Three Port Converter for Public LED Lighting System

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Abstract. *The objective of this research is to present a stand-alone solar power LED lighting system based on a bidirectional DC/DC convert circuit. A non-isolated bidirectional converter is derived from the unidirectional DC/DC converters. The converter is operated in two modes; buck mode operates for charging the battery during the day, and boost mode operates for supplying energy to an LED at night time. The converter is controlled by a PWM signal in accordance with the controlled switching operation for bidirectional power flow. Simulation and experimental results from the 10W prototype are provided to verify the theoretical analysis.*

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1. Introduction

Due to the steadily reducing energy sources and increasing concerns about environmental pollution, the renewable energy are gaining more importance. In the last 20 years, photovoltaic (PV) sources have become increasingly popular because PV systems do not create pollution and highly reliable, which is mainly due to the decreasing costs and prices [1-3].

The public lighting system has been used in newly built urban roads and remote rural areas without an electricity network, because of easy installation and modularity. [4]. The system generates energy from sunlight by PV panel during daytime, and illumination load only works at night, therefore a battery is adopted for energy storage. The system also needs a long life and environmental illumination source, so they have made LEDs one of the best solutions for lightning [5-7]. Fig.1. presents the conventional solar LED street lighting system that is composed by a PV panel in order to charge the batteries during the day through the converter number 1. During the night, the energy stored in the battery supply the LEDs lamp through the converter number 2. Therefore, two converters are required in this structure.

Another structure of public lighting system is shown in Fig. 2. Only one module of a bidirectional DC-DC converter is used to flow the power in different direction depend on time period. In [8], a three-port bidirectional converter was presented, although this converter is suitable for solar lighting application, it is inappropriate to use for high voltage LED. A PV driver for stand-alone lighting system was presented in [9], although this converter can provide for high voltage LED, but it can get complicated control system due to multiple power switches.

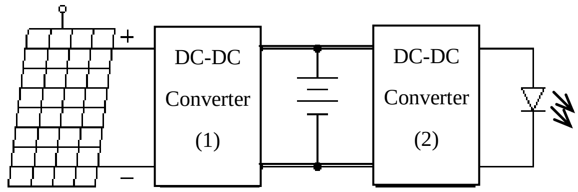


Fig.1 Conventional PV lighting system

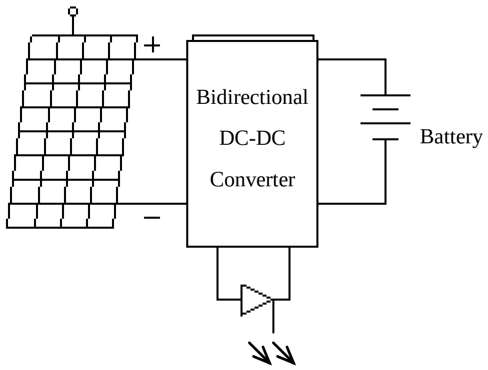


Fig.2 PV lighting system with a three-port converter

In this paper, the bidirectional buck-boost converter is presented. The battery charging circuit is a buck converter and discharging circuit is a boost converter. The converter is controlled by PWM signal in accordance with the controlled switching operation for bidirectional power flow. The analysis is described in the following sections.

2. Circuit Operation

The proposed converter structure is shown in Fig. 3, it can operate in two mode. When the battery is charged, the converter operates in buck mode and the switch S_1 and S_3 are turned off. The PWM technique is used to control the switch S_2. When the battery is discharged, the converter operates in boost mode and the switch S_1 is turned on while switch S_2 is turned off. The PWM technique is used to control the switch S_3.

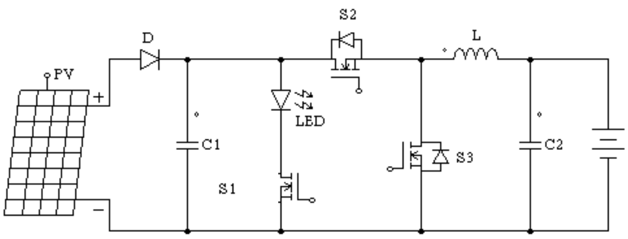


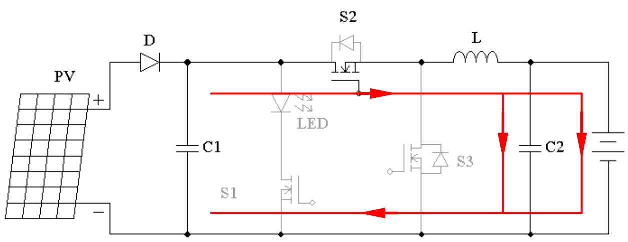
Fig.3 Proposed bidirectional converter of PV lighting system.

2.1 Buck mode

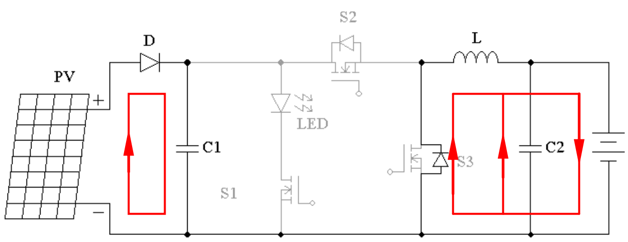
The equivalent circuit of the proposed converter in buck mode (charging) is shown in Fig. 4. The key waveforms of converter in buck mode are introduced in Fig 5. The operating principle in continuous conduction mode (CCM) is described as follows:

Stage 1: [t_0-t_1]: At t_0, the switch S_1 and S_3 are turned off, and switch S_2 is turned on. The current flows through inductor L. The current of inductance L will increase linearly. The capacitor C_2 and battery are charged by PV energy source.

Stage 2: [t_1-t_2]: In this mode, all three power switches are turned off. The body diode of S_3 conducts. The energy stored in the inductor L and the capacitor C_2 are released to charge the battery.



a. Stage 1



b. Stage 2

Fig. 4 Equivalent of circuit diagram for buck mode

By applying the volt-second balance on the inductors, can derive the steady-state output voltage gain as:

$$\frac{V_{Batt}}{V_{PV}} = D_{S2} \quad (1)$$

; where D_{S2} is duty cycle of switch S_2

V_{Batt} and V_{PV} are battery voltage and PV supply voltage consequently.

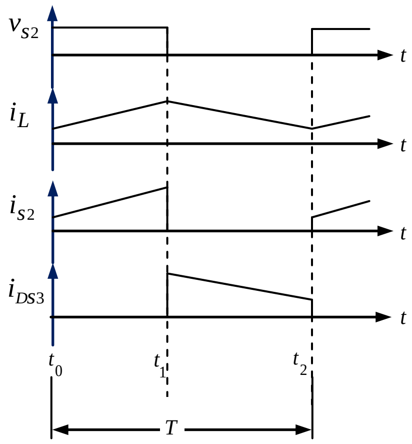


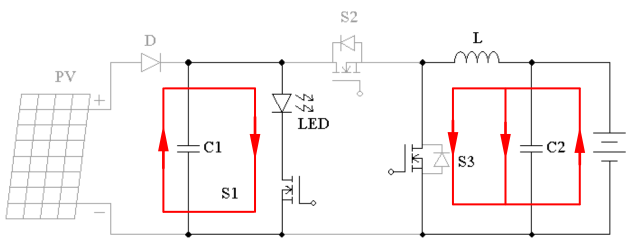
Fig.5 Key waveform of buck mode

2.2 Boost mode

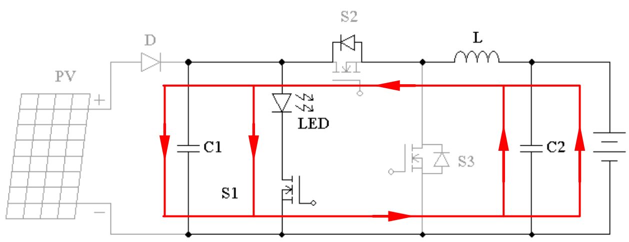
The equivalent circuit of the proposed converter in boost mode (discharging) is shown in Fig. 6. The operating principle in continuous conduction mode (CCM) is described as follows:

Stage 1: [t_0-t_1]: The power switch S_1 and S_3 are turned on, and the switch S_2 is turned off. The current from battery flows through inductor L and also charges to capacitor C_2. The energy stored in the capacitor C_1 is discharged to the LED.

Stage 2: [t_1-t_2]: At t_1, the switch S_3 is turned off while the switch S_1 is still turned on. The energy stored in the inductor L and the capacitor C_2 are released to load LEDs and capacitor C_1.



a. Stage 1



b. Stage 2

Fig.6 Equivalent of circuit diagram for boost mode

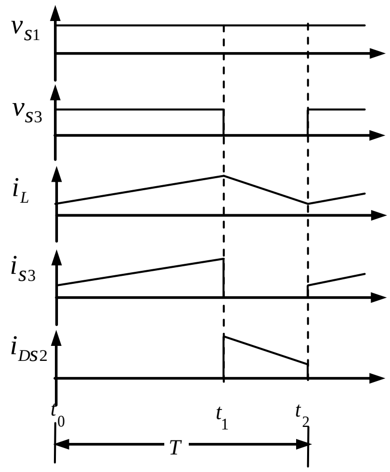


Fig.7 Key waveform of boost mode

By using the voltage-second balance principle, the voltage gain in this mode is obtained as

$$\frac{V_{LED}}{V_{Batt}} = \frac{1}{1-D_{S3}} \quad (2)$$

; where D_{S3} is duty cycle of switch S_3

V_{LED} is a positive voltage applied across the LEDs

3. Design Parameters

The dominant component for the proposed converter is selected especially based on their operating conditions. The selection of the components is presented below:

3.1 Inductors

Since the converter is operated in 2 modes, the inductor design each condition must be satisfied. The inductor must be designed small enough to transfer power to battery in buck mode, and large enough to transfer power to load LED when operated as a boost converter.

To facilitate the CCM condition under buck mode, the minimum inductance value must be satisfied

$$L_{min\_buck} \geq \frac{(1-D_{S2})R_B}{2f} \quad (3)$$

; where R_B is the equivalent load in the battery

f is a switching frequency

To maintain the CCM condition under boost mode, the minimum inductance value must be satisfied

$$L_{min\_boost} \geq \frac{D_{S3}(1-D_{S3})^2 R_L}{2f} \quad (4)$$

; where R_L is a resistance of LED string circuit

Since the inductor value of two operating mode must be obtained, then the intersection of two equations (3) and (4) gives an inductor value as

$$L_{min} \geq \frac{(1-D_{S2})R_{BD}}{2f} \quad (5)$$

; where R_{BD} is the equivalent load in the dead battery (Low voltage battery)

3.2 Capacitors

The consideration for selecting the capacitor C_1 in boost mode and C_2 in buck mode was the size of ripple voltage.

The minimum capacitance of C_1 can be determine by

$$C_1 \geq \frac{D_{S3}}{R_L f \frac{\Delta V_o}{V_o}} \quad (6)$$

; where V_o is an output voltage across the LED string

The minimum capacitance of C_2 can be determine by

$$C_2 \geq \frac{1-D_{S2}}{8Lf^2 \frac{\Delta V_{OB}}{V_{OB}}} \quad (7)$$

; where V_{OB} is an voltage drop across a battery

3.3 Battery

The battery size is determined by the energy requirements of the load LEDs (E_{total}). The daily required energy from battery in Watt-hour/day and the days of autonomy is the determination of battery size. The Depth of Discharge (DoD) of the battery measures how deeply the battery is discharged. DoD is defined as the capacity that is discharged from a fully charged battery, divided by battery nominal capacity. The Ampere-Hour capacity of the battery is calculated by;

$$Ah = \frac{E_{total} \times Days\ of\ \ Autonomy}{DoD \times V_{Battery}} \quad (8)$$

; where $V_{Battery}$ is the battery nominal voltage

In order to maximize cycle life, lead acid battery systems are sized for 50% DoD [10].

3.4 Solar Panels

Difference size of PV panels will produce difference amount of electric power. To find out the size of PV panels, the total peak watt (Wp) produced needs. Total Watt peak rating is calculated using the energy required to be produced from the solar PV modules and the panel generation factor (in Thailand it is 3.43) [11]. The Energy required from PV modules can be calculated by multiplying peak energy requirement in kW h/day times 1.3 (the energy lost in the system) to get the total kWh/day which must be provided by the panels.

$$Wp = \frac{E_{total} \times 1.3}{3.4} \tag{9}$$

4. System Framework

The stand-alone solar power LED lighting system with bi-directional DC/DC converter is shown in Fig.8.

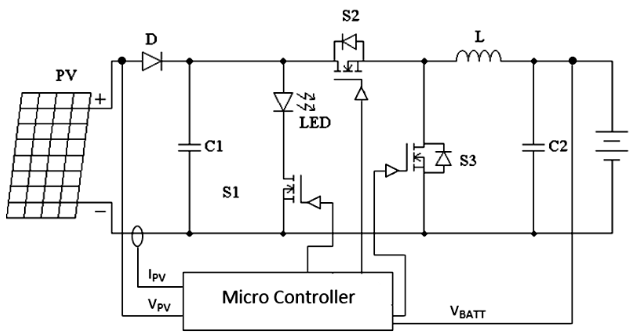


Fig.8 The LED lighting system

The framework consist of a DC converter function and a controller function for operating of a converter. The proposed converter is composed by three switches S_1, S_2 and S_3. For S_2 and S_3 are paralleled with freewheeling diode which is to conduct current in the opposite direction to the switch. The controller algorithm is shown in Fig.9. It's start by reading PV voltage and current. The PV power is obtained by finding the product of current and voltage. If the PV power is lower than 5W and the electric potential difference of the battery is higher than 11V, the converter is operating in boost mode. If the PV power is not lower than 5W and the battery voltage is lower than 13.2V, the converter is operating in buck mode.

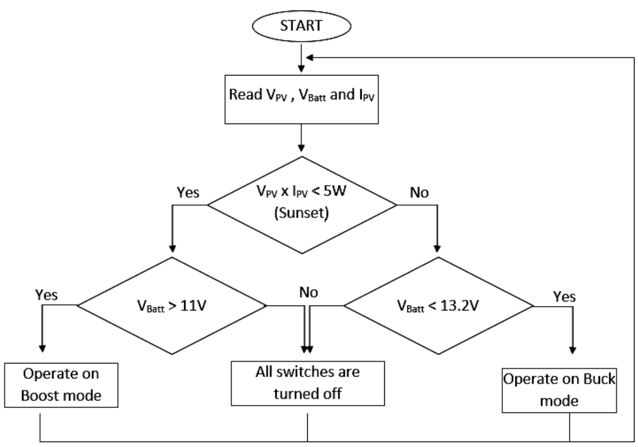


Fig.9 Flowchart of a controller algorithm

For 10 Watts LED lighting load is assumed to be powered 8 hours/day. The main specifications and parameters of the prototype converter are got by using (5), (6), and (7). The parameters are shown in Table 1.

Parameters	Value (Unit)
Inductor L	80uH
Capacitor C1	22uF
Capacitor C2	150uF
Switch S1	TIP31C
Switch S2 and S3	STP105N3LL, 3.5mΩ @40A,10V
Switching Frequency	20kHz

Table 1 Proposed converter parameters

The battery is a 12V Lead-acid type. Two autonomous days are adequate for street lighting applications. Using Eq. (8), the standard 12V, 35Ah battery will be adequate for this lighting application. The selected PV panel having the specifications listed in Table II.

Electrical Data	Value
Maximum Power (P_{max})	40W
Voltage at Pmax (V_{mpp})	17.5V
Current at Pmax (I_{mpp})	2.29A
Open Circuit Voltage (V_{oc})	21.88V
Short Circuit Current (I_{sc})	2.46A

Table 2 PV specifications

5. Experimental Verification

In this section, the converter simulation models without loss of parameters and a prototype circuit are presents. Fig.10, A prototype of bidirectional converter is shown. The control algorithm for all 3 switches is executed by a PIC16F877A microcontroller [12].

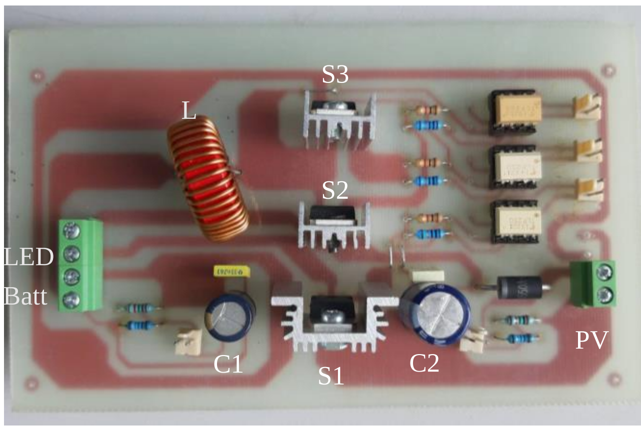


Fig.10 Prototype of proposed circuit

5.1 Buck conditions

By varying duty cycle with constant resistive load of 50 Ω. The relation between V_{in} and V_{out} of converter in buck operation is shown in Fig.11. The simulation result with 0.5 duty cycle is plotted together in the case where the value of D=0.8 experimental result is located. The simulation and experimentation results show that V_{out}/V_{in} increase according to the increase of duty. Its ratio value is always less than 1.

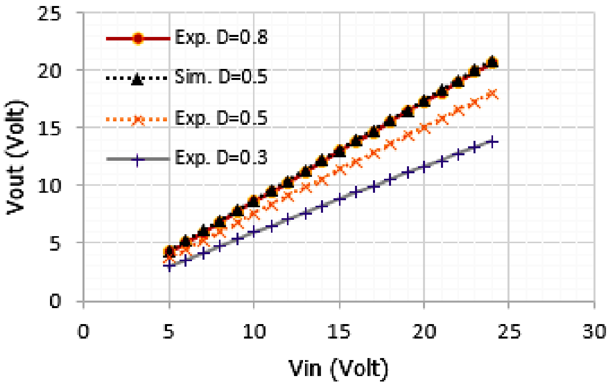


Fig.11 The relationship between V_{in} and V_{out} in buck mode

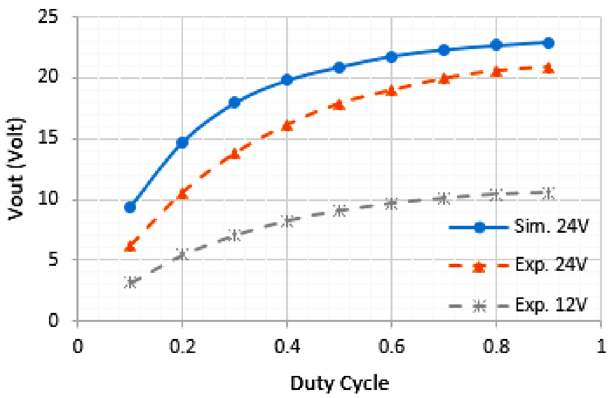


Fig.12 Vout vs Duty cycle in buck mode

Fig.12. show the curve of V_{out} and Duty cycle at difference input supply voltage. The conversion efficiency for the converter is determined by measuring input and output voltage and current using a multi-meter. The experimental result shows the converter efficiency obtaining 82% at around 10W.

5.2 Boost conditions

In this conditions, a 12V simulation and multiple input voltage experimental was tested. Fig.13 depict the change of V_{out} when duty cycle is varied with constant resistive load of 50 Ω.

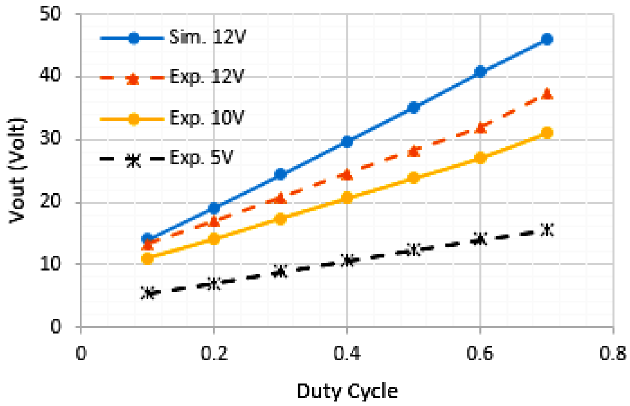


Fig.13 V_{out} vs Duty cycle in boost mode

While doing test, the resulting efficiency of the converter at the 10W target was measured to 85%.

5.3 Lighting conditions

Let the LEDs array fed by the battery source be composed by a string of two LEDs in series, then connect each 3 string in parallel. The illuminators be suspended at a height of 3.00 m. Fig.14 show the LED connections and Fig.15 depict an Illuminance curve.

Parameters	Value
LED technology	48 pcs COB chips
Forward supply	DC 12V
Color temperature	8,000K
Brightness	300Lumens
Input power	12V x 0.13A = 1.6W

Table 3 an LED characteristics

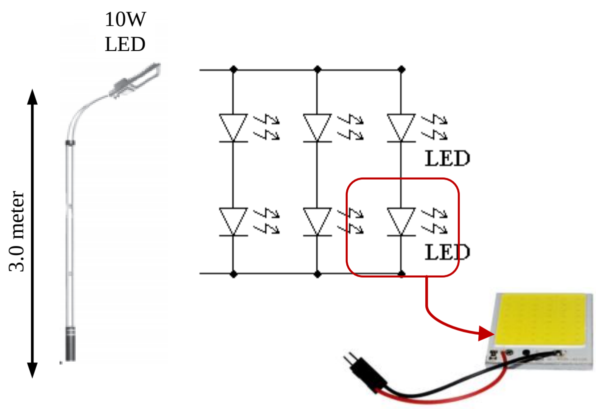


Fig.14 LED QL-4305-4C12B string connections

To reduce switch conduction loss, the switch S_1 should be driven in PWM methods instead of linear controlled.

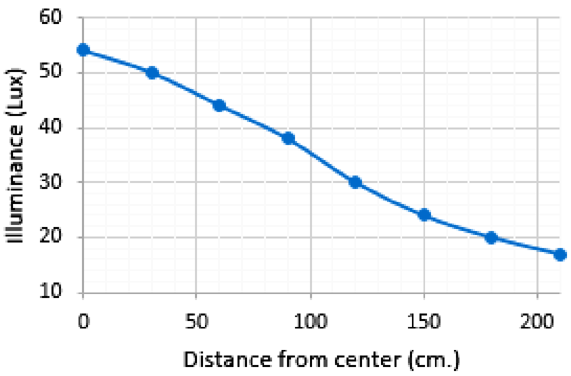


Fig.15 an illuminance curve

In Fig. 15, the results of the experiments indicate that the average illuminance of 3 meters high of LED strip lighting was 30 lux.

5.4 Battery charging conditions

The battery is charged during the day, and later the energy charged is discharged to provide energy for LED lighting in the night. In the test, a PV panel with P_{max} = 40W connects to lead-acid battery of 12V. In Fig.15, the comparison of power between PV cell and battery while the converter operating in buck mode with a P&O MPPT configuration is presented.

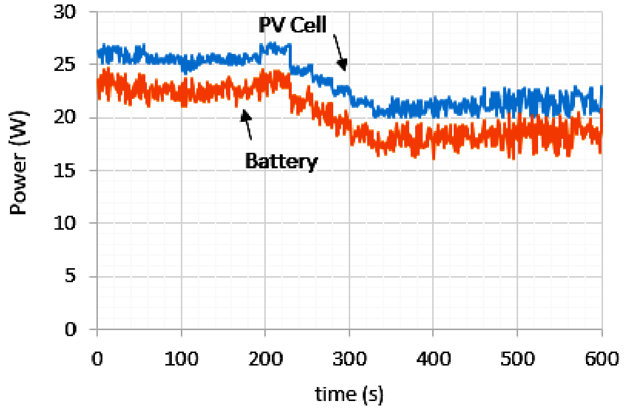


Fig.15 Power production curve.

6. Conclusion

In this paper, a bidirectional converter for standalone solar LED lighting system was presented. A non-isolated bidirectional converter is derived from the unidirectional DC/DC converters. The converter is operated in two modes; buck mode operates for charging the battery during the day, and boost mode operates for supplying energy to an LED at night time. Using the MOSFET body diode for transferring power instead of separate diode is convenient to make converter circuit. The converter proposed circuit was analyzed and proved by a 10W prototype. The experimental result showed the correct operation.

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Biography

Leardpan Piansangsan was born in Bangkok. received his B.S. degree in Electrical Engineering from King Mongkut's University of Technology North Bangkok, Thailand in 2005; his Ph.D. in Engineering from the Mahasarakham University, Thailand, in 2020. He is presently working as a lecturer in the Department of Electrical Engineering, Pitchayabundit College, Thailand. His current research interests include power converters and power generation.