Power Planning in the International Space Station Domain

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Abstract

The International Space Station (ISS) has the most complex power system in space. Power planners for ISS must track hundreds of buses and thousands of loads to ensure safe operation. Part of the responsibilities of the power planners is the composition of load-shed tables and controlled power down procedures. These plans must be made in light of the expected power use and availability onboard station.

We present an adaptation of Microsoft Visio stencils that provide the modeling capability for ISS power planners to model and critique their power plans in a format that they are used to. Our stencil then converts this power diagram to a declarative planning model for use by ASPEN, a declarative planner/scheduler.

We also present our interfacing to the United Space Alliance ISS power prediction tool TurboSPEED.

We then use ASPEN to generate load-shed tables and perform analyses of procedure execution with respect to power availability. The structure of the power model and how ASPEN uses the model is also described.

Introduction

The ISS power system consists of many solar arrays, buses, power controllers, and distribution units, not to mention the myriad loads themselves. Although the system is quite complex, a great deal of effort has been taken to standardize most of the power generation and distribution components. This provides a modular system that can be well characterized without needing to describe in detail the specific circuitry of each bus, converter, and switch. Still, this modular view does not remove all of the complexity of the station's power system, and a great deal of care and time is required currently to plan for operations and contingencies.

One type of contingency that must be planned for is the general case of power underflow, i.e., not enough power is being produced on a bus (or too much power is being drawn by some unknown source) and we must respond quickly by removing non-essential items from the bus to accommodate the reduced capacity. This is what is commonly called "load-shedding". Part of the power planning process is to develop load-shed tables that describe which loads are to be powered-down in the case of off-nominal power availability on any bus. Since many of these buses interact and can be configured to distribute load across power sources, the composition of practical load-shed tables can take a great deal of time and effort.

We should note that load-shedding is not the same as powering-down loads to accommodate other loads as part of the nominal operations plan. This is referred to as controlled power-down. But, composing the list of non-essential loads to power-down to accommodate operations is very similar to the task of composing load-shed tables, thus our techniques are applicable to both of these scenarios.

Currently, the power planners characterize power generation onboard station using the TurboSPEED application. TurboSPEED takes as input the ephemerides and solar illumination products of other tools and converts these to power production profiles for each channel.

The power planners characterize loads on the power system onboard station using Microsoft Visio charts. These charts describe a network that characterizes various distribution modules and their connectivity to power sources and loads. From this network, a set of load-shed tables is prepared by hand and inspected and critiqued by power experts. The same process is followed for controlled power-down procedures.

Our goal is to allow the expression of the power system to remain the same (i.e., in Visio and TurboSPEED), but provide the ability to ingest this model into a planning system, and then use the planning system to automatically generate load-shed tables and controlled power-down procedures, as well as verify nominal operations. This technology also enables response to off-nominal situations that cannot be characterized as simply as the cases explored for load-shed tables as the response can be crafted in the full context of the off-nominal situation.

TurboSPEED Connectivity

TurboSPEED was integrated into the ASPEN planner models using activities that called a compiled TurboSPEED library. This library ingested the appropriate files (as is normal for a TurboSPEED session) and computed the appropriate profiles upon system initialization. Changes in inputs prompt a re-computation of the profiles. Activities in ASPEN interface to these profiles through parameter functions and reflect the information to various timelines (variables reflecting available power over time) for each channel.

Visio Stencil Description

The Visio stencil follows the already existing document used by the ISS power planners. Our stencil is entitled "MCC Power", as illustrated in Figure 1. It contains seven objects that are used to construct ISS power diagrams. These are the Channel, the Channel Bus, the DDCU (DC to DC Converter Unit), the RPCM (Remote Power Controller Module), the Channel Switch, the Channel Connector, and the RPCM Connector.

A Channel is one solar array and its associated power conditioning system and batteries. Channels are the source of wattage that is used throughout the station.

A Channel Bus is a high capacity bus that is used to represent the connection point of channel users.

A Channel Connector is the same as a Channel Bus electrically, but is thinner in the diagram and used to represent the individual connection of units to the channel bus.

A DDCU connects to a channel and provides appropriate voltage to the RPCM or connects to other DDCUs for cross-channel power distribution.

An RPCM is the controller that distributes power to loads. RPCMs can be daisy-chained, where one RPCM provides power. These appear as tables, where the user selects which of the eighteen distribution controllers are used. Each controller is annotated with a name and an optional load value.

An RPCM Connector represents a lower capacity connection that is appropriate between connected RPCMs or RPCMs and DDCUs.

A Channel Switch is a switch (either for a channel or for other distribution capability). These can be selected as *open* or *closed* to represent the initial state of the power system.
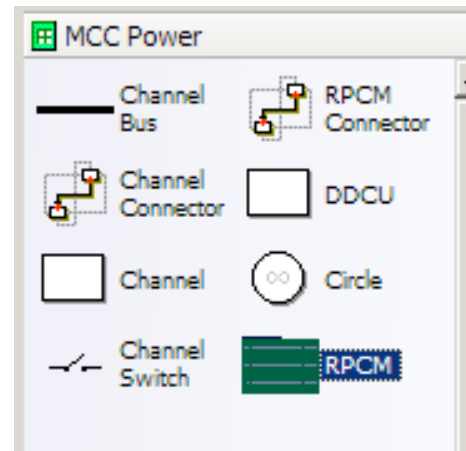

Figure 1 MCC Power Stencil

Figure 2 illustrates how these elements are composed into a power model. Note that this is a very small component of the entire model.
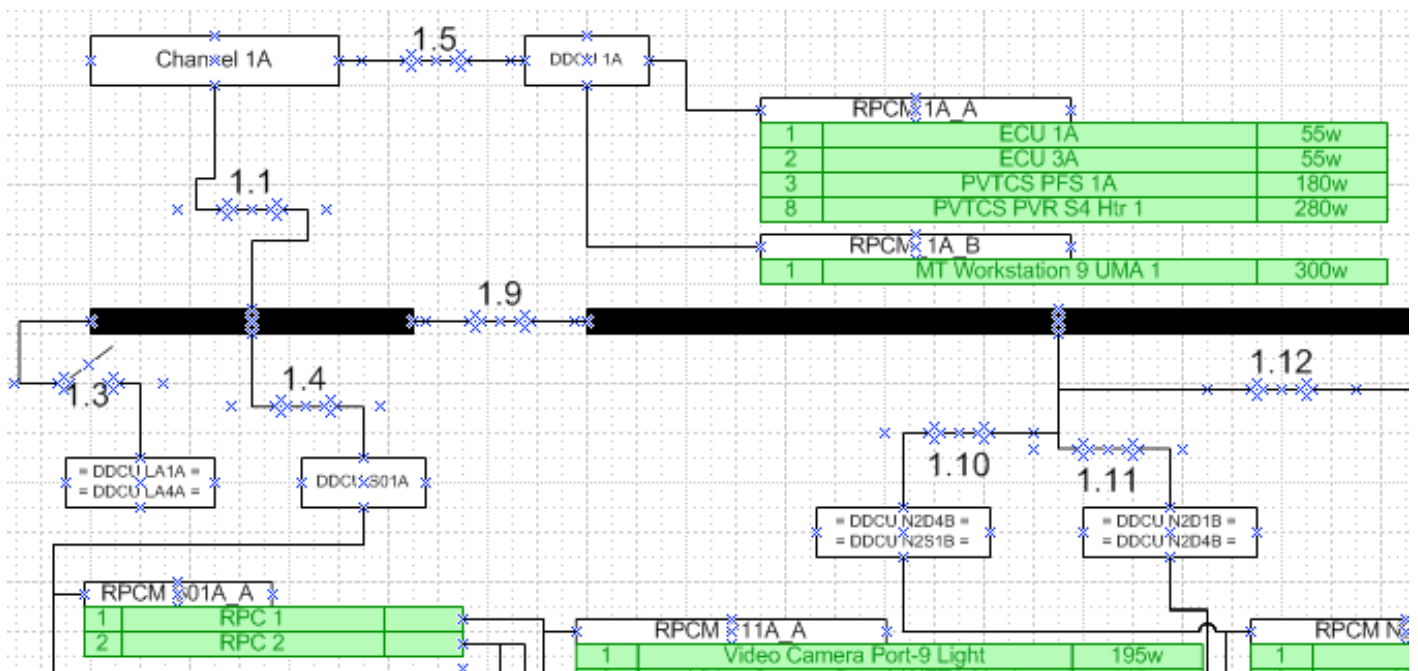
Figure 2 Power System Fragment

Model Structure

Once a complete model is entered using the Visio interface, the user activates a macro that results in the generation of ASPEN model files, ASPEN instance files, and a topology file.

The model files describe the timelines and activities that make up the power system description. A timeline in ASPEN is a representation of a variable over time, and can be constrained by activities or by definition. A constraint on a timeline in an activity is called a reservation. We will call these out where appropriate in the following description of the generated models.

For each channel switch, we include a state-variable timeline (a timeline whose value is a string) where the allowed values are "open" and "closed". We also include an activity that is used to set the switch state. This activity not only changes the value of the timeline of the associated switch, but also computes whether or not any of the DDCUs, RPCMs, or RPCM controllers are available (not isolated from all sources of power).

For each channel, we include a non-depletable resource timeline (a timeline whose values are numeric real values and reservations upon which only last for the duration of the reservation, e.g., power) representing watts of power provided by the solar arrays. We also include a non-depletable resource timeline representing watts of power used by loads. We include a depletable resource timeline (a timeline whose values are numeric real values and reservations upon which are persistent, e.g., energy or propellant) representing battery state of charge. We also include other timelines that represent the tracking mode of the solar arrays and what level of service we are providing to the payloads. Finally, we include activities that map the instantaneous load on the channel from the configuration of the switches and loads on each DDCU, RPCM, and RPCM controller against the power availability profile, thereby populating the timelines representing state of change and power loads, and power provided.

For each RPCM, we include a non-depletable resource timeline representing the overall load on the RPCM as derived from each of its controllers. We also include a state-variable timeline called "availability" representing whether or not the RPCM is receiving any power at all. Allowed states are "available" and "not available".

For each RPCM controller, we include a non-depletable resource timeline representing the load on that controller. We also include a "user" activity that is used to reflect use of the controller. This activity requires the associated RPCM to be "available" over its duration and reflects the use both on the controller load timeline as well as the RPCM load timeline. Thus, any use of a controller enforces that the controller be powered and that the controller and RPCM (and channels providing power) be able to accommodate the usage.

The activities that convert switch states to availability of RPCMs and distribute usage compute these functions based on a topology file that is ingested at initialization time. This file represents the topology of the power diagram and the parameterization of the objects in it.

The final result is a model of the power system where we can introduce switch changes to power down equipment and see the actual effects of these changes as distributed over the power system. Thus, the dynamic topology of the ISS power system is faithfully represented.

Finally, we populate our initial plan with activities that represent the initial states of the switches and the nominal loads of each of the RPCM controllers.

Model Use

The overall purpose of constructing the model is to use it to search for switch configurations that disable a minimum number of low-priority loads to satisfy a given power budget. The generation of each power budget is performed outside of this process, but for each we must generate an appropriate switch configuration.

To achieve this, we simply state the power budget as a constraint in our system with all nominal loads powered on. Since ASPEN can search the infeasible plan space using iterative repair, we allow ASPEN to find a legal plan. Then, we allow ASPEN to search for more optimal plans (where optimality demands no constraint violations and no plan threats and minimizes the number of deactivated RPCM controllers). ASPEN uses an interactive optimization technique to search this space.

With respect to finding feasible plans, iterative repair has a practical advantage to constraint-based backtracking (where only the feasible space of plans is explored, and infeasible propositions are backtracked) as the state of the system immediately previous to the newly required switch configuration is known and presumably close to high quality solutions where distance is measured in plan modification operations. By identifying the culprits of constraint violations and plan threats, iterative repair can focus on a small set of plan modifications that are provably effective.

With respect to finding optimal plans, it isn't clear that iterative optimization has benefits over feasible-space search with backtracking. In practice, good plans are arrived at, but we have yet to develop a provably optimal planner for these domains, and therefore do not know with certainty what level of quality is achievable. Future work might entail characterizing bounds on optimality and possibly constructing or adapting optimal algorithms to task.

With our planner in place, we now have the ability to automatically reason about several hypothetical scenarios. The specific scenario we focused on for this work was the removal of a DDCU that provide power to one of the solar array gimbals (the solar array alpha rotary joint, or SARJ). Since taking the SARJ offline causes the solar arrays on that SARJ not to track, we wanted to know when would be problematic times for this procedure. In addition, we wanted to know when would be problematic times if we were to take the second SARJ offline (leaving no alpha rotary control).

Figure 3 illustrates the ASPEN GUI with a plan instance loaded and being prepared for iterative analysis of a procedure.

Results

The scale of the ISS power model used was somewhat large. There were 40 switches, 7 channels, and over 1200 RPCM controllers.
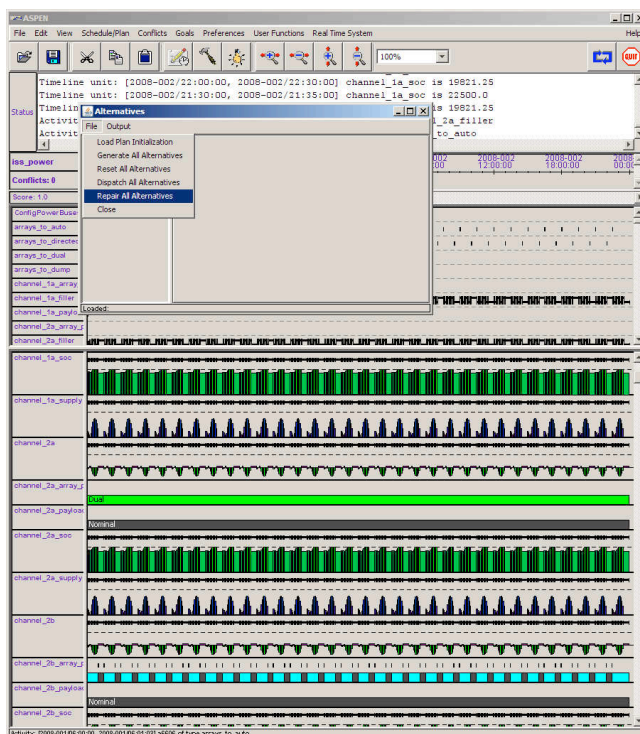

Figure 3 ASPEN GUI

Each controller had profiles that consisted of hundreds of activities, resulting in several hundred thousand activities overall to produce a complete schedule. Even so, ASPEN was able to produce feasible switch configurations in 7 minutes 42 seconds on average with a standard deviation of 1 minute 12 seconds.

Optimization over 1 hour produced configurations of similar quality to hand-generated configurations. Optimization over 2 hours did not improve the results significantly. Memory required was 1.6 Gigabytes.

Acknowledgements

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