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Modified SEPIC Converter Performance for Grid-connected PV Systems under Various Conditions

Rizky Ajie Aprilianto^{*1}, Subiyanto², Tole Sutikno³

^{1,2}Department of Electrical Engineering, Universitas Negeri Semarang, Semarang, Indonesia

³Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

*Corresponding author, e-mail: rizkyajiea@gmail.com¹, subiyanto@mail.unnes.ac.id², tole@ee.uad.ac.id³

Abstract

Step-up converter is widely used to increase DC voltage level on PV systems either off-grid or grid connected. One of the step-up converters often used in PV systems is SEPIC converter. To improve its performance, many SEPIC converters have been modified. However, performance on various conditions has not been further investigated. In this study, the modified SEPIC converter was investigated under various change conditions for grid-connected PV applications. This converter was modelled and simulated using PSIM software. The modified SEPIC converter received input from PV array 15 kWp, and its output was connected to the three-phase inverter through grid and load. The irradiance level and ambient temperature were varied to test its performance and compared to Boost converter and SEPIC converter. For all tests, the performance of modified SEPIC converter was better than other step-up converters because it was able to rectify the quality of output voltage and more efficient.

Keywords: SEPIC, converter, PV systems, PSIM.

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1. Introduction

Smart grid systems refer to the use of controls technology and digital information to increase the security, reliability and efficiency of the electric grid in the world [1]. The smart grid system is possibly integrated from various renewable energy sources [2] such as wind turbine [3, 4, 5], fuel cell [6, 7], and photovoltaic [8, 9, 10]. One of the various renewable energy sources that have great potential to be utilized is photovoltaic [11].

The distribution of power from PV systems is possible standalone or grid-connected. For grid applications, PV systems passed through the three-phase inverter and this condition demands high DC voltage [12]. However, characteristics of photovoltaic generate low voltage and do not meet this requirement. The step-up converter is required to overcome this problem by converting low DC voltage from photovoltaic to high DC voltage [13]. Mostly, the preferred topology of the step-up converter is able to generate high step-up voltage, high efficiency, and low ripple of the output/input voltage and current to avoid power losses on the systems [14].

Many researchers have developed and investigated the performance of the step-up converter for PV systems. Boost converter [15–18] is able to generate high step-up voltage with high duty cycle. Unfortunately, that condition may cause voltage stress on the switching device and decrease the efficiency of the Boost converter. The high step-up voltage can also be obtained from two Boost converters that are arranged in series with a single switch, it is called Quadratic Boost Converter [19, 20]. However, switching device receives high current stress. On the other hand, conduction losses also increase, and the efficiency of this converter decreases [21].

Improving performance of step-up converter using Coupled Inductor is also presented by [22, 23]. High voltage gain is achieved by determining coil of the Coupled Inductor. However, during high step-up operation, current ripple increases and causes leakage inductance so that the efficiency decreases. The Coupled Inductor converter has also combined with voltage doubler circuit, which has been developed by [24, 25]. Voltage stress of the switching device has been reduced, but inductor receives magnetizing current which is double than the switching frequency. Furthermore, in [26] the topology using switched capacitors cell has also been presented to achieve a high voltage static gain. The technique of voltage multiplier cell used in the step-up converter is able to reduce the switching voltage stress and increase the

high voltage gain [39] but it may increase the cost of converter. Many step-up converters have also been combined to increase efficiency and to obtain high voltage gain such as Boost converter combined with Cuk converter in [27, 28], and Boost converter with SEPIC converter in [29, 30]. However, the switching device on this converter received switching voltage stress equal to the average sum of the output and input voltage [21, 1].

The modified SEPIC converter is developed by combining conventional SEPIC converter with Boost converter and diode-capacitor circuit, and it has been presented by [32] to overcome the above drawbacks. This converter for PV systems is capable of generating high voltage gain, low switching voltage stress, and low conduction losses. However, various conditions either irradiation changes or ambient temperature which affect the performance of grid-connected PV systems have not been further investigated on this converter. In this study, the performance of modified SEPIC converter presented by [32] will be investigated under various conditions. This converter is investigated on grid-connected PV systems simulation using PSIM software for 15 kWp power rating by varying irradiance level and ambient temperature. Furthermore, the result of its performance is compared to Boost converter and SEPIC converter.

2. Overview of Step-up Converters

Step-up converter has been popular in the last few years, especially for high voltage conversion on grid-connected PV systems. The voltage from PV array has to be stepped-up before transferred to the inverter on the grid-connected system. Many step-up converters have been modified to improve its performance. In [32], the conventional SEPIC converter has been modified by combining with the Boost converter and diode-capacitor circuit as shown in Figure 1. This converter comprises the main switching device (S), three capacitors (C_1 , C_2 , and C_3), three diodes (D_1 , D_2 , and D_3), two inductors (L_1 and L_2), an output diode (D_0), and an output capacitor (C_0). The presence of the diode-capacitor circuit is able to reduce switching voltage stress on switching device (S). The output voltage from Boost converter is used to charge C_2 . Furthermore, the voltage from capacitor 2 (V_{C2}) is applied to the (L_2) during the conduction period of the switching device (S). This condition increases more voltage gain that is obtained when compared to the conventional step-up converters.

In this study, the performance of modified SEPIC [32] will be investigated and compared to conventional step-up converters. Boost converter is often used as the basic of the conventional step-up converter [33]. Boost converter circuit comprises an inductor, a diode, an output capacitor and the main switching device as shown in Figure 2 [34,35].

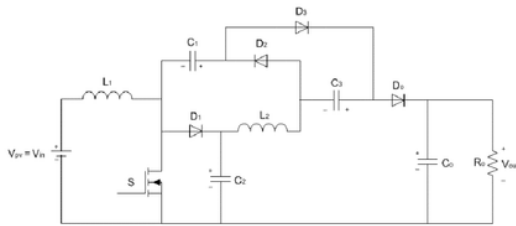


Figure 1. Modified SEPIC converter circuit

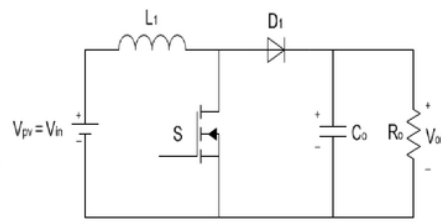


Figure 2. Boost converter circuit

More precisely, Single-Ended Primary Inductor Converter or called SEPIC converter is also often used to step-up DC voltage level. This converter consists of some components such as presented in Figure 3 [35-37]. The energy in SEPIC converter is transferred through capacitor (C_1) and inductor (L_1). Therefore, the switching voltage stress on SEPIC converter is higher than the Boost converter. Each component parameter on step-up converters is calculated by formulas respectively. The formulas of each step-up converter are shown in Table 1.

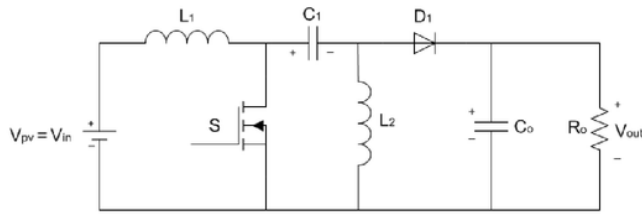


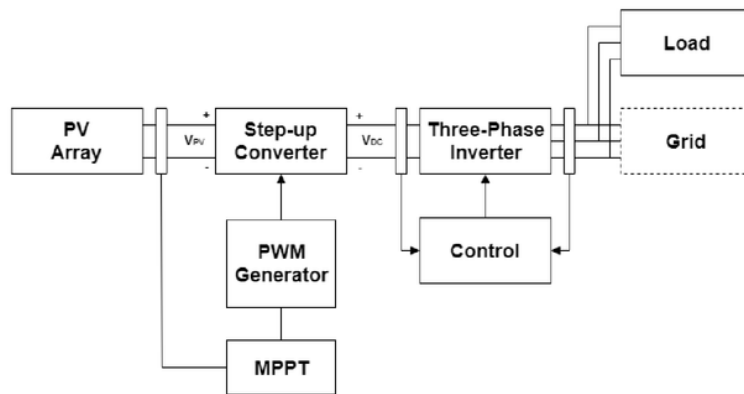
Figure 3. SEPIC converter circuit

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Table 1. Step-up Converters Formulas

Parameters	Boost Converter [35]	SEPIC Converter [35]	Modified SEPIC Converter [32]
Duty Cycle	$D = 1 - \frac{V_{in}}{V_{out}}$	$D = \frac{V_{out}}{V_{out} + V_{in}}$	$D = \frac{2V_{out} - 3V_{in}}{2V_{out} + V_{in}}$
Inductance	$L_1 = \frac{V_{out} D}{\Delta i_{L1} f_s}$	$L_1 = \frac{V_{out} D}{\Delta i_{L1} f_s}$ $L_2 = \frac{V_{out} D}{\Delta i_{L2} f_s}$	$L_1 = \frac{V_{in} D}{\Delta i_{L1} f_s}$ $L_2 = \frac{V_{C2} (1 - D)}{\Delta i_{L2} f_s}$
Capacitors	$C_1 = \frac{D}{R (\Delta V_{out} / V_{out}) f_s}$	$C_1 = \frac{D}{R (\Delta V_{C1} / V_{out}) f_s}$ $C_2 = \frac{D}{R (\Delta V_{out} / V_{out}) f_s}$	$C_1 = C_2 = C_3 = \frac{I_{out}}{\Delta V_C f_s}$ $C_0 = \frac{I_{out} D}{\Delta V_{out} f_s}$

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3. Grid-Connected PV Systems

The whole grid-connected PV systems comprise PV array, Step-up Converter with MPPT and PWM Generator, Three-Phase Inverter with Controller, Load, and Grid as shown in Figure 4 [38]. PV Array produces electricity from solar energy [39], and its performance is affected by various conditions such as irradiance level and ambient temperature [40]. For generating maximum power, MPPT is applied to grid-connected PV systems [41–43]. The MPPT inputs are current and voltage from PV array. The MPPT produces duty cycle as the input of PWM generator. PWM generator generates PWM signal for controlling switching device on the Step-up Converter [9]. The Step-up Converter is used to increase DC voltage from PV array [44] so that input voltage of the inverter on grid-connected PV systems is fulfilled. This study focuses on investigating the performance of the step-up converter on grid-connected PV systems using modified SEPIC converter and further compared to Boost converter and SEPIC converter.



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Figure 4. Block diagram of grid-connected PV systems

4. Modelling and Simulation Systems

4.1. PV Array Modelling

The maximum capacity of PV array generates 15 kWp power that consists of 60 PV modules. PV module uses type JAP6 60-250 3BB with maximum power 250 Wp is arranged in 10 series and 6 parallel as shown in Figure 5.

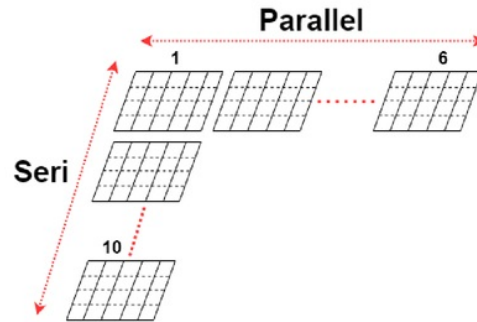
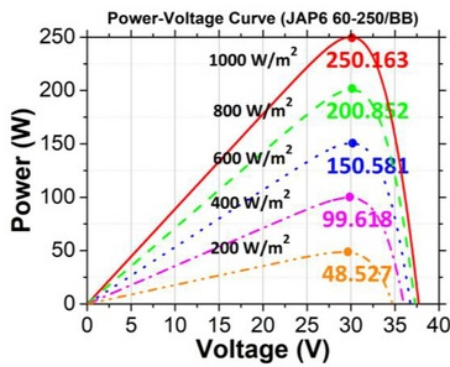


Figure 5. The arrangement of PV modules

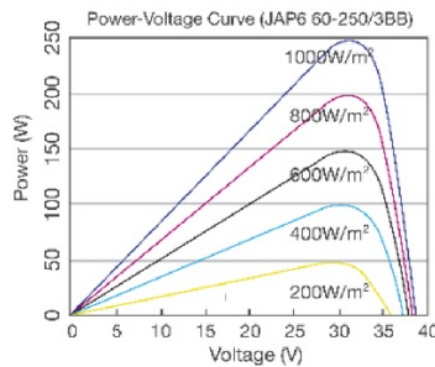
Modelled and simulated PV modules uses PSIM physical model of PV module by entering basic parameters from a datasheet that is shown in Table 2. The results of simulated PV module are presented respectively in Figures 6, 7, and 8.

Table 2. Datasheet PV Module JAP6 60-250 3BB

Parameters	Label	Value
Short Circuit Current	I_{SC}	8.92 A
Open Circuit Voltage	V_{OC}	37.66 V
Current at Pmax	I_{mpp}	8.35 A
Voltage at Pmax	V_{mpp}	29.94 V
Maximum Power	P_{mpp}	250 W
V_{OC} coef. of temperature	KV	-0.33%/°C
I_{SC} coef. of temperature	KI	0.058%/°C
Cell in series per module	N	60



(a)



(b)

Figure 6. P-V Curve of PV module JAP6 60-250 3BB under various irradiance
 (a) Simulated PV module (b) Datasheet PV module

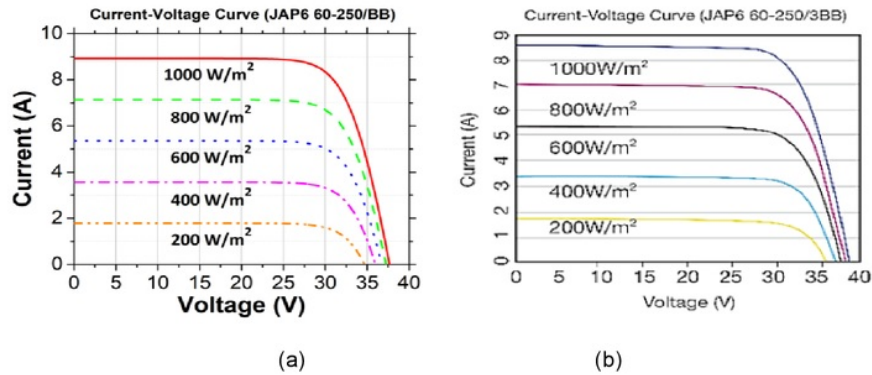


Figure 7. I-V Curve of PV module JAP6 60-250 3BB under various irradiance
 (a) Simulated PV module (b) Datasheet PV module

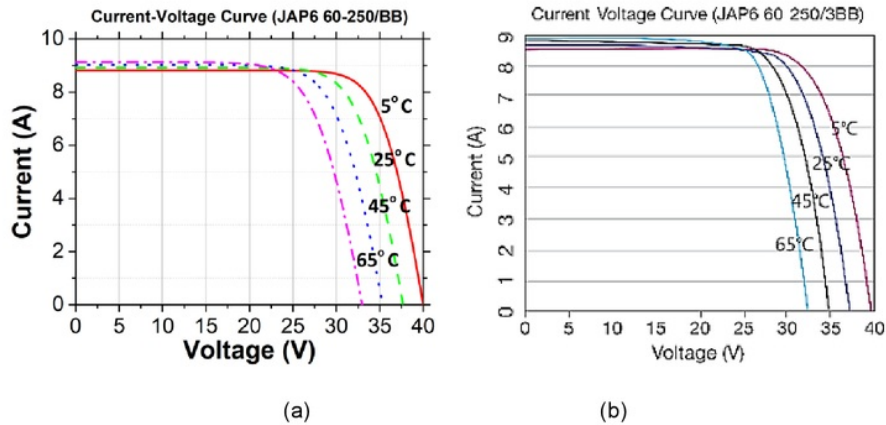


Figure 8. I-V Curve of PV module JAP6 60-250 3BB under various ambient temperature
 (a) Simulated PV module (b) Datasheet PV module

4.2. Modelling of Modified SEPIC Converter

Each parameter either the modified SEPIC converter or the other step-up converters is calculated based on formulas in Table 1 and its result are shown in Table 3.

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Table 3. Step-up Converters Parameters

Parameters	Boost Converter	SEPIC Converter	Modified SEPIC Converter
Input Voltage (V_{in})	299.4 V	299.4 V	299.4 V
Output Voltage (V_{out})	750 V	750 V	750 V
Switching Frequency (f_s)	24 kHz	24 kHz	24 KHz
Duty Cycle (D)	0.6	0.715	0.334
Inductor 1 (L_1)	75 μ H	223 μ H	417 μ H
Inductor 2 (L_2)	-	223 μ H	1.46 mH
Capacitor 1 (C_1)	-	5.68 μ F	6.2 μ F
Capacitor 2 (C_2)	-	-	6.2 μ F
Capacitor 3 (C_3)	-	-	6.2 μ F
Output Capacitor (C_0)	66.67 μ F	5.68 μ F	37.1 μ F

In this study, the types of the components used in modified SEPIC converter, the Boost converter, and SEPIC converter are listed in Table 4. The types are determined based on parameters in Table 3 and matched with datasheet of each component.

Table 4. Component Types

Components	Boost Converter	SEPIC Converter	Modified SEPIC Converter
Power MOSFET (S)	APT60N60BCSG	APT60N60BCSG	APT60N60BCSG
Diodes (D)	DUR6060W	DUR6060W	DUR6060W
Inductor 1 (L_1)	HCS-850M-280A	HCS-301M-1000A	HCS-601M-500A
Inductor 2 (L_2)	-	HCS-301M-1000A	T60405-R6123-X263
Capacitor 1 (C_1)	-	B32754C3605K000	C4GSFUC4300ZA0J
Capacitor 2 (C_2)	-	-	C4GSFUC4300ZA0J
Capacitor 3 (C_3)	-	-	C4GSFUC4300ZA0J
Output Capacitor (C_0)	C4DEIPQ5680A8TK	B32754C3605K000	C4AEHBW5400A3LJ

The modified SEPIC converter on grid-connected PV systems is modelled and simulated using PSIM software to evaluate its performance and compared to the other step-up converters. The modified SEPIC converter receives input from PV array through input capacitor (C_{in}), while switching device is controlled by MPPT through PWM generator. The output from modified SEPIC converter is connected to three-phase inverter which is on the subcircuit afterwards. Figure 9 shows modelling circuit of modified SEPIC converter on PSIM software.

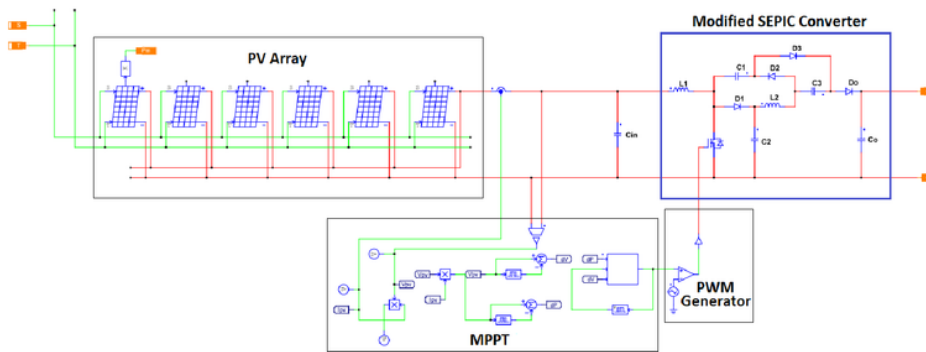


Figure 9. Modelling circuit of modified SEPIC converter

4.3. Modelling of Grid-Connected PV Systems

The whole modelling systems using PSIM software in this study are presented in Figure 10. The modified SEPIC converter on subcircuit PV Source with PV array, an input capacitor, MPPT and PWM generator. The simulation parameters are listed in Table 5.

Table 5. PSIM Simulation Parameters

PSIM Simulation Parameters	
Time Step	2 μ S
Total Time	2.2 S
Print Time	0.6 S
Print Step	1
Systems Parameters	
Frequency Grid System	50 Hz
Voltage Grid System	380 V
DC Link Voltage	750

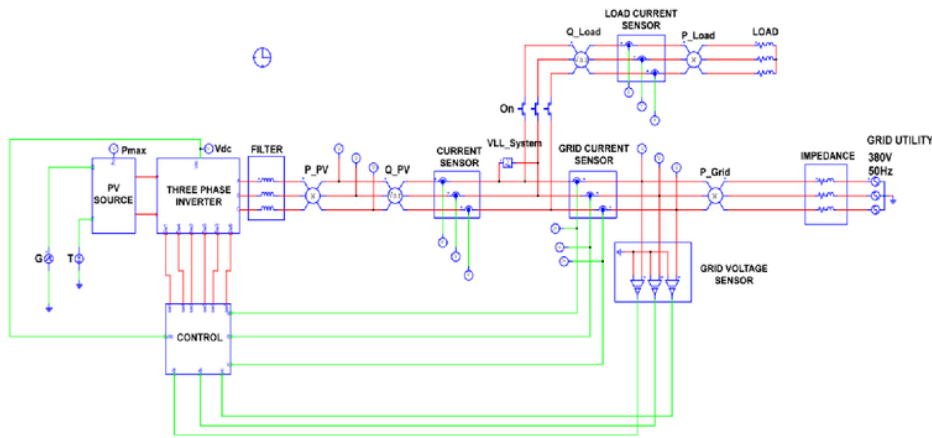


Figure 10. Grid-connected PV systems PSIM simulation

5. Results and Analysis

The various conditions were applied to PV array. It was done to investigate the performance of modified SEPIC converter and compared to conventional step-up converters afterwards. The first test was by changing irradiance level on PV array. It was necessary to validate the performance of modified SEPIC converter due to PV array affected by the dynamic conditions such as irradiance level when generates electricity. Figure 11 shows the irradiance profile that was applied to PV array with a fixed ambient temperature of 25° C. The irradiance level was initially 800 W/m². At 1.2 s until 1.6 s, the irradiance level operated at 1000 W/m². However, it was decreased at 1.6 s became 600 W/m² and operate until 2.2 s.

The result from the first test presented in Figure 12 to investigate the output voltage of step-up converters respectively. It can be seen that irradiance change affected the performance of step-up converters. When irradiance level increased, occurred disturbed on the output voltage so that diverge from 750 V. Boost converter and SEPIC converter were experienced voltage oscillations, while modified SEPIC converter capable was otherwise. The same condition also occurred at 1,6 s, more precisely when irradiance on PV array dropped. It can be observed, modified SEPIC converter was more capable of reducing voltage oscillations than other step-up converters. The results of this test validate the performance of modified SEPIC converter was suitable for grid-connected PV applications. The modified SEPIC converter was able to maintain high voltage gain although PV array received dynamic irradiance.

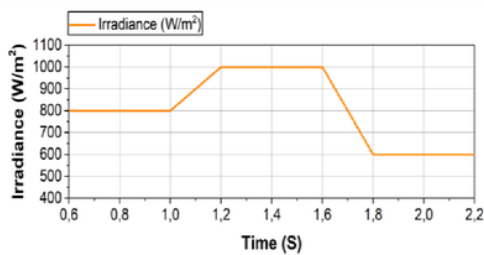


Figure 11. Changes of irradiance level for the PV array input

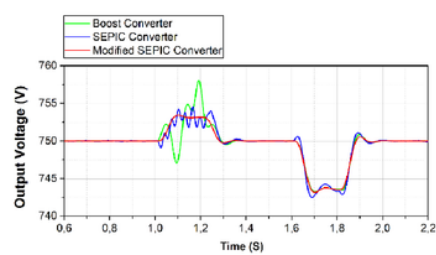


Figure 12. Comparison the output voltage of step-up converters under changes irradiance

The performance of modified SEPIC converter was validated again by changing ambient temperature with constant irradiance. This investigation was to illustrate performance in dynamic behaviour although the real temperature in the world does not change fast. Figure 13 shows ambient temperature profile at irradiance level 1000 W/m². The ambient temperature was initially operated at 35° C and dropped becoming 20° C at 1 s. It condition changes again gradually to 45° C at 1.6 s and operates until 2.2 s.

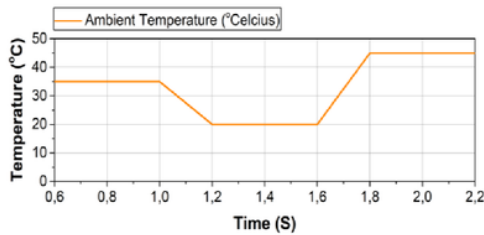


Figure 13. Changes of ambient temperature level for the PV array input

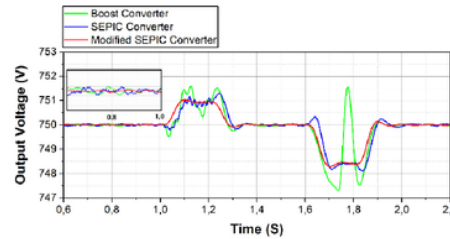
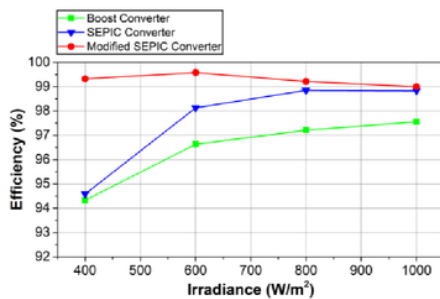


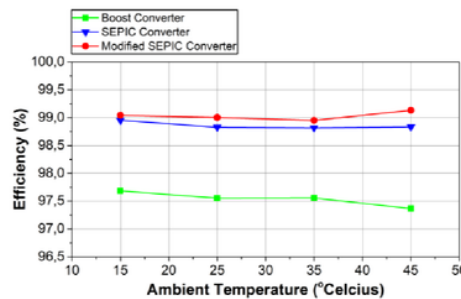
Figure 14. Comparison the output voltage of step-up converters under changes ambient temperature

The output voltage waveforms of step-up converters were given in Figure 14. From the result can be seen that the change of ambient temperature affected the stability of output voltage. Although at the steady-state condition, Boost converter and SEPIC converter still produced voltage oscillations. Its condition was different from modified SEPIC converter that was capable of reducing voltage oscillations in the steady-state condition. The same condition also occurs when the ambient temperature increased. At 1 s, the output voltage of conventional step-up converters experiences voltage oscillations, while the modified SEPIC converter able to the otherwise. The presence of voltage oscillations also occurs at the time ambient temperature increased up to caused Boost converter was experiencing overshoot. From this test, it can be observed that performance of modified SEPIC converter capable of reducing voltage oscillations than other step-up converters. Therefore, the quality of output voltage was increased and more suitable for the three-phase inverter input.

In order to confirm the performance of modified SEPIC converter, varying irradiance and ambient temperature was also applied to calculate the efficiency. Figure 15 shows the efficiency result obtained from this converter and compared to Boost converter and SEPIC converter. From the figures, it can be seen that modified SEPIC converter produced higher efficiency than other step-up converters both under varying irradiance and ambient temperature.



(a)



(b)

Figure 15. Efficiency of step-up converters (a) under varying irradiance (b) under varying ambient temperature

Partial shading condition was also applied to PV array. Basically, its phenom was unavoidable and significantly capable of decreasing the efficiency and also disturbing the stability of PV systems. The pattern of partial shading in this test is presented in Figure 16. Initially, the PV array received irradiance 1000 W/m^2 and generated 15 kW power. However, the partial condition occurred at 0.8 s because 10 of 60 PV modules did not generate maximum power. Its condition caused the PV array power to drop becoming approximately 12 kW and lasted until 2.2 s .

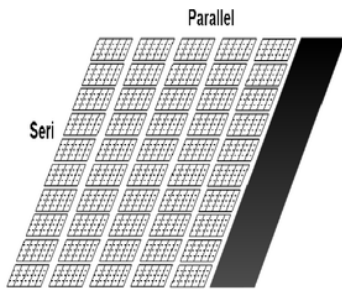


Figure 16. Test pattern of partial shading condition

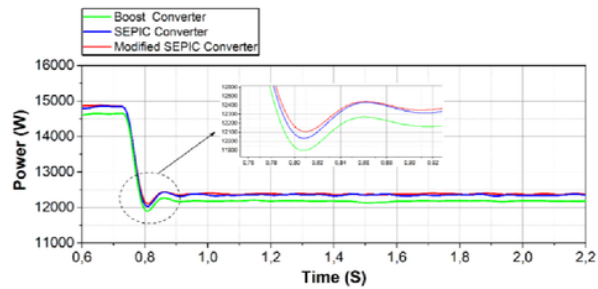


Figure 17. The output power of step-up converters under partial shading condition

Partial shading condition was used to investigate output power from step-up converters under the transient condition. Figure 17 shows the characteristic of each step-up converter when partial shading occurred. The output power from Boost converter and SEPIC converter more dropped than modified SEPIC converter, and its effect on efficiency obtained. From this test, the modified SEPIC converter was increasingly proved to have performed better than the other step-up converters under various conditions.

The power flow from PV systems under transient condition was also investigated as shown in Figure 18 to verify that the systems worked on grid-connected. In this test, PV systems generated 15 kW power. The initial load was 5 kW so that PV systems through the three-phase inverter supplied the remaining power to the grid 10 kW . When at 1 s until 1.6 s , there was an increase of load becoming 19.4 kW . Its condition caused PV systems insufficient to meet the load capacity. Therefore, the grid also supplied power 4.4 kW to suffice the load. Furthermore, the load dropped to 10 kW at 1.6 s . Its condition causes PV systems were capable of sufficing again the load capacity and distributing the remaining power to the grid. Based on this test, grid-connected PV systems using modified SEPIC converter work properly.

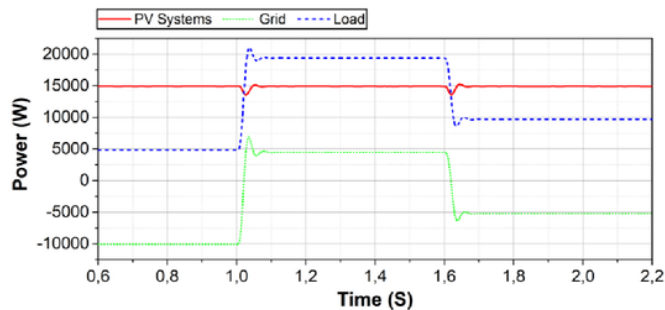


Figure 18. Power flow grid-connected PV systems using modified SEPIC converter

6. Conclusion

In this study, the modified SEPIC converter is implemented to the grid-connected PV system simulation using PSIM software for 15 kWp power rating. The modified SEPIC converter is developed by combining conventional SEPIC converter, Boost converter and diode-capacitor circuit. The conventional step-up converters are also implemented in this systems and compared to the performance of modified SEPIC converter which is tested under various conditions both irradiance and ambient temperature changes. For all tests, the modified SEPIC converter is more efficient and has high stability for maintaining static gain by rectifying the quality of output voltage.

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