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Control Strategy for Solar Energy-Saving Lamps for Optimized Energy Utilization and Sustainability of Operation Durability: Indonesia Case

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Control Strategy for Solar Energy-Saving Lamps for Optimized Energy Utilization and Sustainability of Operation Durability: Indonesia Case

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Abstract

To solve the electrification ratio issue, the Indonesian government has promoted the use of solar energy-saving lamps. This study proposes a control strategy that adopts current reference time-based profiling for solar energy-saving lamps. For optimal energy consumption, the current reference profile is determined according to users' daily energy requirements. From the aspect of user comfort, a gradual step reference profile is also introduced to provide a subtle change in lighting intensity level. The proposed control strategy can minimize energy consumption and optimize the operation durability of the system. The concept is verified by simulating four scenarios, the results of which demonstrate the effectiveness of the proposed control strategy. Computational simulation results indicate that Scenarios C and D which adopt the proposed time-based profiling can respectively reduce the daily energy consumption of the conventional control strategy by 47.14% and 39.79%, respectively. In terms of durability in providing electricity, both scenarios can continue to supply electrical power for two days without any solar irradiance. The proposed method can also improve customer service through the comfort provided in Scenario D.

Abstrak

Strategi Pengendalian Lampu Tenaga Surya Hemat Energi untuk Penggunaan Energi yang Optimal dan Ketahanan Durasi Operasi: Kasus Indonesia. Salah satu program Pemerintah Indonesia untuk mengatasi isu rasio elektrifikasi adalah dengan memperkenalkan lampu tenaga surya hemat energi. Makalah ini mengusulkan strategi kendali untuk lampu tenaga surya hemat energi dengan menggunakan strategi pengaturan profil arus referensi berbasis waktu. Untuk menghasilkan konsumsi energi yang optimal, profil referensi arus ditentukan sesuai dengan kebutuhan energi harian pengguna. Mempertimbangkan aspek kenyamanan pengguna, profil referensi undak dengan perubahan bertahap diperkenalkan untuk memberikan perubahan level intensitas pencahayaan yang lebih lembut. Strategi arus yang diusulkan dapat meminimalkan konsumsi energi dan mengoptimalkan durasi operasi sistem. Untuk memverifikasi konsep ini, empat skenario di sumulation untuk menunjukkan kefektifan strategi kendali yang diusulkan. Hasil simulasi menunjukkan bahwa Skenario C dan D yang mengadopsi profil berbasis waktu yang diusulkan dapat menghemat konsumsi energi harian sebesar 47,14% dan 39,79% dibandingkan dengan strategi kendali konvensional. Dalam hal ketahanan untuk menyediakan listrik, kedua skenario ini masih dapat bertahan menyediakan data listrik selama dua hari tanpa adanya radiasi matahari. Metode yang diusulkan juga dapat memperbaiki pelayanan ke pelanggan dalam hal kenyamanan pengguna yang dapat dipenuhi oleh Skenario D.

Keywords: control strategy, energy utilization, operation durability, solar energy-saving lamp

1. Introduction

Composed of over 17,000 islands, Indonesia is one of the largest archipelagos in the world. Unfortunately, the country's national electrification ratio is still less than 99.9% (as targeted in 2019) [1]. To solve the electrification issue, especially for remote areas, and thereby improve people's quality of life, the Indonesian government has introduced solar-based energy-saving lamps, which are known in *bahasa* as *Lampu Tenaga Surya Hemat* Energy (LTSHE) [2–3]. In 2018, LTSHEs contributed 0.37% (out of 98.30%) to the national electrification ratio. The largest contribution of 25.6% (out of the regional electrification ratio of 90%) was recorded in Papua Province [1].

Generally, an LTSHE consists of a set of photovoltaic (PV) modules, a control unit, a battery, and light emitting diode (LED) lamp(s). LED lamps are chosen because of their excellent energy efficiency, long operating life, and light control [4–5]. These advantages have prompted extensive research efforts to further investigate such lamp type from various aspects [6–8]. In an LTSHE system, the PV module harvests solar energy during the day. The harvested energy is controlled by the control unit to guarantee the maximum amount of energy for battery charging on the basis of the voltage–current characteristic of the PV module.

Numerous manufacturers have produced various types of LTSHEs. However, most of the products are operated using a manual ON–OFF mechanism, which heavily depends on human performance.

A simple control mechanism for a solar-based LED streetlight was proposed by Elsamman and Metwally [9]. In this proposed method, the ON and OFF durations of the lamp can be set on the basis of existing requirements. A different approach was proposed to ensure the match between the maximum power of the PV module and the LED lamp [10]. Other proposals focused heavily on how power quality is considered for system improvement [11-13].

As LTSHEs are mainly deployed in rural areas, user-friendliness is a highly necessary consideration. Existing control mechanisms are mainly focused on obtaining maximum power during the harvest of solar energy, which is then directly used in battery charging. No mechanism has been proposed with consideration of human comfort in line with technical design.

The current work focuses on the automatic control of LTSHEs such that they can be simply and easily operated by users without sacrificing their comfort. To optimize energy consumption, this study adopts a current reference time-based profiling strategy that enables automatic control on the basis of users' daily energy requirements. With consideration of the aspect of comfort, a gradual step reference (a combination of a ramp and a step reference) profile is also introduced to ensure a subtle change in lighting intensity level. Four scenarios are presented to verify and demonstrate the effectiveness of the proposed control strategy.

2. Methods

Proposed system. The proposed LTSHE system consists of four 3 W LED lamps and a USB port for mobile phone charging (Figure 1). The four lamps are operated in the same scenario and have the same light intensity level at all times. The USB port is used 2 h every day. The basic design of the system is tabulated in Table 1. The maximum electrical power capacity of the PV module in watt peak (Wp) is considered to ensure that the system can provide full power in 24 h for two days without solar irradiation (two days: autonomy service). For this purpose, a battery with a depth of discharge (DoD) of 70% and a capacity of 20 ampere hours (Ah) is utilized.

The solar PV module harvests solar energy and converts it to electricity to charge the battery during the daytime and thereby guarantee that the system can be utilized at night. The mechanism of battery charging is controlled by the charge controller, which is equipped with a maximum power point tracking (MPPT) control mechanism to obtain the maximum charging result.

Control scenario. A closed loop control mechanism is adopted to obtain the best automatic control system. It is represented as a block diagram in Figure 2. G_1(s), G_2(s), and G_3(s) represent the transfer functions of the controller, power converter, and LED lamps, respectively. As illustrated in Figures 1 and 2, the controller generates a switching reference signal on the basis of the error, which is easily calculated by subtracting I_{Act} (s) from I_{Ref} (s). For the controller, a direct feedback and a direct feedforward manipulation can be adopted to improve the common proportional integrator (PI) controller's performance [14].

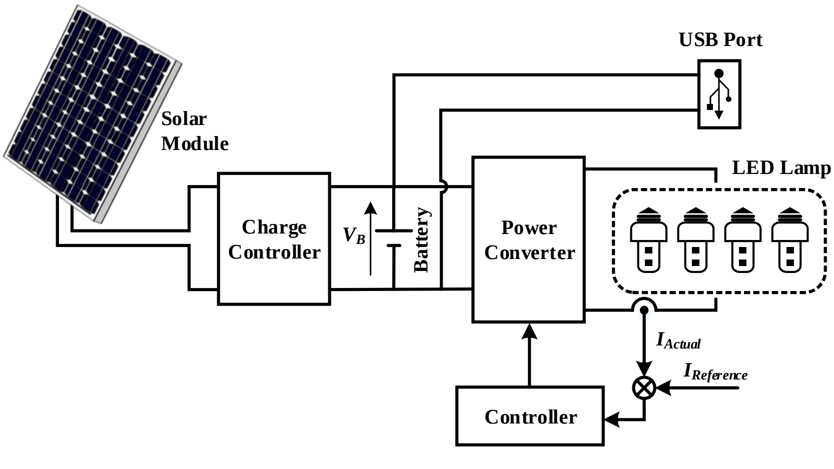


Figure 1. Proposed LTSHE System

Table 1. System Design Specifications

Description	Unit	Specification
PV Power	Wp	31.68
Performance Ratio	%	60
DoD	%	70
Battery Capacity	Ah	20
Battery Voltage	V	12

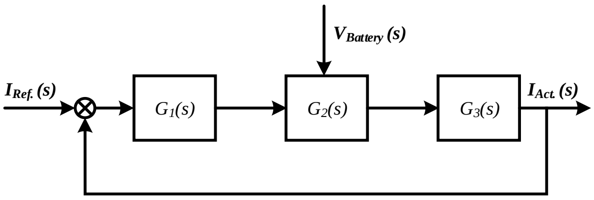


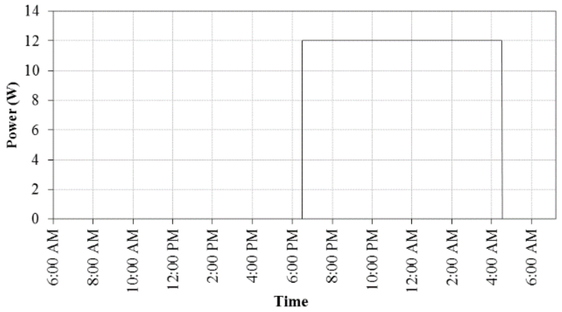
Figure 2. Control Block Diagram

The common LTSHE system generally adopts Profile A, as depicted in Figure 3 (a). Profile A is similar to the manual switch operation mode. In this mode, the user must manually turn on and turn off the switch. When the switch is turned on, the lamp directly consumes power at the maximum level.

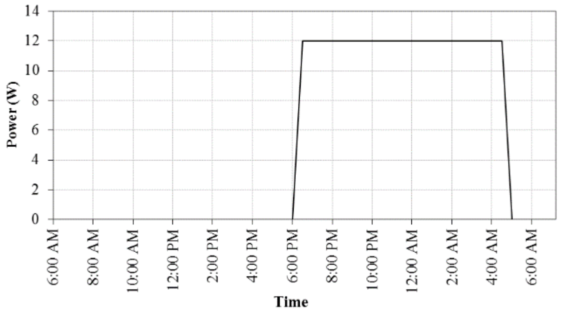
A gradual scenario, such as Profile B (Figure 3 (b)), can be adopted to ensure vision comfort. The value of the ramp profile can be adjusted according to the user's convenience requirement. Assume that the duration of the maximum power level of Profile B is that same as that of Profile A; in such a case, Profile B consumes slightly more energy than Profile A. In this regard, the trade-off between user comfort and energy consumption should be carefully considered.

Profile C is introduced to further achieve optimal energy consumption. As shown in Figure 3 (c), Profile C involves a non-flat power level that is customized according to user requirements. This profile can be easily adjusted to accommodate users' preferences. The combination of Profiles B and C results in efficient energy consumption without sacrificing user comfort. Such combination is reflected in Profile D, which is expected to be the best solution for this system.

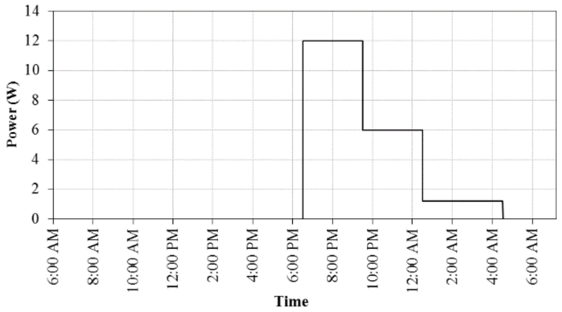
Computational simulation. Several computational simulations are performed in MATLAB® Simulink to verify the proposed control strategy. The simulation block diagram is illustrated in Figure 4. The PV module is modeled using the standard PV array block available in MATLAB® Simulink for modeling typical PV array characteristics (Figure 5) [14].



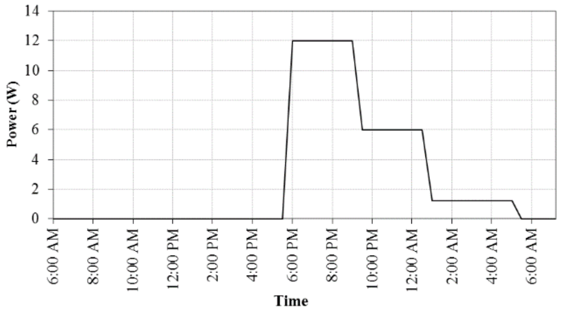
(a) Profile A



(b) Profile B



(c) Profile C



(d) Profile D

Figure 3. Control Profiles

The incremental conductance technique is selected for the MPPT controller [9, 14]. This technique is based on the fact that the maximum point is obtained if the value of dP/dV equals zero, as shown in Figure 5. According to Ohm's law, the following correlation can be obtained:

$$dP/dV = I + V\,(\Delta I/\Delta V) \tag{1}$$

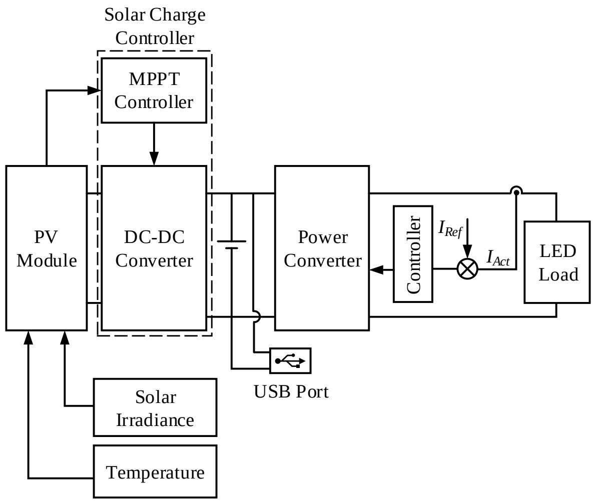


Figure 4. Simulation Block Diagram

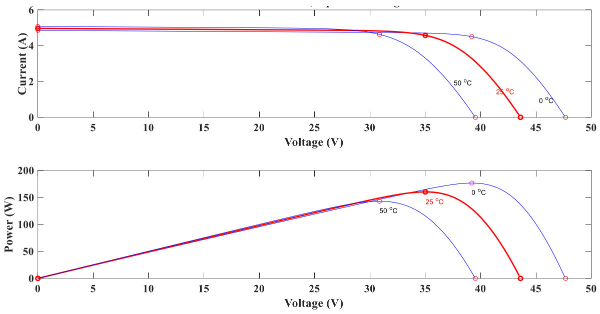


Figure 5. Typical PV Array Characteristics

The MPPT is determined as follows by using the incremental conductance method:

$$I + V(\Delta I/\Delta V) = 0 \text{ at the maximum power point} \tag{2}$$

$$I + V(\Delta I/\Delta V) > 0 \text{ left of the maximum power point} \tag{3}$$

$$I + V(\Delta I/\Delta V) < 0 \text{ the maximum power point} \tag{4}$$

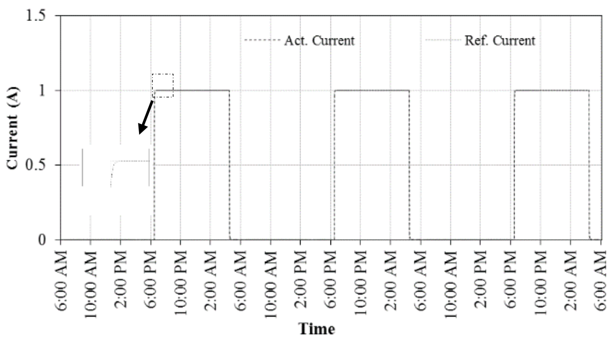
Then, Equatios (1)–(4) can be implemented as the control basis of the solar charge controller to determine whether it should increase or decrease the operating voltage to reach the maximum power point.

3. Results and Discussion

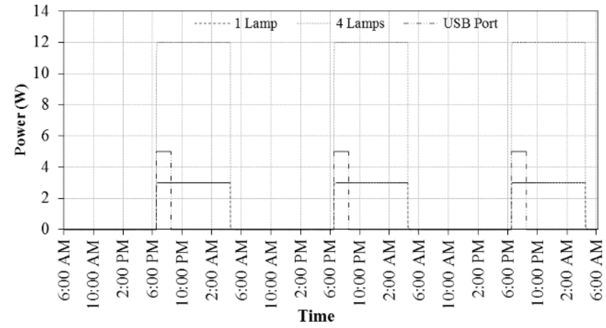
The proposed control strategy is verified on the basis of four operation scenarios. The scenarios adopt the four profiles described in the previous chapter. Scenario A takes Profile A as the current reference. Here, the LTSHEs are similar to the common LTSHE products in the market. They are turned ON and OFF at determined times, as illustrated in Figure 6. In this case, the lamps are turned on at 6:30 PM and then turned off at 4:30 AM the following day, as indicated in Figure 6 (b). The USB port is assumed to be operating for 2 h (from 6:30 PM to 8:30 PM).

The main advantage of this control strategy is its simplicity and easy implementation. A simple conventional PI controller can be adopted to improve system performance. As illustrated in Figure 6 (a), the actual current can follow the reference current well. Figure 6 (c) shows the daily charging and recharging performance. The battery is maintained with a minimum level of charge relative to its capacity, that is, its state of charge (SOC) is 30%.

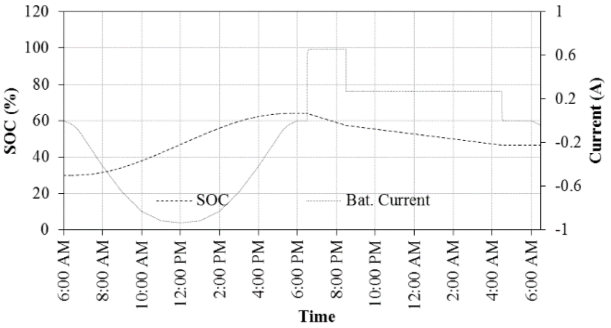
Designed for human comfort, Scenario B adopts Profile B, as shown in Figure 7. The crucial issue in this scenario is how the current is controlled during ramp time. The proposed control method in [14] can be used to solve this issue. In this case, the ramp-up time is set from 6:00 PM to 6:30 PM. Then, the ramp-down time is set from 4:30 AM to 5:00 AM. Similar to that in the previous scenario, the USB port in Scenario B operates for 2 h.



(a) Current control

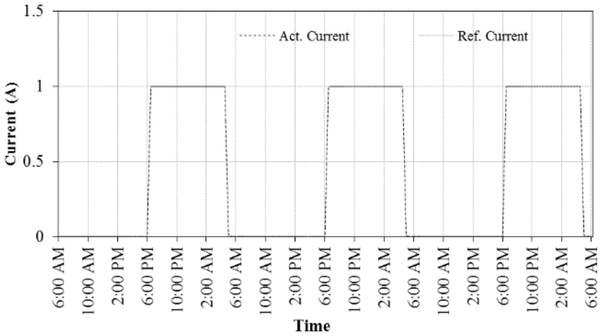


(b) Power

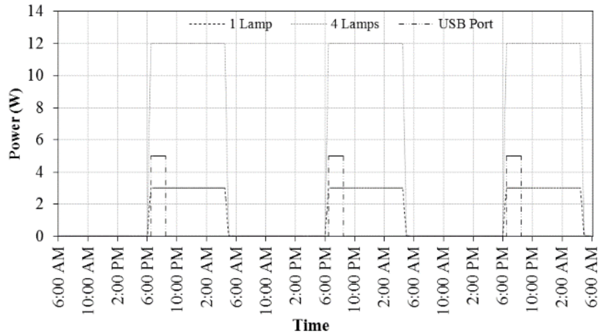


(c) Daily battery charging and recharging

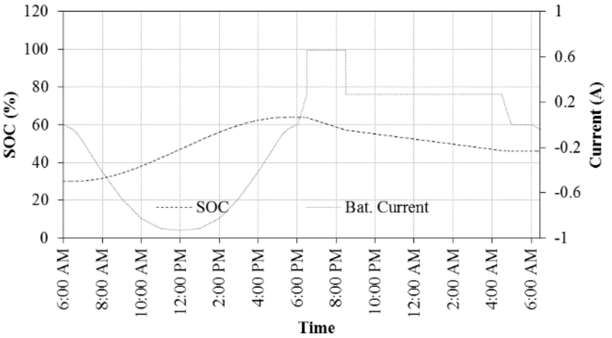
Figure 6. Scenario A



(a) Current control



(b) Power



(c) Daily battery charging and recharging

Figure 7. Scenario B

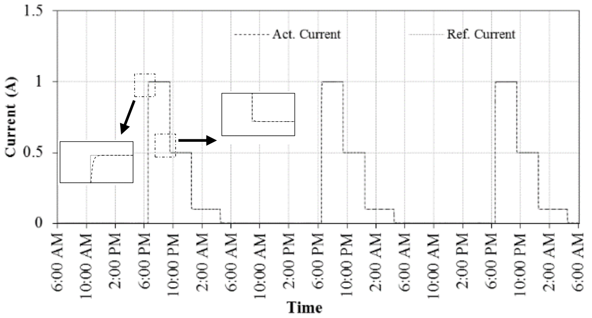
For optimized energy consumption, Scenario C applies Profile C, as depicted in Figure 8. In addition to its optimized energy consumption, this scenario has the superiority of Scenario A. As illustrated in Figure 8 (a), the actual current can track the reference current well for the step-up and step-down references. The operation of the components is detailed in Table 2. The operation duration of the USB port is the same. Each LED lamp has four states of varying intensities.

In terms of energy consumption, the SOC value of Scenario C at the end of a daily cycle is much higher than that of Scenarios A and B, as depicted in Figure 8 (c). This result indicates that by regulating the operation time of the lamps, the energy consumption can be controlled as well.

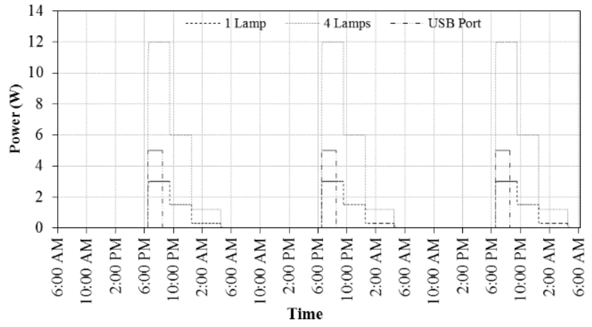
Based on the simple manipulation of the operation duration listed in Table 2 and the maximization of the advantage of Scenario B, Scenario D is proposed to achieve high energy savings while ensuring user comfort. As illustrated in Figure 9, the advantages of Scenarios B and C are realized simultaneously in Scenario D.

Table 2. Duration of Operation in Scenario C

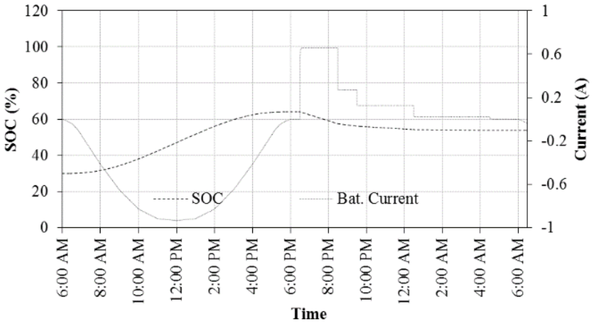
Time	Component	Intensity (%)	Power (W)
4:30 AM–6:30 PM	LED Lamp	0	0
6:30 PM–9:30 PM	LED Lamp	100	3.0
9:30 PM–0:30 AM	LED Lamp	50	1.5
0:30 AM–4:30 AM	LED Lamp	10	0.3
7:30 PM–6:30 PM	USB Port	-	0
6:30 PM–7:30 PM	USB Port	-	5



(a) Current control



(b) Power



(c) Daily battery charging and recharging

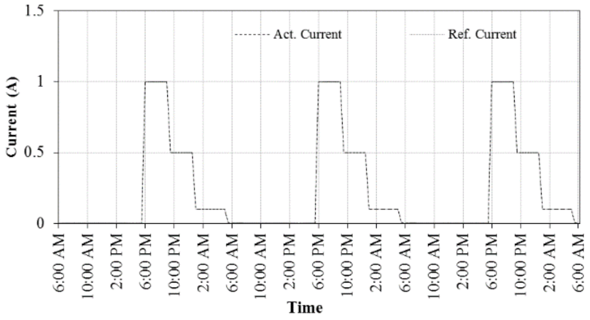
Figure 8. Scenario 2

The daily energy consumption is calculated by integrating the power waveforms in Figures 6–9 as follows:

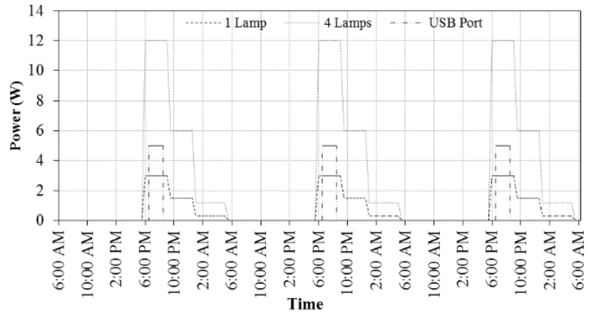
$$E = \int_{t_0}^{t_1} P(t)dt \qquad (5)$$

where E is the energy consumption, $P(t)$ is the power function represented by the power waveform of each scenario, and t_0 and t_1 respectively denote the initial time and final time of integration. In obtaining the daily energy consumption, the value of $t_0 - t_1$ equates to 24 h, which represents one day of operation.

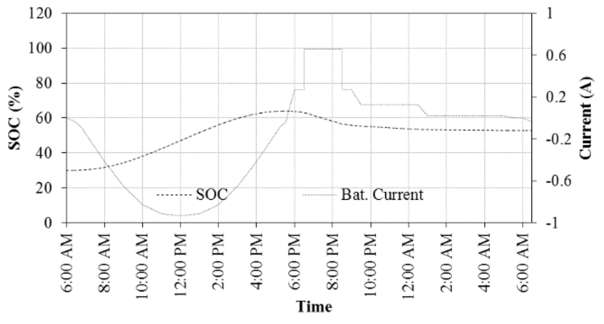
Relative to the conventional control strategy, Scenario D provides superior user comfort and reduces energy consumption by more than 39% (Table 3). If energy efficiency is only the main constraint, then Scenario C is the best choice. If comfort is considered, then Scenario D should be selected as the best solution.



(a) Current control



(b) Power

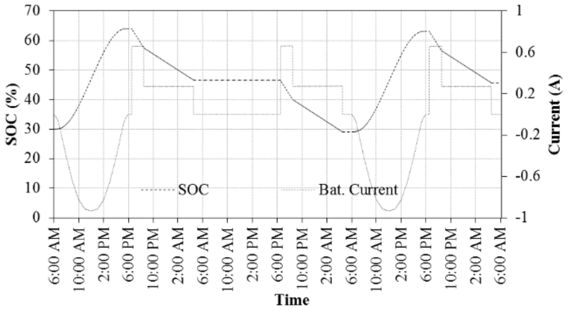


(c) Daily battery charging and recharging

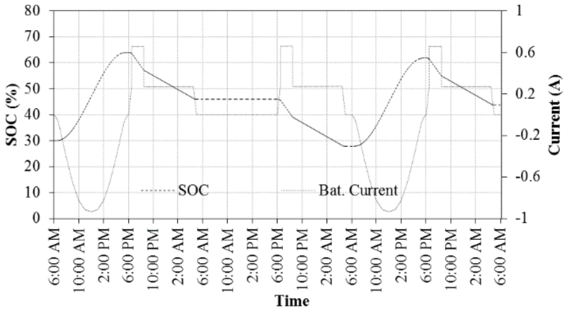
Figure 9. Scenario D

Table 3. Daily Energy Consumption

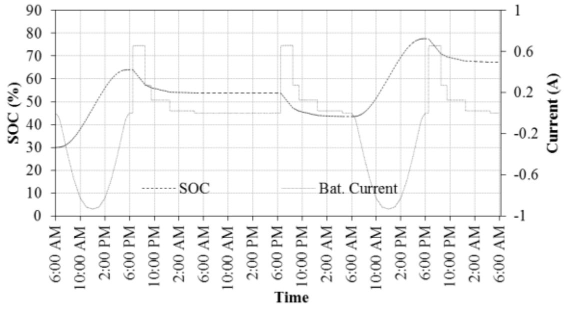
Scenario	Energy Consumption (Wh)			Energy Saving (%)
	LED	USB	Total	
A	120.13	10.00	130.13	0.00
B	125.96	10.00	135.96	−4.48
C	58.78	10.00	68.79	47.14
D	68.36	10.00	78.36	39.79



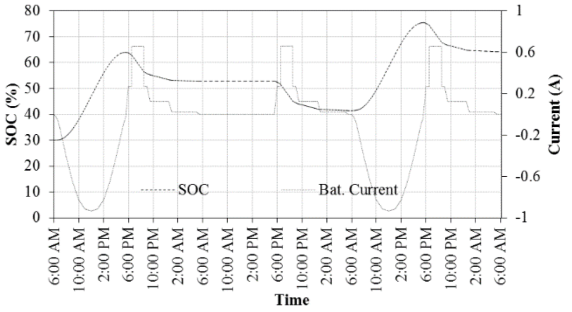
(a) Scenario A



(b) Scenario B

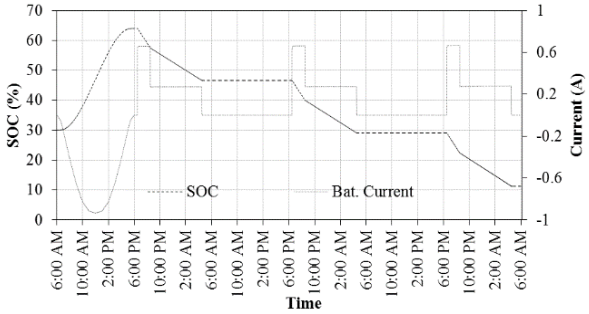


(c) Scenario C

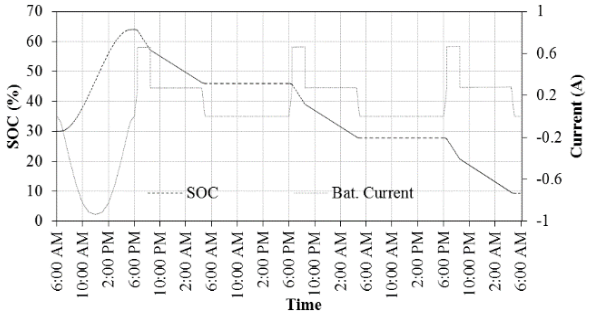


(d) Scenario D

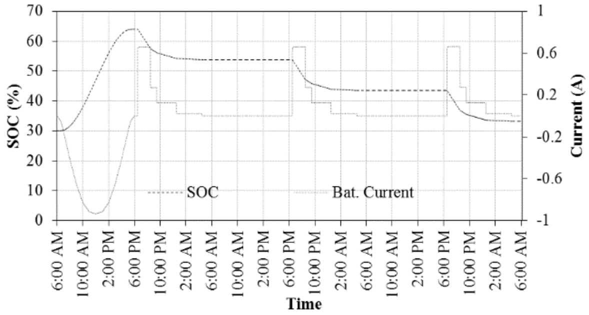
Figure 10. 1-Day Autonomy



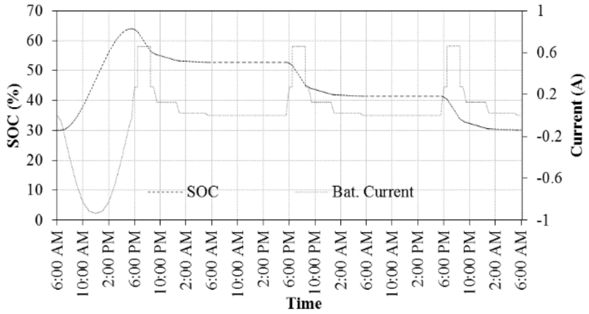
(a) Scenario A



(b) Scenario B



(c) Scenario C



(d) Scenario D

Figure 11. 2-Day Autonomy

Another important aspect that should be considered is the durability of the system in providing electricity in cases in which solar energy cannot be harvested well. Solar energy is highly sensitive to daily weather conditions. In rainy season, sun irradiation may not always be available during the daytime. 1-day autonomy and 2-day autonomy cases are simulated to check the capability of all scenarios (Figures 9 and 10, respectively). In the 1-day autonomy case, one day without sun irradiation is assumed. All scenarios can still provide electricity to the loads. However, if solar energy cannot be harvested in two consecutive days, then only Scenarios C and D can provide electricity.

4. Conclusions

A novel control strategy for solar energy-saving lamps was proposed. The proposed control strategy adopts a current reference time-based profiling scheme. The proposed control strategy can minimize the energy consumption and optimize the operation durability of the system. The proposed method can also improve services by ensuring human comfort.

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