International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 4, August 2023, pp. 3720~3732
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i4.pp3720-3732

Performance numerical evaluation of modified single-ended primary-inductor converter for photovoltaic systems

Tole Sutikno[1,2], Rizky Ajie Aprilianto[2,3], Nik Rumzi Nik Idris[4], Ahmad Saudi Samosir[5]
[1]Department of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia
[3]Department of Electrical and Information Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
[4]Department of Electrical Power Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia
[5]Department of Electrical Engineering, Faculty of Engineering, Universitas Lampung, Bandar Lampung, Indonesia

Article Info

Article history:

Received Nov 23, 2022
Revised Jan 14, 2023
Accepted Feb 26, 2023

Keywords:

Boost converter
Photovoltaic system
Power simulator
Single-ended primary-inductor converter
Voltage gain
Voltage stress

ABSTRACT

Single-ended primary-inductor converter (SEPIC) was considered a good alternative to a DC-DC converter for photovoltaic (PV) systems. The SEPIC converter can operate with an input voltage greater or less than the regulated output voltage, or as a step-up or step-down. As a step-up converter, SEPIC boosts PV voltage to specific levels. However, gain limitation and voltage stress continue to reduce the efficiency of conventional SEPIC converters. Because of this, researchers created a modified SEPIC converter to improve performance. In this paper, six modified SEPIC converters were compared and evaluated. To compare fairly, all modified SEPIC converters are non-isolated and use a single switch. Power simulator (PSIM) software was used to simulate each converter with a BISOL BMO-250 PV module and maximum power point tracking (MPPT) P&O controller. The converter with the highest static voltage gain and lowest duty cycle has been identified. It results in up to ten times voltage increment with a 0.8-duty ratio. All topologies have the same voltage stress, with maximum and minimum values of 30.1 and 29.5 V, respectively. On the other hand, each topology produces different average efficiencies, with the highest and lowest efficiency at 99.5% and 97.2%, respectively.

Corresponding Author:

Tole Sutikno
Department of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan
South Ringroad St., Tamanan, Banguntapan, Bantul Regency, Special Region of Yogyakarta-55191, Indonesia
Email: tole@te.uad.ac.id

1. INTRODUCTION

The increase in fossil fuels used to supply the world's energy needs has attracted much attention from policymakers to researchers. It is a major issue that should be handled seriously due to its contribution to increasing CO_2 emissions [1], [2]. One of the widely adopted solutions is to use renewable energy sources. Many countries are actively exploring and researching renewable energy sources and their related advanced technology applications [3]–[5] due to their sustainable, pollution-free, and abundance. Among the various sources, photovoltaic (PV) has become one of the most popular renewable energy sources that convert energy from the sun into electrical energy [6]. In 2021 the installed PV capacity was at 168 GW worldwide and was expected to be more than 200 GW in 2022.

The general scheme to supply electricity from PV generation can be classified into three categories: stand-alone (off-grid), on-grid connected, and hybrid. All involve a step-up converter to fulfil the allowable voltage level due to the low characteristic PV voltage [7]. The boost topology becomes the basic DC-DC converter to increase voltage, which is popularly applied to PV systems [8]. This topology, however, results in a large ripple in current and voltage, high voltage stress in the switches, duty ratio limitation, reverse recovery problem, and poor efficiency [9]. Hence, the research and development on the DC-DC converter functionality to step-up the voltage is still ongoing.

Single-ended primary-inductor converter (SEPIC) is widely applied to PV systems. This converter offers several merits over conventional converters, including higher efficiency, lower power losses, and better stability in output current [8]. Also, this topology can function as a buck-boost, allowing the output voltage to be higher or lower than the input voltage depending on the control scheme adopted and the power flow desired. By regulating the duty cycle, the input impedance in the SEPIC converter can change. The SEPIC converter provides features similar to the Cuk converter without inverting the output voltage polarity [10], so it has excellent benefits for power conversion. Therefore, this topology is compatible with PV applications as the power extraction process requires module and maximum power point tracking (MPPT) control [11].

The voltage stress across switches still becomes a problem faced by the SEPIC converter, which is equal to the sum of the input and output voltage [12]. Hence, the SEPIC converter has limitations when operating at high gain conversion ratios without sacrificing efficiency [13]. These problems have pushed researchers to introduce novel topologies of SEPIC converters. For instance, by integrating a coupled inductor [14], [15], and a coupled inductor with a voltage multiplier cell (VMC) [16], several variations to the SEPIC-based converter topologies have been investigated. Also, the modification was carried out by combining the boost topology with the SEPIC converter [17], the double boost circuit [18], and the Cuk–SEPIC topology [19]. All of these were done to improve the performance of the SEPIC-based DC-DC converter.

The performance of the modified single-ended primary-inductor converter (SEPIC) converters proposed in the previous works is evaluated and compared in this study. For this reason, six non-isolated topologies with a single switching device applied for PV applications are chosen. The comparison focuses on each duty cycle with the gain voltage obtained, voltage stress across switches, and the converter's efficiency. The evaluations and comparisons are conducted via simulation using PSIM simulation software. The same PV module type (BISOL BMO-250) is used in all simulations. Also, the MPPT controller with the P&O algorithm is used. The study's outcomes are expected to provide information regarding the performance of selected modified SEPIC converters applied to PV systems that will guide the selection of suitable topologies for various PV applications.

This article is organized as: section 2 describes the PV systems and types of conventional DC-DC converters commonly used. Section 3 presents the overview of the six SEPIC converters selected for this study. Section 4 presents the modelling and simulation of PV systems used in this study, which comprise the PV module, the MPPT controller, and modified SEPIC converters. The results, discussion, and performance evaluation of each topology are presented in section 5. Finally, the conclusion and recommendations from this study are given in section 6.

2. PHOTOVOLTAIC SYSTEMS

Figure 1 shows PV systems in a standalone configuration without battery comprising PV modules, MPPT controller, PWM generator, DC-DC converter, and load [20]. PV modules generate electricity from solar energy, whereby the electrical power is highly dependent on irradiance and ambient temperature [21]. Therefore, an MPPT controller is utilized to obtain maximum power point (MPP) [22], [23]. The output from the MPPT controller is duty value or voltage reference as a reference signal to compare with the sawtooth signal as a carrier signal, resulting in a PWM signal [24]–[26]. It triggers the switching device in the DC-DC converter to step-up PV voltage appropriating to the load voltage requirement or inverter voltage when connected to the DC-AC conversion.

The DC-DC converter focuses on topology functioned to step-up voltage because the PV array's low voltage output is unsuitable for many high-voltage applications. Figure 2 shows the conventional DC-DC converters family famous applied to PV systems [27], wherein it can be divided into isolated and isolated type [28]. The isolation type refers to an electrical barrier between the input and the output side involving the high-frequency transformers [29]. However, the electrical barrier makes the converter bulky and heavy in size, and the power losses caused by the barrier are also quite significant. Hence, the non-isolated converter can be a choice to overcome the drawbacks mentioned earlier. In addition, it has been popular in recent years to replace isolated types.

The boost converter is the best option among non-isolated conventional DC-DC converters. However, it is not advised when the voltage gain is more than 8, owing to the rising duty cycle. Furthermore, the voltage stress is equivalent to the output voltage, which makes it unsuitable for high-voltage uses. The

SEPIC converter is offered as a high-step-up DC-DC converter for PV systems to address these issues. SEPIC converter has a non-inverting polarity output voltage, a simple gate-drive circuit, and minimal input current pulsation. Aside from these, the SEPIC converter can be functioned as a DC-DC buck-boost converter, with the ability to increase or decrease the input voltage level at its output. As a result, the operating point of the PV array can be optimized at any voltage level. Nonetheless, the current issues regarding gain limitation and voltage stress impacting the efficiency result have still in the conventional SEPIC converter.

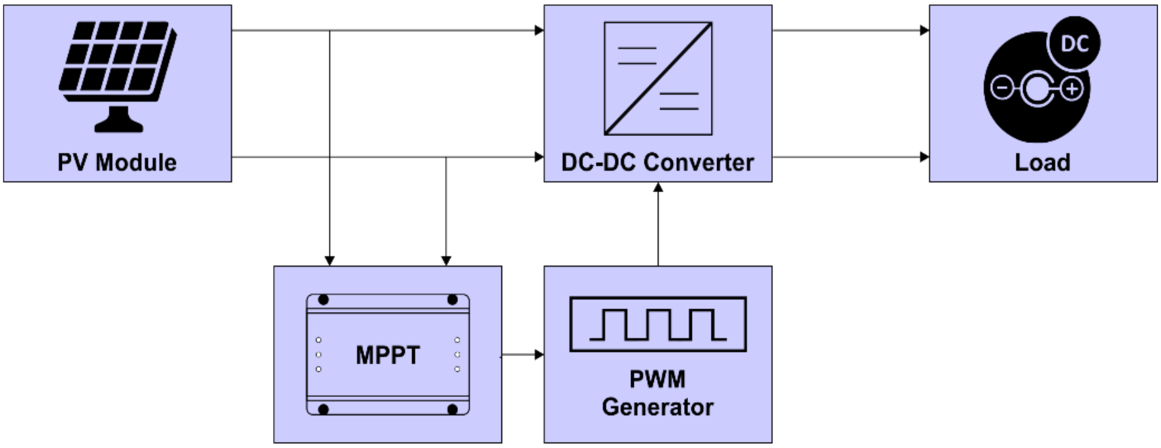

Figure 1. Diagram block for standalone PV systems

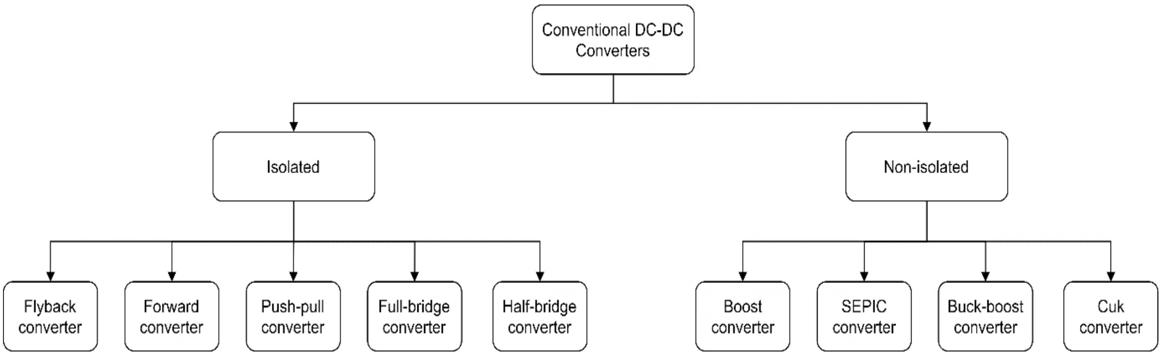

Figure 2. DC-DC converters family famous applied to PV systems

3. OVERVIEW OF THE SEPIC CONVERTER DEVELOPMENT

Conventional SEPIC converter has continuous input currents, which causes significant input current ripples. It restricts MPPT performance because the PV system will vary widely around its MPP [30]. Hence, improving conventional SEPIC converter performance is still continuous, one of modifying the circuit. It also covers several aspects, such as improving the gain ratio dedicated to voltage step-up, reducing power losses, decreasing voltage stress, minimizing cost and components with a compact design, and obtaining high efficiency.

3.1. Proposed topology by [31]

The modified SEPIC converter proposed by [31] only adds two components, a diode D_M, and a capacitor C_M, to form a non-isolated structure without magnetic coupling, as shown in Figure 3. The output voltage charges the capacitor C_M. In addition, the capacitor C_S polarity is inverted, unlike the conventional SEPIC converter. The performance of this configuration showed that the static gain increased by ten times, and reduced switch voltage stress occurred.

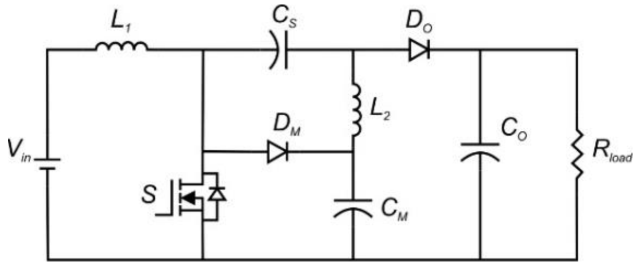

Figure 3. Modified SEPIC converter by [31]

3.2. Proposed topology by [32]

The proposed topology by [31] has motivated further studies to result in a new modified SEPIC converter, as conducted by [32]. One more diode was added to construct a voltage doubler circuit and boost the output voltage result, as depicted in Figure 4. In addition, with this proposed topology, the voltage stress across the switching device is suppressed, and the conversion efficiency is increased.

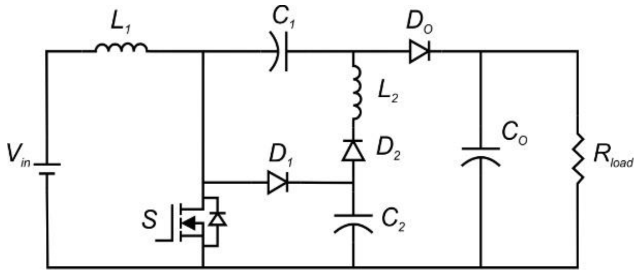

Figure 4. Modified SEPIC converter by [32]

3.3. Proposed topology by [33]

A slight modification was carried out by [33] by changing the placement of the additional capacitor to the series with the output capacitor, as shown in Figure 5. The operation mode of the proposed converter works on boost and SEPIC converter combinations, which is dedicated to reducing inrush inductor current in L_1. As a result, the operation of the proposed converter achieving steady-state conditions is faster than the first modified SEPIC converter discussed.

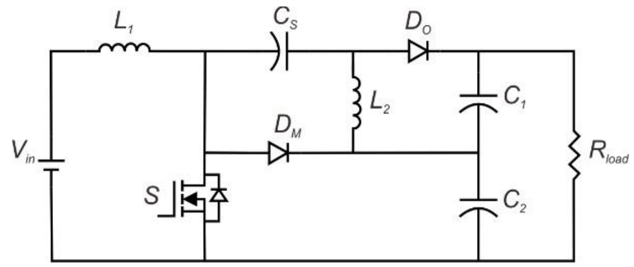

Figure 5. Modified SEPIC converter by [33]

3.4. Proposed topology by [34]

By integrating a diode-capacitor component in series and boost converter to a basic SEPIC converter, a novel modified SEPIC topology has been introduced by [34], as shown in Figure 6. Ten times gain can be obtained. The voltage stress, input current ripple, and output voltage ripple can be reduced. Also, employing MOSFET with low internal resistance makes a high-efficiency result. Hence, this modified topology is suitable for renewable energy applications in the form of PV systems.

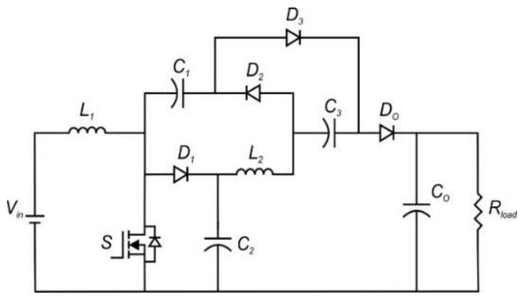

Figure 6. Modified SEPIC converter by [34]

3.5. Proposed topology by [35]

In [35], a modification is carried out by combining the SEPIC converter with one additional inductor and capacitor as a voltage lift circuit, as illustrated in Figure 7. This strategy overcomes losses due to parasitic elements in components used. In addition, the current ripple in the input side can be suppressed, followed by the capability of enhancing output voltage.

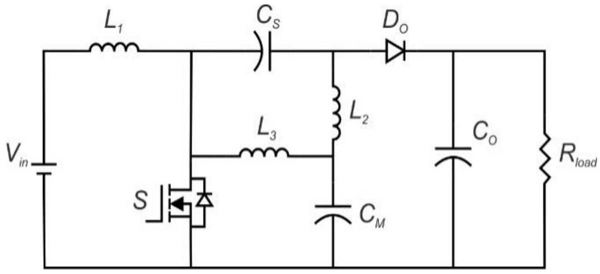

Figure 7. Modified SEPIC converter by [35]

3.6. Proposed topology by [36]

Figure 8 shows a modification based on the SEPIC converter. It was addressed to obtain high gain with low input current ripple proposed by [36]. Low voltage stress can be achieved by applying less turn-off time on the switching device. In addition, this topology is dedicated to the minimize inrush inductor current in L_1.

All the modified SEPIC converters discussed above have close similarities in circuit configuration. The focus of the modification was addressed to maintain the primary topology advantages with increasing voltage gain. All converters were dedicated to enhancing the PV voltage involving the MPPT controller to obtain maximum power conversion. Therefore, all proposed topologies are selected to be evaluated each performance in this study. To identify each topology, these have been notated by A up to F, followed by each reference. Meanwhile, each component can be calculated by the equation listed in Table 1. It excludes the equation is tagged "N/E", which means not explained in the reference article.

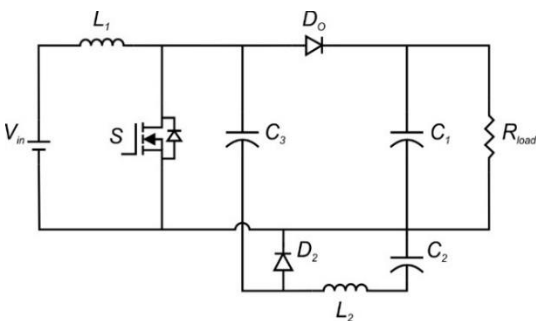

Figure 8. Modified SEPIC converter by [36]

Table 1. Modified SEPIC converter equations

Parameters	Modified SEPIC converter topology					
	A [31]	B [32]	C [33]	D [34]	E [35]	F [36]
Duty cycle	$\frac{V_{out}-V_{in}}{V_{out}+V_{in}}$	$\frac{V_{out}-V_{in}}{V_{out}+V_{in}}$	$\frac{V_{out}-V_{in}}{V_{out}+V_{in}}$	$\frac{2V_{out}-3V_{in}}{2V_{out}+V_{in}}$	$\frac{V_{out}-V_{in}}{V_{out}+V_{in}}$	$\frac{V_{out}-V_{in}}{V_{out}+V_{in}}$
L_1	$\frac{V_{in}\times D}{\Delta i_L\times f_{sw}}$	$\frac{V_{in}\times D}{\Delta i_{L1}\times f_{sw}}$	$\frac{V_{in}\times D}{\Delta i_{L1}\times f_{sw}}$	$\frac{V_{in}\times D}{\Delta i_{L1}\times f_{sw}}$	*N/E*	$\frac{V_{in}\times D}{\Delta i_{L1}\times f_{sw}}$
L_2	$\frac{V_{in}\times D}{\Delta i_L\times f_{sw}}$	$\frac{V_{C2}\times(1-D)}{\Delta i_{L2}\times f_{sw}}$	$\frac{V_{in}\times D}{\Delta i_{L2}\times f_{sw}}$	$\frac{V_{C2}\times(1-D)}{\Delta i_{L2}\times f_{sw}}$	*N/E*	$\frac{V_{C2}\times(1-D)}{\Delta i_{L2}\times f_{sw}}$
L_3	–	–	–	–	*N/E*	–
C_1	–	$\frac{I_{out}}{\Delta V_C\times f_{sw}}$	$\frac{1}{2}\times\left(\frac{D}{R\left(\frac{\Delta V_{out}}{V_{out}}\right)\times f_{sw}}\right)$	$\frac{I_{out}\times D}{\Delta V_C\times f_{sw}}$	*N/E*	$\frac{I_{out}}{\Delta V_{C1}\times f_{sw}}$
C_2	–	$\frac{I_{out}}{\Delta V_C\times f_{sw}}$	$\frac{1}{2}\times\left(\frac{D}{R\left(\frac{\Delta V_{out}}{V_{out}}\right)\times f_{sw}}\right)$	$\frac{I_{out}\times D}{\Delta V_C\times f_{sw}}$	*N/E*	$\frac{\Delta i_{L2}}{8\Delta V_{C2}\times f_{sw}}$
C_3	–	–	–	$\frac{I_{out}\times D}{\Delta V_C\times f_{sw}}$	–	$\frac{I_{out}}{\Delta V_{C3}\times f_{sw}}$
C_S	$\frac{I_{out}}{\Delta V_C\times f_{sw}}$	–	$\frac{I_{out}}{\Delta V_C\times f_{sw}}$	–	–	–
C_M	$\frac{I_{out}}{\Delta V_C\times f_{sw}}$	–	–	–	–	–
C_{out}	*given*	$\frac{P_{out}}{4\pi\times F_G\times V_{out}\times\Delta V_{out}}$	–	$\frac{I_{out}\times D}{\Delta V_{out}\times f_{sw}}$	*N/E*	–
R_{out}	$\frac{V_{out}}{I_{out}}$	$\frac{V_{out}}{I_{out}}$	$\frac{V_{out}}{I_{out}}$	$\frac{V_{out}}{I_{out}}$	$\frac{V_{out}}{I_{out}}$	$\frac{V_{out}}{I_{out}}$

4. MODELING SIMULATION SYSTEMS

4.1. Photovoltaic module

The simulation systems are built up in this study using a PV module with type BISOL BMO-250. By applying the information from the datasheet, modeling is carried out utilizing a physical model feature in PSIM software, where the PV parameters used are shown in Table 2. Meanwhile, the modeling characteristic results are shown in Figures 9, 10, and 11, respectively, which all represent the real PV module. So, the model of the PV module is feasible to use.

Table 2. Datasheet PV module BISOL BMO-250

Parameters	Label	Value	Unit
Maximum power	P_{mpp}	250	W
Short circuit current	I_{SC}	8.80 A	A
Open circuit voltage	V_{OC}	37.9 V	V
Current at P_{max}	I_{mpp}	8.20 A	A
Voltage at P_{max}	V_{mpp}	30.5 V	V
Temperature Coeff. of V_{SC}	KI	0.0029	%/°C
Temperature Coeff. of V_{OC}	KV	-0.0918	%/°C
Number of cells in series	N	60	

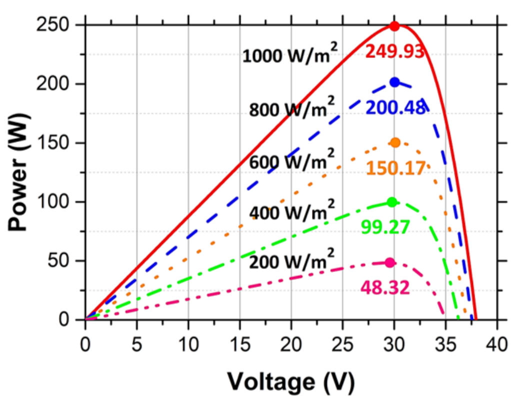

Figure 9. P-V curve of PV module BISOL BMO-250 for various irradiance

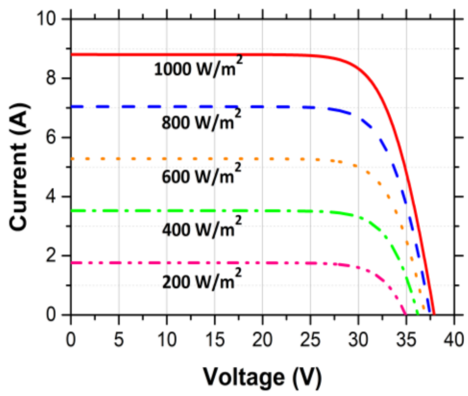

Figure 10. I-V curve of PV module BISOL BMO-250 for various irradiance

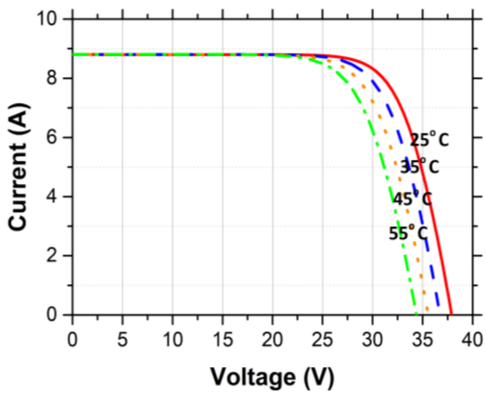

Figure 11. I-V curve of PV module BISOL BMO-250 for various temperature

4.2. Maximum power point tracking

The MPPT controller is applied to enhance power conversion results from the PV module with the P&O algorithm. This algorithm has been adopted by researchers to investigate the PV system's performance [37]–[40]. Also, it is chosen due to having some advantages, consisting of less computational procedure, ease of implementation, low complexity, and low power consumption [41]–[44]. Moreover, P&O is one of the most industry prevalent algorithms besides incremental conductance (INC) and constant voltage (CV) [45]. The flowchart of the P&O algorithm is depicted in Figure 12, then applied to the C code in the PSIM software.

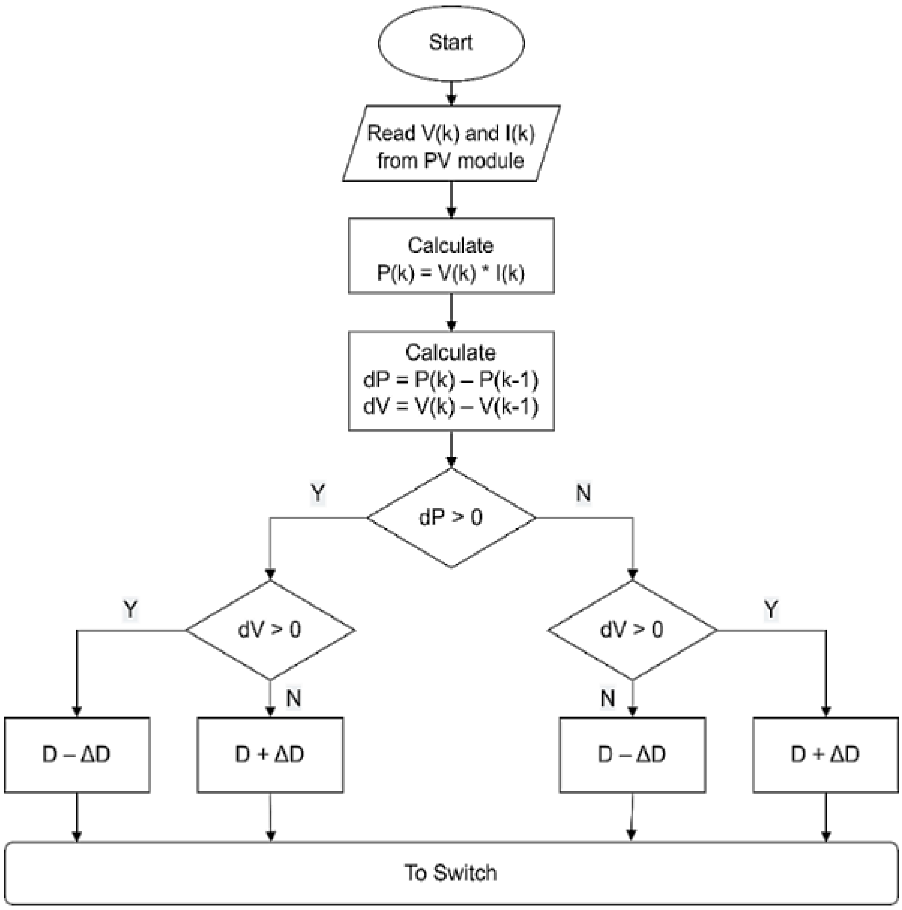

Figure 12. MPPT P&O algorithm flowchart

4.3. Modified SEPIC converter

The modified SEPIC converters explained in section 2 were chosen and utilized to enhance PV output voltage. All calculations of component size use equations listed in Table 1. It considers the same parameter in Table 3 comprising the input voltage from the PV module, the output voltage, switching frequency, allowed ripple in output voltage, inductor current, and capacitor voltage.

Table 3. Component calculation parameters

Parameters	Label	Value	Unit
Input voltage from PV module	V_{in}	30.5	V
Output voltage	V_{out}	61 – 305	V
Switching frequency	f_{sw}	25	kHz
Output voltage ripple	ΔV_{out}	30	%
Inductor current ripple	Δi_L	1	%
Capacitor voltage ripple	ΔV_C	10	%

4.4. Modelling of overall systems

The whole modelling system is shown in Figure 13. It is used to test and evaluate each performance of modified SEPIC converters in PSIM software. The systems involve a PV module, MPPT controller with PWM generator, modified SEPIC converters and load.

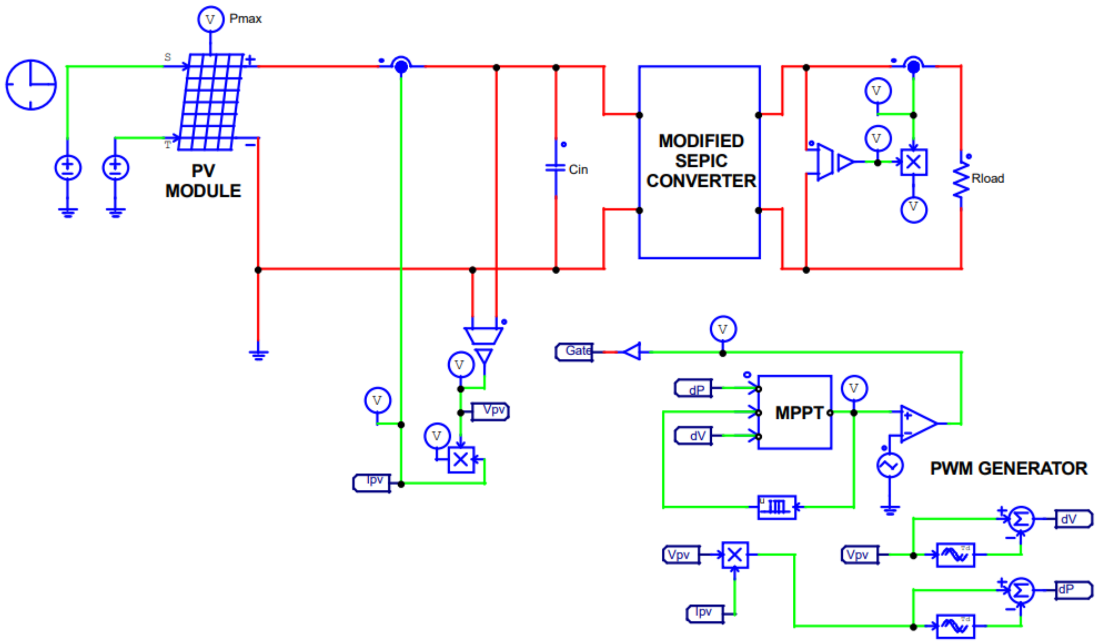

Figure 13. The complete modelling systems

5. RESULTS AND DISCUSSION

Six modified SEPIC converters depicted in Figures 3 to 8 have been simulated using PSIM software to compare and evaluate their performance and operations. The first test was to compare the gain results versus the duty cycle worked, as depicted in Figure 14. The testing results are shown that six converters can be classified into two groups. The first group contains topologies A, B, C, and D, while topologies E and F are in the other group. The first group performs better than the second group in the gain versus duty cycle. In detail, the first group with topology B can achieve the gain with the lowest duty cycle. It results in up to ten times voltage increment with a 0.8-duty ratio. Then, topologies A and D have the same result indicating that both modified SEPIC converters have the same capability in stepping-up voltage. The last is topology C, which generates a higher duty cycle than others to obtain the same gain value. Meanwhile, topology E and topology F have almost the same characteristic for obtaining voltage gain. In detail, topology E generates a duty cycle lower than topology F, which means it is better to realize a high static gain.

In the presence of the voltage doubler circuit, the proposed converter in topology B is proven to achieve high static gain with a low-duty cycle. Therefore, several researchers have used the same method to offer a high gain converter feasible for PV systems applications [46]–[49]. The voltage doubler circuit, also called a multiplier circuit, tends to function by increasing voltage at the end part of the main converter. Hence, topology B is superior to topology A and D because both are constructed without a voltage doubler circuit. Topology A combines a boost converter and SEPIC converter with a single switch, while topology D is further by adding a diode-capacitor configuration in series. In order to the topology C, which connected two capacitors in series to filter the output voltage, combines the boost converter and SEPIC converter with slight modification. The sum of the two capacitors used is the output capacitor itself. The duty cycle in this topology is higher than in the previously explained topologies. However, the proposed converter in topology C will achieve steady-state faster due to offering the feature of decreasing the inrush current in inductor 1.

The capability of the proposed converter in topology E is classified into the second group, wherein the presence of the additional inductor works to store energy with inductor 1 and inductor 2 simultaneously before flowing to the load. The configuration of an additional inductor and capacitor has a role as a voltage lift. In addition, this topology is prepared to handle parasitic effects in the components used. Unfortunately, the duty cycle worked is still categorized in high value compared to modified SEPIC converters in the first group, although the high gain conversion has been successfully achieved. Meanwhile, the proposed converter in topology F combines the boost converter and SEPIC converter, dedicated to the decreased voltage stress in the switching device by minimizing the current flowing in the inductor. However, this topology still produces a high-duty cycle to achieve high voltage gain.

Furthermore, the voltage stress in each topology was investigated by varying the irradiance level with constant ambient temperature in standard test conditions (STC) for the PV module. It is conducted due to the irradiance changing more unpredictably. On the contrary, the characteristic of the actual temperature in the world does not change rapidly. The tested results are listed in Table 4 by measuring drain-source voltage in each switching device. The voltage stress in each topology is averaged to simplify the analysis process, as shown in Figure 15.

The resulting test shows that the difference in voltage stress among all topologies is insignificant. Nonetheless, they have successfully overcome the voltage stress issue in the conventional SEPIC converter, which has high voltage stress equal to the sum of the input and output voltage [50]. Then, by applying the same strategy to investigate each converter's efficiency, the result is listed in Table 5 by comparing output power to input power for each modified SEPIC converter. Moreover, the average efficiency result is depicted in Figure 16.

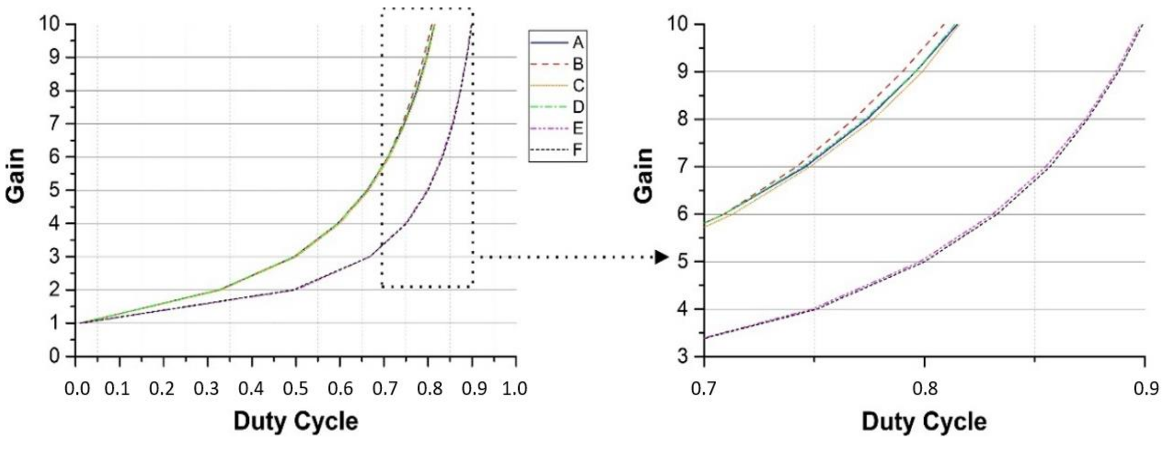

Figure 14. Comparative of gain versus duty cycle in six modified SEPIC converters

Table 4. Voltage stress results testing

Irradiance Level (W/m^2)	Ambient Temperature (°C)	Voltage Stress on Topology (V)					
		A	B	C	D	E	F
200	25	29.4	29.2	29.5	29.3	29.3	29.8
400	25	29.4	29.5	29.7	29.5	29.9	30.2
600	25	30.3	29.8	29.8	30.5	29.3	29.7
800	25	30.8	29.6	30.9	30.6	29.7	30.1
1000	25	30.4	30.4	29.9	30.6	29.1	28.8

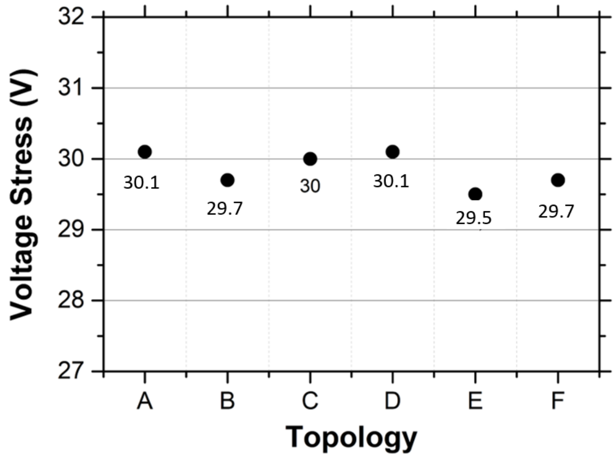

Figure 15. Comparative of voltage stress in six modified SEPIC converters

Table 5. Efficiency results testing

Irradiance Level (W/m^2)	Ambient Temperature (°C)	Topology Efficiency (%)					
		A	B	C	D	E	F
200	25	99.5	99.5	99.1	98.9	98.1	96.7
400	25	99.5	99.4	98.8	98.7	97.7	97.4
600	25	99.6	99.4	98.8	98.7	97.5	97.4
800	25	99.6	99.4	98.8	98.7	97.4	97.4
1000	25	99.5	99.6	98.7	98.7	97.4	97.3

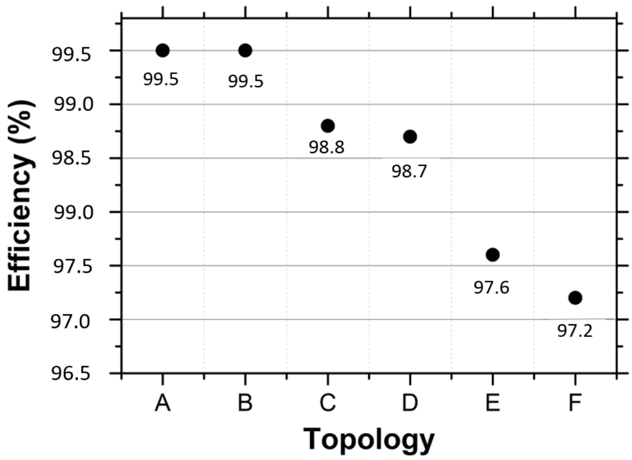

Figure 16. Comparative of average efficiency in six modified SEPIC converters

The highest efficiency can be obtained by topologies A and B, henceforth topology C and D. Afterwards, it is followed by topologies E and F. These confirm that the performances of the topology categorized in the first group are better than the topology in the second group for getting high static gain capability and finally impacted the efficiency results. By configuring a conventional SEPIC converter and boost converter with a single switch involving an addition inductor and capacitor, this modification was sufficient to obtain high gain conversion as conducted by [31]. The existence of D_2, which was added by [32], has a role in getting more lift voltage with minimizing duty cycle operating. Therefore, this modification SEPIC converter is suitable for low-power PV system applications. Topology C can be considered for fast response with minimum inductor inrush current. Meanwhile, topology D can be chosen for PV systems applied to the grid connection through a DC-AC inverter. The appropriate output capacitor can be designed by knowing the grid frequency. Further, topologies E and F can be considered for application with minimum voltage stress requirements in the switch devices.

6. CONCLUSION

This study has evaluated six modified SEPIC converters with the same character in the form of a non-isolated configuration and a single switch for PV systems, which are notated by topology A up to F. The evaluation and comparison were conducted using PSIM software with the same PV module type BISOL BMO-250 and MPPT P&O controller. All converters were compared, focusing on the voltage gain versus duty cycle, voltage stress across switches, and efficiency results. The highest static voltage gain with minimum duty cycle has been achieved by topology B, followed by A and D, C, E, and F. The difference in voltage stress among all topologies is insignificant. Nonetheless, they have successfully overcome the voltage stress issue in the conventional SEPIC converter. Finally, the sequence of highest efficiency results is topology A and B, henceforth topology C, D, E, and F.

ACKNOWLEDGEMENT

This research was supported by the World Class Professor Program 2022, Decree No. 3252/E4/DT.04.03/2022, Directorate General of Higher Education, Research and Technology of the Ministry of Education, Culture, Research and Technology of the Republic of Indonesia, and funded by the Institutional Cooperation Research Grant, Universitas Ahmad Dahlan under contract No. PKK-237/SP3/LPPM-UAD/VII/2022.

REFERENCES

[1] A. Kibria, S. B. Akhundjanov, and R. Oladi, "Fossil fuel share in the energy mix and economic growth," *International Review of Economics and Finance*, vol. 59, pp. 253–264, Jan. 2019, doi: 10.1016/j.iref.2018.09.002.

[2] J. Iqbal and Z. H. Khan, "The potential role of renewable energy sources in robot's power system: a case study of Pakistan," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 106–122, Aug. 2017, doi: 10.1016/j.rser.2016.10.055.

[3] A. Mostafaeipour, M. Qolipour, and K. Mohammadi, "Evaluation of installing photovoltaic plants using a hybrid approach for Khuzestan province, Iran," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 60–74, Jul. 2016, doi: 10.1016/j.rser.2016.01.105.

[4] S. Gorjian, B. N. Zadeh, L. Eltrop, R. R. Shamshiri, and Y. Amanlou, "Solar photovoltaic power generation in Iran: development, policies, and barriers," *Renewable and Sustainable Energy Reviews*, vol. 106, pp. 110–123, May 2019, doi: 10.1016/j.rser.2019.02.025.

[5] E. I. Come Zebra, H. J. van der Windt, G. Nhumaio, and A. P. C. Faaij, "A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries," *Renewable and Sustainable Energy Reviews*, vol. 144, Jul. 2021, doi: 10.1016/j.rser.2021.111036.

[6] L. P. N. Jyothy and M. R. Sindhu, "An artificial neural network based MPPT algorithm for solar PV system," in *2018 4th International Conference on Electrical Energy Systems (ICEES)*, Feb. 2018, pp. 375–380, doi: 10.1109/ICEES.2018.8443277.

[7] E. Arango, C. Ramos-Paja, J. Calvente, R. Giral, and S. Serna, "Asymmetrical interleaved DC/DC switching converters for photovoltaic and fuel cell applications—part 1: circuit generation, analysis and design," *Energies*, vol. 5, no. 11, pp. 4590–4623, Nov. 2012, doi: 10.3390/en5114590.

[8] T. Sutikno, H. S. Purnama, R. A. Aprilianto, A. Jusoh, N. S. Widodo, and B. Santosa, "Modernisation of DC-DC converter topologies for solar energy harvesting applications: a review," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 28, no. 3, pp. 1845–1872, Dec. 2022, doi: 10.11591/ijeecs.v28.i3.pp1845-1872.

[9] S. Nahar and M. B. Uddin, "Analysis the performance of interleaved boost converter," in *2018 4th International Conference on Electrical Engineering and Information and Communication Technology (iCEEiCT)*, Sep. 2018, vol. 8, pp. 547–551, doi: 10.1109/CEEICT.2018.8628104.

[10] H. Komurcugil, S. Biricik, and N. Guler, "Indirect sliding mode control for DC-DC SEPIC converters," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 6, pp. 4099–4108, 2020, doi: 10.1109/TII.2019.2960067.

[11] M. Killi and S. Samanta, "An adaptive voltage-sensor-based MPPT for photovoltaic systems with SEPIC converter including steady-state and drift analysis," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 12, pp. 7609–7619, Dec. 2015, doi: 10.1109/TIE.2015.2458298.

[12] M. V. M. Ewerling, T. B. Lazzarin, and C. H. Illa Font, "Proposal of an isolated two-switch DC-DC SEPIC converter," in *2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC)*, Dec. 2019, pp. 1–6, doi: 10.1109/COBEP/SPEC44138.2019.9065718.

[13] M. Verma and S. S. Kumar, "Hardware design of SEPIC converter and its analysis," in *2018 International Conference on Current Trends towards Converging Technologies (ICCTCT)*, Mar. 2018, no. 4, pp. 1–4, doi: 10.1109/ICCTCT.2018.8551052.

[14] H. Ardi, A. Ajami, and M. Sabahi, "A novel high step-up DC–DC converter with continuous input current integrating coupled inductor for renewable energy applications," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1306–1315, Feb. 2018, doi: 10.1109/TIE.2017.2733476.

[15] R. Moradpour, H. Ardi, and A. Tavakoli, "Design and implementation of a new SEPIC-based high step-up DC/DC converter for renewable energy applications," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1290–1297, 2017, doi: 10.1109/TIE.2017.2733421.

[16] S. Hasanpour, A. Baghramian, and H. Mojallali, "A modified SEPIC-based high step-up DC-DC converter with quasi-resonant operation for renewable energy applications," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3539–3549, May 2019, doi: 10.1109/TIE.2018.2851952.

[17] M. S. Hambali, R. Eriend, and R. Fakhriansyah, "Design and implementation of DC-DC SEPIC integrated with boost converter for photovoltaic system," in *2020 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP)*, Sep. 2020, pp. 7–11, doi: 10.1109/ICT-PEP50916.2020.9249947.

[18] A. J. Sabzali, E. H. Ismail, and H. M. Behbehani, "High voltage step-up integrated double boost–SEPIC DC–DC converter for

fuel-cell and photovoltaic applications," *Renewable Energy*, vol. 82, pp. 44–53, Oct. 2015, doi: 10.1016/j.renene.2014.08.034.

[19] K. Nathan, S. Ghosh, Y. Siwakoti, and T. Long, "A new DC–DC converter for photovoltaic systems: coupled-inductors combined cuk-SEPIC converter," *IEEE Transactions on Energy Conversion*, vol. 34, no. 1, pp. 191–201, Mar. 2019, doi: 10.1109/TEC.2018.2876454.

[20] B. Ahmed, A. Necaibia, A. Slimani, R. Dabou, A. Ziane, and N. Sahouane, "A demonstrative overview of photovoltaic systems faults," in *2019 1st Global Power, Energy and Communication Conference (GPECOM)*, Jun. 2019, pp. 281–285, doi: 10.1109/GPECOM.2019.8778567.

[21] M. Talaat, T. Said, M. A. Essa, and A. Y. Hatata, "Integrated MFFNN-MVO approach for PV solar power forecasting considering thermal effects and environmental conditions," *International Journal of Electrical Power and Energy Systems*, vol. 135, Feb. 2022, doi: 10.1016/j.ijepes.2021.107570.

[22] I. U. Haq *et al.*, "Neural network-based adaptive global sliding mode MPPT controller design for stand-alone photovoltaic systems," *PLOS ONE*, vol. 17, no. 1, Jan. 2022, doi: 10.1371/journal.pone.0260480.

[23] M. B. Anjum *et al.*, "Maximum power extraction from a standalone photo voltaic system via neuro-adaptive arbitrary order sliding mode control strategy with high gain differentiation," *Applied Sciences*, vol. 12, no. 6, 2022, doi: 10.3390/app12062773.

[24] M. Killi and S. Samanta, "Voltage-sensor-based MPPT for stand-alone PV," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 2, pp. 1399–1407, 2019.

[25] R. A. Aprilianto, E. Firmansyah, and F. D. Wijaya, "Review on control strategy for improving the interleaved converter performances," in *2021 4th International Seminar on Research of Information Technology and Intelligent Systems (ISRITI)*, Dec. 2021, pp. 312–317, doi: 10.1109/ISRITI54043.2021.9702804.

[26] J. Ahmed, Z. Salam, M. Kermadi, H. N. Afrouzi, and R. H. Ashique, "A skipping adaptive P&O MPPT for fast and efficient tracking under partial shading in PV arrays," *International Transactions on Electrical Energy Systems*, vol. 31, no. 9, Sep. 2021, doi: 10.1002/2050-7038.13017.

[27] A. Amir, A. Amir, H. S. Che, A. Elkhateb, and N. A. Rahim, "Comparative analysis of high voltage gain DC-DC converter topologies for photovoltaic systems," *Renewable Energy*, vol. 136, pp. 1147–1163, 2019, doi: 10.1016/j.renene.2018.09.089.

[28] K. Varesi, S. H. Hosseini, M. Sabahi, and E. Babaei, "Modular non-isolated multi-input high step-up dc–dc converter with reduced normalised voltage stress and component count," *IET Power Electronics*, vol. 11, no. 6, pp. 1092–1100, May 2018, doi: 10.1049/iet-pel.2017.0483.

[29] A. Affam, Y. M. Buswig, A.-K. B. H. Othman, N. Bin Julai, and O. Qays, "A review of multiple input DC-DC converter topologies linked with hybrid electric vehicles and renewable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 135, Jan. 2021, doi: 10.1016/j.rser.2020.110186.

[30] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg, and B. Lehman, "Step-up DC–DC converters: a comprehensive review of voltage-boosting techniques, topologies, and applications," *IEEE Transactions on Power Electronics*, vol. 32, no. 12, pp. 9143–9178, Dec. 2017, doi: 10.1109/TPEL.2017.2652318.

[31] R. Gules, W. M. dos Santos, F. A. dos Reis, E. F. R. Romaneli, and A. A. Badin, "A modified SEPIC converter with high static gain for renewable applications," *IEEE Transactions on Power Electronics*, vol. 29, no. 11, pp. 5860–5871, Nov. 2014, doi: 10.1109/TPEL.2013.2296053.

[32] S. Saravanan and N. Ramesh Babu, "Analysis and implementation of high step-up DC-DC converter for PV based grid application," *Applied Energy*, vol. 190, pp. 64–72, Mar. 2017, doi: 10.1016/j.apenergy.2016.12.094.

[33] S. Saravanan and N. R. Babu, "A modified high step-up non-isolated DC-DC converter for PV application," *Journal of Applied Research and Technology*, vol. 15, no. 3, pp. 242–249, Jun. 2017, doi: 10.1016/j.jart.2016.12.008.

[34] S. Saravanan and N. R. Babu, "Design and development of single switch high step-Up DC–DC converter," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 2, pp. 855–863, Jun. 2018, doi: 10.1109/JESTPE.2017.2739819.

[35] C. Muranda, E. Ozsoy, S. Padmanaban, M. S. Bhaskar, V. Fedak, and V. K. Ramachandaramurthy, "Modified SEPIC DC-to-DC boost converter with high output-gain configuration for renewable applications," in *2017 IEEE Conference on Energy Conversion (CENCON)*, Oct. 2017, pp. 317–322, doi: 10.1109/CENCON.2017.8262505.

[36] A. Kalaivani and S. K. N. Kumar, "Modified high step-up non-isolated single ended primary inductor converter (SEPIC) for pv applications," in *2018 National Power Engineering Conference (NPEC)*, Mar. 2018, pp. 1–5, doi: 10.1109/NPEC.2018.8476709.

[37] R. A. Aprilianto, Subiyanto, and T. Sutikno, "Modified SEPIC converter performance for grid-connected PV systems under various conditions," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 16, no. 6, pp. 2943–2953, Dec. 2018, doi: 10.12928/TELKOMNIKA.v16i6.10148.

[38] J. Kumar, B. Rathor, and P. Bahrani, "Fuzzy and P&O MPPT techniques for stabilized the efficiency of solar PV system," in *2018 International Conference on Computing, Power and Communication Technologies (GUCON)*, Sep. 2018, pp. 259–264, doi: 10.1109/GUCON.2018.8674909.

[39] H. H. H. Mousa, A.-R. Youssef, and E. E. M. Mohamed, "Variable step size P&O MPPT algorithm for optimal power extraction of multi-phase PMSG based wind generation system," *International Journal of Electrical Power and Energy Systems*, vol. 108, pp. 218–231, Jun. 2019, doi: 10.1016/j.ijepes.2018.12.044.

[40] J. Sahoo, S. Samanta, and S. Bhattacharyya, "Adaptive PID controller with P&O MPPT algorithm for photovoltaic system," *IETE Journal of Research*, vol. 66, no. 4, pp. 442–453, Jul. 2020, doi: 10.1080/03772063.2018.1497552.

[41] T. M. C. T. M. Chung, H. Daniyal, M. H. Sulaiman, and M. S. Bakar, "Comparative study of P&O and modified incremental conductance algorithm in solar maximum power point tracking," 2016, doi: 10.1049/cp.2016.1300.

[42] M. L. Azad, S. Das, P. K. Sadhu, B. Satpati, A. Gupta, and P. Arvind, "P&O algorithm based MPPT technique for solar PV system under different weather conditions," in *2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, Apr. 2017, pp. 1–5, doi: 10.1109/ICCPCT.2017.8074225.

[43] D. K. Mathi and R. Chinthamalla, "Global maximum power point tracking technique based on adaptive salp swarm algorithm and P&O techniques for a PV string under partially shaded conditions," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–18, Apr. 2020, doi: 10.1080/15567036.2020.1755391.

[44] L. Liu, C. Huang, J. Mu, J. Cheng, and Z. Zhu, "A P&O MPPT with a novel analog power-detector for WSNs applications," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 67, no. 10, pp. 1680–1684, Oct. 2020, doi: 10.1109/TCSII.2019.2940212.

[45] M. Taufik, A. Nonaka, F. S. Huzayfa, R. M. Soedjono, and T. Taufik, "Effects of inductor current ripple on the performance of MPPT using boost converter," in *2021 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP)*, Sep. 2021, pp. 202–207, doi: 10.1109/ICT-PEP53949.2021.9600919.

[46] R. Suryadevara, T. Li, K. Modepalli, and L. Parsa, "High-gain soft-switching DC-DC converter with voltage-doubler rectifier modules," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2017, pp. 5692–5697, doi: 10.1109/ECCE.2017.8096946.

[47] M. Altimania, M. S. S. Nia, M. Ferdowsi, and P. Shamsi, “An interleaved non-isolated DC-DC boost converter with voltage doubler cell in CCM,” in *2020 IEEE Green Technologies Conference (GreenTech)*, Apr. 2020, pp. 1–5, doi: 10.1109/GreenTech46478.2020.9289825.
[48] V. Sidorov, A. Chub, D. Vinnikov, and A. Bakeer, “An overview and comprehensive comparative evaluation of constant-frequency voltage buck control methods for series resonant DC–DC converters,” *IEEE Open Journal of the Industrial Electronics Society*, vol. 2, pp. 65–79, 2021, doi: 10.1109/OJIES.2020.3048003.
[49] T. Rahimi, L. Ding, H. Gholizadeh, R. S. Shahrivar, and R. Faraji, “An ultra high step-up DC–DC converter based on the boost, luo, and voltage doubler structure: mathematical expression, simulation, and experimental,” *IEEE Access*, vol. 9, pp. 132011–132024, 2021, doi: 10.1109/ACCESS.2021.3115259.
[50] V. Ravindran, R. Ponraj, S. S. Zameerbasha, N. S. Kanna, S. SamuelRaj, and B. Sabarish, “Dynamic performance enhancement of modified sepic converter,” in *2021 2nd International Conference for Emerging Technology (INCET)*, May 2021, pp. 1–5, doi: 10.1109/INCET51464.2021.9456403.

BIOGRAPHIES OF AUTHORS

Tole Sutikno is a lecturer in Electrical Engineering Department at the Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degrees in Electrical Engineering from Universitas Diponegoro, Universitas Gadjah Mada and Universiti Teknologi Malaysia, in 1999, 2004 and 2016, respectively. He has been an Associate Professor in UAD, Yogyakarta, Indonesia since 2008. He is currently an Editor-in-Chief of the TELKOMNIKA and the Head of the Embedded Systems and Power Electronics Research Group (ESPERG). His research interests include the field of digital design, industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded system, artificial intelligence, intelligent control, information technology and digital library. He can be contacted at email: tole@te.uad.ac.id, tole@ee.uad.ac.id.

Rizky Ajie Aprilianto is currently a researcher at the Embedded System and Power Electronics Research Group (ESPERG), Indonesia. He received a bachelor's degree from the Department of Electrical Engineering, Universitas Negeri Semarang, Indonesia, in 2018 and a master's degree from the Department of Electrical and Information Engineering, Universitas Gadjah Mada, Indonesia, in 2022. His research interests include power electronics, switched-mode power supply (SMPS), DC-DC converters, PV systems, and energy management, planning, and integrating renewable energy power plants. He can be contacted at email: rizkyajiea@gmail.com.

Nik Rumzi Nik Idris received the B.Eng. degree in electrical engineering from the University of Wollongong, Wollongong, NSW, Australia, in 1989, the M.Sc. degree in power electronics from Bradford University, West Yorkshire, U.K., in 1993, and the Ph.D. degree from Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia, in 2000. He is currently a Professor with UTM, and the Head of the Power Electronics and Drives Research Group. His current research interests include control of ac drive systems and DSP applications in power electronic systems. He is also the Past Chair of the IEEE Power Electronics Society, Malaysia Chapter, and is also a senior member of the IEEE. He can be contacted at email: nikrumzi@fke.utm.my, e-nrumzi@utm.my.

Ahmad Saudi Samosir was born in Belawan, Indonesia, in 1971. He received the B.S. degree in electrical engineering from the University of North Sumatera, Medan, Indonesia, in 1995, the M.S. degree in electrical power engineering from the Bandung Institute of Technology, Bandung, Indonesia, in 1999 and Ph.D. degree from Universiti Teknologi Malaysia, Johor, Malaysia, in 2010. He has been a Faculty Member with the Department of Electrical Engineering, Lampung University, Bandar Lampung, Indonesia since 2000. He is a professor in electrical engineering since 2017. His areas of research interest include renewable energy, control techniques, and the application of power converters. He can be contacted at email: saudi@unila.ac.id.