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Design of power system for KNACKSAT satellite

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Abstract. This paper presents the design of a power system for a 1U CubeSat satellite in the KNACKSAT project (KMUTNB Academic Challenge of Knowledge SATellite), which has been started since 2015. The major mission of this KNACKSAT is capturing geographical image. The power system has been designed for continuous operation with high efficiency. It consists of four parts, power generation, power storage, power distribution and power management. Many protections against fault situations have been designed and implemented to enhance reliability and robustness of the power system. Furthermore, the system was constructed using only commercial off-the-shelf components (COTS) in order to prove the possibility to minimize component costs. This paper also discusses the testing conditions with simulated space environment for validating the functionality of the developed power system.

1. Introduction

Space technology is growing rapidly, especially in the field of CubeSat. The CubeSat standard has been published since 1999 by Prof. Jordi Puig-Sauri (from California Polytechnic State University) and Prof. Robert Twiggs (from the Department of Aeronautics & Astronautics at Stanford University). They have also developed Cal Poly's standardized CubeSat deployment system (called a P-POD, Poly Picosatellite Orbital Deployer) to easily integrate with a launch vehicle. The CubeSat size depends on classes of the CubeSat, such as 1U (10x10x10 cm), 2U (20x10x10 cm) and 3U (30x10x10 cm). The weight is limited to 1.33 kg for 1U and 4 kg for 3U. Therefore, the CubeSat is an alternative satellite for starting the space technology in developing countries.

The KNACKSAT project has been funded by The National Broadcasting and Telecommunications Commission (NBTC), which aims to develop the space technology in Thailand. The KNACKSAT goal is to develop a 1U CubeSat. The bus systems have been developed by only the student workforce. The conceptual design of bus systems of the KNACKSAT have been developed based on the successful satellite concepts, such as XI-IV (University of Tokyo), AAU-CubeSat (Aalborg University), SwissCube (École Polytechnique Federale de Lausanne), and EST-Cube (University of Tartu) [3, 4].

This paper is focused on the design of the power system of the KNACKSAT using COTS components. From the power system perspective, a power supply system must be designed to cover all of power consumption of the entire system within limited resources. Furthermore, the reliability and robustness of the power system are very important and must be ensured by many protections to cope with the fault situations, which can be caused by hardware problems and space radiation effects during operation.

2. Mission Requirement

2.1. *Mission Overview*

The major mission of the KNACKSAT is capturing geographical images. For scientific missions, a magnetic plasma de-orbit (MPD) system using a magnetic torquer [2] is demonstrated, while the satellite is flying in space, because a magnetic torquer is normally installed for attitude control of the KNACKSAT mission. The MPD system uses the utilization of a drag force by the interaction between in-orbit plasma and magnetic torquer. According to ISO 24113, a lifetime of object in LEO, which includes the launch vehicle orbital stages, and a life time of operating spacecraft and any object released as part of normal operations or disposal actions, must be less than 25 years; otherwise the objects will become space debris. Therefore, a MPD system will be proven concepts for de-orbit technology by the KNACKSAT.

The KNACKSAT mission after it is released by the launch vehicle. The satellite will deploy the antennas and transmits a beacon signal for the radio communication using the amateur radio frequency. After the satellite can establish the radio communication between the satellite and a ground station, the satellite will start the de-tumbling mode using a magnetic torquer to control the orientation of the satellite.de

The major mission and scientific mission involve variable power consumption. A sufficient power supply during operation is essential to achieve the targeted missions.

2.2. Space Environment Effects

2.2.1. Orbital Period

The orbital period depends on the altitude of the satellite that is measured from the centre of the Earth. Generally, an altitude of LEO is 160 to 2000 km above the sea level. The day time can be calculated as:

$$T_{day} = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{1}$$

,where T_{day} is the day time, a is the semi major axis, and μ is the standard gravitation of the Earth.

The eclipse time can be calculated as:

$$T_{eclipse} = \frac{2a^2}{\sqrt{a\mu}}\left(\sin^{-1}\left(\frac{R}{a}\right)\right) \tag{2}$$

,where $T_{eclipse}$ is the eclipse time, a is the semi major axis, and μ is the standard gravitation of the Earth and R is the radius of the Earth.

2.2.2. Solar Radiation Effects

The intensity of solar radiation is roughly 1361 W/m^2 above the atmosphere. According to 1U CubeSat standard [1], the 1U CubeSat has a dimension of 10x10x10 cm. Therefore, in one panel of satellite will get the sunlight about 13.61 W. Furthermore, the power can be generated by Earth's albedo, which is the sunlight reflection from the Earth. The Earth's albedo has been presented in [5]. The power from the Earth's albedo is less than 10% of the total power that can be generated by solar cells.

2.2.3. *Space Radiation Effects*

Space radiation in LEO [6] can be divided to several different types. The space radiations can impact directly the CubeSat, including the total dose effect and the single-event effects. For LEO, the total dose per year is 4-40 kRad [7]. Electronic components will accumulate the total dose and cause the satellite to fail during operation, but on the other hand the single-event effects, which are Single Latch-ups (SELs) and Single Event Upsets (SEUs), will impact electronic components in the satellite immediately, especially complementary metal–oxide–semiconductor (CMOS) ICs due to internal MOSFETs. The SEL affects the function of the power supply system of CMOS ICs and can cause directly overheating and physical damage of the integral circuits due to high current within the integral circuits. The SEU affects the data storage mechanism in CMOS ICs and can cause an unexpected data change by particle hitting.

2.3. *Power Requirement*

Table 1. The power requirement of the KNACKSAT at -25°C and +55°C

Sub-system	Power Consumption at -25°C (mW)	Power Consumption at +55°C (mW)
Receiver (RX)	556.4	430.48
Transmitter (TX)	373.79	360.81
Transmitter (GFSK)	4030.18	4019.65
Power System (PS)	354	270.57
Command and Data Handling (D&DH)	465.47	383.2
Payload (Camera)	2044.62	1700
Attitude Determination and Control System (ADCS)	1416.17	1349

The power requirement summarizes the amount power that an electric component consumes for operation. The power requirement of the KNACKSAT is shown in Table. 1. The peak power consumption (5.4 W) occurs, while the transmitter (GFSK) is operating to transmit the data and the geographical image to a ground station. The power system must provide a sufficient power to cover the peak power consumption. Furthermore, the power system has been also designed to operate the beacon mode, which is the default mode of the KNACKSAT.

3. Design of the power system

3.1. *General Power System Architecture*

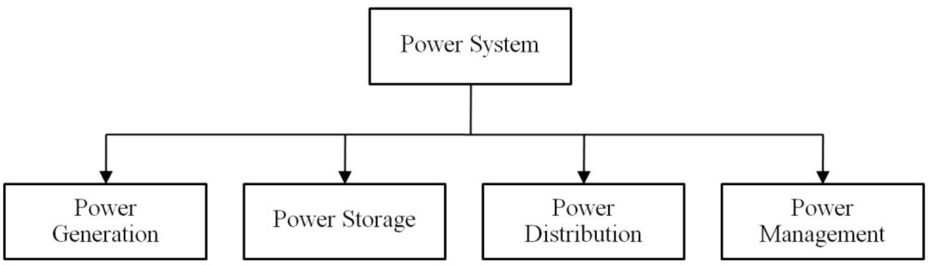

Figure 1. General power system architecture

The power system has been designed as shown in Fig.1. The general power system architecture consists of 4 parts, power generating, power storage, power distribution and power management. The generated power from the solar cells will be transmitted through Main Power Bus (MPB). The batteries are chosen to store the excess power within the power system. It also supplies the power, while the satellite is operating in the eclipse time. The power in MPB will be managed by the power distribution according to the situation of the system. The power system is individually controlled by a microcontroller.

The power system is separated into two boards, power harvesting board and main power board. The solar cells will be connected directly to the power harvesting board. The power storage, power distribution and power management are placed together in the main power board. The dimension of each board is 9x9 cm. The amount of weight of the power system is 160.7 g, including power harvesting board, main power board, and two batteries.

3.2. Power Generation

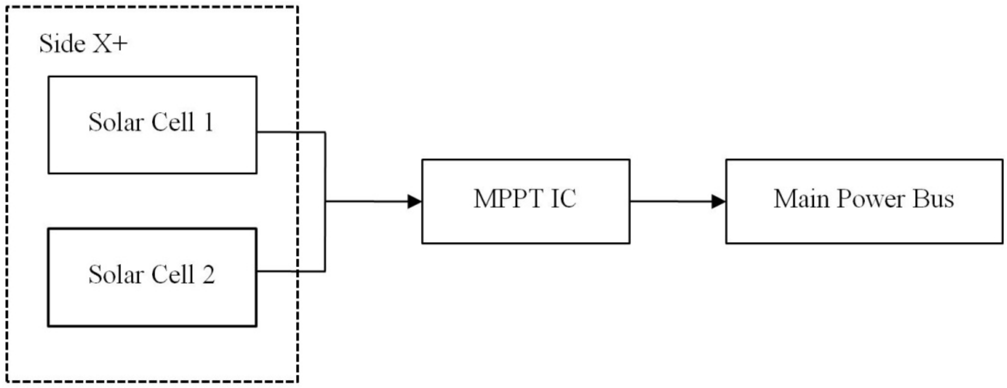

Figure 2. Power generation architecture

The power generation is shown in Figure 2. This system is the most important in the power system because it is the source of power generated by solar cells. The Maximum Power Point Tracking (MPPT) is equipped for maximizing the efficiency of the power conversion by the solar cells. The triple junction GaAs solar cells (from AZUR SPACE Solar Power GmbH) are chosen and mounted to the body of the satellite. They have an efficiency of 30% at the beginning of the life (BOF). Two solar cells are connected in parallel per panel, and can provide the power about 1.2 W per cell.

3.3. Power Storage

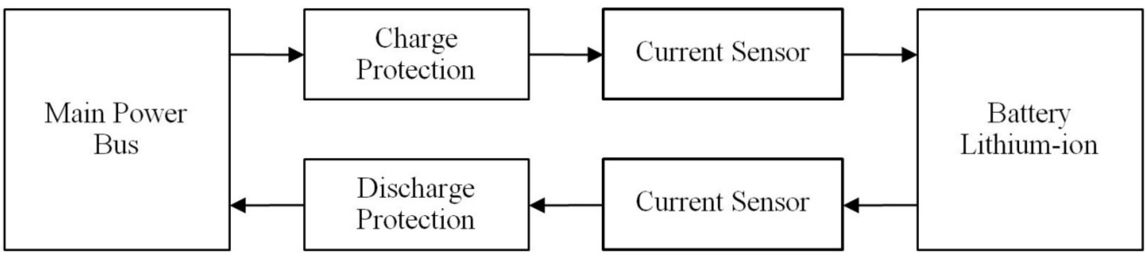

Figure 3. Power storage architecture

The power storage is shown in Figure 3. The excess power within the power system is stored in the power storage and also used to provide into the satellite system during an eclipse time and the insufficient power from the power generation. For the KNACKSAT, the power storage has been designed to use two cylindrical NCR18650Bs that is a Lithium-Ion cell from Panasonic. The NCR18650B can provide the maximum discharged current as 24 W. The Lithium-Ion cell is widely used in space technology. It has a high power density and lightweight. The nominal temperature range is 0ºC to +45ºC. In case of the CubeSat, the satellite does not need the thermal control system to control the temperature range of batteries because it's small size and the orbit period for changing condition between hot to cold and cold to hot is a short time. Furthermore, a protection circuit has been independently designed for each battery to protect an over current due to a short-circuit.

3.4. Power Distribution

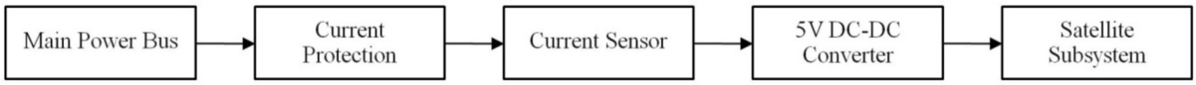

Figure 4. Power distribution architecture

The power distribution system is shown in Figure 4. This system will adjust a voltage within MPB before it is transmitted to the satellite subsystems. However, the voltage within MPB cannot directly be transmitted to the satellite subsystems because the range of voltage within MPB is varying and used to charge the batteries. The voltage in MPB will be converted to 5V by 5V DC-DC converter first. Then, this 5-V voltage is transmitted to the satellite subsystems through standard pin. The power distribution system consists of 5 power lines, 2 power lines for communication, magnetic torquer power line, electronic power line, and power system power line, for increasing reliability of the system. For each power line, a current protection system is installed to protect an over current of each satellite subsystem due to short-circuit, high power consumption or space radiation effects.

3.5. Power Management

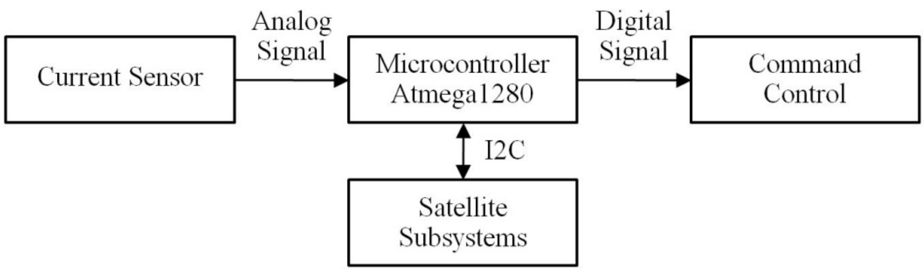

Figure 5. Power management architecture

The power system has been designed to control the system by its own microcontroller, which is an Atmega1280 8-bit microprocessor. It has been used in space by ESTCube-1 [4] and passed the radiation testing [6]. The microcontroller will read analog signals from all of current sensors in the power system. It will then analyze the data by itself for checking and controlling each system in the power system. The microcontroller of the power system can communicate with other satellite subsystems through I2C bus for exchanging the data and commands between each other.

4. Space Environment Testing

4.1. Vibration Testing

The KNACKSAT will be launched by Falcon 9 Rocket, which has been developed by SpaceX. The power system boards are packed in the middle of the satellite to balance the center of gravity due to the weight of batteries. Therefore, the power system must be tested under this condition on a shaker (see Figure 7.) to verify that the power system, including circuit board, components, and batteries, can withstand the mechanical stress and vibration during launching. A Dragon spacecraft random vibration profile was used to emulate the random vibration of the Falcon 9.

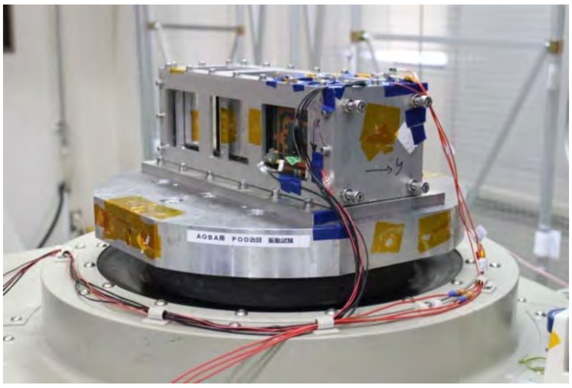

Figure 6. KNACKSAT tested on a shaker

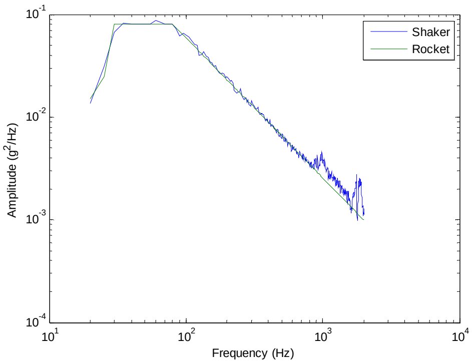

Figure 7. Dragon spacecraft Random vibration profile and the actual vibration profile generated by shaker

4.2. Thermal Vacuum Testing

The satellite will directly get sunlight during day time, during which it has a hot temperature, and also stay in the shadow of the Earth during eclipse time, during which it has a cold temperature. The Thermal Vacuum chamber is a vacuum chamber to thermally cycle products between hot and cold temperatures. The chamber temperature is adjusted to target temperature by heater and liquid nitrogen. In testing the KNACKSAT, it was tested within the temperature range from -25°C to 55°C. The pressure inside the chamber must be less than 10^{-4} Pa because the satellite is unaffected by convection. A thermal vacuum testing profile consists of 7 cycles as shown in Figure 9. During hot and cold temperatures, they have a stable time about 2 hours to do the functional test, while the satellite was tested inside the chamber. Since the nominal temperature range of battery is 0°C to 40°C. Therefore, the temperature of the batteries must be controlled within a nominal temperature range during testing.

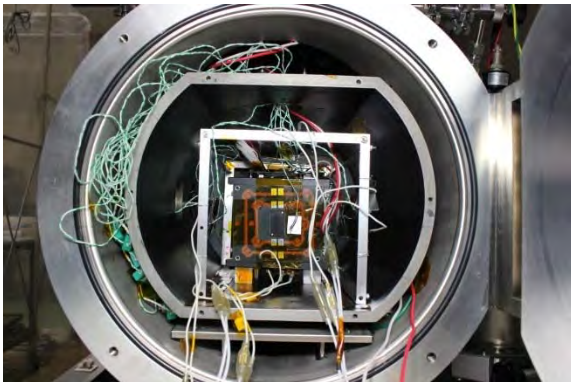

Figure 8. KNACKSAT inside Thermal Vacuum chamber

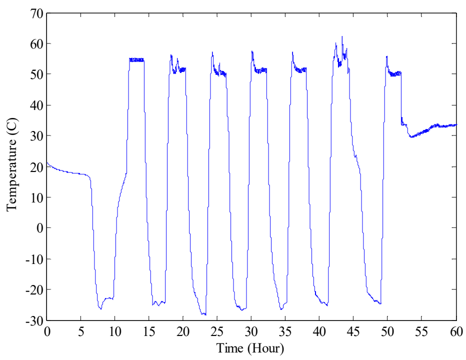

Figure 9. Thermal vacuum testing profile with temperature range from -25°C to 55°C

4.3. Thermal Cycle Testing

According to the orbital period at 500 km, the day time and eclipse time are approximately 60 minutes and 35 minutes, respectively. The Thermal Cycle chamber can achieve target temperatures by convection, using hot air by heater and cold air by liquid nitrogen. The condition was changed from hot to cold and cold to hot immediately. In KNACKSAT testing, it was tested with temperature range from -5°C to 45°C. A thermal cycle testing profile consists of 15 cycles as shown in Figure 11.

Figure 10. KNACKSAT inside Thermal Cycle chamber

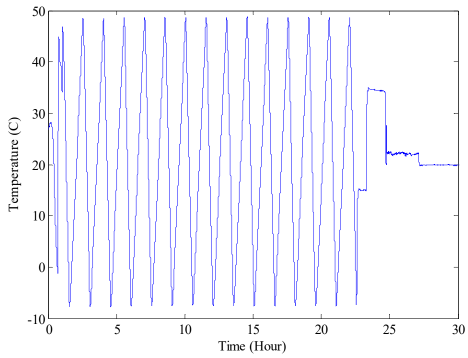

Figure 11. Thermal cycle testing profile with temperature range from -5°C to 45°C.

5. Conclusion

The architectures of power system have been designed for the KNACKSAT. The power is generated by solar cells with Maximum Power Point Tracking. The power within the power supply system is transmitted through the Main Power Bus. The excess power is stored in two lithium-ion batteries. The charged and discharged protection circuits are located for protecting an overcurrent of each battery. Each voltage line is converted by 5V DC-DC converters and the 5-V DC power is transmitted to the satellite subsystems through standard pins. Furthermore, a current protection of each voltage line is implemented to prevent damages by the single event latch-up due to space radiation effects.

The power supply system uses an Atmega1280 microcontroller for controlling hardware and also reading all current sensors in the power system.

The power system has passed the space environment testing that consists of the Vibration Testing, the Thermal Vacuum Testing and the Thermal Cycle Testing. It has been proven that the power system could be constructed by COTS components to minimize component costs. During testing, the power system can provide the continuous power all the time effectively.

Acknowledgment

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