An Autonomous Power Controller for the NASA Human Deep Space Gateway

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Autonomous control of a spacecraft is an enabling technology that must be developed for deep space human exploration. NASA's current long term human space platform, the International Space Station which is in Low Earth Orbit, is in almost continuous communication with ground based mission control. This allows near real-time control of all the vehicle core systems, including power, to be controlled by the ground. As the focus shifts from Low Earth Orbit, communication time-lag and bandwidth limitations beyond geosynchronous orbit does not permit this type of ground based operation. This paper presents the ongoing work at NASA to develop an architecture for autonomous power control system and a vehicle manager which monitors, coordinates, and delegates all the onboard subsystems to enable autonomous control of the complete spacecraft.

I. Introduction

NASA is continuing to explore deep space exploration, "Expanding human presence into the solar system and to the surface of Mars to advance exploration…"[1] It is therefore necessary to develop new technologies to solve the challenges associated with deep space exploration. One of these enabling technologies is spacecraft automation, including the automation of core spacecraft subsystems, e.g. power, communications, thermal, avionics, propulsion, etc. The focus on automating these core subsystems stems from current human exploration operations taking place aboard the International Space Station (ISS) in Low Earth Orbit (LEO). Communications with vehicles in LEO are nearly instantaneous (taking into account that they use the Tracking and Data Relay Satellite network in geosynchronous orbit). The ability to communicate with vehicles in LEO, enables most of the core systems to be operated from the ground or with a great deal of real-time ground intervention. As human space exploration pushes further out, especially beyond cislunar space, the communication time increases. A mission to Mars, or one of its natural satellites Demos and Phobos, involves a total travel time of 6 to 9 months and communication latency times that can vary anywhere from 6 to 44 minutes[2] roundtrip.

Due to the longer communication times associated with deep space exploration, the ground-based mission control center will no longer have the ability to assist the astronauts in real-time to diagnose and correct problems with the spacecraft.[2] It is anticipated that the astronauts that support these missions will not be experts in the respective subsystems required to operate the spacecraft. Consequently, each of the vehicle core subsystems will contain built in intelligence to permit autonomous operation for both normal and contingency operations which includes fault diagnosis and corrective actions.

This paper will describe the most recent ongoing development of an autonomous controller for electrical power systems that can be used for a deep space exploration spacecraft. This extends previous work on developing an autonomous power control[3] which includes developing a control architecture for deep space vehicles,[4,5] the use of software agents,[6] and constructing a control simulation lab for demonstrating this capability.[7] This paper will begin with a discussion of the representative future power architectures that will be required for deep space exploration vehicles. It will describe spacecraft control architecture and how the power controller will integrate with the vehicle, followed with a discussion of the autonomous power controller. Next it will describe the test setup used to evaluate the performance of the controller, and finally show some of the test results. To develop the type of controller

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envisioned, it will be necessary to employ a detailed real-time simulation to evaluate its performance and ultimately verify its functionality. The strategy to develop this type of simulation is outlined.

II. Power System Architecture

Studies have been conducted to develop a notional power architecture for a prospective Deep Space Vehicle, shown in Figure 1, which would require an autonomous control system to operate it.[4] This system consists of a Power Module and a Habitation Module. The power module is characterized by two independent power channels with multi-level cross strapping. The arrays and batteries are sized to allow fly potential Design Reference Missions[8] that requires operation in other orbits with an eclipse. Each power channel operates at 120V, is compatible with SAE spec AS5698,[9] and has a solar array regulator to provide conditioned power to the main bus switching unit (MBSU). From the MBSU, the power is used to charge the battery during insolation (through the battery charge/discharge unit, BCDU), or is distributed to the power distribution units (PDUs), which feed power to the user loads. For redundancy and reliability considerations, the MBSUs can be cross-strapped and each PDU can be fed from either power channel. Finally, the MBSU can also feed bi-directional converters that can supply or draw power from the three Habitat Module docking ports.

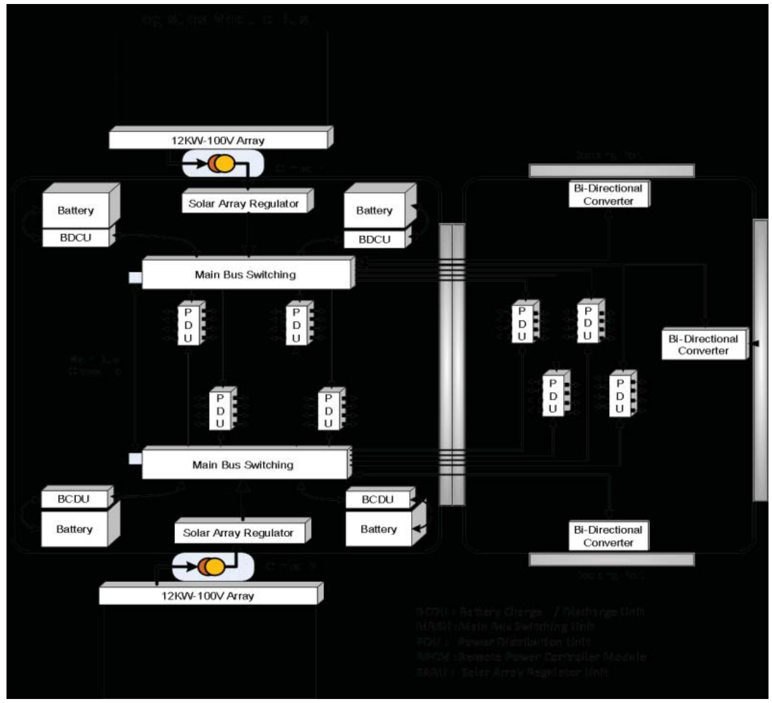

Figure 1. Notional Deep Space Gateway Vehicle Power Architecture

III. Spacecraft Control

A simplified version of the current spacecraft control architecture is shown in Figure 2. With this control architecture, mission operations receives the telemetry from the spacecraft, which includes the status of each critical subsystem and operating data, and sends commands to the vehicle. Ground-based mission operations personnel have the ability to interpret the vehicle status, make critical decisions based on previous experience and mission objectives, and can alter the vehicle commands, including the power profile, reactive layer controller set points, and enable or disable loads to meet current and future mission objectives. Another critical role of the ground controller is to respond to faults and develop recovery plans to restore the system to a fully operational state. Any hard faults, e.g. line short, overvoltage, etc., will be detected and mitigated by the electrical power system components (reactive layer). However, mission operations will have to develop a plan to restore power to any loads that have been impacted by the fault. Mission operations is also responsible for observing the trends of the system and anticipating future problems, typically associated with system degradation, and take corrective action to eliminate potential (future) faults and/or mitigate system impact.

This type of spacecraft control architecture relying on ground-based mission controls to operate the vehicle is suitable for LEO since communication with the vehicle can be achieved in real-time. As human exploration operations pushes beyond LEO to deep space, the roundtrip communication time increases and cannot support the needs and constraints of these deep space human exploration missions. For these missions, an autonomous spacecraft controller is proposed and shown in Figure 3.

The main functional change with the autonomous space control architecture, shown in Figure 3, is that the planning and execution of the vehicle operations is moved from ground based mission operations to on-board the vehicle. With the autonomous system, mission operations sends high-level, longer term mission objectives and provides oversight for both the vehicle and crew operations. The spacecraft controller becomes a vehicle manager, responsible for managing the vehicle operations and ensuring that the mission objectives are successfully met. To accomplish these tasks, the vehicle manager analyzes and coordinates amongst all the subsystems and manages global (vehicle level) issues between subsystems, crew time, and mission objectives, but does not control the actual subsystems. In addition, the vehicle manager is also responsible for diagnosing faults that manifest themselves across all systems and then take corrective action. This includes the ability for the vehicle manager to make critical decisions until the ground has the opportunity to provide guidance for the vehicle and crew. The vehicle manager is also able to provide recommended actions when a fault occurs and is able to re-plan crew time, system operations, etc. after a fault is detected, but is not responsible for fault identification or immediate corrective action in the actual subsystem.

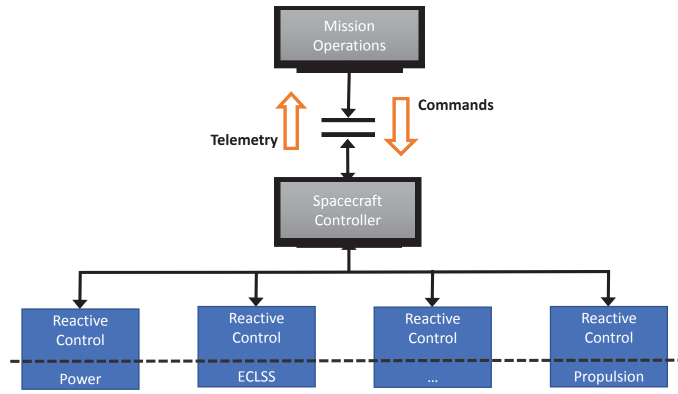

Figure 2. Simplified current spacecraft control / mission operations architecture

The vehicle manager coordinates with the autonomous subsystem controllers, which are responsible for the safe operation of each subsystem and are referred to as the reactive layer that contains the actual hardware components. Each of these autonomous controllers are designed to handle local control problems, such as fault detection and recovery. The subsystems operate on a schedule provided by the vehicle manager, which dictates the roles, responsibilities, and constraints of the subsystems for the remainder of the planning window, which on the ISS is typically for the next 24 hours.

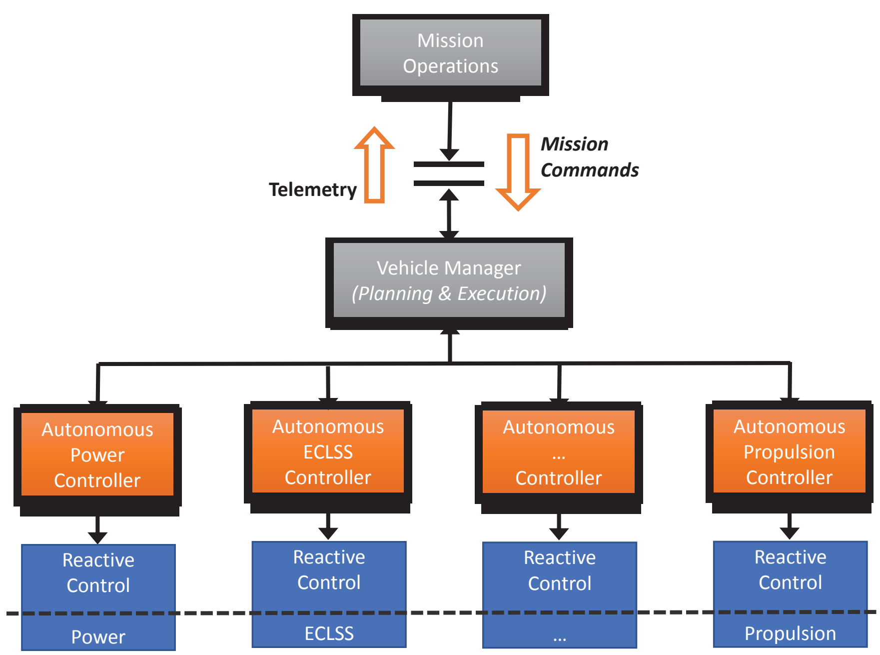

Figure 3. Simplified autonomous spacecraft control architecture

IV. Operation of the Autonomous Power Controller

The autonomous power controller (APC) is responsible for safely operating the power system (reactive layer) and coordinating with the vehicle manger to collectively meet the mission objectives. The APC mainly provides the vehicle manager with an energy availability schedule, the evaluation results from load profiles (schedules) develop and proposed by the vehicle manager, electrical power system fault identification information, and power system configuration. The APC also interfaces with the actual electrical power system, sending commands to the hardware (switches, voltage set points, etc.) and receiving telemetry.

The operational philosophy of the autonomous power Controller is covered by two principles:

1. The reactive control layer will instantaneously contain hard faults and safe the system to minimize damage and large deterioration. Therefore, the reaction time of APC does not have to be instantaneous but could be on a slower (multi-second) response.
2. The autonomous controller will insure that for the long term, the power system is operating safely and services the highest priority loads within power system constraints.

In fulfilling the operating principals stated above the APC will generally operate in one of three states. These operational states were first articulated for terrestrial power system.[10] The main operational states are normal, emergency and restorative. The state diagram that shows the states and their definitions are shown in Figure 4.

A. Normal State

The system is operating nominally with all operating parameters. The APC is providing the energy availability to the vehicle manager and executing vehicle manager's desired and approved operating plan. Assuming there are no failures it could continue in the state indefinitely.

B. Emergency State

Some type of fault or anomaly has occurred in the power system. The reactive control will generally put the system in a temporary safe mode, however, depending on the fault, additional action may need to be taken to reconfigure the system (change feeder lines, shed loads, etc.) so that it can operate in a degraded mode indefinitely. The system is then transitioned to the Restorative State

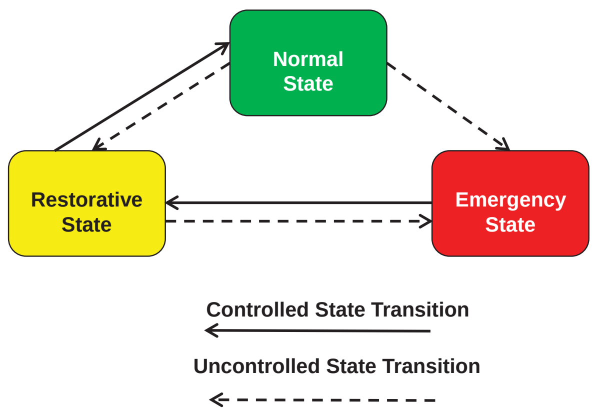

Figure 4 Autonomous Power Controller State Diagram.

C. Restorative State:

In this state the system is in a safe and stable state but in may not be servicing a complete normal load set. In this state, the APC can actually perform the same functions as in the normal state. This state develops and executes a recovery plan to restore the system to a normal state.

D. State Transitions

For the system to get to the emergency state, it requires some type of fault in the power system or the communication system to produce an uncontrolled transition to get into the emergency state. Once in the emergency state, APC can make a controlled transition to the restorative state. In the restorative state a second failure could send you back to the emergency state in an uncontrolled transition. In the restorative state the APC can provide a controlled transition to the normal state, however, if there is an unseen problem with recovery path, the system could transition back to an uncontrolled manner to the restorative state.

By using the operating principles outlined above and moving the control and the power system through the various operational states depending on the health and fault status of the power system it is possible to have an initial instantiation of an autonomous power system controller. The implementation of how this is done is explained in the following section.

V. Functions of Autonomous Power Controller

The implementation of APC can be broken down into a few functions that operate independently of each other and provide information and action to the APC as a whole. These functions, or modules of the APC, include an executioner, reactive layer, fault manager, energy manager, and recovery and restoration planner. Each of the modules operate in concert with each other to implement the operational philosophy above. Descriptions of each of the modules and their associated functions is discussed below.

A. Energy Management

The energy manager is responsible for operating, monitoring, and communicating the capability of the power generation and energy storage system based on external vehicle constraints as well as the system state. These functions include:

- Calculating the battery state of charge (and estimating future state of charge based on the current value)
- Calculating the solar array energy based on vehicle state vector data and projected vehicle path provided by the vehicle manager
- Calculating the power availability timeline for the pre-defined planning window (power profile and total energy availability)
- Evaluating proposed load schedules for potential issues (such as over drawing from the battery or overloading any individual component or feeder line)
- Provide solar array set points for array pointing
- Provide voltage set points for array regulation
- Provide battery charge and discharge set points (to battery charge/discharge unit)

The energy availability communicates the maximum power that is available to the loads as a function of time, the nominal (anticipated) power available to the loads as a function of time, and the total energy available from the source over the planning window. The energy availability becomes constraints for the vehicle manager to schedule power amongst the loads.

B. Maintenance, Mitigation, and Recovery

The maintenance, mitigation, and recovery (MMR) planner is designed to operate when either a fault is detected or a fault can be cleared, through either an internal/external reset signal or power cycle and provides the following functionality:

- Develop a new electrical power system configuration based on current system state (and individual components availability)
- Initiate a request to the energy manager to develop a new power availability based on current system state (fault condition or clearing of fault)
- Develop load shed commands based on load current priorities (which were provided by vehicle manager and are part of the current executed load schedule)

C. Fault Management

The fault manager is responsible for detecting and identifying faults in the electrical power system. The current fault detection strategies that are being investigated and implemented include:

- Check incoming data for current status from hardware due to a trip (overcurrent or overvoltage)
- State estimation to check for noisy or erroneous sensor data
- Communication checks including a heartbeat from each smart component in the system to ensure that the smart component is communicating to the controller.

D. Executive Management (Executioner)

The executioner oversees the operation of the modules within the APC, changes the state of the APC, and communicates information with the vehicle manager. This includes:

- Changing the state of the APC (which may end other processes and calculations)
- Monitor the load schedule and communicate with the vehicle manager if a new load schedule needs to be developed (avoid extending the current load schedule if possible)
- Notify the VM of a fault and provide the updated load schedule with any low priority loads shed

E. Electrical Power System

The reactive layer consists of the actual hardware components and interact with the APC by:

- Implements commands and operates the system based on commands from the APC
- Sends operating power system data (voltages, currents, etc.) and switch status (on, off, trip) to the APC

F. Implementation and Communication

Each of the functional modules outlined above are implemented in a multiprocessor environment shown in Figure 5. As shown in the figure each of the functional modules resides on its own processor and coordinates with the other modules and the APC executioner through a shared database. This database contains tables that act as communication blackboard for the various control modules. Furthermore, the APC sends commands and gathers data from the reactive layer through the database.

G. External System - Vehicle Manager

Operating in concert with the APC, the vehicle manager provides monitors and reports activities across the entire spacecraft as well as coordinating activity between the various subsystems. For the power system the vehicle manager does the following:

- Provide communication (command and telemetry) to ground based mission operation
- Navigation / traffic information for power system to develop power / energy profile
- Displays caution and warning alarms to the operator and/or ground based mission operation
- Develop an integrated load schedule for all of the subsystems and crew based on power availability provided by the APC
- Resolve faults between multiple subsystems

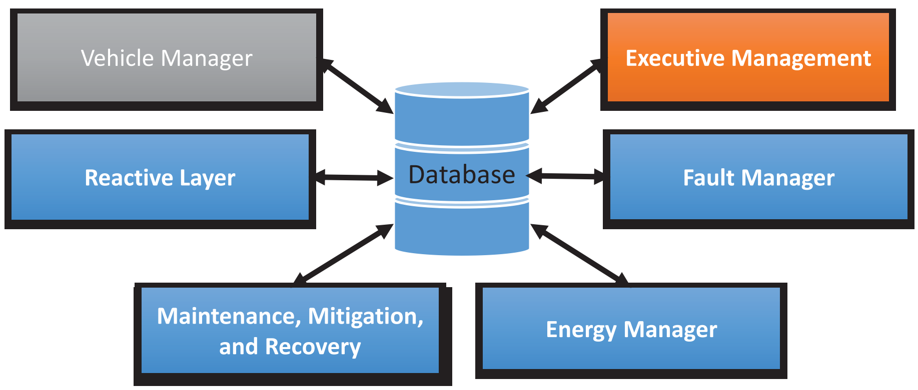

Figure 5. Subsystems (components) of the Autonomous Power Controller.

VI. Demonstration of the Autonomous Power Control Testbed

Current ongoing work at NASA Glenn Research Center in the Power Systems Division includes the design and buildup of a prototype testbed and autonomous power control system (APC). The APC is capable of communicating with these systems at the Glenn Research center and the power hardware at the Johnson Space Center (JSC), as shown in Figure 6. For the first phase of this development effort, a simplified power system has been implemented in the JSC Integrated Power and Avionics Software (iPAS) test bed and a representative prototype has been implemented at GRC. The simplified system, shown in Figure 7, consists of two power strings. Each power string contains a battery and a regulated solar array which are both connected to a main bus switching unit (MBSU) and connects to a power distribution unit (PDU) with eight loads. The PDUs are connected to the loads via remote power controller (RPC). Each PDU is rated for 32 Amps maximum at 120 V (3.84 kW power rating). The MBSU from one string, or channel, is cross tied to the other PDU so that the battery and/or solar array from one channel can actually power the other channel's loads. In total, there are 16 loads that can be powered by this power system.

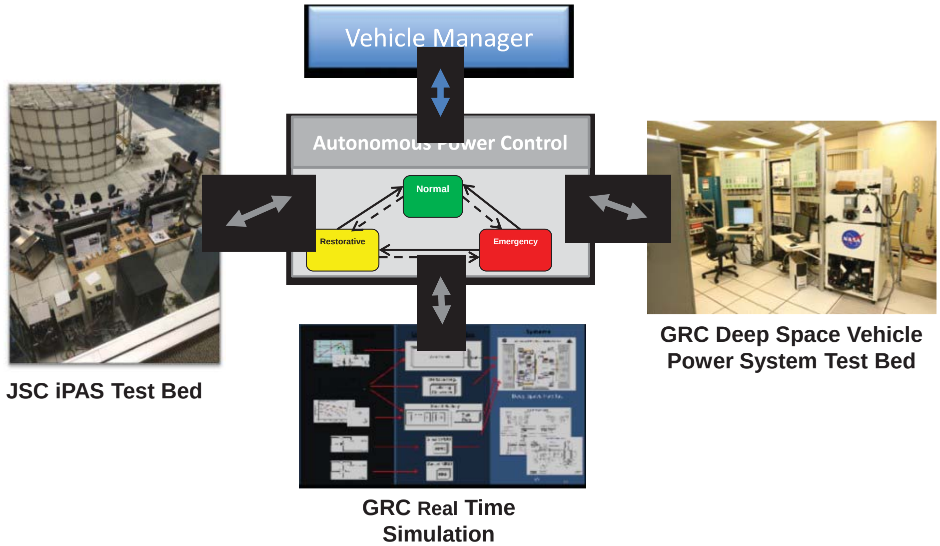

Figure 6 Test and evaluation capability of the autonomous power controller

The APC is currently being developed on five computers with an additional computer to interface with the hardware or, when required, run a MATLAB®/Simulink® (the, Math Works, Inc.) model based on the hardware developed by PC Krause & Associates. In addition, the lab contains the ability to interface with JSC through an internal agency network. For this past year, the team focused on developing the APC system and demonstrating the APC working in the normal mode and the ability to detect and identify faults within the power system. These will be discussed in more detail in the following subsections.

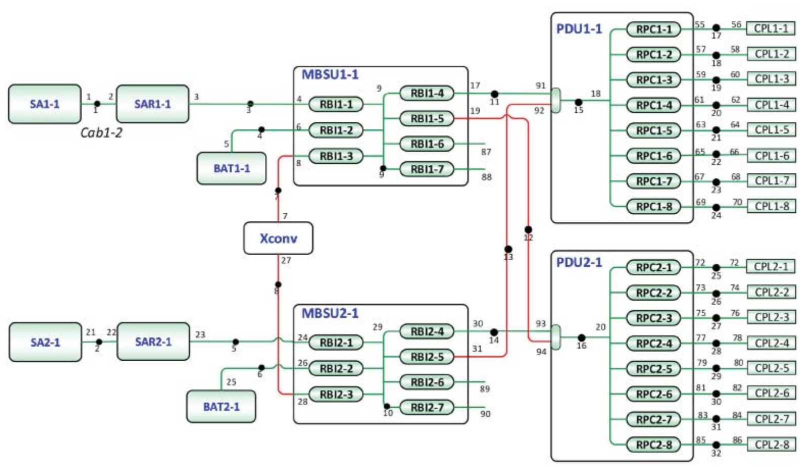

Figure 7 Simplified Deep Space Gateway Power System

A. Nominal Operation (no-fault)

As previously stated, when in the normal state the electrical power system is operating properly (no faults detected) and the main tasks of the APC are to i) respond to requests from the vehicle manager, and ii) monitor the electrical power system for faults. Monitoring of the electrical power system will actually be covered in the next section discussing responding to faults. The two main requests from the vehicle manager is to forecast energy available and to approve/implement a new load schedule.

The energy forecast consists of a power profile and total energy availability over a pre-defined time range or window; for the current work it is assumed to be 2 hours. The peak power and nominal power is defined for the 2 hours in 5 minute increments. The peak power is the maximum power that can be delivered to the loads through the available hardware, e.g. RPCs. Typically the peak power would only be reduced if a PDU or RPC becomes unavailable for some reason. The nominal power is the amount of power that is typically required to be delivered to the loads. This value would be determined during the design of the system and in this scenario is assumed to be 75% to 80% of the peak power. The nominal power values are reduced when there is less power available from the power and energy storage systems, due to a battery or solar array fault, a short from the battery to the MBSU, etc. Depending on the vehicle manager and its capability, the nominal power can also be reduced when the battery is overdrawn to force the loads to reduce their power draw equally over the next planning window. Note that it is possible to have more nominal power available during insolation than eclipse. The energy availability is a single value that is the total energy available for the loads over the planning window and is typically the sum of the nominal power over the planning window. This value could be impacted if the battery state of charge is less than the desired battery state of charge based on the current position of the vehicle in the orbit. The energy manager has a state of charge profile for insolation and eclipse, and if the battery state of charge at the specific instance in time is less than the desired state of charge, then the energy availability is reduced in order to increase the state of charge of the battery to the desired over the next forecast window. The power profile from the APC to the vehicle manager with no faults in the system and the batteries correctly charged is shown in Table 1.

The second request from the vehicle manager is for the APC to accept a new load schedule. Ideally, this would be a two-step (or more) process where the APC would evaluate the load schedule and if deemed acceptable, the APC would implement the schedule. If not acceptable, then the APC would inform the vehicle manager of the constraint violation. For the current work, the vehicle manager always met the objective and did not try to use more power than the APC allowed and therefore the APC did not analyze the proposed load schedule. In this case, the vehicle manager will send a new load schedule and the APC will implement the schedule starting from the time it is received. A load schedule from the vehicle manager for PDU #1 is shown in Table 2. Each load that is powered on for a given time unit is assigned a number corresponding to its priority for the time unit. The priorities range from 1 (highest priority) to 16 (lowest priority). A load given a priority 0 is assumed to be turned off. In the event that a fault occurs and loads have to be shed, the lowest priorities will be turned off until the anticipated power (based on assumed load levels) is less than the nominal power determined by the current configuration and energy availability.

Table 1. Power Profile with an Energy Availability for the 2 hour window of 11.52 kW Hours.

Time (time unit)	Peak Power (kW)	Nominal Power (kw)
1	7.68	5.76
2	7.68	5.76
3	7.68	5.76
4	7.68	5.76
…	…	….
24	7.68	5.76

B. Faulted Operation

To demonstrate the fault mode, the APC will be in the normal state and a fault will be inserted into the system. There are two different types of faults that are tested in the demonstration, non-critical power and critical power system faults. Non-critical power system faults do not impact the distribution of power to the PDUs. These failures include RPC faults, shorts in the line from the RPC to the loads, shorts in the loads, senor faults such as a sensor bias, excessive

Table 2. Load schedule for PDU#1. Each load that is on is numbered from 1 (highest priority) to 16 (lowest priority) and is assigned a 0 if the load is off.

RPC	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Time 23	Time 24
1	7	0	7	0	7	0	7	0
2	1	1	1	1	1	1	1	1
3	0	7	0	7	0	7	0	7
4	2	2	2	2	2	2	2	2
5	9	9	9	9	9	9	9	9
6	11	11	11	11	11	11	11	11
7	6	6	6	6	6	6	6	6
8	0	0	0	0	0	0	0	0

noise, or even signal dropout, etc. Critical power system faults however impact the power distribution system and could impact the availability of power. These faults include battery faults, solar array faults, feeder line faults, etc.

In the case of a non-critical fault, the APC would begin operating in the normal state and a fault is inserted into the system (or model). The APC fault manager detects and identifies the fault (such as RPC 2-7 sensor bias or RPC 1-2 faulted open). The fault manager notifies the APC executioner that a non-critical fault has been detected, the faulted component, and fault type. Since this is a non-critical fault, the APC executioner moves the APC from the normal state to the restorative state and notifies the vehicle manager of the change in state. The system continues operating and can still respond to requests from the vehicle manager, as done in the normal state. Once the fault is removed, the faulted component's reset signal is toggled, the APC executioner notifies the vehicle manger that the fault has been cleared and updates the list of faulted components, the APC executioner then moves the APC from the restorative to normal state.

In the case of a critical fault, the APC will again be operating in the normal state and a fault is inserted into the electrical power system. Either the electrical power system hardware will detect the fault and take immediate action such as opening the switch, or the APC fault manager will detect the fault in the system and then identify the fault that is present in the system. In either case, the fault manager is aware of the fault type and faulted component. The fault manager notifies the APC executioner that a critical fault is detected, the faulted component, and fault type. The APC executioner i) moves the APC state from normal to emergency, ii) requests for the recovery and restoration planner to create a new configuration for the power system based on the fault, and iii) notifies the vehicle manager that a fault occurred, the impacted equipment, and the fault type. This notification is necessary so the vehicle manger knows that the APC cannot accept a new load schedule based on the previous energy availability. Once the recovery and restoration planner creates a new configuration, it requests a new energy availability based on the fault to determine if any loads need to be shed. Loads will be shed starting with the lowest priority load and will continue to be shed until the anticipated power is below the new nominal power based on the new energy profile and new configuration. Once the loads are shed, if any, the recovery and restoration planner notifies the APC executioner that the new configuration is complete. The APC executioner notifies the vehicle manager as to what loads have been shed and the new energy availability which serves also as a request for a new load schedule based on the current updated energy availability. The vehicle manager then provides the updated load schedule, the APC will implement the new load schedule and transition the APC state from emergency to restorative, where the system can safely operate until the fault is cleared.

Once the faulted equipment has been addressed, the faulted component is reset via the reset signal. At this point, since the system is being cleared from a critical fault, the APC executioner requests a new configuration based on the new available equipment (since the faulted hardware is now available). It also request a new energy availability profile based on the new configuration, which is coordinated through the recovery and restoration planner. Once this is complete, the APC executioner notifies the vehicle manager that the fault has been cleared and of the new energy availability. Once the vehicle manager responds with the new load schedule, the APC implements the new load schedule and the APC executioner changes the APC state from restorative to normal.

C. APC Demonstration Results

The capability of the APC has been successfully demonstrated. In the demonstration, the energy availability was calculated and provided to the vehicle manager. The vehicle manager proposed a load schedule and the APC was able to implement the new schedule. In this demonstration, two different non-critical faults were inserted into the system to test the ability of the APC to correctly identify the issues and then move to the restorative state. The first non-critical fault introduced an excessive bias to one of the RPCs. Next, one of the RPCs was failed open. In both cases, the APC was able to detect and identify the fault, and correctly moved the APC state from normal to restorative. After the fault was cleared, the APC state changes from restorative back to normal.

In this demonstration, two different critical faults were inserted into the system. First, a feeder fault that shorts the line from MBSU1-1 to PDU1-1 was shorted (Figure 7). The hardware system takes immediate action and will open the RBI output to turn off power to PDU1-1. In this situation, the recovery and restoration planner uses an algorithm to determine that power can be rerouted to the PDUs by using the cross tie. The system reconfigures to power PDU2-1 from MBSU1-1 and PDU1-1 from MBSU2-1. Using the cross ties to provide power to both PDUs does not impact the energy availability and therefore no loads are shed. In addition, the energy availability and power profiles remains the same as shown in Table 1. The faulted component, fault type, energy availability, and current load schedule (to indicate that no loads were shed) are sent to the vehicle manager. The APC waits for a new load schedule to be sent. When the load schedule is received from the vehicle manger, the APC accepts the load schedule and the APC executioner moves the APC state from Emergency to Restorative.

For the second fault, a battery fault was simulated by adding a short from Bat2-1 to MBSU2-1. In this case, RBI2-2 faults open (due to the short) and the APC fault manager detects and isolates the fault. Note that for the current work, there is a requirement that the power available in eclipse and insolation are equal, therefore when the battery is removed from the system so is the solar array; the recovery and restoration planner will remove the MBSU connected to the battery from the system configuration, which for this system is MBSU2-1. In this case, the system reconfigures to power both PDU1-1 and PDU2-1 from MBSU1-1. The nominal power (from the power profile) and the energy availability is reduced to about 50%, shown in Table 3, and several of the loads are shed (all loads after priority 8 are shed). The APC executioner sends the vehicle manger the fault, faulted component, updated load schedule to indicate the shed loads, and the energy availability. The APC waits for a load schedule to be proposed by the vehicle manager that meets the new energy availability, at which point the APC executioner changes the state from Emergency to Restorative.

Table 3. Power Profile after losing a solar array and batter with an Energy Availability for the 2 hour window of 5.76kW Hours

Time (time unit)	Peak Power (kW)	Nominal Power (kw)
1	7.68	2.88
2	7.68	2.88
3	7.68	2.88
4	7.68	2.88
…	…	….
24	7.68	2.88

Once the system is in restorative state, if the fault is removed then the reset signal for the faulted component can be reset. This triggers the recovery and restoration planner to reassess the system configuration based on the current list of faulted components and allow the now repaired component to come back on line. A new energy availability is created based on the new system configuration. The APC executioner notifies the vehicle manager of the updated list of faulted components and new energy availability. Once the vehicle manager sends the new energy availability, then the APC executioner will move the APC state from Restorative to Normal.

VII. Conclusion

The capability of the autonomous power controller (APC) has been successfully demonstrated. The essential capability of the autonomous power controller includes the ability to detect and identify faults, ability to automatically reconfigure the system based on identified faults, ability to recalculate the energy available to the loads based on the current configuration, and the ability to restore power to loads after a fault has been cleared (or fixed). The system that has been implemented employs a database to communicate to various APC subsystems; such as the fault manager, contingency planner, reactive layer, energy manager, and executioner; as well as the vehicle manager. Now that the capability has been demonstrated on a simple two string system, the next step is to improve the system and add more fidelity. This includes adding a messaging system for better communication between all the subsystems, adding historical data capturing for trending analysis in the database, enhance fault management capability include detecting and diagnosing multiple faults, and enhanced configuration with distributed energy storage devices. This technology is critical to enabling human space exploration beyond low lunar orbit as well as future missions to Mars.

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