Paper IJPEDS 2022

by Suroso Suroso

Study of novel parallel H-bridge and common-emitter current-source inverters for photovoltaic power conversion system

Suroso, Hari Siswantoro
Department of Electrical Engineering, Jenderal Soedirman University, Purbalingga, Indonesia

Article Info

Article history:

Received Jul 26, 2021
Revised Feb 8, 2022
Accepted Feb 15, 2022

Keywords:

Inverter
Parallel operation
Photovoltaic

ABSTRACT

A novel operation of three-level H-bridge and common-emitter current source inverters (CSIs) proposed for photovoltaic power converters is presented in this paper. Two photovoltaic systems with two different inverter circuits, i.e. H-bridge and common-emitter CSIs, were connected in parallel to supply a sharing ac power load. In order to regulate the power supplied by each inverter system, proportional integral current controllers were employed. Triangular carrier and sinusoidal signals-based modulation techniques were implemented to both inverters. Some parameters such as load current, inverter's output current, total harmonics distortion (THD), and efficiency were tested and analyzed. Test results showed that in the parallel operation of these inverters, the average THD percentage of the load current was 0.34% for load power factor 0.996 and 0.62 % for load power factor 0.782. Minimum waveform distortion of inverter ac currents during parallel operation can be achieved if the current magnitudes of both inverters were set the same. In the case of efficiency, the maximum efficiency of the system was 89.07%. Operating the H-bridge CSI with a higher magnitude of the output current will result in higher efficiency of the system.

Corresponding Author:

Suroso
Department of Electrical Engineering, Engineering Faculty, Jenderal Soedirman University
Mayjen Sungkono St. km. 5, Blater, Purbalingga, Central Java 53371, Indonesia
Email: suroso.te@unsoed.ac.id

1. INTRODUCTION

Recently, the application of renewable energy sources especially photovoltaic systems has been increasing in many countries around the world. It is because of some merits introduced by the photovoltaic system, such as reducing environmental pollution, low operating cost, and availability from a few watt power to a larger megawatt-scale system [1]–[4]. Simplicity in installation such as on rooftop is a feature that attracts more interest to photovoltaic for residential application [5]–[7]. Even more so, some governments issued policies giving incentives for the development of renewable energy sources such as photovoltaic power generator to increase its application in their countries. Fortunately, the latest efficiency of a photovoltaic module has achieved 47.1%, realized by using multi-junction concentrator solar cells [8]. It will boost the total efficiency of solar energy conversion into electrical energy.

Moreover, the availability of supporting technologies such as photovoltaic power converters is also another important factor to increase the wider application of the photovoltaic system. Power electronic converters are essential parts of the development of renewable energy applications [9]–[11]. Some renewable energy sources generate electrical energy in the form of dc power, such as photovoltaic systems, and fuel cells. The generated power of other energy sources such as micro hydro power, wind power system, tidal, and sea wave energies are commonly in the form of ac power. They use an ac machine generator to produce electrical energy. For the dc load system, the generated dc power can be used to supply power load after processed by the dc-dc converter to have stable dc voltage and current as required. In the case of an ac load system, the dc power should be converted into ac power by utilizing dc to ac power converter or power inverter [12]–[14]. The power inverter generates ac power with adjustable frequency, magnitude, and phase angle of its output voltage and current. In case the input of the inverter is dc voltage, and the output is a controllable ac voltage, the inverter is classified as a voltage source inverter (VSI). However, if the input is in dc current form, and the output is controllable ac current, the inverter is called a current source inverter (CSI) [15]–[17]. These two kinds of inverters are applicable for photovoltaic energy conversion systems.

A single-phase power inverter is suitable to be used in a residential PV system, i.e. rooftop installed photovoltaic, where most residential loads are single-phase systems. For a single-phase grid-tied inverter application, the current source inverter introduced some features compared to voltage source inverter such as more immune to short circuit fault, longer lifetime of its power inductors than capacitors, and better quality of ac output current [18]–[22]. Moreover, some circuit topologies of the current source inverter have inherent boost-up voltage capability. Hence, it will eliminate the need for a power transformer to raise the output voltage of the inverter [23]–[25]. For a higher power residential photovoltaic system, a single inverter may not be enough to proceed with the total generated power. The capacity of a commercially available single-phase inverter is limited. Moreover, a single inverter system is weak in reliability issues. Hence, operating some power inverters in parallel is a realistic option to address these issues. In fact, parallel operation of many inverters is an unavoidable situation when many residential photovoltaic systems are operated in grid-tied operation. These inverters can be many types with different circuits and characteristics [26]–[34].

The basic concept of paralleling inverters is shown in Figure 1. As shown in this figure, N number of photovoltaic systems with N number of inverters work in parallel. A study of operation parallel between two H-bridge current source inverters has been discussed in [17]. However, power transformers were applied in this system, and the inverter circuits were the same type. This paper investigates and presents a novel photovoltaic system constructed by two different types of current source power inverters, i.e. H-bridge and common-emitter current source inverters. Each inverter is connected with a different photovoltaic system working in parallel to supply a common ac power load. The proposed system introduces some features such as more immune to short circuit fault, higher power capacity, the possibility of backup operation mode, and better quality of load current. Computer simulation tests were performed to investigate the performance of the system.

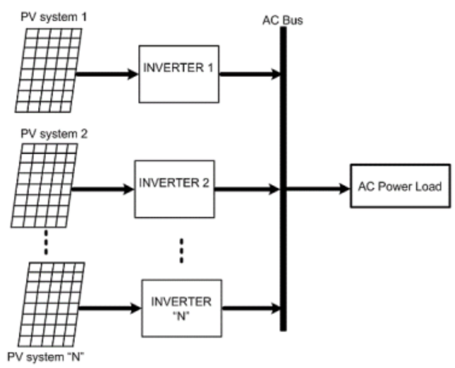


Figure 1. Parallel operation of inverters for photovoltaic systems

2. PROPOSED PHOTOVOLTAIC SYSTEM

Figure 2 presents circuits of a three-level H-bridge current source inverter. The power inductor (L) is utilized to generate dc current source from the input power (V_{in}) for inverter circuits. Total five controlled power switches with four isolated gate drive circuits are required, including the switch for dc current generator circuit Q_c. Table 1 is the switching combination of power switches Q_1, Q_2, Q_3, and Q_4 to produce a three-level output current, i.e. +I, 0, and –I currents. Moreover, Figure 3 is a three-level common-emitter current source inverter circuit. It is also composed of five controlled power switches. The power inductors L_1 and L_2 in this circuit are employed to create two dc current sources of the inverter. These two inductors have a common core as shown in the figure. Four power switches are connected together at their emitter terminal at a common point, hence a single isolated power supply can be applied to supply four gate drive circuits of the inverter's switches.

Moreover, because of the common-emitter connection of its power switches, a lower gradient voltage can be achieved. Hence this inverter is also more suitable for higher speed switching operation, compared to the H-bridge current source inverter. Both inverters need only a single dc current sensor for current controller function as shown in Figure 2 and Figure 3. Table 2 is the switching operation of this three-level common-emitter current source inverter circuit.

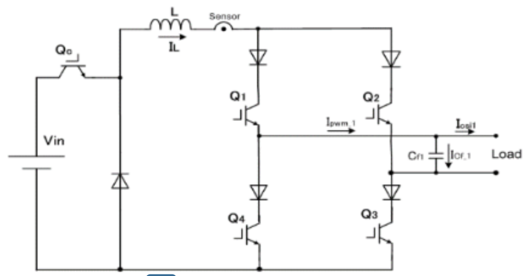


Figure 2. H-bridge current source inverter [35]

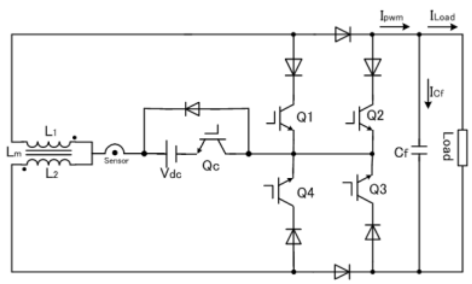


Figure 3. Three-level common-emitter current-source inverter [36], [37]

Table 1. Switching modes of H-bridge CSI

Q_1	Q_2	Q_3	Q_4	I_{out}
ON	OFF	ON	OFF	+I
ON	OFF	OFF	ON	0
OFF	ON	ON	OFF	0
OFF	ON	OFF	ON	-I

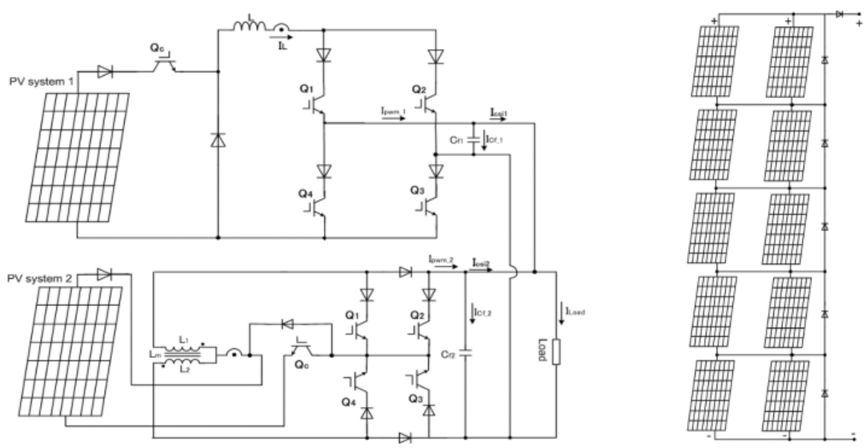
Table 2. Operation mode of common-emitter CSI [18]

Q_1	Q_2	Q_3	Q_4	I_{out}
OFF	OFF	ON	ON	+I
ON	OFF	OFF	ON	0
ON	ON	OFF	OFF	-I

In this paper, the three-level H-bridge and common-emitter inverter circuits are applied together to process the dc power delivered by two photovoltaic systems to be transformed into ac power to supply power load as depicted in Figure 4. The proposed parallel operation of these circuits is shown in Figure 4 (a). It can be a new alternative operation of inverters to proceed with two photovoltaic systems. Ten photovoltaic modules with a total capacity 1 kWp were applied as dc power source of each inverter circuit. Two arrays of photovoltaic systems were designed in the system. Five photovoltaic modules were connected in series to construct a photovoltaic array as shown in Figure 4 (b). A more number of photovoltaic systems of course will need more inverter circuits to achieve higher power. A common ac power load is connected to both inverters.

The current controlled operation mode was utilized to regulate the power delivered by photovoltaic via inverters to the load. Proportional integral (PI) current controllers were applied to both inverters as shown in Figure 5 and Figure 6. These controllers will adjust the output current and power of each inverter. In the case of a common-emitter inverter, two power inductors with a single core were implemented to generate two dc input current sources for inverter circuits. However, even two inductors were used, only a single sensor was applied to regulate the currents in inductor 1 and inductor 2 as shown in Figure 5. Hence it can simplify the required sensor number. In the case of the H-bridge CSI, the dc current source was created by a single power inductor. Hence, a single sensor was required to sense the inductor current for control purpose. The action of a current control signal, and maximum power point tracking (MPPT) was realized by power switch Q_c that will regulate the magnitude of dc current thru changing its duty cycle. Diode D_F was required to ensure the current path for the inductor's current during switch Q_c turn-off.

To generate a pulse width modulation (PWM) ac current, two triangular carrier signals with opposite offset value plus a single sinusoidal signal were applied to the modulation system as shown in Figure 7. These signals feed in two comparators to generate PWM switching signals. The frequency of carrier signal provides the working frequency of the inverter's power switches, and the main frequency of ac current is assigned by the frequency of modulating signal. The sinusoidal modulating signal will work also to synchronize the frequency of the two inverters. The comparators will produce PWM signals from the comparison between the carrier and modulating signals. The produced PWM signals will be amplified by gate drive, and on-off controller circuits to operate power switches turn-on and turn-off.



(a) (b)

Figure 4. Proposed inverter system (a) proposed parallel system of H-bridge and common-emitter inverters and (b) configuration of photovoltaic system for each inverter

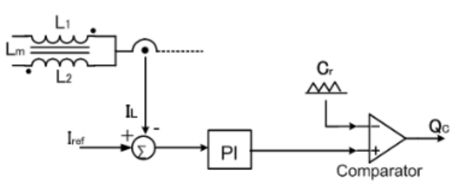


Figure 5. Control of CE-CSI

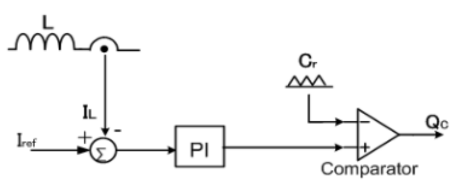


Figure 6. Control of H-bridge CSI

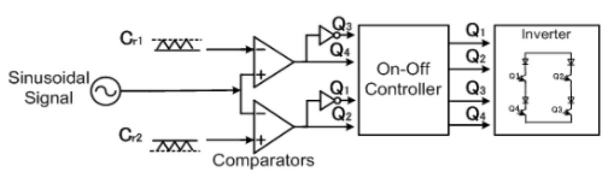


Figure 7. PWM modulation strategy of inverters

3. RESULTS AND DISCUSSION

To investigate the performance of the proposed inverter system, computer simulation tests were performed using PSIM software. The tested inverter circuits and PV system is shown in Figure 4. Table 3 presents test parameters of the common-emitter inverter circuit, while Table 4 lists test parameters of the H-bridge inverter circuit. The common-emitter inverter utilizes a transformer with the same winding number on both sides functioned as power inductors. The primary winding of a transformer is applied as the first inductor L_1, while the secondary winding is set as the second inductor L_2. The inductance of inductor L_1 and L_2 are the same as 0.01 mH with a winding resistance value of 0.1 mΩ. The magnetizing inductance of this transformer is 0.5 mH. In the case of H-bridge CSI, a single power inductor 0.01 mH was applied to generate the input dc current.

The switching operation of both inverters was set the same as 20 kHz, while the modulation index in this test was adjusted at a value of 0.9. A filter capacitor 10 µF was connected to each inverter's output terminal to filter the harmonics components of its PWM ac current. The two inverters shared a common inductive power load with resistance and inductance connected in series. To investigate different load power factor operations, two inductors with different values were tested with inductance 1 mH and 10 mH. These inductors were connected with resistor 4 Ω which gave load power factors of 0.996 and 0.782, respectively. Moreover, the specification of a photovoltaic module is indicated in Table 5. Ten photovoltaic modules with a capacity per module of 100 Wp were utilized for each inverter system. A constant light intensity of 1000 W/m^2 was applied to all photovoltaic modules.

Table 3. Parameters of common-emitter inverter

Parameters	Value
Inductance L_1 and L_2	0.01 mH
Resistance of inductors	0.1 mΩ
Magnetizing inductance	0.5 mH
Filter AC capacitor	10 µF
Working frequency of power switches	20 kHz
Modulation index	0.9
Main output frequency	50 Hz
Load	R = 4 Ω, L = 1 mH, and 10 mH

Table 4. Parameters of H-bridge inverter

Parameters	Value
Power inductor	0.01 mH
Filter AC capacitor	10 µF
Working frequency of power switches	20 kHz
Modulation index	0.9
Main output frequency	50 Hz
Load	R = 4 Ω, L = 1 mH, and 10 mH

Table 5. Parameters of PV system

Parameters	Value
Light intensity	1000 W/m^2
Temperature	25 ^{o}C
Series resistance	0.0032 Ω
Parallel resistance	2000 Ω
Short circuit current	12.14 A
Number of modules	10
Capacity per module	100 Wp

The system was tested by varying the current controller reference value of the inverter's output currents from 1 A to 9 A, based on the photovoltaic system capacity. Three possible operating conditions of the inverter system were evaluated to approach the real probable operation as follow:
- The current magnitude of H-bridge CSI was lower than the common-emitter CSI, $I_{csi1}<I_{csi2}$.
- The magnitude of two inverter currents were the same, i.e. $I_{csi1}=I_{csi2}$
- The current magnitude of H-bridge CSI was higher than the common-emitter CSI, $I_{csi1}>I_{csi2}$.

Figure 8 presents the injected current by H-bridge CSI (I_{csi1}), common-emitter inverter (I_{csi2}), and load current (I_{Load}) waveforms when the reference magnitude of H-bridge CSI current was lower than the common-emitter CSI, $I_{csi1}<I_{csi2}$, i.e. 1 A and 9 A. As can be observed, the output currents of the two inverters are sinusoidal currents. High-frequency ripples were more visible for common-emitter inverter current (I_{csi2}) where its magnitude is lower than I_{csi1}. Figure 9 shows the current waveforms of H-bridge CSI (I_{csi1}), common-emitter inverter (I_{csi2}), and load current (I_{Load}) when the magnitude of two inverter currents was adjusted the same, i.e.

I_{csi1}=I_{csi2}. The current waveform of I_{csi1} was a sinusoidal current with a smaller distortion than the first test condition. Furthermore, current waveforms when the current magnitude of H-bridge CSI is higher than the common-emitter CSI, I_{csi1}>I_{csi2} were depicted in Figure 10. The high-frequency current ripples appeared in the current generated by H-bridge CSI (I_{csi2}). Current waveforms of I_{csi1} and load current (I_{Load}) were closely sinusoidal current waveforms.

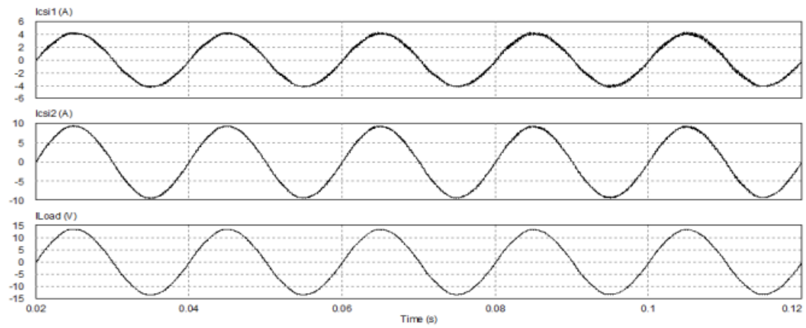


Figure 8. Injected current by H-bridge CSI (I_{csi1}), common-emitter inverter (I_{csi2}), and load current (I_{Load}) waveforms when I_{csi1}<I_{csi2}

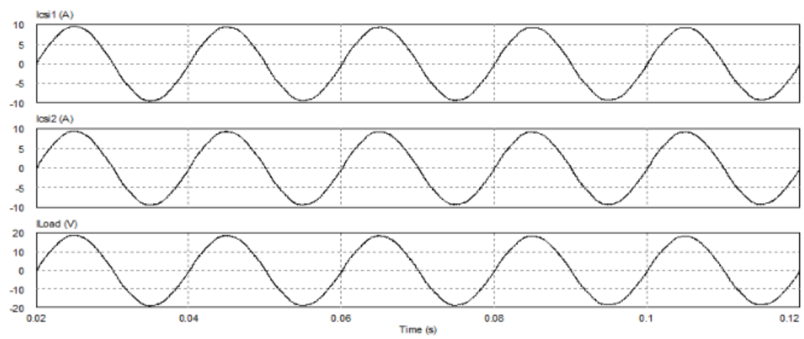


Figure 9. Injected current by H-bridge CSI (I_{csi1}), common-emitter inverter (I_{csi2}), and load current (I_{Load}) waveforms when I_{csi1}=I_{csi2}

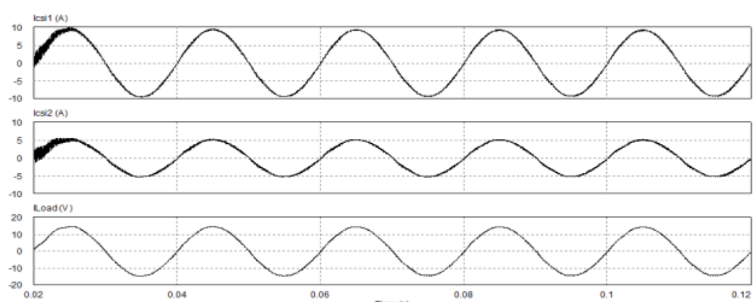


Figure 10. Injected current by H-bridge CSI (I_{csi1}), common-emitter inverter (I_{csi2}), and load current (I_{Load}) waveforms when I_{csi1}>I_{csi2}

To make a more detailed analysis of the waveform distortion, Figure 11 presents the harmonics profile of currents I_{csi1}, I_{csi2}, and I_{Load} for different magnitudes at load power factor 0.996. As can be noticed in Figure 11, in the case of an H-bridge inverter, if the magnitude of output current increases, the THD of output current will decrease. The minimum THD value of H-bridge CSI was 0.50% at output current 5A, and its maximum value was 21.27% at output current 1 A. In contrast, in the case of a common-emitter inverter, if the magnitude of output current increases, the THD will increase. The minimum THD value of I_{csi2} was 0.81% CSI at output current 5A, and its maximum value was 21.3% at output current 9 A. However, as can be seen in the graph, the THD values of load current were almost constant at around 0.34%. Even the THD value of both inverters varied, the THD value of the load current did not change. Figure 12 is the THD profile for different magnitudes of ac current at power factor 0.782. The minimum THD value of load current was 0.617% when output current H-bridge and common-emitter CSIs were 1 A and 9 A, respectively.

Total harmonics distortion (THD) profile for different load conditions with the same current magnitudes of common-emitter and H-bridge CSI, i.e. 5 A, is described in Figure 13. As can be viewed in the figure, if the resistance of load increases, the THD of the inverter's output current will also increase. The lowest THD value of load current was 0.38% when the load was 4 Ω, and the maximum THD was 0.51% when the load was 8 Ω. Moreover, the efficiency profile of the inverter system for different current magnitude operations is shown in Figure 14. The power inductors and diodes count of common emitter CSI is larger than H-bridge CSI. It will cause more power losses in the circuits. Hence, the efficiency of common-emitter CSI is basically lower than H-bridge CSI. Operating the H-bridge CSI in a larger current magnitude will give higher efficiency to the system. Compared to the system applying voltage source inverters, a lower efficiency is a limitation of the proposed current source inverter system. From the data, the minimum waveform distortion of inverter ac currents during parallel operation can be achieved if the current magnitudes of both inverters were set the same.

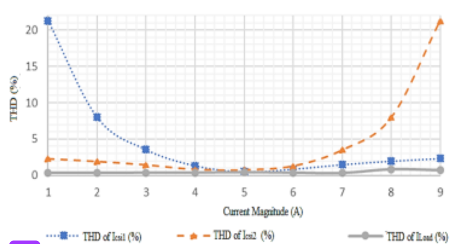


Figure 11. THD versus output current of inverters for power load R 4 Ω, L 1 mH

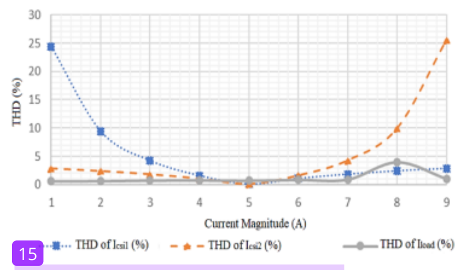


Figure 12. THD versus output current of inverters for power load R 4 Ω, L 10 mH

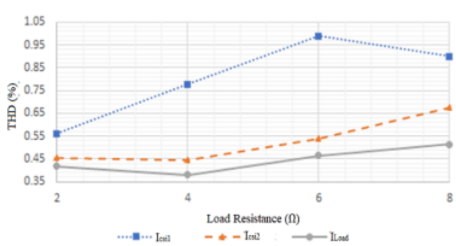


Figure 13. THD profile for different power load

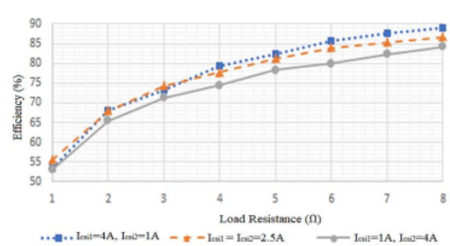


Figure 14. Efficiency profile for different load resistance and magnitude of output current

4. CONCLUSION

A novel photovoltaic energy conversion system constructed using H-bridge and common-emitter current source inverter circuits connected in parallel has been proposed and presented. In the case of dc current source generation, the H-bridge CSI circuit is less complex than the common-emitter CSI because it needs a single power inductor only. However, for gate drive circuit requirements, the common-emitter CSI is simpler because of the common-emitter connection of its power switches. The proposed system can be a new alternative for a photovoltaic system with a high-quality load current waveform. Test results have shown that the distortion of load current was less than 1%. Higher efficiency of the inverter system can be achieved by operating the H-bridge CSI with a higher magnitude of output current than the common-emitter CSI.

ACKNOWLEDGEMENTS

This work was funded by research grant provided by Jenderal Soedirman University, Indonesia.

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BIOGRAPHIES OF AUTHORS

Suroso received the B. Eng. degree in electrical engineering, from Gadjah Mada University, Indonesia in 2001, and the M. Eng. degree in electrical and electronics engineering from Nagaoka University of Technology, Japan in 2008. He was a research student at electrical engineering department, Tokyo University, Japan from 2005 to 2006. He earned the Ph.D degree in energy and environment engineering department, Nagaoka University of Technology, Japan in 2011. He was a visiting researcher at electrical and electronics engineering department, Shizuoka University, Japan from 2009 to 2011. Currently, He is a professor at department of electrical engineering, Jenderal Soedirman University, Purwokerto, Jawa Tengah, Indonesia. His research interest includes static power converters, and its application in renewable energy conversion system. He can be contacted at email: suroso.te@unsoed.ac.id.

Hari Siswantoro received B.Eng. degree in electrical engineering, Universitas Gadjah Mada in 2002. The master's degree in electrical engineering was awarded to him by Universitas Indonesia in 2013. Then he received a Ph.D. degree in ICT from the University of Trento, Italy, in 2018. Currently, he is an assistant professor at the electrical engineering department, Universitas Jenderal Soedirman. His research interests include formal verification of hardware and software design. He can be contacted at email: hari.siswantoro@gmail.com.

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