Future Concepts for Modular, Intelligent Aerospace Power Systems

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NASA's recent commitment to Human and Robotic Space Exploration obviates the need for more affordable and sustainable systems and missions. Increased use of modularity and on-board intelligent technologies will enable these lofty goals. To support this new paradigm, an advanced technology program to develop modular, intelligent power management and distribution (PMAD) system technologies is presented. The many benefits to developing and including modular functionality in electrical power components and systems are shown to include lower costs and lower mass for highly reliable systems. The details of several modular technologies being developed by NASA are presented, broken down into hierarchical levels. Modularity at the device level, including the use of power electronic building blocks, is shown to provide benefits in lowering the development time and costs of new power electronic components. At the functional component level, modularity decreases costs and mass while increasing fault tolerance and reliability. The concept of "true modularity" is introduced describing the need for distributed, master-less solutions in developing modular power components. Ultimately, the development of system-level modular technologies can result in highly reconfigurable and interoperable systems that are able to seamlessly share resources and burdens. To achieve the modular visions presented, digital control and peer-to-peer communications are required. These modern capabilities applied to power electronics will finally enable the on-board autonomy and health management required for reliable electrical power systems operating far from Earth for long periods of time. Summary results from recent development efforts are presented along with expected future technology development needs required to support NASA's new Human and Robotic Space Exploration Initiative.

I. Introduction

NASA's new Space Exploration Initiative unveiled by President George W. Bush on January 14, 2004 marks a turning-point in the Agency. The President clearly laid a path for NASA to follow in reinvigorating manned and robotic space exploration beyond low-Earth orbit – namely back to the Moon and eventually on to Mars. This ambitious program is much different than other large programs that NASA has pursued in the past – namely, that these goals be achieved *affordably* and be *sustained* over long periods of time.

One of the most critical systems in any space vehicle or surface asset is the electrical power system. Almost every critical subsystem relies on a reliable source of electricity to function. However, the electrical power system is really made up of three primary subsystems – energy generation, energy storage, and power distribution. Energy generation and energy storage work hand-in-hand to provide the critical source of electricity, but simply generating the electricity will not ensure that it is delivered to the subsystems and loads that require it. The power management and distribution (PMAD) subsystem is critical to ensure reliable delivery of power from the sources to the loads. Without a reliable system to control, condition, and distribute the electricity, all power generation and storage capability would go for naught.

The primary functions of a PMAD system are to control, condition, and distribute electrical power safely and reliably. Since the PMAD system is really the "interface" between the power sources and the power users, the design of the PMAD subsystem is often highly dependent on the sources and the loads chosen for the specific vehicle or mission. In the past, this has led to "point designs" for PMAD systems where the system is designed

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specifically for a single applications. However, it is believed that the use of point designs will hamper NASA from delivering an *affordable* and *sustainable* exploration program.

What is needed instead is the ability to re-use PMAD components in many applications, and systems that can be built by connecting common, "building block" modules together in various ways. Whether those "building blocks" are common switches, modular converters, modular switches, or even complete modular systems – it is clear that a more modular and intelligent PMAD system is necessary to achieve an affordable exploration program.

II. Definition and Benefits of Modularity

Modularity is defined as something being designed with standardized units or interfaces for easy assembly and repair or flexible arrangement and use. Much as modular furniture can be stacked and arranged in numerous configurations to meet the specific needs for several different applications, technologies that enable similar flexibility and commonality would be an enormous benefit to achieving NASA's exploration goals, especially in electrical power systems.

Some level of modularity does exist in the power electronics industry today, but much of the functionality provided is not ideal for use in critical space applications. Current modular technology relies on centralized controllers or master-slave configurations which can be susceptible to single-point failures. While these technologies may be sufficient for terrestrial applications, aerospace applications require a higher level of fault tolerance.

A more ideal modular power component would have the ability to operate independently or in collaboration with electrically connected neighbors without relying on a central or master controller. A distributed, master-less design would provide the fault tolerance needed by NASA missions. The modular collaboration would take the form of parallel or series connections in order to process higher currents or voltages than one module is designed to handle. Functionality would include the ability to share current or voltage, coordinate switching cycles to improve power quality, maximize efficiency, and be able to ride through failures of one or more modules.

A. Benefits of Modularity

Modularity in electrical components and/or systems offers many benefits to aerospace power systems, especially those that are large, complex, and long-lived. The first benefit that modularity offers is increased power system reliability at minimum mass penalty. In many critical space applications, power system reliability is achieved by adding redundant hardware. For example, a life support sub-system requires power conversion. In order to mitigate the failure of a converter, an additional converter is flown. If the power converter is designed exclusively for the life support system, then the mass penalty is 100%, meaning that twice the electrical hardware is flown than is necessary for nominal operation. If, however, the power converter was a modular design and nominal operation required 2 converters to operate the life support system, then one additional converter added to achieve redundancy would only result in a mass penalty of 50%. As the chart shows in Figure 1, as the level of modularity is driven higher, the mass penalty for adding a redundant unit in lowered considerably - even accounting for a "modular mass penalty" which is how much additional mass is required to make a converter modular. Interestingly enough, the graph displays a point of diminishing returns around an N of 3 to 4 meaning that very high levels of modularity are not required to achieve these mass savings.

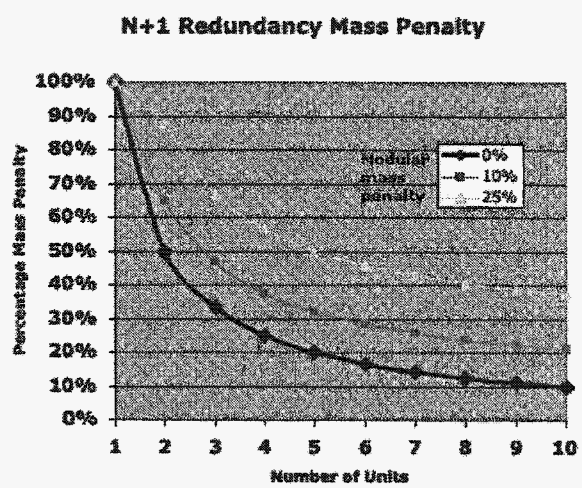

Figure 1. Mass penalty for redundancy decreases as the number of modular units increases, even if modular units have significant mass penalty.

Another expected benefit of increased modularity in electrical power components and systems is that of lower total cost. Total cost is defined as the sum of non-recurring costs (design, development, etc.) and recurring costs (parts, assembly, verification testing, etc.) for an entire system.

$$Cost_{total} = \$NR * N_{unique} + \$R * N_{total} \quad (1)$$

If a spacecraft is comprised of 100 power electronic boxes (N_{total}), a traditional system design may result in 20 unique hardware boxes (N_{unique}) and require 5 copies of each. A system that makes use of component modularity in order to reuse identical components in more than one application may have a balance more like 5 unique boxes with 20 copies of each. To calculate the total cost, one must know the non-recurring costs ($NR), and the recurring costs ($R). The number of unique boxes is used to determine the total non-recurring costs since each unique box requires design, development, and verification costs. The total number of boxes determines the total non-recurring costs.

In this example, the number of total boxes, N_{total}, is a constant as is $R, so it is clear that the total cost can be reduced if the number of unique boxes, N_{unique}, is lowered.

The graphs in Figure 2 show the trending of this cost improvement. The cost savings depend on two factors: the ratio of costs between non-recurring costs and recurring costs, and the ratio of unique boxes between a modular system and a traditional system. In the graph shown in Figure 2a, it is assumed that $NR > $R. As the costs differences increase, the cost benefits increase. Similarly, Figure 2b shows that when less unique hardware has to be developed, cost benefits increase. Just like in the reliability benefit described above, the benefits are realized quickly with costs savings tapering off as the ratios increase.

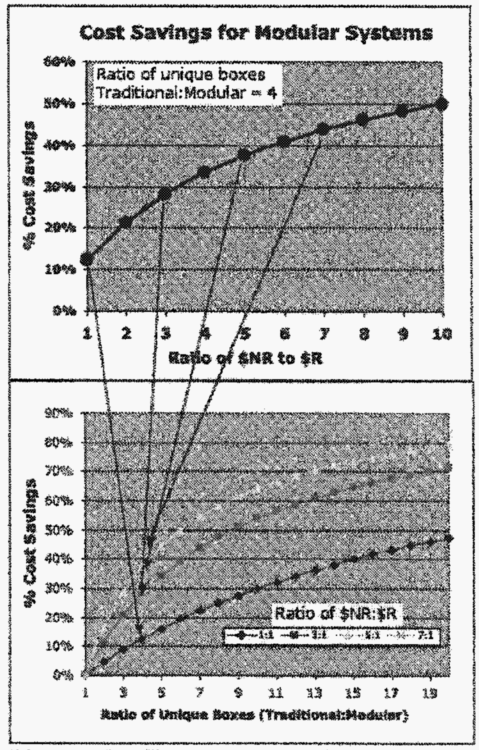

Figure 2. Cost savings for modular components depends on non-recurring costs and the number of unique boxes.

Other benefits that can be accrued from modular systems include increased performance in both efficiency and power quality. It has been shown that paralleled power converters that coordinate and stagger their switching cycles improve power quality greatly [1]. The phase stagger switching results in both reduced ripple amplitude and increased ripple frequency, which means that power quality filters can be smaller. Additionally, shutting down paralleled modules when the load is reduced can maximize power converter efficiency. This forces the remaining modules to operate at higher power levels closer to their peak operating efficiency [2]. This type of group efficiency optimization is not possible with monolithic converters.

Finally, the truly modular technologies described in this paper really require much higher levels of awareness and control than can be achieved with pure analog circuitry. Much of the work described below has been made possible using high-speed digital controllers and communication networks. Once these capabilities are prevalent in an electrical power system, even more functional benefits can be realized such as active stability control, health management, distributed topologies, and automated fault recovery.

B. Disadvantages to Modularity

There are obviously some disadvantages to modular components and systems that would make their use in all applications ill advised. First, modular designs are non-optimal by definition. If a component or system is designed to meet the needs of more than one application, there is no way it can be an optimal design for each. For example, modular components will result in slightly larger and heavier solutions due to increased packaging needs, over specified components, and uneven module sizes. However, these disadvantages will be outweighed by the redundancy mass benefits as described above when designing for very high reliability and fault tolerance.

Another expected disadvantage is that of slightly higher costs, especially non-recurring costs. The design of a module for more than one mission/application is expected to require additional development costs. Again, this disadvantage is expected to be more than offset by the cost savings described above.

III. Modular Electrical Power Systems

The power management and distribution (PMAD) system can be modularized at three distinct levels: 1) power electronic building blocks (PEBBs), 2) modular converters and switchgear, and 3) modular systems. Each of these levels are believed to be independent of the others, meaning that modular converters do not depend on PEBBs, and modular systems do not require that modular converters or switchgear be developed first. These modular PMAD technologies can be worked at any one of these levels depending on the technology development maturity, the expected benefits, or the specific needs of the exploration systems.

C. Power Electronic Building Blocks (PEBBs)

Power electronic switches are the most common building blocks in any PMAD system because all regulators, converters, motor drives, protective switches, etc. can be built using them. Power electronic building blocks (PEBBs) would be common power electronic switches, or perhaps half-bridges as shown in Figure 3, integrated with all the supporting circuitry they require for operation – isolation, drivers, and sensors [4]. With the addition of a flexible digital controller and passive devices, new PMAD functional elements can be developed very quickly, thereby lowering design and development costs. Controllers built into the PEBB would ensure that the switches would not fail due to incorrect control, such as controlling safe operating area and providing shoot-through protection. PEBB interface standards would accelerate adoption and would include mechanical packaging, thermal, power, and data. Aside from lowering development costs, if all PMAD elements are constructed using common PEBBs, then the need for large numbers of "spares" necessary for long duration space missions is greatly reduced.

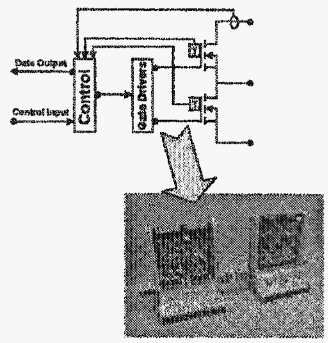

Figure 3. Power Electronic Building Block Concept

D. Modular Converters and Switchgear

At the next level are the modular converters and switchgear elements that make up a PMAD system. The idea here is to build common elements that can be connected in series and parallel combinations in order to meet the needs of several applications. These modules would follow defined interface standards including mechanical, thermal, electrical, and data interfaces. As shown in Figure 4, one common DC-DC converter module, with the appropriate interfaces, can be connected in parallel (input and output) to service higher current loads. Similarly, the converter outputs can be connected in series in order to service higher voltage loads. These are simple techniques that have been used frequently in the past.

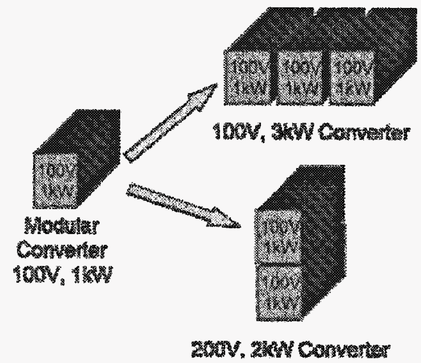

Figure 4. Modular Converter Building Block Concept.

However, one configuration that has been rarely used is to connect converter or switch inputs in series, thereby dividing input voltage. Technologies exist that allow converters to be connected in series to service distribution voltages *exceeding* their individual part ratings.[5] Developing such a DC-DC converter that could function as a building block module in any series or parallel combinations could greatly reduce the number of unique converters required across all space exploration missions.

As discussed earlier, this modular approach increases reliability as N+1 redundancy can be used without large system mass penalties, and the number of unique hardware to be developed is reduced, thereby making systems more affordable.

While some amount of modularity exists in the power electronics industry today, all solutions rely on a central controller in order to coordinate the operation between the interconnected modules. What is needed for a truly modular solution is to develop the ability of modules to function independently while also being able to coordinate with their interconnected neighbor in a "master-less" collaboration. Such a capability has been demonstrated in the system shown in Figure 5.[2] This distributed, coordinated control can only be achieved using digital control and a local communication capability.

Once digital control exists in the modular converters and switchgear, additional capabilities that improve upon the system performance, reliability, and safety can be implemented. These include active stability control, hidden fault detection (arcing and leakage faults), and component health monitoring.

Active stability control is the ability of a PMAD element to adjust its control in response to internal or external changes so that local and system instabilities can be avoided.[3] Hidden faults such as arcing faults and leakage faults pose dangers to mission success and human occupants and are currently uncovered in today's PMAD systems. The data processing and communications capability inherent in modular, digitally controlled power components enable the detection of these uncovered faults.[6]

Health management first requires advanced detection algorithms to determine the "health" of power electronics. Once that is determined, the health of the system can be managed by controlling what assets are brought to bear in delivering electrical power. Modules and power sources that are "less healthy" than others can be rested in the hope of extending their operating life and, by extension, increasing the probability of mission success. Finally, pervasive digital control and communication networks enable new distribution system topologies that offer higher levels of reconfiguration, fault tolerance, and reliability.

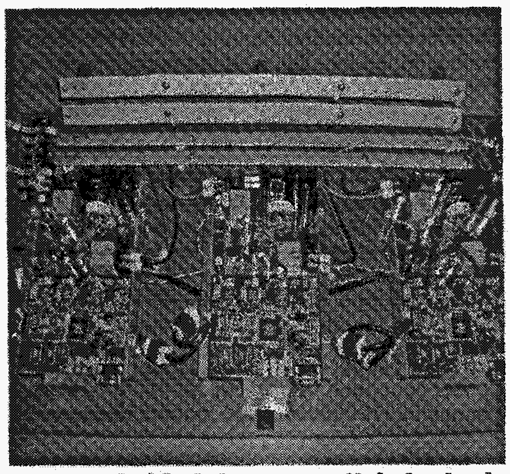

Figure 5. Modular, paralleled dc-dc converters with distributed, master-less digital control and phase stagger operation.

E. Modular Power Systems

Ultimately, the PMAD system can be modularized at the system level by breaking the entire power system into smaller sub-systems – much as the International Space Station does today. However, these modular systems for long duration exploration missions will have to be more collaborative than the ISS "channelized" approach. They must be able to readily share power resource (sources) and power burdens (loads), and they must be able to collaborate across dissimilar vehicles and platforms. For instance, it would be very desirable if the power system of the Crew Exploration Vehicle (CEV) could collaborate with the power system of the lunar lander, and the lunar lander power system collaborate with a lunar habitat module.

An example of such a modular power system is that of the multi-ring bus distribution system shown in Figure 6. This system is comprised of 3 ring bus subsystems, each with their own energy generation, storage, distribution, and control. Each ring is able to crosstie and parallel with the other rings by coordinating the control of each ring bus. Power system collaboration across vehicles and systems can also be achieved. This technology also would allow for integrating the power distribution system into the space vehicle structure – thereby saving mass. Finally, because all three rings are distributed throughout the space vehicle, it is very easy to take high priority and critical loads and connect them to multiple power subsystems – thereby further increasing the reliability of the electrical power system.

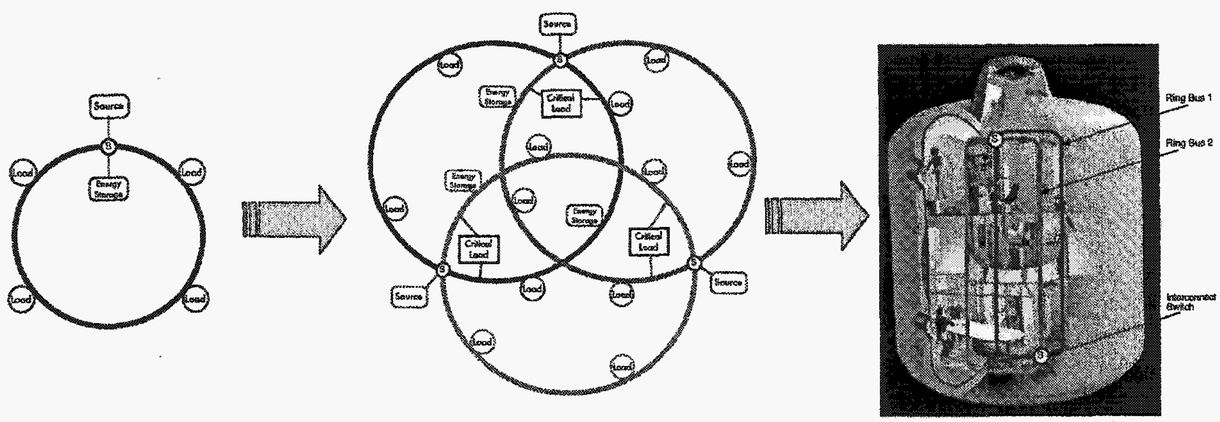

Figure 6. A modular power system concept for space exploration using a unique ring-bus distribution

IV. Intelligent Power Systems

Finally, it is desirable to develop technologies that enable autonomous operation of the electrical power system. Higher levels of autonomy are crucial in achieving the affordable and sustainable space exploration that NASA has been tasked to undertake. Without autonomy, the large, complex power systems required for exploration will require unprecedented levels of ground support equipment and personnel – both of which will require significant funds over the entire life of the missions and space exploration initiative. In addition to autonomy, infusing the electrical power system with digital control and communications will also enable health management of the power system. Similar to the development of modular technologies, these autonomy and health management benefits can also be realized at different hierarchical levels throughout the power system.

A. Device Intelligence

First, it must be recognized that processing power and communication bandwidth at the various power system hierarchical levels will limit and determine what functions can be performed at what level. The diagram shown in Figure 7 shows how this hierarchy could breakout at the various levels.

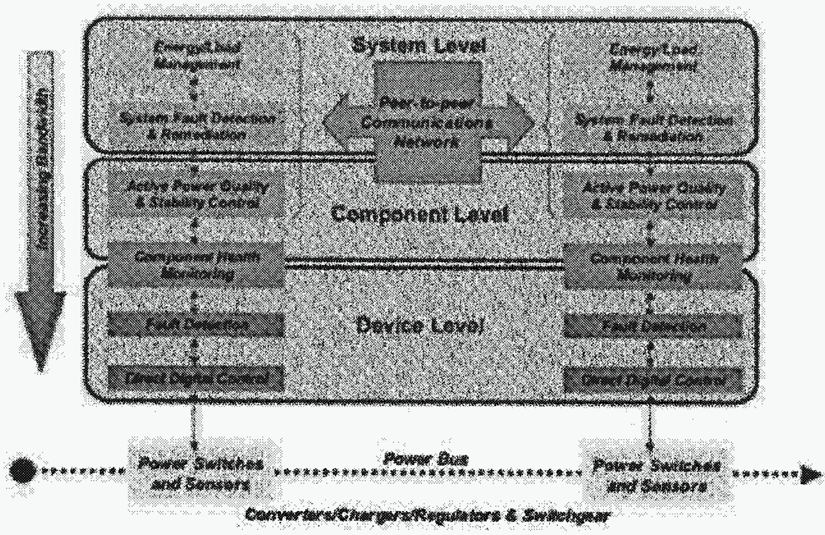

Figure 7. PMAD system intelligence diagram showing functional hierarchy based on bandwidth requirements.

At the lowest levels, direct digital control of the power switches and sensors requires the highest bandwidth and processing speed in order to deal with the sub-millisecond events and provide the control performance expected from power electronics. Directly above that level would reside the fault detection and device health monitoring functions that could be implemented within a device without relying on external data and communications. An example of this low-level, localized control would include the intelligence that could be found in PEBB devices.

A PEBB device would be expected to have dedicated, high-speed digital and analog controllers in order to gather sensor data and make control decisions within several microseconds. Such control would include safe-operating area protections to ensure that the switch did not experience over stressed conditions that threaten its health and continued operation. These include detectable and controllable events such as over-current protection, single event upset (SEU) protection, and thermal overload protection. Additionally, the PEBB controller would be expected to have the bandwidth necessary to capture and record short-term "stress events" as they occur, and provide a count or record of these events to a higher-level controller in response to queries dealing with health monitoring. These events would be more detectable, but not necessarily controllable such as over-voltage spikes that can occur in inductive systems.

B. Component Intelligence

At the next hierarchical level of intelligence is that of the power electronic component module such as dc-dc converters, regulators, and switchgear. At this level, intelligence can be included to provide optimized, non-linear digital control of the component. Health monitoring and management algorithms can also be implemented to estimate the "health" of the power electronics. Additionally, advanced fault detection capabilities requiring digital signal processing and analysis can be implemented in distribution switchgear at this level. "Soft" faults such as arcing and corona faults can be detected much more effectively using digital controllers and advanced detection algorithms. [6]

Additional features such as active power quality and stability control can be included that only digital controllers can provide. Active stability control is a technique where the component can vary its control loop as changes in the "plant" occur over time or changes in the system configuration begin to cause control loop interactions. The active stability control algorithms would have the capability to detect these changes and vary the operating control loop in order to prevent large system oscillations from occurring. [5]

Active power quality describes a component's ability to coordinate and stagger its switching phase with collaborative neighbors in order to reduce current and voltage ripple. This capability requires the first requirement for direct, peer-to-peer communications between collaborative neighbors that is necessary to realize many of the intelligent system benefits.

This communications capability is itself hierarchical with the highest-speed communications necessary at this component, or "local" level, and lower-speed communication networks being implemented at the higher system level. Examples of this localized communications would include high-bandwidth, low latency serial interfaces such as custom serial interfaces or commercial interfaces such as CAN-bus. Once this localized communication capability exists, other collaborative functions such as efficiency optimization and health management of the collective modules can be performed. As mentioned earlier, the difficulty will be in providing this functionality in a distributed, master-less fashion.

C. System Intelligence

Finally, intelligence can be applied at the system level to bring the benefits of autonomy and health management to the electrical power system. At the system level, intelligence depends largely on communication networks gathering data from all over the power system in order to analyze and inference system status. The bandwidth of data collection can be much slower than at the component and device level, since the events that affect the entire power system can and should be detected and acted upon at a much slower speed so as not to interfere and interact with the higher speed control taking place at the lower levels. Functionality that can be achieved at the system level includes automated fault detection and recovery, energy management, and system health monitoring.

Automated fault detection and recovery requires the development of data gathering and computing algorithms to detect the presence of faults and autonomously determine the optimal actions to take to mitigate the fault. Faults can take the form of "hard faults" such as source failures, distribution switch failures, or load converter failures. Failures can also include "soft", or hidden faults such as arcing faults, corona discharge, shunt (leakage) faults, series (resistive) faults, and general component degradation. These hidden faults are not readily detected and really require the presence of system intelligence for detection.

Once a hard or soft fault has been identified and isolated at the local level, it would be desirable to have the power system autonomously reconfigure the system topology in order to mitigate the fault. This automation function must be performed at the system level since the algorithms must have knowledge of the entire power system in order to make the optimal decisions. Of course this automation technology is only useful if a power system topology is used that enables some level of reconfiguration, such as the multi-ring system shown earlier in Figure 6.

Energy and health management is the ability of a system to manage the power flow and stress levels on power sub-systems in order to balance energy sources, storage, and loads in relation to the health of the system. For example, if one solar array in a multi-channel power system has experienced higher levels of degradation than others, it would be desirable to have the system manage the energy balance between the sources so that they are supplying unequal amounts of power based on their "health". An ability to do this autonomously and actively could greatly increase the reliability and expected life of an electric power system

V. Conclusion

Concepts of modular and intelligent electrical power systems have been presented. It is believed that many of the technologies discussed above will be required in order for NASA to achieve the **affordable** and **sustainable** Space Exploration Initiative enumerated by President Bush in January 2004. Many of the technologies discussed have been demonstrated and/or are under development at the NASA Glenn Research Center in Cleveland, Ohio. However, more work is surely needed in order to mature the technologies and foster NASA program and aerospace contractor buy-in in order to ensure that these technologies are ready when most required by future NASA programs.

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References

[1] Button, R., Kascak, P., Lebron, R., "Digital Control Technologies for Modular DC-DC Converters", IEEE Aerospace 2000, Big Sky, MT, March 2000.

[2] Gray, M., Gao, Z., Button, R., "Distributed, Master-less Control of Modular DC-DC Converters", 2nd International Energy Conversion Engineering Conference, Providence, RI, August 15-19, 2004.

[3] Zane, R., Miao, B., Maksimovic, D., "Active System Identification of a DC-DC Converter Using Digital Control", 2nd International Energy Conversion Engineering Conference, Providence, RI, August 15-19, 2004.

[4] "Power Electronics Building Blocks (PEBBs)," Project Report by Virginia Power Electronics Center, April 1996.

[5] A. Bhinge, N. Mohan, R. Giri, R. Ayyanar, "Series-parallel connection of DC-DC converter modules with active sharing of input voltage and load current," in Proc. IEEE Applied Power Electronics Conf. (APEC'02) 2002, vol. 2, pp. 648 -653.

[6] Gonzalez, M., Button, R., "Detection of High Impedance Arcing Faults in Radial Distribution DC Systems", 1st International Energy Conversion Engineering Conference, Norfolk, VA, August 2003