General

JERG-2-214

DESIGN STANDARD

POWER SUB SYSTEM

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Japan Aerospace Exploration Agency

This is an English translation of JERG-2-214. Whenever there is anything ambiguous in this document, the original document (the Japanese version) shall be used to clarify the intent of the requirement.

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1. Scope of application

This Design Standard was established for the purpose of being applied to the power subsystem design of spacecraft developed by the Japan Aerospace Exploration Agency (JAXA). The contents of this Design Standard specify the major requirements to be applied to the design and development of a spacecraft power subsystem.

2. Applicable documents

JERG-2-200	Electrical design standard
JERG-2-211	Electrostatic charge and discharge design standard
JERG-2-212	Wire derating design standard
JEGR-2-213	Insulation design standard
JERG-2-215	Solar Paddle Subsystem Design Standard
JMR-001	System safety design
JMR-002	Rocket payload safety standard

3. Terms, definitions and abbreviations

3.1 Definitions of terms

Explanations and definitions of the terms used in this Design Standard are given below.

(1) Analog Type

Is a type of power control by which the control elements are used in their linear region.

(2) Albedo (of the earth)

Is the intensity ratio of the light reflected from the earth to the incident light from the sun and varies greatly depending on various factors. Cannot be ignored for a low orbiting spacecraft as a heat input, etc.

(3) Regulated Bus

Is a type of bus in which the bus voltage supplied to the load is kept nearly constant by the power subsystem.

(4) Umbilical Cable

Is a cable to electrically connect the rocket and AGE (aerospace ground equipment) and has the function of being disconnected at a prescribed time during launch of the rocket. In addition to supplying power from a ground power source to the rocket or spacecraft, it transmits various signals necessary for launch operations.

(5) Energy Density (Specific Energy)

One of the performance indices of a power subsystem (power controller, solar array wing/cell, battery/cell, DC/DC converter, etc.) indicating the stored energy per unit mass or volume. Its unit is Wh/kg or Wh/liter, sometimes differently used as specific energy for the former and as energy density for the latter. For a battery/cell, it refers to the discharge energy in actual operation and is sometimes multiplied by depth of discharge to show usable specific energy or usable energy density.

(6) Ground (Umbilical) Power

Is ground power to supply power to the spacecraft through an umbilical connector until just before launch of the rocket. It generally supplies bus equipment power and battery charging power to the spacecraft.

(7) Pyrotechnics

Refers to an explosive processed in accordance with the intended use; in this Standard, it refers to such a device that has a built-in bridge wire and is detonated by an electrical signal {electro-explosive device (EED)}.

(8) Over-charge

Refers to charging further after fully charged. A sealed battery has an over-charge resistance in the specified range of current, temperature, etc. An excessive over-charge exceeding the range lowers the life characteristics.

(9) Over-discharge

Refers to discharging the battery beyond the depth of discharge allowed by the design. A further discharge can incur the risk of causing a reversal charge.

(10) Conditioning

Refers to the operations to bring the battery to a usable state after it is stored or unused (not charged) for a long time by charging and discharging it in the specified way.

(11) Solar Array Simulator

Is AGE that simulates the voltage-current output characteristics of a solar array as to its BOL, EOL, etc. In a ground test it supplies power to the spacecraft instead of the panel.

(12) Reversal Charge

If the battery consists of cells of uneven capacity, the cells with small remaining stored charge reverse their polarity by continuing to discharge even in a state where the battery sustains the discharge voltage.

The reversal charge reaction can incur the risk of causing an irreversible change, gas generation, etc. in such a cell.

(13) Cant

Refers to a wing shape where the wing shaft is not contained in an extension of the panel plain.

(14) Light Load Mode

A mode to force the on-board equipment load power to a minimum if it is difficult to supply power from the power subsystem.

(15) Nominal capacity (rated capacity or name plate capacity is also used)

The nominal value used to show the battery capacity. Generally, about 80 to 90% of the initial capacity under the specified temperature and charge and discharge conditions is used. It is used as a reference for setting the depth of discharge or charge and discharge rate and is also called rated capacity. Its unit is Ah.

(16) Cold Launch

A launch with each piece of spacecraft equipment not powered up during the flight of the rocket.

(17) Sequentially Control Type

A type of control in which the control elements, etc. are controlled in a sequence. In this type of control, for example, the solar array is divided into multiple array circuits, each of which is equipped with a shunt and controlled in a sequence.

(19) Self discharge

Refers to a decrease in the remaining charge of the battery without current being taken out by an external circuit. The decrease rate is generally larger at higher temperatures.

(20) Shunt (regulator) type

A type of control in which the output current of the solar array is split (and shunted) to the control elements and the shunt currents are controlled so that the power bus voltage takes the prescribed value. The solar array output end and a load are directly connected by a power supply line (Direct Energy Transfer) without passing through a control element.

This type of control is used to treat the surplus power of the power source, so it is not commonly used for power regulators of commercial power. A simple constant-voltage (Zener) diode circuit to obtain a reference voltage falls under this type of control.

(21) Shadow diode

Is a diode connected to an array circuit of a potentially shadowed solar array with the reverse polarity in the series direction of the cells and in parallel with that array circuit. It lets the current of the array circuit flow while bypassing shadowed solar cells and, in addition, suppresses the heat generation, etc. of the shadowed array circuit.

(22) Charge/discharge rate

Refers to indicating a charge or discharge current using hour rate and nominal capacity. The t-hour rate is equal to the current value obtained by dividing the nominal capacity by t and is expressed as C/t using the nominal capacity C.

(23) Series (regulator) type

A type of control in which a control element is inserted in series in the power supply line from the solar array to the load side to control the difference between the solar array end output voltage and the prescribed power bus voltage.

This type of control is widely used for commercial power. Because a control element of an analog type will adjust the voltage drop, it is sometimes called a dropper.

(24) Switching control type

Is a type of power control in which the control element is used in the ON/OFF region. In contrast to the analog type, it is sometimes called a digital type.

(25) Skew

A solar array wing shape that does not allow the pitch axis of the spacecraft to coincide with the rotation axis of the solar array wing.

(26) Sneak circuit analysis

Techniques to ensure the safety and reliability of the system by identifying and removing a potential state (called a sneak circuit) bringing about a current flow, status change, etc. which causes the occurrence of an unintended function, suppression of a desirable function, or the like. A sneak circuit is apt to occur when turning on or off or changing over the power, return, etc. or changing equipment connections, or connecting or disconnecting a connector, etc.

(27) Thruster plume

A flow of hot gas particles ejected from the thruster. Becomes a contaminant for a solar array, thermal bracket, optical sensor and other spacecraft part exposed outside.

(28) Battery cell

Individual cells making up a battery. Generally, it is called simply a cell.

(29) Solar simulator

An artificial light source to simulate and generate the irradiation light intensity and spectral radiant distribution of AM0 (air mass zero) sunlight. Also called an artificial solar radiation source or simulated sunlight source.

(30) Solar constant

Is the solar radiation energy received during a unit length of time by a plane of unit area perpendicular to the solar rays at the top of the earth's atmosphere (at an altitude of 80 km or more from the earth's surface) when the earth is at the mean distance from the sun and is called AM0. For details, refer to JERG-2-141 Space Environmental Standard. The sunlight in the neighborhood of the earth exhibits seasonal variations of ±3% (approximately +: winter solstice / -: summer solstice) due to earth-sun distance variations. For this reason, the solar array output generally becomes minimum around the summer solstice at EOL. Therefore, the maximum and minimum sunlight intensities are (1366±10W/m^2) × (seasonal variation due to sun-earth distance change) including the uncertainty in the solar constant. Assuming that on the earth it is 1, the amount of solar radiation on other planets is as follows: 6.7 on Mercury, 1.9 on Venus, 0.43 on Mars, 0.04 on Jupiter, and about 0.01 on Saturn.

(31) solar array wing (paddle)

Is an inclusive term for a solar battery and a structural body supporting it and it has a shape where it juts out of a spacecraft like the wing of a boat, hence the name.

(32) Solar array

Inclusive name for the power generation circuits of a solar array wing.

(33) Majority vote redundancy

One of the redundant configurations. Is employed in the case where normal output cannot be judged with simple parallel redundancy. In the power subsystem, it is used in the voltage detection section of voltage control and generally has a configuration where the output of three detection sections is judged by a majority circuit. In this case, a failure of one detection section is allowed.

Another example is on-board computers, which have a majority configuration of three units, five units, etc. depending of the allowed number of failures. Such a redundant configuration needs to provide a means to ensure in advance that each individual function is normal. The function of making a majority judgment of multiple inputs can become critical if it fails.

In a power subsystem, it is used mainly in an error amplifier circuit of bus voltage control.

(34) Stored energy

Refers to the energy a battery or a battery cell can deliver at a specified or higher discharge voltage starting from a fully charged state. Its unit is Wh and it is calculated as the product of mean discharge voltage and capacity.

(35) Charge array

A type of charge control in which the charge current is set to a prescribed value using the current (limited) region of the voltage-current characteristics. It is often employed in a geostationary orbit spacecraft using a relatively low charge current.

(36) Dead band

A non-operating region of control, set between operating regions of charge and discharge control or solar array output control to prevent operations from interfering with each other harmfully. A similar term “dead zone” is used in general control theory and it refers to one of the nonlinear characteristics of a control element. Incidentally, it is a synonym for dead zone from a comprehensive viewpoint of power control in which charge and discharge control and panel output control are considered as control elements.

(37) DC/DC converter

A circuit or device which makes a control element operate on the input voltage of DC power on the switching mode to convert it into a different DC output voltage. The DC power is converted inside by switching into an alternating current, which is converted again into a direct current and delivered. Multiple output voltages are used in many cases, so the converter is indispensable in a spacecraft for the function of obtaining output voltages suitable for the operation of IC, operational amplifier, TWT and other electronic devices from an input voltage of several ten volts or more. There is the isolated type, in which the output is isolated from the input, and the non-isolated type. Generally, the isolated type is required for equipment other than a power subsystem according to the specifications, etc. of the Electrical Design Standard.

(38) Battery charge method

(a) Constant current charge

Generally, refers to a charge method in which charging takes place with a constant battery charge current.

(b) Constant voltage charge/taper charge

Generally, corresponds to constant voltage charging in which charging takes place at a constant battery voltage. Has this name because the charge current usually decreases exponentially during a constant voltage charge.

(c) Trickle charge

Refers to charging with a very small current continuously or intermittently to make up for the self-discharge of the battery and always keep it in a highly charged state.

(39) (Primary) power bus

The line to make a solar array and battery and these power sources’ power control functions operate in a coordinated way.

The required power of a spacecraft is supplied from this bus through the power distribution function.

(40) Transient

Is transient characteristics and refers to the voltage/current change occurring at a transition from a steady state to other modes.

Other modes include also a transient due to an abnormality disturbance and test disturbance.

(41) Missing number

(42) Secondary cell

Refers to a cell that can be used repeatedly by recharging (rechargeable cell).

(43) Partial shunt type

A type of control in which a shunt tap is taken from the middle of the solar cell string to reduce the number of shunted cell tiers with the aim of reducing shunt power and process power.

(44) Battery simulator

AGE that simulates the charge and discharge characteristics of a battery to evaluate the charge and discharge control by a ground test, regardless of the state of charge of the battery.

(45) Unregulated bus

A type of bus in which the bus voltage supplied to the load varies in a relatively large way.

(46) Specific power (or specific output)

Is a performance index of a solar panel (wing) and shows the output power per unit mass or unit area. Its unit is W/kg or W/m2. For batteries as well, the specific power per unit mass is sometimes used as a performance index. In this case, the operating conditions (depth of discharge and discharge time) are involved.

(48) V/T curve

For a charge without imposing excessive stress on the battery, the charge current is reduced after the battery voltage has reached a specified value. The specified voltage value is shown by this. This is called a voltage-temperature curve because the specified value is compensated for temperature considering the temperature characteristics of the battery and its abbreviation is used. Also called a V/T level.

(49) Multiple power bus configuration

A configuration in which there are multiple power lines (power supply buses) and each line supplies power to its load. Each power line does not necessarily have the same configuration or characteristics (different bus voltages suitable for the load are supplied).

(50) Boost converter

Is a kind of DC/DC converter and is a circuit or device to convert the input voltage into a higher voltage. It is often used for the discharge control function of the regulated bus type, and the non-isolated type is generally employed for efficiency and other reasons.

(51) Full charge

Refers to charging a battery to the fully charged state. The charge current value at which the charge proceeds rapidly is called the full charge current. Under actual operation conditions, if a charge with the full charge current is continued to the fully charged state, the battery experiences unnecessary stresses due to a temperature rise, etc. Therefore, except for an evaluation test on a cell proper, the state of charge is monitored and the charge current is reduced.

(52) Blocking diode

A diode to prevent reverse flow of current, it is also called a reverse current prevention diode. It is attached to the output end of a solar array or battery connected in parallel.

(53) Depth of discharge

The ratio of the amount of discharge (electricity) to the nominal capacity of the battery, expressed as a percentage. Also called DOD. SOC (state of charge, remaining stored charge), which is the ratio of the actual state of charge to the charge complete state (fully charged state) expressed as a percentage, is often used as an index to show the state of the battery.

(54) Hot launch

Refers to a launch with each piece of spacecraft equipment powered up during the flight of the rocket.

(55) Bonding

Refers to sustaining electrical conductivity between equipment and system structures to prevent accidents associated with a lightning discharge, static electricity, lightning stroke, or other similar event and suppress electromagnetic interferences.

(56) Full charge state

The state of a battery being fully charged. A charge procedure or other similar document generally gives a criterion to judge that full charge is reached.

(57) Memory effect

A phenomenon in which a battery exhibits a lower discharge voltage than normal during a discharge due to the operating conditions, hysteresis, etc. Removal of this phenomenon can be expected by reconditioning.

(58) UVC (under voltage control) function

A function for battery over-charge prevention. It monitors the terminal voltage of a battery, battery cell or battery cell group and reduces the load power when the terminal voltage falls under a certain value.

(59) Capacity

The amount of electricity a battery (battery cell) can deliver at a specified or higher voltage (for example, 1.0 V/cell) starting from the charge complete state. Sometimes called actual capacity. Its unit is Ah.

(60) Reconditioning

When the discharge voltage or remaining stored charge of a secondary battery drops by memory effect or such phenomenon is expected, the battery is temporarily discharged to a deep depth of discharge with a very small current in order to recover the battery characteristics.

(61) Ripple and spike noise

Refers to periodical voltage variations superimposed on the bus voltage.

(62) Lock-up

Refers to entering the following situation: the solar array operating point, which is determined as the intersection of the characteristics of the solar array, charge and discharge control, loads, etc., does not transfer to the appropriate position, and while there is sunshine, discharge control operates regardless of whether the load power and charge power can be supplied by the panel. The load power is adjusted (reduced) to make a transition to a normal state or other measures are taken.

3.2 Abbreviations and symbols

[Abbreviations (alphabetical order)]

• AGE	Aerospace Ground Equipment	AGE
• AM0	Air Mass Zero	Solar constant in vacuum space (without atmospheric attenuation)
• BOL	Beginning of Life	Beginning of life
• DOD	Depth of Discharge	Depth of discharge
• EMC	Electro Magnetic Compatibility	Electromagnetic compatibility
• EOL	End of Life	End of life
• EPS	Electrical Power Subsystem	Electrical power system (it is a subsystem)
• ESD	Electrostatic Discharge	Electrostatic discharge
• FMEA	Failure Mode and Effects Analysis	Failure mode and effect analysis
• GEO	Geosynchronous Earth Orbit	Geostationary orbit
• ICD	Interface Control Documentation/Interface Control Drawing	
• LEO	Low Earth Orbit	Low earth orbit
• LLM	Light Load Mode	Light load mode
• SOE	Sequence of Event	A correspondence table of events and their times
• UVC	Under Voltage Control	Under-voltage control

[Symbols]

• Ah: Unit of electrical charge It is the product of current and time (ampere-hours) and is used as a unit of battery capacity, etc.
It is related to the coulomb, a unit of electrical charge: 1 Ah = 3600 coulombs.

• C: Symbol to denote the charge and discharge rate using the nominal capacity.

• Wh: Unit of energy. It is the product of electrical power and time (Watt-hours) and is used as a unit of discharge energy, stored energy, etc. of a battery.
The discharge energy of a battery is the product of the amount of discharge and (mean) discharge voltage.
It is related to the joule, a unit of energy: 1 Wh = 3600 joules.

4. Design requirements

4.1 General

A spacecraft power subsystem has the role of supplying electrical power necessary for the spacecraft without interruption within the prescribed voltage characteristics throughout the entire mission period. The definitions, intrinsic properties, design restraints to be considered when designing a power subsystem to implement this requirement and related considerations are described below.

4.2 Definitions and restraints of items

4.2.1 Configuration and components

A schematic example of a spacecraft power subsystem configuration is shown in Figure 4.2-1. This document covers those parts of the instrumentation subsystem which are related to power and those parts of a solar array wing or load equipment which are related to the interface requirements and defines them as a power subsystem. The power subsystem performance requirements required in this document are applied at the power output interface point. For the solar paddle subsystem, refer to JERG-2-215.

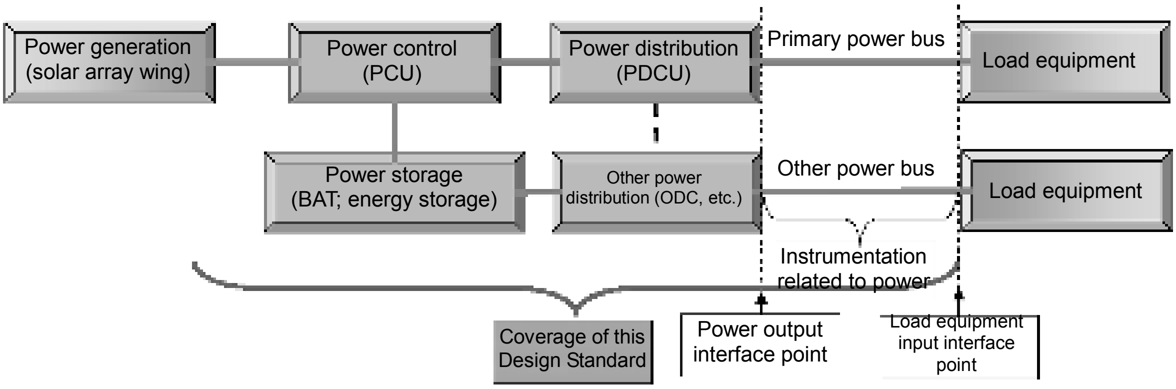


Figure 4.2-1 Schematic diagram showing example of power subsystem configuration

As shown in Figure 4.2-1, a power subsystem is made up mainly of the following functions:

(1) Power control function (including surplus power control, bus voltage control and battery charge and discharge control)
(2) Power storage function
(3) Power distribution function (including power supply to pyrotechnics and voltage conversion for other power buses[*Note 1])
(4) Protection related to the above, i.e., failure and abnormality limiting function (this is implemented as a function in the configuration of the three functions above)

Note 1: Other power buses refer to the power buses of voltages used in the past (28V, 50V, etc.).

For a specific power subsystem architecture (selection of bus voltage, regulated/non-regulated bus type, multiple bus type, etc., design of hardware and software components, implementation techniques (circuit type), etc.) to implement the functions above, the selection should be made in light of the requirements and restrictions at the spacecraft mission level. As a selection example, the following may be included.

- Power control function

  (Solar array power generation and voltage control type)

  a. Series control type

  b. Shunt control type

  (Digital sequential shunt type and analog partial shunt type)

  c. Peak power tracking control type

  (Battery discharge type)

  a. Floating type

  b. Step-up or step-down converter regulation type

  (Battery charge type)

  a. Charge array type

  b. Charge regulator type

- Power storage function

  (Selection of power storage element)

  a. Nickel-cadmium battery

  b. Nickel-hydrogen battery

  c. Lithium ion battery

- Power distribution function

  Includes the following functions:

  b. Over-current protection function

  b. Multiple bus isolation and coupling function

  c. Bus changeover function in case of the backbone distribution type

  e. Others

- Related considerations -

If the peak power tracking type is selected out of the power control function class, it is difficult to keep track of the operating point on the solar array V-I curve. Hence, it is difficult to predict and manage the maximum possible power generation in response to on-orbit degradation and in response to using voltage and current telemetry of the solar array itself. For a spacecraft which requires prediction and management of possible on-orbit solar array power generation, it is recommended to take prediction and management measures by mounting a monitor cell or using other means.

4.2.2 Operation mode and transition conditions

The operation modes of the selected power subsystem and their transition conditions should be clarified, and the relationship with the operation state of components and its confirmation method, etc. should be clarified by telemetry data and status to make clear the specification of the characteristics, etc. described below. As a related consideration, an operation mode example is shown below.

- Related considerations -

The definition of operation modes of a power subsystem should be described to make clear the specification of the characteristics, etc. described below. An operation mode example is shown below.

- During the launch
  Charge by ground equipment, change over from ground power to battery, battery off/automatic on during cold launch, etc.
- When in a transfer orbit
  Pyrotechnic ignition, wing deployment, orbit or attitude change, etc.
- When in a stationary orbit
  Charge (constant current/constant voltage/voltage control/trickle charge), shunt operation, reconditioning/battery off, discharge in a penumbra or during an eclipse, etc.
- When protection function is in operation
  Load abnormality, UVC, battery temperature abnormality, etc.
  When using a special term, abbreviation, etc., its definition should be shown.

4.2.3 Definition of interface

Define the interfaces of the power subsystem with the spacecraft system, its related subsystems, etc. and specify their requirements, restrictions, common design standard, information about interface FMEA, etc. In the spacecraft system, these are organized into ICD (interface control document/drawing) or other documents and managed collectively.

(1) Electrical interface

a. Power supply

For power supplying bus power lines (including redundant lines), specify the diagram of the interface with every piece of equipment (including the presence/absence of a relay, fuse and current limiter) and the mean and peak of supplied power to each piece of equipment (including the causal factors, period, duration, etc. of the peak). For the power consumption of a component of the power subsystem, separately specify it together with similar specifications.

Of the power supply characteristics, specify the input end voltage on the load side besides the bus voltage reference point. Besides the on-orbit supply characteristics, specify the transient at power-on from zero volts, which cannot be avoided in a ground test, and at power-off at an emergency, etc.

For electromagnetic compatibility and power control design analysis, the power input impedance on the load side should be presented.

- Related considerations -

The specifications for power supply are design requirements for the power subsystem and power distribution, and they specify the upper limit in the design stage and are taken as a reference to confirm that the subsequent power supply level updates in the development stage are within the upper limit. In connection with this, the supply (consumed) power serves as source data of a required power profile. As such and as an allocation item of the system, it is desirable to separately specify and manage it using a table, clearly describe the grounds for the setting (prediction/measurement, etc) in the remarks field, and update the specified value as well as review the description as the development stage proceeds.

For the specification of supply characteristics, pay attention to matching with the load-side interface besides the power supply bus output characteristics. For this purpose, set this specification considering the line drop of the system harness. Separately specify the conditions at power-on or power-off during a ground test to prevent equipment damage, status change or other similar situation which could occur at power-on/power-off if designed only with always on on-orbit conditions. In the design of AGE, ensure that an excessive inrush current, which however will not occur during actual operation, is not applied to the power subsystem equipment.

b. Telemetry/command

For telemetry, select items for which it is possible to monitor the health check of functional operation, performance and equipment operation and the supply power flow (power control, power storage and load power supply), and all telemetry specifications (analog/digital distinction, sampling rate, accuracy, etc.) and their content should be clarified. For a command to set a power subsystem operation, verify telemetry should be issued by which the result of its execution (change of operation states) can be known. For especially important items, ensure that a redundant telemetry or a cross check with other items is possible.

For a command, clarify the command specifications (discrete/serial distinction, parameter setting accuracy, etc.) and its content (the functional operation set by the command). Exclude any single command that can damage the power subsystem or bring it to an unrecoverable state.
For the operation state of an automatic judgment function (over-voltage and over-current protection functions, etc.) of the power subsystem, pay attention to a telemetry output by which operation can be confirmed and a reset function triggered by a command.
For the details of telemetry/command item setting standards and electrical interfaces, conform to the specifications of the Signal Interface Example (JERG-2-200-TM001), etc. Telemetry/command is a system allocation item, so it should agree with the specifications for it.

Telemetry items whose output is recommended for the power subsystem are given below.

- All function settings, operation statuses and on/off status of the power subsystem
- Main bus voltage (including secondary bus voltage)
- Bus voltage error amplifier output signal
- Overall load supply current (should have a resolution that is sufficient to keep track of the load behavior. If necessary, divide into multiple load supply groups and obtain the load supply current of each. The same applies to the secondary power bus current.)
- Shunt current and shunt drive signal
- Overall generated current of solar array (if the current on the RTN side is to be detected, the structure short-circuit current can be calculated from the load supply current, shunt current and battery charge current values.)
- Battery voltage (individual battery cell voltages or unit group voltage as the need arises) and battery charge and discharge voltages
- In case of a Ni-H_2 battery, the internal pressure of at least one battery cell per battery assembly

The temperature at a reference point of each component and, for a battery assembly, the temperature at a representative point in the assembly (main redundant configuration is desirable)

c. Control signal

For an interface related to control signals between the power subsystem and another subsystem, specify its functions, boundaries, electrical characteristics, sending and receiving circuits of the signal, comprehensive signal lines and operations, etc. In some types of design such as integrated design, an algorithm processing component belonging to another subsystem performs control related to a power subsystem function based on power subsystem telemetry. For these control signals as well, specify their lines and operations. In this case, operation control takes place not by individual control signals but by on-board commands in some types of design. However, clearly specify those control signals as a function also in the control signal category.
The control signals include the following, for example,

- LLM signal
- Spacecraft separation signal
- Solar array wing deployment signal

- Battery charge voltage control (V/I control)[Note 2]
- Battery reconditioning control[Note 2]
- Battery high temperature protection[Note 2]
- Heater on/off control[Note 2]

Note 2: For the functions formerly implemented by hardware of the power subsystem but now, through integration, etc., implemented by processing of computer software or other subsystem, make sure there are no omissions.

- Related considerations -

Control of related and coordinated signals of these multiple subsystems takes place at the system level. For a design change to one subsystem, in particular, it should be possible to judge the effect on the involved subsystems, comprehensive function ensuring, etc. quickly and appropriately. For this purpose, the related matters should be specified also in the specification, etc. of the involved subsystems from a comprehensive point of view.

For the simulated signals needed when testing these control signals, consider their generation method, etc. in advance from the design stage.

d. Pyrotechnic function

Specify the all power lines (including redundant lines) from the ignition power supply source to the pyrotechnics including the boundary to the power subsystem and relationship with the spacecraft grounding.

Specify the major specifications of the power source, pyrotechnics, relays, anti-static resistances, etc., the battery and ODC input voltages, ignition current and supply duration, and the sequence of operations up to ignition.

e. Grounding

The return of the power supply bus line should be in principle grounded to the spacecraft structure at a single point. For the details of the requirements for grounding, conform to the Electrical Design Standard (JERG-2-200).

- Related considerations -

Grounding should be designed to exclude a place of indeterminate potential with respect to the spacecraft structure and not to let a stray current flow to the spacecraft structure. It is desirable to place the single grounding point so that it is possible to verify that there is no return current. Defective grounding can cause a malfunction, etc. due to electrostatic charge (electrostatic discharge in the worst case). The effects of electrostatic charge and discharge are sometimes examined by an ESD test as a part of an EMC test.

f. AGE

For all items of the spacecraft power subsystem with which the AGE has an interface, specify the diagram, content, specifications (voltage and current ranges, signal pattern, accuracy, etc.) of each component, separately for umbilical cable and for test cable. For the return line of each item, show its relationship with the grounding of AGE and with the spacecraft structure grounding in a systematic way. In addition, show their status and pattern of use during each ground support test and the launch and their treatment while they are not used.

For AGE involved in power supply, provide a treatment to prevent an excessive inrush current, excessive voltage application due to failure or an operational mistake, reverse flow of battery power, etc. and use a design that does not damage the spacecraft. If voltage remote sensing is to take place in supply voltage control, a fail-safe design is necessary in case an abnormality occurs in that connection. If on-board equipment changes its status, etc. at power-on or power-off, it should not be dealt with on the ground side or manual operations but its cause should be searched for and the result should be reflected in equipment design.

- Related considerations -

For the interface with AGE, consider not only the items necessary for power supply and power subsystem state setting (for example, battery on/off) during a test or launch but also the items to make it possible to ensure the comprehensive performance of the power subsystem. It is desirable to clearly describe the relationship of each item with the functional configuration of the power subsystem. For battery-on/off, the design is made so that the state of all batteries can be set by one command because of a restriction of umbilical cable. Pay attention to ensure that internal failure of the spacecraft receiver of that command will not become critical (battery fixed to the off state, etc.).

For grounding, fully know the power lines of test equipment and range equipment and take measures for measured data error prevention, clarification of the power supply return, electrical shock prevention, lightning protection, etc. For power supply in the range (at the launch point in particular), consider the effects of umbilical line impedance.
For a short-circuit or other failure on the AGE side (including its cable), a protective resistor or other consideration is made for the signal line. However, this is difficult on the power supply line, so it is necessary to deal with it on the ground side. In this case, avoid dealing with it by using an operation procedure but reflect it in the device design. If a diode is used for reverse current prevention, etc., pay due attention to its heat generation.

g. Inside the power subsystem

Referring to the configuration diagram of the power system, specify all interface items between components, including the intervening harnesses and slip rings, and the correspondence between shunt operations and arrays through a slip ring (prescribed shunt sequence and shunt operations corresponding to shunt drive elements), etc. Specify detailed specifications in a management document, etc.

- Related considerations -
For the solar array and battery, clearly describe the reference points of output power, etc. and their voltage and current ranges. In solar array output control, etc., the control element and control signal processor belong to different components in many cases. In such cases, it is necessary to specify that interface from the aspect of comprehensive operations of the control subsystem. As for the items involved in the connection, etc. of the solar array and spacecraft, there are items that are difficult to verify by a ground test. For design error prevention, therefore, it is necessary to clarify wire connections and, in particular, the polarity and relationship between return and ground, and the like.

(2) Mechanical interface

For a power subsystem component, specify its mounting position on the spacecraft, including the coordinate axes.
For the mechanical interface between each component and spacecraft structure, show its outer dimensions, the dimensions and reference hole positions of the attachment portion, mass, center-of-mass position, materials used and surface treatment, roughness

and flatness of the mounting surface, and mounting method (bolts, tightening torque, etc.).
Identify the connectors of each component and clarify their compatibility with their counterpart of the spacecraft system. The mass and dimensions of a component are specified along with its physical properties, and this specification must agree with the system allocation.

(3) Thermal interface

For each component, specify the heat capacity, amounts of heat absorption and generation, radiating surface absorptance, amount of heat flux and thermal mathematical model (as necessary), and heater power. As for the amounts of heat absorption and generation, amount of heat flux and heater power, specify them for each operation state.
Show the allowable temperature range and allowable temperature change rate of each component (during storage and transportation, on-orbit operation, at power-on/off, and in non-operating state). For a thermally critical component (battery and the like), specially mention the reasons and requirements for it and show the specifications for the measure to deal with it (active temperature control, etc.).
Clarify the temperature reference point that is basic to the interface. Obtain the temperature at the reference point through telemetry.
For the battery charge operation as a range operation with the spacecraft mounted, pay attention to the possibility of taking an interface which can ensure a sufficient amount of charge for the heat rejection environment during the charge.
In particular, a Ni-H2 battery generates a large amount of heat at the end of charge and due to self-discharge. To sustain a sufficient charge, therefore, it is desirable to keep the ambient temperature environment as low as possible. In some cases, however, it is difficult to keep a sufficient temperature environment for charging a Ni-H2 battery in a mounted state with the air conditioning capacity of the range facility including the fairing air conditioning. Therefore, pay due attention to thermal interface design for range charge from the spacecraft system design stage.

(4) Functional interface

Enumerate the items that functionally interface (coordinate/interfere, etc.) with another subsystem and, if the functional requirement is a requirement from the power subsystem, specify its content and specifications.

- Related considerations -

As a functional interface, the following items, for example, may be cited.

a. Matters with the attitude control subsystem related to a pyrotechnic ignition signal or abnormality
b. Matters related to the supply of bus voltage and (sensor, heater, etc.) power other than pyrotechnic ignition power.
c. Matters related to the spacecraft separation switch
d. Battery charge voltage control (V/T control)[Note 2]
e. Battery reconditioning control[Note 2]
f. Battery high temperature protection[Note 2]
g. Heater on/off control[Note 2]

Note 2: For the functions formerly implemented by hardware of the power subsystem but now, through integration, etc., implemented by processing of computer software or other subsystem, make sure there are no omissions.

(5) Work interface

For each of the components, specify the item name, fabrication number, serial number and other identification for configuration management. As shipment preparation, designate the delivery configuration and specify the history management, handling-related documents and transport and packing method.

In addition, specify the special work in spacecraft integration or a test, support content related to legal procedures, etc. of high-pressure gas, etc. and the points to consider with regards to work safety.

- Related considerations -

For a heavy component, it is necessary to make a design considering not only the actual on-orbit operation state but also the workability on the ground from the viewpoint of weight and dimensions.

4.2.4 Common design standard

In the design of a component of the power subsystem, the following common standard should be complied with.

(1) Electrical design

The power subsystem and each component should be designed to implement the requirements for the electrical interfaces and performance as simply and as efficiently as possible.

The power supply and telemetry/command interfaces should conform to the electrical interface conditions. Design the interface so as to prevent failure propagation.

In response to the presentation of a power input impedance from the load side, verify the electromagnetic compatibility and power control feasibility as the power subsystem.

Set the connector pin arrangement considering the electromagnetic compatibility, redundancy, etc. The use of a fuse and the management of magnetic characteristics should be done according to the Electrical Design Standard (JERG-2-200).

\- Related considerations -

When a fuse has to be used because short-circuit protection measures other than a fuse are not practical as a short-circuit protection means (for example, short-circuit protection measures for an electrolytic capacitor, power transistor, or other similar devices and for a power processing unit), requirements in principle are appended as for the conformance to the criteria set about fuse type, derating, redundancy, etc. and as for a means to judge from outside the equipment whether the installed fuse is good or bad.

As for magnetic management, etc., pay attention to the following in the design of a power subsystem.

a. The power line should be of a twisted pair construction.
b. Ground the return of the power supply bus at a single point in principle (do not use the structure for a return). If, however, a structural body is used as a power return line, do it according to the requirements of the Electrical Design Standard (JERG-2-200) and lay wire along the spacecraft structure to minimize the current loop and harness inductance.
c. For devices that use magnetism (transformer, inductor, etc.), select a construction, etc. of low flux leakage.

(2) Mechanical design

Design the construction of each component based on implementing high-density packing and aiming at compactness and lightness. Considering the prescribed environmental conditions (including not only the mechanical environment but also thermal stress, etc.) and the characteristic change or degradation of the materials used due to this, make a design to satisfy the strength requirements and rigidity requirements for the prescribed load conditions. For a pressure vessel, design it to satisfy the prescribed proof pressure and burst pressure requirements.

The attaching method, etc. should conform to the mechanical interface. For large heavy equipment or a panel or other similar equipment for which an interference is expected with the system structural characteristics or attitude control subsystem, present a structural model and perform a coupling analysis, etc. with the system.

As an example, a Ni-H2 battery is sometimes designed in such a configuration that the battery cells are arranged individually using a battery cell bracket (sleeve) from the point of view of ensuring a heat path for each battery cell. In this case, the vibration mode becomes complex and the stress on the harness between battery cells becomes large. If needed as a result of a coupling analysis with the system, ensure there is sufficient overall rigidity as a battery assembly by having a mechanical design such as mutually connecting the sleeves or otherwise reinforcing them.

(3) Thermal design

Design each component while ensuring that the temperature of a device, etc. used falls within the specified allowable range and minimizing the heat path for a spot of high heat generation in particular.
And, carry out design while considering the characteristic change and degradation of the materials, etc. used due to the prescribed environmental conditions and heat.
Pay attention to prevent the thermal conductivity, etc. from declining due to the mechanical environment.
The attaching method, surface roughness, surface treatment, etc. related to thermal design should conform to the mechanical interface.
For a component with a large temperature gradient across its attaching surface, a modularized power subsystem, a panel, or other equipment exposed to the outer space

environment, present a thermal model and perform a coupling analysis, etc. with the system.
The harness bundles including power wires should satisfy the specifications of JERG-2-212 Wire Derating Design Standard.

- Related considerations -
In the thermal design, heaters are used as a means of active temperature control; however, a thermal design involving much heater power even at EOL is not desirable in view of power budget. Ensure that the maximum generated current value at BOL will not deviate the shunt element's allowable temperatures. From the viewpoint of heat dissipation surface area design, consider the change in shunt current value and thermal control material characteristics from BOL to EOL and consider a combination of design conditions so as not to overdesign.

(4) Electromagnetic compatibility design

Design each component to suppress electromagnetic noise generation and keep it as low as possible and not be influenced by external electromagnetic noise as much as possible. For static electricity prevention, etc., provide the heat control thermal blanket, etc. besides the equipment chassis with bonding according to JERG-2-211. If an insulating material is used for surface treatment, obtain the agreement of the system side.
The requirements of electromagnetic compatibility are specified concerning the following items:

a. Electrical bonding and insulation resistance
b. Conducted noise (in a steady state or during a transient)
c. Conducted susceptibility (ditto)
d. Radiation noise (electric and magnetic fields)
e. Radiated susceptibility (ditto)

The test method is specified in the electromagnetic compatibility document. As a condition, select an operation mode which forms the worst case when conducting the test. (As an example, employ the upper limit of bus voltage if voltage is intended and the lower limit of bus voltage if current is intended. Conduct the test also in operation modes which generate periodical noise or transient noise.)

In a test on a component on the receiving side of a power supply line, use the designated power supply side impedance model.

- Related considerations -
The power supply characteristics of the power subsystem are parameters which determine the limit level of an electromagnetically compatible power line's conducted susceptibility. On the other hand, the requirements for a power line's conducted interference noise are parameters which determine the power supply characteristics of the power subsystem. Therefore, the design of the power subsystem must proceed while considering the electromagnetic compatibility requirements. In a general electromagnetic compatibility design, a specification related to power supply voltage transients sometimes requires an application, etc. of a voltage twice as high as the steady-state voltage. However, this should be specified considering the causes, etc. for the occurrence. The applied level in the test should be consistent with the electrical interface conditions including the allowable setting tolerance of test conditions.
When using a power supply side impedance model, the power supply capacity of the transient inrush current, etc. at power-on are influenced by the power supply capacitance connected to that input side. In the case of the power subsystem, it is also necessary to verify that the bus line transient voltage occurring at a load variation or load failure is kept within the applied voltage level in the steady-state disturbance and abnormality disturbance requirements.

(5) Environmental conditions

For the environment of each component, determine the following items in each stage from testing, storage, transportation, launch to orbit insertion, and on-orbit operation. These are specified as a reference for environmental resistance design.

a. Temperature (should conform to the thermal interface, except for on ground)
b. Pressure (from ground surface to high vacuum state in outer space)
c. Humidity (On ground: Generally 60% or more in relative humidity)
d. Cleanliness (On ground: Generally ISO Class 8 (Class 100 thousand) or higher)
e. Acoustics (applied to exposed area)
f. Acceleration (including the steady acceleration component and low-frequency vibration acceleration component)
g. Vibration (sinusoidal and random: level depends on the mounting position.)
h. Impact (impact associated mainly with spacecraft separation and pyrotechnic ignition: level depends on the mounting position)

i. Radiations (from launch to on-orbit operation)
j. Exposed area environment (excluding acoustics)

For an object exposed outside the spacecraft, an environment under the influence of thermal radiation from the fairing, free molecular flow heating, thermal radiation and jet heating from the rocket, etc., atomic oxygen, meteoroids/debris, solar radiation, terrestrial radiation, and plasma and thruster plume gas around the orbit is specified. The environment of each component should be determined concerning the following items for each stage from testing, storage, transportation, launch to orbit insertion and on-orbit operation and these should be specified as a reference for environmental resistance design.

- Related considerations -
The environmental conditions differ for qualification/acceptance tests and are set with a design margin included. For example, temperature is set as expected maximum temperature ±5°C and vibration or impact is set as expected maximum level plus 3 decibels. However, it is necessary to set them appropriately considering the margin of the expected condition, design impact on the equipment side, avoidance of unnecessary stress application on the flight model (e.g., on the battery, etc.), and others.

(6) Safety design

When developing a power subsystem (fabrication, testing, transportation, unpacking, range work, etc.), analyze the level (catastrophic, serious, critical) of risk items (hazardous substance, explosion, pointed object, heavy object, heat generation, UV ray, electric injury, static electricity, corrosion, rupture, short-circuit, etc.) and their possibility of occurrence and take effective measures (change of materials, etc. used, thoroughgoing danger marking, complete provision of a work environment, fixtures, etc., installation of protective and alarm devices, preparation of emergency procedures, and others) to ensure the safety of the personnel and hardware.

(7) Reliability design

Each component of the power subsystem should be designed to ensure that the power subsystem will satisfy the prescribed performance requirements throughout the life period with the reliability specified by the system allocation. By FMEA associated with the inside and interface, analyze the failure mode, propagation effects and criticality and make a design to ensure that a failure of a single part in particular will not become

critical including its propagation. Examine the related troubles that occurred in previous developments or preceding research to know their causes and take recurrence prevention measures.
A failure of the power subsystem influences normal power supply. Because it is difficult to ensure redundancy in the subsystem or equipment, a redundant design (majority decision, series parallel, etc.) of the circuit or device level is employed. In this case, consider a means to verify that the redundancy was not lost during fabrication or testing.
In the design, perform a worst case analysis considering the characteristic variance of a device or the like, its (electrical and thermal) operation conditions, changes due to environmental conditions (vibration, impact, radiation, etc.) malfunctions due to contact chattering, etc. of a relay or slip ring, redundancy-free state, and others. Keep the number of adjusting points in the process to the minimum necessary in order to ensure fabrication reproducibility and prevent deviations from the design.
Damage to a device, etc. due to radiation includes that due to accumulation of exposure dose (total dose effect) and that caused by the incidence of one heavy ion particle (single event effect). In the power subsystem, attention is paid mainly to the total dose such as characteristic changes of semiconductor devices. In the signal processor, etc., however, it is also necessary to examine the resistance to single events
The setting of the worst case should be consistent with the reliability prediction model.
Perform a sneak circuit analysis to prevent an unintended current flow, status change, etc. from occurring at power-on or -off, changeover, and connector connection or disconnection concerning the power supply line and return from power supply (in particular, multiple) buses, ground power, etc.
Clarify the selection criteria of the devices, materials, and processes used. When applying a device or material, perform an analysis on the electrically, thermally, mechanically, radiation-, high vacuum- or otherwise induced stresses in it. For a device, in addition, do appropriate derating concerning power, voltage, current, and temperature according to the applicable standards. Employ a proven design, device and material for a part that is not in conflict with the development objective. If the device used, material used, or the like necessary for the design lacks its application data, conduct a qualification test, etc. separately.
Select measurement data so that the normal operation of the power subsystem can be known by a test, etc. and set an evaluation criterion for the trend, etc. of the data. Consider redundancy also in data acquisition and make a design considering the case where data measurement becomes partly impossible and also a substitution with other data in such a case.
Evaluate the accumulated fatigue of a flight item by ground tests to confirm that the

fatigue does not influence the durability necessary when in actual use. For a battery, relay, connector or other limited life item subject to wear and aging degradation and an item with a restricted number of times of operation, set and manage restrictions on the time and the number of times of operation to the launch. For a battery, specify its storage method before being mounted and maintenance method after mounted.

- Related considerations -

In a redundant design of the power subsystem, standby and changeover is not allowed in most parts. Therefore, even if a trouble occurs in a part of the redundant line on the ground, its confirmation is difficult in many cases. As a measure and at the equipment proper level, a signal to force a part of redundancy to become inoperative is applied from outside and a means to verify that the remaining part is normal is taken. Or, a test connector is used to measure characteristics (voltage drop of a diode, capacitance of a capacitor, etc.). Yet another method is to provide a signal to monitor the operation of each individual part as an output and monitor those signals. However, these methods are generally difficult to conduct at the system test level. As an alternative means, trend assessment of measured data is utilized. In trend assessment, it is important to verify not only that the data lie within the specification but also that the data have reproducibility and change as predicted. So, pay attention to subtle data variations as well. A relevant item is telemetry data. Besides this, for important items, provide a test connector output and pay attention to the steady-state value and transient waveform although under the restraints of the test configuration.

(8) Maintainability design

In the period from fabrication and installation in a spacecraft to launch, there may be a case where a component requires inspection, repair, replacement, etc. Allow for such an occasion, that is, make a design to ensure that the work can be done easily and has little influence on other pieces of equipment or systems.

- Related considerations -

Concerning the power subsystem, battery replacement must be considered. A flight battery is a limited life article and its maintenance after being mounted on a spacecraft is troublesome. So, it is desirable to mount it just before the launch within the realm of possibility and store it separately until then. Therefore, in spacecraft structural design, work schedule setting, fixture preparation, etc., be conscious of item replacement. If the power distribution section has an upstream fuse for short-circuit fault isolation, pay attention to the connector accessibility to confirm fuse integrity.

4.3 Power supply capacity

The power subsystem should have a power supply capacity that satisfies the required power profile throughout the entire mission period of the spacecraft. The following specifications are an item of basic performance of the spacecraft system and should be consistent with the applicable requirements of a specification document, etc.

4.3.1 Required power profile

Specify the require power profile throughout the entire mission period as follows: In the case of multiple buses, specify for each bus.

(1) Define the reference point of supply power to a load.

(2) Define all operation modes from the spacecraft launch to the end of mission (including contingencies, etc.)

(3) For each power-allocated load item (irrespective of its bus voltage but including a load which operates continuously), calculate the power consumption in each of its operation modes. In the power consumption, include the load power and the loss by the harness from the supply power reference point.

(4) Calculate the supply power in each operation mode.

(5) Along the operation plan from the spacecraft launch to the end of mission, show the required power change with time (required power profile) at every constant period (for example, from launch to orbit insertion and then at every revolution in orbit).

- Related considerations -

For clauses (2) to (4), it is desirable to organize items as shown in Table 4.3-1.

The supply (consumed) power serving as the source data for the required power profile is generally updated as the development stage progresses. Therefore, the required power profile is usually specified as the upper limit of the level required in a certain period of the development stage. It is desirable to separately track the update history using a table, clearly describe the grounds for the update in the remarks field, and review the descriptions together with the specified value update with the progress of the development stage. However, the acceptance or rejection of an update is examined based on a power budget analysis, etc. performed at an appropriate time.

For the supply (consumed) power in a required power profile, the transient peak power is generally ignored. For example, the pyrotechnic ignition power is ignored. In general, an upper limit (including a margin) is specified, and its positioning (development target value/expected worst value of a test model/measured worst value) and setting margin depend on the management policy of system development and the progress of the development stage.

For the operation modes associated with the required power profile, consider the predictable worst case from the viewpoint of power budget.

Table 4.3-1 Example of supply power table by operation mode

(Unit: W)

	Operation mode	In the sunshine					During shade		
		1	2	3	4	5	6	7	8
	TT&C subsystem	60	60	60	60	60	60	60	60
	Attitude and orbit control subsystem	125	125	125	125	125	125	125	125
	Power and paddle subsystem	25	25	25	25	25	25	25	25
	Secondary propulsion subsystem	77	77	77	77	77	48	48	48
	Thermal control subsystem	184	184	184	184	184	114	114	114
Total power consumption of bus lines		471	471	471	471	471	372	372	372
	Mission equipment A	429	132	0	0	124	429	0	124
	Mission equipment B	200	300	300	100	300	200	300	300
	Mission equipment C	50	0	0	100	200	50	0	200
	Mission equipment D	50	0	120	120	100	50	120	100
Total power consumption of mission equipment		729	432	420	320	724	729	420	724
Total power consumption of bus and mission		1200	903	891	791	1195	1101	792	1096
Harness loss (2%)		24	18	18	16	24	22	16	22
Total supply power		1224	921	909	807	1219	1123	808	1118

4.3.2 Required size of power source

The required size of a solar array and battery is specified according to the characteristics in Sections 4.5.1 and 4.5.2. The characteristics of this power source should conform to the required power profiles of all operation modes and the depth of discharge should be kept within the allowable value for the battery. Judge conformity with the required power profile by power budget analysis and present the specifications of that power budget analysis model.

- Related considerations -
In the power budget analysis, establish and maintain a power budget based on the peak power value and an energy budget based on the mean power value. Take the following items into consideration.
Distance from spacecraft to sun
Duration of sunshine and eclipse

- Aspect angle of sun
- Orientation accuracy
- Effects of environmental temperature and degradation
- Matters associated with reliability and safety (effects of failure)
  Based on the final power budget analysis in the design stage performed on the required power profiles of all operation modes, the required size of the solar array and battery is evaluated as follows:
- Required size of solar array
  Show the required power generation profile during the entire mission period.
- Required size of battery

Specify the required discharge energy profile during the entire mission period. Or, set the stored energy of the battery and show the required depth-of-discharge profile of that battery.
Applying an appropriate margin for power budget analysis to these values, the characteristic requirements for a solar array and battery are determined and they become specifications for the required size from then on. For the appropriate margin, each project should determine an appropriate margin in each design phase. Margin examples include the following:

Spacecraft configuration	Design phase		
	PDR	CDR	PSR
New bus design and new payload/mission design	15%	10%	6%
In the case where large-scale design changes are made to an existing bus or payload design	10%	8%	6%
In the case where minor changes are made to an existing bus or payload design	5%	8%	4%
Existing bus design and existing payload/mission design	5%	5%	3%

As the available power, supply of the required power should be possible even when one solar array circuit or one battery cell fails at the end of the specified life of the power subsystem.

Incidentally, once characteristic requirements for solar array and battery hardware are specified, there is no scope for making a change after that. In the stage of determining these specifications, it is common practice to proceed with a solar array and battery design simultaneously with a power budget analysis for the required power profile.
On this occasion, pay attention to the following:

a. The allowable depth of discharge of a battery is generally specified for the maximum level in the stationary discharge energy profile. If a large transient depth of discharge is expected, identify that operation mode and specify an allowable value separately.
b. If a battery discharge may occur in the sunshine, it is desirable that a battery charge completes before an eclipse begins.
c. It is desirable that the battery charge power can be supplied at the upper-limit level of charge current set by charge control. For a LEO spacecraft, there may be a case, depending on operational requirements for the mission equipment, where it is difficult to ensure the upper-limit charge current. In this case as well, it is desirable that a battery charge completes before an eclipse begins.

d. If it is often the case that a charge is not complete in the sunshine, the operation plan ideally should ensure that the depth of discharge does not become large during the succeeding eclipse. Conformity with the required power profile and power source size is evaluated by power budge analysis at an appropriate time as the development stage proceeds. Present the specifications for the power budget analysis model (see the example of Appendix I) used for these analyses together with the required power source size specification and, in the same way as the data associated with the required power profile, use the values updated with the progress of the development stage. The required solar array and battery sizes specified here are the lower limit values that satisfy the requirements, and the margin, redundancy, etc. on the hardware side are considered in each design.

4.4 Power supply characteristics

The power supply characteristics of the power subsystem should be consistent with the electrical interface conditions related to the spacecraft. Here, only the characteristics of the bus voltage generated by the power subsystem itself are considered. Take the reference point at the power distribution output end (power subsystem output end). Unless otherwise specified, use all the spacecraft load conditions and environmental conditions as specified conditions.

4.4.1 Bus voltage

Show the steady-state voltage range for bus voltage. In the case of the regulated bus type, it is desirable to select from among 28 V, 50 V and 100 V. For a selection guide, refer to the Electrical Design Standard (JERG-2-200). In the case of the non-regulated bus type, appropriately divide and show the range considering the operation from the launch to stationary orbit insertion and the operation modes while there is sunshine/an eclipse and in-between transient period on a stationary orbit.

Example: 50-V non-regulated bus: 33.0 to 52.0 V

4.4.2 Voltage stability

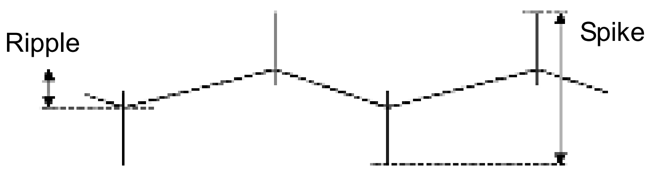
In the case of regulated bus type, show the bus voltage stability considering the steady state and a load transient. The stability is desirably defined including the time of a load transient; however, it may be defined separately in Section 4.4.5. Specify the time of a load transient, for example, as the case of a 50% load change.

In the case of non-regulated bus type, leave this out of the scope of application by showing the bus voltage range according to Section 4.4.1. If a stable operation by a shunt is involved while there is sunshine; however, it is effective for understanding the operation to show the voltage stability in the sunshine.

Example: 100-V regulated bus: 100.0 to 103.0 V while there is sunshine
When shaded: 97.0 to 100.0 V

4.4.3 Ripple and spike

Show the upper limit of peak-to-peak value of periodic voltage variations superimposed on the bus voltage. Specify it in the time domain and take the frequency band of the measurement system to be 50 MHz and above. As the specified value, show a maximum considering the operation modes while there is sunshine/an eclipse and a transient.
In addition to the above-stated ripple voltage, show the upper limit of spike voltage also in the time domain.
As the ripple voltage specified here, only the voltage generated by the power subsystem itself and appearing at the power subsystem output end is considered.
For the definition of ripple and spike, refer to Figure 4.4-1.



• Ripple: Periodic voltage variations superimposed on the power bus
• Spike: A variation in the form of a spike generated by a switching power source but not forming an energy source.

Figure 4.4-1 Definition of ripple and spike

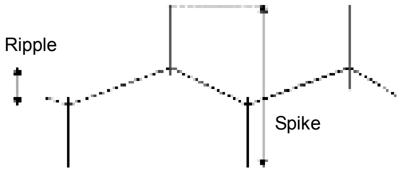
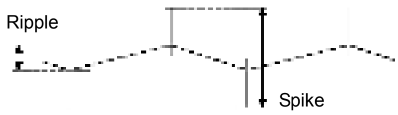
(Example)

Regulated bus: Ripple voltage = 0.5 Vp-p or less, Spike voltage = 2.0 Vp-p or less
Non-regulated bus: Ripple voltage = 0.2 Vp-p or less, Spike voltage = 0.5 Vp-p or less

Note: A setting examination example for the above-stated specification is shown in Table 4.4-1.

If seen as a spacecraft system, the ripple voltage on the bus voltage will contain not only the ripple generated by the power subsystem itself as described above but also the rebound component consisting of the superimposed conduction interference noise current of each load and applied to the power subsystem. Therefore, the ripple specification as a spacecraft system will be set at the level coming from the power subsystem as described above plus the rebound component from each load.

Table 4.4-1 Characteristics of ripple and spike

Bus type		Regulated bus	Non-regulated bus
Schematic diagram			
Ripple voltage	During charge	0.2Vp-p	0.2Vp-p
	During discharge	0.5Vp-p	0.1 Vp-p or less
Spike voltage	During charge	0.5Vp-p	0.5Vp-p
	During discharge	2.0Vp-p	None

- For each bus type, the respective maximum values of ripple voltage and spike voltage are shown with a circle.
- The specification for ripple voltage and spike voltage will be set based on the maximum values above.

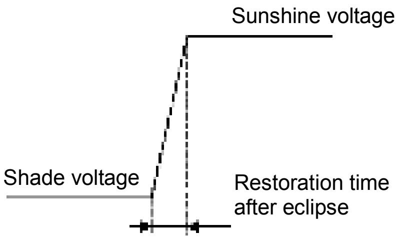
4.4.4 Output impedance

Show the upper limit of output impedance of the power subsystem proper in the frequency range from 1 Hz to 100 kHz. Appropriately divide and show the specification considering the operation modes while there is sunshine/an eclipse.

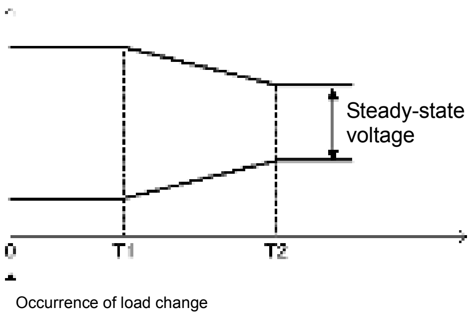
4.4.5 Transient characteristics

Considering the power subsystem transient operation involved in peak power supply to a load, power-on, power-of, paddle deployment, abnormality inside the power subsystem, load abnormality/restoration, etc., show the bus voltage transient with time at the time of a

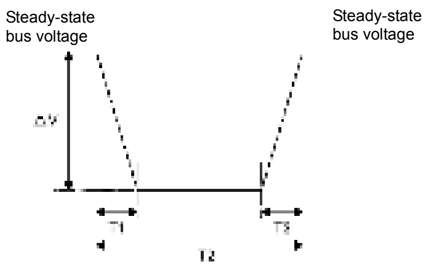
load change and abnormality. Appropriately divide and show the specification considering the operation modes while there is sunshine/an eclipse and in-between transient (penumbra) period. Specify the time of a load change, for example, as the case of a 50% load change. Determine it considering the actual loads and coordinating with the system.
If, in the above-stated case, the spacecraft system has a pulse power load, it is necessary to consider it as a load involving a transient operation. As a load abnormality/restoration, for example, the case of a fuse blown and then restored is assumed.



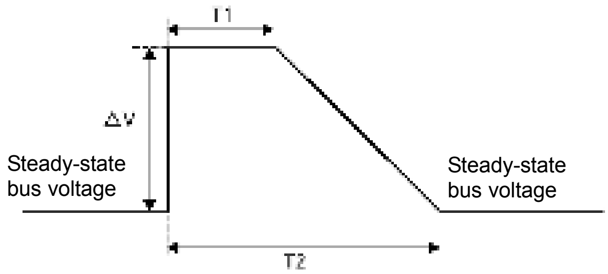
(a) After eclipse (non-regulated bus)



(b) Transient characteristics involved in load change



(c) Transient characteristics involved in load abnormality/restoration



(d) Transient characteristics involved in wheel stop

Note: Consider this if the wheel side does not have a bleeder resistance or other regenerative power absorption means.

Figure 4.4.2 Types of transient characteristics

- Related considerations -

As the reference point, designate a point at which the power supply characteristics can be evaluated. Figures 4.4-3(a) and (b) show methods of power distribution. Because the power distribution characteristics of a power subsystem take the reference point at the power subsystem output end, it is necessary to consider the contribution of the system harness to the characteristics at the load input end. In the case of the backbone method in Figure 4.4-3(b), separately specify using an electrical interface, etc. for a dedicated unit end or load end.

Specifications for ripple are specified in Section 4.4.3 as the level generated by the power subsystem itself; however, at the spacecraft system level, they are specified as containing also the rebound component consisting of the conduction interference noise current of each load superimposed and applied to the power subsystem but not considering only the voltage generated by the power subsystem itself. The actual output impedance to convert (rebound) an interference noise current into a ripple may be related not only with the output impedance of the power subsystem proper but also with the connected load input filter. Therefore, it is necessary to keep track of each load input part in management of electrical interfaces or electromagnetic compatibility.

A transient depends on the peak power of the load, amount and rate of current change at power-on/-off, assumption of failure modes, etc. Therefore, these values and assumptions must be specified by electrical interfaces, etc.

The specifications for power supply characteristics are premised on the actual operation state; however, they sometimes include the transient at ground power start-up, shut-off, etc. in a ground test. (See Clause a of 4.2.2, (1).)

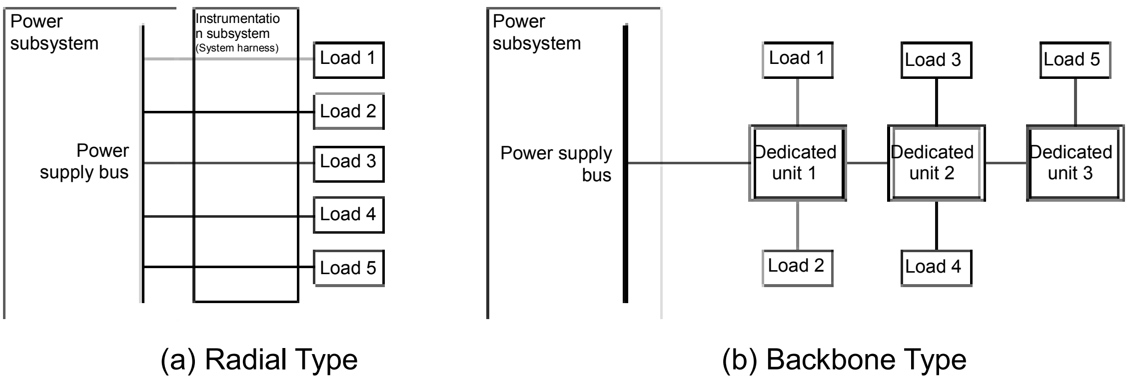


Figure 4.4-3 Methods of power distribution

4.5 Power subsystem

The power subsystem consists of the interface with a solar paddle subsystem having the function of power generation, a battery having the function of energy storage, and equipment having the function of power control, distribution, protection, etc. A specific configuration and these pieces of equipment, etc. are designed based on the examination of spacecraft system and its actual performance. Here, major components of a power subsystem are outlined, and their characteristics, related technology and methods, specific condition of use, considerations in design, etc. are described.

4.5.1 Interface with solar paddle subsystem

In the design of the interface with a solar paddle subsystem, clearly specify the following items.

(1) Interface reference point

Clearly specify an interface reference point to specify the power generation of the solar paddle subsystem. In many cases, a system with a paddle drive mechanism (PDM or SADM) takes the paddle drive mechanism output end as an interface reference point and a system with no paddle drive mechanism takes the solar array output connector end as such a point.

(2) Maximum voltage and maximum current at interface reference point

Specify the upper limit current value considering the power subsystem shunt element specifications and the maximum on-orbit current output conditions (time, direction of the sun, temperature, etc.) of an array circuit.

(3) Round-trip line resistance between interface reference point and PCU

(4) Shunt operation sequence

Clearly specify the correspondence between the shunt operation sequence, set in the system design, of the array circuits on the solar array and the operation sequence of the power subsystem shunt circuits. If the analog partial shunt method is used, specify the shunt tap voltage range.

As another interface the power subsystem has with the solar paddle subsystem, it has an interface with the pyrotechnic. For details, refer to Power Distribution (Section 4.5.4).

4.5.2 Battery

The battery cell capacity, charge and discharge voltage characteristics, number of batteries, etc. should be designed considering the conditions of use (depth of discharge, temperature, etc.), characteristics of the cell (including its life), margin for the life characteristics, redundancy, etc. and should be designed to satisfy the requirements in 4.3 Power Supply Capacity and be compatible with charge and discharge control in 4.5.3 Power Control.

(1) Configuration
Show the specifications of the cell used (type, nominal capacity of the cell, etc.), number of cells connected in series, electrical diagram of the battery (including the installed sensors and heaters), insulation performance of the cell case, allowable temperature range and allowable internal temperature difference of the battery, allowable depth of discharge for each operation mode, etc. (during a contingency, a required discharge energy within a limited time may have to be set), and the number of batteries.

(2) Ground initial characteristics
Specify the charge and discharge current, time, temperature and other conditions and show the requirements for initial charge and discharge characteristics and, if necessary, for short-cycle characteristics. If there is an intermediate tap or the like for a pyrotechnic, show its required characteristics.

(3) Life prediction
Show a long-term characteristic change prediction in the state not considering the (batter level/cell level) redundancy under the on-orbit actual conditions of use.

(4) Sealing/pressure-proof characteristics.
A battery cell functions using electrochemical reactions, and chemical changes of the electrode materials and electrolyte associated with the reaction proceed inside. Therefore, the structure of a battery cell or battery must prevent leakage of the internal materials and endure increasing internal gas pressures. These structural endurance requirements specify the initial characteristics and long-term characteristics associated with corrosion resistance, pressure cycle characteristics, etc.

(5) Battery redundancy
Considering a single failure of a battery, the battery should be designed to have a redundant function so that the battery function will not be lost.

(6) Precautions for preservation and use of battery

(a) The spacecraft design should ensure that the battery can be removed from the spacecraft and replaced without influencing other equipment, etc.

(b) A battery cell or battery preserved for a long time should be brought to the ambient temperature state gradually. In addition, perform the low-current conditioning cycle according to the manufacturer's specifications to bring it to the nominal performance state.

(c) As the minimum conditions for the use and preservation of a battery cell and battery, comply with the precise preservation and reconditioning requirements for the following items.

- Longest ground preservation period (before and after reconditioning if applicable)
- Longest unused period in the state of no special start-up cycle taking place.
- Maximum battery temperature and its duration in the pre-launch stage and operation stage.
- Battery maintenance in the integration stage and pre-launch stage including a launch delay time.
- Requirements for preservation procedure, preservation temperature, and battery cell discharge
- Humidity and packing during preservation
- Reconditioning procedure after preservation
- Preservation procedure, preservation temperature, charge state, whether or not to short-circuit the battery cells individually, details of trickle charge, and regular maintenance

(d) To prevent damage and performance degradation over the entire remaining life after that, the flight battery shall not be used for ground operations as far as possible.

(e) Make sure before the launch that the requirements for preservation, handling, and operation (for example, longest allowable time of being at the upper-limit temperature, exactness of a maintenance activity schedule, etc.) are satisfied.

(7) Battery safety requirements

Almost all batteries mounted on and used in a spacecraft can pose a risk if not managed appropriately. In most batteries, for example, a very large current can flow when they are short-circuited. If a battery cell is abused, the internal pressure can become excessively high and the contents may gush out; in an extreme case, even an explosion can occur. Moreover, the emitted electrolyte, reactants and/or reaction products of the battery cell are corrosive, inflammable and poisonous, so they can jeopardize all personnel present nearby in addition to adjacent devices. Therefore, perform safety verification for each one. The safety requirements for a lithium ion battery are described below. For conventional Ni-H2 and Ni-Cd batteries, refer to the specifications of JMR-001 and JMR002.

(a) Safety requirements for battery cells

- The battery cell should be provided with a rupture part to avoid a severe rupture.
- The battery cell should be provided with the rupture part at two places to have redundancy.
- The battery case should have a safety margin of three times the ordinary working pressure.
- It should be provided with a rupture part that surely operates at a lower pressure than the case withstand pressure. This should be demonstrated by a test.
- The battery cell should have external short-circuit protection function.
- The cell should have the safety for a forced discharge. This should be demonstrated by a test.

(b) Battery

- In the battery design, each cell should be provided with a shunt function to protect against an over-charge.
- The design should be such that when battery cells are assembled into a battery, the cell safety valve operation is not hindered.

(c) Battery transportation and handling tools

- For battery transportation, pack the batteries securely to prevent an external short-circuit.
- The battery transportation packing should be proven as to the following by carrying out a drop test from 1.2 m. 1) The batteries inside and battery cells are not damaged. 2) The batteries inside and battery cells do not experience an external short-circuit. 3) The batteries inside and battery cells are not thrown out.
- When handling the battery proper, provide a strong protective gear for a drop,

etc. This protective gear should have a design to prevent an external short-circuit and a battery cell's forced out of the battery even when dropped from 1.2 m.

(d) Others

(1) If a battery cell group is connected in parallel, an effective means for reverse current prevention should be provided.
(2) Control should take place to prevent the upper-limit operation temperature from being exceeded.
(3) Conduct a test to verify that the battery cells and battery function safety even at the upper-limit operation temperature. Also consider the heat generation of battery cells due to external heat input and internal loss.
(4) Identify the processes important for safety. These important processes are subject to an examination by JAXA.

4.5.3 Power control

Power control of the power subsystem consists mainly in output control of the solar array and charge and discharge control of the battery.
Each control should be designed to be compatible with the solar array and battery characteristics and satisfy the requirements of 4.4 Power Supply Characteristics.

(1) Control system
Show the diagram and control law of all functions involved in power control. For solar array output control and battery charge and discharge control, clarify the operating range and priority of control, and coordination management not to allow control operations to overlap each other detrimentally.
In the case of a shunt-type 50-V non-regulated bus and charge control by a battery charge controller, the operating range and priority of control are, with increasing bus voltage, in the order of bus voltage control by charge control (bus voltage width about 1 V), a gap (arbitrary) and bus voltage control by shunting (bus voltage width about 1 V) as standard.
In the case of Multibus, show the functional diagram and control law for each independent operation. If there is a coordinated operation of multiple buses, show their operation in the coordinated state separately. For the parallel operation of multiple buses and multiple batteries, specify the allowable level of their current share.

For a single failure inside the power subsystem and an abnormality on the load side, designate the place of the failure and failure mode and specify the bus voltage transient involved in the failure.

- Related considerations -
In a coordinated operation, provide a monitoring means to keep track of its state and design to ensure that there is no detrimental interference or alternating intermittent operation.
The abnormality bus voltage transient should be consistent with the specifications of Section 4.4.5.

(2) Operating point analysis
Clarify the behavior of the operating point of all voltages (bus voltage, control voltage, and their monitoring voltage, etc.) in voltage control.

- Related considerations -
In the operating point analysis of voltage, clarify the operating point of the solar array, bus voltage and battery voltage. In the analysis, it is necessary to consider BOL, EOL, shade/sunshine transient, load characteristics and their variations, etc.
If the lock-up phenomenon (the battery discharges regardless of whether the load power can be supplied by the solar array) is expected to occur, take steps to identify and, if necessary, prevent that.

(3) Control diagram
For all operating and non-operating regions of power control, show a control diagram (equivalent circuit, simulation model, etc.), by which the bus voltage stability, output impedance, control stability, and transient response characteristics can be evaluated, and the effective frequency region of each.
For a feedback loop, ensure a gain and phase margin of about 5 to 15 dB and 25 to 50 degrees or more, respectively.
An appropriate gain crossover frequency is several hundred to several ten kHz or so.

- Related considerations -
In the control diagram, clarify the calculation grounds for the characteristic value of each control element.

Have a design so that the control performance will not be impaired by temperature, radiation degradation, load conditions, etc.
When evaluating the effects of load conditions, it may be necessary to know the input impedance of all pieces of equipment on the spacecraft.
The gain and frequency band width of feedback loop control should at such a level that a sufficient margin can be ensured for the requirements for bus voltage stability, impedance and transient response characteristics, battery charge and discharge current and temperature. The design should be such that an appropriate gain/phase margin can be ensured and, even in the worst case, control stability can be ensured.
Have a design so that, for each control, not only the static stability in a control mode but also the transient response characteristics at a transfer within a control mode and between control modes satisfy the transient specifications.
The modeling on which a control diagram is predicated generally needs approximation, etc. of nonlinear characteristics into a linear form. So, pay attention to its validity limit.
For a simulation model, use a high frequency equivalent circuit as close to the actual circuit as possible in the model, by using parasitic parameters not present on the circuit diagram or otherwise.

(4) Characteristics of each power control
In some design, a control function consists of multiple elements (pieces of equipment). In such a case, it becomes necessary to specify interface boundaries and specify the characteristics individually. Here, the characteristics by control function are described.
Specify the loss by (efficiency of) power control taken in as a parameter of the power budge analysis mode, individually in the relevant part.

a. Solar array output control
The solar array output control should have a processing capacity compatible with the solar array characteristics. Specify this in terms of the power for that processing (mean and peak current and voltage). Specify the monitoring method to keep track of the operation state of solar array output control.

b. Charge control
Specify the set values for the control parameters (voltage, current, temperature, etc.) to be compatible with the battery characteristics.

And, specify the operations of the protection function (charge suspension at an temperature abnormality, etc.) for heater control (if built in) and charge of the battery. Pay attention also to the transient of bus voltage and battery charge current at a charge suspension and resumption due to the action of a protection function.

c. Discharge control
Specify the requirements for discharge power (peak and abnormality values, in addition to mean value).
Specify the operations of reconditioning function and protection function (UVC, isolation of a short-circuit on the load side, etc.) for discharge of the battery.

- Related considerations -
For solar array output control, consider that the output characteristics are varied on a short-term basis by temperature, sunlight incident angle, etc. and on a long-term basis by radiation degradation, etc. In addition, an environmental resistance at the same level of the solar panel is required for the solar paddle and other control elements attached outside the spacecraft. If direct measurement of solar array power generation is difficult, a monitoring means to keep track of the operation state of output control is utilized as an indirect evaluation means in some cases.
For battery charge and discharge control, it is desirable, considering the long-term change in the battery characteristics, to provide multiple control levels (V/T curve, over-voltage protection, over-heat protection, UVC level, etc.).
In general, a fuse blowing capability to isolate a short-circuit on the load side is also required in discharge control.

4.5.4 Power distribution

4.5.4.1 Power distribution pattern

(1) Bus configuration
If broadly divided, there are architectures of single bus configuration and multibus configuration. Because each has its own merits and demerits, consider an appropriate bus configuration based on the system requirements.

(2) Wiring pattern
As the power distribution wiring pattern for a component made of main/subordinate components (including a component of an internally redundant configuration), do not use a wired OR connection (so-called π connection) at the connector but employ individual power distribution. If a protective circuit (fault isolation function) of a circuit-breaker or fuse is to be provided on the power distribution side, install it on each power distribution

line.

(3) Selection of wire and wiring method used for power distribution
For the selection of wire and wiring method used for power distribution, conform to Section 4.6.1 of JERG-2-200 Electrical Design Standard.

(4) Supply power monitor
With an understanding of keeping track of the state of power supply to the load side during a system test and on-orbit operation, consider an appropriate supply power monitoring function (resolution and system).

4.5.4.2 Operating temperature of power distribution harness
For a harness of bundled wires engaged in power distribution, perform a thermal analysis considering the effects of heat from mounted peripheral equipment, etc. and the heat generation by current flowing in the harness itself, and confirm that the operating temperature satisfies the specifications of JERG-2-212 Wire Derating Design Standard.

4.5.4.3 Inrush current/outrush current
When an inrush current/outrush current flows at power-on/off by normal operation of equipment on the load side or at an operation of a protective circuit (on both the power distribution side and load side), the protective circuit on an unintended distribution line should not malfunction.

4.5.4.4 Specification of power distribution specifications
As the output of a power distribution design based on the requirements of Sections 4.5.4.1 to 4.5.4.3, specify the following specifications concerning each item of power distribution by the bus voltage and in the form of a power distribution management table.

a. Supply pattern (normally on, on/off by a command, on/off by a designated sequence, etc.)
b. Supply current (mean/peak/profile mean in the operation mode)
c. Voltage drop from the power supply bus to each power supply end
d. Harness type and voltage drop from each power supply end to the corresponding input end on the load side
e. On/off relay switch type (predicted number of operations, related command number, installed place)
f. Telemetry number related to keeping track of power supply state (voltage/current/status and there measuring positions)
g. Fuse or power-off function provided or not (rating and other specifications, and placed position)

Also for power distribution by other than bus voltage (by adapting a prefabricated component or otherwise), specify the power supply characteristics within the necessary scope and according to Section 3.3 and specify items similar to the above. If, as with pyrotechnic ignition power, a supply sequence function is incidental to the power subsystem, specify its details, etc.

- Related considerations -
Because of an inappropriate design or with the progress of the design stage, a related specification or the like may have to be changed. When examining the impact of such a change, End-to-End management concerning power supply is performed. Therefore, even if the above-mentioned related specification is an item not classified as a function of the power subsystem, the specification should not be divided or omitted.

For a platform spacecraft*Note 3 bus, power distribution to unitized subsystems, etc. is employed. In such a configuration, the functions of power supply and distribution to the equipment in a unit are dispersed to each unit. For Clauses “a” to “g” above, however, specify and manage them as belonging to the power subsystem.
These specifications are sometimes collectively incorporated in a related document of electrical design or interface management. The specifications desirably use a table in which they are used in common with Clause (1), a of Section 3.2.2.
For pyrotechnic ignition power distribution, consider Clauses (1) to (7) and specify and manage it using an actual system diagram including the pyrotechnic harness and in the same was as above.

(1) For sure ignition, give redundancy to the ignition system (ignition circuit, wire, pyrotechnic). Provide the automatic ignition sequence, etc. with a backup of ground command.
(2) Letting the sequence to ignition have three stages (enable/disable, ignition), monitor the status.
(3) In the sequence, incorporate the spacecraft/rocket separation signal, the attitude control subsystem’s pre-operation completion signal, etc. in a circuit.
(4) For malfunction prevention, simplify the system, clarify the relationship, etc. with spacecraft grounding, and connect an antistatic resistor to the wire to the pyrotechnic.
(5) Because the heating wire to fire the powder in the pyrotechnic (bridgewire) cannot fulfill the firing function if the supply current or time is insufficient, know the transient response set the supply time of the power supply source.
On the other hand, an unexpected contingency (release becoming impossible, short-circuit to the structure, etc.) occurs if an excessive current flows. Therefore, incorporate a current limiting function (should have the function to prevent an excessive current and the function to prevent continuous voltage application) so that the recommended firing current of the pyrotechnic flows.
(6) A relay is generally used for powering on, etc. a pyrotechnic. However, contact reversal or chattering due to vibration or impact poses the risk of causing serious troubles from system malfunction. Therefore, evaluate the environmental resistance of the relay, pyrotechnic controller, etc. in advance and take measures.
(7) In the case where the number of operations is limited, verification using actual equipment is difficult. Therefore, implement a test plan to verify the system performance after sufficiently examining it.

*Note 3: Refers to the spacecraft type of ADEOS and ADEOS-II.

4.5.5 Protection

4.5.5.1 Overview

The protection function has the roll of localizing failure or abnormality, which may have a serious adverse effect on power supply, to avoid a critical situation as a system or a situation affecting mission accomplishment.

For the power subsystem, uninterrupted operation is required, so it is necessary to have a design on the premise that the primary functions cannot be interrupted as fail-safe.

4.5.5.2 Protection in power subsystem

(1) Redundancy

(a) The power subsystem should not have a single failure point that can be assumed by failure analysis.
If a single failure point subsists, identify that single failure point and show the grounds for the subsistence. The grounds for this include the need for a technical evaluation of occurrence possibility and, if any, an examination of a means that can remove the single failure point and measures to reduce the probability or latent effect of failure occurrence.

(b) For an abnormality or failure of a device due to an open circuit or short circuit, take measures such as series-parallel connection, circuit and equipment redundancy, etc. Pay attention to the failure rate of the OR circuit, change-over circuit, etc. to achieve a redundant configuration.

(c) No two protection functions supporting an essential function in the converter or regulator should be performed in the same hybrid or monolithic IC; they should use independent reference voltages and drive power sources.
This does not apply to a hybrid IC which accommodates function groups physically isolated to prevent failure propagation.

(d) The primary power source should be recoverable when the abnormal condition (for example, abnormal attitude, etc.) is removed, including the case of loss of secondary power.

(2) Insulation

Insulation should be in accordance with the Insulation Design Standard (JERG-2-213). The matters to be specifically noted as a power subsystem are described here.

(a) In power distribution from the primary power bus, there are parts where over-current protection cannot be implemented (include the bus bar, harness, connector, and PCB). Protect these parts by double insulation to the point of the first protective device (fuse, current breaker or current limiter, or reverse current prevention diode)

(3) Over-current protection

(a) Install a protective circuit as close to the power source as possible to minimize the primary power bus length.

(b) If a fuse is used to protect the distribution wire of the primary power bus, the rating of this fuse shall be selected considering the maximum current in the load path including the transient state (of inrush current, etc.). In addition, the power source should be able to supply such a current that can blow the fuse by the time when the bus voltage reaches the abnormality lower limit.

(c) If a fuse is used to protect the distribution line of the primary power bus, the power subsystem should be designed so that, when the load is short-circuited, this fuse can be blown within the specified time determined by the electrical design standard of each project.

(d) If a fuse is used to protect the primary power bus, an open circuit of the fuse can be confirmed from outside the component. It is desirable that the fuse is accessible and can be replaced even when the spacecraft is integrated.

(e) If a fuse is to be installed in the subsequent stage of a DC/DC converter, consider the melting characteristics of that fuse to ensure that the DC/DC converter has the ability to blow the fuse for certain.

(4) Battery protection

(a) A battery cell should have protection function so that a short circuit, open circuit or other abnormality of it does not affect other battery cells or primary power bus.

(b) A battery should have protection function such as suspending the charge to prevent the battery from ending up critical failure if an over-temperature occurs in the battery.

4.5.5.3 Protection in cooperation with other subsystem

For the protection functions related to power supply shown in (1) to (5) and in cooperation with other subsystem, specify the specifications of Clauses a to f in the form of a protection function summary table. An example of protection function summary table is shown in Table 4.5.5-1. For a complex function, specify it using a system diagram, state transition diagram, etc.

(1) Malfunction of attitude control subsystem, tracking subsystem, etc.
(2) Abnormality of operating point, etc. of solar array
(3) Over-discharge of battery
(4) Load short circuit of battery
(5) Abnormality of multiple cooperating buses

a. Operating conditions (detection level and response) and operation confirmation method (monitoring, etc.)

b. State transition and recovery procedure
c. Self-diagnosis method of protection function
d. Protection function and malfunction measures (reset, override, etc.)
   Override refers to setting of ENA/DIS, forced protection cancellation, etc.
e. Normality and operation confirmation method by ground test, etc.
f. Related (protection for others, etc.) function and interference prevention measures

Table 4.5.5-1 Protection function summary table

	(1) Malfunction of attitude control and tracking subsystems	(2) Abnormality of solar panel operating point, etc.	(3) Battery over-discharge	(4) Battery load short-circuit
Verification function	Survival mode detection (UVC function) Power recovery function survival power	Prevention of lock-up by load variations	Operation confirmation of LVC Transition to survival mode Confirmation of survival power Confirmation of abnormal load disconnection function	Confirmation of overload function
a. Operating conditions (detection level and response) and operation confirmation method (monitoring, etc.)	Input power source dynamic variations simulating attitude control subsystem, tracking subsystem, etc. UVC monitor, bus voltage, and input power	Solar battery current monitor by load variations Generated voltage monitor	Simulation of battery over-charge by load variation Output voltage, current monitor, battery temperature monitor, and bus voltage monitor	Confirmation of power supply shut-off function and power recovery characteristic function by overload characteristics Output voltage, current monitor, battery temperature monitor, and bus voltage monitor
b. Status transition and recovery procedure	Normal power → UVC mode → survival power → power recovered → normal power	Normal power → Maximum load mode → Power drop → Normal power → Light load power → Normal power	Normal power → UVC mode → Load disconnected → survival power → power recovered → normal power	Normal power → overload mode → Load disconnected (UVC mode → survival power) → power recovered → normal power
c. Self-diagnosis method of protection function	Transition to survival mode due to input power decrease by abnormality of attitude control subsystem, tracking subsystem, etc. and power supply after restoration to normality from this abnormality.	Solar battery lock-up (lock-up does not occur) by load variations and restoration function by light load	Over-discharge the battery by short-circuiting the battery (load variation) and then disconnect the short-circuited part and confirm the power supply resume function.	Disconnection of short-circuited part and power supply resume function
d. Protection function and malfunction measures (reset, override, etc.)	Automatic restoration	Automatic restoration (or reset)	Automatic restoration (or reset)	Automatic restoration (or reset)
e. System test allowed or not	Characteristic confirmation by input power source dynamic variations which simulate the attitude control subsystem, tracking subsystem, etc.	Confirmation of solar battery lock-up by load variation (confirmation of no lock-up occurring) and confirmation of recovery function by light load	Simulate a battery over-discharge by varying the load and disconnect the short-circuited part, and confirm the power supply resume function after that.	Not allowed
f. Risk in case of performing as a system test, and the reason for impossibility	It is difficult to cause a malfunction of the attitude control subsystem, tracking subsystem, etc. actually at the satellite level.	Impossible with the solar battery connected.	This is very dangerous operation confirmation and difficult at the satellite level.	It is impossible to form a short circuit actually. This is utterly impossible especially if a fuse is used for battery output protection.
g. Alternative confirmation method	It is difficult to cause a malfunction of the attitude control subsystem, tracking subsystem, etc. actually at the satellite level; however, operation confirmation of the power subsystem is relatively easy by taking this event as an effect on the power subsystem and simulating the malfunction of the attitude control subsystem, tracking subsystem, etc. by reducing the test equipment input power.	Operation can be confirmed by disconnecting the solar battery and simulating the solar panel operation point with the test equipment input power.	Although it is very dangerous operation confirmation and difficult at the satellite level, it is possible to confirm a battery over-discharge by reducing the test equipment input power as a battery over-discharge.	For an over-current prevention circuit using an electronic circuit, implementation may be possible by issuing a simulated signal after over-current sensing.

4.5.5.4 Protection against ground equipment abnormalities

It is not practical to take measures on the spacecraft side against ground equipment abnormalities. Therefore, verification of spacecraft should be performed using sufficiently verified ground test equipment.

5. Design verification

5.1 General

Verify that the power subsystem is appropriately designed and the requirements for power supply are satisfied.
The verification takes place in a design review based on fabrication and test of EM, etc. to the design stage, a component test of PM/FM by the fabrication and test stage, a combination test of the power subsystem, a spacecraft system test, and a board of review after these tests. The requirements, plan, organizational structure, method, etc. for the board of review and tests are specified in the following documents.

- Reliability Program Common Specification and Quality Assurance Program Standard
- Power Subsystem and Spacecraft System Specification
- Test Requirements for Spacecraft

The requirements for the power subsystem shown under Design Standard of Section 4 should be organized into a confirmation matrix showing the classification of confirmation methods (inspection, analysis and similarity, test) in the quality assurance clauses of the Power Subsystem and Spacecraft System Specification. According to this, for a test in addition to analysis, its purpose, specifications of a specimen, configuration, method, decision criterion, timing of execution, organizational structure, etc. should be specified in a plan, etc. The verification results should be organized into a design review material, post-test review material, pre-delivery review material, etc. and their conformance to the requirements should be confirmed.
Table 5.1-1 shows the basic policy of verification for design standard items in the form of a confirmation matrix for use as a check list, etc. of a design review. In the table, Inspection, Analysis (including similarity), and Test show the classification of verification methods. For the tests related to the power subsystem, there are levels and items as follows:

- Component proper test (electrical performance, temperature, mechanical environmental, electromagnetic compatibility, thermal vacuum and thermal cycle, etc.)
- Power subsystem combination test (electrical performance, temperature, etc.)

For a unitized[*Note 4] power subsystem, the object of the combination test takes the flight form and mechanical, thermal vacuum, etc. tests are performed.

- System integration and system test

(Electrical performance, mechanical environmental, electromagnetic compatibility, thermal vacuum and thermal balance, etc.)
Besides these, a charge and discharge cycle test is conducted for the purpose of confirming the battery life. In addition, the execution contents, conditions, etc. are different in the classification of model (development, qualification and acceptance) tests according to the development stage.
Comments on these test classes, etc. are shown in Table 5.5-1.
Here, points to consider about the tests, analyses, etc. recommended to be done as the power subsystem are described.

* Note 4: Refers to the spacecraft type of ADEOS and ADEOS-II.

Table 5.1-1 (1/3) Design verification matrix

Design requirements		Design verification method: Inspection	Analysis	Test	Remarks
4.2	Definitions of and restrictions on goods items				
4.2.1	Configuration and components				
	• Configuration diagram/components (equipment)	○			Check actual articles, drawings, etc.
	• Operation modes/transition conditions		○	○	Systematically confirm in a system test.
4.2.2	Definition of interface				
(1)	Electrical interface				Confirm pin arrangement before connection.
a	Power supply (power consumption)	○		○	↓
b	Telemetry/command				Confirm connection in integration process.
	• List/calibration curve	○		○	(Pay attention to paddle I/F confirmation method.)
c	Control signal	○		○	↓
d	Pyrotechnic ignition power				Confirm characteristics, etc. of electrical performance tests.
	• Diagram/sequence	○		○	
	• Grounding (single grounding/diagram)	○		○	
e	AGE				
f	Umbilical/test line	○		○	
g	Inside the power subsystem				
	• Between spacecraft and paddle, etc.	○		○	
(2)	Mechanical interface				Confirm by system integration.
	• Mass/dimensions/attachment /connector, etc.	○		○	
(3)	Thermal interface				Confirm by thermal vacuum and thermal balance tests.
	• Heat generation/thermal characteristics/temperature range, etc.	○	○	○	
(4)	Functional interface				Pay attention to configuration.
	• Cooperation/interference with other subsystem	○	○	○	
(5)	Work interface				Check actual articles, documents, and work history.
	• Identification/shipment preparation/work support	○		○	
4.2.3	Common design standard				
(1)	Electrical design	○	○	○	Confirm by design review.
(2)	Mechanical design				
	• Strength/rigidity/proof and failure pressures, etc.		○		Requirements and restrictions
(3)	Thermal design		○		Application criteria
(4)	Electromagnetic compatibility		○		
(5)	Environmental conditions				
a	Temperature		○		Measures taken in design
b	Pressure		○		
c	Humidity		○		Results of preliminary trial fabrication / test
d	Cleanliness	○	○		
e	Acoustic		○		Validity of design analysis
f	Acceleration		○		
g	Vibration		○		Results of individual qualification test
h	Impact		○		
I	Radiation		○		
j	Exposed part environment				Inspection items and test method
	• Heating during launch		○		
	• Atomic oxygen		○		Test items and test method
	• Meteoroid/debris		○		
	• Sunlight/albedo/earth radiation		○	○	Property assessment data
	• Orbit peripheral plasma		○		
	• Thruster plume		○		Management and maintenance items

Table 5.1-1 (2/3) Design verification matrix

Design requirements		Design verification method: Inspection	Analysis	Test	Remarks
(6)	Safety design	○	○		
(7)	Reliability design				Confirm by design review.
	• Reliability		○		
	• Trouble (recurrence prevention) measures		○	○	Requirements and restrictions
	• FMEA		○		Application criteria
	• (Critical) single failure measures	○	○	○	
	• Confirmation of redundant design		○	○	
	• Worst-case analysis (Variance, temperature, radiation, etc.)		○		Measures taken in design
	• Sneak circuit analysis		○	○	Results of preliminary trial fabrication/test
	• Selection of device/ material/ process	○	○		
	• Stress analysis		○		Validity of design analysis
	• Derating		○		
	• Individual qualification test		○	○	Results of individual qualification test
	• Trend assessment		○	○	
	• Limited life/operations articles	○	○		Inspection items and inspection method
	• Ground maintenance of battery	○		○	
					Test items and test method
					Property assessment data
(8)	Maintainability design				Management and maintenance items
	Battery exchange procedure	○		○	
4.3	Power supply capacity				Check validity by design review.
4.3.1	Required power profile				↓
	• Operation mode/supply capacity by mode		○	○	Update data according to test results, etc.
4.3.2	Required size of power source				↓
	• Power budget analysis		○		Check power budget by power analysis.
4.4	Power supply characteristics				Compare and evaluate analysis and test results.
	• Reference point/measurement method				
	• Power subsystem operation mode/simulated power source				Component unit test
	• Trend assessment				↓
					Power subsystem combination test
4.4.1	Bus voltage		○	○	↓
4.4.2	Stability		○	○	System test
4.4.3	Ripple		○	○	
4.4.4	Output impedance		○	○	
4.4.5	Transient characteristics		○	○	
4.5	Properties of major components				
4.5.1	Interface with solar paddle subsystem				
	• Interface reference point	○			Inspect by drawings, etc.
	• Maximum voltage and current specifications at reference point		○	○	Check paddle subsystem irradiation test data.
	• Line resistance between reference point and PCU	○	○		
	• Shunt operation sequence	○		○	Confirmation by drawings, ICD, etc. and the operation on the simulated solar array power in a system test.
4.5.2	Battery				
(1)	Configuration	○			Inspect by drawings, etc.
(2)	Ground initial characteristics			○	
(3)	Life prediction				Do quality confirmation, operation simulation test, etc.
	• Related actual data		○	○	
(4)	Sealing/pressure-proof characteristics		○	○	In-process test, etc.
(5)	Battery redundancy	○			
(6)	Precautions for storage and use of battery	○			Check actual articles, documents, and work history.
(7)	Safety requirements for batteries	○	○	○	

Table 5.1-1 (3/3) Design verification matrix

Design requirements		Design verification method			
		Inspection	Analysis	Test	Remarks
4.5.3	Power control				Compare and evaluate analysis and test results.
(1)	Control system				
	• Functional diagram and control law		○	○	Development (partial trial fabrication, etc.) test
	• Cooperation management		○	○	↓
(2)	Operation point analysis		○	○	Component unit test
(3)	Control diagram		○		↓
(4)	Characteristics of each power control				Power subsystem combination test
a	Solar array output control				(Pay attention to solar paddle I/F.)
	• Compatibility with solar array characteristics	○	○	○	Confirmation by a system test using simulated solar array power.
	• Operation (power generation) monitor		○	○	Ditto
b	Charge control				Check by battery combination test and system test (thermal vacuum).
	• Compatibility with battery characteristics		○	○	
	• Battery protection function		○	○	
c	Discharge control				
	• Required discharge power		○	○	
	• Battery protection (maintenance) function		○	○	
4.5.4	Power distribution				Integration → System test
	• Power distribution management table	○	○	○	
4.5.5	Protection				Pay attention to prior examination of test method.
	• Protection function summary table		○	○	

5.2 Definitions of and restrictions of goods items

5.2.1 Configuration and components

The configuration and components of the power subsystem should be verified by inspecting goods items, drawings, etc.

All operation modes of the power subsystem should be verified by confirming the functions and operation by a test.

When confirming an operation mode transition, confirm by telemetry data, status, etc. that the operation mode transition takes place under the desired transition conditions.

Operation confirmation is desirably done for all modes by the time of completion of subsystem tests and under the condition of the full configuration and actual operation simulated within the realm of possibility.

Related considerations

In some of the tests involving the solar panel (paddle), on-orbit simulation is difficult because of restrictions on the test equipment, etc. Simulated solar array power is used as AGE that simulates panel output; however, this is not the full configuration as a power subsystem. Operation confirmation involving UVC or protection function will also use a simulated signal, etc. It is necessary to make a confirmation for all modes (including the protection function, etc.) without any omission in the end, considering these restrictions and using analysis, etc.

5.2.2 Definition of interface

The requirements for the definition of an interface should be confirmed at each stage of the design review, unit test of elements, and combination test and should be verified by a system integration test and system test in the end.

(1) Electrical interface

a. Power supply

It should be confirmed that the prescribed power supply characteristics are ensured and the supply current (level/waveform) satisfies the specifications and, in addition, when integrated, the similarity to the unit state should be confirmed. Confirm that the transient at power-on or power-off in a ground test is also within the specification. Consider normality confirmation of a line and redundant function part (connector, wire, etc.) which use a parallel (redundant) fuse.

Related considerations

The power consumption of the power subsystem is divided into a part depending on power control operation and a steady part and is generally defined as the steady part. From the viewpoint of evaluating the parameters in a power budget analysis model, it is desirable to measure, as source data for example, the (input) current at the interface point between the solar array and a power control element and the (output) current at the interface point between the power control element and a power distribution element in a typical operation mode, etc.

b. Telemetry/command

In a unit test, it should be confirmed using a dedicated test and adjustment equipment, etc. and by the specified method that the timing, input and output characteristics, etc. are in accordance with the desired design.

At the system level, confirmation of all telemetry/command list items should be made by a functional test, etc.

However, for other than the functional test items related to LLM/UVC, protection function, pyrotechnic ignition power, etc., a confirmation should be made in the relevant test as the need arises.

The source data (calibration curve) involved in engineering value conversion of telemetry data should be obtained in each EM and PFM unit test and be confirmed to meet the accuracy requirements before use in the system EM and system PFM tests.

c. Control signal

As a unit, all functions related to a control signal should be confirmed by a dedicated test and adjustment equipment using the simulation circuit, etc. defined in the interface.

At the system level, an End-to-End functional confirmation should be made within the realm of possibility for all control signal items.

(The considerations for simulated signal generation are described in the relevant clauses of Chapter 3.)

d. Pyrotechnic ignition function

In the unit test, a functional test of the whole system (including redundancies) should be performed using dedicated test equipment to confirm that the input voltage, ignition current, supply duration and operation sequence to ignition are in accordance with the desired design.

Also in a functional test on a system EM or system PFM not using a pyrotechnic, a confirmation should be made for the same items stated above, and an End-to-End functional confirmation should be made in the full configuration within the realm of possibility.

In the case of a design with a limited number of times of operation, verification of the design and fabrication should be performed by confirming sequence-based conduction, insulation, etc.

e. Grounding

Confirmation related to grounding and bonding should be made in system integration, and it should be confirmed by individual measurements that the specified resistance values are satisfied. A single-point grounding of the primary bus return is usually confirmed in the power subsystem if it is to be connected within the power subsystem. If it is not connected within the power subsystem, a confirmation should be made during system integration.
The comprehensive validity of a grounding system should be verified by confirming the non-occurrence of loop formation on the grounding system diagram, conforming no return current present at the single grounding point and by a system EMC test, etc. Evaluation of a grounding design to prevent the effect of static charge and discharge should be performed and verified by an EMC test.

f. AGE
For all umbilical cable/test cable items, confirm that the requirements of a prescribed specification, etc. are satisfied, before connecting the device to the spacecraft, etc. and using it. In particular, pay attention to the following:

- Test results of the (overvoltage and overcurrent) protection of a power supply line, etc. for prevention of damage to the spacecraft, etc.
- Fool-proof design to prevent damage to the spacecraft, etc. due to a mistake in setting, etc. by test personnel or operator.

For connection of ground test equipment, pay attention to the grounding system on the ground side and spacecraft side. For umbilical cable items, in particular, confirm the compatibility with the lightning measures of the range. Confirm the risk prevention measures from the viewpoint of work safety.

g. Inside the power subsystem
As a unit, confirmation of the conformance to the specification takes place, and a considerable part is confirmed by power subsystem combination tests. On this occasion, also combine the simulated solar array power and other AGE used in the system test. The data thus obtained becomes source data for evaluation of system test results.
For an interface between the solar array and power subsystem (spacecraft), its operation confirmation with current, etc. actually flowing is difficult even if they are connected. Therefore, the (conduction and insulation) normality of a connection will be confirmed from a connector pin, etc. On this occasion, pay attention to the review of drawings, etc. and clarification, etc. of instructions in advance because a trouble may be brought about in orbit if there are errors in drawings, etc. which form a criterion for confirmation. There are practical examples of operation confirmation using a simulated lamp, etc., and it is desirable to examine some operation confirmation method from the design stage.
For an interface between the solar array and power subsystem (spacecraft), its operation confirmation with current, etc. actually flowing is difficult even if they are connected.

(2) Mechanical interface

As a unit, conformance to ICD, etc. should be inspected.
In the end, verify the conformance in the system integration process of assembling it in the spacecraft main body.

(3) Thermal interface
Confirmation of thermal interface validity at the unit level should be made by confirming the grounds, etc. for numerical value calculation. At the system level, verify by confirming the reference point temperature by a system thermal balance test.
For a thermally critical component, model validity evaluation should be made according to the instructions of the thermal model and related test results.

(4) Functional interface
Verification of linked items is performed at the place of the relevant function, and its conditions and method are specified in a related document, etc. Therefore, confirm that there is no omission in the related documents of the two and check the related item of the power subsystem, for example, the protection specifications for an abnormality signal, the relevant power distribution specifications for pyrotechnic ignition power, and the specifications of a signal receiving function, etc. for an isolation switch.
Verification of interfering items is performed by a review of analysis results and confirmation of the data, etc. used for the analysis.

(5) Work interface
On receipt, inspect to ensure that the identifications, history/instruction manual, packing method, etc. are as specified.

5.2.3 Common design standard

For the items required by the Design Standard, their compatibility is proven by a review of the design and analysis results, etc. except for the specifications to be confirmed by an inspection or test. Here, the validity of the analysis technique itself is also subject to the review. For an item which is related to the design policy and whose assessment criterion in the review is not clear, that is, simply stated, for example, efficient, high density packaging, and small size and light weight, consider a comparison with past records or similar cases and the current technical level, etc.
Items to be confirmed mainly by inspection or test are described below.

(1) Electrical design
For a connector pin arrangement, confirm by the drawing, etc. For a fuse, review the validity of its type, conditions of use, etc. as well as checking the traceability of its usability after it is installed and the usability results.
For magnetic characteristics, besides conducting a review, make a magnetic characteristic measurement at the component or system level though this depends on the system.

(2) Mechanical design
The validity of a design is evaluated and confirmed mainly by (vibration, acoustic, impact, acceleration, etc.) mechanical environmental tests at the unit level and, for a pressure vessel, by a proof pressure test and destructive test. For large, heavy equipment, perform a validity evaluation of its numerical model by a test, etc. on its structural model and perform an evaluation and confirmation of the compatibility with the system by coupling analysis

(3) Thermal design
The validity of a design is evaluated and confirmed mainly by (thermal vacuum, thermal balance, etc.) thermal environmental tests at the unit level. As the order of precedence, thermal environmental tests should be performed as a general rule after mechanical environmental tests to confirm no characteristic degradation caused by the mechanical environment. For equipment needing a thermal model, perform a validity evaluation of a numerical model by thermal balance test, etc. on the thermal model, etc. and evaluation and confirmation of the compatibility with the system by coupling analysis, etc.
For a harness bundle not satisfying the requirements of the Wire Derating Design Standard (JERG-2-212), it should be subjected to a harness temperature evaluation test using a thermal model and temperature evaluation and confirmation (acquisition of harness temperature data) by a system thermal vacuum test.

(4) Electromagnetic compatibility design
The validity of the design should be verified by the unit-level and system-level electromagnetic compatibility tests specified in the electromagnetic compatibility management document. For the system-level electromagnetic compatibility test, employ the test conditions which simulate the on-orbit operation within the realm of possibility.
From the viewpoint of the Related Considerations described below, it is necessary to always confirm the bus voltage behavior over the entire period of the unit-level and system-level tests, so it is desirable on this occasion to pay attention to the varying waveform not only by telemetry data of limited information content but also by test connector outputs, etc.

Related considerations
The power supply characteristics are closely related to electromagnetic compatibility of conductivity and the operating conditions of each load is related to the power supply characteristics. On the other hand, keep in mind that the output impedance of a power subsystem depends on the operating region of power control of the power subsystem.

(5) Environmental conditions: Ditto, except for the representation below.
The environmental resistance related to the requirements for mechanical and thermal design should be verified by an environmental test according to the conditions and method specified in related standard, test specification, etc. Each item is described below.

a. Temperature and pressure
Should be evaluated and confirmed by a thermal vacuum test. The power subsystem is equipment operating from the launch and the pressure decreases from the ground level to the on-orbit level. Make a confirmation that no trouble occurs due to a corona discharge, etc. during this period.
Prior to a component thermal vacuum test, a temperature test using a thermostatic oven is sometimes conducted at the card level or module level to evaluate and confirm the effects of temperature alone. By this temperature test, evaluate and confirm the validity of the design (to determine the comprehensive characteristics with devices of temperature characteristic variations reduced by a negative feedback circuit, etc.) to hold down the effects of temperature to the lowest possible level and the effects, etc. of temperature characteristic variance of the devices. In particular, for the operation of a protection circuit and other functions whose operation is difficult to confirm by a test at the component level, verify by this test.

b. Humidity and cleanliness
No particular test is conducted concerning these conditions.

c. Acoustic, acceleration, vibration (sinusoidal and random), and impact
The power subsystem is equipment operating from the launch. The environmental test applied in the Environmental Resistance Standard should be conducted in its operating state of operation simulation as a general rule. Do inspection, performance test, etc. before and after these tests to confirm that no degradation has occurred.

Related considerations
- The acoustic test is applied to a panel and other exposed equipment, etc.
- ・ The acceleration test is intended for verification concerning the strength and rigidity requirements; however, the acceleration-induced load conditions seldom become critical. In the power subsystem, there is no case where a test is actually conducted, except for the battery element, (to evaluate the effects of acceleration on the electrolyte). Of the effects on the electrolyte, the directional steady acceleration component is more important than the vibration acceleration component considered in the load conditions.

By vibration and impact tests, confirm, besides the environmental resistance, for equipment having relays, slip rings or other movable parts built in that there is no abnormality in the power subsystem due to chattering, contact reversal, etc.

d. Radiation and exposed part environment (excluding acoustic)
As for radiation resistance, verify the design validity at the equipment level by the analysis results based on existing data at the device and material levels.
Also for evaluation of the effects of the exposed part environment, verification by a test at the equipment level is difficult in many cases. So, conduct an effect evaluation by analysis for each influential element (effects of thermal radiation from the fairing, free

molecular flow heating, heating by thermal radiation and jet from the rocket, etc., atomic oxygen, meteoroid/debris, sunlight radiation, terrestrial radiation, plasma and thruster plume gas around the orbit, etc.) and, if necessary, verify the validity of the design by an element test.

(6) Safety design
Review the safety analysis results and check that the measures indicated by the results are reflected appropriately in the design, work environment, fixture, relevant equipment, procedure, etc.

(7) Reliability design
The main work is a review of reliability, FMEA and analysis results; however, the measures against a single failure are subject to confirmation redundancies and, depending on their content, to an in-process inspection, etc. For redundancies, the integrity of all should be confirmed before the system delivery as a general rule. However, for a redundant design, etc. at the circuit level whose direct confirmation in the system is difficult, make an indirect confirmation by trend assessment or the like. Worst-case analysis is subject to a review; however, an evaluation using circuit analysis software or trial fabrication model is also made at the design stage. Devices, materials, process selection, stress analysis, and derating are subject to a review, and for the devices, materials and processes, whether they are implemented and managed according to the selection is subject to the in-process inspection. In an individual qualification test, review the test plan (method and decision criteria) and confirm that the expected results can be obtained. In a trend assessment, do a preliminary review of the intended items and a confirmation of the assessment results in each test. For a limited life/operations article, make a preliminary review of the intended items and manage the cumulative time/number of times in each test. For ground maintenance of batteries, carry out a review of the validity of its method, an inspection of maintenance condition, and a performance test after the maintenance (before mounting).

(8) Maintainability design
Confirm in the design review that actions and preparations (procedures, etc.) as per the design are ready. The workability of battery replacement should be confirmed in the system EM phase or system PFM.

5.3 Power supply capacity

Verification of power supply capacity is to verify that the power supply capacity satisfies the required power profile during the entire mission period, and this is done by confirming the power supply capacity required from power budget analysis of the system.
Verification of power supply capacity is done in the development phase and by the following approach.

- From conceptual stage to design stage: Review of design results
- Fabrication and test stage: Review of fabrication and inspection results of each component

5.3.1 Required power profile

Based on the examination and test results, etc. in each stage, update the table of supply power by operation modes and the operation plan to keep the profile up to date and confirm that the design requirements are satisfied.

In the fabrication and test stage, the source data of the table of power supply by operation mode is updated with the measured values of power consumption of the component. Moreover, in a system test, or a simulation test and thermal balance test of the operation modes in particular, the supply power and required power profile by operation mode are updated in a comprehensive way. However, there are limitations to a simulation of operation modes because of restrictions, etc. on a ground test, so the power consumption of the mission subsystem, ion engine, attitude control subsystem, thermal control heater, etc. cannot be set in a ground test as assumed on orbit. Thus, make an appropriate correction to the obtained data by analysis.

5.3.2 Required size of power source

The hardware characteristics for the required size of a solar array and battery are verified in 4.5.1 and 4.5.2. The specifications for required size are set by power budget analysis to a level satisfying the final required power profile in the design stage. Therefore, if the hardware fabrication and tests proceed as designed and it is confirmed that the required power profile and the requirements for a solar array and battery are satisfied, this establishes verification that the power subsystem can supply power to achieve the spacecraft mission. However, the source data (power consumption, model variables, etc.) will be updated with the progress of the development; therefore, it is necessary to appropriately confirm that the power budget is kept in balance. Therefore, manage the power budget analysis model and its source data continuously in and after the design stage of development.

Related considerations

A policy, etc. of coping with the case of severe operation as to power budget is shown below.

In such a case, when examining the depth of discharge or stored energy recovery state of a battery, it is desirable, considering the limitations to power budget analysis, to conduct an operation simulation test (see Clause (3) of 4.5.2) on the battery to obtain data for that.

(1) Initial stage of launch

In the case of a paddle-shaped solar panel, the power budget is generally severe in the period from launch to paddle deployment and sun orientation. As a measure, scaling up the panel and battery is conceivable, although this results in a mass increase. It is conceivable to increase the depth of discharge of the battery in this period; however, what to do first is thorough power saving of the entire spacecraft in this period (by reducing the power consumption of equipment, etc., putting unnecessary equipment in the non-operating state, or otherwise).

(2) Contingencies
At an abnormality covered by the protection function, prediction of the depth of discharge of a battery takes place also by power budge analysis. In such a situation, there are limitations to the prediction of panel power generation, load condition, duration, etc. So, thorough energy saving of the entire spacecraft should be pursued as far as possible.

(3) In case where balancing the budget of one orbital revolution is difficult
While there is sunshine, a battery discharge does not continue in general and is negligible in most cases. For a LEO spacecraft, stored energy recovery during one orbital revolution (charge completion while there is sunshine) is difficult in some cases. If this state continues, the stored energy in the battery will continue to decrease, so a sole measure is to enlarge the solar array size except for power saving. If this state does not continue and the stored energy is recovered after several orbital revolutions, a design subject to this may be judged to be valid (considering the effect on the life) Even for an LEO spacecraft, a significant battery discharge takes place even in the sunshine if there is necessity for power supply to an ion engine or other large load.

5.4 Power supply characteristics

The requirements related to power supply characteristics are verified by a design review based on analysis, etc. and by a system test, and the element unit tests and power subsystem combination tests are done for the purpose of judging that a power subsystem component may be subjected to a system test. Here, paying attention to a system test as final verification, overall points to consider are described.

(1) Reference point/measurement method
In a system test, monitoring items are restricted, and a precondition is that the method of monitoring the characteristics subject to verification has a sufficient accuracy. Therefore, a review and confirmation of reference points, voltage monitoring method, etc. should be done in advance. Because detailed evaluation is difficult with telemetry data alone, provide a hardware line monitor terminal, etc. using a test connector. Because the power subsystem is a subsystem operating at all times, AGE that can continuously monitor and record acquired data from the power start-up at the beginning of a test to the power shut-off at the end of the test should be prepared. Besides voltage, current monitoring is desirably possible for its evaluation, etc. (by clip-on or otherwise).

(2) Power subsystem operation modes/simulated power source
Conduct a power supply characteristic verification test for all operation modes of the power subsystem in 3.2.1 and under the conditions in combinations including the expected maximum and minimum of the solar array output characteristics, battery's state of charge or depth of discharge, and supply (load) power. For this purpose, prepare

a solar array simulator and battery simulator that can set the expected solar array output characteristics and a battery's charge and discharge (voltage) characteristics. These simulated power sources are desirably those which were used for a unit test, etc. For the battery, conduct a series of tests on an actual one, besides using the simulator. For the solar array, it is desirable to conduct a test for the purpose of confirming the connections, etc., using a simulated sunlight source, lamp, etc. For the load, designate in advance the conditions to evaluate the supply power characteristics based on the table of supply power by spacecraft operation mode. On this occasion, it is necessary to examine and prepare in advance the heat rejection measures of large power equipment and thermal control heaters during a ground test.

(3) Trend assessment

The verification is to confirm that the specifications concerning power supply characteristics are satisfied. However, the specification itself assumes the situation where an abnormality of a redundant part, or a trouble of a battery cell, etc. had occurred.

Therefore, it is impossible in some cases to judge the inside to be normal even within the specification. Thus, the test should designate bus voltage or other power supply characteristic as a trend assessment item and evaluate the reproducibility of characteristic behavior in all test processes.

5.4.1 Bus voltage

The specifications in 3.4.1 assume the state of actual operation. So, confirm in the pertinent operation state that the bus voltage data remains/varies as designed and there is no abnormality in the trend.

5.4.2 Voltage stability

In a state where the active bus voltage stabilization function operates, measure the bus voltage under the most favorable/adverse operating conditions to confirm that the specification is satisfied and there is no abnormality in the trend.

5.4.3 Ripple and spike

Measure the ripple and spike in each operating mode to confirm that the respective specifications are satisfied and there is no abnormality in the trend. On this occasion, besides the ripple component generated by the power subsystem, the reflected ripple component from the load side is also intended. So, obtain source data in advance to evaluate these components. It is not practical to make an evaluation in all test conditions. Set the condition of the solar array, battery, and load (for example, a condition for large ripple) in advance and evaluate the data of that case in detail. To measure ripple and spike, a band of 500 MHz or more is required, so it is impossible to evaluate them with telemetry data.

5.4.4 Output impedance

This specification intends the output impedance of the power subsystem proper and is a confirmation item in a power subsystem combination test. So, it is deleted from an confirmation item of a system test. However, it is also possible to incorporate the power subsystem at the time of system integration and conduct a system test in the configuration with no load connected.
Stability, ripple, and transient characteristics can serve for indirect evaluation and confirmation of output impedance.

5.4.5 Transient characteristics

Measure the bus voltage transient at the transient operations (paddle deployment, load connection and disconnection, peak power supply, sunshine/eclipse and in-between transient, etc.) imposed on the power subsystem according to the spacecraft operation to confirm that the corresponding specification is satisfied and there is no abnormality in the trend. On this occasion, set certain conditions in advance as with ripple and evaluate the data of that case in detail. The transient at a load abnormality or an internal abnormality of the power system is generally deleted from a confirmation item of a system test as with output impedance (if otherwise, it is necessary to prepare a dedicated line for the system harnesses and test connectors) and is taken to be a confirmation item of a power subsystem combination test and unit test.

5.5 Power subsystem

5.5.1 Interface with solar paddle subsystem

Because of restrictions of AGE, it is very difficult in general for the solar paddle subsystem to verify by a test the consistency of the power subsystem interface design in a configuration in combination in the system. Therefore, verify the satisfaction of the requirements by the results of an analysis designed based on existing data, results of a unit test and inspection of the two subsystems, consistency confirmation of the two subsystems' ICD and other drawings, operation confirmation on the simulated solar array power (solar array simulator), etc.

A verification example of the interface design requirements in Section 4.5.1 is shown below.

(1) Interface reference point
Consistency confirmation of two subsystem's ICD

(2) Maximum voltage and maximum current at interface reference point
Confirmation of solar paddle subsystem irradiation test results and analysis.

(3) Round-trip line resistance between interface reference point and PCU
Confirmation of power subsystem (system harnesses of power lines) unit inspection results.

(4) Shunt operation sequence
Two subsystems' ICD consistency confirmation and confirmation of shunt operation sequence by operation on simulated solar array power.

5.5.2 Battery

For the requirements for a battery, perform a verification by unit tests, system tests, etc., except for the life-related characteristics. For capacity and some other characteristics, however, evaluate the trend in voltage, etc. because these cannot generally be evaluated by a system test. Life-related verification is made by a battery and battery cell design review based on related past records and preceding test results, confirmation of fabrication and test results, and (if specified in the battery specification document) quality confirmation test results of shipment lots.

(1) Configuration

Besides ordinary inspection of appearance, dimensions, mass, etc., confirm the insulation between the battery cell case and battery cell holding structure. Additionally, in relation to insulation, measure the voltage between the case and battery cell terminals (positive/case and case/negative) to confirm it to be proper.

For the temperature difference in the battery, confirm in a thermal vacuum test that it is kept under the allowable value when under specified charge and discharge conditions.

(2) Ground initial characteristics

Under the specified conditions of charge and discharge current, time, temperature, etc., confirm by a test that the requirements for initial charge and discharge characteristics are satisfied. And, confirm that there is no abnormal behavior, etc. in the characteristics related to the short-cycle characteristics required as a characteristic trend.

For example, reproducibility exists in the characteristic results of an initial test and final test under the same conditions.

The characteristics of a battery cell may be influenced by its history. Therefore, keep the conditions before and after the test as constant as possible. If the test is suspended, give the same treatment as for storage.

In a unit test, measure the voltage of each battery cell to evaluate the matching quality and its trend of the characteristics of the battery cells making up the battery.

(3) Life prediction

Review the results of design analysis (similarity) and preliminary evaluation to confirm that the life requirement is satisfied.

Confirmation that the battery cell used has the same characteristics as the battery cell subjected to the preliminary evaluation is made by evaluating the battery cell’s fabrication process data, delivery test results, and (if required in the battery cell specification document, etc.) lot quality confirmation test results.

When conducting an operation simulation test for preliminary evaluation, make a spacecraft actual operation plan and a test plan to simulate charge control to evaluate the validity of the entire operation of the battery. In particular, it is desirable not to limit to charge and discharge operation in a stationary orbit but to incorporate the charge at the launch (the temperature condition is generally severe), transient operation in a transient orbit (the depth of discharge tends to go deep until paddle deployment), contingencies (confirm required energy supply at an abnormality/evaluate the validity of battery charge control during steady-state operation/estimate the restoration period) and confirmation of the effect of battery cell refresh (*1) or reconditioning (*2).

In power budget analysis, for an operation, etc. in which the budget balance of one orbital revolution cannot be ensured, there are limits to analysis of the battery behavior, which therefore should be evaluated by an operation simulation test.

*1: Battery cell refresh

A lithium ion battery has no saturation voltage (the voltage is not constant at completion of charge) unlike conventional NiCd and NiH2 batteries. Therefore, if an imbalance of the state of charge occurs among the battery cells connected in series, this variance remains unchanged and the series-connected battery will be restricted by this varying state of charge of the battery cells. Battery cell refresh is a function to recover the battery capacity by equalizing the battery cell voltage, and the equalization takes place by a bypass circuit connected to, and in series with, each battery cell to make the state of charge even among the battery cells.

*2: Reconditioning

NiCd and NiH_2 batteries have a property (memory effect) in which, if charge and discharge are repeated at a level before reaching a complete discharge, it becomes impossible for discharging to take place exceeding that amount of discharge even though there is a margin of capacity. Reconditioning is a function to prevent this and recover the amount of discharge by periodically deepening the amount of discharge to activate the electrodes.

(4) Sealing and pressure-proof characteristics

If possible with the battery, conduct a leak test of the electrolyte and an air-tightness evaluation trace (He) gas. Confirm related data at a delivery test and process data related to the sealing/pressure proof characteristics. If a leak test is conducted on the battery, it is desirable to employ the same conditions as for the battery cells.

The pressure-proof characteristics should be verified with a battery cell proper.

(5) Battery redundancy

In a battery-redundant design, etc., verification should be made on all redundancies as a general rule to confirm the integrity of the batteries. If, however, a trouble, etc. of a specific battery cell cannot be verified, the verification should be made by analysis.

(6) Safety verification

For a lithium ion battery, do the following.
Safety verification of a battery should take place, as basic verification, by managing all processes from battery cell fabrication to battery test completion so that they are done appropriately. Because a direct safety test on a payload article can damage that article, conduct such a test on a lot sample of the battery cell. Because a safety test of a battery cell can endanger the operating personnel and neighboring equipment, conduct the test while paying due attention to each risk.

(a) Safety of battery cell
As a safety test of a battery cell, conduct an external short-circuit test and overcharge test on each type of battery cell for safety verification. For the safety valve (rupture part) of the battery cell, do a test for each production lot of the rupture part. By this rupture test, confirm the design operation pressure.

(b) Safety of battery
For the protection function for battery overcharge, make an operation confirmation of the protection circuit not only in its proper state but also in the its incorporated state in a battery.

(c) Transportation safety
The battery transportation test is conducted on the dedicated battery packing and is to drop it from 1.2 m. The following requirements should be satisfied.
[1] The battery and battery cells inside are not damaged.
[2] The battery and battery cells inside does not form an external short-circuit.
[3] The battery and battery cells are not forced out.

(d) Parallel connection protection
For the protection circuit for parallel connection of batteries, make a confirmation, or verification by analysis, of its operation.

(e) Others
For the means provided for battery protection, do a test in the respective subsystems (temperature control and voltage control).

5.5.3 Power control

Design related to power control is verified in a comprehensive way in 5.4 Power Supply Characteristics. However, there are some items whose verification is difficult to make with a system test. Here described is an overview of the overall confirmation items in the unit test and combination test performed before the system test and the evaluation items in the system test.

5.5.3.1 Unit test

Confirm that the characteristics of each element are within the required specification value or design specification value. In particular, a comparison between the measured and predicted effect of the variations of device characteristics in a temperature test and a confirmation of characteristic reproducibility of EM/FM under the influence of variance of device characteristics are effective for validity evaluation of the design. In spite of device characteristic degradation, etc. due to radiations, etc., the required specifications have to be satisfied, and verification for that is made by a review of design analysis results.

Because the simulated solar array power source, battery simulator, external start-up power source, etc. are used also in combination tests and system tests, make a plan so that the effect of the difference in test configuration will not pose a problem in subsequent tests.

Redundant design confirmation at the circuit level, transient evaluation at an internal single failure or load abnormality, etc. are items for which it is difficult to do a system test. Thus, do a unit test for all such items.

The electromagnetic compatibility test becomes complete by a unit test alone in some cases (especially for FM), so a characteristic comparison with the EM, etc. whose compatibility with the system was confirmed is important.

For data belonging to a trend evaluation item in a system test, obtain source data for the evaluation, and obtain calibration curves for all telemetry data.

5.5.3.2 Combination test

Although there is a difference from a system test because no system harness or actual load is connected, confirm by a combination test that the comprehensive operation (power control, in particular) of the power subsystem is in accordance with the design, the required power supply characteristics can be ensured, and a transition to a system test may be made. On this occasion, make an evaluation that the results of a unit test of each element are reproduced and do management of the trend items and calibration curves.

In a combination test, confirm the monitoring method of comprehensive operation and evaluate the data behavior of voltage, current, status, etc. for all operation modes of the power subsystem in 4.2.1 and at power-on and power-off to obtain source data for evaluating the power supply characteristics (see 5.4, (2)) in a system test.

In a temperature test, confirm that the condition setting of equipment in combination is in accordance with the prediction of actual operation.

5.5.3.3 System test

Mainly make a confirmation of the power supply characteristics in 5.4, and evaluate the comprehensive operation of the power subsystem based on the combination test results.

(1) Control system

By comprehensive operation confirmation by a combination test and system test, confirm that solar array output control, charge control, and discharge control operate systematically, the operation range, priority and coordination management of control agree with design, and the functions related to operation modes are operating normally. For parallel operation of multiple buses or multiple batteries, confirm that current share is appropriate.

(2) Operation point analysis

Along with verification of the control system, evaluate the behavior of operation monitoring data of bus voltage, solar array output current, load current, etc. to confirm that the operation point of each control operation agrees with the design prediction. For lock-up and other operating point abnormalities, confirm the identification method and measures (automatic restoration) by load reduction, etc.

(3) Control diagram

Confirm that the power supply characteristics by a unit test, combination test and system test agree with the characteristics predicted from the control diagram. Although the prediction and measurement (of dynamic characteristics in particular) may not necessarily agree depending on the characteristics of the simulated solar array power source (including the test cable), load, etc., evaluate that the basic behavior does not differ from the prediction to confirm the validity of the control diagram. Also confirm that an abnormal shift of the operation point does not occur due to load variations, solar array output variations, a shift of the state of charge of the battery or other disturbances, and unstable vibrations, latch-up, etc. of control do not occur due to inappropriate damping characteristics, parasitic oscillation, etc.

Because it is difficult to measure and simulate the dynamic characteristics of a solar array, it is common practice to design so that the dynamic characteristics do not influence the control characteristics However, if the degree of this influence poses a problem for ensuring the control stability, etc., it is necessary to make an evaluation, etc. of an analysis model for a partial panel. For the simulated solar array power source, use a power source having a small output capacitance, a higher speed of response than power control, and frequency characteristics close to the actual solar array.

(4) Characteristics of each power control

The control characteristics are evaluated by a unit test, combination test and system test, and design verification is performed for the items of (1) to (4). Here, points to consider related to the test of each control element are described.

a. Solar array output control

Prior to a test, confirm that the simulated solar array power source incorporates the solar array output (V-I characteristics) prediction and can simulate the characteristic change from BOL to EOL in particular and the output ripple, etc. before paddle deployment. The solar array output characteristics change greatly due to the rapid temperature rise after an eclipse, and it is desirable that this situation can also be simulated.

The monitoring means to keep track of the operation condition of output control should be confirmed as a monitoring method of comprehensive operation of the power subsystem. Besides this, if direct measurement of power generation of the solar array is difficult, obtain and evaluate related data as an indirect measurement means of power generation.

If the operation of the control element of solar array output control is switching (digital shunt), shielding of the noise associated in principle with the operation cannot be accomplished as with general equipment and, in addition, it is difficult to use an actual solar array. Therefore, when conducting an electromagnetic compatibility test on other equipment while solar array output control is taking place, it is necessary to examine the test method or analysis means in advance.

b. Charge control

When testing the charge control function of a battery, it takes a considerable time if an actual battery is used. Therefore, use a test power source and, by making adjustable the simulated signals battery voltage, temperature, etc. by a battery simulator and test adjustment device, make a confirmation of the V/T level, change-over of charge current, constant current/constant voltage charge control, bus voltage control function, heater control, protection function, etc. The battery simulator is convenient for characteristic evaluation, etc. of equipment and is used in a combination test and system test in some cases, besides a unit test. However, a simulator (including harnesses) does not completely simulate the characteristics of a battery. For a combination test before a system test which uses an actual battery, it is desirable to plan to also connect an actual battery.

For a spacecraft needing to confirm the efficiency (loss) in the power budget, measure the power conversion efficiency paying attention especially to constant-current charge and bus voltage control operations, in the above-stated charge characteristic confirmation.

On this occasion, note that the efficiency varies with temperature, battery voltage and charge current.

c. Discharge control

As with charge control, make a confirmation of the discharge function and protection function (UVC, etc.) using a battery simulator.

The blowing capability of the fuse at a load abnormality should be confirmed by analysis or a test using a battery.

When confirming the efficiency (loss), note that it varies with temperature, battery voltage and discharge current, as with charge control.

5.5.4 Power distribution

The requirements for power distribution should be verified along with the confirmation of power supply of the electrical interface of 2.2, (1) under System Test. Arrange the results in a power distribution management table and confirm that the requirements are satisfied.
In a unit test, besides confirming the distribution function (conduction, voltage drop, turn-on/off, and monitoring), make a confirmation of the normality of built-in protection functions (fuse and shut-off function) which are difficult to confirm by a system test.
Design involving the operating conditions of a fuse (current, time, etc.) should be verified by evaluations up to the design stage.
For pyrotechnic ignition power supply, in the case where the number of operations is limited, what to do with FM is, in some cases, only to confirm all functions such as conduction, insulation and an ignition sequence using small current. In such a case and in an EM test, etc., a function and performance confirmation using actual current (actual pyrotechnic) should be made as verification of the design.

5.5.5 Protection

5.5.5.1 Overview

The power subsystem is required to operate at all times and its fault tolerant design is made on the premise that its major functions cannot be stopped as fail-safe. Therefore, it is necessary to make verification considering that verification of its protection function is not easy.
In particular, when simulating the occurrence of an abnormality, it is necessary to take care not to impose an unnecessary overstress on the devices, etc.

5.5.5.2 Protection in power subsystem

(1) Redundancy

(a) For a single-point failure, make design verification using FMECA, etc.

(b) For an abnormality or failure of a device, etc. due to an open-circuit or short-circuit, make design verification using FMEA at the device level and functional FMEA.
In addition, if a module or equipment takes a redundant configuration, conduct a test assuming that one module or piece of equipment failed.

(c) If a protection function is to be performed in the same hybrid IC, make design verification by the circuit diagrams, manufacturing drawings, etc. of the hybrid IC to ensure that no chain of failures will occur.

(d) When the solar battery (simulated power source) starts output, confirm that it operates without needing a special command.

(2) Insulation

(a) Perform insulation measurements in units of components. Determine the applied voltage considering the function of the component.

(3) Overcurrent protection

(a) Using interface FMEA, etc., confirm that the primary power bus is protected by a protection circuit.

(b) If a fuse is used to protect a primary power bus distribution wire, show the fuse's rating and, by analysis, the maximum current in the load path, including transient states (due to in-rush current, etc.), and show that the rating of the fuse is appropriate. Perform analysis of fuse blowing to verify that the bus voltage can satisfy the lower limit at an abnormality.

(c) If a fuse is used to protect a primary power bus distribution line, verify by analysis that the power subsystem can blow this fuse when the load is short-circuited within the specified time determined in the Electrical Design Standard of each project.

(d) If a fuse is used to protect the primary power bus, confirm at the time of system delivery and at the component level that there is no open-circuit in the fuse. After integration of the spacecraft, confirm as the need arises that there is no open-circuit in the fuse.

(e) If a fuse is installed in the subsequent stage of a DC/DC converter, consider the melting characteristics of that fuse and verify by a unit test of the DC/DC converter that the DC/DC converter has the ability to blow the fuse for certain.

(4) Battery protection

(a) Perform a test or analysis which assumes that one battery failed.

(b) If an over-temperature occurs in the battery, charge suspension or other protection function will operate. Verify this by a test. If a test battery is not available, simulate the battery over-temperature state by a simulation signal to avoid an overload on the battery.

5.5.5.3 Protection in cooperation with other subsystems

For all protection functions related to power supply, confirm them according to the operation confirmation method by a ground test in the protection function summary table specified in Section 4.5.5.3. For confirmation of a function, make confirmation, etc. of simulation signals and statuses to establish end-to-end verification from detection to protection action in the realm of possibility.

Confirmation of a protection function about an item requiring cooperation with other subsystem can only be performed systematically by a system test. Thus, specify the points in time of confirmation in advance and arrange the evaluation results in a summary table to confirm at the end of the system test that all items have been tested and evaluated.

5.5.5.4 Protection for abnormality of ground equipment

Ground test equipment should be subjected to sufficient validation before used for verification of a spacecraft.

Appendix-I Design Overview (as reference materials)

Of the electricity subsystem (power subsystem plus solar paddle subsystem) of a spacecraft, this appendix mainly describes an overview of design of the power subsystem.

I.1 General

The electricity subsystem of a spacecraft has the role of supplying required electrical power at the prescribed voltage and other various characteristics without interruption over the entire mission period.
For this purpose, the electricity subsystem has the following functions:
[Solar paddle subsystem]
(1) Power generation
[Power subsystem]
(2) Storage of electrical energy
(3) Power control
(4) Power distribution
(5) Protection: Limitation of failure or abnormality

Figure 4.2-1 in the text shows an overview of the electricity subsystem configuration. The electricity subsystem has, besides the basic functions shown in the figure, a telemetry/command processing function.
Generation of electrical power is achieved by a solar paddle and storage of electrical energy by a battery, and the size of these power sources determines the power supply capacity of the electricity subsystem. The power supply capacity must satisfy the required power profile over the entire mission period of the spacecraft.
Power control consists of the functions of solar array output control and battery management (charge and discharge control), and these determine the power supply characteristics (voltage and other various characteristics). The power supply characteristics must satisfy the electrical interface conditions related to power supply to the spacecraft system.
Power distribution is the function of distributing power to each load in the spacecraft, and its output end forms an interface boundary of power supply and is taken as a reference point of power distribution characteristics.

The power subsystem has a power supply bus to cooperate the functions of the solar paddle, battery and power control, and power is supplied from this bus. And, the voltage at the reference point of power supply characteristics is called primary bus voltage. As a power subsystem configuration, the power supply bus consists of one line (single-bus) or multiple lines (multiple-bus), and in some multiple-bus configurations, the lines do not necessarily have the same structure or characteristics and the bus voltage is set to multiple levels. For power supply, besides power to the equipment, a secondary power bus is needed for propulsion motors, paddle and antenna deployment, etc. and a pyrotechnic ignition power bus is provided to supply power there from the battery through a dedicated distribution line.
Protection is a function to keep normal power supply. It suppresses propagation of failure or

abnormality not only inside the power subsystem but also of other subsystems, and shares functions and coordinates the operation with other related subsystems.

The electricity subsystem occupies a large system share of mass, etc. and is closely related to the (electrical, structural, attitude control, etc.) design of the whole system.
Development proceeds at the levels corresponding to the development stages of conceptual design, basic design, detailed design, and maintenance design/fabrication and test. In the meanwhile, a review is performed on the results of preceding study, investigation of current technology, analysis, trial fabrication, tests, etc., and validity confirmation, revision and change of the design are made based on the technical feasibility of the development target, development time, risk, cost, etc. For a design change, it is necessary to consider its effects, etc. on others. On and after the basic design stage, therefore, it is reviewed and treated based on the configuration program plan.
Described below is an overview of major system considerations, major specifications of the power subsystem (amount of power supply and power supply characteristics) and major components when proceeding with power subsystem design up to the detailed design stage.
Figure I.1-1 classifies the necessary considerations in power subsystem design into System Level Examination Items, Subsystem Level Examination Items and Major Component Level Examination Items and shows their relationship.

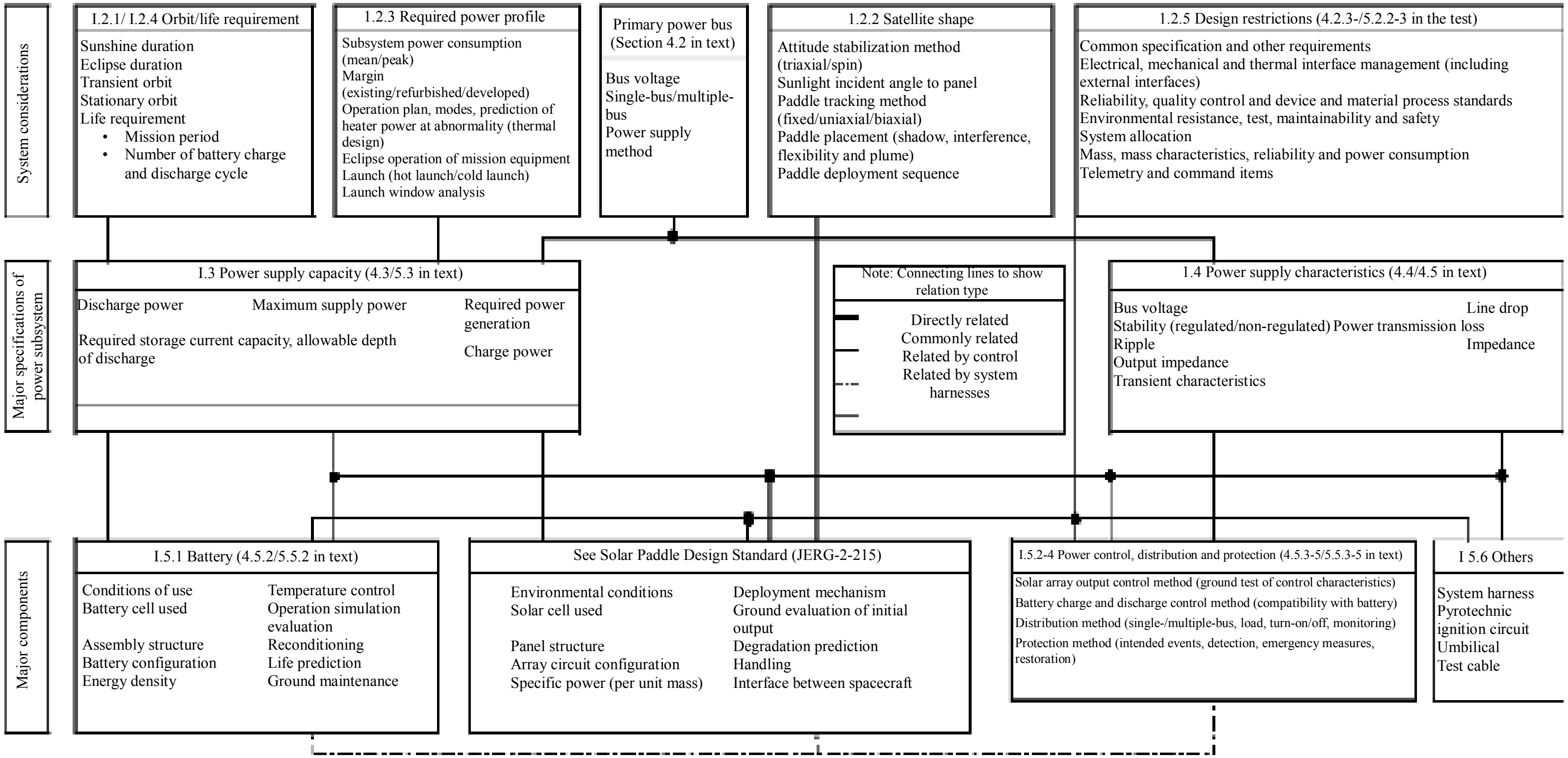


Figure I .1-1 Overview of power supply design

I.2 System considerations

The power subsystem of a spacecraft needs a design suitable for the mission requirements for the spacecraft from the viewpoint of mass, efficiency, reliability, etc. These mission requirements are basic conditions to determine the spacecraft shape (including the attitude conditions), required power profile and life requirement.
Design examination of a power subsystem is closely related to system design concerning [1] orbit, [2] spacecraft shape and [3] required power profile and proceed in pace with the design of these.
To implement a system, [4] design restrictions are set on its subsystems and components, and the design proceeds in compliance with these.
An overview of the basic conditions of [1] to [4] above is described below.
This design overview does not cover the power subsystem of a spacecraft for which replenishment or recovery is intended. Therefore, such considerations specific to a system are not described individually. With such a spacecraft, most operations are transient in nature, and the required power and time, attitude conditions (extent of sunlight utilization), power transfer to or from other systems, operations to avoid abnormality propagation (collision, impact outside the planned area, etc.), required level of redundancy (triple redundancy, etc.), etc. in the mission period have a large influence on the design of the power subsystem.

I.2.1 Orbit

An orbit determines eclipse conditions (time of occurrence and duration), sunshine duration, and sunlight incident angle to the orbit plane and dictates the environmental conditions of the spacecraft main body and solar paddle and the charge and discharge conditions, etc. of the battery.
Typical examples of orbits are the geostationary earth orbit (GEO) and a low-altitude earth orbit (LEO). On the GEO, an eclipse of about 70 minutes at the longest occurs only in 20-odd days before and after the vernal and autumnal equinoxes, so more than 20 hours can be taken for a charge and the state of full charge is kept for most of the mission period. On the other hand, on an LEO, an eclipse of about 30 minutes occurs at every revolution around the earth in most cases, and the charge time is one hour or so, and the number of eclipse occurrences a year reaches about 5,000 or 6,000 in some cases.
The solar panel temperature changes rapidly in the transient period between an eclipse and sunshine. On the GEO, for example, the temperature falls from about 50°C during sunshine to about minus 200°C during an eclipse.
In addition, the power generation output of a solar array degrades due to radiations, etc. in outer space, however, this situation depends on the orbit. An orbit is divided into a stationary orbit for fulfilling a mission and a transient orbit up to a transition to the stationary orbit. For GEO, power supply on a transient orbit tends to depend on the battery.

I.2.2 Spacecraft shape

In general, the shape of a spacecraft is related to its attitude stabilization method, that is, the spin method takes a cylindrical form and the triaxial method takes a box-like form with a deployed paddle. And, the solar array is attached on the main body cylinder in the case of the spin method and on the deployed paddle in the case of the triaxial method. Therefore, the sunlight incident angle to the panel is determined by the spacecraft attitude in the case of

the spin method. In the case of triaxial method, the placement of the solar paddle and tracking method are involved. The tracking method is generally uniaxial, however, the biaxial or fixed method is also used. For a paddle-shaped solar panel, power is transmitted to the spacecraft main body through the slip ring of the solar paddle drive mechanism.
In the case of the spin method, the dimensions of the panel generally coincide with those of the spacecraft main body. Thus, the power generation requirement is restricted by the size of the spacecraft. On the other hand, few restrictions are imposed on the triaxial method because of a deployed paddle. The placement, tracking method and shape of a paddle are determined by a comprehensive examination of the power generation requirement, efficiency of the solar cell used (consider the temperature characteristics and degradation characteristics as well), field interference with the sensors and antennas, shadow of the spacecraft main body, interference and contamination from the propulsion subsystem, attitude disturbances, etc. In this process, the required dimensions, etc. of the solar paddle are also determined.
For a deployed paddle, power supply depends on the battery in the period from launch to deployment. Therefore, it is necessary to set the deployment sequence and the required power profile during this period to maintain the depth of discharge of the battery within the allowable value.

I.2.3 Required power profile

The required power profile is determined by the component power consumption of each subsystem and the operation mode based on the spacecraft operation plan, etc. If the required power changes in time many times, it is expressed as a time series of operations. The power consumption intends mean power and peak power, contains a margin according to the records of a subsystem, component, etc. (newly developed/refurbished/new), and is updated with the measured value, etc. with the progress of the development stage.
For such an update of source data, the power consumption of the on-board equipment can be based on the measured value of a test. However, for example, the heater power, etc. in thermal design of the spacecraft system is difficult to keep track of accurately even in a (thermal balance, etc.) test. Thus, such a quantity will have to rely on prediction even though the accuracy is improved from the design stage. In addition, at EOL when the power budget is severe, it is necessary to predict the required heater power (smaller than at BOL in general) considering the deterioration of surface characteristics of the thermal blanket. Therefore, for a system in which source data, like the thermal control heater power, relying on a predicted value occupies a large proportion of the required power profile, how to deal with the margin of a prediction becomes challenge.
Set the operation mode for the entire mission period, that is, for the launch stage, transition stage and steady-state operation, and consider contingencies (abnormality of attitude, etc.) as well. In the triaxial method, the solar paddle is deployed by the time of transition to a stationary orbit, and the power supply until the deployment tends to depend on the battery. Include such a transient operation mode as well.
The eclipse operation of mission equipment influences battery size determination.
Of the launch types, cold launch does not put the spacecraft in operation until the rocket separation, so it reduces the burden on the battery. However, hot launch which put the spacecraft in operation using the battery before the launch is generally employed. The requirements concerning electricity in the launch stage are considered in launch window analysis.

I.2.4 Life requirement

Design and consider to satisfy the battery life (on-board life, charge and discharge cycle life, ground storage life, etc.) required by the spacecraft mission requirements. Other life requirement examinations should be in accordance with Clause (7) Reliability Design in Section 4.2.4 Common Design Standard of the text.

I.2.5 Design restrictions

For development of a spacecraft system, common restrictions (requirements) to comply with are established and set.
These matters are indispensable for proceeding the development on a full scale and are documented in the form of a common specification or system allocation. However, determination of details consumes a considerable time for coordination, etc. between the system and subsystem parties concerned.
The power subsystem and its constituent components are designed and fabricated in compliance with these matters, and the design validity is demonstrated by a test or analysis.

(1) Common specifications, etc.

The following common specifications, etc. are established in accordance to the architecture (example) of specifications and standards of each project.

a. Electrical Design Common Specification (Standard)
b. Mechanical Design Common Specification (Standard)
c. Thermal Design Common Specification (Standard)
d. Electromagnetic Compatibility Common Specification (Standard)
e. Environmental Resistance Design Standard
f. Interface Management Specification
g. Test Common Specification
h. Device, Material and Process Standard
i. Maintenance Program Standard
j. System Safety Standard
k. Reliability Program Common Specification
l. Quality Assurance Program Standard

The power subsystem has interfaces with other subsystems for power supply through system harnesses, and the power supply characteristics are incorporated in the common specifications for electrical design and electromagnetic compatibility. The grounding lines of the power lines of the spacecraft system are managed by the common specification and grounding is taken at one point in the spacecraft structure.
The constituent elements (components) to implement the required function of the power subsystem are electrically connected by the system harnesses in general. Therefore, although management of the relevant harness takes place in the system, it is necessary to incorporate the characteristics of the harness in the design of the power subsystem.

Power subsystem components involves various types of heat generation and absorption when they do an energy conversion, storage and control. Therefore, for maintaining their temperature within a range to ensure the prescribed performance and characteristics, the thermal interface with the spacecraft system is an important design and management item.
The power subsystem protection function plays the role of preventing an abnormality/failure of some subsystems (including the power subsystem) from propagating throughout the spacecraft through the power bus as far as possible. Assumption, preventive means, etc. of intended abnormalities/failure are designed and managed from the viewpoint of the spacecraft system, and function sharing, etc. are set.
During a ground test or launch, the power subsystem receives charge power for the battery from AGE and power, etc. from a simulated solar power source through a dedicated line (of umbilical cable, etc.). This interface must be appropriately designed and managed considering its purpose.

(2) System allocation (design budget)

System allocation is an important management item for the success of a mission, and it is set concerning mass/mass characteristics/power/reliability/telemetry and command items, etc.
The target values should be appropriately allocated to each subsystem/component and managed based on the system design. The maintenance state of system allocation is reported in progress management.
When changing a set value, examine all influences on others. For example, increasing a power-related set value will change the required power profile, which in turn makes it necessary to reevaluate the compatibility with the power supply capacity of the power subsystem. If incompatible, an increase in mass, a change to the operation plan, etc. may be involved.

I.3 Power supply capacity

I.3.1 Overview

The mean value of power supply capacity of a power subsystem is roughly determined by the scale of the solar array and battery and from the following relation.

[Power supply capacity during sunshine] ≈ [Solar array output power] - [Battery charge power]
[Power supply capacity during an eclipse] ≈ [Battery discharge power]

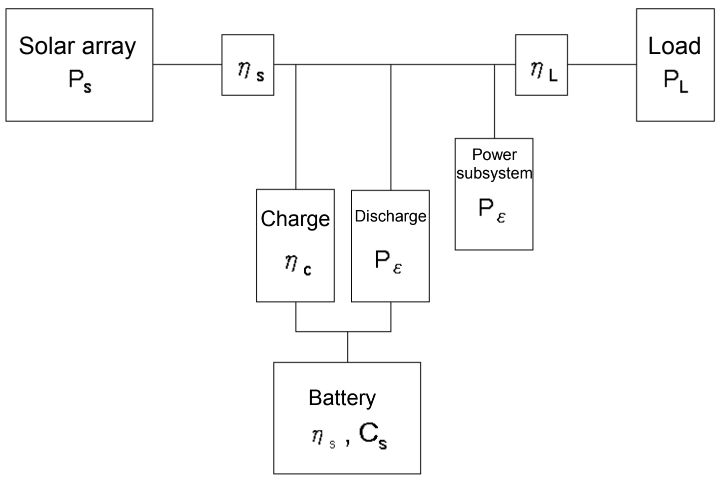
Here, the charge power is necessary for recovering the discharge power of the battery. If energy recovery does not take place appropriately, the stored energy of the battery gradually decreases and it becomes impossible to ensure the power supply capacity during an eclipse, possibly affecting the spacecraft operation. The discharge power of a battery is restricted by the total stored energy of the battery {= (stored energy per battery unit) × (number of battery units)}, allowable depth of discharge and discharge time.

When in sunshine as well, the peak value of power supply capacity is given as the sum of the solar array power generation and (allowable) discharge power
From these relations, a rough value of power supply capacity is determined by the size (power generation, stored energy, etc.) of the power sources (solar array and battery). The fundamental requirement for power supply capacity is to satisfy the required power profile over the entire mission period. Power budget analysis is performed to evaluate the compatibility with this requirement.

I.3.2 Power budget analysis
In power budget analysis, evaluate the compatibility between the required power profile and the power supply capacity of the power subsystem, that is, verify that the stored energy of the battery is appropriately maintained with respect to the required power profile.
Figure 2.3-1 shows an example of a power subsystem model for power budget analysis (example of main array type). In the analysis, the parameters to consider include:

P_S: Solar array output power
C_S: Instantaneous stored current capacity of battery
P_E: Power consumption of power subsystem
P_L: Load power
N: Number of battery power lines

η_S: Transmission efficiency of generated power
η_C: Charge control efficiency
η_B: Energy efficiency of battery charge and discharge
η_D: Discharge control efficiency
η_L: Transmission efficiency of power supply



	Transition equation for instantaneous stored current capacity CS (Δt: Time interval of calculation)
In the sunshine	Battery charge power = $[(P_S \bullet \eta_S)-(P_L/\eta_L)-P_E] \bullet \eta_C$ = Limit value by charge control: in case where the value of the above equation is larger than the limit value $Cs(t+\Delta t) = Cs(t) + \eta_s \bullet$ (Battery charge power) $\bullet \Delta t$/V_bat(chg) Note: In case where no discharge is taking place
During an eclipse	Battery discharge power = $[((P_L/\eta_L) + P_E]/\eta_D)/N]$ $Cs(t+\Delta t) = Cs(t) -$ (Battery discharge power) $\bullet \Delta t$/V_bat(dischg) Note: V_bat(dischg) denotes the mean battery discharge voltage.

Figure I.3-1 Example of power budget analysis model

The definitions of these parameters are described below.

P_S: Solar array power generation Because solar batteries degrade by radiation, etc., the power generation requirement at the beginning of life (BOL) is set from the power generation requirement at the end of life (EOL) based on a degradation prediction and determines the size of the solar array. P_S varies due to panel temperature, sunlight incident angle, shadow from the spacecraft body, etc., besides long-term degradation. The surplus power generation of P_S is treated by output control of the solar array.

ηS: Transmission efficiency of generated power Set considering power transmission loss due to the system harnesses, etc. from the solar array to the power subsystem.

ηC: Value corresponding to power conversion efficiency, etc. of charge control

ηD: Value corresponding to power conversion efficiency, etc. of discharge control

ηB: Amount of discharged current (Ah) divided by the minimum amount of charge current (Ah) necessary for that recovery. In particular, the charge energy after completion of a charge becomes heat in the battery, so it does not contribute to an increase in stored energy.
The upper limit of CS is the total amount of stored electricity C_B determined by battery capacity, discharge voltage and the number of battery units. This C_B determines the size of the battery.

C_S: Is the instantaneous stored current capacity (Ah) and can be called remaining current capacity (Ah). There is no data that directly represents this value and it is an analytical parameter. The depth of discharge is given in percentage of the expression $(C_B - C_S)/C_B$) from the CS at the end of discharge. The allowable depth of discharge is set considering the file requirements for the battery. In relation to life and depth of discharge, operation at a nearly 100% depth of discharge is not common considering an insufficiency of solar array power generation if an attitude abnormality, etc. occurs immediately after an eclipse.

PE: Steady-state power consumption of power subsystem itself.

ηL: Efficiency of power supply to load. Set considering the power transmission loss due to the system harnesses, etc. from the power subsystem output end to each subsystem or component.

PL: Load power. Specified by the required power profile and varies with spacecraft operation modes, etc.

Power budget analysis is usually performed by a power subsystem simulation program built up on a computer. In a power budget analysis using a computer program, make time series of PL, PS, etc. and calculate the instantaneous stored current capacity C_S (Ah) or the depth of discharge. And, if this value is kept within the allowable value, the power supply capacity is judged to be compatible with the required power profile. The simulation of a power subsystem in Figure Ⅰ.3-1 is the simplest one and hardly considers the voltage-current characteristics of the solar array, bus voltage behavior, change and discharge characteristics of the battery, the effect of temperature on these, and the like. To deal with this, set and update the parameters to appropriate average values by hardware test results and evaluation repetition. In another method for this purpose, a power subsystem operation analysis program incorporating the hardware characteristics as much as possible is applied for the power budget analysis considering the following items.

- V-I characteristics of solar array (consider temperature characteristics, radiation degradation, etc. as well.)
- Electrical characteristics including state of charge of battery (consider temperature characteristics, aging, etc. as well.
- Electrical characteristics of each piece of equipment of power subsystem (solar array output control, charge and discharge control, etc.)
- Load characteristics (constant power, constant current, resistance)

For example, in a constant-voltage charge, which is one of the battery charge methods, the charge current decreases exponentially and this change in time depends of the characteristics of the battery. In addition, to analyze the change of stored current capacity C_S (Ah) in time, which is a key parameter for power budget analysis, it is necessary to consider the charge and discharge energy efficiencies as well, besides the correlation between this charge control and battery characteristics. However, modeling of the charge characteristics, etc. of a battery for operation analysis involves many problems, and improvements through accumulation of application experience or otherwise are required. In addition, a comprehensive operation analysis program is conceivable for the spacecraft system, including the power subsystem-related operations, etc. of the thermal control subsystem. However, to maintain and develop such a program effectively, a repeated improvement of modeling through application experience is required. Considering this, a long-term policy to use the same type of spacecraft system a considerable number of times is a precondition.
For reference, an example of power budget analysis is shown in Figure I.3-2.

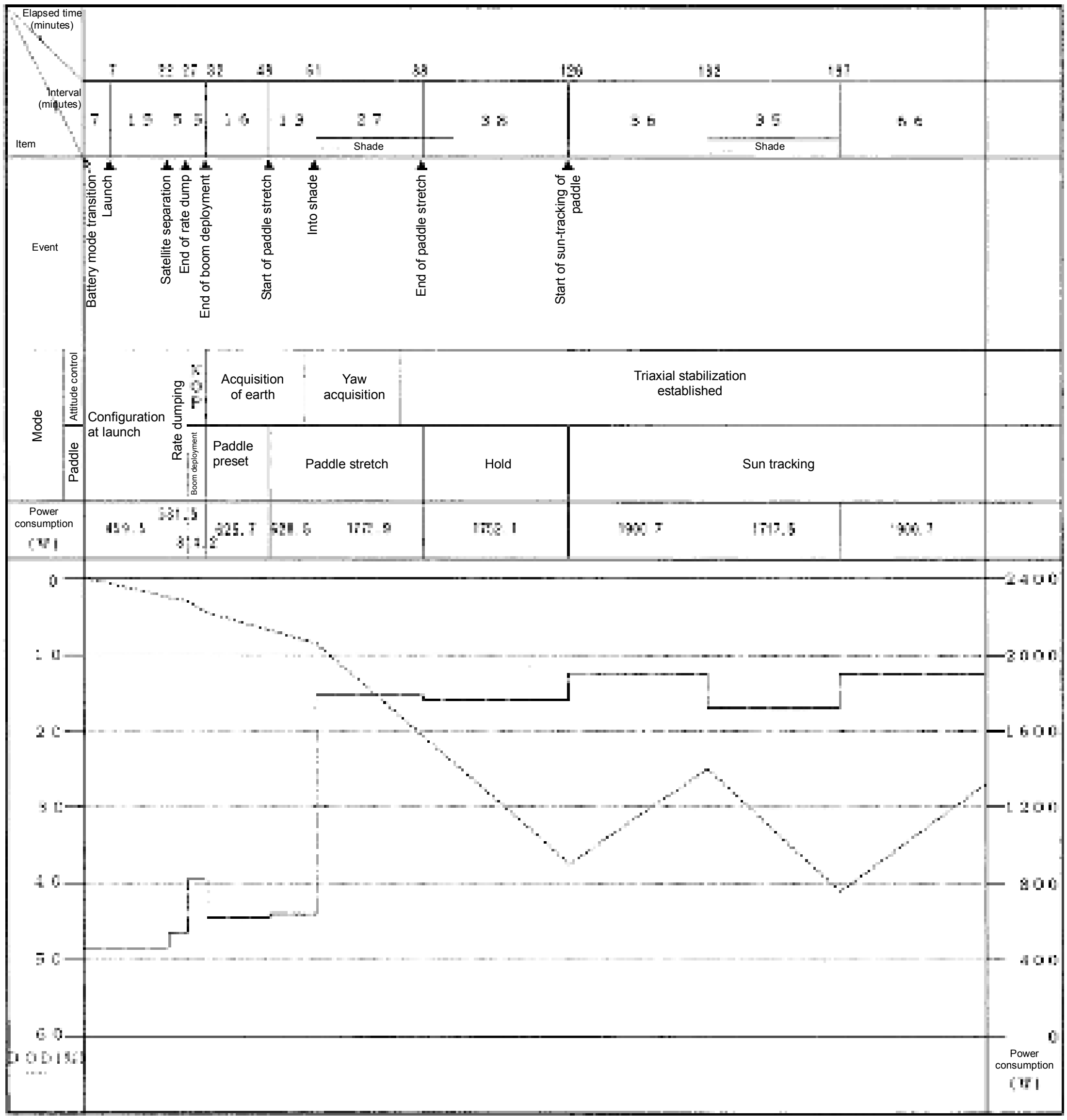


Figure I.3‑2 Example of power budget analysis (sun-synchronous sub-recurrent orbit)

I.3.3 Related tasks in each development stage

Setting of required power supply capacity, namely, of the required size of the solar array and battery, is an important item in spacecraft system design. Power budget analysis is a means to evaluate power supply capacity and its compatibility. Here, tasks related to the analysis in each development stage are described.

(1) Conceptual design stage

In this stage, a rough framework of the system to achieve the mission is examined. The greater part of the system considerations related to the power subsystem are indeterminate and are subject to trade-offs. For the required power profile, orbit conditions and power

consumption level are assumed. As power supply capacity, rough sizes of the solar array and battery are subjected to a case study considering the records, current state of technology, results of previous studies, etc. In this stage, a rough value of the mean power supply capacity described in I.2.1 Overview is discussed, but a full-scale power budget analysis is not performed. On this occasion, besides development period and risk and cost, the required mass, dimensions, etc. associated with power supply capacity become evaluation criteria with respect to performance.
For reference, for the mean on-orbit load power P_L, take the allowable depth of discharge as DODA, the eclipse duration as T_E, then the required total stored current capacity C_B (Ah) of a battery is as follows:

$$CB=\{[(P_L/\eta_L)+P_E]/\eta D\ \} \bullet (T_E/DOD_A)\}/V\_bat\ (dischg)$$

Taking the sunshine duration as TS, the required mean charge power PC is:

$$PC=\{([(P_L/\eta_L)+P_E]/\eta_D)/V\_bat(dischg)\} \bullet \{(T_E/T_S)/\eta_B\} \bullet V\_bat\ (chg)$$

From these, a rough value of the required power generation PS of the solar array becomes as follows:

$$PS=\{[(P_L/\eta_L)+P_E+(P_C/\eta_C)]/\eta_S$$

From PC and CB above, the required size of the solar array and battery is roughly set considering characteristic degradation and redundancy.

(2) Basic design stage
In this stage, the baseline of the system is determined based on trial fabrication tests of trial models, etc. For the power consumption of each component or subsystem, which acts as a load, rough values exist but are indeterminate. Nonetheless, a power budge analysis with respect to a required power profile is conducted based on such an indeterminate power consumption (containing margins) and operation plan, to set the required value of power supply capacity.

(3) Detailed design stage
In this stage, through fabrication and test of a development modes, etc., the power consumption of a component settles with a certain error range and the required power profile containing an operation plan become definite.
In parallel with this design progress, power budget analysis is performed at appropriate times and the compatibility between the previously set power supply capacity and required power profile is evaluated. If not compatible, the required size of the solar array and battery, allocation of power consumption, operation plan, etc. are revised. However, the freedom of revision is restricted as the design proceeds. In particular, the required size of the solar array and battery exerts a large impact, etc. on the mass, and in the case of a panel, on the

system shape, etc. In general, therefore, a large revision is difficult. The parameters of power budget analysis are updated to reflect the progress of the design, etc. of the relevant part.

(4) Maintenance design/fabrication and test stage

In this stage, the specifications for each individual component have been determined, and evaluation of management of their feasibility are performed. To reflect the characteristics of actual hardware, the source data (required power profile, analysis parameters, etc.) involved in power budget analysis are updated. The power budget analysis in this stage has the purpose of evaluate the impact of these updates. A power budget-related margin is incorporated in the design of each component in the design stage, and these margins are aggregated in this stage as a system margin. In this stage, if the required power supply capacity is not compatible with the required power profile, the only measure that can be taken is a revision of the operation plan in ordinary cases.

(5) Evaluation stage

Major tasks related to power supply capacity in the stage toward hardware development are as follows. The power budge analysis used in this process is utilized also in the subsequent launch, tracking control and evaluation stages and forms a part of database of the actual operation plan. On this occasion, the final parameters in the fabrication and test stage are used for analysis and, in addition, by updating them or otherwise, application records of analysis are accumulated and utilized for the next development.

I.4 Power supply characteristics

The power supply characteristics of a power subsystem include bus voltage, stability, ripple, output impedance and transient characteristics. The reference point of these characteristics are taken to be the output end of power distribution.

I.4.1 Bus voltage

For the bus voltage, about 30 VDC has been used conventionally. This is partly because the supply power was small but mainly because the design platform, including applied devices, was the 28 VDC power system of aircraft, etc.

With the increasing size and power usage of spacecraft, it is possible indeed to rely on the conventional bus voltage. However, to suppress a mass increase of the power supply harness (including the wiring on the solar panel), etc., the bus voltage was raised. In several-kW spacecraft, a voltage of about 50 V is already used. For 10 kW or so, 100 V or higher is thought to be efficient.

When raising the voltage, the following items must be examined.

(1) Restrictions of applied devices
Restrictions of devices are a problem involving the design platform. So, attention must be paid to that the problem involves the design not only of the power subsystem but also of all subsystems supplied with power. In particular, with respect to withstand voltage and switching durability, power semiconductors, relays and capacitors may be used (a measure by using them in parallel is possible but causes an increase of mass and volume). Their availability and applicability must be confirmed in advance (consider alternatives, etc. if circumstances require).

(2) Paschen's dielectric breakdown law and interaction with outer space plasma environment
The breakdown is caused by the presence of residual gases or an outer space plasma environment (of coexisting electrons and positive ions of 100 keV or less) which is electrically conductive. With the interaction, in particular, a problem occurs in a low orbit where the plasma density is high.

(3) Safety
Safety is a matter related mainly to an electric shock of workers. First, make the relevant work (assembly, test, range work, etc.) conform to the safety standard. Then, it is necessary to pay attention to reflecting the results into the design of equipment (including AGE).
As a voltage for power supply, besides direct current, the alternating current of aircraft, etc. using ground commercial power or engine generator output is also conceivable. In a spacecraft, however, alternating current is rarely used because the spacecraft power source is a solar array and battery and their output is direct current. Alternating current has the following advantages: a voltage change and insulation between primary and secondary sides are easy with a transformer, direct drive of a rotating machine is possible, and short-circuit breaking is easy because of the existence of zero current point. For alternating current, however, reverse current prevention by a diode is impossible unlike direct current. Because of power factor (reactive power) due to phase difference between voltage and current and waveform distortion as an effect of harness impedance at the AC frequency, and the like, the specifications and function sharing for power supply interfaces become complex. In addition, when link the AC outputs of multiple power sources, phase synchronization is necessary. Thus, there are many challenges.
High frequencies are indispensable for size and weight reduction, and as a waveform, sinusoidal waves are desirable with respect to electromagnetic compatibility, etc. However, a considerable amount of development efforts are involved to solve the problems above and realize the advantages of alternating current.

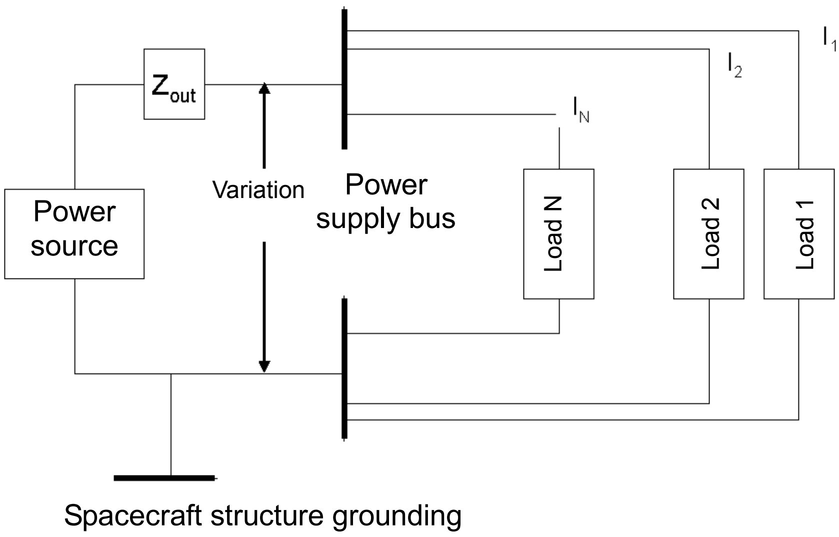
I.4.2 Regulated bus/non-regulated bus

The power subsystem types are broadly divided with respect to the variation width of bus voltage into regulated bus and non-regulated bus.
On a regulated bus, the variation width of bus voltage is narrow (for example, nominal ±1%). In each subsystem receiving power, no active regulation (line regulation) function or performance for input variations is required in general.

On the other hand, a non-regulated bus has a wide bus voltage variation width and requires active line regulation function and performance in each subsystem.
With respect to quality of supply power, regulated bus is superior. To implement a regulated bus, however, the power subsystem must add and improve (load) regulation functions and performance compared to non-regulated bus. Therefore, the difference between regulated bus/non-regulated bus types can be restated as centralizing the necessary regulation to the power subsystem or distributing it to each subsystem, and this choice of type affects the design of the entire spacecraft system.
At the choice, design examination becomes necessary with respect to regulation mass/loss (heat generation), reliability (fault propagation, redundancy, etc.), etc. Consideration must be paid also to the situation of technology to implement the regulation (in particular, switching regulator circuit technology and applicable related devices).
With a regulator using a regulated bus, a design remaining intact not only for the predictable peak power but also for failure of a load is necessary.
For bus voltage variations, the voltage drop due to spacecraft system harness must also be taken into consideration.

I.4.3 Relation with electromagnetic compatibility

Power supply characteristics are closely related to the specifications for conductivity of the electromagnetic compatibility design. Figure I.4-1 simplifies the power supply configuration from the power supply bus to each load and shows the relationship between noise voltage δV_{BUS} in the bus voltage and conductive noise current δI_N of a load, output impedance Z_{OUT} of the power supply bus, and noise voltage δV_{GEN} generated in the power subsystem. The term converted by Z_{OUT} into a voltage is called the rebound component and Z_{OUT} is called common impedance.



$$\delta V_{BUS} = \delta V_{GEN} + Z_{OUT} \times \Sigma \delta Ii$$

Figure I.4-1 Relationship between bus voltage noise component and noise generated on load side

For each load, the noise voltage at its input end becomes the allowable required level of its conducted susceptibility and is the sum of δV_{BUS} and $Zi \times \delta Ii$, taking the impedance of the system harness as Zi. Therefore, to hold down the noise voltage, it is necessary, besides reducing the noise generated in the power subsystem, to hold down the output impedance Z_{OUT} and the noise current of each load. On this occasion, it is a basic policy for electromagnetic compatibility design to make a design balanced all over the system without imposing severe requirements on one part, and the power subsystem design proceeds along this policy.
For δIi related to the rebound component, if these cannot be treated as the sum of noises and a beat of frequency fluctuations (low frequency component, in particular) occurs, its reduction becomes troublesome. Thus, management of, for example, switching frequency of the DC/DC converter on the load side is taken into consideration.
Grounding of the power line of the spacecraft system is taken at a point on the spacecraft structure from the power supply bus (on the return side in general). Grounding is taken elsewhere than the places where the potential is indeterminate with respect to the spacecraft structure and in such a way that no stray current flows in the spacecraft structure. The potential of the spacecraft structure itself depends on the environment. Changes of structure potential become a common-mode noise with respect to the power supply bus (by making the grounding at one point, DC-like influence is suppressed).
With regards to this potential, pay attention to the following points.

a. Ground
During integration or a test of the system, connect the spacecraft structure to the grounding of the workshop or test site.
When connecting a simulated solar battery or external power serving as a power source during a test, the power supply line on the equipment side must be connected to the grounding of the workshop or test site by the grounding of the spacecraft structure to prevent a current from flowing on the grounding line. If the connection to such equipment is disconnected from the spacecraft, the relevant line's potential becomes indeterminate. If joined to the rocket in the range, systematically manage the relationship between the grounding of the rocket structure and the grounding, etc. of a range facility.

b. In orbit
The potential is determined by the interaction with the plasma environment in outer space. In the state where there is no sunlight incidence, the spacecraft is negatively charged because of the velocity difference between ions and electrons, so it prevents an inflow of electrons but collects ions and reaches a negative potential where the current between the spacecraft and plasma becomes zero (this depends on plasma temperature; several volts in a low orbit and 10 kV or over during a magnetic storm in a stationary orbit). On the other hand, if sunlight is incident, the potential changes toward positive by the photoemissive effect. In a spacecraft in stationary orbit, this interaction makes a potential difference of about several kV between the structure and an insulated part and induces an electrostatic discharge.
The structure potential is related to the plasma environment which depends on the orbit altitude, etc. as well as on the shape, surface characteristics, etc. When docking spacecraft, the potential difference between them becomes a factor to cause a discharge. At an electrical connection of a solar array exposed to plasma, a bias in proportion to the bus voltage with respect to the plasma is superimposed on the potential. In a low orbit where the plasma density is high, the resultant potential causes, besides a leak

current (power loss), a discharge due to local concentration of electric fields.

I.5 Major components

A power subsystem consists of a battery serving the function of energy storage and equipment serving the function of power control, distribution, protection, etc. A specific configuration, equipment, etc. are designed based on an examination of the spacecraft system, past records, etc. Here, an overview of major components of the power subsystem, characteristics, related technology and method, particular use conditions, and consideration in the design are described.

I.5.1 Battery

A battery consists of battery cells assembled and connected in series to obtain the necessary voltage. It is charged when in sunshine using the output power of a solar array and discharges power during an eclipse or other period when the solar array output is insufficient to serve the function of supplying the spacecraft.
The capacity of the battery (capacity of cells used), number of cells connected in series, and the number of battery units are determined considering the service conditions (life, depth of discharge, temperature, discharge voltage, etc.), redundancy, required discharge energy, and the like. As an important performance index of a battery, stored energy per unit mass (energy density, mass efficiency: Wh/kg) or stored energy per unit volume (energy density, volume efficiency: Wh/liter) is used.
The battery cell used, battery structure, matching necessary for the constituent cells of a battery, service conditions, and redundant design concerning a battery are described below.

(1) Battery cell

As the battery cell used for spacecraft, the nickel-cadmium (Ni-Cd) cell and nickel-hydrogen (Ni-H2) cell are common. The Ni-Cd cell is a secondary cell using nickel hydroxide for the positive electrode and cadmium hydroxide for the negative electrode and has a long track record of use.
The Ni-H2 cell is same as the Ni-Cd cell for the positive electrode but uses a hydrogen catalyst electrode for the negative electrode and is a secondary cell using hydrogen gas as an active material. Because it does not use a cadmium electrode which is easily degraded, it is good at cycle life characteristics and has the advantage of being able to take the depth of discharge deep. However, because its external shape is a pressure vessel, it is poor at volume efficiency and requires a large installation area. Usually, the hydrogen gas reaches a gauge pressure of 1 MPa or over, so the cell is subject to the High Pressure Gas Safety Act.
On spacecraft, cells with a capacity of several Ah to 100 Ah or so are used. For the Ni-Cd cell, a rectangular type is usual although a cylindrical type with small capacity is available, and 50 Ah or less is usual.
The Ni-H2 cell is not suitable for small capacities because of the pressure vessel shape, etc. and 35 Ah or more is usual.
Besides these two types of battery cells, another nickel-hydrogen cell (Ni-MH cell; to

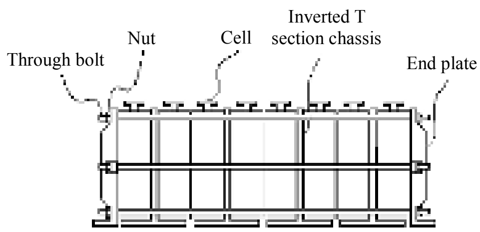
distinguish from the Ni-H2 cell, it is sometimes called a high-pressure nickel hydrogen cell) is also used. There are expectations that a lithium ion cell will be a future battery cell for spacecraft.
The lithium ion cell is a generic term for battery cells made of a combination of a positive and negative electrode that can absorb and release lithium ions not associated with the solution or precipitation reaction of lithium. Compared to the above-mentioned cells, It has two or more times as high a mass efficiency. In the lithium ion cell developed in Japan, the positive electrode used lithium cobaltate ($LiCoO_2$) and the negative electrode uses a carbon material (C). Development of new electrode materials is now under way and a further performance improvement can be expected.

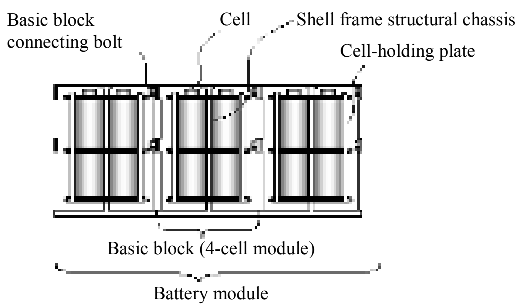
(2) Structure

A battery consists of battery cells assembled and connected in series to obtain the necessary voltage. In structure, a heater for battery temperature control and connectors, etc. for data transmission of power, cell voltage and temperature are attached. The cell holding method differs depending on the battery type. For the Ni-Cd battery, the cells are tightened and held using an end plate and tie rods. Heat release takes place by the cell support rib placed between cells, and heat is released to the mounting surface from there. For the Ni-H2 battery, it is held using a base plate and sleeve and heat release takes place also by the sleeve. For a lithium battery in an extended elliptical cylindrical shape, shell frame structure in which the cells are fixed to an structural chassis by a thin metal cell-holding plate is employed in some cases. A structural conceptual diagram is shown in Figure I.5-1 in comparison with the stack structure used for Ni-Cd batteries.
An appearance of a Ni-Cd battery is shown in Figure I.5-2, and an appearance of an Ni-H2 battery in Figure I.5-3. In structural design, etc., the following matter is examined.

a. Insulation between the cell case and cell-holding structure
(If insulation quality is not ensured, the case suffers from electrolytic corrosion.)
b. Bonding, fixing and placing method of cell, heater, etc.
c. Heat release path
d. Wiring design
e. Mechanical strength enduring launch environment, cell's internal pressure, etc.
f. Method of fixing to spacecraft and preparing
g. Ground handling ease

In view of handling ease, etc., for some batteries with a large capacity, a unit is assembled with half the necessary number of series cells and one combination battery unit is made up of two such units electrically connected in series.





(a) Stack structure (conventional)

(b) Shell frame structure

Figure I.5-1 Conceptual diagram of shell frame structure

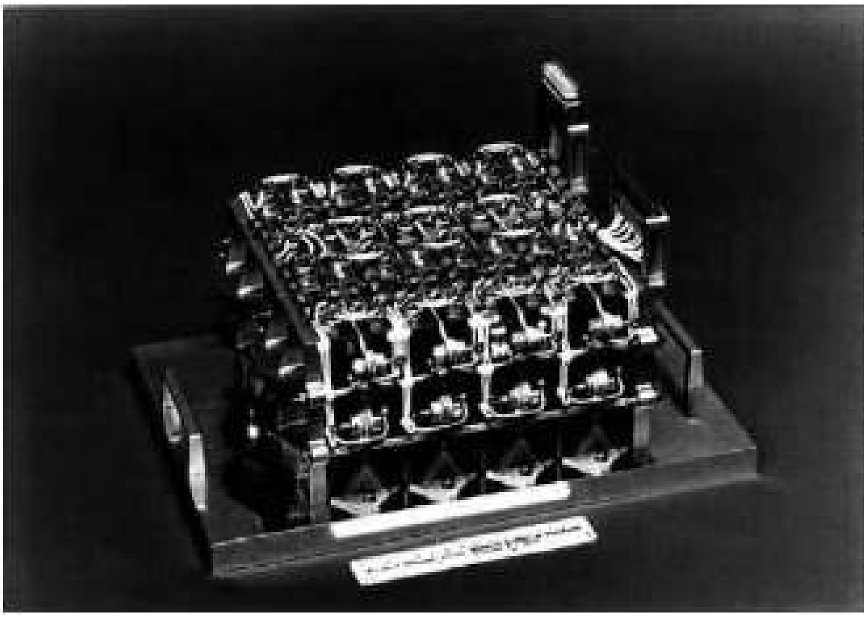


Figure I.5-2 Appearance of Ni-Cd battery

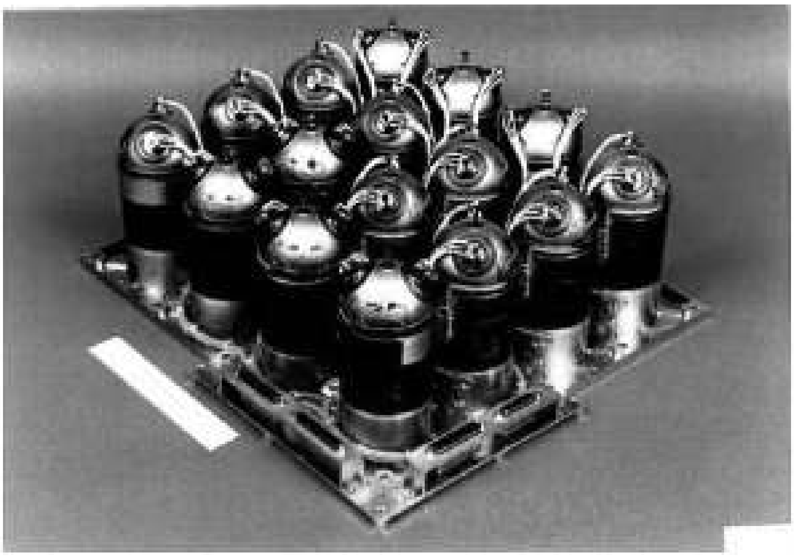


Figure I.5-3 Appearance of Ni-H_2 battery

(3) Matching of battery constituent cells

The capacity of a battery is determined by the minimum of the capacities of the constituent cells. Therefore, if there is even one cell with insufficient capacity or a defective cell in the battery, the characteristics of the entire cell will become poor. Besides this, the variance of charge characteristics of the constituent cells (voltage and internal pressure) also form a factor that hinders appropriate charge, etc.

When assembling a battery, therefore, it is necessary to line up constituent cells with no characteristic variance or as little variance as possible (matching). For that, it is necessary to select cells based on the capacity data, charge characteristic data, etc. at the cell receiving test.

From the viewpoint above, it is necessary to have cells of the same product (type) number. In addition, from the viewpoint that the lot-to-lot variance and long-term characteristics depend on the fabrication process, cells are generally selected from cells of the same lot.

(4) Conditions of use

Because a battery cell functions using electrochemical changes (oxidation and reduction reactions) of the internal materials, its characteristics tend to be influenced by its service conditions and history. Thus, the following service conditions must be given consideration. From this viewpoint, to ensure life, a battery used for a test for a long time is not used in a flight, and another flight article is prepared separately in general cases.

a. Temperature conditions

The characteristics of a battery cell have a strong dependency on temperature. Besides the charge and discharge voltage, discharge capacity, charge acceptability, the charge and discharge cycle life also differ with temperature. In general, the higher the temperature, the lower the charge voltage and discharge capacity and the shorter the life tends to be. On the other hand, at low temperature, charge and discharge reactions, etc. are hindered. Therefore, it is necessary to consider keeping the battery temperature in an appropriate temperature range.

The recommended range of battery temperature differs with the cell type. In general, it is 0 to 20°C for a Ni-Cd cell, -10 to 10°C for a Ni-H2 cell, and 10 to 25°C for a lithium ion cell. Outside this range, a characteristic degradation may be brought about. Thus, make sufficient examination concerning the service temperature range.

Concerning temperature control, the charge and discharge reactions, etc. of a battery cell are associated with complex heat generation and absorption. In ordinary cases, a thermal shield or the like is placed to improve the heat release performance of the battery-mounting part and suppress the influence on other equipment, etc. To avoid an extremely cold state of the battery, temperature measurement and temperature control take place to make the heater operate as the need arises.

The temperature difference between multiple batteries or units of batteries is desirably suppressed as low as possible, and it is necessary to decide the mounting place considering such a thermal viewpoint besides the electrical and mechanical designs and maintainability.

b. Charge conditions

The charge current level, which forms the basis of charge conditions, depends on the orbit. In GEO, the eclipse duration is at most 72 minutes and the sunshine (charge) duration is 20 hours or more. Therefore, the charge current may be the 20-hour rate or so. The charge current at the 20-hour rate is such a value that when charged for 20 hours, the stored electricity reaches the nominal capacity of the battery. In an LEO, on the other hand, because the orbital period is about 100 minutes and the sunshine duration is about 60 minutes, a rapid charge is required to recover the amount of discharge. For this charge current, to charge more electricity than the depth of discharge during sunshine, for example, for a depth of discharge of 25%, about the 3-hour rate or higher is set to charge one-third the electricity of the nominal capacity for one hour.

For the current set by the orbit conditions, the current value of full charge is generally employed. An overcharge with this charge current causes the voltage, temperature and internal pressure to rise rapidly and impose a stress on the battery. Thus, reduce the charge current using the V/T curve, etc. In the case where the charge current is changed over to a lower level, this charge is sometimes called a trickle charge. During the total sunshine period in GEO, a trickle charge takes place to make up for self-discharge and keep the state of charge. In LEO, a further charge by a trickle charge is expected in some designs.

The current adjustment as a charge condition is set as a function of charge control. The temperature condition as a charge condition takes place by temperature control.

c. Discharge conditions

(i) DOD: Depth of discharge

In general, the shallower the depth of discharge of the battery, the longer the battery life tends to be. Therefore, it is necessary to set the allowable depth of discharge and manage the amount of discharge of the battery. When setting the allowable depth of discharge, it is necessary to duly consider the operation conditions and mission period of the spacecraft, and life characteristics, etc. of the battery cell.

(ii) Overdischarge prevention measures

When using (discharging) the battery, make sure to set the discharge under-voltage to avoid an overdischarge. In particular, if discharging completely, an overdischarge of a cell must be avoided in the usage to a deep depth of discharge. Thus, It is necessary to monitor the discharge voltage of each cell. If a Ni-Cd cell is reverse charged, there is the risk that an unrecoverable capacity reduction or a rapid increase of cell internal pressure may destroy the battery case (explosion, in the worst case). If a lithium ion cell is discharged to lower than the appropriate voltage, (even if not reverse charged), an unrecoverable short-circuit fault can occur.

It is necessary to pay due attention to overdischarge prevention measures, not only during on-orbit actual operation, but also during a ground test in which complete discharge treatment takes place (management is apt to become sparse because of the tasks before and after the test). In general, from the experience of consumer apparatuses with a built-in secondary battery, a lack of understanding of battery overdischarge is seen in test personnel, etc. An overdischarge of a battery with several ten parallel cells is a very dangerous event, and this must be made known and understood thoroughly in the test procedure, etc. Overdischarge prevention (under-voltage control function) is considered as a protection function of discharge control. If the function of measuring each cell voltage, etc. to prevent an overdischarge is provided, pay attention to the discharge current (very small in general) to the measurement circuit. When leaving the battery in an open-circuit state for a long time on the ground, the connections of the measuring system can become a factor that induces a difference in the state of charge between cells. Disconnection or other treatment is necessary.

d. Storage condition

When storing a battery for a long time, treatment before storage differs greatly for the Ni-Cd cell, Ni-H2 cell and other aqueous batteries and for the lithium ion battery. For the Ni-Cd battery, etc., all cells are discharged completely before storage while the lithium ion battery is not discharged completely for the purpose of avoiding the overdischarge shown in Clause c and stored in a certain level of the state of charge considering self-discharge, etc.

Store either battery cell at a low temperature in a dry atmosphere so as not to bring about corrosion, etc. of the terminals and cell case. For the short-circuit/open-circuit treatment during cell storage, comply with the recommended condition of the cell manufacturer. Storage in a charged state can cause characteristic degradation due to self-discharge or other change of internal materials. When using a battery which has been stored for a long time, a rapid increase of cell voltage or internal pressure must be avoided. For this purpose, it is common practice to do an activation by discharging after charging at a low rate lower than the 20-hour rate or otherwise.

e. Maintenance conditions (on orbit)

In the case of the Ni-Cd cell, Ni-H2 cell and other aqueous battery, if keeping the battery in a charged state for a long time or repeating a charge and discharge, a decrease of the discharge voltage of the internal materials not yet discharged (memory effect) occurs. Therefore, when the battery is used or discharged to a deep depth, the discharge voltage is lower than the ordinary voltage. Because this phenomenon can be removed by a very small current of the 50- to 100-hour rate or so, do this before the launch of the spacecraft and before and after the stationary spacecraft enters an eclipse. This operation is called reconditioning. For a low-orbit spacecraft, reconditioning for a long time involves a suspension, etc. of mission operation or temporary imposition of a large load on other batteries. So, do not do reconditioning unless it is necessary. Because reconditioning involves a deep discharge, it is ordinarily included as a related function of discharge control.

As a reconditioning method, the battery is discharged simply to the prescribed battery voltage. Besides this, in one method, each cell voltage is monitored to avoid an overdischarge or overcharge. In another method, a resistor is connected to each cell and the battery is discharged to a considerably low voltage.

The lithium ion battery does not have a memory effect in general and does not need the above-stated reconditioning. In some cases, however, the stored electricity variance between battery cells is leveled by bypassing the charge current in the necessary amount to the circuit connected in parallel to a cell. To suppress the degradation due to long sunshine duration, a charge takes place at a low temperature or a low voltage.

(5) Redundancy design

The battery cell is taken as a limited-life item because its characteristics degrade. Even now, its design and process management rely on technology that is not adequately understood. Therefore, redundancy design for mechanical failure is required in general. In some cases in the early period of space development, many batteries were mounted considering multiple occurrences of battery failure. Now, because of the accumulation of records and improvement of design and process management, failure of multiple batteries is not assumed though this depends on the required reliability. A short-circuit fault of a battery cell merely causes a decrease of battery charge voltage while an open-circuit fault of one battery cell causes battery failure. Thus, redundancy design depends in part on the assumed failure mode of the battery cell.

As a design example, besides unit redundancy which is disadvantageous with respect to mass, the following element level (to cope with open-circuit/short-circuit) is available.

These are a contrivance to keep the charge and discharge functions of the battery even when a battery cell fails by using other normal battery cells as far as possible.

a. Use of cell bypass relay (effective only in short-circuit mode)
   In a parallel charge of multiple batteries, to match the discharge voltage of normal batteries to the discharge voltage of a battery with element failure, some battery cells of the normal battery are bypassed.
b. Use of cell bypass diode

A charge and discharge bypass diode is connected to every cell in parallel. The power subsystem is configured in advance so that the power supply bus can respond (configuration change) on each battery.

c. Use of cell short-circuit relay or switch (responds open-circuit mode)
In this configuration, a relay or a switch is connected instead of the bypass diode in Clause b.

d. Discharge control on each battery (effective only in short-circuit mode)
By discharge control, each battery is discharged irrespective of the difference in discharge voltage.
These contrivances assume random failure of battery cells and are not effective for characteristic degradation common to the manufacturing lot of the element.

(6) Destructive failure mode of battery

The battery accumulates energy. If a phenomenon to release the energy for a short time is induced, failure doing catastrophic damage to the periphery of the battery will result. However, such a mode is prevented for an element and a battery appropriately designed and subject to sufficient process management by using the battery appropriately and providing a protection function for emergencies. Defenses against the released energy or other measures are not generally taken on the spacecraft.

For the cell failure prevention measure in (5), it is necessary to examine in advance the effect of a (short-circuit or other) failure of that measure itself on the cell.

Concerning such battery hazard, the mode, causes, effects, measures and their confirmation methods are reviewed.

I.5.3 Power control

Power control of the power subsystem include solar array output control, battery charge control and battery discharge control. The operation region of these control functions is usually designated by the (bus) voltage of the power supply bus as shown in Figure I.5-4 and there the coordination of the control functions is kept appropriate. Then, the specifications for supply of required load power and for bus voltage of the power supply characteristics are satisfied.

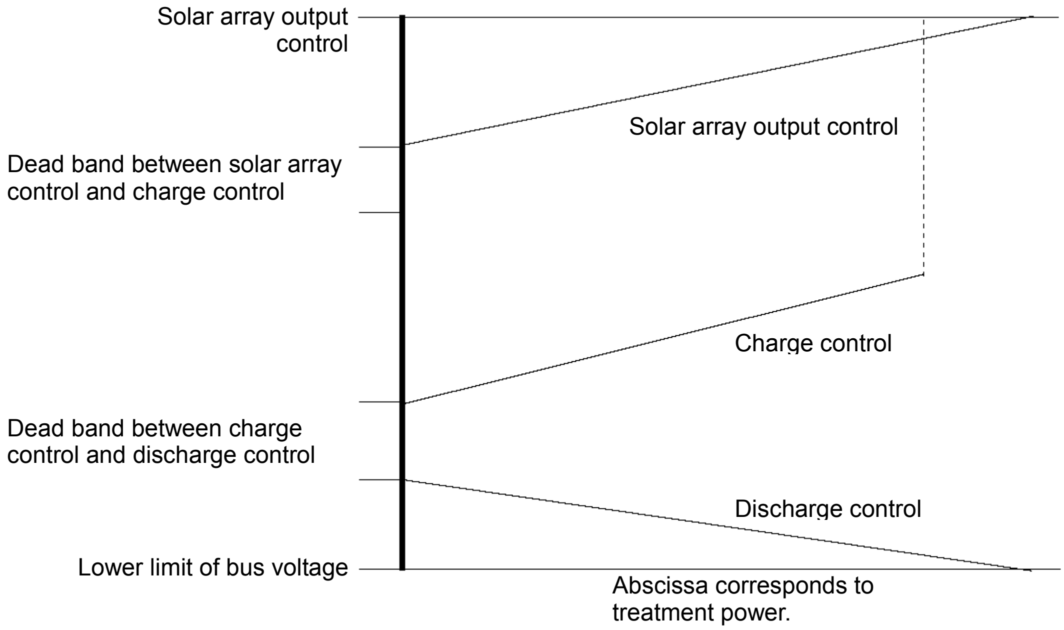


Figure I.5-4 Operation region of control

For the bus voltage, if it falls, discharge control keeps it higher than the lower limit, and if it rises, charge control charges the battery first. Then, the battery charge power is held there because it keeps the charge conditions appropriately (corresponding to the region in broken line in Figure I.5-4). If the bus voltage rises further, solar array output control keeps it lower the upper limit.
The operation point of the bus is determined by the intersection of the characteristics of the solar array, charge and discharge control, load, etc. As an unusual case, a (lock-up) state can occur in which discharge control operates within the charge control region. To leave this state, the load power is decreased or other means are taken.
The bus voltage variation range is specified by the upper limit and lower limit. A regulated bus corresponds to the case where this region is ±1% or so of the nominal voltage. On the other hand, for a non-regulated bus, the upper limit is generally specified above the voltage to charge the battery and treat the maximum surplus power, and the lower limit is specified by the battery discharge voltage. The region is ±20% or so of the mean of the upper and lower limits.
The lock-up state poses a problem especially in the case of a non-regulated bus with a wide bus voltage range. Coordination of control functions is achieved by issuing, from the bus voltage detection processor, a signal to operate the control function corresponding to the prescribed operation region. Failure of this processor influences the entire power control and causes abnormal variations of bus voltage. In redundancy design to prevent the grave effect of this single failure, a standby method or simple parallel method cannot be employed. Thus, the majority-decision method is applied.
An overview, type, etc. of each power control is described below.

(1) Solar array output control

The voltage-current characteristics of a solar array is as shown in Figure I.5-5, and its output current (power) is determined by the operation point of the solar array. When simply connecting the panel and load, the operation voltage is determined by the intersection of the load (voltage-current) characteristics and solar array characteristics., and the power supply (bus) voltage will vary due to load power variations, panel temperature variations, etc. As a measure for this, suppressing the bus voltage variations is a function of solar array output control. That is, by adjusting or otherwise handling the power generation of the solar array, load power (power of the required power profile, power consumption of the power subsystem, charge power, etc.) is supplied from the solar array and the bus voltage is kept within the range specified by the power supply characteristics.

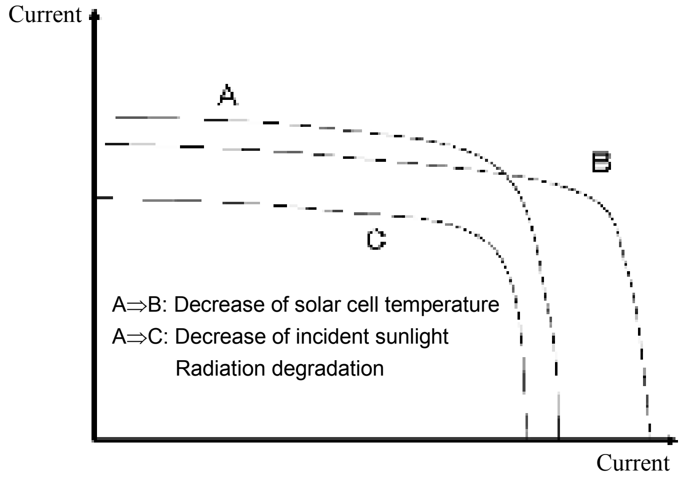


Figure I.5-5 Solar array current – voltage-current characteristics

The adjustment methods are divided as follows: A schematic configuration of it is shown in Figure I.5-6.

Panel output control
- Shunt type
  - Full shunt
  - Partial shunt
- Series type

Of the shunt type, in full shunt, the operation point voltage of the solar array corresponds to the bus voltage. Although it cannot adjust the power generation of the panel itself, it diverges (shunts) surplus power to the control element, supplies power to the load, and keeps the bus voltage within the specified range. This control element operates corresponding to a relief valve in a pressure line.

In partial shunt, a control element is connected to the intermediate tap of the solar array. It makes adjustable the surplus power diverging to the control element and thereby adjusts the power generation of the solar array itself. On this occasion, the operation voltage of the upper panel is determined by the load current while the operation voltage of the lower panel is made adjustable by the control element.

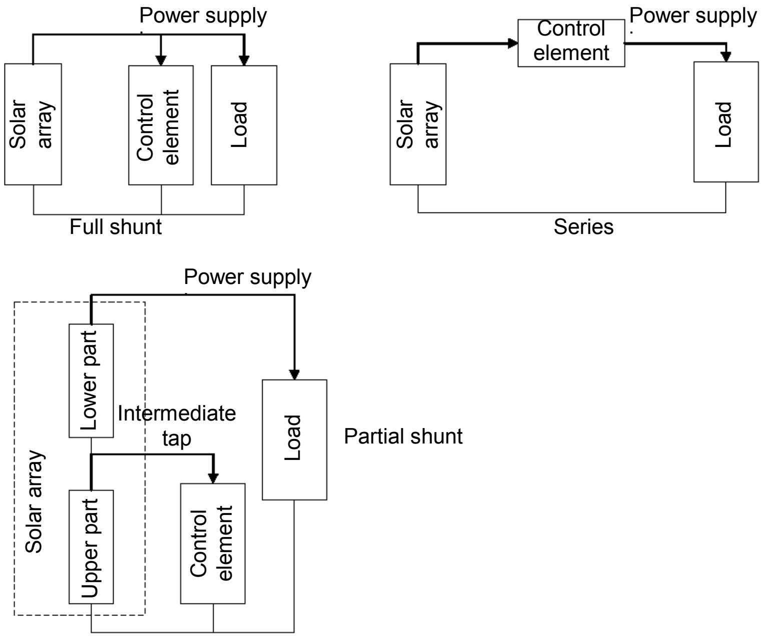


Figure I.5-6 Types of solar array output control

The series type inserts a control element in series between the solar array and load. It keeps the bus voltage within the specified range, makes adjustable the operation point voltage of the panel and adjusts the power generation. This control element operates corresponding to a throttle valve in a pressure line.

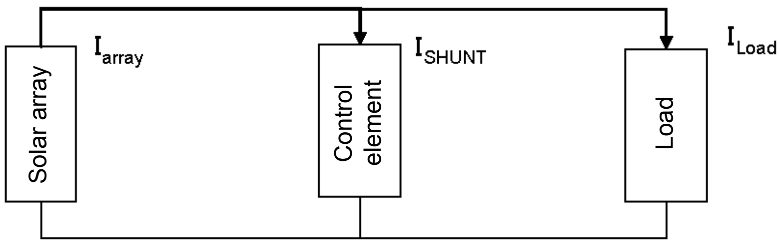
For the shunt type, adjustment is treatment of surplus of solar array power generation, and solar array delivers the maximum power with the control element in a non-operating state. The characteristics do not appear in the budget analysis model in Figure I.3-1. On the other hand, for the series type, when the solar array output is at the maximum, the treated power of the control element also becomes maximum and the effect has an influence on ηS in Figure I.3-1.

a. Features, etc. of type

In solar array output control, adjustment (treatment of surplus power, etc.) of power generation of the solar array is associated with a considerable amount of heat generation, and a smaller amount of such heat is more suitable for the system from the viewpoint of thermal design. From this viewpoint, features, measures, etc. of each type are described below.

(i) Features of shunt type

For this type, the larger the load power, the smaller the surplus power is treated. In partial shunt, the configuration, etc. becomes complex compared to a full shunt in that an intermediate tap is used; however, because the heat generation is small, it is suitable for spacecraft that use a large amount of power. The operation of the control element is broadly divided into analog and switching (see Figure I.5-7), and switching is superior in view of heat generation; however, it needs attention to electromagnetic compatibility, etc. As a method to reduce the power generation, there is a configuration in which the circuit in the solar array and connection of the control element are further divided and operated in sequence (sequential operation) (Figure I.5-8), and it is suitable for control of large power; however, the interface becomes complex.

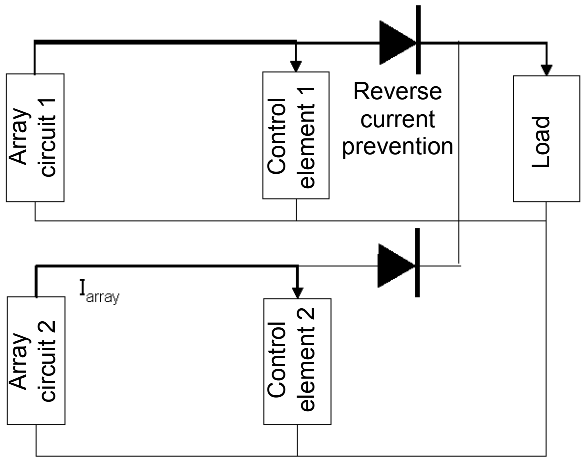


Current balance : $I_{LOAD} = I_{array} - I_{SHUNT}$

Analog type : Continuously adjusts I_{SHUNT} (surplus) to keep balance.

Switching type : Turns ON/OFF the control element and adjust the ratio D of that ON time to make I_{SHUNT} in the balance equation above equal to D × I_{array} or so. Actually, a function to smooth the voltage variations due to switching is needed.

Figure I.5-7 Operation of control element (in case of full shunt)



The control element appropriate for the load is operated in sequence. For example, under a light load, only control element 1 is operated and all others are put in the ON state so as not to supply the output of the corresponding array circuits to the load.
On the other hand, under a large load, only element N is operated and all others are put in the OFF state so as to supply the output of the corresponding panel to the load. As the operation of a control element, either the analog type or the switching type may be employed.

Figure I.5-8 Sequential operation of control elements (in case of full shunt)

(ii) Features of series type

For this type, all of the power generated by the solar array applied to the load passes through the control element, the loss (heat) by the control element must be reduced. Therefore, the operation of the control element is switching. An advantage is that the bus voltage is not equal to the operation point voltage of the panel, so the interface with the solar array has flexibility and it is also possible to add a function to track the maximum output of the panel, thus making up for the loss by the control element.

As for selection of type, the shunt type can be applied for both GEO and LEO while the series type is effective for LEO because the share of charge power in the solar array power generation is large. In GEO, the greater part of power generation of the solar array is load power, and the loss by the control element of the series type reduces the power supply capacity to the load, so the advantages of this type (e.g., the operation point of the panel can be made adjustable) cannot be realized.

b. Solar array power generation monitoring

Figure I.5-9 shows an example of a power subsystem telemetry arrangement (full shunt type) for solar array power generation monitoring. To evaluate on-orbit solar array performance (maximum generation capacity), a method to put the control element in the non-operating state and increase the load or change the sunlight incident angle or otherwise handle it is necessary. These are difficult to employ in part from the viewpoint of operation and design. However, to evaluate the integrity of the solar array, the necessary minimum integrity evaluation is possible by the telemetry arrangement shown in Figure I.5-10 as necessary telemetry as a power subsystem. To monitor the generated current of the solar array, the following two methods are available.

(i) Evaluation by the total of currents on the HOT side

Evaluate as $I_{array}=I_{LOAD}+I_{SHUNT}+I_{bat\_chg}$. To evaluate in terms of power, make an evaluation in a simple way by multiplying the bus voltage or multiplying the corrected paddle interface reference point voltage.

(ii) Evaluation by the total array RTN current

Evaluate as $I_{array}=I_{array\_RTN}$. To evaluate in terms of power, make an evaluation in a simple way by multiplying the bus voltage or multiplying the corrected paddle interface reference point voltage.

Evaluation is possible by above-mentioned [1] alone; however, together with [2], identification of an open-circuit or short-circuit is possible when an array circuit fails.

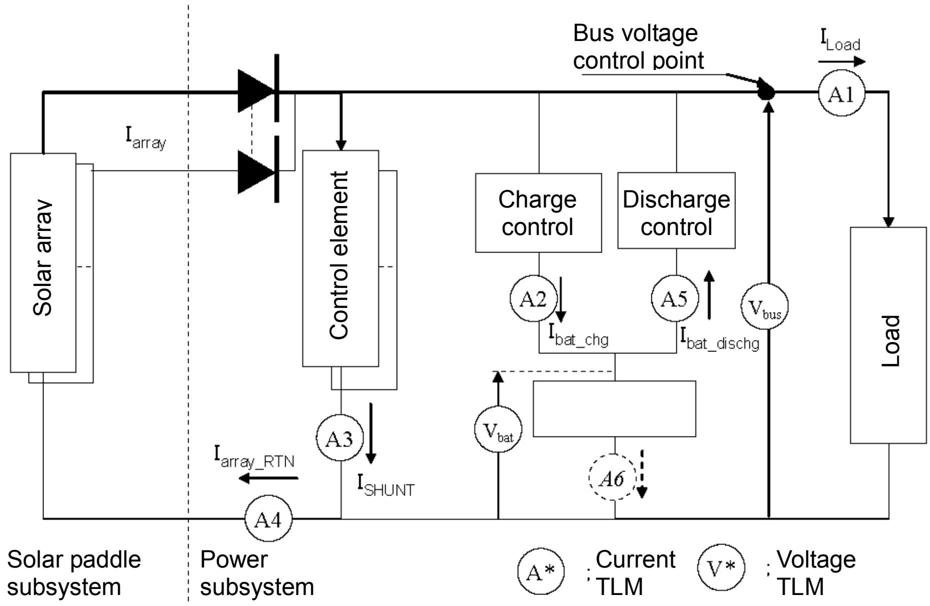


Figure I.5-9 Example of solar array power generation monitoring (full shunt type)

c. Simplification of output control

There is a method in which the solar array output is not adjusted finely but the output characteristics are used as they are. For the series type, it is conceivable to divide the solar array as shown in Figure I.5-8 and use relays for the control elements in series and turn them on and off. In these methods, the power supply characteristics become coarse and the battery has the role of a shunt. Thus, they cannot simply be employed; however, they are effective for system simplification.

In some cases, the required capacity of the control element can be reduced by using a relay, etc. For a paddle-shaped panel, it is conceivable to change the sunlight incident angle by the paddle tracking subsystem to do output control of the solar battery. However, this poses a problem concerning response and operation coordination between the attitude control and power subsystems (the propagation range of malfunction becomes larger), so they can hardly be said to be an ordinary design.

(2) Charge control

Charge control has the function of keeping the battery charge conditions appropriate. In the appropriate range, it actively control the bus voltage by this operation using all the solar array power generation, excluding the load power, for charge (continuous line in Figure I.5-4). The appropriate range of charge conditions is set by charge current, voltage, temperature and the like so as not to impose an excessive stress on the battery. In general, charge control functions so that the charge current and voltage will not be inappropriate (upper limit) value (broken line in Figure I.5-4). As a type for that, the two types of constant current-constant current and constant current-constant voltage are commonly used.

If sensing the battery RTN side (A6 in Figure I.5-9) as a telemetry detection point used for battery charge control, pay due attention to, and examine, the design so that charge control takes place normally during an operation associated with a battery discharge during sunshine.

a. Charge type

(i) Constant current-constant current

First, charge taking the upper limit of charge current as the full charge current value. The charge current at this time is usually the full charge current value though this depends on the panel power generation and load power. When the charge proceeds and the battery reaches the specified state (when the voltage rises and reaches a set level), lower the upper limit of charge current below the full charge current value to suppress the stress on the battery and continue the charge. Charging with a lowered level is sometimes called trickle charge or supplementary charge and is generally aimed at maintenance of the state of charge.

In a total sunshine period in GEO, the state of charge of the battery is maintained for a long time by trickle charge. Instead of a trickle charge, it is also possible to maintain the state of charge of the battery with a constant voltage charge as shown in (ii).

(ii) Constant current-constant voltage

First, a charge takes place taking the upper limit of charge current as the full charge current value in the same way. However, after the battery has reached the specified state, charge continues with the battery voltage kept constant. The charge current during this constant voltage charge usually decreases exponentially. That is, since the voltage is held at the constant voltage value Vc, the current (Ic) decreases when the stored electricity (Q: Ah) increases. Thus, assuming the following proportional relation:

$$\triangle Ic \approx - K \times \triangle Q$$

Here, because of $\triangle Q = I\,c \times \triangle t$, after all, the charge current becomes as follows:

$$dIc/dt \approx - K \times Ic \;\therefore\; Ic \approx Ico \times \exp(-Kt)$$

Since the charge current changes with time like this, it is sometimes called a taper charge.

Thus, during a charge, when the battery reaches the specified state, the charge current is reduced to suppress the stress. Reaching the specified state is judged generally by considering that the battery voltage has reached a set level, and that level is set taking into consideration the characteristics and service conditions of the battery. With too low a level, the amount of discharge is not restored by a charge sufficiently, and with too high a level, unnecessary stresses are imposed on the battery. It is necessary to pay attention especially to the aging of the battery characteristics. It is common practice to provide multiple levels and select from them during operation. In case of doing temperature compensation, these levels are sometimes called a V/T (voltage-temperature) curve. As a technique to judge that the charge has reached the specified state, besides the technique by V/T, the following is available.

[1] Introduce measurement of the amount of electricity (time integral of current) and judge whether the amount of charge electricity has reached a specified value with respect to the amount of discharge electricity.

[2] Detect that the element temperature rises due to the heat generation associated with charge completion or that the charge voltage decreases by this temperature rise. With a stationary spacecraft, ground operation of confirming this voltage change (called Head Poking because the value goes down after rising in the charge) and issuing a command to make a current change-over is available.

[3] Monitor a physical phenomenon (for example, change in internal pressure or generation of oxygen, etc.) in which the state of charge inside the battery cell is reflected.

Note: The lithium ion cell does not cause the water-splitting reaction or other side reactions seen in the Ni-Cd cell, Ni-H2 cell or other aqueous batteries. Therefore, full charge judgment in [2] and [3] is impossible.

In relation to the effect of temperature on charge of an aqueous battery, when charge is almost complete, charge power changes into heat, and this tends to raise the battery temperature if heat rejection is poor. The temperature change during charge poses a problem especially during constant voltage charge. That is, because of the temperature characteristics of the battery, even if the voltage is held constant, if the temperature rises, the charge current increases. Therefore, the tendency of a taper charge in which the current increases with an increase in the amount of stored electricity is lost, and the temperature rise and charge current rise enter a positive feedback relation, and fall into a state of thermal runaway. The charge conditions are not set merely by the charge current determined by the orbit and depth of discharge. This setting requires sufficient knowledge about the battery characteristics and temperature environment.

The lithium ion battery causes no exothermic reaction if charged in an appropriate voltage range. Therefore, it never falls into a state of thermal runway.

b. Control type

The types are broadly divided into the shunt type and series type, as with the types of solar array output control.

For the shunt type, the control element of full shunt in Figure I.5-6 takes a configuration in which the charge circuit and battery are in series. In the series method, the panel output control in the series method doubles as charge control and takes a configuration in which the battery is contained in the load in series in Figure I.5-6. A design in which charge control is superimposed on panel output control is the shunt type at the same time; however, this integration of control tends to coarsen the charge control capability of the battery and reduce the flexibility.

As operation of the control element, the selection is made from the viewpoint of loss considering the level of treated power, etc. In LEO where charge power is large, switching is indispensable for reducing the loss.

For charge control of multiple batteries, it is common practice to provide each battery with dedicated charge and discharge functions to keep the charge conditions appropriate individually. When doing charge control of multiple batteries connected in parallel, it is necessary to pay due attention to the battery temperature uniformity, etc. to ensure equalization of charge currents. Separation of a battery exhibiting a low-voltage abnormality (charge current becomes excessive) is essential.
Charge control includes the function of detecting an abnormal temperature and suspending the charge to operate the battery at an appropriate temperature (power subsystem protection function).

(3) Discharge control

Discharge control has the function of keeping the power supply characteristics within specification using the stored energy in the battery when the required power profile cannot be maintained with the power generation of the solar array. In one type, it is common practice to insert the relevant function between the battery output and power supply bus. Figure I.5-10 shows the most common arrangement of charge and discharge control using charge control of the shunt type. The control element is associated with the type of regulated bus/non-regulated bus. In the case of a regulated bus (to raise the battery charge voltage above the lower limit of bus voltage), it has an active power conversion function. In the case of a non-regulated bus, it is made up only of a passive reverse current prevention diode and on/off relay. And, in the case of an active function to treat large power, switching is indispensable for operation of the control element to reduce the loss.

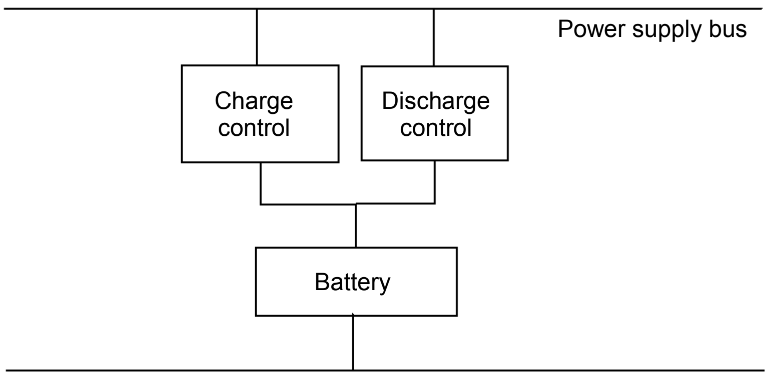


Figure I.5-10 Arrangement of charge and discharge control (in case of shunt type)

For discharge control of multiple batteries, on/off and other functions are installed individually, and power is discharged in parallel in general. In this case, the variance of discharge current is suppressed by equalizing the resistance, etc. of the discharge lines because the discharge voltage of the battery is relatively stable. On the other hand, some designs provide each battery with an active power conversion function to equalize the discharge current.
To prevent an overdischarge, etc. of the battery, discharge control has an under-voltage control function (power subsystem protection function), which monitors the battery discharge voltage and, when the specified level is reached, issues an LLM signal to change the spacecraft operation over to low load.

I.5.3 Power distribution

Power distribution is the function to supply power from the power subsystem to each subsystem, component and the like with the prescribed characteristics. In the case of a spacecraft, the power transmission line, which is the output of the power subsystem, is taken as a part of the system harness. Here, without regard to this division, an overview of the types, bus configuration, switchgear, monitoring function, etc. is described.

(1) Distribution type

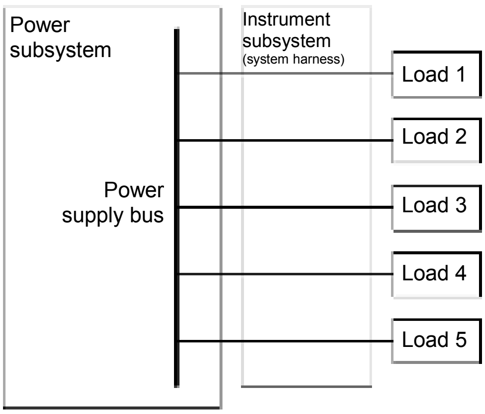
The distribution types include the radial type and backbone type in Figure I.5-11 (viewpoint of redundancy omitted). Besides these, there is also the ring type and others; however they are not common on spacecraft. Major features of each type in Figure I.5-11 are described below.

a. Radial type

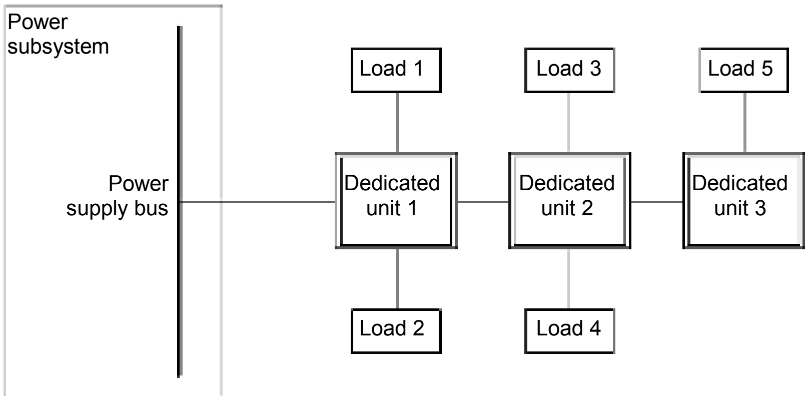
In the power subsystem, there is a bus, which dictates the power supply characteristics and supplies power to each load through a dedicated harness. Therefore, its design is easy and it is excellent with respect to supply characteristics, sharing of fault protection measures, etc. However, it makes the system harness complex and is poor in terms of extensibility. On spacecraft, this type is common conventionally.

b. Backbone type

The power supply bus branches out to the system harness and the power supply interface to the load is implemented by dedicated Vnits. Therefore, in this configuration, most of the distribution function is distributed to the dedicated units. (The reference point becomes ambiguous.) The power supply characteristics are inferior to the radial type if a voltage regulation function is not given. However, the system harness is organized and response to extensions is easy.



(a) Radial type



(b) Backbone

Figure I.5-11 Types of power distribution

For a modularized spacecraft, the loads of the radial type correspond to subsystems, etc., and power supply to each component takes place radically by the dedicated units. An hierarchical structure is sometimes taken.
In a redundancy, it is common practice to provide a dedicated harness from the power supply bus. If the redundancy is incorporated in one chassis, the interface part with the power subsystem is made common.

(2) Bus configuration

As a configuration of a power subsystem, (in the case of a single-bus), the power supply bus combines the solar array, battery and power control function and consists of one line, and (in the case of multiple-bus) it consists of multiple lines. A single-bus configuration is commonly used because it is simple in configuration while a multiple-bus configuration is sometimes employed because the features are associated with the following distribution function.

a. Basic equipment of a spacecraft is supplied with power from multiple bus lines (diode-or connection, etc.). Therefore, in the event of a failure of one line, loss of function can be prevented.
b. Different bus voltages, etc. suitable for the load can be supplied.
If multiple buses having the same configuration and characteristics are used, linked operation of the buses is sometime employed for accommodation,etc. of power supply capacity among the buses.
In this case, also in a state of not being linked, it is necessary to pay attention to the allocated power share and required power profile of each bus so as to prevent the difference in service conditions of the battery of each bus from becoming large.

A multiple-bus configuration is sometime employed to implement buttery redundancy in units of batteries by connecting one battery to multiple buses.

(3) Switching function

The switching function is generally implemented using a relay with a break or by using a mechanical contact or a semiconductor device. In the case of a relay, chattering or contact reversal can occur due to vibrations or impact. The design must consider measures for that (as to occurrence of such a phenomenon, select a device with no possibility, or implement a method to exclude an occurrence or to prevent the effect at an occurrence). However, it is suitable for switching a power line because the power loss is small. Semiconductor switchgear has superior characteristics to those of a relay in terms of response, electromagnetic compatibility, reliability, operation easiness, etc.; however, a power loss occurs.

The service conditions of a relay and load characteristics in particular influence the life of the contact. In the transient period of current switching, an electrostatic discharge occurs inevitably between the pair of approaching contacts (the electron emission by an electric field becomes a trigger for a temperature rise of the contact material, which promotes evaporation of the metal and ionization of the environmental gases, and occurrence of an arc plasma). While the discharge conditions are satisfied, the discharge continues to promote contact ablation and deformation

The duration of a discharge has a proportional relationship with the power being conducted. Special care is required when handling a large-power load or inductive load. For discharge suppression, it is effective to reduce the increasing rate of contact voltage versus contact opening speed and, as a measure to take, a snubber circuit (which forms a transient route for the current at contact opening) is connected to the relay in parallel.

In some cases, the relay is used only for a switch-over of connections and turning-on/off of equipment is done separately.

If the number of times of opening/closing poses a problem, it is common practice to use a switchgear using semiconductor devices.

(4) Monitoring function

To monitor the power supply condition, supply current, etc. are monitored. This also is included in the distribution function; however, monitoring takes place not on each load but on total output current, etc. in general. When evaluating the operating condition, etc. of many loads by monitoring the total output, there are restrictions as with monitoring of solar array power generation. So, it is necessary to accumulate and evaluate sufficiently detailed related data by ground tests, etc. in advance. Especially for equipment in which it is necessary to know current consumption data to know its operating condition, for example, mission equipment experiencing large load variations during operation, it is desirable, if possible, to individually include current data, etc. as a telemetry item.

In relation to the switchgear function, the on/off status is included in the distribution function in some cases. The sharing of these functions should belong to the design policy at the system level and specified in the design specification, etc. of the system.

(5) Power supply other than primary power bus

The distribution function of a power subsystem covers the power supply at the bus voltage. Besides this, as power that the power subsystem distributes, special power, for example, pyrotechnic ignition power for paddle or antenna deployment, is included in some cases. For that, the battery output is directly used in general, and a dedicated distribution function is provided. Another special case is equipment or a subsystem that does not require many electric or electronic circuits, for example, power supply to the heaters and sensors to the thermal control subsystem, propulsion subsystem, etc. By using existing components, a means to supply power other than the bus voltage (a specific stable voltage in case of a non-regulated bus) is used in some cases.

I.5.4 Protection

The protection function has the role of localizing a failure or abnormality that causes serious effects on power supply to avoid a critical situation as a system or a situation hindering mission achievement. The phenomena it covers are defined as a contingency, etc. based on FMEA in reliability design. For abnormalities or failure of a device due to an open-circuit or short-circuit, measures such as a series-parallel connection and device or equipment redundancy are considered in the design. The power subsystem is required to operate at all times and its fault tolerant design is made on the premise that its major functions cannot be stopped (for example, like the engine of an automobile) as fail-safe. Therefore, its fault tolerant design is made by incorporating the following measures.

- Multi-connection of array circuit and redundant connection between array circuits
- Reverse current prevention diode on each one-series circuit of array circuit
- Redundancy in the number of slip rings/brushes and harnesses
- Battery cell bypass circuit, unit redundancy and isolation relay of battery
- Reverse current prevention diode and reverse current detection/change-over mechanism of battery
- Series-parallel connection of diode, transistor, etc.
- (Parallel coupling) redundancy and current limiting circuit of power supplies for internal circuit
- Majority vote redundancy method for bus voltage monitoring of power control subsystem
- Short-circuit detection/circuit isolation relay or fuse
- Reinforced insulation of power wiring, etc.
- (Parallel coupling) redundancy of power control section, etc.
- Cross strap coupling of battery output and discharge control section

Therefore, the phenomena covered by the protection function are mainly non-critical abnormalities such as an open-circuit and short-circuit and malfunction of a subsystem due to such an abnormality. Detection and emergency measures (isolation) of these are the role of the protection function.
Conventionally, restoration (correction) has been done by a command from the ground in general. A ground monitor is necessary to supplement the protection function and for operation evaluation and abnormality indication detection by trend analysis of important data and for contingency measures. Currently, to respond to these on board, a protection function, etc. having intelligent capabilities is being applied. For example, if multiple abnormality detection inputs are available for emergency measures of the protection function, recoding what has happened in detail is useful for ground work (establishing an action plan) for which limited data is available.

Table 3.5.5-1 in the text shows an example of the phenomena covered by the protection function and their detection and isolation methods, etc. Of these phenomena, those which require action considering the degree of influence and frequency of occurrence by FMEA, etc. are objects of the protection function.
The circuit, etc. for the required original function should not be made complex by adding a protection function. Some emergency measures do not necessarily require to be automated depending on the spacecraft and some depend on the situation of the abnormality. Restoration (correction) should be performed based on the survey and investigation of the causes of the abnormality. As a correction, besides a change-over to a redundant line, changing the power subsystem configuration (reconfiguration) is also conceivable. For emergency measures involving power supply, such as a transition to a light-load mode, increase or decrease in load, shut-off or isolation of a load, flowing of a fuse, and linking of multiple buses, it is necessary to do interface coordination, function sharing, etc. with a related subsystem, etc.
As a feature of the protection function, although it is in operation at all times, its operation itself does not emerge at times other than an emergency. So, its malfunction or failure has a grave influence on the system and, in addition, its confirmation test is not easy to conduct. In the design of such a protection function, matters to consider are as follows:

a. Status monitoring

If the protection function has a status to detect an abnormality, at an occurrence of an emergency measures-requiring state, it must be confirmed whether it is due to an operation of the protection function or not, and monitoring takes place for that. If multiple protection functions do one emergency measure, the status of each protection function must be monitored. The operation history, etc. of the protection function may become necessary for post analysis, etc.

b. Override

Refers to making it possible to disable or cancel the protection function from the ground at its malfunction, abnormality, etc. However, pay attention to the fact that a decision between normality and abnormality of the protection function itself can be made from other data for over-temperature protection, etc. in many cases while it is not easy for overcurrent shut-off, etc.

c. Reset

As a premise of a protection function, set it so that it can operate again at re-closing (restoration). If the protection function has hysteretic characteristics as to detection level, do not re-close until it enters an operable state again.

d. Use of fuse

It is useful for isolation of an internal local short-circuit, etc. of equipment. Design and select it so that it will not melt during a normal state. At an emergency, the power subsystem should be able to deliver the melting current without being damaged. Use of a fuse should be based on a electrical design standard, etc.

e. Detection level and response

Ensure that the protection function will not operate under a normal transient situation. If degradation cannot be avoided during the life period, provide multiple levels and make a change-over.

f. Coordination of protection

Ensure that multiple protection functions do not operate in succession (like dominoes). A transient state due to operation of one protection function can cause another protection function to operate in some cases. As a conceivable example, an instantaneous battery voltage drop due to a short-circuit may be judged as an over-discharge of the battery; when isolating a short-circuit on the load side, the circuit-breaker of the power subsystem also operates to shut off power supply to other load; during a transient period of a transition to an emergency measures-requiring state, it may be judged to be an abnormality of the bus linkage or may influence the operation of another subsystem. Prevent these situations and ensure coordination between protection functions. After emergency measures are taken, contingency analysis, etc. is performed to prevent the spacecraft from going into a worse state.

g. Confirmation test

Examine a method to confirm by a ground test, etc. in advance that the protection function will operate normally. When adding an intelligent capability the protection function, a self-diagnosis function, etc. is indispensable.

I.5.5 Others

Although not classified as an element of a power subsystem, system harness, pyrotechnic control, umbilical cable, test cable, etc. are closely related.

(1) System harness

Power of the power subsystem is supplied to subsystems and equipment through a system harness. The voltage drop, etc. associated with this power transmission has an influence on the power supply characteristics at the load's receiving end. And, the power loss due to a voltage drop has an influence on power supply capacity. For example, a 1 V voltage drop for a 1 kW load's receiving end voltage of 50 V means a system harness resistance of 50 mΩ, supply end voltage of 51 V and a loss of 20 W (2% of load power), that is, the power the power subsystem must supply is 1020 W.

In general, the power supply characteristics at a load's receiving end is an electrical interface management item; however, their details are closely related with major specifications of the power subsystem.

A system harness consists of many cables bundled and formed in a shape that is easy to install at a prescribed position in the spacecraft. It is taken as one of the components for hardware integration of a spacecraft and is designed based on the Electrical Design Standard.

Besides the system harness, hardware integration includes, electrical elements, etc. involved in bonding, shielding, antistatic measures, etc. Selection of connectors, harness cables, service

conditions (arrangement, current derating, etc.) are specified in the Electrical Design Standard.
A harness is classified into categories for power supply, signal (high level/low level), pyrotechnic, high frequency, etc. Isolate different categories as far as possible to avoid electromagnetic interference. An especially critical harness line is fabricated with shielding.
A system harness test consists of confirming the prescribed connector pin connections at both ends, insulation from other cables, withstand voltage, etc. However, because may cables are bundled, the confirmation is not easy.
Measurement, confirmation, etc. of line resistance also takes place on this occasion.
If a polarity reversal of a power line or a confusion with another cable is overlooked, equipment damage results at the initial current application. At an integration, therefore, follow a procedure such as confirming the voltage again before connecting to equipment. At a ground test, meticulous inspection is necessary for a line whose operation cannot be confirmed in full configuration. The environmental resistance of a system harness is considered in design. Besides this, in its single state, a vacuum test is conducted, and at the system level, the normality, etc. of installation and contact are confirmed using vibrations, impact, etc.

(2) Pyrotechnic ignition circuit

For paddle or antenna deployment and AKM ignition, etc., pyrotechnic (EED: electro explosive device) is used. Failure or non-operation of this circuit brings about a critical situation for the system and forms a grave hindrance to achievement of the mission. In the ignition circuit design, therefore, pay attention to the following items.

a. For certain ignition, make the ignition line (ignition circuit, wiring, pyrotechnic) redundant.
   Provide the automatic ignition sequence, etc. with a backup of ground commands.
b. Make a sequence to ignition as a 3-stage sequence (enable/disable, ignition) and monitor its status.
c. In the sequence, incorporate a spacecraft/rocket separation signal, attitude control subsystem’s pre-operation completion signal, etc. in a circuit.
d. To prevent malfunction, simplify the line, clarify the relationship, etc. with the spacecraft grounding, and connect an antistatic resistance to the wire to the pyrotechnic.
e. Because the heating wire (bridgewire) to fire the powder in the pyrotechnic cannot fulfill the firing function if the supply current or time is insufficient, know the transient response of the power source and set the supply time. On the other hand, an unexpected contingency (release becoming impossible, short-circuit to the structure, etc.) occurs if an excessive current flows. Thus, insert a current-limiting resistance or use a constant-current power supply circuit to ensure the recommended firing current of the pyrotechnic,
f. To turn on, etc. the pyrotechnic power, a relay or semiconductor device is usually used. However, contact reversal or chattering due to vibration or impact poses the risk of causing serious troubles from a system malfunction. Therefore, evaluate the environmental resistance of the relay, pyrotechnic power controller, etc. and take measures in advance.

g. If a relay is used, that line is limited as to the number of times of operation and verification using an actual piece of equipment is difficult. Therefore, pay special attention to the test plan to confirm the performance of the system, and carry it out.

(3) Umbilical cable

From assembly to launch of a spacecraft/rocket, power supply, state monitoring and battery charge take place at an umbilical cable. As to the power subsystem, the following items are included under an umbilical cable.

a. Insert a reverse current prevention function to ensure that the spacecraft is not damaged inside by a short-circuit outside the external power lines (for power supply in the range and for battery charge). Restrict the supply power to the necessary amount and take protection, etc. measures for failures or operational mistakes so that no excessive power or current is delivered to external power sources.
b. Insert a protection resistance, etc. to ensure that the spacecraft is not damaged inside by an external short-circuit of the monitor lines of bus voltage, battery voltage, relay status, battery temperature, etc. Pay attention also to the noise immunity of ground monitoring lines (in particular, CMR: common mode rejection to electromagnetic interference of ground lines) and treatment of connection ends not yet connected.
c. Battery ON/OFF relay drive line
   Treat in the same way as a range power supply line.

Besides this, an umbilical cable includes propellant-related pressure and temperature lines, etc. For an umbilical cable, it is necessary to make a design so that, when a connector is pulled out, no effect (status reversal, etc.) will be induced inside the spacecraft.
Know the lightning protection measures of the range and give consideration so that the measures for the umbilical cable can be taken promptly. In range work, a prior confirmation is conducted by paying attention to the above.

(4) Test cable, etc.

In a ground test, it is difficult to operate the power subsystem with the power generated by the solar array, and a simulated solar array is generally used. Test cables include, besides this connection line of a spacecraft and simulated power source, various types of simulation signal lines such as for hardware line monitors, sensors, etc. of spacecraft state, redundant function confirmation line, etc. This test cable line operates in a more severe environment as to installation and handling situation, etc. than an umbilical cable. The same measures are necessary to ensure that the spacecraft will not be damaged by its abnormality (short-circuit, etc.). When using a reverse current prevention diode, consider the measures for its heat generation. The spacecraft's receiving side of a simulated power source is the connection part of a solar paddle subsystem output. It is not fixed in many cases (wire, etc. of a slip ring on the triaxial type) and its treatment and fixing method require care. In addition, it is necessary to provide the simulated power source with measures so as not to deliver an excessive voltage.

Because a test cable and test equipment are not included in the flight model, their design review and other checks are apt to be insufficient. However, they are connected to the flight model indeed, so their inspection, etc. before use should be duly performed.