electronics equipment through lower losses, faster switching speeds, and superior temperature capability.

Among other emerging technologies that can help improve power electronics for electric aircraft, cryogenic cooling can further lower the loss of power electronics components and potentially utilize liquified hydrogen fuel as coolant. On the other hand, these emerging power

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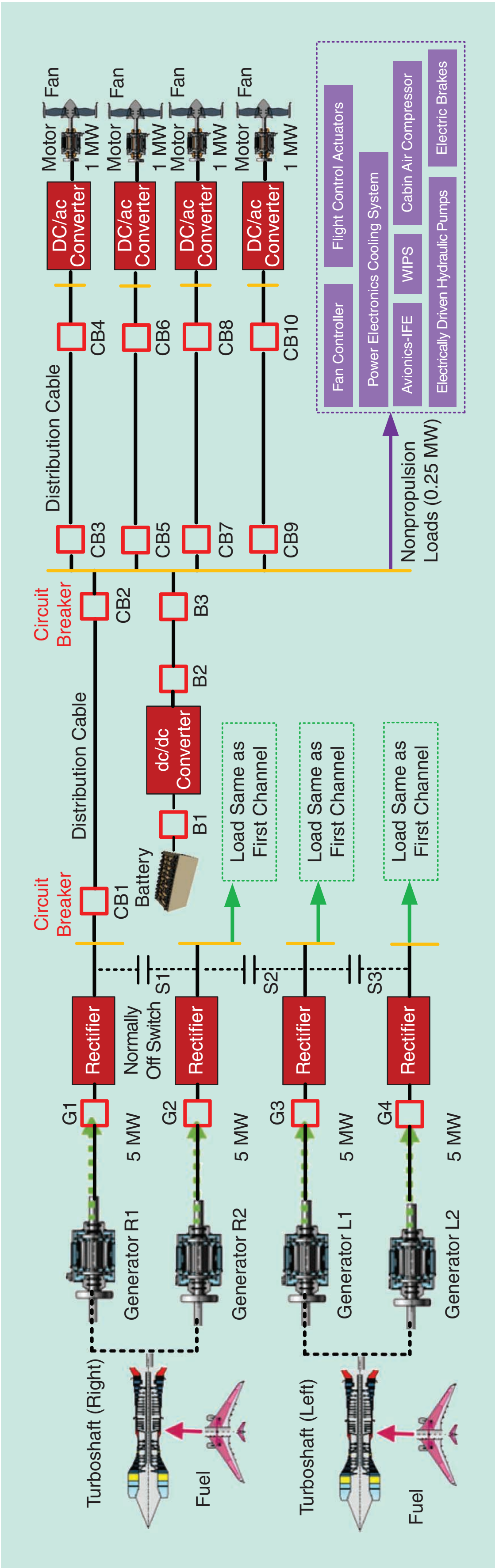

Figure 1. An aircraft electrical system: turboelectric propulsion with dc distribution. IFE: in-flight entertainment; WIPS: wing anti-ice protection system.

electronics technologies are still in early development stages. Power electronics for aircraft applications, especially for high-power propulsion, which would require much higher voltage and current levels than those used in today's aircraft electrical systems, are also new. High-altitude, low-pressure, and harsh temperature environments will make the electrical design for power electronics extremely challenging. Much research is needed in power electronics for the future viability of hydrogen–electric aircraft systems.

Power Electronics in Electrified Aircraft

Figure 1 shows an example electrical system of a future aircraft with a turboelectric propulsion configuration and corresponding dc electrical power distribution. The fuel, which can be hydrogen, powers the turbine, which, in turn, drives the three-phase ac electric generators on turbine shafts. The three-phase ac electricity from the generators is rectified to dc and distributed to various loads, including ac motors that drive the ducted fan propulsors. Before the dc electricity can be used for powering ac motors, it has to be converted or inverted to ac electricity with appropriate voltage and frequency. Clearly, the power electronics ac–dc rectifiers at the generator terminals and the dc–ac inverters at the motor terminals are essential for the aircraft electrical system. The system in Figure 1 also has batteries for energy management and emergency use, which need dc–dc converters to connect to the dc distribution system.

In addition to propulsion motors, there are nonpropulsion loads. Although these are not as large as propulsion loads, the net power requirements can still be considerable and cover a broad variety of demands, as in the case of a more-electric aircraft, such as a Boeing 787, where there are many power electronics converters. Obviously, power electronics converters are essential to electrified aircraft. Note that the turbine generators in Figure 1 can be replaced by fuel cells for future hydrogen-powered electric planes. In this case, dc–dc converters are needed between the fuel cells and the dc distribution system. Turboelectric propulsion is one of the architectures under consideration. Other configurations include series and paralleled hybrid systems and their combinations. In any case, power electronics converters are critical.

In addition to power electronics converters, which include dc–dc converters, dc–ac inverters, and ac–dc rectifiers, equipment in the aircraft electrical system can be power electronics based. One notable example is the solid-state power controller (SSPC). It can replace traditional mechanical breakers and contactors and provide additional functions. One key benefit of the SSPC is its fast current interruption, which will reduce the need for high overcurrent capability for equipment, cables, and connectors, thereby reducing sizes and weights. Another benefit is the elimination of arcing, leading to longer life spans. Compared to breakers, the SSPC has other functions, including condition monitoring, remote control, soft start, and so on. With power electronics, the SSPC can also be made smaller, lighter, and more reliable than its counterpart mechanical breakers.

Various power electronics converters and other equipment function through controllable electric circuits based on semiconductor switching devices. There are many circuit topologies that can be selected based on semiconductor devices, other circuit components, and applications. The real functional physical power electronics converters and other equipment are more than just converter circuits. As an example, Figure 2 illustrates the functional composition of a physical dc–ac inverter-based motor drive, which is among the most important types of power electronics converters in aircraft electrical systems, as in Figure 1.

High-altitude, low-pressure, and harsh temperature environments will make the electrical design for power electronics extremely challenging.

Switching Devices

At the heart of any power electronics equipment are power semiconductor switching devices. The switching networks or converter circuits, e.g., the inverter circuits in Figure 2, are made up of switching devices. The advancement of power electronics has been largely driven by improvements to power semiconductor devices. Currently, Si insulated-gate bipolar transistors (IGBTs) dominate power electronics in aircraft applications except at low-voltage (e.g., fewer than hundreds of volts), low-power (e.g., <1-kW) levels, where Si MOSFETs can be used. Compared with mature Si devices, the emerging WBG SiC and GaN semiconductors feature lower losses, faster switching speeds, higher junction temperature capabilities, and higher thresholds against cosmic rays. These attributes are extremely attractive for electrified aircraft applications, as they can lead to power electronics with higher efficiency, power density, and reliability.

Energy Storage Passives

Energy storage elements, i.e., inductors and capacitors, are vital to any power electronics converters. The essence of power conversion is to convert electricity from one form to another. Power electronics converters realize voltage- and current-form conversion by using energy storage passives to temporarily make up the power/energy difference between the source and load, with the help of the switching network. In Figure 2, the energy storage passive is the dc link capacitor. Since energy storage inductors and capacitors are generally bulky and heavy and can incur significant losses, their design and selection are important to overall power electronics converter performance.

Filters

Power electronics rely on switching devices, which inevitably generate noise, ripples, and harmonics. Switching transients can also lead to voltage and current spikes. As a result, filters are needed for protection, electromagnetic compatibility (EMC), and power quality. Fast-switching WBG devices may result in more demanding requirements for filters. Since filters are mostly realized with passive components, i.e., inductors and capacitors, they can be important contributors to power electronics equipment loss, size, and weight, in addition to cost. The main filter types include harmonic filters to meet power quality requirements, electromagnetic interference (EMI) filters for EMC, and delta V (dV)/delta t (dt) filters to relieve stress on loads, especially motor loads with limited insulation capability.

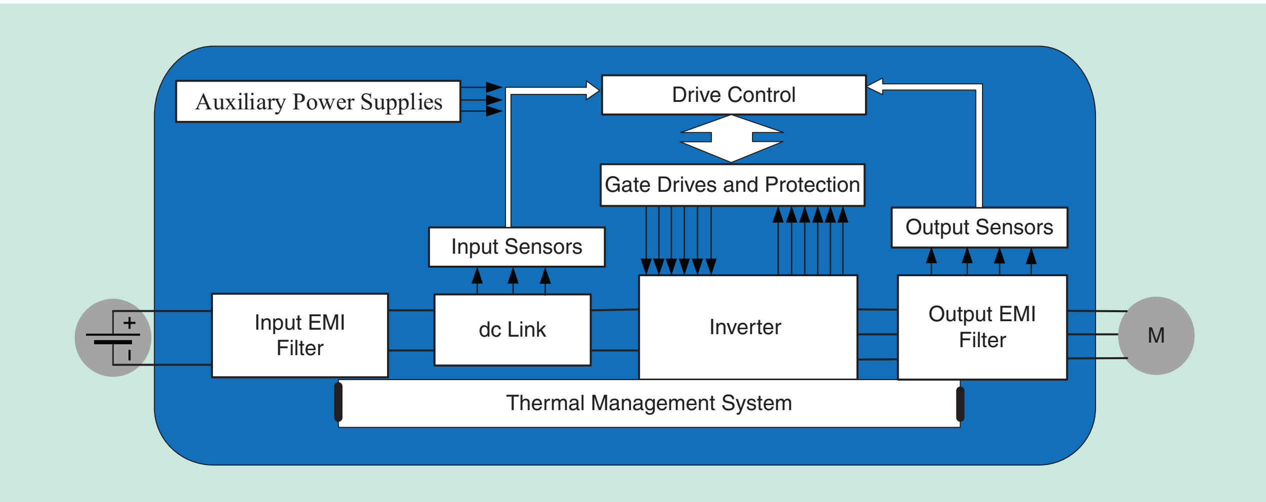

Figure 2. The functional block of a typical motor drive. EMI: electromagnetic interference.

Thermal Management System

Thermal management is integral to power electronics equipment. All electrical components, including power semiconductor devices and passives, incur losses during operation. In addition, components have a limited operating temperature range. Appropriate thermal management (mostly cooling) is necessary for power semiconductor devices and other components to maintain a safe operating temperature range. Popular power electronics cooling types include forced-air cooling and liquid cooling. A typical air-cooling system includes a heatsink, fan, and air duct; a typical liquid cooling system includes a cold plate, liquid coolant, pump, and heat exchanger to the ambient. The thermal management system can impact the performance of a converter by influencing the power loss, efficiency, and reliability of the device. Additionally, the thermal management system usually accounts for a significant percentage of the total converter size, weight, and cost. It is important to identify and choose efficient and effective thermal management strategies. For future aircraft with electrified propulsion, including hydrogen-powered electric airplanes, it is conceivable that liquified fuel (natural gas or hydrogen) could be used as the coolant. Consequently, liquid cooling will be preferred.

The key requirements that set power electronics in electrified aircraft apart from other applications are high specific power and high efficiency.

Controller and Auxiliary Components

Control is a foundational part of power electronics converters, which function through controlled switching actions of power semiconductor devices. The control system includes controller hardware and software. To realize control functions, several important auxiliary components are needed, including gate drivers, sensors, and auxiliary power supplies. The controller and auxiliary components are of low power and low voltage (typically <30 V) and need to be electrically isolated from the main power circuits at high voltage levels (typically above hundreds of volts) for insulation and noise immunity. With higher-voltage systems (e.g., >1 kV) envisioned for future large electrified aircraft and faster-switching WBG devices, isolation in power electronics becomes increasingly challenging.

Mechanical Assembly

Mechanical assembly in power electronics plays multiple roles, not only meeting the structural requirements of converter installations but also electrical and thermal functions. In addition, mechanical assembly contributes significantly to the overall converter size, weight, cost, and reliability. It is therefore important to consider mechanical assembly in the overall design. In power converters for high-power applications, one particularly important piece of mechanical assembly is the bus bar, which contains metal conductors to carry current and electrical insulation among conductors to withstand voltage. Mechanically, the bus bar provides structural support for the components connected to it, such as power semiconductor devices; passive components, including dc link capacitors; and filters. Thermally, the bus bar contributes to power loss due to its electrical resistance and can impact thermal performance as a thermal conductor. The enclosure is another fundamental part of power electronics, providing structural integrity. It can also affect grounding, insulation coordination, and EMI; thermally, it provides the interface to the ambient.

High-Density, High-Efficiency Power Electronics

The key requirements that set power electronics in electrified aircraft apart from other applications are high specific power and high efficiency. The NASA Advanced Air Transport Technology (AATT) Project, in 2015, called for the megawatt-level inverter for future electric propulsion to have a specific power of 19 kW/kg, which was more than an order of magnitude higher than incumbent commercial products while simultaneously achieving an efficiency of 99% at half the rated power. A number of projects were successfully carried out under this program. Zhang et al. 2019 presented a 1.26-MW inverter prototype developed by GE, which reached an 18-kVA/kg specific power and 10-MVA/m^3 power density.

To better explain the loss and weight contributors of power electronics equipment in aircraft, a benchmark baseline design for a 1-MW inverter system is executed using the two-level voltage source inverter (VSI) and EMI filter configuration in Figure 3. The specifications for the inverter are listed in Table 1. For this inverter, SiC semiconductor power devices are employed. The fast switching and low on-state resistance of SiC devices enable reduced switching and conduction losses. Also, the high switching frequency and operating temperature shrink the weight of the passive components and cooling system. In the baseline design, Wolfspeed generation 3 SiC MOSFETs are used, with a switching frequency of 30 kHz.

Figure 4 details the loss breakdown and efficiency of the baseline design. Note that the assessed 98.7% efficiency is below but close to the target efficiency of 99% at 500 kW for the 1-MW inverter. Semiconductor power devices and the EMI filter are the main contributors to the power losses. Additionally, the weight breakdown and specific power displayed in Figure 5 indicate that the estimated 6.2-kW/kg specific power is far below the target of

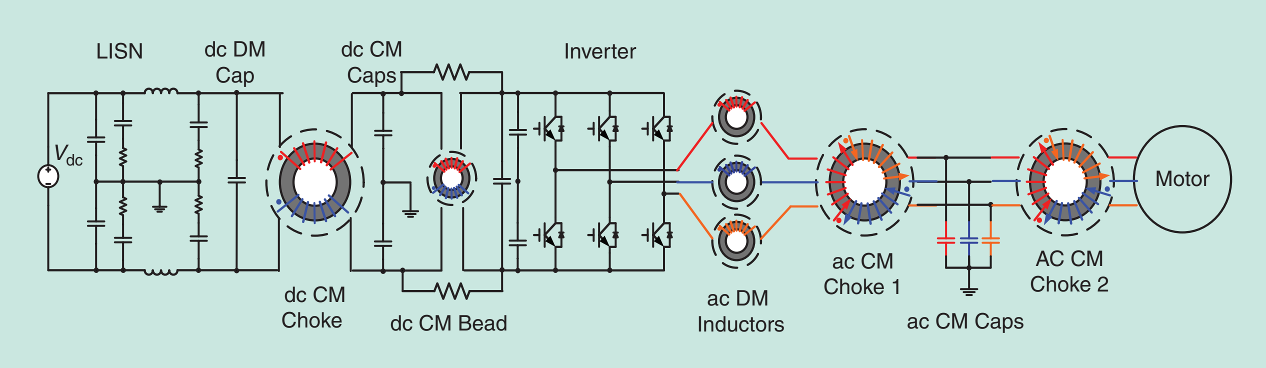

Figure 3. The baseline configuration of the 1-MW inverter and its EMI filter. LISN: line impedance stabilization network; CM: common mode; DM: differential mode.

19 kW/kg. As expected, the EMI filter with bulky magnetic components is the key limiting factor, especially because of the need for the dc- and ac-side filters, as specified in Table 1. In fact, excluding the EMI filter, the inverter's specific power would be 27.4 kW/kg, and its efficiency would be 99.43%.

Many techniques can help achieve a high-density power electronics converter. They include, but are not limited to, power semiconductor devices, inverter circuit topology, control strategy, EMI filter topology and components, thermal management, and advanced integration. In general, a high-density design should combine as many available techniques as possible to achieve an optimal architecture. Each of the various techniques is illustrated here through its impact on improving the aforementioned benchmark design. The first is to optimize the use of semiconductor devices. Larger-rating SiC devices or, equivalently, more SiC devices of the same rating can be paralleled to reduce the conduction loss. As observed in Figure 4, in the baseline design, 27.5% of the total loss of the inverter comes from the device's conduction loss. Meanwhile, the contribution of power devices to the inverter weight is very small. By doubling the number of devices employed in the inverter, the total power loss declines by 14%, with only a 0.7% increase of the total weight.

The second technique is to utilize a suitable circuit topology. In this case, a three-level interleaving topology can be applied, which will reduce EMI noise and the corresponding EMI filter weight. Note that in the baseline design, 55% of the total loss and 77% of the total weight are contributed by the EMI filter. The physical design shows that a three-level interleaving topology enables the EMI filter weight to be reduced 38% as compared to that of the two-level VSI in the baseline design, eventually enabling the total inverter weight to be decreased by 29%.

TABLE 1. The 1-MW inverter specifications.

Power	dc Bus Voltage	AC Frequency	Ambient Temperature
1 MW	1,000 V	200–3,000 Hz	20 °C
Power quality	Conducted EMI	Specific power	Efficiency
DO-160 standard for the dc side and 4% total harmonic distortion for the ac motor	DO-160 for the dc and ac sides	>19 kW/kg	>99% at 500 kW

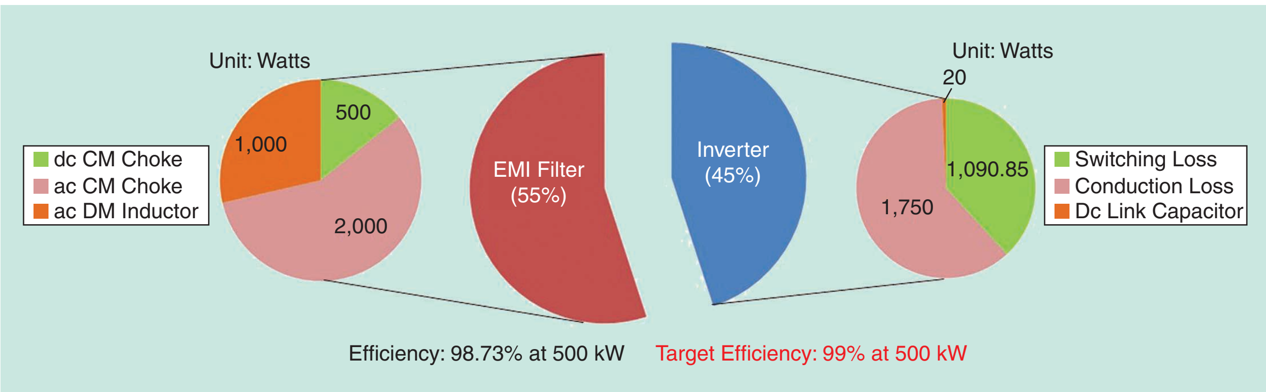

Figure 4. The loss breakdown and efficiency based on the benchmark design of the 1-MW inverter.

The third technique involves using an intelligent gate drive to minimize the switching loss of SiC power devices. As illustrated in Figure 4, in the baseline design, 17% of the total loss of the inverter comes from the device's switching loss. The intelligent gate drive increases the switching speed of the devices without causing crosstalk and can reduce the switching loss by 20% when compared to the conventional gate drive, resulting in a 3% total loss reduction.

One particularly promising technology for future hydrogen–electric aviation applications relates to cryogenic power electronics.

The fourth technique is to adopt variable switching frequency (VSF) pulsewidth modulation (PWM) schemes to attenuate EMI noise and minimize switching loss. One VSF PWM scheme adjusts the switching frequency to control the ac current ripple peak so that it is constant below its threshold. This can lead to a 14% switching loss reduction as compared to the constant switching frequency PWM in the baseline design, which enables a 2.4% total loss reduction of the inverter. Furthermore, with the same VSF PWM, the EMI noise peak can be suppressed, and an approximately 10-dB reduction of the conducted EMI noise peak can be achieved, per DO-160 EMI standards. Thanks to the EMI noise attenuation, the required attenuation of the EMI filter decreases, enabling the bulky magnetic components of the EMI filter to be significantly reduced in size. As a result, the weights of the dc-side common mode (CM) choke, ac-side CM choke, and ac-side differential mode (DM) inductor are reduced by 7, 12, and 71% respectively. In the end, the total EMI filter weight is 73% of that in the baseline design. Also, due to less winding and smaller cores in the CM choke and DM inductors, lower losses will result, leading to an EMI filter loss reduction of 30%.

The fifth technique employs advanced EMI filtering strategies. The dc CM filter can be realized by constructing the bus bar as a filter, based on the transmission line theory. This type of filter structure utilizes the dc bus bar of the inverter as the winding of the dc CM choke, thus eliminating the extra winding weight. The bus bar design adopts a standard multilayer structure, which, together with external magnetic cores, can greatly enhance the dc CM inductance. The CM capacitance is also provided with high-permittivity insulation layers. The bus bar filter enables a reduction of the total EMI filter weight by 14%. By adopting hybrid ac and dc filters with an extra 30-dB of attenuation, the weight of the ac CM choke can be reduced by a factor of four. Note that the negative impact of the active filter induces extra loss, causing a 9% increase of the total loss of the inverter system in this benchmark design.

Combining all the aforementioned techniques and their resultant influence on power loss and weight, the efficiency of the 1-MW inverter operating at 500 kW is 99.07%, which exceeds the 99% target efficiency. Additionally, the specific power is improved to 18.1 kW/kg, which approaches the 19-kW/kg target in Table 1. Figure 6 presents the evolution of power loss and weight reduction when different approaches are employed. Additional methods, such as additive manufacturing, can be applied in mechanical, filter, and thermal designs to further reduce weight. It should be pointed out that the GE inverter (Zhang et al. 2019) did not adopt all the high-density techniques described here. Its high specific power and power density resulted from the fact that it did not have

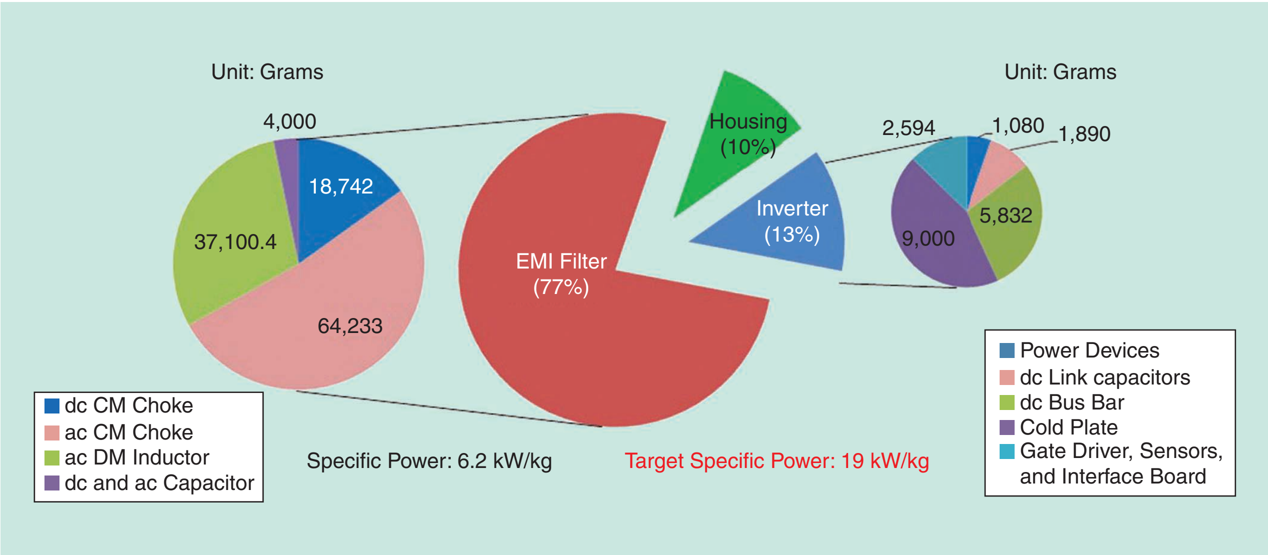

Figure 5. The weight breakdown and specific power based on the baseline design of the 1-MW inverter.

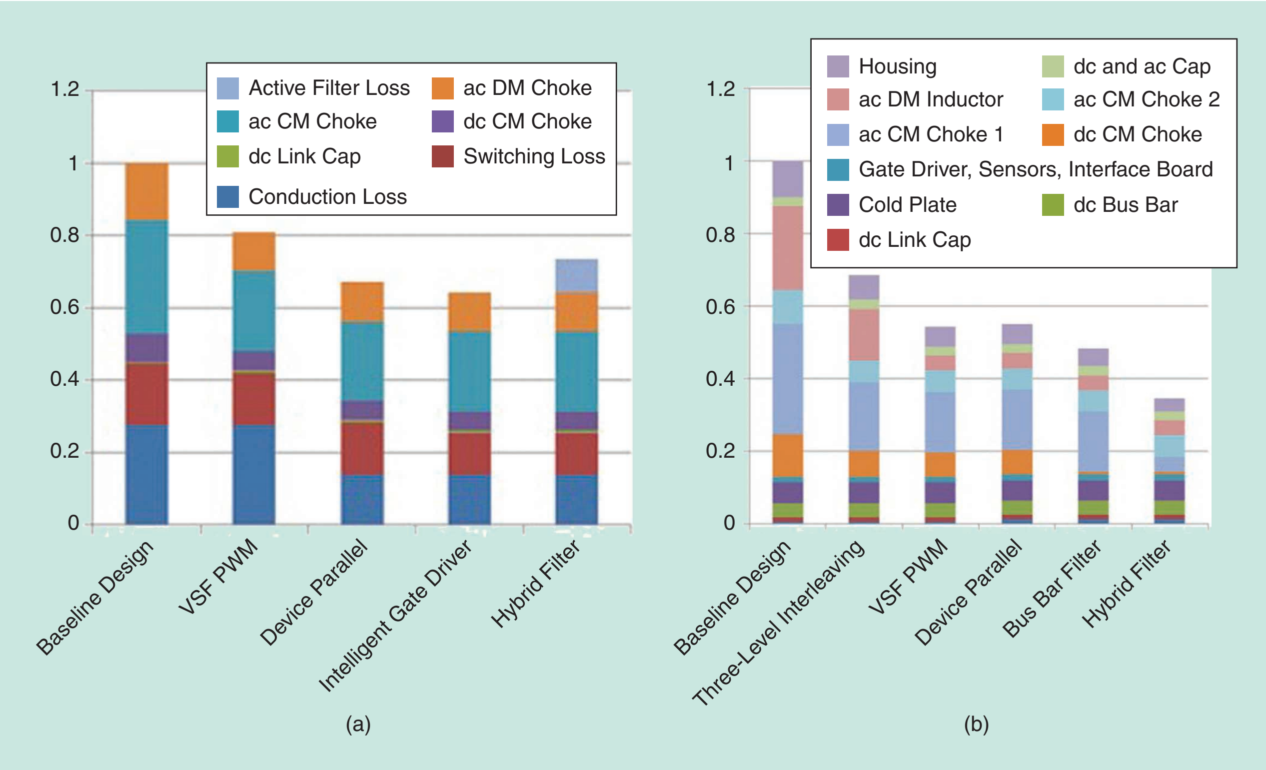

Figure 6. The power loss and weight evolution when different approaches are employed. (a) The power loss reduction. (b) The weight reduction.

an ac-side EMI filter, instead using a smaller dV/dt filter to meet the motor insulation requirement.

Another example of high-density power electronics in future electric aircraft, especially with electrified aircraft propulsion (EAP), is the SSPC, which can perform as a circuit breaker while carrying out many other functions. The power electronics-enabled dc distribution in Figure 1 can suffer from high and fast-rising fault current due to large dc energy storage elements (e.g., capacitors and batteries) and low fault impedance. Moreover, there are no zero-current crossings for the dc distribution load current. Mechanical dc circuit breakers are generally more complex and bulkier than ac breakers. The slow interruption time of the mechanical breakers, on the order of milliseconds, also cannot meet the EAP protection requirements for energy storage and components and power electronics equipment. A power electronics-based solid-state circuit breaker (SSCB) with fault current interruption times that are shorter than 100 μs can be used to significantly improve system performance. Compared to the simple SSCB, the SSPC takes advantage of the built-in intelligence of the power electronics equipment and incorporates more functions, including remote control, soft start, ground fault indication, and condition monitoring. These functions enable smarter coordination with other protection devices and better adaptability in the EAP system.

A practical SSPC or SSCB also needs to have high density and high efficiency. Table 2 lists the specifications for a dc SSPC developed by the University of Tennessee, Knoxville (UTK), with sponsorship from Boeing. The UTK SSPC prototype appears with and without the device enclosure in Figure 7. To reduce its loss and weight, several techniques were applied. The first was to utilize high-power-density

TABLE 2. The SSPC specifications.

Type	Bidirectional dc
Operation	Four-quadrant switch (can block voltage in both directions when open and conduct current in both directions when closed)
Rated voltage (V_{rated})	1 kV
Rated current (I_{rated})	500 A
Efficiency	>99.5%
Specific power	>100 kW/kg
Protections	Overcurrent and short circuit protections
Control	Close, open, and reset via controller area network bus command
Other functions	Soft start and ground fault indicator
Indication	Switch status, current, voltage, temperature, and fault type
Cable inductance	5 μH

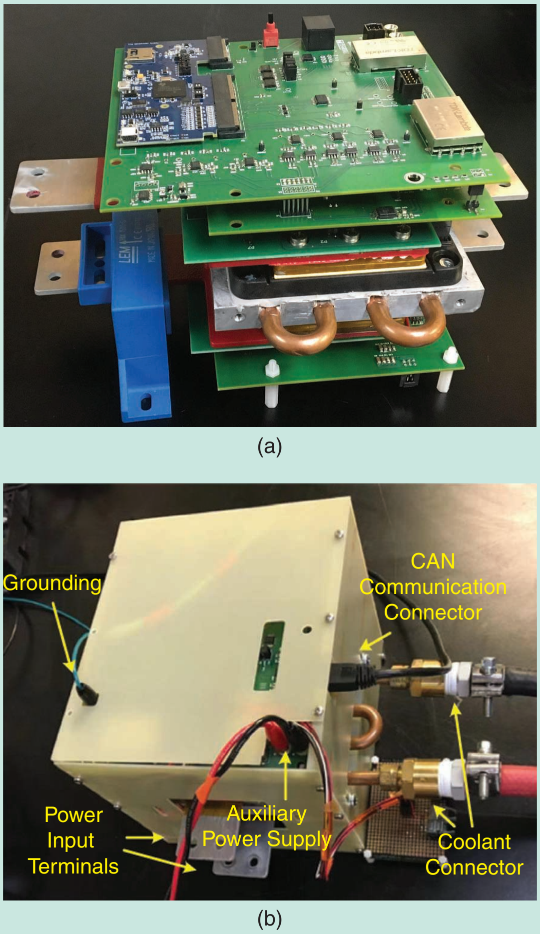

Figure 7. The developed 1-kV, 500-A SSPC prototype (a) without an enclosure and (b) with an enclosure. CAN: controller area network.

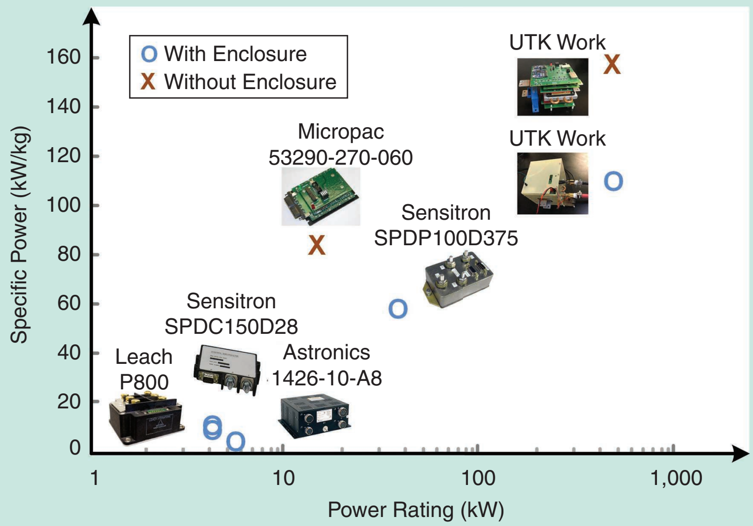

Figure 8. The comparison of the power rating and specific power.

WBG power modules as the semiconductor switch to minimize the conduction loss and required cooling surface area. Wolfspeed HT3220 common source SiC power modules for bidirectional applications were selected. Two modules were paralleled for the 500-A rated condition. For two SSPC cells in series, the overall loss is 2,400 W, which corresponds to an efficiency of 99.52%. The second approach was to utilize an efficient thermal management system. Liquid cooling was employed for thermal management because of its low thermal resistance. The cold plate has a double-sided cooling structure, so devices can be placed on both sides of it to eliminate half of the required surface area.

The third method was to utilize transient voltage suppression diodes with a lower clamping ratio compared to the metal oxide varistor (MOV) as the energy absorption unit. The incorporation of MOV devices tends to be less attractive for aircraft applications due to known degradation issues. The main contributors to the SSPC's weight are mechanical-related parts, including the enclosure and bus bar components. The total weight of the prototype in Figure 7, with and without the enclosure, is 4.45 and 3.16 kg, respectively, corresponding to a specific power of 112.4 and 158.2 kW/kg. Figure 8 provides a specific power and power rating comparison of the developed SSPC and other reported SSPCs. It is worth noting that all other reported SSPCs are unidirectional.

Cryogenic Power Electronics

One particularly promising technology for future hydrogen–electric aviation applications relates to cryogenic power electronics, i.e., power electronics with cryogenic cooling. Temperature can typically be classified as cryogenic when it is lower than 123 K, or –150 °C. Many materials and components, including electric conductors and semiconductor devices, can have superior loss performance and even become superconducting at cryogenic temperatures. Much work has been done on superconducting electric machines for aircraft applications. Liquid hydrogen fuel is available at 22 K, and it can be used as coolant to enable a cryogenic environment for associated power systems and electronics. Clearly, it makes good sense to operate electric machines and power electronics for efficiency and power density gains. Other cryogenic coolants include liquefied natural gas at 111 K, liquid nitrogen at 77 K, and liquid helium at 4 K.

There are a number of benefits from using cryogenic power electronics, including the following:

1) Certain power semiconductor devices, such as Si MOSFETs and GaN high-mobility electron transistors (HEMTs) have significantly lower on-state resistance, as demonstrated in Figure 9, and faster switching speed. Therefore, with a given operating condition and switching frequency, the conduction and switching losses of power devices for cryogenically cooled power electronics are reduced, leading to improved efficiency.
2) The faster switching speed of power devices at cryogenic temperatures can be utilized to increase the switching frequency, reducing the need for passives. In particular, this approach lessens the requirements placed on EMI filters, resulting in reductions in weight and loss. Additionally, the resistivity of conductors (e.g., copper and aluminum, which are widely used for inductor windings) significantly decreases as temperature falls. Hence, a much higher current density of the inductor winding can be used, leading to fewer conductor materials. Furthermore, the operation of devices in a superconducting state can be employed for conductors and windings on the dc side of power electronics to reduce the weight and loss of the dc-side EMI filter.
3) In addition to the benefits provided by the cryogenic cooling system for lower losses and filter weights, the technology can improve the efficiency and power density of the power electronics system, due to fewer cooling system requirements, considering the extremely low coolant temperature and correspondingly high allowable temperature rise. Mechanical parts, including bus bars and electrical connectors, can be lighter and more efficient as a result of the low conductor resistivity at cryogenic temperatures.

Boeing and UTK developed a 1-MW cryogenically cooled inverter as part of the AATT project. The design specifications are the same as those in Table 1 except that the target specific power and efficiency are 26 kW/kg and 99.3% at 500 kW, respectively, which are even higher than those for the ambient temperature inverter. Using the high-density and high-efficiency techniques explained in the "High-Density, High-Efficiency Power Electronics" section plus cryogenic cooling, the expected loss and weight reduction are illustrated in Figures 10 and 11, respectively. Combining the resultant influence of these techniques on power loss and weight, the efficiency of the 1-MW inverter operating at 500 kW will be 99.47%, and the specific power will improve to 27 kW/kg. Both are above the targets.

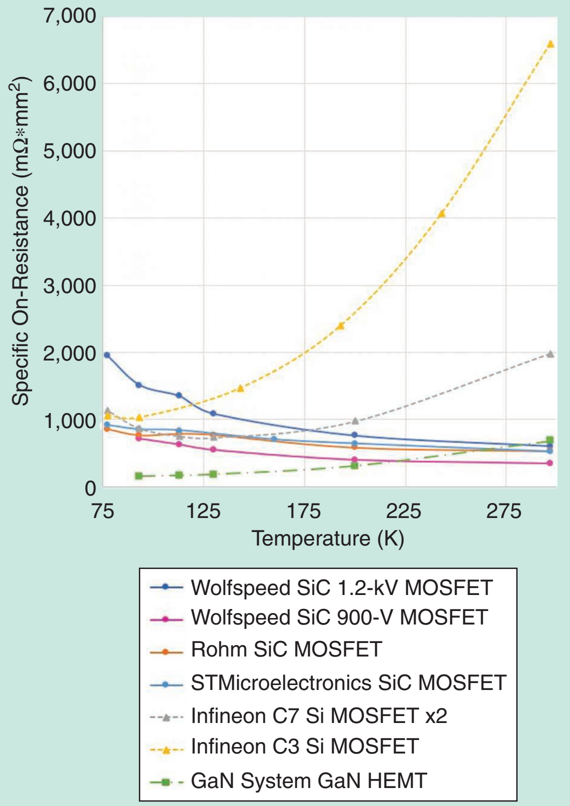

Figure 9. The specific on-resistance of the state-of-the-art Si MOSFET, SiC MOSFET, and GaN HEMT devices at cryogenic temperatures.

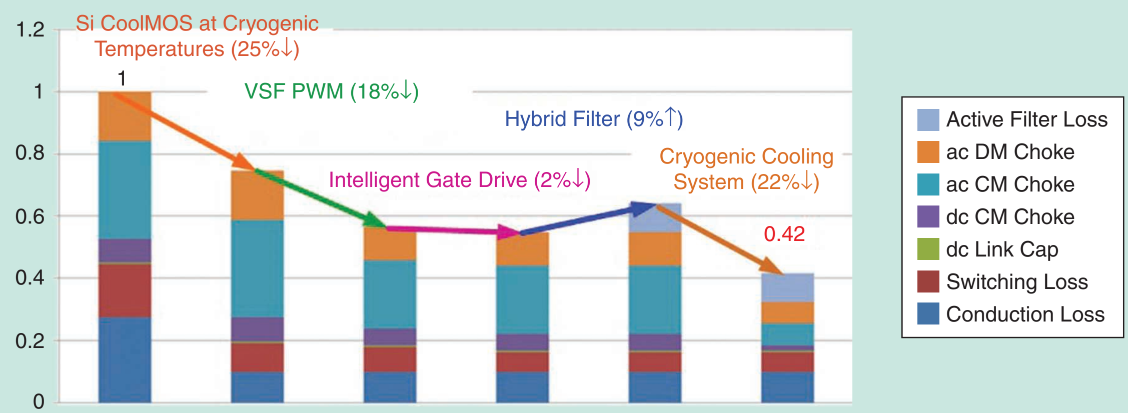

Figure 10. The loss reduction evolution for the 1-MW cryogenically cooled inverter when different approaches are employed.

Note that the 600-V Si CoolMOS is assumed as the power semiconductor device in the design of Figures 10 and 11, due to good performance at cryogenic temperatures. Alternatively, another type of the power semiconductor device, a GaN HEMT, with excellent performance at cryogenic temperatures (see Figure 9), can also be used. However, to build a 1-MW inverter prototype, too many discrete Si CoolMOS and GaN HMET devices need to be paralleled since there are no commercial Si CoolMOS and GaN modules. Even with commercial modules, the packaging is not built to operate at cryogenic temperatures. In addition, Si CoolMOS and GaN HMET devices are commercially available only at 600 and 650 V, and a series connection is needed to meet the voltage requirements of the three-level active neutral-point-clamped topology, which is challenging for ultrafast devices at cryogenic temperatures.

As a result, the Boeing/UTK team adopted the 900-V, 800-A SiC MOSFET module in its prototype to build two paralleled 500-kW inverters to achieve the required 1 MW. Figure 12 displays the 1-MW inverter structure, and Figure 13 shows the actual hardware. The 1-MW inverter consists of two paralleled 500-kW inverters, dc and ac EMI filters, and a coupled inductor for limiting circulating currents between the 500-kW inverters and suppressing the DM EMI noise. The EMI filters are directly

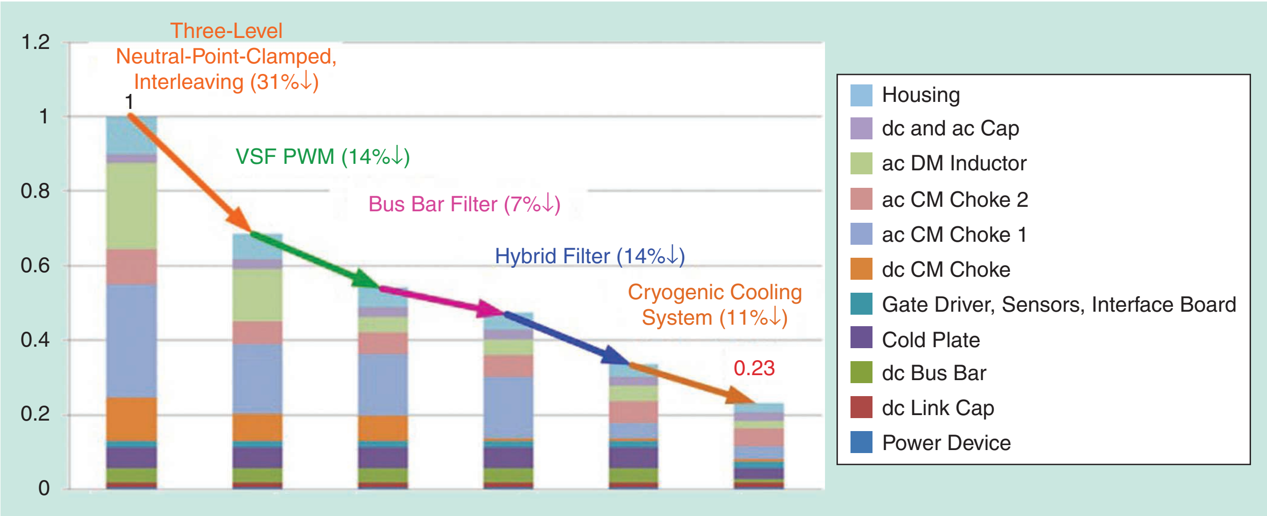

Figure 11. The weight reduction evolution for the 1-MW cryogenically cooled inverter when different approaches are employed.

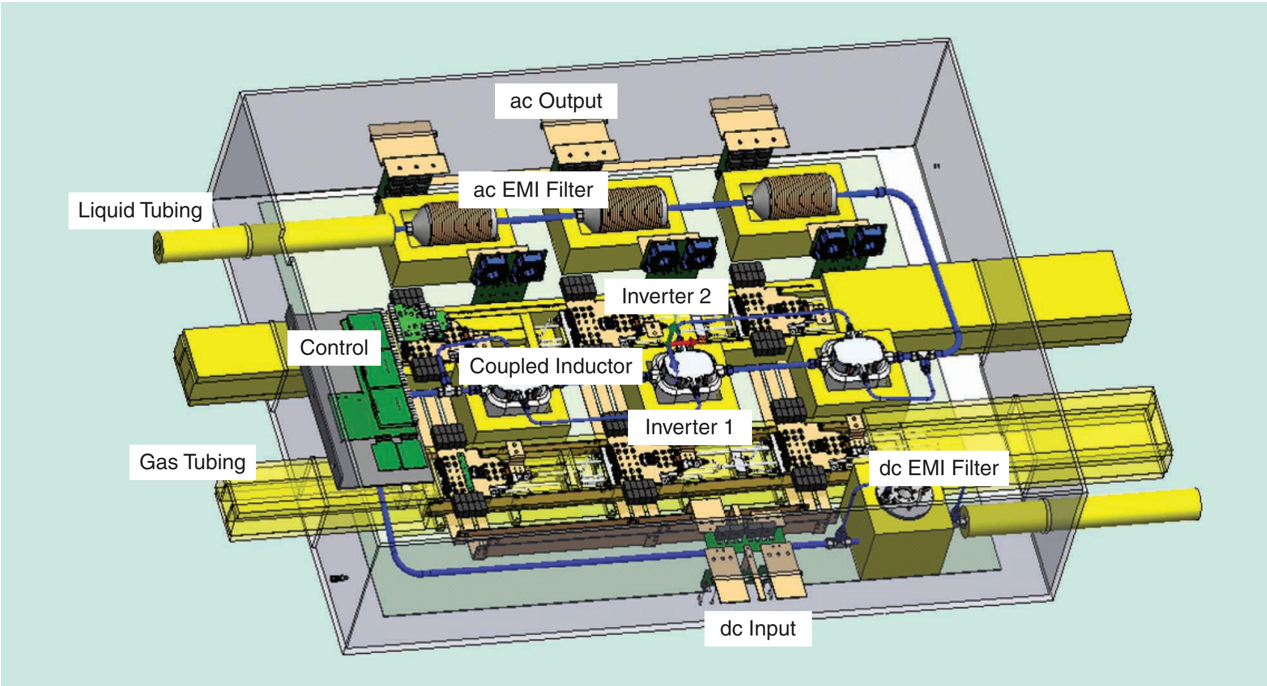

Figure 12. The integrated cryogenically cooled 1-MW inverter.

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 around room temperature for better loss performance and to avoid the SiC MOSFET module temperature being too low due to packaging material limitations.

Figure 14 gives the weight breakdown of the 1-MW inverter hardware. With a weight of 55.6 kg, the specific power is 18 kW/kg. The inverter was successfully tested at the rated voltage and current, with a measured efficiency at 500 kW, corresponding to 99%. The efficiency and specific power are below the targets set in the NASA program, mainly because of current technology limitations. The most critical issue is the lack of suitable semiconductor devices and device modules that can perform well at cryogenic temperatures and support higher switching frequencies (e.g., 280 kHz in the design for the Si CoolMOS). By using the SiC MOSFET modules with their junction temperature regulated around and above room temperature, the conduction and switching losses are significantly higher than the Si CoolMOS and GaN HEMT at cryogenic temperatures. As a result, the switching frequency had to be lowered from the designed 280 to 60 kHz, leading to much larger EMI filters, especially DM filters. In addition, the complex cooling scheme of liquid and gaseous nitrogen cold plates add to the inverter weight. To unlock the full potential of cryogenic power electronics, it is essential to develop Si CoolMOS- and GaN HEMT-based device modules capable of operating at cryogenic temperatures.

The specific power of megawatt-level power electronics inverters for aircraft applications is approaching 20 kW/kg, and the peak efficiency can be above 99%.

Cryogenically cooled power electronics can also be used for SSCBs and SSPCs. In fact, this could be a "killer" application for cryogenic technology. One drawback of the SSCB compared with the mechanical circuit breaker is its relatively high loss during normally closed operation. As a result, a hybrid breaker scheme with a paralleled power electronics switch branch and a mechanical

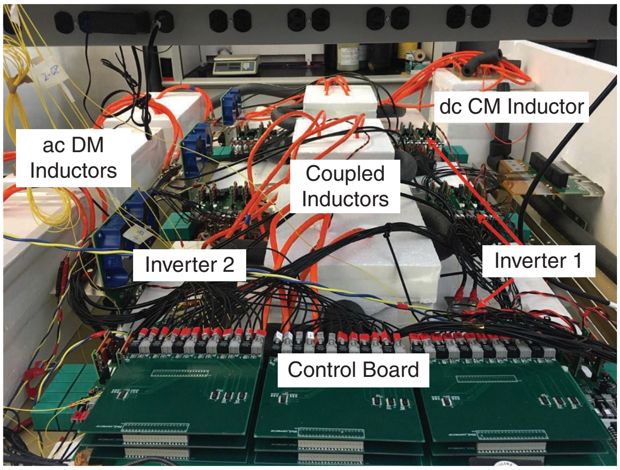

Figure 13. The cryogenically cooled 1-MW inverter hardware.

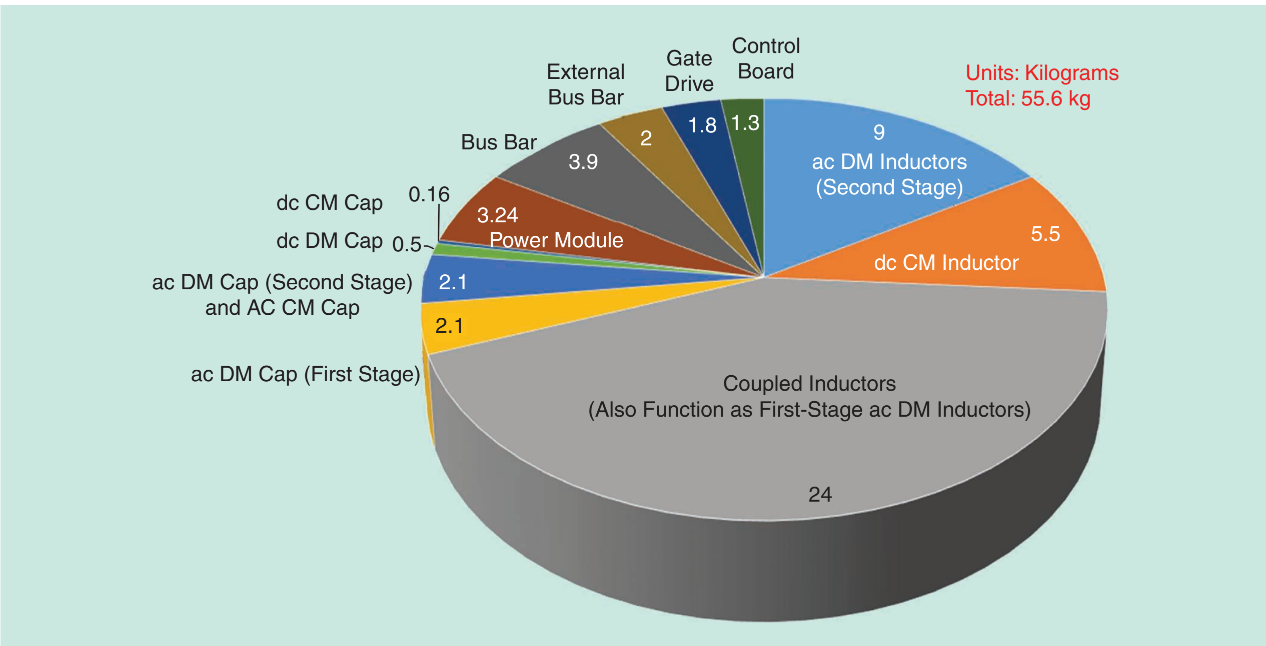

Figure 14. The weight breakdown of the 1-MW inverter.

switch branch has to be used, with a significant weight and cost penalty. With a much lower conduction loss at cryogenic temperatures, the cryogenically cooled SSCB can be significantly more efficient. Currently, under the Advanced Research Project Agency–Energy's Connecting Aviation by Lighter Electrical Systems program, UTK and Boeing, together with the University of Houston and Clemson University, are developing a GaN-based cryogenically cooled SSCB, which is expected to achieve an efficiency of 99.9%, comparable to that of the mechanical breaker. In the meantime, extremely light weight can be expected due to fast current interruption times and no need for heavy and bulky components.

Power electronics for future electrified aviation, including aviation using hydrogen–electric systems, are expected to advance rapidly.

Conclusions

Power electronics are a key enabler of hydrogen–electric systems for aviation. They will facilitate the conversion of electric power and energy generated from hydrogen to suitable voltages and frequencies for propulsion motors and other loads. In addition, they can be used to control power flows and protection, with notable advantages for flexibility, ease of control, fast response, and built-in intelligence. The essential requirements for power electronics for electrified aircraft are high specific power and high efficiency. With the help of the emerging low-loss and fast-switching WBG semiconductor devices, the specific power of megawatt-level power electronics inverters for aircraft applications is approaching 20 kW/kg, and the peak efficiency can be above 99%. By using cryogenic cooling, which could be provided by liquid hydrogen fuel, the weight and loss of the power electronics can be further reduced.

Power electronics for future electrified aviation, including aviation using hydrogen–electric systems, are expected to advance rapidly. More ground and flight tests will be conducted to demonstrate and validate the performance and reliability of various power electronics technologies, especially power electronics based on new WBG semiconductor devices. For large and long-range aircraft, where a hydrogen–electric system makes the most sense, a voltage in the range of several kilovolts to more than 10 kV may become necessary. As a result, high-voltage power electronics for a high-altitude, low-pressure environment, with consideration for insulation and thermal performance, will be developed.

For cryogenic power electronics, packaging technology for GaN and Si power devices suitable for cryogenic operation will be advanced. Progress is also expected for the system-level performance, design, operation, and control of power electronics in hydrogen–electric systems, including, but not limited to, stability, transient ride through, and protection coordination. Utilizing built-in sensors and intelligence in power electronics for equipment and system health management, operation, and control is also a promising pathway to future advances.

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For Further Reading

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