Estimation of Energy Storage Status in Power Supply System Using Power over Fiber for Outdoor Environment

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Abstract: We demonstrate that our model for estimating power charging regimes of the power supply system combining power over fiber and an energy storage is very accurate as it accounts for the temperature dependence. © 2024 The Author(s)

1. Introduction

Power over fiber (PoF) systems, which are immune to electromagnetic noise and have low transmission loss, are a significant candidate for powering devices installed outdoors and far from regular power sources. Conventional PoF systems can drive various electrical devices that consume optical power of some hundreds mW, as reported in [1, 2]. However, such PoF systems can be used only a limited area because the optical powers used are not safe for use in general optical access networks. Safety rules for optical power are standardized in IEC 60825-2 [3], which mandates the optical power in optical access networks to be below 100 mW. Therefore, we proposed a PoF system with Energy storage that uses low optical power enough to use in optical access networks and can operate various devices, e.g., 1x16 optical switches with a power consumption of 130 mW[4]. When energy storage is employed, the voltage of the storage should be controlled in an appropriate range to keep the energy conversion efficiency of PoF system high, because the efficiency is changed depends on the voltage. To control the voltage, we must know the value of it. However, the constant monitoring of the voltage consumes too much of power because the remote node of the PoF system always works to measure the voltage and send the results. Therefore, we have studied the estimation of the voltage without the measurement and the communication with the remote node in our PoF system. For the accurate estimation, we have to consider the temperature tendency of our PoF system because the changes of the properties of the electric elements affect much to the estimation in the very small power circuit like our PoF system.

In this paper, we propose a model for estimating the voltage of the energy storage in a remote node of a PoF system in different temperature conditions of -25°C, 25°C and 70°C considering use in the outdoor environment. We demonstrate that the voltage of the energy storage can be estimated with high accuracy by considering the temperature characteristics of the photoelectric conversion elements, the energy storage element, and remote node controllers.

2. Proposed power supply system

The configuration of our PoF system is shown in Figure 1 (a). The devices to be driven are installed in the remote node. An optical power is supplied by a central controller and a LD in central office (CO) thorough a single-mode fiber of the access network. A capacitor in the remote node works as an energy storage. The controller estimates the voltage of the capacitor by referencing the environmental temperature at the remote node using an external information, for example, weather information. A photovoltaic converter (PVC) is installed at the remote node to convert the received light into electricity, which is stored in the capacitor. The remote node also has a micro processing unit (MPU) as a controller that processes commands from the CO. To minimize power consumption of the remote node during standby, the MPU goes into sleep mode and electrical devices are turned off. For communication by the remote node, a portion of the continuous downlink light from the CO is branched, modulated by the optical signal modulator (OSM), and returned to the CO.

Figure 1 (b) and (c) show the equivalent circuit model of a remote node equipped with PVC, energy storage, and an MPU. The model consists of two parts: Fig. 1 (b) considers when the light is supplied by the LD and the energy is being charged, and Fig. 1 (c) considers when the light is turned off and the stored energy is discharging. In Fig. 1, we assume an electric double layer capacitor (EDLC) with small size and large capacitance as the energy storage. The EDLC has equivalent series resistance R_{ESR} and leakage resistance R_{leak} in addition to the capacitance. In MPU sleep mode, the drain consists of a steady current, I_{CC}, and current I_{MPU} which varies depending on the voltage applied to the MPU. In Fig.1 (b), PVC output current is given as [5]

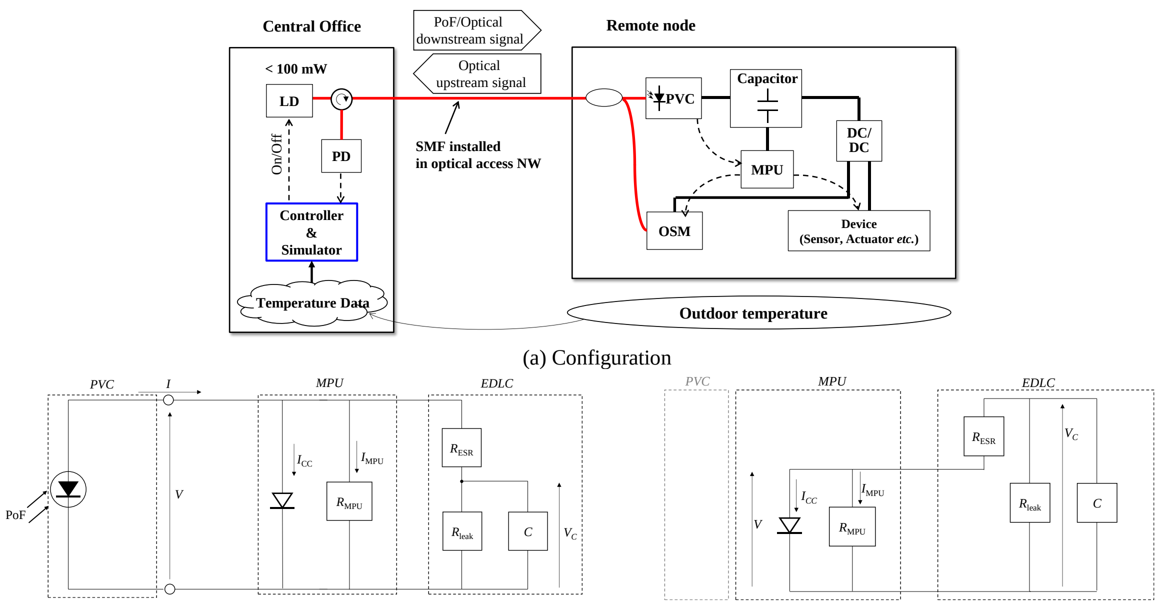
$$I = -J_0 \left\{ exp\left(\frac{eV}{nkT}\right) - 1 \right\} + \frac{\eta P e \lambda}{hc} \quad , \qquad (1)$$

where J_0, e, V, n, k, T, η, P, λ, h and c are the inverse saturation current, elementary charge, output voltage of PVC, diode ideal coefficient, Boltzmann's constant, temperature of PVC, quantum efficiency of PVC, the optical input power, the optical input wavelength, Planck's constant, and speed of light, respectively. In Fig. 2 (a), when the LD is ON, the voltage of the capacitor can be described as

$$\frac{dV_c}{dt} = \frac{R_{MPU}}{C(R_{MPU}+R_{ESR})}(I - I_{cc}) - \frac{R_{MPU}+R_{ESR}+R_{leak}}{CR_{leak}(R_{MPU}+R_{ESR})}V_c \quad , \qquad (2)$$

and when the LD is OFF, the voltage can be described as

$$\frac{dV_c}{dt} = \frac{R_{MPU}+R_{ESR}+R_{leak}}{CR_{leak}(R_{MPU}+R_{ESR})}V_c + \frac{R_{MPU}I_{cc}}{C(R_{MPU}+R_{ESR})} \quad . \qquad (3)$$



(a) Configuration

(b) Equivalent circuit while power charging (LD ON) (c) Equivalent circuit while power discharging (LD OFF)

Fig. 1. Proposed power supply system using power over fiber and equivalent circuit model of remote node.

3. Experimental Results

To confirm the accuracy of the capacitor voltage estimation, we fabricated a prototype remote node and compared the estimated results with the measured results with the prototype at -25°C, 25°C and 70°C. To estimate the capacitor voltage of the prototype, each parameter of the current I_{cc}, resistances R_{MPU}, R_{ESR}, R_{leak} and capacitance C of the electrical elements of the prototype were obtained separately by experiment. For the MPU and the capacitor, we derived the parameters from the measurement results of the current-voltage characteristics of it at each temperature. For the PVC, the parameters, J_0, n, η were derived from the measured results of the short-circuit current and open-circuit voltage of the PVC. Table 1 (a) shows the results of the parameter measurements of the electrical elements. From the Table 1 (a), we calculated the saturation voltage of the capacitor and employed the 90% value of it as the upper limit (V_H) of the voltage control of the capacitor, because the energy conversion efficiency of the PVC greatly decreases when the capacitor voltage is near of the saturation. The lower limit (V_L) of the voltage control was employed as the value of V_H – 0.5 in the experiment. Table 1 (b) shows the calculation results of the saturation voltage, V_H and V_L. To control the voltage of the capacitor, we turned off the LD when the estimation voltage reached to the V_H and turn on it when the voltage reached to the V_L. Figures 2 (a), (b), and (c) show the estimated and experimental capacitor voltages when the PVC receives 5 mW of light at -25°C, 25°C and 70°C, respectively. In Fig. 2, the maximum estimation error was 3.4% and 7.4% for charging and discharging, respectively. Comparing the result in Table 2 (b) and the measured result in Fig. 2 (c), the capacitor voltage estimation without consideration of temperature characteristics derives the V_H of 3.02 V as shown in the calculation result at 25°C, however the actual voltage at 70°C never reaches to the V_H because its saturation voltage is 2.76 V. It means that the estimation model with the consideration of temperature characteristics is mandatory for the voltage control of the power supply system combining power over fiber with low optical power and an energy storage installed in the outdoor field.

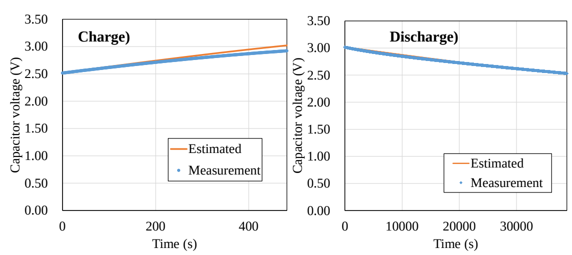
Table 1. Parameters to Control Proposed Power over Fiber System

(a) Parameters of Electrical Elements

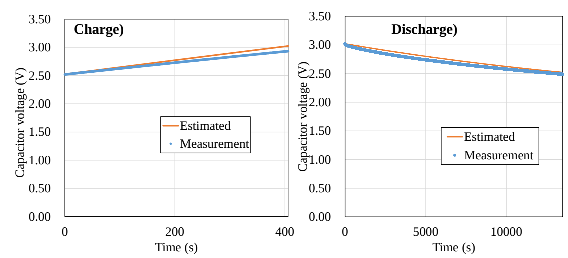
	-25℃	25℃	70℃
J_0 (A)	7.64×10^{-12}	8.07×10^{-10}	5.35×10^{-8}
η		0.096	
n		9.6	
C (F)	0.463	0.488	0.511
R_{ESR} (Ω)	15.8	4.36	1.63
R_{leak} (Ω)	5.40×10^{6}	2.05×10^{6}	4.90×10^{5}
R_{MPU} (Ω)	5.40×10^{4}	3.11×10^{5}	6.26×10^{5}
I_{CC} (A)	5.34×10^{-6}	3.82×10^{-6}	4.59×10^{-6}

(b) Parameters for Voltage Control

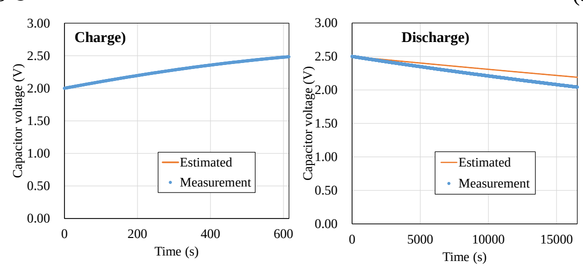
	-25℃	25℃	70℃
Saturation voltage (V)	3.76	3.35	2.76
V_H (V)	3.02	3.02	2.50
V_L (V)	2.52	2.52	2.00



(a) 25℃



(b) -25℃



(c) 70℃

Fig. 2. Estimation and experimental results.

4. Conclusion

We introduced a model for the power supply system combining Power-over-Fiber and a capacitor for energy storage that can accurately estimate capacitor voltage, which is the key to keep high energy conversion efficiency of PoF system. The model takes into account the temperature characteristics of the capacitor, a photoelectric converter and a micro processing unit in -25°C, 25°C and 70°C which are assumed to be used in an outdoor environment. We confirmed experimentally that the model can estimate the capacitor voltage with 3.4% and 7.4% estimation accuracy in charge and discharge phases in each temperature, respectively.

5. References

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