Three Hundred Fifty Volt Photovoltaic Power Generation in Low Earth Orbit

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350-V Photovoltaic Power Generation in Low Earth Orbit

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I. Introduction

HIGH-voltage photovoltaic power generation becomes necessary as the power consumed by a spacecraft increases. Generally speaking, the voltage scales up with the square root of power to minimize cable mass or transmission loss. So far, the highest power generation voltage in orbit has been 160 V onboard the International Space Station (ISS). It is known that arcing occurs on solar arrays due to an interaction with the surrounding plasma once the generation voltage exceeds 200 V [1]. There is a growing need for a higher voltage in the range of 300-400 V. At that level, a large megawatt-class space platform becomes possible. Direct drive for electric propulsion also becomes possible [2]. There have been several on-orbit experiments that investigated high-voltage solar array technologies [3,4,5,6,7]. All of them, except the Space Flyer Unit (SFU), employed a DC/DC converter to expose test specimens to plasma with a negative voltage of several hundred volts. Because we need to connect many solar cells in series to generate a high voltage, this leads to a large experimental area. The SFU[6] employed a deployable solar panel but it failed, as the cable connector was accidentally separated. A DC/DC converter is not ideal for experiments with high-voltage solar arrays. It often fails (for an example see Ref. 4), and the arc current path is not exactly the same as one that would fly with solar cells only. To perform a high-voltage experiment using a large- or medium-class satellite that can provide the bias voltage with series-connected solar cells is often difficult due to safety concerns raised with regard to other experiments sharing the satellite. To do the experiment on a small satellite is also difficult due to its size limitation.

The Kyushu Institute of Technology developed a nanosatellite, “HORYU-II”, which has a cubic shape of 350×310×315 mm and a weight of 7.1 kg. Its main mission is to do an on-orbit demonstration of high-voltage solar array technologies developed at the Institute[8]. The satellite was launched into a 680-km sun-synchronous orbit on May 18, 2012 (JST). HORYU-II uses series-connected micro solar cells instead of a DC/DC converter to negatively bias the test specimen to plasma. The purpose of the present Technical Note is to do a quick report

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II. Experimental System

Figure 1 shows an overview photograph of HORYU-II. HORYU-II has two high-voltage solar panels where 66 Sphelar® cells are connected in series. The Sphelar® solar cells were developed by the Sphelar Power Corporation. Each Sphelar® cell is composed of 12 series-connected silicon solar cells housed inside a polycarbonate case. The total size is 24(L) x 9.5(W) x 5.1(H) mm. According to the manufacturer spec sheet, one Sphelar® solar cell has an open-circuit voltage of 7.3 V and a short-circuit current of 2.3 mA under the condition of 100 mW/cm^2 AM1.5 at 25ºC (Sphelar® is not meant for space use; only AM1.5 data is available). See http://sphelarpower.com for product details. The high- voltage solar panels are placed on opposite sides of the satellite and connected in series. Although the two panels in series can have an open-circuit voltage of more than 900 V, we limited it to approximately 350 V using three 100-V and one 50-V series-connected zener diodes. The satellite uses a permanent magnet and hysteresis dumper to do passive attitude control using the Earth's magnetic field. Therefore, only one panel can be exposed to sunlight at one time. Behind the panel, a bypass diode was soldered in parallel to each Sphelar® cell. Because it is not our intention to allow arcs to occur on the Sphelar® cells, we covered all the exposed metallic parts with S-691® silicon adhesive. The total weight of each panel is 186 g and the size is 122 x 214 mm. We tested panels for 15 thermal cycles of -100ºC to +70ºC in a nitrogen gas environment and observed no anomalies. We developed the high-voltage solar panel for use as a power supply for high-voltage experiments in space, not for practical power generation. The thin double-junction solar array cells seen below the high voltage solar panels in Fig. 1 provide the power to the satellite bus.

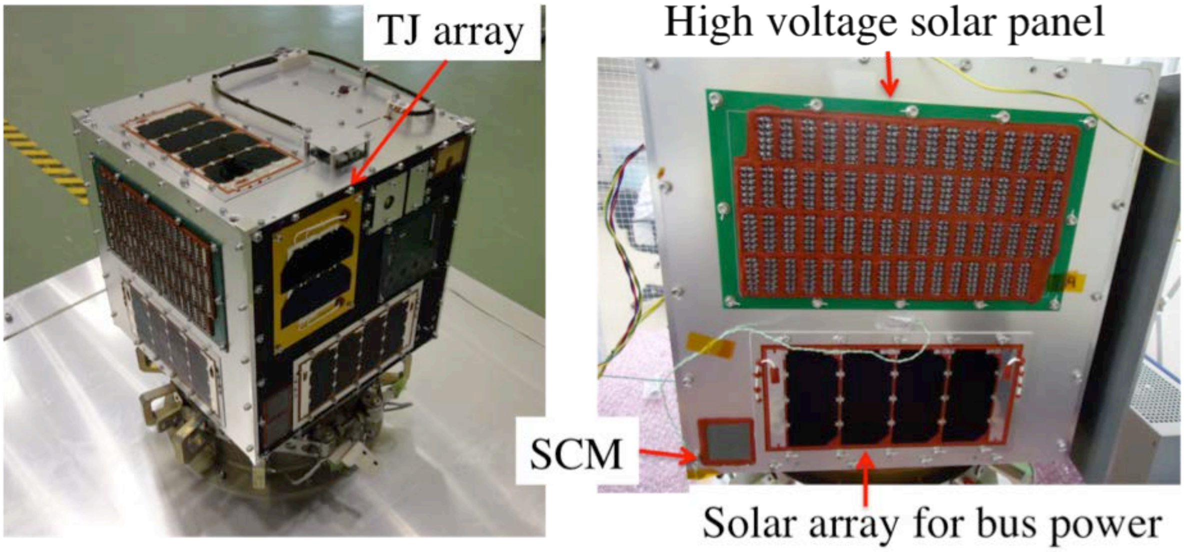

Fig. 1 HORYU-II (left) and close-up of the high-voltage solar panel (right)

Figure 2 shows a schematic of the circuit used to carry out the high-voltage solar array experiment. The 300-V system is completely insulated from the satellite bus. The power and the signals are transmitted through an isolation DC/DC converter and a magnetic coupler, respectively. At the positive end of the high-voltage solar panel, we have an electron collector, which is a 40 mm x 20 mm copper plate exposed to space conditions. The electrons collected by the copper plate drive the potential of the experimental ground point to a negative value comparable to the power generation voltage. The experiment is started by opening the switch between the negative and positive ends of the solar panel by a command from the microprocessor. At the negative end, there are three types of solar arrays, where two GaAs/InP/Ge triple-junction (TJ) solar cells are connected in series. We can see one such array in Fig. 1. One type is a nominal array whose design is the same as the conventional one, where no arc mitigation is done. The other two types employ arc mitigation designs. One utilizes a transparent film over a conventionally designed solar array [8]. The other utilizes a transparent semi-conductive coating. We individually connect one of the three solar arrays to the negative end of the high-voltage solar array and bias it to the plasma at a potential as negative as -350 V. The results of the experiment in which we bias those solar arrays will be presented in the future. The power generation voltage is measured by a voltmeter across an 820 kΩ resistor. The voltage is divided by two resistors, 100 MΩ and 820 kΩ. A capacitance of 10 pF is inserted in parallel to the two resistors to stabilize the generation voltage.

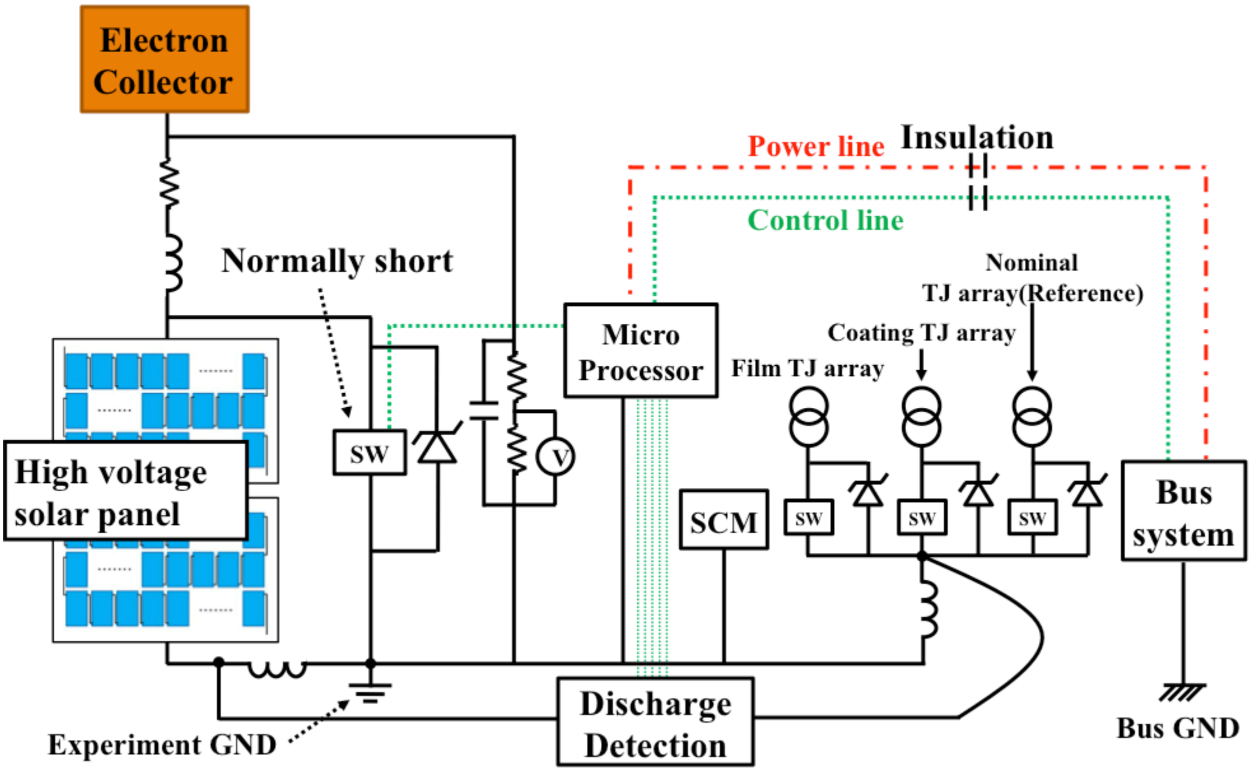

Fig. 2 Schematic of experimental circuit

At the negative end of the high-voltage solar panel, we attached an spacecraft charging monitor (SCM). The SCM is based on a surface charging sensor developed by Lockheed Martin and the Jet Propulsion Laboratory[9], which has already been flown in space. The SCM measures the surface potential of the insulator material exposed to space conditions by inserting another capacitor between the isolated electrode that is behind the surface insulator and the circuit ground. Once we know the capacitance of the surface insulator and the additional capacitor, we can know the insulator surface potential with respect to the circuit ground by measuring the electrode potential. We coated a copper plate of 30 mm x 30 mm with a fluoropolymer resin. The capacitance of the coating is approximately 150 nF and that of the additional capacitor is 50 nF. The SCM surface potential is most likely near the plasma potential, comparable to the electron temperature, which is 0.2 eV at maximum in LEO. By measuring the SCM surface potential, we can know how negative the experimental ground floats with respect to the plasma.

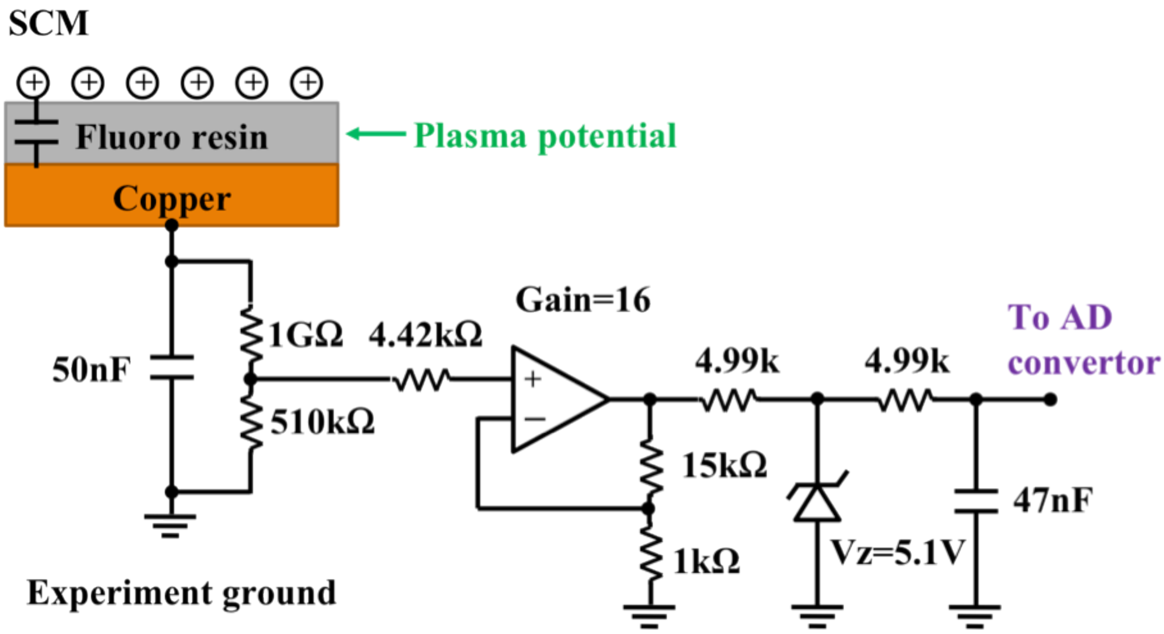

Fig. 3 Schematic of an SCM circuit

III. Experimental Results

Figure 4 shows the results of our experiment. The experiment commenced at 16:52 November 28, 2012 (UT) over New Guinea. The satellite exited the eclipse over Antarctica 10 min after the start of the experiment. It crossed the equator from south to north and the experiment was terminated over Canada at 17:52 Nov. 28, 2012 (UT). In Fig. 4, the circle indicates the power generation voltage and the triangle indicates the SCM output potential. The rectangle indicates the temperature of the circuit board. The temperature data show a gradual increase in satellite temperature after the conclusion of the eclipse. All the data were taken at 1-min intervals. The maximum generation voltage was about 356 V at approximately 45 min, corresponding to the breakdown voltage of the zener diode. The SCM output potential initially shows a fluctuation between 250 and 310 V. The satellite rotation speed was less than 1 deg/sec. The minimum resolution was 1 deg/sec. Therefore, it is possible that the SCM output reflected the rotation of the satellite and dropped when the SCM faced the wake direction. The sampling rate of the satellite housekeeping data related to its attitude was limited to 1 sample every 10 min. In Fig. 4, the limited data show no sign of the SCM receiving sunlight during the initial 40 min. After 45 min, the SCM output was closely matched with the power generation voltage, indicating that the experimental ground floated negatively at a voltage close to the power generation voltage. The combination of plasma density, satellite attitude, solar illumination, the presence of precipitation electrons, and other factors determines the charging of the surface insulator and the experimental ground. Due to the limited resources of the satellite, we have little information about those parameters. The purpose of this Technical Note is to make a quick report on the world's first 350-V power generation in space. We will accumulate more experimental data to investigate the exact reason for the charging behavior of the experiment ground and present our results in the future.

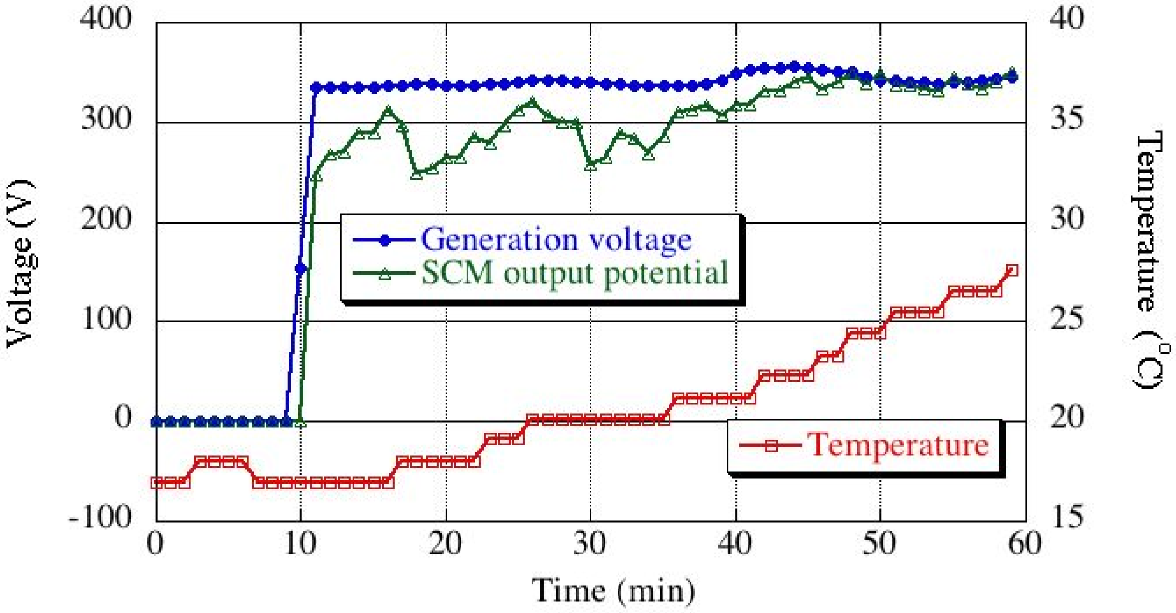

Fig. 4 Result of high-voltage power generation experiment

IV. Conclusion

A nanosatellite, HORYU-II, weighing only 7.1 kg achieved the highest photovoltaic power generation in orbit, at 350 V, breaking the previous record from the ISS, at 160 V, by more than a factor of two. This high-voltage experiment is suitable for a micro-/nanosatellite where the high risk associated with the use of high voltages is acceptable. Using series-connected micro solar cells, the satellite can carry out high-voltage experiments in space. The high-voltage solar array developed for HORYU-II is suitable for other scientific experiments that make use of high voltages, such as electric propulsion, spacecraft charging, etc. onboard a micro-/nanosatellite. It is free from the electromagnetic noise associated with high-voltage DC/DC converters and robust enough to operate for a short time (HORYU-II has already been operating high voltage solar arrays for more than 50 hours) in orbit. The experiments onboard HORYU-II are still ongoing, including an experiment to demonstrate the effectiveness of arc mitigation design solar arrays. After enough data has been accumulated, those results will be presented in the future.

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