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Power Electronic Technologies for Planetary Science and Astrobiology Missions

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Introduction

Future planetary science and astrobiology mission concepts would need more advanced power system electronics, to take full advantage of the new power sources and energy storage technologies in development. Operating highly capable science missions and surviving in increasingly extreme environments will require both new power electronics technologies and new power architectures. The destinations of these future mission concepts could range from the inner to outer solar system, and many would operate on the surface of moons and planets in extreme environments for longer durations than prior missions. As the power system density improves, the power system electronics would need to keep pace by improving the power control flexibility, distribution simplification, thermal control, power conversion efficiency, and packaging density. Some of these new power technologies are *enhancing* (by improving the overall system efficiency, reducing power system mass and supporting more science instrumentation), whereas others are *enabling* (e.g., tethered power transfer, to enable exploration of difficult-to-access regions of planetary surfaces).

Advanced Power System Architectures

More advanced distributed power system architecture would connect the power control function to the functions distributed throughout the system. New power electronics technology should enable the embedding of the power switching, valve driving, pyro firing and thermal control into the subsystems requiring the function. These functions traditionally have been centralized into large assemblies requiring large point-to-point system harnesses to deliver the power to the load. Advance communication protocols, micro-controllers, mixed signal ASICs, power switches and packaging technology would need to be developed, radiation hardened and qualified to enable a distributed architecture (Fig. 1). The result would be a fault tolerant architect that can adapt to a wide variety of mission concepts reducing overall system level impact by eliminating point-to-point harnessing, large warm electronic boxes and large electronic assemblies. In addition, architectures that consider modularity and interoperability across elements should be the goal in order to minimize costs and logistics burdens on the mission lifecycle. Additionally, as NASA's SMD becomes increasingly involved in human space flight precursor missions modularity and interoperability will even be enabling across enterprises This is particularly true for long duration missions where ideally assemblies on a rover/probe can be useful on crewed elements minimizing the logistics burden.

Figure 1. Distributed Power Architecture. The block diagram shows a modular and distributed power architecture that can adapt to wide variety of missions.

Power Control Technology

Power sources would require more advanced power control architectures to optimize the delivery of available power throughout the mission solar range and external environment. As new power electronic technology is developed, efficiencies are improving enough to shift the balance from standard linear direct energy transfer architectures to power control architectures that can maximize the available power.

The power control architecture adapts to the different power technologies such as advanced solar arrays, radioisotope power and high energy/power density batteries. The power control architecture would optimize the performance between the power source and energy storage technology taking advantage of advanced digital control techniques leveraging low power high-density microcontrollers. New power conversion topologies could be enabled by digital control improving the efficiency and power density by increasing switching frequency and sequencing of multiple power stages to optimize the performance of advanced Gallium Nitride (GaN) power switching technology.

The new digital controllers could integrate the traditional Maximum Power Tracking (MPT) approach with more advanced power conversion topologies leveraging the higher frequency power switching technology (GaN). The improvement in efficiency and power density would result in more missions flying MPT architectures that traditionally have been direct energy transfer architectures. A common set of power control building blocks could be scaled to the varying mission concepts leveraging the new technology across a larger mission suite.

Some deep space missions would utilize advanced SEP technology needing more advanced power control architectures to maximize thrust and efficiency. The Power Processing Units (PPUs) that power the electric thrusters need high voltage at the input to reduce cable mass. The advanced avionics would need lower voltage and energy storage. The power control architecture would be optimized for the performance of the higher voltage and lower voltage loads improving the overall system mass (Fig. 2). The system would operate on the maximum power point safely without the need of ground operation adjusting thrust levels to maintain energy balance.

Figure 2. Dawn High Voltage Electronics Assembly (HVEA). The HVEA provided power control from the high voltage solar array to the battery dominated power bus for the avionics and payload.

In-situ system concepts such as landers, rovers and probes would operate on the surface of planets and moons in extreme environments (Fig. 3). Each system would need different architectures that adapt power control to enable science objectives by extending the life, maximizing performance under various scenarios. Some systems would sleep for the majority of the duration on the surface preserving a primary battery, which needs very low power, knowledge of state of charge, and the ability to wake up perform science and go back to sleep.

Figure 3. Europa Lander Concept. This is a concept of a Europa Lander powered by primary batteries.

Other In-situ missions would need to transfer of power over a tether or laser between a lander and probe, requiring efficient high voltage power conversion technology on both the lander and probe. Depending on the power transfer mechanism, the power electronics would need to step up to higher voltage transmit and then step down on a dense extreme environment probe (Fig. 4). The power control approach needs advanced topologies, high voltage switching technology, dense packaging that can operate in extreme environments. The application could vary from low duty cycle pulsed power to continuous power delivery requiring an integrated advance thermal design. Digital control should enable advanced higher frequency topologies (e.g. Modular Multilevel Converters MMLCs, or resonant LLCs) to reduce the mass/volume and improve efficiency.

Figure 5. Tethered Rover Concept. This is a concept power architecture a tethered Axel Rover.

Power Distribution Technology

As the power control architectures evolve, the power distribution approach needs to adapt to the varying mission concepts ranging from 20kW lunar landers and deep space SEP vehicles to low power CubeSats, In-situ landers, rovers and probes. The traditional state of the art (SOA) centralized power distribution increases mass with high volume electronic assemblies and kilometers of point-to-point harnessing exponentially affecting the system's volume and mass. Some systems are block redundant with large fault containment regions doubling on the amount of mass needed to meet the mission reliability requirements. The centralized power distribution cable harness drives the mechanical design of the system.

Advanced technology electronics should simplify the power distribution architecture by going from a centralized system to a hierarchal or distributed embedded system. The aviation and automotive industry have advanced distributed architectures leading the way in defining proven communication protocols required to achieve a distributed architecture. Rad-hard electronics need to be developed to integrate the proven communication protocols with power control for a distributed power switch assembly or embedded power switch (Fig. 5). The electronics would protect the hierarchal distributed system level power bus by providing serial communication, fault protection and visibility into the subsystem receiving power. The new advanced technology

microcontrollers and mixed signal ASICs should enable the power switch to be local to or embedded in the subsystem's power supply with acceptable impacts on the packaging.

Figure 5. Europa Clipper Power Switch Slice (PSS) and “gum stick” switch. The Europa PSS and individual switch have been designed to be located centrally or distributed throughout the spacecraft.

Other centralized functions such as valve drive electronics and pyro firing could use the same technology to be placed local to the element. The same communication protocol that could be used for power distribution should be used to either pulse the valve, fire the NASA Standard Initiators (NSIs) or actuate non-explosive actuators (NEAs). The use of mixed signal ASICs and microcontrollers with advanced packaging would enable the units to be located outside of the warm electronics enclosure local to the devices. The system level protected power bus could be armed and enabled prior to being distributed through the vehicle.

Distributed Thermal Control

A major number of the centralized power distribution switches have been dedicated to thermal control function driving heaters that are controlled by flight software. This centralized approach with the control loop implemented across the C&DH and Power subsystems add to the system level complexity and mass. This approach needs more hardware to be powered when the system is sleeping in order to maintain thermal control to survive the environment. Some electronics have been developed on passed missions to take over this function when C&DH is sleeping to reduce power; however, the implementation is still centralized and a duplicated function. Some instruments with tighter control requirements have used distributed thermal control. Using the same technology developed for distributed power switching, distributed thermal control should be developed to reduce the cabling and the number of units powered during sleep mode. The thermal control loop would be closed near the heater.

Linear thermal control has been flown on GRACE Follow On, where the linear power switch is packaged on the heater delivering all the power to heating the element. The system delivers improved control and efficiency. However, the reading of the temperature sensor and linear control is still packaged centrally, resulting in no reductions of the cable harness. A distributed linear thermal control function would be implemented in the same package as the power switch to provide local closed loop control reducing system level complexity and the need for flight software to close the loop. The flight system can send a command to maintain a certain temperature while the flight system sleeps. The same unit should be used for tighter thermal control with flight software actively managing the temperature across the system. Survival thermal control would be implemented using the same distributed control unit eliminating thermostatically controlled heaters.

Power Conversion Technology

A key area to advance technology should be in power conversion. Power conversion technology is used in every major flight subsystem. A new power switch technology (GaN) has emerged over the past decade to create a revolution in terrestrial power conversion. The GaN power switch operates at a higher switching frequency with lower switching losses as compared to the standard MOSFET. The device can switch higher voltage in a smaller package. Many new topologies have been developed to take advantage of this power switch technology. GaN technology has been approved for flight in some limited applications. More qualification and process improvements need to be complete to enable the GaN technology to be used for long life critical functions on the spacecraft. Advanced high voltage Silicon Carbide (SiC) power switches and diodes could improve the performance of high-voltage and PPU's by limiting the number of power stages connected in series, reducing complexity and mass.

With the advancement of a new power switch technology, digital pulse width modulator (PWM) controllers, and gate drivers should be developed to fully utilize the capability of the switching technology. Many of the advanced topologies are being developed and proven on terrestrial smart grids and electric vehicles. Radhard digital PWMs and drivers should be developed to use these topologies in flight. The new topologies combined with new switching technology raises the efficiency and increases the power density. New Point of Load (POL) converters should be developed to be embedded in the subsystem improving the end-to-end system level efficiency. The higher efficiency and increased switching frequency leads to a smaller footprint enabling more functions to be distributed to the subsystem power converter as identified in the power distribution technology section.

Advanced electronic packaging would be needed to incorporate the new power switch technology with the new controller ASICs to take full advantage of the performance improvement and get the heat out. Three-dimensional packaging techniques with high density flexible interconnects could reduce the volume, but require novel thermal management approaches to remove the heat, as the power density increases.

Needs and Technologies for Outer Planet Missions

Missions to the outer planets could be either solar powered or radioisotope powered, and could use either chemical propulsion or electric propulsion. The solar range and life variation of the power source would need advanced power control technology to optimize the performance over the mission concepts life. MPT would be used for the solar powered missions for both the chemical and electric propulsion systems. Depending on the type of radioisotope power system being planned, the power control would need to adapt for optimum performance over the lifetime of the mission. This electrical conversion step is needed in most cases in addition to the heat to electrical power conversion present in current and developing nuclear sources.

The deep space missions would benefit from a distributed power system architecture to reduce system level volume and mass. Advanced thermal control could reduce the peak power needs and provide more efficient thermal control with a reduction in cabling. As an example, the distributed architecture would reduce mass by minimizing harness to a central location and by reducing duplication in distribution switching both of which also result in lower parasitic power losses on future Ocean Worlds lander concepts. In addition, this approach could create a more efficient sleep mode, to extend the length of the mission concepts which operate on primary batteries only (e.g., the Europa Lander mission concept).

Advanced power conversion technology should improve the end-to-end system efficiency (on the order of 10%). The new technology is being developed to be radiation hardened for the Jovian missions. The improved end-to-end system should reduce the size and impact of the solar array on the mission. As solar array technology improves to become viable for some missions to Saturn and beyond, the performance of the power architecture and electronics would contribute to enabling these missions.

For some mission concepts bound beyond Saturn, a distributed power system architecture can improve the system performance of Radioisotope Thermoelectric Generators (RTGs). Advanced power control architectures can increase the power available by about 5% over the power bus voltage range and reduce the size of a shunt radiator, further reducing the mass penalty of the power system.

Needs and Technologies for Inner Planet Missions

Mission concepts to explore the inner planets and the sun require a compact and more efficient power system architecture that can operate over wider temperature range to reduce the burden on the thermal control subsystem. Higher temperature switching technology and control electronics can enable insitu Venus probes. Thermal management is a key element in packaging the power electronics. Advanced packaging to remove heat dissipation with a distributed architecture to spread the thermal load can enable and extend the life of certain missions with active thermal control. The flexibility of the distribute architecture can support the use of shields and active thermal control reducing the volume and cable harness of the system.

Needs and Technologies for Mars Missions

The burden of the mass and volume for a centralized power distribution architecture has driven the volume for Mars landers and rovers over the past decades. A distributed system reduces the volume and mass. In combination with a smarter thermal control this would reduce the power through the night and average power overall. Higher efficiency power conversion can increase the energy available from the battery over the power bus voltage range through the night, and increase the power available from the solar array. Electronics designed for the extreme environment can enable rovers and landers to hibernate at night or through a season.

The Mars Helicopter, shown in Figure 6, uses a direct energy transfer power bus at a lower voltage due to the constraints on the battery. With advancement of power electronics technology an MPT can improve the end-to-end energy balance extracting more usable power from the array without paying out the entirety of this gain in conversion efficiency losses while still meeting mass and volume constraints.

Figure 6. Mars Helicopter. The Mars Helicopter is shown during test under simulated Martian conditions. The power bus is direct energy transfer with the battery (six Li-Ion cells in series).

Needs and Technologies for Small Bodies

Mission concepts for small bodies span a variety of scenarios, such as landers on the asteroid Ceres, sample return from comets and exploration of the Trojan asteroids. Missions to distant bodies, such as the Trojans or Centaurs, would share much in common with missions to outer planets. Solar-powered missions could need MPT for both solar electric propulsion (SEP) and chemical propulsion. Improved efficiency and thermal designs should reduce the size of solar arrays (10%) for the orbiters and extend the life of primary batteries (10-20%) for the probes.

Needs and Technologies for Lunar Surface Missions

Lunar mission concepts range from the multi-kilowatt landers to small distributed in-situ rovers and probes. High voltage/power GaN based power converters would improve the performance of the components on these grids. Transmission line, tether and power beaming distribution architectures would be enabled with the GaN power conversion technology. Extreme environment power electronics can enable hibernation through the lunar night offsetting energy required to perform thermal management, which in several lunar concepts is significant and a driving design constraint.

Summary and Recommendations

The next decade of missions need power system electronic technology to improve the end-to-end system level efficiency, mass and volume. The footprint of the power system architecture needs to be reduced to enable the future missions.

Based on these observations, the following recommendations are intended to maximize NASA's investment in power system architecture and electronics technology for planetary science and astrobiology. Investment in the qualification of GaN and SiC switching technology will have the greatest impact on the end-to-end power system efficiency. A more advanced distributed power system and thermal control architecture will drastically reduce the spacecraft harness and volume. Modularity and interoperability of these elements will also be enabling through reduce lifecycle costs.

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