I recently came across a really well thought out and technically valid paper that constructed a possible future road for power electronics. This paper was solidly based on sound engineering principles and hard facts. I will apply the findings of this paper, in conjunction with NASA’s needs for future power in space, to paint a picture of the power needs of NASA and how these needs can be met in future space travel endeavors.

In this article I will outline some existing power management designs presently being used by NASA with a look forward to new concepts in power for the future of space travel. And, yes---NASA will be shaping space travel in the future. I know that SpaceX, Orbital Sciences, Virgin Galactic, and Boeing are always in the news regarding trips to Mars and the moon and beyond, but no one has the talent, expertise and prior experience with manned space travel and safety of those intricate vehicles for space travel than NASA. Trust me---I have been in the NASA Life Sciences labs at NASA Ames Research Center in California where the Life Sciences Lab scientists and engineers are ever improving spacecraft environmental systems, food, water and other life-support systems inside present spacecraft and the Space Station and are working toward the future with new power concepts as well, especially at the NASA Glenn Research Center (GRC) in Cleveland, Ohio.

The future vision for Power Electronics

Let’s first look at the general marketplace of Power Electronics as Reference 1 explains it. This generalized and varied market progression will certainly affect Power electronics in the space program.

Power electronics is a challenging discipline because the power levels being created and controlled range across multiple orders of magnitude, with a huge variety of functions for an endless variety of applications.

Most development in the Power Electronics field has been driven by semiconductor suppliers with
their specific semiconductor technologies and topologies of power converters. Efficiency has been an elusive target in which tenths of a percent improvements have been applauded.

Reference 1 indicates that although semiconductor companies seem to be approaching limits and maturity of their internal metrics, those external technologies of packaging, manufacturing, electromagnetic and physical impact, and converter control technology still have ample room for development. Wide bandgap semiconductors have been a remarkable internal development and will be driven by future application such as space travel.

**A new paradigm is coming**

Past converter concepts need to be shed and a new converter concept embraced that encompasses all equipment between the source and the load whose objective is the conversion and control of electromagnetic energy flow between the electric source and load. See Figure 1.

![Figure 1: The internal functions of an electronic power converter. These functions relate to the propagation, conversion and control of the electromagnetic energy flow at all power levels and in all types of converters. (Image courtesy of Reference 1)](image)

Next we must map the fundamental functions in Figure 1 to design reality by any type of technology. When this is done other constituent technologies are found. See Figure 2.

![Figure 2: The interrelationships of the constituent technologies in power electronics (Image courtesy of Reference 1)](image)

Figure 2 shows groupings that show the powerful impact that electromagnetics and manufacturing can have on power electronics design. Those technology elements in Figure 2 deemed internal to power electronics are the power switch, power switching network and passive component.

Cooling, manufacturing, packaging, environmental impact and converter control technology are all considered external constituent technologies.
The Power Electronics Space concept

This concept can help visualize the tremendous range of power electronics technology by looking at Power levels, Functions and Applications. We will now define a specific power electronics technology for an Applicable Technology Space (ATS).

So we can look at technologies suitable only for a specific ATS like the voltage regulator module-space or power supply on a chip, uninterruptable power system-technology space, wind power converter space, fuel cell converter space, etc.

Emerging applications and technologies

Distributed Systems

With processor technology and FPGA’s lower voltages and higher currents above 100 A, coupled with GHz clock frequencies, the technique of moving between sleep and wake-up modes occurs quite frequently in designs in order to save energy.

Multiphase voltage regulator (VR) modules are now being used for new Intel Pentium processors. See Figure 3a and b.

Figure 3a: Multiphase VR for new generation of processors (Image courtesy of Reference
Figure 3b: Efficiency improvements at light load are obtained using phase shedding and burst-mode operation. (Image courtesy of Reference 1)

The multiphase VR has improved power bricks with a new architecture using a two-stage solution: a basic DC/DC transformer (DCX) going into a multiphase VR. This change has improved efficiency, power density and cost. See Figure 4.

Figure 4: The DC/DC brick converter is replaced by the DCX and Point of load (POL) VR. (Image courtesy of Reference 1)

Modern power architectures have been changed for the better. With distributed point-of-LC we have gone away from the older concept of centralized/custom power to a distributed power supply (DPS) concept. See Figure 5.

Figure 5: A distributed power architecture (Image courtesy of Reference 1)

We now look to the future as the authors of Reference 1 predict that DPS will evolve into a more simplified structure in which any power system can be made up of basic building blocks like boost PFC, DCX, and buck VRs. See Figure 6.
Integrated Power Electronics Modules (IPEM)

An integrated system will be best suited to push the envelope of performance, reliability and cost of electric energy processing systems. The basic functions that are needed in a power electronics system are as follows:

- Switching elements
- Control so that operations can execute properly
- Electromagnetic energy storage and transformation
- EMI filters
- Thermal management
- Mechanical and structural stability of components, modules and the entire assembly.

Let’s look at the DPS converter in Figure 7 as an example of the IPEM at the module and system level.

Advances in design improvements have gone from wire bond to planar metallization in these systems. Integrated EMI filters use equivalent parallel capacitor cancellation which improves performance with a decrease in size. Techniques such as stacking two transformers built with two planar E-cores and share a common I-core have simplified assembly and shrunk sizes.

Most major semiconductor suppliers have adopted new products such as DrMOS, similar to IPEMs. This development improved upon the transient response performance and integration density. See Figure 8.

So we can see that the traditional internal drivers for advanced development of power electronics
are improved switching devices leading to new/improved topologies. That said, we look for added driving forces that can advance the power electronics industry with other external technologies such as packaging, EMI filters, and control.

**Some more emerging technologies**

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Improved thermal management will be needed going forward. Power Electronics Building Blocks (PEBBs) have been proven by ABB into the MW ranges. ABB has a 20 MVA MV voltage source module and a 6 MVA H-bridge or 2-phase converter block.

The external power electronics constituent technologies of packaging, manufacturing, cooling, control, and sensing will be driven from outside by emerging future applications such as the challenging space program for example.

Phase-shifted, isolated DC/DC converters may be the key to improved medium voltage (MV) modular power converters going forward with smaller size and improved performance.

Better modeling and simulation techniques will also improve the Power Electronics industry by optimizing designs and increasing efficiency and lifetime.

All of these efforts in the general power industry will ultimately help NASA’s space program.

**NASA science objectives and power electronics needs for the future**

In order to have a successful future space program, NASA has determined that it will need lighter weight, lower power electronics plus radiation hardened, extreme environment electronics for planetary exploration. This will especially be important for missions such as those planned for Earth Orbiting, Venus, Europa, Titan/Enceladus Flagship, Lunar Quest and Space Weather missions.

**Power Electronics and Management**

Radioisotope power systems (RPS) and Power Processing Units (PPUs) for Electric Propulsion (EP) are two programs that are high on the priority list. A high efficiency, rad-hard 3.8 kW Silicon Carbide (SiC)-based PPU is now being developed for the High Voltage Hall Accelerator (HiVHAC) Hall effect thruster. The power converter uses SiC JFET power switches with Ron (On resistance) an
order of magnitude smaller than equivalent 600 V rad-hard Silicon MOSFETs. A prototype was developed in 2012 that achieved 700 V output voltage at 1.3 kW output power level, 2.55 kW/kg gravimetric power density and up to 92% efficiency. The converter operates on 80-160 V input and can dynamically control the output voltage between 200-700 V.

The prototype PPU power converter. (Image courtesy of Reference 8)

The push-pull topology utilizing novel resonant switching cells (RSCs) for the main power. RSC topology replaces a single switch to increase overall efficiency. (Image courtesy of Reference 8)

The Outer Planet Assessment Group is looking for high power density/high efficiency power electronics for Titan/Enceladus Flagship and planetary exploration missions.
Simulated Titan Trio during the Titan Saturn System Mission (TSSM) (Image courtesy of NASA)

These missions, as well as Mars Sample Return using Hall thrusters and PPU’s, will require advances in Rad Hard power electronics and systems beyond the present state-of-the-art.

Improvements must be made in energy density, speed, efficiency and wide-temperature operation (125 °C to over 450 °C) with a number of thermal cycles. The need to minimize the weight of PPU’s is needed as well as advancements in power electronics, in programs with power, ranges from a few watts for minimum missions to 20 kW for large missions. In addition to electrical component development, RPS needs intelligent, fault tolerant Power Management and Distribution (PMAD) technologies to efficiently manage the system power for these deep space missions.

Technologies of interest are:

- High voltage, Rad Hard, high temperature components
- High power density/high efficiency power electronics and associated drivers for switching elements
- Lightweight, highly conductive power cables and/or cables integrated with vehicle structures
- Advanced electronic packaging for thermal control and electromagnetic shielding; integrated
packaging technology for modularity.

Challenging to say the least.

**Energy Storage**

_Energy Storage^5,6_

Future science missions will need advanced primary and secondary battery systems capable of operating at temperatures ranging from -100 °C for Titan missions to 400 to 500 °C for Venus missions, and a span of -230 °C to +120 °C for Lunar Quest. The Outer Planet Assessment Group and the 2011 PSD Relevant Technologies Document have called out for high energy density storage systems for Titan/Enceladus Flagship and planetary exploration missions. In addition, high energy-density rechargeable electrochemical battery systems that can provide more than 50,000 charge/discharge cycles (10 year operating life) for low-earth-orbiting spacecraft, 20 year life for geosynchronous (GEO) spacecraft, are needed. Advances in battery technology energy storage capabilities with high specific energy and density (>200 Wh/kg for secondary battery systems) plus radiation tolerance is needed.

**Specific NASA program needs and challenges**

The biggest challenge is to enable the stay of human presence in space. One of the key enabling technologies is high efficiency power conversion and high specific energy power systems and components. This is needed to maintain life for an extended period of time outside of the near-earth environment.

I will use the Space Station power system as an example here.

**NASA Electric Power System (EPS) on the International Space Station (ISS)**

One of the most complex Power Systems that NASA has is the EPS on the ISS. It provides all of the power which is critical for continuous, reliable operation of the Space Station.
The EPS is composed of hardware components called Orbital Replacement Units (ORU). Each ORU is a replaceable subsystem and can be replaced via robotics or Extra-Vehicular Activity (EVA)—a Spacewalk as we know it.

The ORUs, when connected together as a system, provide power generation, power distribution and energy storage for the ISS.
Solar energy is collected by the solar arrays and roughly conditioned by the Sequential Shunt Unit (SSU), tightly regulated by the Direct Current (DC) to DC Converter Unit (DDCU), and stored in the batteries. See Figure 9 which shows the Integrated Equipment Assembly (IEA) which consists of the EPS plus the Solar Arrays.

**Figure 9: Power System block diagram of the Integrated Equipment Assembly (IEA) (Image courtesy of Reference)**

**DDCU**

The DDCU regulates the widely varying voltage from the arrays (115 to 173 V) to a constant 124.5 +/-1.5V. The load can vary from less than 1 A to more than 50 A with 80 A being an overload condition. The output is short circuit proof. The DDCU communicates via a Mil-Std-1553-type bus on which all modules in the power system share their status. The input and output current and voltages are internally monitored and reported over the bus.
The DDCU will turn off when the input voltage exceeds the 173 V maximum, if the output current exceeds the 52 A maximum set to 125% or 150%, or if the input current exceeds a pre-defined safe limit.

Efficiency was critical here since in orbit, there is a limited amount of power available from the arrays and batteries. Waste heat is a major consideration as well. Heat is rejected through an ammonia-cooled baseplate and radiator system facing deep space. An estimated 5% efficiency decrease in the DDCU design would have increased the cooling system weight by 100 lb. on one IEA. Weight, size and power efficiency are critical parameters in space.
This is why a flyback-current-fed push-pull (Weinberg) topology was chosen. The advantages of this topology are high power conversion ratio (efficiency), continuous conduction to the output node, lack of flux imbalance in the power transformer, and no possibility of damaging the switching elements due to switching overlap.

One shortcoming is that the power switching elements have to be rated at a higher voltage than those of other circuit types. The minimum voltage impressed upon the switching elements is 2X the input voltage due to the push-pull configuration of the power transformer. Added to this is the voltage spike generated each switching cycle by the flyback inductor. The combined leakage inductance of both magnetic units provides another voltage overshoot that further increases the instantaneous voltage seen by the switching elements.

The power switching element was chosen to enhance efficiency. High-current bipolar devices require a great deal of base –drive power, which lowers efficiency unless regenerative drives are used. High-gain bipolar devices, such as Darlington, have a high saturation voltage drop. IGBTs have a similar problem with conduction losses. Thyristors are not noted for radiation hardness and are also subject to noise/rate triggering as well as junction voltage drop losses.
Power FETs were the optimum choice for this application due to their potential for radiation hardness and very low “ON” resistance. At design time, FETs that were capable of the required power (low Rds ON) were not available. So the development of a new type of power FET that could switch 100 A, rated at 500 V minimum was started. After a lengthy design cycle, the FET was developed.

(Of course, this was in 2002 and we have come a very long way with GaN, SiC and Si MOSFET technologies at present. Improved power element technologies will greatly enhance future space flight missions.)

Many more details of this design can be found in Reference 7.

Battery ORU

Battery ORU
Batteries are critical on the Space Station. The ISS must use stored solar energy to power the spacecraft during its eclipse mode. The Battery Charge Discharge Unit (BCDU) will charge the batteries using the energy from the solar arrays during insolation (when accessing direct sunlight) and must draw energy from the batteries during eclipse to provide ISS power. The batteries are designed to last 10 years in space. Due to the ISS orbit, there are a total of 16 battery charge/discharge cycles in a day. This is very harsh on the life of the battery.

For the future, in 2017, Lithium Ion batteries will replace the existing nickel-hydrogen cells since they have higher specific energy than the present batteries. One Lithium Ion battery will be replacing two nickel-hydrogen cells with a weight savings of 299 lbs.

Conclusion
In order to effectively explore our solar system and beyond with manned and unmanned vehicles, the bar is raised for requirements of power efficiency, low weight and small size, as well as new and innovative Power electronics architectures, components, materials and heat removal techniques. Radiation hardness and extreme temperatures await us as we venture beyond the Earth and the moon.

Power storage technology must reach the next level of increased specific energy and smaller size and weight. New and innovative propulsion systems must be discovered with creative electronic controls. It’s an exciting time to be an EE and we will all be amazed at the creativity of man to reach for the outer limits of space to see what’s out there and how we came to be.

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