Hardware Development and In-orbit Demonstration of the Electrical Power System for TSUBAME High-powered Micro-satellite*

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This paper describes the development and in-orbit demonstration of an electrical power system (EPS) for the 100 W/50 kg-class micro-satellite TSUBAME. Due to the high power consumption per surface area of the TSUBAME and the high power-to-mass ratio, we encountered several technical issues to be solved before the launch. TSUBAME’s power demand varies drastically depending on the operation mode, from 2 W to 90 W. Therefore, we could not use the shunt regulator widely used for satellites. To suppress the exhaust heat from the dump power during low-power mode, we developed a series linear regulator that supplies less than 31 V to the main bus. Using this method, the operation point of the current-voltage curve for solar arrays was optimized automatically. However, this control law possesses a hysteresis which invokes a deadlock mode called battery lockup. In addition, the PWM current controller in the battery charger had 35 Vpp spike noises, which resulted in system-wide failure. To resolve the fatal problem, we redeveloped the EPS, specifically the noise charger, taking into account physical mechanisms that emitted noise. After environmental and integration tests, the EPS placed on the satellite, which was launched and worked correctly on orbit.

Key Words: Satellites, Electrical Power System, Series Linear Regulator, Charging Circuit, Battery Lockup

Nomenclature

\[ C: \text{ capacitance} \]
\[ E: \text{ energy} \]
\[ f: \text{ frequency} \]
\[ I: \text{ current} \]
\[ L: \text{ inductance} \]
\[ V: \text{ voltage} \]

Subscripts

\[ \text{bus: satellite bus} \]
\[ \text{in: input} \]
\[ \text{pk: peak} \]
\[ \text{p: parasitic} \]
\[ \text{oc: open circuit} \]
\[ \text{out: output} \]

1. Introduction

Very small satellites below 50 kg have been accepted as a platform for demonstrating advanced technologies and challenging science missions.1,2) To achieve an attractive satellite mission, system resources such as size/weight of the payload and electric power are the hardest technical issues to be solved. The TSUBAME3) (Fig. 1, Table 1) is a 100 W/50 kg-class micro-satellite developed to demonstrate advanced Earth remote sensing and astrophysical observation. It was developed by the Matunaga laboratory using the authors’ technologies, which were acquired through a series of CubeSat projects: the world’s first CubeSat, CUTE-L,4) Cute-1.7 + APD,5) and Cute-1.7 + APD II.6,7) TSUBAME’s power consumption per unit surface area is rather high compared to other recently launched micro-satellites such as SDS-4, INDEX, LAPAN-A2, RapidEye, and SkySat-2, as shown in Fig. 2. TSUBAME is also a higher specific power (1.9 W/kg) satellite. In terms of cost performance, high specific power looks attractive for building a high-performance, low-cost, multi-mission spacecraft, but the technical difficulty is much higher. In our case, the open issue to be solved was the on-board computer (OBC) embedded in the command and data handling system and the attitude control system. Since we employed commercial off-the-shelf (COTS) devices, there remained the risk of accidental freezing caused by radiation damage. These troubles may eventually result in a fatal power failure. At the time of a power crisis, the satellite must have a low-power mode used only for survival. On the other hand, the high-speed attitude control system requires more than 40 W. As a result, power consumption varies from 2 W to 90 W depending on the operation mode. The large variation in power demand increases the difficulty of thermal design.

Currently, most spacecraft utilize direct energy transfer (DET) systems with a shunt regulator, which has a power control device, a path of remaining current in parallel with loads to regulate voltage. The shunt regulator is designed
to maximize the generating efficiency, and operating point of the solar cell is locked. Therefore, the remaining power must be converted into exhaust heat. This is not suitable for our satellite because of the variation in power demand. To deal with this issue, we developed a non-DET system with a series linear regulator (series regulator), which has a power control device, a voltage dropper in series with loads. This system can optimize the operating point of the current-voltage (I-V) curve for solar arrays and suppress exhaust heat into the satellite structure. Non-DET systems with series regulators are useful for nano/micro-satellites in low-Earth orbit (LEO).

In this paper, we show the design concept of the EPS and the problems experienced in the development (Section 2–4). Finally, we also show the results of an in-orbit demonstration of the EPS (Section 5). The remainder of this paper is presented as follows: Section 2 discusses an EPS architecture with an ultra-low drop series regulator for high-powered micro-satellites; Section 3 introduces remedial measures to eliminate spike noise and dissipate heat from a charging circuit; Section 4 presents findings about a battery lockup due to a buck-boost converter in boost mode; Section 5 discusses operation results; and Section 6 offers conclusions.

2. Electrical Power System Architecture

2.1. Series regulator system

The EPS (Fig. 3) is a series regulator system with an ultra-low drop series regulator. The primary source of power is four deployable solar array paddles consisting of 12-strings of 15 series-connected cells. Power from the solar array is transferred indirectly to the spacecraft bus, which is limited to under 31 V through the series regulator. The energy storage is a 6-series/6-parallel lithium-ion polymer battery system. Power from the battery system is transferred directly to the spacecraft bus. A distributed power system and point-of-load (POL) power supplies were adopted for compliance to FPGA power requirements for low noise and multiple low voltages. The EPS is also a non-isolated power system because it was difficult to isolate all signal lines. The advantages of the TSUBAME series regulator system are as follows:

- Heat generation of the series regulator is less than that of the shunt regulator, especially at high temperatures
- Less heat dissipation inside the spacecraft body
- High power transfer efficiency from battery to load
- No need for power control algorithms

The disadvantages are as follows:

- Battery lockup concern
- More complex load converters

In comparison with the peak power tracker (PPT), this series regulator is simple, and the pass transistors, which are control switches between input and output pins, have less heat loss. However, there were battery lockup concerns. This series regulator system is suitable for large variations in illumination and temperatures in the solar array throughout missions with limited resources, such as nano/micro-satellites in LEO. Note that the buck-boost DC/DC converter was eventually retired due to the lockup problem (Section 4.2).

2.2. Ultra-low drop series regulator and its thermal design

The ultra-low drop series regulator (Fig. 4) was developed by the Matunaga laboratory. Using P-MOSFETs, the dropout voltage is approximately 0.1 V. Therefore, the power loss is very low while the solar array voltage output is under TSU-
Table 2. Comparison of shunt, series linear and switching voltage regulators. In addition, the ultra-low drop series regulator to have higher reliability than a switching regulator. In the case of TSUBAME, when the open circuit voltage ($V_{oc}$) of the solar arrays is the estimated average value of 33 V and the bus voltage ($V_{bus}$) is 31 V, the efficiency of the ultra-low drop series regulator is approximately 0.94 ($=31/33$), which is comparable to that of a switching regulator. Although the size of the ultra-low drop series regulator is large, the pass transistors composed of four P-MOSFETs in parallel enable the series regulator to have higher output power and lower dropout voltage than general series regulators. A combination of solar arrays and a regulator gives spacecraft the following characteristics of power and thermal design. For series linear and switching regulators, waste heat during the light-load mode of a satellite is low because the operation point on the $I$-$V$ curve of a solar array can move. Therefore, these regulators are suited for high-powered micro-satellites, which can overheat. On the other hand, for shunt regulators, waste heat at low load is high because the operation point is fixed. Thermal designs of satellites using shunt regulators can become simpler than those of satellites using series linear and switching regulators because the entire power consumption of satellites using shunt regulators is stable.

Figure 5 shows the comparison between power loss, heat generation of shunt regulators and that of series regulators. The green points are operation points of the $I$-$V$ curve for a solar array using a shunt regulator and a series regulator corresponding to required power consumption. Whereas the operation point of a shunt regulator is fixed, that of a series regulator is able to move on the $I$-$V$ curve for a solar array depending on the power required. Series regulators can reduce much more heat generation than that of shunt regulators if $V_{bus}$ can be sufficiently close to $V_{oc}$. The power loss is maximized at the end of eclipse because $V_{oc}$ is high at low temperatures. However, the power loss decreases immediately because the temperature of solar arrays increases rapidly. In the case of TSUBAME ($V_{bus} = 31$ V, $V_{oc} = 31–45$ V), the power loss of the series regulator is a maximum of 77 W at the end of eclipse, but 10 minutes after that, it drops to under 6 W.

Heat dissipation of the pass transistors in the series regulator is important because heat in the pass transistors can be large. The pass transistors consist of four P-MOSFETs in parallel for dissipating heat (Fig. 4). The pass transistors are insulated from the satellite body. The front side of the heat-dissipating board of the P-MOSFET is covered with a metal mask for heat transfer enhancement.

### 3. Charging Circuit

#### 3.1. Overview of charging circuit

Figure 6 shows the overview of the charging circuit (CC: 3 A, CV: 24.6 V). The charging circuit consists of a P-channel MOSFET switch, an N-channel MOSFET synchronous rectifier, a battery charger, which is a step-down pulse-width-modulation (PWM) controller, and a LC filter. When the battery voltage or charge current reaches the required optimum level, the battery charger switches off the P-MOSFET and on the N-MOSFET. Figure 7 shows a flight model (FM) of charging circuit in a battery management system (BMS) board.
3.2. Remedial measures against spike noise

Figure 8 shows 35 Vpp (peak-to-peak voltage) spike noises on a battery cathode line. The spike noise caused fatal errors, which caused some MOSFETs in the BMS to fail and a microcontroller to stop.

The spike noise is due to a resonance of parasitic inductance in circuit patterns and stray capacitance of the switching P-MOSFET. The noise energy $E$ is obtained as

$$E = \frac{1}{2}L_p I_{pk}^2$$  \hspace{1cm} (1)

where $L_p$ is parasitic inductance in circuit patterns, and $I_{pk}$ is the peak current when the P-MOSFET is being turned off. In terms of satellite system design, it is difficult to change the parameters of the charging current. Therefore, $L_p$ should be reduced to diminish the noise energy $E$. The frequency of the spike noise $f$ is a resonance frequency of $LC$, that is,

$$f = \frac{1}{2\pi \sqrt{L_p C_p}}$$  \hspace{1cm} (2)

$C_p$ is parasitic drain-to-source capacitance of the P-MOSFET. Since $f \propto 1/\sqrt{C_p}$, a P-MOSFET with small $C_p$ raises $f$. This means that the spike noise becomes hard to occur.

Figure 9 shows causes and remedies of the spike noise. The following were the main points for improvement in the charging circuit of TSUBAME:

- Minimizing pattern and optimizing circuit layout of electronic parts to reduce $L_p$
- Replacing the switching P-MOSFET with a high-speed MOSFET to reduce $C_p$

Although minimizing pattern and optimizing circuit layout took much time and cost more than exchanging the P-MOSFET, it was a very effective solution. The spike noise rejection was confirmed through a verification test using a constant current 3 A charge. Figure 10 shows the AC component of the voltage waveform on a battery cathode, which was 1 V acceptable ripple noise.

3.3. Remedial measures against heat

A unit thermal testing of the BMS board detected an overheat problem with the charging circuit. The battery charger IC abnormally stopped when it was working at the maximum charging current of 3 A at the maximum expected ambient temperature of 45°C in orbit. This is because its temperature exceeded the upper limit of the operation temperature of 85°C even in air. The two-dimensional temperature distribution of the charging circuit under the condition was not able to be measured because an infrared camera could not meas-

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measure the temperature through a window of a thermostatic bath. Instead of the ambient temperature of 45°C, we measured the temperature distribution in the air at a room temperature of 19°C, as shown in Fig. 11. The main heat sources were the inductance of the LC filter and the switching MOSFETs in the charging circuit. We concluded that the temperature distribution would be similar even if the room temperatures are different for each experiment. The value measured for the heat generation was approximately 10 W, and that of charging efficiency was approximately 85% taking into account 70 W charging.

A remedial measure was to connect an A5052 aluminum plate of satellite structure to the heated parts using five-layer graphite sheets (0.07 mm, 1,000 W/(m K)) for heat dissipation. Graphite sheets are widely used for other satellites. For instance, three-layer graphite sheets were adopted for the X-ray astronomy satellite ASTRO-H in order to enhance thermal conductivity.\(^2\) The charging circuit with graphite sheets is shown in Fig. 12. Note that graphite sheets should be used with care due to their conductivity and brittleness.

Vacuum testing was conducted to measure the thermal resistance between the circuit board with graphite sheets and the aluminum plate and estimate maximum temperature in orbit. Figure 13 shows the BMS board including the charging circuit on the aluminum plate in a vacuum chamber. Temperatures of the BMS board around the charger IC and the aluminum plate were measured with thermocouples. The standard error of measured differences in temperature between the thermocouples was ±0.1°C. The pressure in the vacuum chamber was approximately 10\(^{-3}\) Pa. The input power of the external heater that simulated heat from the converter. This is because this remedy was the most relia-

Table 3. Measurement results of thermal resistance and maximum expected temperature in orbit.

| Parameter                        | Graphite sheets |
|----------------------------------|-----------------|
| Thermal resistance @ 10\(^{-3}\) Pa (°C/W) | 3.5             |
| Maximum expected temperature in orbit (°C) | 86              |

sheets can decrease thermal resistance by approximately 50%. The maximum expected temperature in orbit was 67°C, which was smaller than an upper limit of the operating temperature of the battery charger of 85°C.

4. Battery Lockup Problem

4.1. Battery lockup

The battery lockup is explained as follows. Although the solar array was capable of delivering full power, the battery continued to deliver the load power. The bus voltage remained latched to the battery voltage and was unable to recover to the regulated voltage derived from the solar array. Battery lockup can occur when the solar array current is less than the battery current upon entry into sunlight.\(^{11}\)

4.2. Battery lockup due to a buck-boost converter in boost mode

The following fault was found during system integration testing with the solar array simulator, which can simulate the dynamic I-V characteristic of solar arrays in orbit. Although there was sufficient sunlight, the battery lockup remained while the buck-boost converter (Fig. 3) was in boost mode. That is, the buck-boost converter kept the solar array voltage low. It is important to note that the fault did not occur when the satellite was turned on with a stabilized power supply. Therefore, it is related to the start-up time of the power supply. This would be why the buck-boost converter was activated in boost mode while the solar array voltage output was rising. The remedies for avoiding this fault are shown in the following:

- Terminate the boost function
- Temporarily disconnect solar arrays to loads with a MOSFET switch controlled by a microcontroller

Although the boost function was useful when the solar array can only output low voltage, it was decided to turn off the buck-boost converter, and short-circuit input and output of the converter. This is because this remedy was the most relia-
able and easy way. Another remedy, as mentioned above, is less reliable because malfunctions sometimes occur. There was a possibility that the microcontroller failed to detect the battery lockup and a few attempts to reset the buck-boost converter were needed. In the case of battery lockup without a boost converter, it was effective to shut off some non-essential loads or limit charge current temporarily. However, it should be noted that these ways of lightening loads are useless in the case of the battery lockup due to the boost function.

5. Operation Results

TSUBAME was successfully launched on November 6, 2014. Then, housekeeping (HK) data was received by radio amateurs in Germany and Japan, and by us. This section shows the operation results, which indicate that the EPS worked properly.

Figure 14 plots the bus voltage profile. The bus voltage was equal to the series regulator voltage in sunlight. This means that the series regulator was able to regulate solar array voltage. Since the power bus was an unregulated bus, the bus voltage was equal to the fluctuating battery voltage in eclipse. The bus voltage was stable while the electricity consumption fluctuated as shown in Fig. 15. The rough trend of the power consumption depends on whether on-board equipment was turned on or off. In the beginning of the in-orbit operation, the power consumption increased because some components were checked out. After that, the power consumption decreased because TSUBAME entered safe mode on November 12, 2014. There was a difference in the power consumption between sunlight and eclipse duration because magnetorquers were active in sunlight and passive in eclipse. A continuous wave (CW) transmitter always caused a relatively small variation of approximately 1 W. Unfortunately, reliable data of the solar array voltage were not downlinked. The mean voltage of the solar arrays was calculated to be 33 V from the design. Using this value, the mean efficiency of the ultra-low drop series regulator was expected to be 0.94 in orbit.

Figure 16 shows the battery voltage profile. In sunlight, the battery voltage was stable and equal to the voltage of constant voltage (CV) charging. That is, the charging circuit worked normally. In eclipse, the battery voltage was discharge voltage. This data also indicates that the satellite was able to point to the sun stably. There were fluctuations during a transient period from the launch day, November 6 to 7, on the left side of Fig. 16. In this initial phase, TSUBAME was pointing towards the sun, and the battery voltage was decreasing from the full-charge level to the stable level. Therefore, the decreasing trend of battery voltage can be seen during this stage in sunlight and eclipse.

Since the battery voltage had been stable (Fig. 16), it was confirmed that battery lockup was prevented. If the lockup phenomenon had occurred, TSUBAME could not have charged the battery and the battery voltage would have decreased until the battery went into a state of over-discharge. Although we could not confirm whether TSUBAME charged the battery so quickly that spike noise could occur, the HK data suggests that there was no spike noise that made TSUBAME abnormally reboot. Based on a result of ground testing, it was found that the 35 VPP spike noise caused the satellite to fail. HK data of command and data handling subsystem shows the number of resets had been zero in orbit. This indicates that TSUBAME did not have the spike noise on orbit. However, we confirmed that the depth of discharge (DOD), which is the ratio of how deeply batteries are discharged to their discharge capacity, had been under 50% for the whole operation period. In this case, there was a possibility that the battery had been charged without switching, which means that the spike noise had not been created in principle.

Figure 17 plots the battery temperature profile. The battery temperature represents the temperature of the whole satellite body insulated from the heat of the series regulator. The battery temperature varied with the power consumption (Fig. 15). Because the battery temperature was in a proper temperature range, this data suggests that the general thermal design of the EPS was appropriately done. Furthermore, when the power consumption was roughly stable, the meas-
ured battery temperatures were almost constant during both sunlight and eclipse, which implies that the heat dissipation of the series regulator during sunlight was effectively suppressed, and the thermal insulation between the pass transistors of the series regulator and the whole satellite body was sufficient.

The operation results of the battery imply that, although it was unclear whether the charging at full-power had been performed, the operation temperatures of the charging circuit had been within the suitable range for the entire operation period. If the charger temperature had become abnormally high, it would have been observed that the HK data of the battery voltage (Fig. 16) was dropping because the charging circuit could not charge the battery until reset. Therefore, the HK data of the stable battery voltage suggests that the charger had not reached an abnormally high temperature.

6. Conclusion

An EPS with an ultra-low drop series regulator was successfully developed for the 100 W/50 kg micro-satellite TSUBAME. Series regulators can be more efficient than shunt regulators, and are useful for high-powered nano/micro-satellites in LEO. TSUBAME was launched on November 6, 2014, after which the EPS worked correctly on orbit. Future work will include the study of a simple function to avoid battery lockup, such as maximum power point tracking.

Acknowledgments

We are grateful to Shigeaki Koga, Nobuhiko Kisa, and Toshiyuki Nishihara for their participation in the EPS development. This work was supported by a grant from the Japan Society for the Promotion of Science (JSPS) through the “Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program),” initiated by the Council for Science and Technology Policy (CSTP) and also supported by JSPS KAKENHI Grant Numbers 26289329, 21840025, and 24740121.

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