Article

Over-Temperature-Protection Circuit for LED-Battery Power-Conversion System Using Metal-Insulator-Transition Sensor

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Abstract: Extracting renewable energy from solar and wind energy systems, fuel cells, and tidal power plants requires DC distribution and energy storage devices. In particular, a metal-insulator-transition (MIT) sensor can be applied to the over-temperature-protection (OTP) circuit, to stop the LED-battery power-conversion system when over-temperature occurs. Recently, there have been instances of battery systems catching fire because of poor battery design, over-charging, over-voltage, cell balancing failure, and an inadequate battery management system circuit. For continuous stabilization using an LED-battery power-conversion system, a 450 Wh class battery system that can monitor the temperature of battery packs with an MIT sensor was developed in this study. Furthermore, an OTP circuit involving an MIT sensor to protect LED-battery power-conversion systems is proposed. According to the results, this approach is required to continuously perform the stabilization of LED-battery systems.

Keywords: metal-insulator-transition (MIT); over-temperature-protection (OTP); energy storage system (ESS); LED-battery; power-conversion

1. Introduction

Recently, LEDs have attracted considerable attention because of their brightness and efficiency [1–7]. In particular, they are widely used for street and road-lighting, while LED lighting systems powered by solar panels and lithium-ion batteries are actively used for outdoor-lighting. However, an LED-battery power-conversion system involves photovoltaic power generation, and there is a risk of a fire or an explosion occurring in the lithium-ion battery because of over-voltage, over-current, and/or over-temperature. Therefore, battery stability is a very important factor in renewable energy systems [8].

In this paper, an over-temperature-protection (OTP) circuit based on a metal-insulator-transition (MIT) sensor for LED-battery power-conversion systems with a lithium-ion battery involving photovoltaic power generation is proposed. The most important feature of this study is the use of an MIT sensor for temperature detection [9–18].

Thermo-couplers, which are widely used as conventional temperature sensors, have relatively good characteristics, but are very expensive [19]. In the case of inexpensive negative temperature coefficient thermistors, the resistance change is very moderate at fire-start temperatures, which is in the range of 80 to 100 °C, and so there is the problem that an additional op-amp circuit is required [20].

In this study, an MIT sensor, which is cheaper and has better characteristics than conventional thermo-couplers and negative temperature coefficient (NTC) thermistors, was used. According to the results, the OTP circuit that protects the LED-battery power-conversion system was required to continuously perform the stabilization of LED-battery systems.

2. Theory of MIT

Mott [9,10] was the first to propose a theory for MIT in 1949. His theory is that if the Coulomb energy between metals and free-electrons becomes very large, transition to an insulator can occur suddenly and discontinuously, without accompanying structural changes in the material.

Subsequent studies were conducted by Morin [11] and Imada [12], although they did not fabricate MIT-based devices. In 2000, Kim [13] theoretically analyzed the possibility of MIT at the Electronics and Telecommunications Research Institute (ETRI). Since 2004, Kim has developed MIT transistors made of vanadium oxide (VO_2) [14–17]. In 2007, Kim developed a critical temperature sensor (CTS), which is an MIT sensor in which the resistance rapidly decreases when the insulator is heated to the critical temperature [18].

Figure 1 shows the theory of MIT. The theory implies that a Mott insulator with uniform Coulomb energy can momentarily change its resistance to a value that corresponds to a metal when an electron escapes [13].

Figure 1. The theory of metal-insulator-transition (MIT) [13]: (a) Mott insulator and (b) Inhomogeneous.

Figure 2 exhibits the conventional and proposed temperature sensors. Among the representative conventional temperature sensors, thermo-couplers show relatively high accuracy for temperature detection, but are expensive [19], while NTC thermistors are inexpensive but characterized by resistance that changes slowly at temperatures above 70 °C [20]. In contrast, the MIT sensor used in this study is inexpensive (made of VO_2), and its resistance changes rapidly at temperatures above 70 °C [15,18].

Figure 2. Conventional and proposed temperature sensors: (a) thermo-coupler [19], (b) negative temperature coefficient (NTC) thermistor [20], and (c) MIT sensor [18].

Figure 3 displays the resistance change in a NTC thermistor and a MIT sensor according to temperature. Unlike the MIT sensor, the NTC thermistor does not exhibit a significant change in

resistance at 25 °C room temperature, and is practical, as 70–80 °C is the first-start temperature range at which a battery can catch fire. The problem with the NTC thermistor is that it is difficult to clearly detect the change in its resistance value at the fire-start temperature [20–22]. By contrast, the proposed MIT sensor's resistance decreases abruptly at a temperature of around 70 °C. This facilitates the accurate detection of a rise in temperature preceding the fire-start temperature and the prevention of fires and explosions in the battery [15,18].

Figure 3. Resistance variation according to temperature: (a) NTC thermistor [20–22] and (b) MIT sensor [15,18].

Figure 4 shows resistance measurement data at different temperatures for the MIT sensor invented at the ETRI. The resistance was evidently 372.1 kΩ at 70 °C and rapidly decreased to 44.49 Ω at 75 °C.

Figure 4. Resistance measurement data for the MIT sensor.

3. OTP Circuit Based on the MIT Sensor

Figure 5 shows the proposed lithium-ion battery system with an MIT sensor, while Figure 6 presents the proposed LED-battery power conversion system with an OTP circuit.

Figure 5. The proposed lithium-ion battery system with a MIT sensor.

Figure 6. The proposed LED-battery power-conversion system with an over-temperature-protection (OTP) circuit.

The MIT sensors can be placed at the desired position in the lithium-ion battery, and all the MIT sensors are connected in parallel. The proposed LED-battery power-conversion system in Figure 6 was designed to prevent the occurrence of explosions and fires because of over-temperature in the lithium-ion battery. It is based on the control of the flyback converter's output. Power generated from the solar cell charges the lithium-ion battery of the flyback converter, and the battery supplies power to LED modules #1 to #8 and the load (LOAD). The MIT sensors (MIT1 to MIT4) detect the temperature of a specific part of the lithium-ion battery, and the OTP circuit detects the reference voltage (V_{ref}) when over-temperature occurs. V_{ref} of the flyback converter controller is controlled to be 2.5 V. However, when over-temperature occurs, the voltage applied to the OTP circuit V_{cc} rises to 12 V. At this voltage, the flyback converter controller does not generate a gate signal, resulting in the operation of the converter being terminated.

Figure 7 shows details of the proposed OTP circuit of the LED-battery power-conversion system. The MIT sensors are connected in parallel, and the resistance of resistor a (R_a) and the MIT sensors divides the V_{cc} voltage, after which the resistances of resistor b (R_b) and resistor c (R_c) divide the V_{cc}

voltage again. The contact between R_a and the MIT sensor is applied to the emitter terminal of the NPN transistor, and the contact between R_b and R_c is applied to the base terminal of the NPN transistor. The MIT sensors have resistance R_{MIT} in the range of 1700 k Ω to 372.1 k Ω , at temperatures below 70 °C. Therefore, for the application of a voltage of 3 V to the base terminal of the NPN transistor, the operating conditions of the OTP circuit can be expressed as

$$\left(\frac{R_c}{R_b + R_c} - \frac{R_{MIT}}{R_{MIT} + R_a} \right) \times V_{cc} \geq 3[V] \quad (1)$$

where,

R_a : resistance R_a [Ω];

R_b : resistance R_b [Ω];

R_c : resistance R_c [Ω];

R_{MIT} : MIT sensor's resistance [Ω];

V_{cc} : voltage applied to the OTP circuit [V].

Figure 7. The proposed OTP circuit.

In this study, R_a , R_b , and R_c were set to 10 k Ω . Therefore, according to the voltage division law, the contact between R_a and the MIT sensors was almost 12 V, which was applied to the emitter terminal of the NPN transistor. The contact between R_b and R_c that was applied to the base terminal of the NPN transistor was 6 V.

The NPN transistor cannot be turned on up to a temperature of 70 °C. Consequently, the PNP transistor connected to the collector terminal of the NPN transistor can also not be turned on. Therefore, since the OTP circuit does not generate any voltage with capacitor C_a and diode D_a , V_{ref} is 2.5 V, which is generated by the flyback converter controller. At temperatures above 70 °C, the resistance of the MIT sensors decreases rapidly from 372.1 k Ω to 44.49 Ω . Therefore, the voltage at any point between R_a and the MIT sensors is almost 0 V. Consequently, the voltage applied to the emitter terminal of the NPN transistor is 0 V, and a voltage of 6 V is applied to the base terminal. The condition of Equation (1) is then satisfied, and the NPN transistor is turned on. This leads to $V_{cc} = 12$ V turning on the PNP transistor and C_a being charged at 6 V through resistor d (R_d).

The output through the cathode of D_a is around 6 V, resulting in the control circuit of the flyback converter having a reference voltage of 2.5 V or more. V_{ref} causes the gate voltage (V_{gate}) to become 0 V, and thereby terminates the charging of the lithium-ion battery.

4. Experimental Results

Table 1 reports the parameters of the circuit elements, and Figure 8 shows the experimental apparatus.

Table 1. Specifications and parameters of the LED-battery power conversion system.

Device	Quantity	Value
Solar Cell (LG Ltd., LG250SIC-23, Two Series Connections)	Maximum Voltage	29.9 V
	Maximum Current	8.27 A
Flyback Converter (Prototype)	Input Voltage	15–60 V DC
	Output Voltage	27 V DC
	Maximum Power	50 W
	Main Switch	IRF640, Fairchild
	Diode	DSSK28-01A, IXYS
	Main Transformer	PQ2625, TDK 20: 10, $L_{lk} = 25 \mu\text{H}$
18650 Li-ion Battery (Samsung SDI Ltd.)	Output Capacitor	2000 μF
	Operating Voltage	21–28 V DC
	Maximum Current	15 A
	Maximum Capacity	450 Wh
LOAD	Size	297 × 85 × 335 mm
		Non-inductive Bulk Resistance of 15 Ω
LED Module (LG Innotek Ltd., Eight Parallel Connections)	Operating Voltage	25–30 V DC
	Maximum Current	0.5 A
Over-temperature Sensor (ETRI, MIT Sensor)		120 nm thick VO_2 film on an AlN/Si substrate MIT temperature: 70 °C

Figure 8. Experimental apparatus.

Figure 9 shows the voltage and current waveforms of the main switch for an input voltage of 40 V and an output of 27 V/0.5 A, while Figure 10 shows the voltage and current waveforms at an input voltage of 40 V and an output of 27 V/1 A. The flyback converter was designed to operate in the input voltage range 15 to 60 V to match the output voltage of the solar cell, and it is evident that it operates in a discontinuous current mode.

Figures 11 and 12 show the waveforms of V_{ref} and the output current of the flyback converter (I_o) (0.8 and 1.5 A, respectively) when the temperature of the MIT sensor changed from a normal temperature to over-temperature, which is characterized by a sudden increase in V_{ref} . The over-temperature of 70 °C increases the reference voltage rapidly and reduces the output of the flyback converter to zero.

The waveforms of V_{ref} and I_o are shown for the temperature change sequence normal temperature → over-temperature → normal temperature.

V_{ref} is 2.5 V at normal temperature and 5 V at over-temperature. When the reference voltage reaches 5 V at over-temperature, I_o is cut off. Thus, the charging of the lithium-ion battery is terminated when over-temperature occurs.

Figure 9. Voltage (V_s) and current (I_s) waveforms of the main switch (input 40 V, output 27 V/0.5 A).

Figure 10. Voltage (V_s) and current (I_s) waveforms of the main switch (input 40 V, output 27 V/1 A).

Figure 11. Reference voltage (V_{ref}) and the flyback converter output current (I_o) when the temperature of the MIT sensor changed from normal to over-temperature (0.8 A).

Figure 12. Reference voltage (V_{ref}) and the flyback converter output current (I_o) when the temperature of the MIT sensor changed from normal to over-temperature (1.5 A).

Figure 13 shows the V_{gate} of S and the I_o waveform for an output current of 1.2 A when normal temperature changes to over-temperature. When over-temperature occurs, the duty cycle of V_{gate} decreases drastically, and I_o decreases from 1.2 to 0 A.

Figure 13. Gate voltage (V_{gate}) and flyback converter output current (I_o) when the temperature of the MIT sensor changed from normal to over-temperature (1.2 A).

Therefore, the proposed OTP circuit changes the V_{ref} of the flyback converter based on 70 °C, and performs the function of stopping the battery charging.

Figure 14 shows the V_{gate} of S and the I_o waveform when the over-temperature changes to normal temperature for $I_o = 1.2$ A. After the change, V_{gate} increases and I_o increases from 0 to 1.2 A. In particular, when the status changes back to normal temperature, I_o transiently increases to 2.4 A instantaneously, and then gradually decreases to 1.2 A.

Figure 15 shows the voltage (V_{LOAD}) and current (I_{LOAD}) waveforms for changes in the load (2.5 A). Clearly, V_{LOAD} (or battery voltage) is 27 V, even for a load of 15 Ω . Thus, it was confirmed that the proposed LED-battery power-conversion system stably follows load fluctuations.

Figure 14. Gate voltage (V_{gate}) and the flyback converter output current (I_o) when the temperature of the MIT sensor changed from normal to over-temperature (1.2 A).

Figure 15. Voltage (V_{LOAD}) and current (I_{LOAD}) waveforms for varying load (0–2.5 A).

5. Conclusions

An MIT-sensor-based OTP circuit for an LED-battery power-conversion system was proposed. The MIT sensor is cheaper than conventional thermo-couplers and NTC thermistors. An analysis of the characteristics of the MIT sensor showed that it had a resistance of 372.1 k Ω at 70 $^{\circ}\text{C}$, that rapidly decreased to 44.49 Ω at 75 $^{\circ}\text{C}$. An OTP circuit was proposed for expanding the MIT sensor. If the MIT sensor over-heats, the reference voltage of the OTP circuit is set to 5 V. Consequently, the main switch's gate signal in the flyback converter is turned off, resulting in the output of the converter being blocked. This terminates the charging of the lithium-ion battery.

Furthermore, an LED-battery power-conversion system was proposed, in which the output current of the flyback converter returns to normal when the temperature changes from over-temperature to normal temperature. The proposed LED-battery power-conversion system with OTP effectively suppresses the over-temperature generation of lithium-ion batteries for outdoor-lighting. This power-conversion system is expected to help enhance the stability of lithium-ion batteries in photovoltaic power and renewable-energy-based systems. The results of this study will lead to the provision of OTP for lithium-ion batteries, thereby helping to secure battery stability for electric vehicles.

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