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WIDE-BANDGAP POWER ELECTRONICS FOR THE MORE ELECTRIC AIRCRAFT

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ABSTRACT

For over 40 years, developments in solid-state electronics have provided the United States Air Force with the most sophisticated and capable avionics systems in the world. Steady advancements in solid-state devices and integrated circuits have enabled modern electronic warfare, navigation, and flight and propulsion control electronics. While conventional silicon (Si)-based solid-state devices have continually been the workhorse of microprocessors, digital signal processing, large memory, analog I/O, and power control electronics, compound semiconductors such as gallium arsenide (GaAs) and HgCdTe are generally used in radar and sensor electronics, respectively. Recently, interest has also been generated in wide-bandgap semiconductors such as silicon carbide (SiC) for advantageous use in high-temperature and high-power device applications. Wide-bandgap electronic devices are capable of operating at both higher temperatures and higher efficiencies compared to Si-based devices. The effect of higher efficiency reduces the amount of heat dissipated by the electronics, thus enabling a reduction in, or elimination of, existing heavy, single-redundant distributed aircraft electronics cooling systems. To insure aircraft electronics reliability and longevity, the junction temperature of conventional Si-based devices is currently maintained within the MIL-STD temperature range of -55°C to 125°C. The higher temperature capability of wide-bandgap devices (operation has been demonstrated up to 600°C) will significantly improve device reliability and enable use in remote locations where cooling is impractical, e.g., mounting of electronics on engines for control and sensing, in aircraft skins for sensing stress and temperature, and in electronic warfare or other "stores" attached to the fuselage or wings of the aircraft. Also, the efficiency of thermal transport between the electronics and heat sink increases with increasing temperature, further reducing the required cooling system capacity. Consequently, wide-bandgap (WBG) high-temperature electronics (HTE) are expected to play an enabling and vital role in the design of the future concept More Electric Aircraft (MEA). The system-level benefits of employing WBG-HTE in the MEA include a reduction in flight control system weight and improved reliability; a reduction in size and weight, or elimination of, the environmental control system (ECS) required to cool power management and distribution (PMAD) and flight control electronics; a reduction in engine control system weight and increased reliability using a distributed processing architecture; and the improved reliability and maintainability of stores management system (SMS) avionics. The following sections address important aircraft subsystem wide-bandgap electronics applications, the temperature range in which electronics will be expected to operate if they are to be un-cooled, and a description of WBG-HTE components desired for use in future MEA electronic systems.

MORE ELECTRIC AIRCRAFT (MEA)

High-temperature electronics represent an important technology in the development of the More Electric Aircraft (MEA). They are critical to implementing both a distributed flight control system and reducing the PMAD heat load that the aircraft environmental control system must dissipate. Recent advancements in high-power solid-state switches, converter circuit topologies, motors and generators, and the evolution of a fault-tolerant electrical power system coupled with electrically driven actuation, have generated renewed interest in MEA. In the MEA concept, electrical power is utilized to drive aircraft subsystems that have historically been driven by hydraulic, pneumatic, and mechanical systems [Quigley, 1993]. Subsystems such as hydraulic-driven flight control actuators, engine-gearbox driven fuel pumps, and air-driven environmental control system would be powered electrically via electric motors

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[Weimer, 1995]. Studies on F-16 and F/A-18 fighter aircraft have shown that the MEA offers many subsystem level benefits in areas of reliability, maintainability, supportability, and overall cost [Eicke *et al.*, 1992; Shah and Rohr, 1992].

In recent years, a series of Air Force/Navy technology programs have been initiated at Air Force Wright Laboratory in support of MEA. The major MEA subsystems under consideration are shown in Figure 1. In this concept, aircraft power is produced by an internal starter generator (ISG) that is directly driven by the main engine. The ISG design under consideration has the potential to produce up to 375 kW when driven by an F-110 after-burner fighter engine. The ISG power is fed to a fault-tolerant power management and distribution (PMAD) electronics network that drives all aircraft electrical subsystems. Major subsystems include those for electric actuation, engine starting, braking, environmental control, anti-icing, and fuel pumping. An integrated auxiliary/emergency power unit (IPU) and battery system provides uninterrupted power for redundancy and engine-start-up.

MEA DISTRIBUTED FLIGHT CONTROL

Significant improvements in aircraft flight control system reliability, mass, volume, and reduced dependency on environmental control can be realized through the use of wide-bandgap electronics. In the MEA architecture, conventional hydraulic-driven flight control actuators will be replaced with electric motor driven actuators and a distributed flight control (DFC) electrical system. Electrically driven flight control actuation offers subsystems benefits in fault tolerance, redundancy, reliability, and power density. A distributed flight control system eliminates the major drawbacks of centralized control, in which actuators and co-located control electronics are connected via a

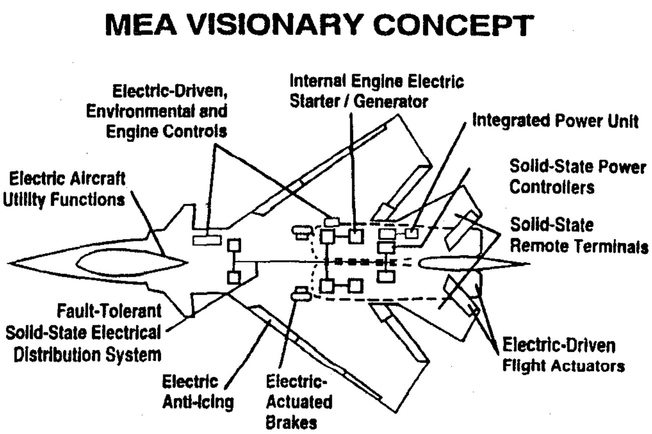

FIGURE 1 CONCEPTUAL PERSPECTIVE OF MORE ELECTRIC AIRCRAFT SUBSYSTEMS

data bus to a centrally located flight control computer. In a centralized control architecture, all power control electronics would be displaced from the actuators and centrally located in the aircraft. The DFC architecture has several major advantages: (1) It eliminates long and heavy wiring/shielding runs to actuators and sensors; (2) It increases reliability because of the reduction in the number of connector pins between control electronics and sensors and actuators; electronics system reliability is estimated, in part, as a function of connector pin count (MIL-HDBK-217F); (3) It increases survivability since centralized control electronics are located in just one location, and (4) It reduces or eliminates active cooling. Although none of the drawbacks of centralized control are prohibitive, a distributed scheme offers a significant opportunity for improving the performance and economic viability of the flight control system.

In present-day fighter aircraft, a centralized hydraulic system provides both flight control power and a thermal transport medium to remove heat from the actuators. However, in the electrically based MEA distributed flight control architecture, power control electronics will be mounted on or near the actuators without the benefit of hydraulic assisted cooling. Since it is impractical and highly undesirable to distribute an active, closed-loop network to cool remotely located electronics (e.g. wing and empennage), because this would offset the benefits of eliminating the hydraulics, "uncooled" electronics will be required. Power control, sensor, and interface and data-bus electronics are needed to provide reliable operation at ambient temperatures well in excess of the Si-based device MIL-STD temperature limit of 125°C.

Unlike Si-based devices, WBG electronics have good potential for operating in "uncooled" environments because they can: (1) generate significantly less heat due to increased efficiency, and (2) tolerate higher temperatures because they liberate smaller leakage currents (I_L). Wide-bandgap devices rival silicon devices in efficiency through reduced conduction and switching losses. In the case of power devices, conduction losses depend on the thickness (W) and doping level (N) of the semiconductor layers used for blocking reverse voltages; where conduction losses decrease with smaller W and larger N. In the case of a p/n junction, which is the fundamental voltage blocking structure in power switching devices, we find $W \propto E_c^{-1}$ and the maximum value of $N \propto E_c^{2}$, where E_c is the electric breakdown field strength of the semiconductor. The value of E_c increases with semiconductor bandgap (E_g) as approximately $E_c \propto E_g^{3/4}$. Consequently, the ideal resistive conduction loss for power switching devices using 4H-SiC with $E_g \sim 3.3$eV will be less than 80 times that for Si devices with $E_g = 1.1$eV. Similarly, wide-bandgap devices will exhibit lower switching losses than do Si devices, which primarily depend on device size through the magnitude of device capacitance. Increasingly smaller-geometry power switching devices can be designed using WBG materials, resulting in smaller capacitance values and lower switching losses. Since device conduction losses vary as $\propto$ (device area)$^{-1}$ and device capacitance varies as $\propto$ (device area), the WBG devices can be made smaller to give lower switching losses while still yielding conduction losses that are substantially lower than that for Si-devices.

Wide-bandgap devices can also tolerate higher ambient temperatures compared to Si-devices because they generate smaller leakage currents. The maximum device operating temperature is limited to maintain a sufficiently small leakage current (I_L), such that the ratio of device "on-current (I_{on})"/I_L > 10^5-10^7. In the case of the Si or SiC p/n junction, the leakage current decreases exponentially with semiconductor bandgap (E_g) according to $I_L \propto \exp(-E_g/2kT)$, where k is Boltzmann's constant and T is the temperature. This relation shows that WBG devices, such as SiC with E_g = 3.3eV, are capable of operating at temperatures ~ 3X greater than for Si-based devices with E_g = 1.1eV. In the past, the Department of Defense system development directives have specified a maximum Si-device junction temperature of 110°C to ensure reliability. Several major aircraft programs have even limited Si junction temperatures to less than 70°C to yield major reliability improvements. A conservative estimate for the highest ambient temperature to be encountered by actuator-mounted electronics (without cooling) in MEA supersonic aircraft is ~ 200°C. At present, however, high-power electronics capable of long-term reliable operation at temperatures greater than 200°C do not exist. Consequently, the current MEA distributed flight control (DFC) baseline design is forced to employ Si-based electronics that require active cooling, and the full potential of DFC cannot be realized. Thus, the use of WBG-based power devices capable of reliable operation at temperatures of ~ 300°C would clearly meet the MEA DFC requirements, and enable the benefits of reduced system mass and increased reliability.

MEA FAULT-TOLERANT PMAD

Wide-bandgap electronics can also significantly reduce the total power management and distribution (PMAD) heat load that the aircraft ECS must handle. This would allow a reduction in the massive size and weight of the aircraft ECS (along with other advantages discussed later) and improve overall aircraft flight performance (e.g., range, maneuverability). The envisioned MEA concept imposes increased demands on existing PMAD technologies in the areas of power handling, fault-tolerance, and reliability; these in turn, require innovations in power generation, distribution, and source and load management. In response to these demands the Air Force has initiated the Power Management and Distribution for a More Electric Aircraft (MADMEL) ground demonstration program [Maldonado *et al.*, 1995).

In this effort, a hybrid power system will supply 270 VDC, 28 VDC, and 115/400 V 3ϕ @ 400 Hz power to MEA-type simulated loads [Weimer, 1995]. Electrical load management centers (ELMCs) will distribute remotely controllable power to high-power, medium-power, and rotary vane actuators, and engine start, radar, resistive bank, and avionics load simulators. Important PMAD subsystem functions include 270 V to 28 V DC-DC conversion, 270 V to 115/400 V DC-AC inversion, fault detection and isolation, and load reconfiguration.

MEA-type loads require 270 VDC power for driving actuator motors and 28 VDC for driving motor control logic. Most Stores Management Systems (SMS) avionics are driven by 28 VDC, and the envisioned active phased-array radar will require 270 VDC. The 400 Hz power is only required for some externally mounted weaponry.

Silicon-based switching devices and driver control electronics will be employed in MADMEL's baseline design. They will be cooled by a poly-alfa olefin (PAO) and vapor-phase heat-exchanger ECS. A similar ECS design also provides electronics cooling for the advanced F-22 fighter aircraft. The junction temperature of silicon-electronics utilized in both MADMEL and on the F-22 is maintained below 90°C by the ECS to ensure reliability. As previously mentioned, the advantage of employing WBG power devices in future PMAD or MADMEL subsystems will be to reduce the electronic heat load that the ECS must dissipate, thereby reducing the required ECS capacity. The ECS could then be made smaller and lighter. A reduction in PMAD electronics mass and volume can also be expected using WBG power devices; reduced conduction and switching losses will result in greater device power densities. A further advantage of employing WBG high-temperature electronics results because the heat transfer rate (g) between the electronics package cold plate at temperature T_1 and the ECS PAO transport medium at temperature T_2 are related as $g = h\,(T_1 - T_2)$, where h is the heat transfer coefficient, and the temperature gradient between the source and sink drives the heat transfer. Increasing the allowable electronics junction temperature and corresponding package and cold plate temperatures increases the efficiency of thermal transfer to the PAO. This would further reduce the necessary capacity of the ECS. Additional benefits of reducing or eliminating the dependency of aircraft electronics on the ECS are discussed below.

ENVIRONMENTAL CONTROL SYSTEM CONCERNS

An important long-term goal is to reduce the total electronics heat load that the aircraft environmental control system (ECS) must handle in order to reduce its size, weight, and cost. As mentioned, the use of wide-bandgap electronics can reduce or even eliminate active cooling of remotely located actuator control electronics and PMAD subsystems. The current approach used to cool most avionics and power control electronics on fighter aircraft employs a closed-loop ECS. Greater than 90% of the ECS cooling capability on modern fighter aircraft is utilized by the electronics; this includes cooling of radar electronics. Hence, it is highly desirable to reduce the total electronics heat load. Eliminating the aircraft ECS altogether may not be feasible, since it is needed to handle the few hundred watts generated by the pilot.

Today's ECSs are large (in size and weight) and consume a significant amount of power, which adversely affects aircraft performance. Existing fighter aircraft electronics can generate up to 50 kW of heat. The ECS in turn requires approximately 50 kW of power from the engines to dissipate this heat. The ECS is single-redundant because of its massive size, and its failure results in an aborted mission or catastrophic failure. A significant reduction in ECS size could make redundancy feasible. Today's ECSs are also very expensive, and with the anticipated growth of tomorrow's electronics systems, projected future costs are enormous. Further, the ECS aboard many fighter aircraft transfers the electronics heat to the aircraft fuel via a heat-exchanger, which in turn transfers the heat into the environment around the aircraft. This approach has several drawbacks. The aircraft must reserve a finite amount of fuel to provide an adequate heat sink for the ECS, and maintaining the fuel reserve decreases the aircraft range. An eloquent solution to many of these issues would be to significantly reduce the required capacity of the ECS through employing wide-bandgap electronics.

MORE ELECTRIC PROPULSION CONTROL

High-temperature wide-bandgap electronics can also significantly contribute to the performance of the "more electric engine (MEE)," a design that seeks to eliminate the use of hydraulics on an engine by employing electromechanical hardware for nozzle, guide-vane, and metering-valve actuators and fuel pumps [Przybylko, 1993]. High-temperature electronics will be needed to control electrical power to the electromechanical devices and communicate over a distributed data bus, because it will not be feasible to cool remotely mounted devices with either air or fuel. Aircraft engine control systems have employed electronics for many years. The full-authority digital electronic control (FADEC) processor currently controls all fighter engine functions and provides onboard, real-time monitoring and diagnostics. As the engine workload increases in the future, the required capabilities of the FADEC can also be expected to increase. Analog-to-digital (A/D) and digital-to-analog (D/A) signal processing have become an increasing part of the FADEC's computational workload, challenging its throughput capability. Consequently, as the functional complexity of the FADEC grows, so too will the size of its housing and number of outside connectors. This results in major maintenance and weight issues, due to long cabling between the FADEC, sensors, and actuators. The solution to these problems is to employ distributed processing.

In distributed processing, a "local engine network" provides communication between the FADEC, actuators, and sensors. "Smart electronics" remotely located at the actuators and sensors perform signal processing functions, loop-closure calculations, and diagnostics. Autonomous control of some subsystems may even be possible. The local network would significantly reduce the number of connectors, the total cable length, and the computational requirements of the FADEC. The result would be a reduction in the total weight and physical and functional complexity of the propulsion control system. Since it is not feasible to cool remotely located engine-mounted electronics with fuel or ram air, they must endure the high-temperature environment of the engine. The projected engine-case temperature experienced by electronics mounted on a F-100 class of afterburner fighter engine is as high as approximately 315°C at Mach 2.5. This temperature clearly exceeds the MIL-STD high-temperature limit of 125°C for Si devices. In the absence of cooling, it is clear that Si-based electronics cannot be employed in the distributed "local engine network" control architecture. High-temperature electronics capable of reliable operation at temperatures of 350°C or greater will be required. Existing engine-mounted Si-based FADECs are typically cooled (derated) with air or fuel to approximately 80°C to ensure reliability. It is anticipated that the FADEC will remain Si-based in the near future, due to the high level of technology required to develop the central processor. However, when the development of high-temperature WBG devices and integrated circuits progresses to the stage of VLSI technology, the FADEC will also be based on high-temperature WBG materials.

STORES MANAGEMENT SYSTEMS AVIONICS

High-temperature electronics also hold a number of important applications in Stores Management System (SMS) avionics for supersonic military aircraft. SMS electronics control all weapons, electronic warfare, and other stores (e.g., fuel tanks) attached to the fuselage or wings of the aircraft. Supersonic flight causes high aircraft skin temperatures due to aero-heating (friction). The heat generated is transferred to the various compartments within the aircraft fuselage and wings via aircraft skin and frame conduction and compartment air convection. Consequently, Si-based SMS avionics housed within these compartments require cooling to maintain the upper MIL-STD temperature limit of 125°C. The interface between the SMS and the store itself is located, ideally, at the store interconnect to allow for simple addition or modification of new stores. The result is electronics remotely located on the aircraft wings, which are nearly impossible to cool. In some cases the SMS electronics are stored in pylons attached to the wings; the pylons provide mechanical support for the store. Under certain emergency conditions, it is desirable to jettison the pylons to significantly improve aircraft flight characteristics. However, providing a pylon jettison capability practically eliminates the ability to cool the SMS electronics. If the pylon were cooled, the cooling system would be momentarily opened during jettison until a self-sealing valve closed. If the valve failed, the ECS coolant would drain. Since this could produce failure of other flight-critical systems, centralized ECS cooling of pylon stores electronics is not considered feasible.

Current approaches for cooling SMS electronics include ram air, self-contained ECS conditioning, and conductive transport to the store skin or case. Various electronic countermeasure (ECM) stores use forced air obtained from the aircraft's jet stream. While this is a logistically simple approach, it also bleeds air from the jet stream, which creates aerodynamic drag that reduces aircraft performance. The Low Altitude Navigation and Targeting Infrared and Targeting System for Night (LANTIRN) pods employed on F-15E and F-16 aircraft utilize ram air and a small self-contained PAO/Freon ECS to condition electronics. The drawbacks of this hybrid approach include ram air aerodynamic drag, added ECS weight, and single-point failure. Many deployable smart weapons and missile and bomb stores simply dump electronics heat to the outer skin via thermal conduction; electronics boxes are mounted on or near the armament case. In each of these scenarios, the stores would benefit through the use of high-temperature WBG electronics. As in the case of DFC and PMAD electronics, benefits would derive from the reduction in electronics heat generation and high temperature capability. Potential advantages include reducing stores aerodynamic drag, eliminating ECS conditioning to reduce weight and improve reliability, and increasing armament electronics design flexibility; moreover, electronics mounting would not be restricted to the outer case of the weapon.

HIGH-TEMPERATURE ENVIRONMENT

It is difficult to predict with precision what the exact environmental and solid-state device junction temperatures will be for the various aircraft electronics subsystems. Many factors, such as electronics location, maximum aircraft speed, duration of flight at that speed, altitude and ambient air properties, electronics packaging and mounting techniques used, and internal electrical losses, determine the final operating temperatures. However, under assumed aircraft performance envelopes, it is possible to make conservative predictions for the highest ambient temperatures encountered. A projection for the operating temperature of actuator flight control, PMAD power control, and SMS electronics can be obtained for a modern advanced fighter aircraft by considering the calculated skin temperatures given in Figure 2 for an F-15 fighter aircraft. The skin temperatures shown represent the stagnation temperatures calculated for 1.0 g flight at the altitude and speed indicated. Ignoring the regions adjacent to the engines, the skin temperatures shown range between approximately 90°C - 200°C. If it assumed that no active cooling is provided to the electronics via the ECS, the only available heat sink for the electronics boxes will be the environment around the aircraft, reached via the aircraft frame/support structure and skin.

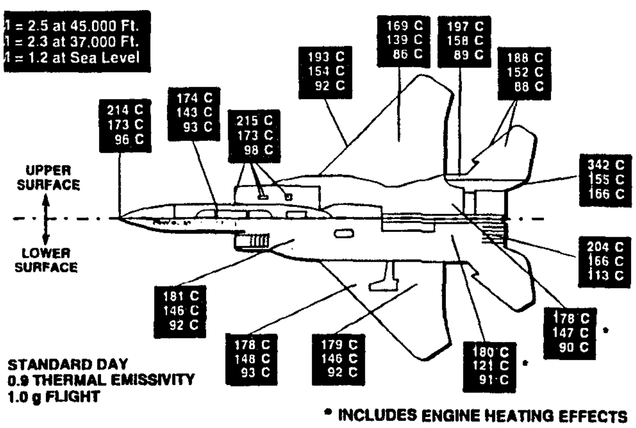

FIGURE 2 CALCULATED SKIN TEMPERATURES FOR A SUPERSONIC F-15 AIRCRAFT

Heat is generated in all electronics by internal resistive losses. This heat must be efficiently dissipated to prevent catastrophic device failure due to the degradation of the metal contacts and packaging structure, and device degradation due to substrate and p-n junction leakage currents. As mentioned earlier, an adequate temperature gradient must exist between the heat source (the electronics) and the sink (ultimately, the aircraft skin) to drive heat transfer to the environment around aircraft. Obviously Si-based electronics with a MIL-STD maximum temperature limit of 125°C (typically derated to < 100°C to ensure reliability) cannot be used in this uncooled supersonic flight scenario. Due to thermal resistance between the solid-state chip containing the devices, the device package, the electronic box, the aircraft frame/support structure, and the aircraft skin, solid-state devices capable of reliable operation at junction temperatures of at least 250°C will be required to support PMAD, actuator control, and SMS electronics in the absence of active cooling. A more detailed analysis may show a reduction in the maximum required operating temperature, however, at present the conservative assumption of 250°C is useful in defining the electronics challenges that lie ahead.

In the case of the electronics required for propulsion control, the projected engine-case temperatures for an F-100 class afterburner fighter engine are shown in Figure 3. Engine-case temperatures at locations where the electronics would be mounted range from approximately 175°F (80°C) at Mach 0.9 and 40,000 ft. to 600°F (315°C) at Mach 2.5 and 50,000 ft. This temperature range clearly exceeds the MIL-STD high-temperature limit of 125°C for existing Si-based devices. Hence, once again it is obvious that existing Si electronics cannot do the job in the absence of active cooling. It is assumed that electronics capable of reliable operation at temperatures of at least 350°C will be required to enable the local engine network distributed control architecture.

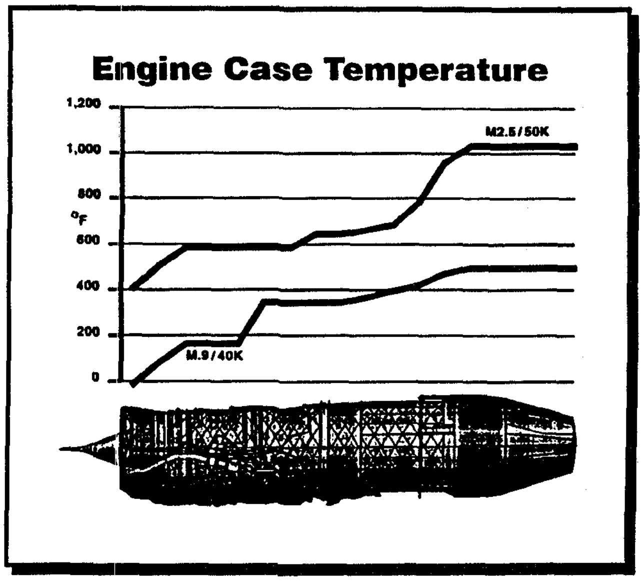

FIGURE 3 TEMPERATURE DISTRIBUTION FOR A F-100 AFTERBURNER FIGHTER ENGINE (PRZYBYLKO, 1995)

REQUIRED HIGH-TEMPERATURE COMPONENTS

In order to implement these advancements in aircraft electronics subsystem performance, a wide variety of components capable of high-temperature operation must be developed. The electronic components required to enable each of the four aircraft subsystems (DFC, PMAD, MEE, and SMS) are very similar

Electronics for power control and digital signal processing employ nearly identical components in each application. The DFC system requires electronics for actuator power control and smart actuator functions. A typical resonant link inverter circuit used for actuator power control will require capacitors, switches (MOSFETs, IGBTs, and MCTs), and rectifying devices (p/n and Schottky diodes). Expected power requirements include 50, 100, 200, 400, and 800 amps at voltages up to 1000 V. Smart actuator electronics are necessary for actuator position and pressure transducers, servovalve and solenoid drivers, and data bus interfaces. The minimum requirement for these electronics is a chip-module containing a 16-bit microprocessor with on-chip ROM, RAM, and I/O, a high speed bus serial interface, and D/A and A/D signal converters. The power control electronics required for PMAD system DC-DC and DC-AC power conversion and MEE distributed network engine control are comprised of the same fundamental components employed by the DFC system; capacitors, switches and rectifying devices. Digital signal processing requirements necessary for driver circuits, sensors, and diagnostics are essentially the same as those listed above as well.

CONCLUSIONS

An opportunity exists to significantly improve the overall performance and economic viability of military aircraft flight control, propulsion control, power management and distribution, and stores management subsystems through the use of wide-bandgap (WBG) semiconductor devices. WBG-based electronics are potentially more efficient, can dissipate less heat, and are capable of operating at much higher temperatures compared to conventional Si-based electronics. These attributes will help enable the development of future distributed engine and flight control systems, as well as allow the reduction (in size) or elimination of heavy, single redundant aircraft environmental control systems (ECS). Reduction in the ECS size, and utilization of distributed control offers substantial payoffs in aircraft capability, reliability, maintainability, and supportability; this includes lowering fly-away and life-cycle costs, and increasing aircraft payload and range capabilities.

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