Orion Power Transfer: Impacts of a Battery-on-Bus Power System Architecture

Spencer C. Furin[1]
NASA Glenn Research Center, Cleveland, OH, 44135, USA

The Orion Multi-Purpose Crew Vehicle (MPCV) has the capability to transfer power to a co-manifested payload (CPL) during transit from low-Earth orbit to the lunar vicinity. This paper discusses a time-phased parametric power analysis to determine the Orion power transfer capability limit. Charge and discharge curves were generated for various power transfer conditions and measured against various minimum system voltage limits.

The Orion electrical power system (EPS) utilizes an unregulated bus architecture, which has important implications when the system is operating under very high load demand conditions, such as during power transfer. This analysis highlights three important effects of this architecture. First, increasing load demand decreases the maximum state of charge (SOC) the batteries can reach when charging. Second, increasing load demand also decreases the allowable battery depth of discharge. These two together can significantly reduce the effective useable capacity of the batteries. Finally, low battery voltage decreases the power generation of the solar arrays. This can lead to significantly longer recharge times or even push the system out of energy balance. These effects have important implications for mission design and vehicle operations and must be accounted for when conducting sizing and design of an unregulated spacecraft EPS.

I. Introduction

The Orion Multi-Purpose Crew Vehicle (MPCV) is a crewed spacecraft for deep space exploration missions as part of NASA's Artemis program. The Orion electrical power system (EPS) consists of four solar array wings (SAWs) for power generation and four lithium-ion batteries for energy storage. The EPS distributes power to other subsystems and components by means of four 120 VDC, unregulated power busses, also known as a "battery-on-bus" architecture [1].

The Artemis program also includes several other spacecraft, including the Human Landing System (HLS) and the various modules of the Gateway space station. Orion has the capability to dock with many of these vehicles, and the Orion EPS supports the capability to provide power transfer to a docked vehicle. This is designed for contingency scenarios as well as for nominal power transfer to a co-manifested payload (CPL) during transit from low-Earth orbit (LEO) to the lunar vicinity. This capability introduces a unique challenge for power system design, since the CPLs are independent vehicles; this means that their power consumption will undoubtedly be much greater than the load demand of an additional internal component that is typically considered in an EPS design. Additionally, CPLs were not well defined when the Orion EPS was being sized and designed, so the specifics of their power budgets and load demands were outside of the initial Orion design space.

These other vehicles are earlier in their respective design cycles than Orion, which has flight articles already in production and processing for launch. As a result, Orion must determine its power transfer capability to inform the CPL designs. It is relatively straightforward to find the hardware limit on power transfer by examining the electrical current ratings of the EPS components and harnessing up to the docking interface. However, this limit alone does not determine the power transfer capability; just because the hardware can transfer a certain amount of power does not mean that Orion will always have that amount of power available to transfer. This paper discusses the results of a time-phased parametric power analysis, using the System Power Analysis for Capability Evaluation (SPACE) program

[1] Electrical Engineer, Power Architecture and Analysis Branch, AIAA Member

to determine the maximum continuous power transfer level that Orion is capable of supporting on top of its own nominal load demand.

The analysis highlights several counterintuitive impacts of a high-power load demand on Orion's EPS performance. These impacts are inherent to the unregulated bus EPS architecture and provide several lessons learned that should be considered when sizing EPS components.

II. EPS Architecture and Power Regulation

An important function of the EPS is to control and regulate the power and voltage provided to the various electrical loads. EPS architectures can be divided into several different categories depending on how they provide that regulation. For a typical spacecraft EPS with a photovoltaic power generation source and chemical batteries for energy storage, the defining architecture features are the controllers for the solar arrays and batteries.

A. Solar Array Control

Solar arrays must be controlled to prevent excessive power generation. Generating too much power above and beyond the vehicle loads can damage the batteries by overcharging them. Additionally, almost all electrical energy generated by a spacecraft's solar arrays must ultimately be dissipated as thermal energy, so excessive power generation can also stress the vehicle thermally. The two most common power control options are a peak-power tracker (PPT) or a direct energy transfer (DET) design. A PPT is a DC-DC converter in series with the solar array that, as the name implies, allows the solar array to track the peak power point of its characteristic current-voltage (I-V) curve to maximize power production. It can also be used to purposefully operate the array at a different voltage, producing less-than-peak power to control overall power generation. A DET design involves a shunt regulator in parallel with the solar array that shunts excess power back through the array for dissipation to space. DET designs are generally simpler, lower mass, and more efficient than PPT systems and are thus more common in spaceflight applications [2], [3].

Orion utilizes a DET design for solar array regulation. The primary power management and distribution (PMAD) components within Orion's European Service Module (ESM) are the two power conditioning and distribution units (PCDUs). Each PCDU contains sequential switching shunt regulators (S3Rs) that shunt sections of the SAWs as needed to limit the total power generation.

B. Battery Control

Unlike solar arrays, batteries do not always require a controller to regulate their interaction with the electrical bus, as batteries themselves have a regulating effect on the bus voltage. The type of controller, or lack thereof, determines whether a bus is regulated, quasi-regulated, or unregulated. A fully regulated bus features a constant-current charge controller as well as a boost regulator that operates when the battery is discharging. The combination results in a highly stable bus voltage, but at the cost of low efficiency. A quasi-regulated bus features only a battery charge controller, which maintains the bus at a constant voltage only when the battery is charging. During discharge, the bus voltage follows the battery voltage without any active regulation. An unregulated bus does not have any controller on the battery and the battery connects directly to the bus. For this reason, it is also sometimes referred to as a "battery-on-bus" architecture. This architecture is highly efficient but results in a significant variation in bus voltage on the order of 20% [2], [3].

Orion utilizes an unregulated bus design, and its four batteries are each connected to one of the four nominally 120 VDC buses. Due to the unregulated architecture, the bus voltage can vary between 98 V and 136 V. The power and data units (PDUs) do contain instrumentation to monitor battery status and provide circuit protection to the bus, but there is not a true controller that regulates the battery.

III. Analysis

A. Model

This analysis was conducted using the SPACE computer program. SPACE was initially developed at NASA's Glenn Research Center to model the EPS of the International Space Station (ISS) and has since been modified to model the EPS performance of several other spacecraft, including Orion. There are currently no flight data from Orion to validate the SPACE performance predictions against, but SPACE has been extensively validated with on-orbit data from ISS over several decades. Additionally, several code-to-code comparisons have been conducted between SPACE and the EPS model developed independently by Lockheed Martin, the Orion prime contractor [4].

While most of the specifics of the SPACE code's operation are beyond the scope of this paper, it is worth briefly discussing the basics of the battery model used within SPACE. Modeling the performance of any battery is a difficult task as there are a multitude of non-linear factors that affect battery performance. While battery technologists may use complex first principles models to simulate the chemical reactions within the battery, batteries are usually represented by an equivalent circuit model for the purposes of power system analysis. Specifically, batteries are typically modeled as an ideal voltage source in series with a resistor and some number of parallel resistor-capacitor (RC) pairs used to model transient effects. A power system model focused on overall energy balance, such as SPACE, can be considered a quasi-steady-state analysis, and as such the RC pairs can be ignored. SPACE uses a simple resistive model as shown in Fig. 1, where V_{OC} is the battery open-circuit voltage and R_{int} is the battery internal resistance.

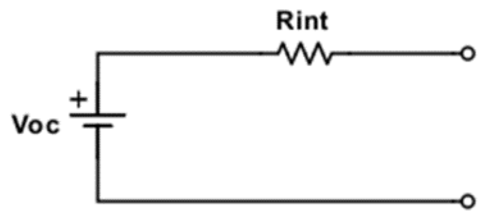

Fig. 1 Equivalent circuit battery model used in SPACE

The resulting battery terminal voltage, V_{batt}, is therefore a function of V_{OC}, R_{int}, and the battery current, I_{batt}, as shown in Eq. 1. I_{batt} is assumed to be positive when the battery is charging.

$$V_{batt} = V_{OC} + I_{batt} R_{int} \tag{1}$$

While this resistive model results in a very simple relationship between V_{batt} and V_{OC}, R_{int}, and I_{batt}, the complexity is introduced by the fact that none of these parameters are constants. I_{batt} is a function primarily of the total system load demand but is also dependent on V_{batt}, and as a result the battery current and voltage must be solved for iteratively as part of a load flow model. Both V_{OC} and R_{int} depend on various factors, including degradation, temperature, and the battery state of charge (SOC). These curves also change depending on whether the battery is charging or discharging. The dependence on SOC dominates the other factors, and for a lithium-ion chemistry the most significant variation is the change in V_{OC}, which increases as SOC increases and vice versa. R_{int} also depends on SOC but remains nearly constant over most of the operating range, with significant changes only occurring near full charge and full discharge.

B. Input Assumptions

Orion is designed to nominally operate in a solar inertial attitude with the aft (or tail) pointing towards the Sun, which is referred to as a "tail-to-sun" attitude. This attitude provides the best possible power generation from the SAWs. Dynamic events such as main engine firings are stressing periods for power; they often include maneuvers away from the tail-to-sun attitude, restrictions on the solar arrays' ability to track the sun due to thruster plume or structural loading concerns, and increased electrical loads from propulsion and guidance components associated with the burns.

However, the overall mission trajectory for an Orion/CPL lunar transit is not yet fully defined, which leaves several important details unknown. In particular, the number of eclipses, burns, and other off-pointing events and their phasing and proximity to one another are not yet known. Similarly, Orion's nominal steady-state power load demand varies throughout the mission, and a detailed time-phased load profile has not yet been developed. As a result, instead of a detailed study of a particular mission, this analysis was set up as a parametric characterization of the EPS performance under a variety of load conditions.

For each case, Orion was held in the standard tail-to-sun attitude with a constant relative sun vector. All thermal effects from the Earth and moon were ignored to approximate the translunar coast environment. For discharge cases, all solar array strings were shunted to simulate an eclipse without duration limits.

C. Analysis Approach

Orion's nominal steady-state load demand was set at 7.5 kW as a typical value for non-dynamic events during translunar coast. Various CPL designs have requested different levels of power transfer from Orion, so cases were run with the baseline load of 7.5 kW, plus 0.0 kW, 1.8 kW, 2.5 kW, and 3.0 kW of additional power transfer. All crossties between busses were closed for this analysis to remove any effects from load imbalance between different power channels.

The Orion EPS has several minimum voltage limits, referred to here as the system design limit, software limit, and operational limit. All are measured at the battery terminals. The system design limit is the minimum battery voltage required to keep the entire EPS within the power quality specification. The software limit is several volts higher and is the point at which the vehicle will automatically take action to prevent further battery discharge. Finally, the operational limit is set by a flight rule to allow time for operators to react before the vehicle automation begins taking action.

One of the counterintuitive effects discussed later in this paper is that the vehicle load has an impact on the maximum SOC that the batteries can reach when charging. Similarly, since the relationship between SOC and voltage varies with battery current, the SOC corresponding to a given voltage limit is not known *a priori*. As a result, an iterative process was used to characterize the full charge and discharge curves for each load demand level. First, each case was charged from an arbitrary 50% SOC until steady state to determine the maximum SOC the batteries would reach under the given load condition. This SOC value was then used to initialize a case fully discharging from the maximum to the minimum SOC corresponding to each of the voltage limits. Finally, each minimum SOC was used to initialize a case fully charging from the minimum to maximum SOC.

IV. Results

Fig. 2 shows the battery voltage while discharging from steady state to the system design limit at various power transfer levels, and Fig. 3 shows the battery SOC under the same conditions. Increasing power transfer decreases the time it takes to reach the minimum voltage limit, as expected. Note, however, that the difference is due not only to the difference in discharge rate (as indicated by the slope of the curves), but also due to the difference in initial conditions, which will be discussed below. Additionally, Fig. 3 shows that although each case was run down to the same minimum voltage, the corresponding SOC for that voltage changes depending on the load conditions.

Fig. 4 and Fig. 5 show battery voltage and SOC, respectively, when charging from the software limit back up to steady-state conditions. Here, the differences in both recharge rates and final steady-state conditions are readily apparent. The initial conditions in Fig. 5 also show more clearly the differences in SOC for a given voltage under various loads.

The specific charge/discharge times and rates are important for the operation of the Orion EPS during power transfer to a CPL, but what is more relevant to a wider audience is the set of counterintuitive or unexpected impacts of very high load demand on an EPS utilizing an unregulated bus architecture. Three of these phenomena are discussed in more detail below.

A. Impact to Maximum Battery SOC

The first and most easily apparent impact of high overall load demand on an unregulated bus is the limitation it imposes on the maximum state of charge that the batteries can reach when charging. This is clearly shown in Fig. 4 and Fig. 5, where the batteries reach a steady-state condition at approximately 86% SOC with 3.0 kW of power transfer, as opposed to a steady-state condition of 95% SOC with no power transfer.

Without a charge/discharge controller isolating the battery from the bus, battery charging is controlled by the PCDU S3R. As discussed earlier, the open-circuit voltage of the battery increases as it charges, and it is clear from Eq. (1) that the battery terminal voltage increases as well. This in turn will raise the voltage of the entire bus. However, as the batteries approach full charge and the bus voltage continues to rise, the S3R will begin to shunt SAW strings to limit the voltage at the SAW/PCDU interface to the commanded PCDU setpoint. As the batteries continue to charge and their voltage continues to increase, the voltage delta between the PCDU and the batteries decreases. This decrease in voltage delta naturally decreases the current flowing into the batteries, eventually tapering and reducing the current to zero. This is expected behavior and is the nominal method of battery charge control in an unregulated system; rather than an active charge controller, the physics of the system prevents battery overcharging.

The final voltage delta between the SAWs and the batteries at steady state is not zero, however, as there is some voltage drop across the system. An increase in power demand increases the current draw from the components in between the SAWs and batteries, increasing the voltage drop across those components. As a result, the voltage delta between the SAWs and battery terminals is proportional to the total vehicle load demand. Under high load demand conditions, the increase in voltage delta is significant. Since the batteries will only charge up to the voltage available to them at the terminals, this increase in voltage drop ultimately decreases the SOC that the batteries can reach.

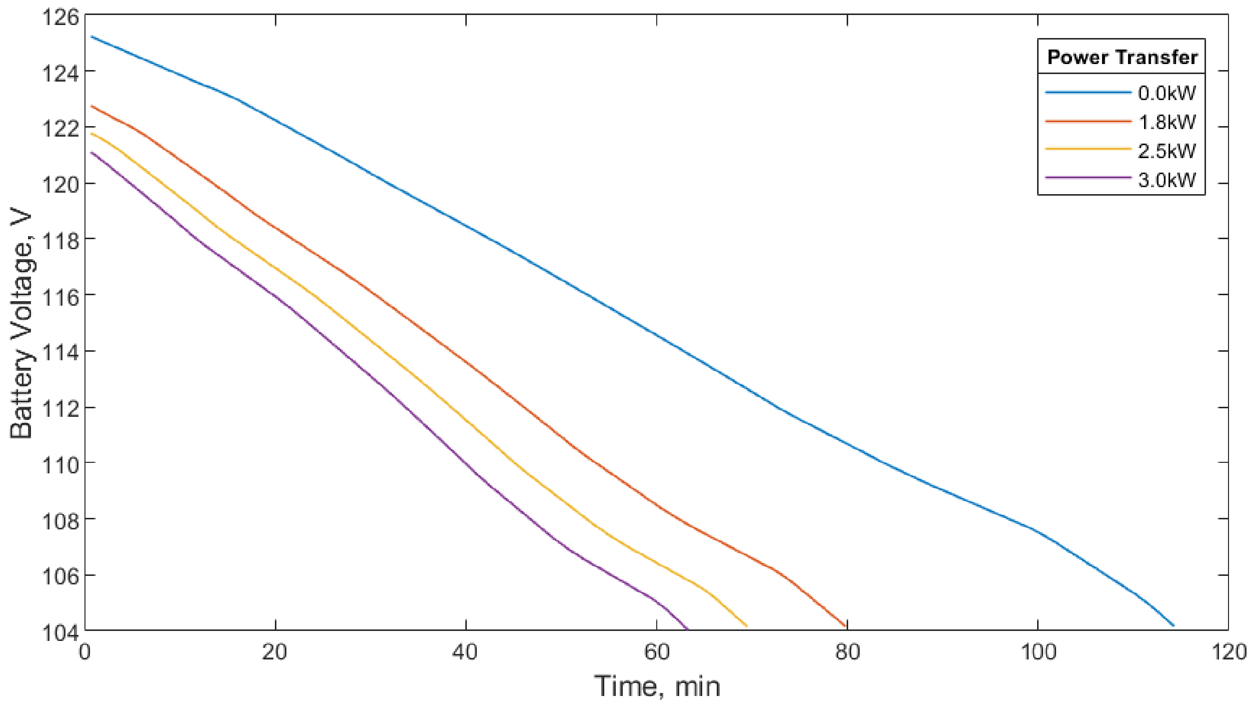

Fig. 2 Battery voltage during discharge

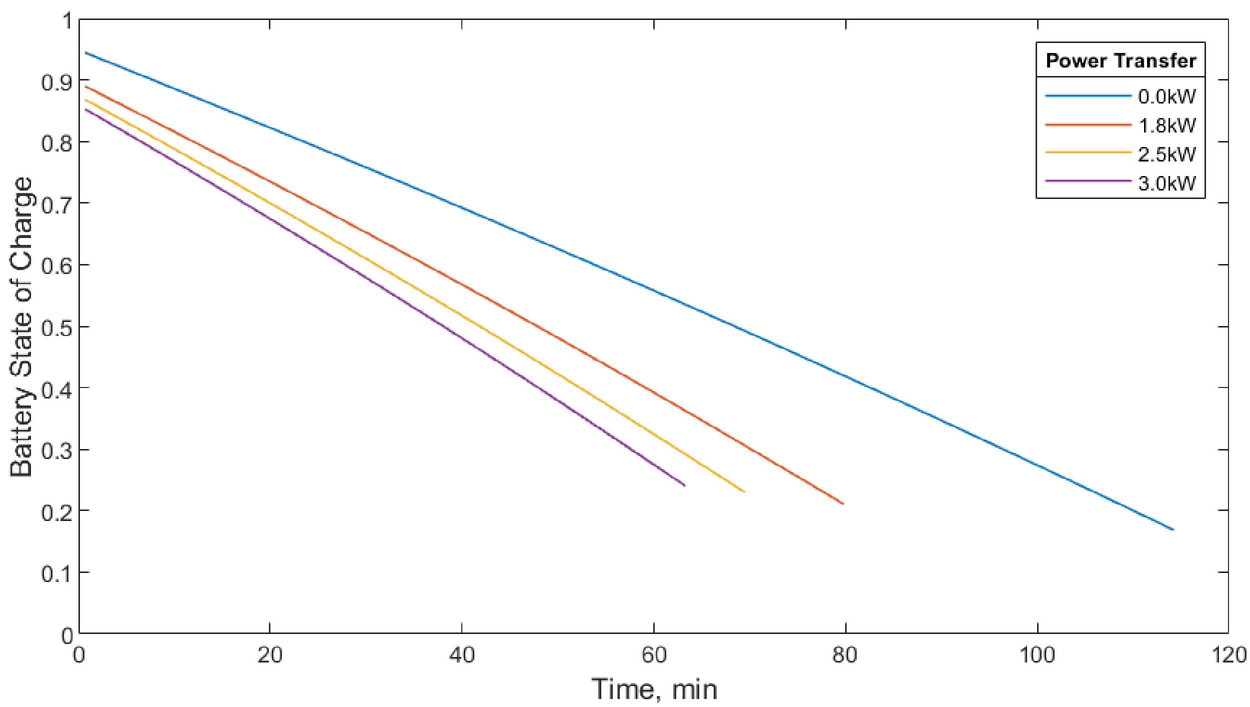

Fig. 3 Battery SOC during discharge

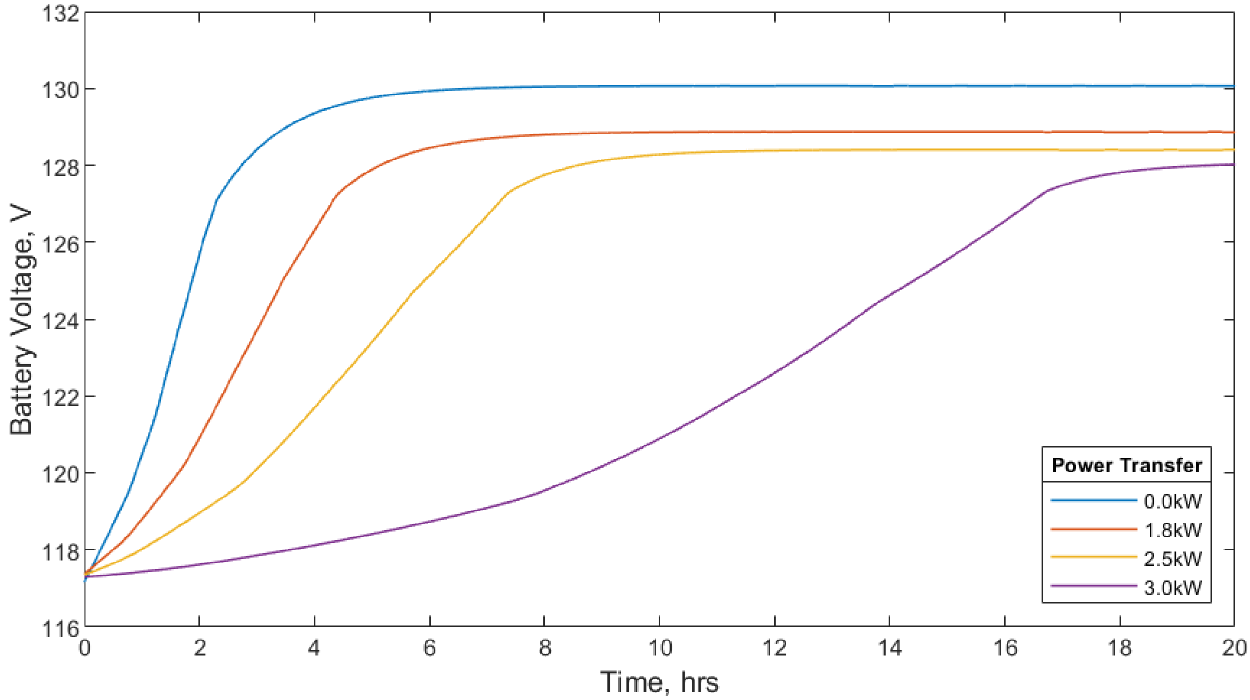

Fig. 4 Battery voltage during charge

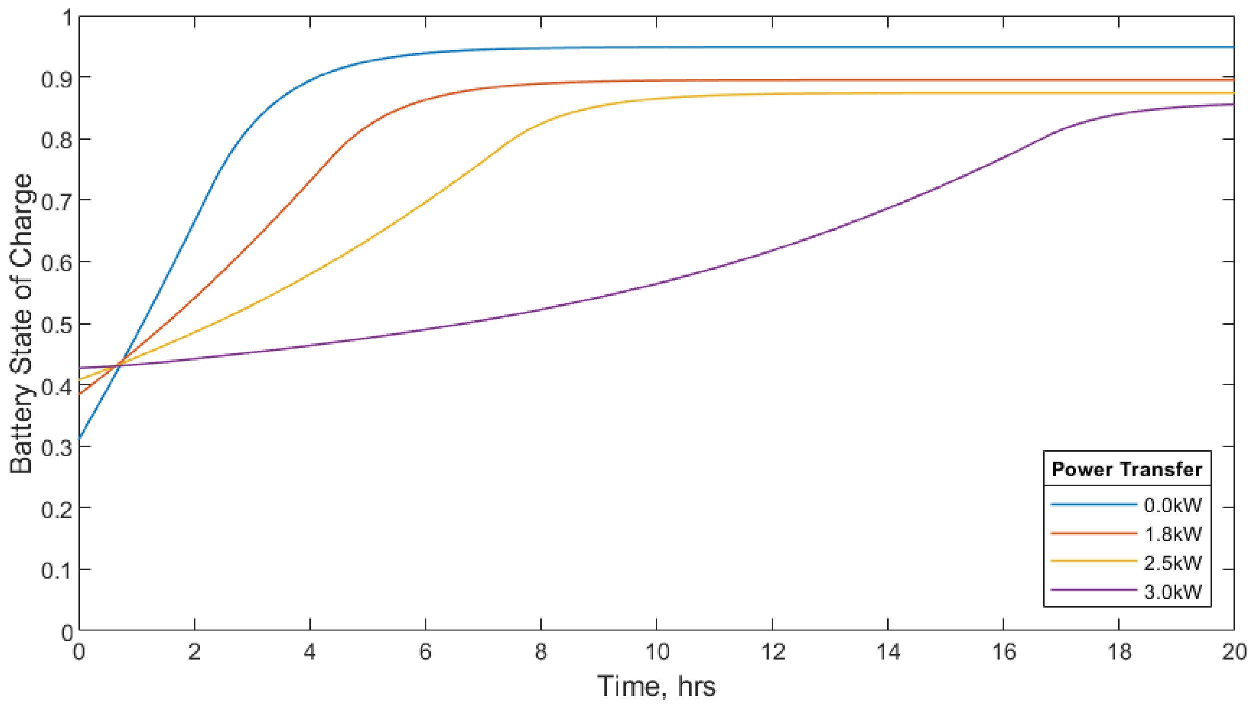

Fig. 5 Battery SOC during charge

B. Impact to Minimum Battery SOC

The second, similar effect is that high power load demand reduces the allowable battery depth of discharge. This can be seen in the final SOC values of Fig. 3 as well as the initial conditions in Fig. 5. Under baseline loads without power transfer, the batteries reach the system design limit at 18% SOC when discharging. With 3.0 kW of power transfer, the batteries reach the same voltage limit at 25% SOC.

This phenomenon is easy to understand by looking at the battery equivalent circuit model in Fig. 1. The resistive element means that the battery voltage is determined not only by SOC, but also by the current flowing into or out of the battery. This happens in the "same direction" as the overall voltage change with SOC; that is, increasing the current will cause the battery voltage to increase when charging and decrease when discharging. When the vehicle is in an eclipse or the SAWs are pointed in such a way that they generate no power, the entire vehicle power load is fed from the batteries, and the battery discharge current is directly proportional to the load demand. As a result, increasing the total vehicle load demand increases the battery discharge current and leads to a lower battery terminal voltage for the same SOC. Since the EPS operation is limited by minimum voltage limits rather than by SOC limits, this will cause the system to reach those limits sooner and at a higher corresponding SOC.

Combined with the first effect, this means that the useable portion of the battery capacity is reduced when load demand is high. The first effect limits the amount of energy that can be stored in the batteries, and the second limits the amount of energy that can be extracted while remaining within the system voltage limits. This difference is significant for vehicle operations; comparing at the software limit, adding 3.0 kW of power transfer decreases the effective capacity of the battery by approximately 20%.

C. Impact to SAW Power Generation

The final counterintuitive effect of an unregulated EPS architecture is that low battery voltage decreases the power produced by the SAWs. Solar arrays are an assembly of solar cells, which are semiconductors whose behavior can be described by an I-V curve. A typical I-V curve of a triple-junction solar cell, the type used on Orion, is shown in Fig. 6 [5], [6]. The full SAW I-V curve changes with degradation, temperature, and the number of shunted strings, but the general shape remains the same. The curve has a current leg, where the current output is close to constant as voltage varies, and a voltage leg, where the current output drops rapidly in a small voltage range near the maximum open-circuit voltage.

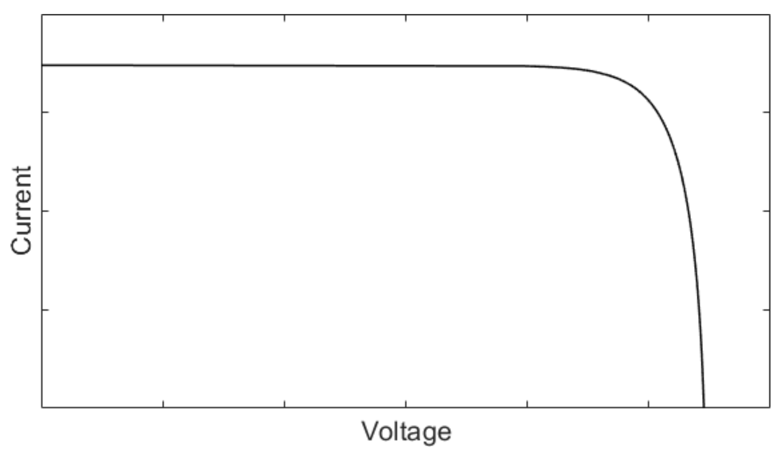

Fig. 6 Typical solar cell I-V curve

The Orion SAWs operate primarily on the current leg of the I-V curve for the entire bus voltage range, meaning that the SAWs generally output approximately the same current regardless of the bus voltage. In that sense, they can be thought of as a constant current source within the EPS. When the batteries are at a low SOC, the bus voltage is correspondingly low, and the SAW voltage is decreased as well. Since power is directly proportional to both current and voltage, a lower voltage with approximately the same current will result in decreased power generation by the SAWs.

The net effect, which the author has termed the "voltage pit," has important operational implications. The lower the battery SOC reaches during discharge, the more difficult it is to recharge from that condition. This can be seen in the concavity of the curves, particularly those for higher power transfer levels, in Fig. 4 and Fig. 5. Note how the rate of recharge increases as the batteries charge despite the steady-state conditions for load demand and power generation. This phenomenon is less dependent on the total load demand than the previous two effects and will still occur under baseline conditions with no power transfer. However, the effect is exaggerated by higher loads as it forms a feedback loop; increased loads results in less power available to charge the batteries, which keeps the bus voltage at a low level longer, which decreases SAW power generation, which keeps the available battery charging power low.

This results in extreme sensitivity to load increases and a drastic drop-off in capability when the loads are already high. For example, in Fig. 4 and Fig. 5, increasing the power transfer level from 2.5 kW to 3.0 kW nearly doubles the time it takes for the batteries to charge back to a steady state, for an increase of only 5% in the overall vehicle load. In extreme cases, the voltage pit effect can even push the entire EPS out of energy balance. In another charge case not shown in the figures, the batteries were initialized at the system design limit. With 3.0 kW of power transfer, the low battery voltage so severely limits the SAW power production that the SAWs cannot meet the increased load demand on their own. The batteries continue to discharge despite the SAWs being in full sun with no off-pointing or shadowing.

V. Conclusion

The phenomena observed here are inherent to the battery-on-bus EPS architecture and are not unique to Orion. As a result, there are important lessons to be learned here for broader power system design and sizing. Extra care must be taken when sizing power generation for an unregulated EPS since solar arrays may produce less than their nominal power output when the bus voltage is low. Similarly, the total load demand can have a significant impact on the portion of the battery capacity that is available to use, and this must be accounted for when sizing the system's energy storage. Beyond the system design, these effects also have important implications for mission planning and operations. EPS designers must communicate these behaviors to mission managers and vehicle operators so that they are aware of these impacts as they design and operate the mission.

This analysis also reinforces the importance of performing a time-phased analysis to determine the ability of an EPS to accommodate increased loads, rather than relying on more basic estimation techniques. This is particularly important for a case like this where significant power loads are added later in the design after power generation and energy storage have already been sized. While these are best practices for designing any spacecraft EPS, the nonlinear effects seen here make them especially important when designing or analyzing battery-on-bus architectures.

References

[1] Berthe, P., Over, A. P., Gronowski, M., and Richard, B., "Orion European Service Module (ESM) development, integration and qualification status," AIAA Paper 2018-5146, *2018 AIAA SPACE and Astronautics Forum and Exposition*, Orlando, FL, September 2018, URL: https://doi.org/10.2514/6.2018-5146.

[2] McDermott, J. K., "Power," *Space Mission Analysis and Design*, 3rd ed., edited by W. J. Larson and J. R. Wertz, Microcosm Press, El Segundo, CA, 2006, pp. 407-427.

[3] Chetty, P. R. K., "Electrical Power System for Low Earth Orbit Spacecraft Applications," AIAA Paper 1987-9191, *22nd Intersociety Energy Conversion and Engineering Conference*, Philadelphia, PA, August 1987, URL: https://doi.org/10.2514/6.1987-9191.

[4] Miller, S. G., Klefman, B. T., Korn, S., Nowden, T. V., Delleur, A. M., and McKissock, D. B., "The SPACE Computer Code for Analyzing the International Space Station Electrical Power System: Past, Present, and Future," AIAA Paper 2018-4635, *2018 International Energy Conversion Engineering Conference*, Cincinnati, OH, July 2018, URL: https://doi.org/10.2514/6.2018-4635.

[5] "ZTJ Space Solar Cell: 3rd Generation Triple-Junction Solar Cell for Space Applications," ZTJ data sheet, SolAero Technologies Corp., April 2018.

[6] Rauschenbach, H. S., "Theoretical Solar Cell Models," *Solar Cell Array Design Handbook*, Vol. 1, NASA CR-149364, October 1976.