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Operational Mode Analysis of Cooler Driver Electronics in Satellite and System Safety Margin

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Abstract

Cooler driver electronics (CDE) for maintaining low temperature of the satellite payload IR sensor consists of a compressor that has a pulsation current load condition when it is operated. This pulsation current produces large voltage fluctuation, which affects both load and regulated bus stability. Thus, CDE power conditioning system consists of a primary bus, infrared power distribution unit for battery charging and protection, reverse current protection diode, and battery, which is used as a buffer. In this study, the operational mode analysis is performed by each part with equivalent impedance modeling verified through system level simulation. From this mode analysis, the safety margin for state of charge and open circuit voltage of the battery is determined for satisfying the minimum operational voltage of the CDE load.

Key Words : Satellite, Payload Powering, Cooler Drive Electronics, Battery System, Mode Analysis, Safety Margin

1. Introduction

Cooler drive electronics (CDE) units, which are used to maintain the satellite payload infrared (IR) sensor at low temperatures, have a compressor that produces a pulsation current load condition when it is operated. This pulsation current causes a large voltage fluctuation at the load input[1], thus affecting the stability of the regulated 28 V bus power source in the power control distribution unit. Therefore, for a stable power supply of CDE units and stability of satellite-controlled buses, the CDE power conditioning system employs batteries to act as buffers. The system consists of primary buses, battery, IRM power distribution unit (IPDU) for battery charging and protection, reverse current protection diode, and CDE loads, as shown in the block diagram of Fig. 1[2].

In the existing battery power supply systems, the range of operation is determined based on the end of discharge voltage, which is guaranteed by the manufacturer in terms of battery protection when implementing algorithms for over-discharge protection of batteries. However, the battery for bus power stabilization used in the CDE battery power conditioning system has a drive voltage range of 17.5 V–29.4 V, which is wider than the voltage range for actual load driving; thus the battery does not discharge to 17.5 V under actual operating conditions. Therefore, to design safety margins related to CDE battery, a protection algorithm in which the battery is completely discharged when no charging operation is viable should be implemented, and securing normal operation of voltage in the CDE unit must be considered. The pre-existing methods implement protection algorithms without analyzing the system operating modes or minimum operating point designs. In this study, the operational mode analysis was performed using the equivalent model of each unit constituting the CDE power conditioning system. Furthermore, the operation point and safety margin for the system to operate reliably at the battery voltage were derived from this mode analysis.

2. Characteristics and Equivalent Circuits of CDE Power Conditioning System

The primary power of the CDE conditioning system is supplied to the load via the 28 V power distribution unit of the power conditioning distributor on a regulated 28 V bus. An IPDU, a field box that provides the load power supply, battery over-current charging prevention, load over-current prevention,

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and switching operation, has a built-in current limiting charger to prevent over-charging. The current is designed at 3.8 A considering the root mean square (RMS) capacity of the load. A reverse current protection diode is also located within the system to prevent the reverse current produced by the battery. We used an 18750 type 7s8p lithium-ion battery with a nominal capacity of 12 Ah[3].

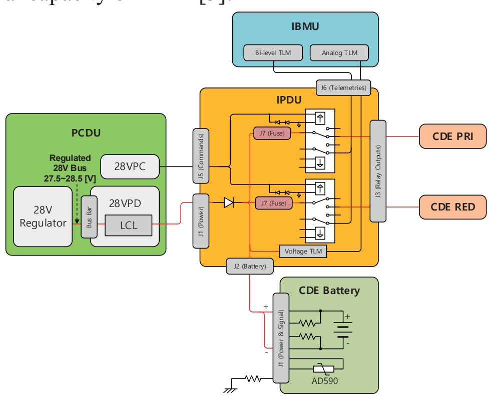


Fig. 1 Block Diagram of CDE Power Conditioning System

2.1 CDE Load Characteristics

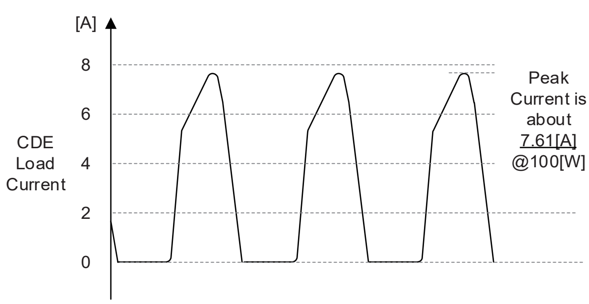


Fig. 2 Load Profile of CDE with Pulsation Current

The CDE operates by switching the compressor to maintain low temperatures, and thus, such switching operation produces a large current pulse, as shown in Figure 2. Compressor loads used by satellites operate with an ON/OFF switching of 100 Hz frequency, as shown in Table 1, and under normal operation, at 100 W power, the RMS current is 3.57 A and the maximum current is 7.61 A.

Table 1 Major Parameters of CDE Load

Parameter	Value	Unit	Remarks
Power (Nom.)	100	W	Normal Mode
Frequency	100	Hz	
Current	3.57	A	RMS Current
Current (Peak)	7.61	A	Peak Current

2.2 Equivalent Circuit of CDE Power Conditioning System

The CDE power conditioning system using lithium-ion batteries can be expressed as a simplified equivalent circuit, as shown in Fig. 3. This configuration is a simplified form of Fig. 1 and consists of a 28 V regulated bus power source, an IPDU, internal current limiting charger, reverse protection diode, a lithium-ion battery, and a pulsation load.

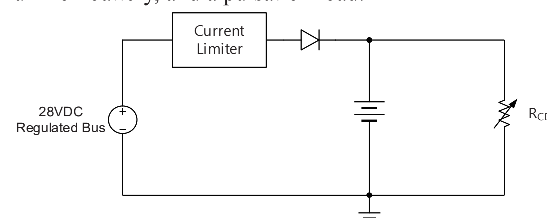


Fig. 3 Simplified CDE Power System

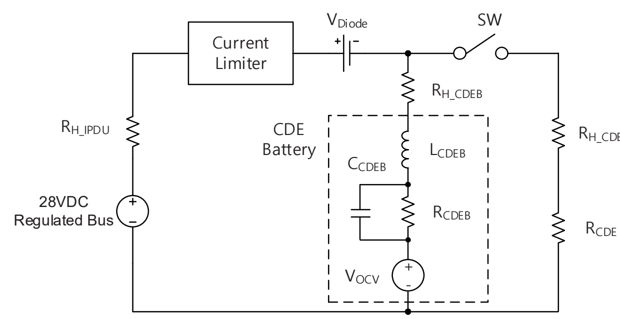


Fig. 4 Equivalent Model using Impedance Model of Li-ion Battery and Load considering Harness Resistance

For the analysis of CDE power conditioning system operating modes, the configuration of Fig. 3 may be represented as an equivalent model, as shown in Fig. 4, in the form of a battery equivalent impedance model (V_{OCV}, R_{CDEB}, C_{CDEB}, L_{CDEB}), a load switch for simulating load operations (SW), and a harness impedance between units (R_{H_IPDU}, R_{H_CDEB}, R_{H_CDE}).

The battery impedance model can be expressed as a combination of the open circuit voltage (OCV) of the battery and internal impedance. The internal AC impedance may use the BoL R-L-C impedance value provided by the manufacturer or the EoL R-L-C impedance value that considers 1-string failure and deterioration [4,5]. The mode analysis was performed with a combination of OCV and DC internal resistance [6, 7]. The IPDU internal current limit charger operates at a 3.8 A limit; thus, the maximum current is equal to 3.8 A. The diode assumes a voltage source of 0.7 V for forward voltage drop (V_{Diode}) when powering the load in a forward direction or when charging the battery. Finally, the load(R_{CDE}) consists of a combination of 3.68 Ω, assuming a SW with ON/OFF operation, and a maximum load current of 7.61 A. The harnesses connected between each unit were interpreted based on the values derived by considering their length and width.

3. CDE Power Conditioning System Operational Mode Analysis

3.1 Mode 1) CDE Powering (Load SW On)

In Load SW On, i.e., a mode in which the CDE load is energized, two voltage sources are powered by the bus and load in the battery, as shown in Fig. 5.

To interpret the two voltage sources, the principle of overlay was used and the mode could be analyzed through the absence of both the voltage source battery and 28 V bus power, as shown in Fig. 6. The bus voltage can be obtained by adding the current values of each case; thus, a battery OCV that reaches 3.8 A, the maximum current supplied by the bus, can be obtained.

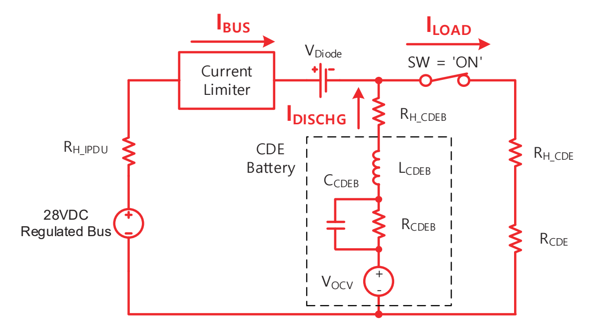
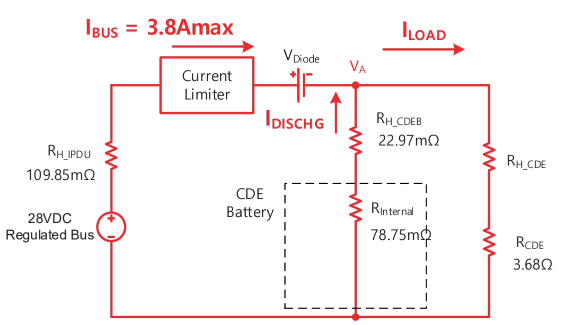
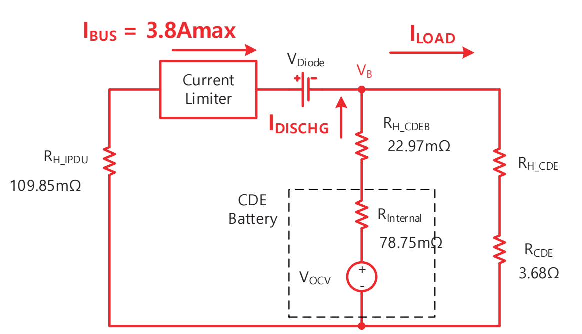


Fig. 5 SW = 'ON' Mode with Powering to the Load



(a) 28 V Bus Powering Mode without Battery Source



(b) Battery Powering Mode without 28 V bus

Fig. 6 SW = 'ON' Mode with Charging the Battery

First, in the case of the battery OCV for a short circuit, we can obtain Eq. 1~4 from Fig. 6, as shown below.

$$I_{LOAD} = I_{DISCHG} + I_{BUS} \tag{1}$$

$$I_{BUS} = \frac{V_{BUS} - 0.7 - V_A}{R_{H\_IPDU}} \tag{2}$$

$$I_{DISCHG} = \frac{-V_A}{R_{H\_CDEB} + R_{internal}} \tag{3}$$

$$I_{LOAD} = \frac{V_A}{R_{H\_CDE} + R_{CDE}} \tag{4}$$

In this mode of operation, to obtain each current, the VA voltage must be obtained first, and the associated parameter values are shown in Fig. 6(a). By substituting Eqs. 2–4 into Eq. 1 and forming a linear equation, the VA voltage was derived as 12.942 V. Calculating the current at each branch by substituting the derived VA voltages into Eq. 2–4 results in Eq. 5–7.

$$I_{BUS} = \frac{28 - 0.7 - V_A}{109.85m} = 130.703A \tag{5}$$

$$I_{DISCHG} = \frac{-V_A}{22.97m + 78.75m} = -127.231A \tag{6}$$

$$I_{LOAD} = \frac{V_A}{51.3m + 3.68} = 3.468A \tag{7}$$

Second, for the bus voltage source short circuit, Eqs. 8–10 can be obtained from Fig. 6(b).

$$I_{BUS} = -\frac{V_B + 0.7}{R_{HIPDU}} \tag{8}$$

$$I_{DISCHG} = \frac{V_{OCV} - V_B}{R_{H\_CDEB} + R_{internal}} \tag{9}$$

$$I_{LOAD} = \frac{V_B}{R_{H\_CDE} + R_{CDE}} \tag{10}$$

In this mode of operation, to obtain each current, Eqs. 8–10 are substituted into Eq. 1 to obtain the VB voltage first, and the values of parameters shown in Fig. 6(b) are also substituted. The calculated VB voltage and the current at each branch are presented in Eq. 11 and Eqs. 12–14, respectively.

$$V_B = 0.511967 \times V_{OCV} - 0.331854 \tag{11}$$
$$I_{BUS} = -4.66060 \times V_{OCV} - 3.351352 \tag{12}$$
$$I_{DISCHG} = 4.797808 \times V_{OCV} + 3.321412 \tag{13}$$
$$I_{LOAD} = 0.137209 \times V_{OCV} - 0.088938 \tag{14}$$

Adding the two cases, Eq. 15~17 can finally be derived as below.

$$I_{BUS} = 127.352 - 4.66060 \times V_{OCV} \leq 3.8A \tag{15}$$
$$I_{DISCHG} = -123.910 + 4.797808 \times V_{OCV} \tag{16}$$
$$I_{LOAD} = 3.379062 + 0.137209 \times V_{OCV} \tag{17}$$

Because the current supplied from the bus is limited to 3.8 A by the current limiting charger in the IPDU, the OCV of the battery must be greater than 26.510 V for normal load operation according to Eq. 15. If the battery OCV is greater than 26.510 V, the current supplied by the battery is 3.80 A and the current supplied to the load is 7.6 A.

3.2 Mode 2) CDE Battery Charging (Load SW Off)

The SW = 'OFF' mode, which results in the battery charging operation, can be expressed as a simplified DC equivalent model, such as Fig. 7, and the charging current of the battery can be calculated with Eq. 18. The charging current of the battery is limited to 3.8 A by the limit current of the IPDU Charge Block. Therefore, the battery OCV under the boundary conditions is 26.496 V, as derived from the aforementioned equation, and the battery charging current is 3.8 A or less at higher voltages. The importance of deriving the battery OCV from the current and boundary conditions of the battery discharge and charge modes are as follows: First, to prevent stress from the IPDU Charger Block owing to over-current charge before the battery is mounted during ground testing. Second, to determine the mounted battery voltage considering the self-discharge characteristics, because the CDE battery is not charged separately before satellite assembly and launch. Finally, to ensure a range of motion and a critical parameter (CP), or risk management for stable operation of the CDE operational system in orbit. Values set to CP are protected by algorithms defined in the relative time command sequence (RTCS) without ground commands in the event of a hazardous operation.

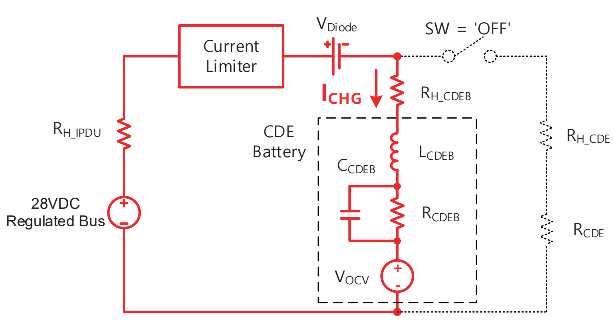


Fig. 7 SW = 'OFF' Mode with Charging the Battery

$$I_{CHG} = \frac{V_{BUS} - 0.7 - V_{OCV}}{R_{H\_IPDU} + R_{H\_CDEB} + R_{internal}} \leq 3.8\,A \quad (18)$$

$$V_{OCV} \geq 26.496V$$

Furthermore, in this system, consisting of regulated bus power, batteries, and CDE loads, the battery is a structure in which the voltage drop by harness resistance, and the forward voltage drop of the anti-reverse diode cannot be more than the above voltage. Following this principle, the second mode, charger mode, in which the load SW if switched OFF and is purely battery charged, the battery OCV operates in constant current (CC) mode and 27.3 V constant voltage (CV) mode at or under 26.496 V. Therefore, to solve the problem of determining the limited current size of the battery's charger block, the battery charge/discharge current and the load supply current size should be considered.

3.3 Analysis of the Minimum Voltage of Battery to Satisfy the Operational Voltage of CDE

If the CDE battery is over-discharged, the current supplied from the bus is operated in CC mode due to the current limiter, which can be interpreted as a constant current source that supplies 3.8 A, as shown in Fig. 8. The battery voltage, which is a CC source of operation, is derived from the formula in Section 2.2, and is approximately 26.5 V. Eq. 10 represents the case in which the battery voltage drops to 24 V due to continuous use of CDE loads or rapid load increase. The maximum value of the load current is 7.61 A; the current discharged from the battery is 3.81 A; the CDE input voltage, i.e., the voltage supplied to the load, is 23.22 V. However, in this case, the minimum operating voltage range required by the CDE load is not achieved; thus, CDE battery voltage must be managed by classifying it as CP in the satellite. The battery voltage should be greater than 25.78 V according to Eq. 19 to meet the minimum voltage required by the CDE load.

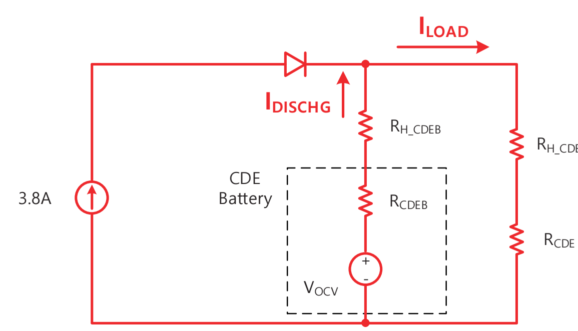


Fig. 8 Simplified DC Equivalent Model for Over-discharging CDE Battery

$$I_{DISCHG} = I_{LOAD} - I_{BUS}$$
$$V_{CDE} = V_{OCV} - I_{DISCHG} \times R_{CDEB} - I_{LOAD} \times R_{H\_CDE} \quad (19)$$

4. CDE Power Conditioning System Interpretation

To analyze the satellite payload CDE power conditioning systems, TINA-TI Spice simulation tools were configured, which schematic is separated with three sections, current limit charger, battery R-L-C impedance model and pulsation current load of CDE as shown in Fig. 9.

Two different simulation is performed to confirm how different the variation in voltage supplied to CDE load without battery and the variation in voltage supplied to load when battery is introduced. Similarly, the OCV voltage status of the battery that meets the CDE minimum operating demand voltage was determined in this simulation by examining the margin that performs the current limit charge.

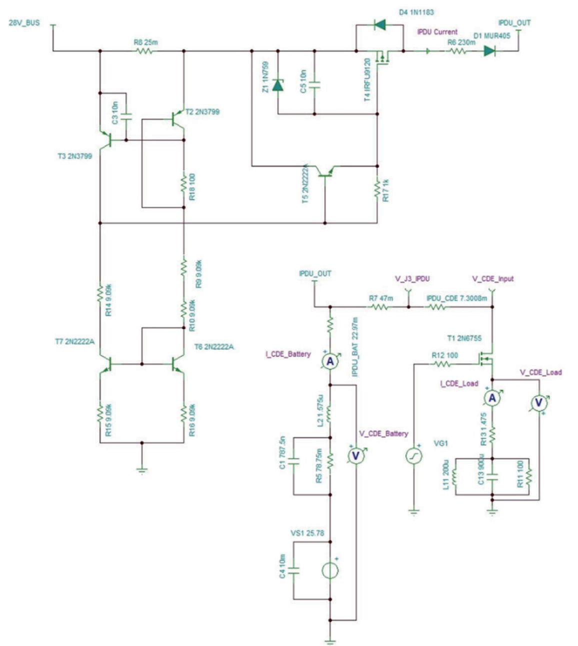


Fig. 9 Simulation Schematic for CDE Power Conditioning System

4.1 Simulation Case without Battery

In this satellite payload CDE power conditioning system, the battery is operated as a buffer to reduce the variation in the load supply voltage; thus, when there is no battery, the load input voltage is large, as shown in Fig. 10. This is because the p-MOSFET on the load side is operated in the active region due to the 3.8 A limited operation of the IPDU internal current limit charger.

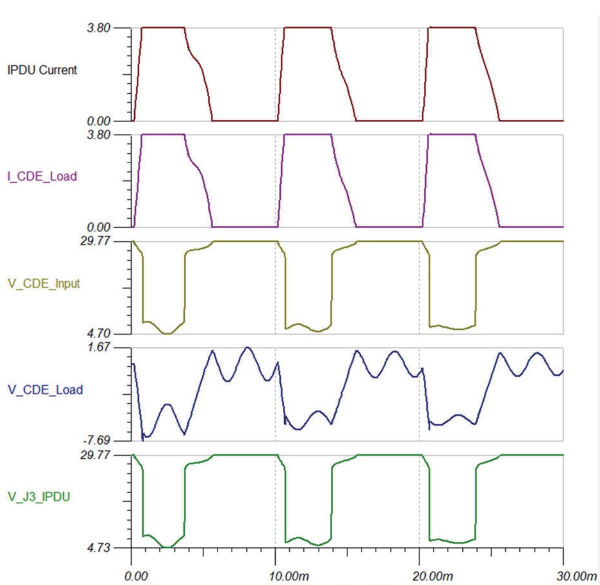


Fig. 10 Simulation Results of CDE Power Conditioning System without Battery

4.2 CDE Operational Minimum Range Simulation

According to the design of Section 2.3, for normal operation of CDE loads, the minimum applied voltage must be greater than 25 V, and the OCV voltage, which indicates the state of charge of the battery at that time, must be 25.78 V.

Figure 11 shows a simulation of the input voltage applied to the CDE when the battery OCV is 25.78 V, and the first waveform shows that the OCV voltage is less than 26.5 V, limiting the current supplied by the regulated bus to 3.8 A owing to the operation of the current limiting charger. Similarly, if the load SW is switched off, it can be observed that the charged battery is also charging the CC at 3.8 A. The second waveform shows the current supplied by the battery to the load, and confirms that it is discharging at the peak, when the current is 3.81 A, due to the current distribution. In addition, the fourth battery terminal voltage is important for battery voltage control, indicating that the terminal voltage is 25.5 V when the OCV voltage is 25.78 V. This voltage allows for the determination of the CP voltage, which can be derived from the CDE battery EMF (Electro-Motive Force) versus SOC (State Of Charge) curve and the battery nominal capacity information in Section 4.3.

The fifth waveform shows that the input voltage applied to the CDE varies from 25 V to 26.17 V, and meets the minimum applied voltage for normal operation of the CDE load.

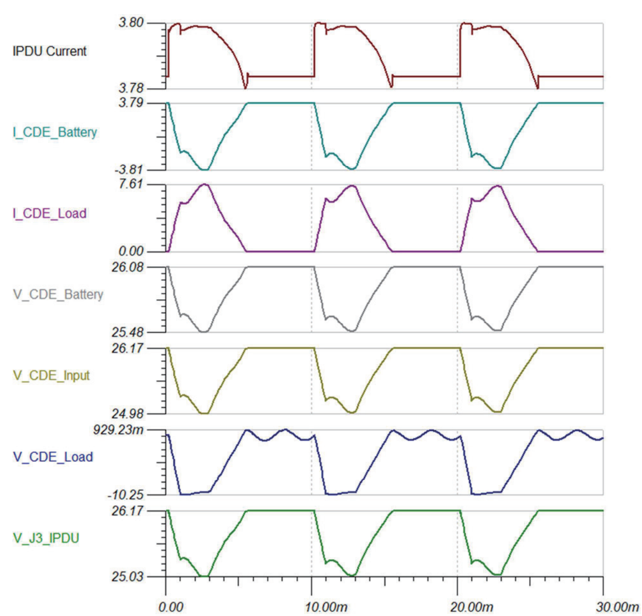


Fig. 11 Simulation Results for the Minimum Operational Voltage of CDE Load

4.3 Setting CP Voltage According to Battery Charge Time

The existing satellite programs using CDE batteries have set the CP CDE battery voltage, which is set to perform battery over-discharge protection and CDE load normal operation to

24 V. However, if the CP operation voltage is set to 24 V, the battery terminal voltage derived from Sections 3.3 and 4.2 must reach 25.5 V to achieve the minimum required voltage of 25 V for CDE load and this takes approximately 18 min. Through this value, the time it takes for the nominal 12 Ah battery from the CDE battery EMF versus SOC curve of Fig. 12 to charge from 18.5% SOC to 28% SOC with a 3.8 A CC can be derived. Setting the CP voltage too low requires time for purely charging and stopping load operations to perform normal operation of CDE loads, and thus the corresponding charging time should be considered from a satellite operation perspective. For satellite operation that does not consider charging time, the CP voltage can be set to 25.5 V, and if it is possible to secure a separate battery charging section, there is no danger with battery over-discharge protection even if it is set to 24 V.

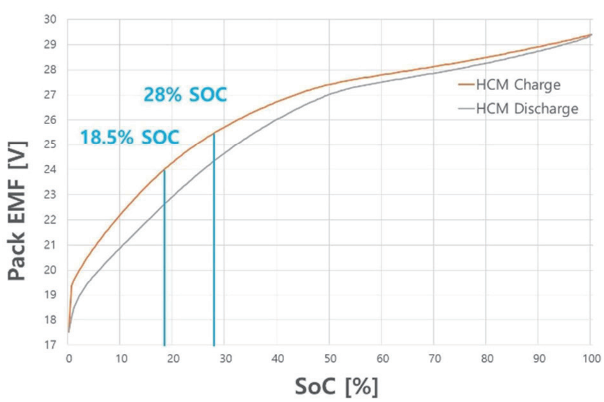


Fig. 12 EMF vs. SOC Curve for 7s8p CDE Battery

5. Conclusions

In this study, we analyzed and interpreted the operating mode of the battery power conditioning system used for power supply and power stabilization of CDE unit for maintaining low temperature of the payload IR sensor. According to this mode analysis and interpretation, the SOC of the battery in the CDE power conditioning system determines the operation of the current limiting charger as well as the boundary voltage of the CC charging mode and CV charging mode. In addition, the battery OCV, which depends on the SOC of the battery, is a major parameter that determines the minimum operating demand voltage of the CDE unit, and the CDE unit cannot perform normal operation if the battery discharges at a significantly low voltage. Therefore, battery charge status management and battery voltage monitoring are important for stable mission operation.

To determine the charging voltage of the battery, it is necessary to know the charging time to reach the minimum required voltage of the CDE load upon charging at 3.8 A as well as the CDE load use time in orbit. In future studies, we will derive the optimal CP voltage from an operational aspect perform system level tests in satellite.

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