INTERNATIONAL JOURNAL of SMART GRID
T. Ishiyama, Vol.12, No.4, December, 2022

Correlation Assessment Between Power Generation and Storage Characteristics by Indoor Photovoltaic Energy Harvesting

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Received: 20.12.2022 Accepted:30.12.2022

Abstract- The paper presents indoor photovoltaic (PV) energy harvesting and the correlation assessment of power generation and storage devices for "Internet of Things (IoT)" devices. To estimate the photovoltaic cell and capacitor parameter optimization, the correlation of charge time to capacitance of indoor PV cells was measured. Several capacitors with different capacities were used to charge the power generated by the photovoltaic cells, and the charging time of the capacitors was measured. Indoor PV cells can generate a sufficient amount of power by obtaining sunlight from windows as well as artificial lighting. Therefore, IoT devices can be operated even at night by supplying power from the energy storage circuit. These results suggest that charging time and capacity are correlated to provide enough power for operation of IoT devices. The brightness in the room is composed of lighting and sunlight from the windows. Based on the experimental results, a correlation of charge time to capacitance of indoor PV cells was formulated using a logarithmic function.

Keywords Energy harvesting, battery charging, photovoltaic cell, indoor solar-power, energy storage.

1. Introduction

Energy management systems, known as home energy management systems (HEMS) and building energy management systems (BEMS), are spreading to homes and offices [1]. Electronic devices equipped with sensors and radios are placed in various locations to collect data, communicate, and control equipment. Such electronic devices are expected to be connected to the network. They send and receive data via networks and must operate on the network at all times [2-3].

The electronic devices use networks to transmit information about themselves and their surrounding environment [4-5]. Such devices are called "Internet of Things (IoT) devices" or "sensor nodes" [6-9]. These devices are connected to the network at all times. The IoT devices contain various electronic components and parts, and can continuously transmit information by being connected at all times. Many IoT devices operate indoors at all times. The challenge is to supply an adequate electric power. This means that the IoT devices must be managed without exchanging the battery [10-11].

Installation of solar cells is one of the most effective ways for IoT devices used indoors to operate without exchanging the battery [12-13]. The IoT device, which is made by EnOcean company, can operate on solar cells in addition to batteries [14-16]. Energy harvesting with solar power generation is one of the best ways to generate electric power all the time [17-18]. However, electric lights in a room are only 1/100 to 1/1000 of the brightness of outdoor sunlight during the day. Thus, energy harvesting using electric lights in a room does not provide significant output. In order to drive the indoor solar-powered equipment, it is necessary to minimize power loss due to the circuit by optimizing various parameters. [19-22]. By minimizing the power loss, the IoT devices will operate in the indoor light.

This paper presents the effect of indoor PV energy harvesting and correlation between harvested power and the storage device, and explains operation of the IoT devices in the room. The circuit parameters were measured to minimize the power loss. To minimize the power consumption of IoT devices, a correlation was also formulated between the capacity and time required for charging.

2. Correlation of Capacities for Storing Electricity Obtained from Indoor PV Generation

When small photovoltaic cells are used in the room, they struggle to generate enough electricity. By optimizing the parameters of the power supply circuit, it can make up the circuit to use the electric power effectively [23].

To overcome the issue of low power generation, electricity is stored for a long period of time with a capacitor of large capacity [24]. To optimize the parameters of the power supply circuit, the resistive component should be suppressed by reducing the capacitance. The power generation and capacitance of solar cells were compared, and a low-loss power circuit was fabricated. The capacitance was optimized to operate the application circuit with low power. Then, the circuit can be operated for a long time.

3. Experimental

Fig. 1 shows an experimental setup to measure the current-voltage characteristics obtained with the indoor PV power generation system. The indoor PV power generation system is equipped with a power supply unit and a load unit. The power supply unit contains solar cells, control circuits, and a capacitor with large-capacity.

Fig. 1. Experimental setup to measure output characteristics.

The output power generated by the solar cells was compared against the capacitance. Experiments were conducted with capacities varying from 10 μF to 0.47 F. Fig. 2 shows the electronic circuit which was used to measure the current-voltage characteristics. During measurements, the resistance of the variable resistor was varied to evaluate the combination of current and voltage to achieve the maximum output power (maximum power point tracking: MPPT) [25-27].

For the indoor PV system, 1 cm x 2.5 cm size photovoltaic cells, as shown in Fig. 3, were used for installation in IoT devices. A small spherical silicon solar cell was selected for installation in the IoT device. For comparison, an amorphous silicon solar cell was prepared, which was the same size and used in calculator applications.

The current-voltage characteristics of both cells were evaluated. The spherical silicon solar cell (KSP-F12) was tested with products manufactured by Sphelar Power Corporation. The amorphous silicon solar cell (AM-5815-CAR) was tested with products manufactured by Panasonic Solar Amorton Corporation.

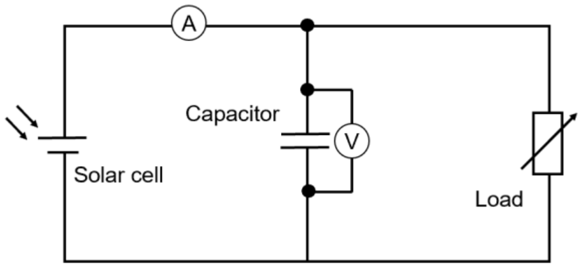
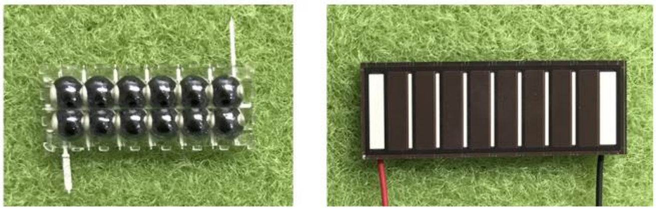


Fig. 2. Electronic circuit used for current - voltage measurements of solar cells.



(a) Spherical silicon cells (b) Amorphous silicon cells

Fig. 3. Photovoltaic cells used in the experiment.

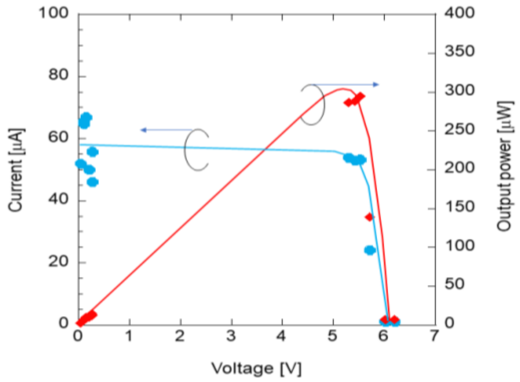
4. Results and Discussion

4.1. Experimental Results

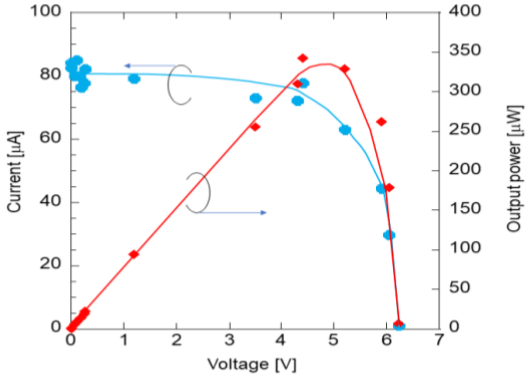
Fig. 4 shows the Output characteristic of indoor photovoltaic cells. Both cells were compared under the same conditions, which were operated in the indoor light. In the experiment, two types of solar cells, spherical silicon solar cells and amorphous silicon solar cells, were compared. The experiment was performed in a north-facing room, the weather was cloudy, and the room brightness was 350 lx with fluorescent and sunlight.

The maximum output power (Pmax) of the spherical silicon photovoltaic cell was 295 μW, and maximum output power of the amorphous silicon photovoltaic cell was 341 μW. Considering that brightness due to sunlight fluctuated during the experiment, both power generation characteristics were equivalent.

To evaluate further power generation performance, both photovoltaic cells I-V and P-V characteristics were measured under various conditions. The maximum output power of both photovoltaic cells is shown in Fig. 5, which shows the amount of power obtained depending on the illuminance of the sunlight. In this experiment, the illuminance was varied over a wide range by using a south-facing room in addition to a north-facing room. The maximum power output of two kinds of photovoltaic cells could be plotted on a single straight line. This confirms the results displayed in Fig. 4, showing that the output power of both types of photovoltaic cells is comparable.



(a) Spherical silicon photovoltaic cell



(b) Amorphous silicon photovoltaic cell

Fig. 4. Output characteristic curves of solar cells.

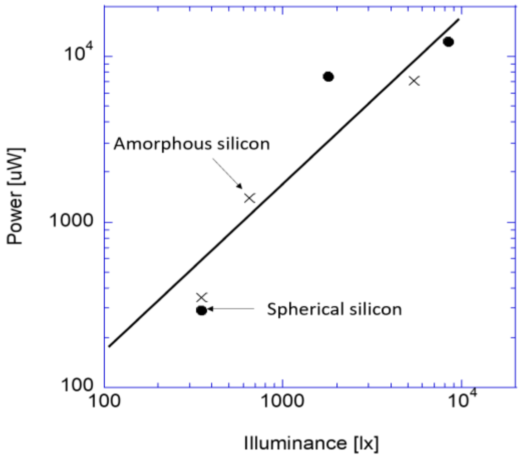


Fig. 5. Maximum output power of both types of photovoltaic cells.

Fig. 6 shows the correlation of charge time to capacitance of indoor PV cells evaluated experimentally. Charging times were measured indoors with power generated by the spherical silicon photovoltaic cells. The time required for charging was determined based on the voltage of the capacitor. Taking into account the brightness of the room, charging time was measured against capacity at three different illuminance tness levels.

The measurement results suggest that the charging time can be approximated from the capacity and the brightness of the room. Fig. 6 also suggests that the charge time for a given capacity can be reduced with higher illumination.

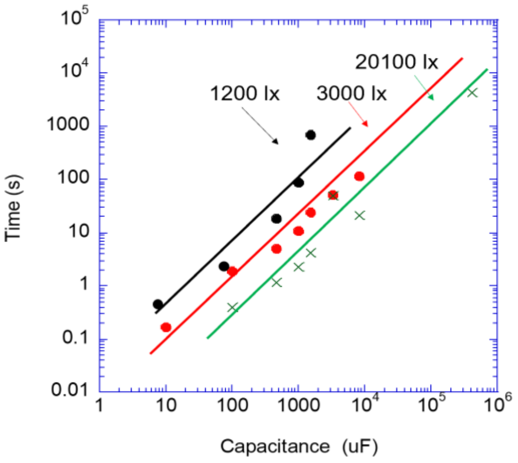


Fig. 6. Correlation of charge time to capacitance of indoor PV cells.

4.2. Discussion

The wireless sensor terminal is operated by indoor solar power generation. The amount of electricity required was discussed. The following power quantities were assumed to calculate: for 12 hours of the day, the capacitor is charged while generating electricity. For the remaining 12 hours, the equipment is driven by consuming power from the capacitor. A wireless sensor device, which is called "TWELITE", was assumed as a load [28]. It operates at a voltage of 3.3V. Its power consumption is 70 µA/s in operating mode and 6 µA/s in standby mode. If it is considered that sufficient constant power supply is not available indoors, the device was assumed to be activated once in 60 s. Though the device, "TWELITE", actually operates at a rate of once every 10 s, the calculations were performed under the assumptions described above. Therefore, the device consumed 23.7 µW [29].

If the IoT device is activated once in 60 s, power required in 12 hours was calculated to be 1.02 J. In 12 hours during the day, the system would require a total of 2.04 J, considering that 1.02 J of energy is needed to power the IoT device and an additional 1.02 J is needed to charge the capacitor.

The charging energy of a capacitor is represented by the following equation:

$$W = \frac{1}{2}CV^2 \tag{1}$$

where W is the stored energy [J], C is capacitance [µF], and V is voltage [V]. In this system, the capacitor begins charging when a voltage of 5.3 V or higher is applied [29], so a capacitance of 145 mF or higher is required. From Fig. 6, it can be seen that at an illuminance of 20100 lx, indoor light charged the capacitor in 1800 s. At an illuminance of 3000 lx, indoor light charged the capacitor in 8000 s.

An equation relating charging time to capacitance was derived. Fig. 6 shows that charging time and capacitance are represented by a straight line. Therefore, the relationship between charging time and capacitance can be expressed by the following formula:

$$log_{10}\, t = \alpha\, log_{10}\, C + \beta \qquad (2)$$

where t is the charging time [t], and C is the capacitance [μF]. The parameters α and β can be obtained from the experimental data on charging time and capacitance. The parameter α is obtained as 1.14. The parameter β, which depends on the room illumination, is expressed as follows:

$$\beta = -0.97\, log_{10}\, I + 1.29 \qquad (3)$$

where I is Illuminance [lx]. It should be noted that the parameter β is expressed as a function of room illumination. Therefore, it was determined that indoor solar power could be used to supply and charge the sensor terminals.

5. Conclusion

A correlation assessment between power generation by indoor PV energy harvesting and storage characteristics was investigated for the power source of IoT devices. To confirm that the IoT devices can operate in the room without charging batteries externally, the correlation between charging time with small solar cells and the capacity of storage devices were studied. It was confirmed that IoT devices can work with power obtained from weak light in the room.

To estimate the photovoltaic cell and capacitor parameter optimization, the correlation of charge time to capacitance of indoor PV cells was measured. Several capacitors with different capacities were used to charge the power generated by the photovoltaic cells, and the charging time of the capacitors was measured. The current-voltage and power-voltage characteristics of two solar cell types, which were spherical silicon photovoltaic cells and amorphous silicon photovoltaic cells, were measured by changing the illuminance.

The amount of output power fluctuates on an order level in indoor PV power generation. It depends on the installation location and the amount of sunlight entering through the window. Indoor PV cells can generate a sufficient amount of power by obtaining sunlight from windows as well as lighting. Based on the experimental results, the correlation of charge time to capacitance of indoor PV cells was formulated. The relationship between the system's energy storage devices and charging time with respect to the amount of power consumed was also clarified. As a result, it was determined that IoT devices can be operated even at night by using an energy storage circuit.

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