JOURNAL OF TECHNICAL EDUCATION SCIENCE
Ho Chi Minh City University of Technology and Education
Website: https://jte.hcmute.edu.vn/
Email: jte@hcmute.edu.vn

ISSN: 2615-9740

Design and Simulation of High-Power DC-AC 3-Phase Inverter for Island's Power System Using Solar Energy

Nguyen Phan Thanh, Nguyen Quang Luc *
Ho Chi Minh city University of Technology and Education (HCMUTE), Vietnam
* Corresponding author. *Email: 1980606@student.hcmute.edu.vn, quangluc5228@gmail.com*

ARTICLE INFO

Received:	16/11/2021
Revised:	6/2/2022
Accepted:	8/8/2022
Published:	30/8/2022

KEYWORDS

DC-DC Boost Converter;
4-Phase Interleaved Boost Converter;
Sinusoidal PWM;
SPWM Inverter;
Three-phase Inverter;
PI Controller;
MPPT Controller.

ABSTRACT

This paper presents the design of a DC – AC 3 phase 2 stages converter using programmable controllers which is performed on PSIM simulation software. The idea of this strategy is to present a method of controlling a large capacity DC-AC 3-phase AC voltage converter, with 380±20 VAC voltage output and 50Hz frequency, which is used for areas that need 3-phase electricity from the solar power system. In order to achieve a stable 3-phase AC voltage output, the converter is designed using the DC-DC 4-phase Interleaved Boost Converter in a double circuit and the Maximum Power Point Tracker (MPPT) of the solar system. In this scheme, the electrical energy obtained from the DC-DC boost converter circuit will provide power to the 3-phase inverter that operates on the sine-PWM technique. The power circuit and quality control of the converter are enhanced by using the DC-DC 4-phase Interleaved Boost Converter and phase shift technique. The control parameters of two power converters will be controlled by the PI controller. A 10kW DC-AC 3-phase converter model was carried out on PSIM to illustrate the simulation results and validate the effectiveness of the proposed method, so it is ready to be implemented for practical applications.

Doi: https://doi.org/10.54644/jte.71A.2022.1044

1. Introduction

Facing the increasing demand for 3-phase electricity in the areas that far from the mainland, it can be obviously seen that a 3-phase DC-AC voltage converter from a solar panel system is necessary. There are some techniques that combine the various methods such as finding the maximum power point of a solar panel (MPP) and phase shift voltage modulation techniques will contribute to the maximum capacity and efficiency of the system.

The previous DC-AC converters were usually single phase or 3 phases with small capacity and they were studied based on the maximum power point tracking (MPPT) method with P&O algorithm combined with a converter DC-DC is simple to regulate DC power, but the system performance is not optimal [1]. Therefore, an improved algorithm of the P&O algorithm has been designed [2] and combined with a DC-DC booster circuit based on the 4-phase Interleaved Boost Converter method in the aim of improving DC power and efficiency [3]. As for the DC-AC inverter, it uses a 3-phase sine wave phase shift control strategy to generate the sine-PWM (SPWM) to convert energy from DC to 3-phase AC, which is an easy pulse width modulation method implemented and is being studied and applied widely [4].

2. Theoretical Background

As shown in Figure 1, a 3-phase DC-AC converter is a combination of two DC-DC and DC-AC power converters, along with two programmable operation controllers.

The DC voltage output from the solar panel system will be directly connected to the DC-DC booster circuit; after the DC booster process, the energy source will directly supply power to the 3-phase inverter circuit in order to generate 3-phase AC voltage. The feedback voltage and current values at each conversion stage will be sent to the central processor to convert into modulation ratios. These modulation ratios are compared with the current and voltage reference values, and are regulated through the PI control algorithm to generate the PWM and SPWM signals. Finally, these PWM and SPWM signals will be fed to the DC-DC and DC-AC power circuits.

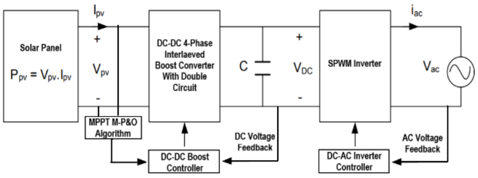


Figure 1. *The overall design schematic of DC-AC three-phase converter.*

2.1. The MPPT Method With M-P&O Algorithm

In the solar system, the DC/DC converter is tightly connected to the MPPT circuit. MPPT circuit consists of a DC/DC converter to adjust the input voltage taken from the solar cell, then convert and provide the maximum power for the load or the inverter.

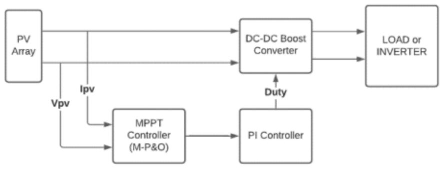


Figure 2. *Block diagram of MPPT-based PI controller.*

In this proposed scheme, the Modified-Perturb and Observer algorithm (M-P&O) is used to stabilize the input power threshold for the system. The M-P&O algorithm will operate as a "Latch" of the input power changing detection which will decide the value of the DC voltage reference for the boost converter that need to change or not. This is an improved algorithm from the basic P&O method with two improvements that are:[2]

- The new reference value index will be updated every 5 scan cycles of the system.
- When the power is increased or decreased by a value below the epsilon threshold ε (where ε is considered a small positive real number), the new reference value index will remain at its value, these additions can minimize fluctuations in the output power, as well as improved performance.

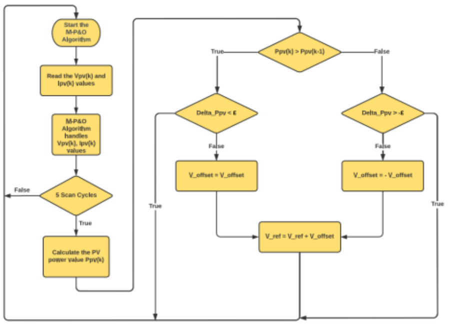


Figure 3. *The flowchart of M-P&O algorithm.*

2.2. Four-phase Interleaved Boost Converter

The design circuit of the four-phase interleaved boost converter has been shown as Figure 4 [5].

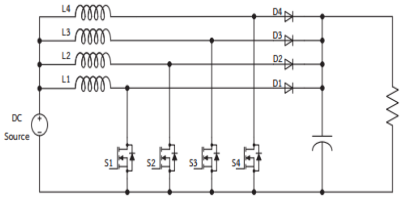


Figure 4. *Circuit of 4-phase interleaved boost converter (4-phase IBC).*

The circuit of four-phase interleaved boost converter is created by the parallel integration of 4 single boost converters, where each boost conversion consists of fast switching diodes D1, D2, D3, D4, power semiconductor S1, S2, S3, S4, and inductors L1, L2, L3, L4; they will be connected to a filter capacitor C and load R.

Commented [ĐM1]: four-phase

The gate pulses for the four-phase interleaved boost converter are phase shifted according to the following formula [5][6].

$$\theta = \frac{360}{N} \tag{1}$$

Where: N is the number of phases chosen for the boost converter.

The DC-DC four-phase interleaved boost structure takes advantage of expanding the power range of the converter. On the other hand, the phase shift pulse width modulation will help reduce the input current ripple, thus improving the quality of the boost circuit. The method to generate PWM signal for DC-DC booster circuit is shown in Figure 5.

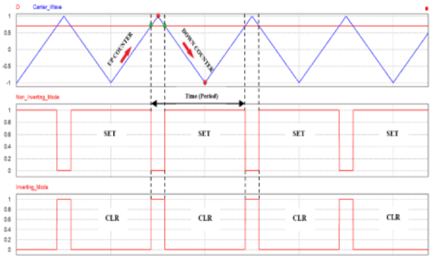


Figure 5. *PWM signal for DC-DC booster circuit*

The equation of duty cycle design for switching can be designed based on equation (2) [5][6].

$$D = 1 - \frac{V_{in}}{V_{out}} \tag{2}$$

Where:

- V_{out} is the output voltage of the converter.
- V_{in} is the input voltage of the converter.
- D is the duty cycle of operation.

The boost inductors L= L1 = L2 = L3 = L4 are calculated based on the switching frequency f_s, input and output voltages, V_{in} and V_{out} and the inductor current ripple ΔI_L [6].

$$L \geq \frac{V_{in} \times (V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} \tag{3}$$

The output capacitor is calculated [6].

$$C \geq \frac{V_{out} \times D}{R \times \Delta V_{out} \times f_s} \tag{4}$$

Where:

ΔV_{out} is the output voltage ripple.

The effect of the input current ripple relevant to the number of parallel branches in the boost circuit can be illustrated in Figure 6 [7].

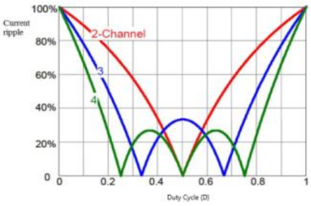


Figure 6. *Voltage ripple corresponding to the number of parallel branches of boost circuits.*

2.3. Three-phase Inverter Based on SPWM

A three-phase SPWM inverter is controlled by three sinusoidal modulating signals which displaced from each other by 120^O are compared with a triangular carrier waveform of suitably high frequency. The basic three-phase inverter circuit consists of 6 switches as shown in Figure 7.

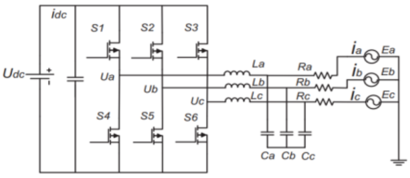


Figure 7. *The main circuit of three-phase inverter.*

Let m_a is the modulation ratio of the 3-phase inverter, we have:

$$m_a = \frac{V\_{ref}}{V_c} \tag{5}$$

Where:

- Vc is the carrier amplitude with high frequency.
- V_ref is the reference or sine wave of the modulated signal.

The value of the fundamental of this voltage varies linearly with the depth of modulation m_a.

$$V_{A-n} = m_a . \frac{V_{dc}}{2} \tag{6}$$

Where:

- V_{A-n} is the measured line-neutral voltage.
- Vdc is the voltage from the DC source.

The value of the fundamental line-line voltage is:

$$V_{A-B} = m_a.\frac{\sqrt{3}.V_{dc}}{2} \tag{7}$$

Where: $V_{A\text{-}B}$ is the measured line-to-line voltage.

The production of switching signals by sinusoidal PWM is shown in Figure 2. There are three sinusoidal reference waves ($V_{\_refA}$, $V_{\_refB}$, $V_{\_refC}$) each shifted by 120^{O}. The carrier wave Vc is compared to the corresponding reference signal to produce the switching signals of a phase [8].

$$\begin{aligned} V_{\_\mathrm{refA}} &= m_a.\sin(\omega t + 0^0) \\ V_{\_\mathrm{refB}} &= m_a.\sin(\omega t + 120^0) \\ V_{\_\mathrm{refC}} &= m_a.\sin(\omega t + 240^0) \end{aligned} \tag{8}$$

The SPWM result signal for three-phase are shown in Figure 8 for the inverter.

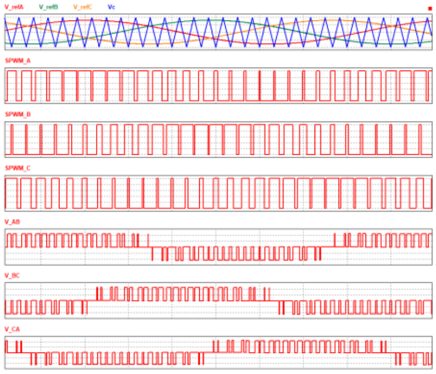


Figure 8. *Sinusoidal PWM for three-phase inverter.*

3. Designing of DC-AC 3-phase Converter Circuit

3.1. Designing & Simulation of Solar Photovoltaic (SPV)

The solar panels used in the system are Jinko solar cells with product code JKM540M-72HL4-V-STC with parameters in Table 1.

Table 1. *Parameters of SPV*

Parameters	Ratings
Maximum power point current	13.17 (A)
Maximum power point voltage	41.1 (V)
Parallel Resistance	1000 (Ω)
Series Resistance	0.0167 (Ω)
Ideality Factor	1.2
Short circuit current	13.85 (A)
Open circuit Voltage	49.53 (V)
Irradiation	1000w/m2

Because it is difficult to avoid the change in solar radiation, so the capacity of the solar panel system will be calculated according to the following:

$$P_{array-pv} = 1.2 \times P_{INV} = 12\ kW \tag{9}$$

Thus, for each solar panel, with a capacity at MPP of Ppvmax=504.76W, to achieve a total capacity of 12kW, we need at least 24 solar panels.

3.2. Design & Simulation of Four-phase Interleaved Boost Converter (4-phase IBC) with Double Circuit

Considering a system with an input voltage from the solar panel system of Vpv = 160~200 VDC, the expected output voltage of the boost circuit is V_{OP} = 600-800 VDC with current ripple across the inductor ΔI_L = 0.5A and the system supplies power to a load with a capacity of 10 kW.

Based on the formula in (1), (2), (3) and (4), the parameters for the simulation of DC boost circuit are shown in Table 2.

Table 2. *Parameters of 4-phase IBC circuit*

Parameters	Ratings
Degree of switching	90^O
Input voltage (Vpv)	160~200 (VDC)
Switching frequency (f_{SW})	20 kHz
Inductors (L1-L8)	12mH
Output capacitor (C1, C2)	540uF

3.3. Design & Simulation of Three-phase SPWM Inverter.

At the output of the inverter, it is connected to an LC filter for the purpose of stabilizing the voltage and suppressing harmonics emitted by the inverter to improve the voltage quality.

The value of inductor L and capacitor C in the LC filter are determined as the below formula [9][10].

$$f_C = \frac{1}{2\pi\sqrt{LC}} \tag{10}$$

Where: f_C: is the cut-off frequency of the system within the threshold: $f_C \leq \frac{f_{sw}}{10}$.

Thus, a simulation of a three-phase inverter with the parameters is defined in Table 3 as below:

Table 3. *Parameters of 3-phase inverter*

Parameters	Ratings
Degree of switching	120^O
Input voltage (Vdc)	600 (VDC)
Switching frequency (fSW)	20 kHz
Input capacitor (C1, C2)	560uF
Filter capacitor (C_filter)	1.2uF
Filter conductor (L_filter)	5mH
Induction Motor (IM1, IM2)	5kW

4. Results and Discussion

The circuit below is a combination of a double of four-phase interleaved DC-DC boost converter, SPWM three-phase inverter, and the controller inside each circuit. The simulation model uses six lines of solar panel which are connected in parallel. Radiation will be changed at a particular duration between 400W/m2 and 1000W/m2, the temperature is kept at 25°C. The parameters and circuit scheme of the DC-AC 3-phase circuit is shown in Table 4 and Figure 9, respectively.

Table 4. *Simulation parameters of DC-AC 3- phase converter*

Parameters	Rating
DC Degree of switching	90^O
AC Degree of switching	120^O
Switching Frequency	20 (kHz)
Input Voltage	160~200 (VDC)
Output Voltage	380±20 (VAC)
Output Frequency	50 (Hz)
Inductors	12 (mH)
Capacitor DC-link (C1, C2)	560 (uF)
Load Induction Motor (IM1 & IM2)	5kW

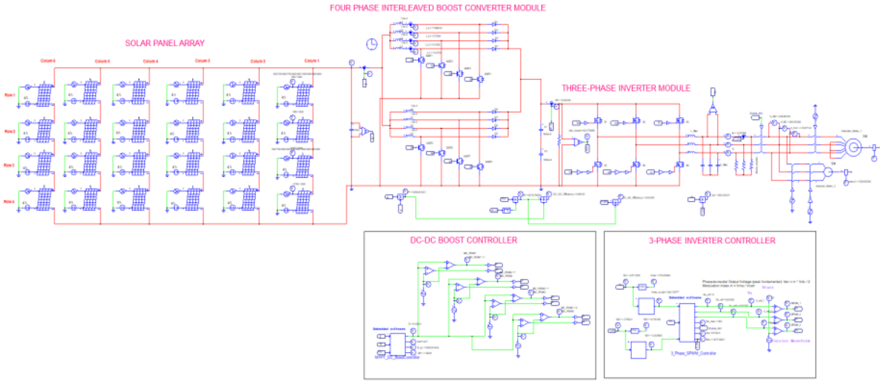
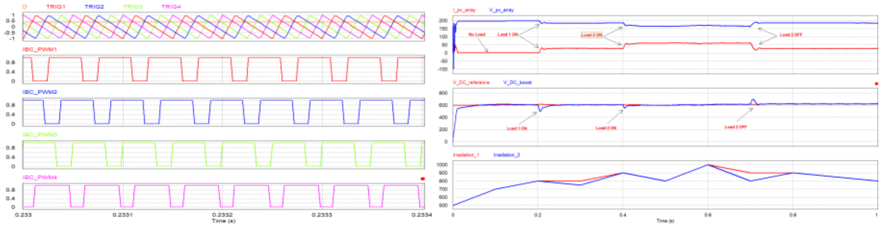


Figure 9. *Circuit scheme of DC-AC 3-phase converter*.

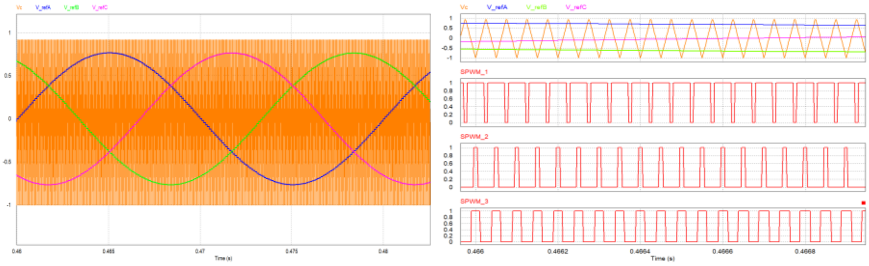
The simulation results of the DC-DC boost circuit are shown in Figure 10 with the required input voltage from the solar panel array from 160VDC to 200VDC and the slow-changing output voltage from 600VDC to 800VDC. It is controlled and maintained by PI controller.



(a) *(b)*

Figure 10. *Simulation results of 4 modulation waves 4-phase IBC(a) and DC-DC boost circuit output(b).*

The simulation results on the 3-phase inverter are achieved, showed in figures 11, 12 with the required output line voltage $V_{line\text{-}to\text{-}line} = 380\pm20$ VAC and output phase voltage $V_{line\text{-}neutral} = 220\pm10$ VAC, frequency = 50Hz, total harmonic distortion THD <5%.



(a) *(b)*

Figure 11. *The result signal of three reference waves V_refA, V_refB, V_refC (a) and SPWM simulation (b).*

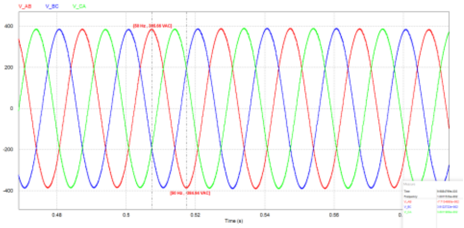
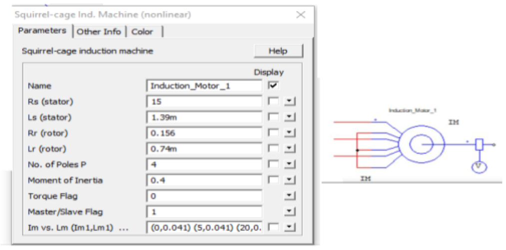


Figure 12. *The result of line – line inverter output simulation.*

The converter uses PI controller in the aim of improving efficiency and responsiveness to changes in input DC power as well as load changes on the output of the converter. On the other hand, PI controller also plays a role in reducing the inrush current of the converter in case of load variation in the power system.

The load used in this simulation are two induction motors with the parameters are shown in Figure 18.

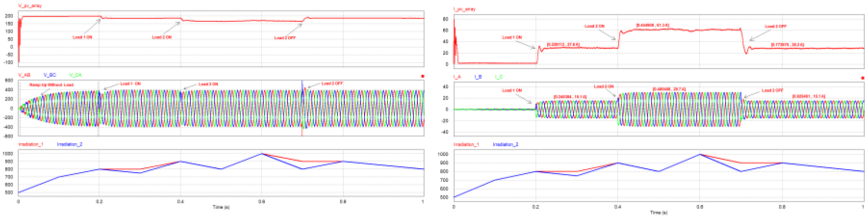


Squirrel-cage Ind. Machine (nonlinear)

Squirrel-cage induction machine

Name: Induction_Motor_1 ☑
Rs (stator): 15 ☐
Ls (stator): 1.39m ☐
Rr (rotor): 0. 156 ☐
Lr (rotor): 0. 74m ☐
No. of Poles P: 4 ☐
Moment of Inertia: 0.4 ☐
Torque Flag: 0
Master/Slave Flag: 1
Im vs. Lm (Im1,Lm1) ...: (0,0.041) (5,0.041) (20,0. ☐

Figure 13. *The parameters of the load induction motor.*



(a) *(b)*

Figure 14. *The voltage(a) and current(b) response of the converter while changing load.*

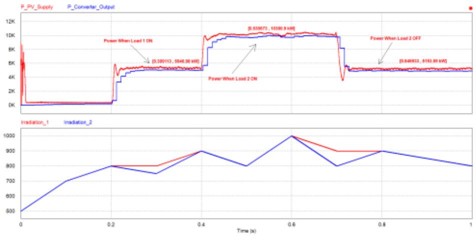
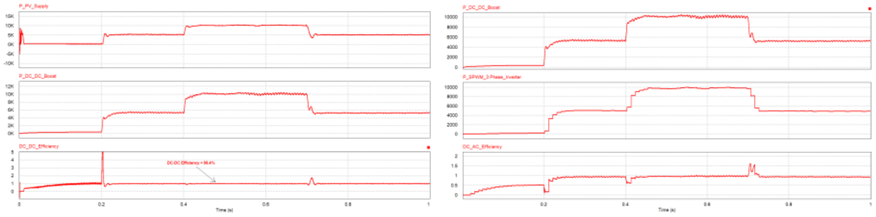


Figure 15. *The active power response of the converter while changing load.*

As we can see, Figures 14 and 15 show that the responsibility of the whole system always adapts with the changing of load (two induction motors) and the changing in solar radiation. The voltage is always kept at a steady state when changing the power of the load and the current adapts with the increasing or decreasing of the load.

The efficiency of the whole system is greatly improved by combining DC-DC 4-phase IBC double-unit techniques with the Maximum Power Point Tracking with M-P&O algorithm, besides the regulation of the PI controller on the DC-DC boost circuit and the SPWM 3-phase inverter circuit.

The simulation results demonstrate that the efficiency of the DC-DC boost circuit and the SPWM 3-phase inverter circuit is 99.4% and 96%, respectively, and is stable when there is a change in load, are shown in Figure 16.



(a) *(b)*

Figure 16. *The efficiency of 4-phase IBC with double the unit of circuit is 99.4% (a) and the SPWM 3-phase inverter is 96%(b) .*

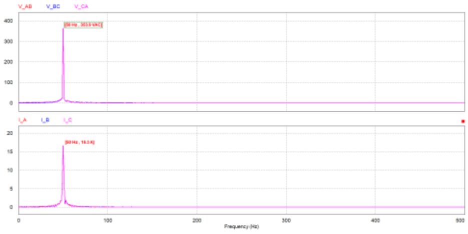


Figure 17. *The FFT (Fast Fourier Transform) analysis THD of output current and output voltage.*

Figure 17 shows that the value of total harmonics distortion THD is less than 5%; it means the quality of the output current and output voltage is officially validated for the proposed method.

5. Conclusions

This paper focuses on the design of high-power DC-AC 3-phase converter for areas far from the mainland that need to use 3-phase electricity from solar systems. The simulation results of the phase shift modulation techniques show that the system can contribute up to 10kW 3-phase electrical power. The converter can be run effectively at high-power factor, up to 96%.

Reaching the requirements of the research target, the converter output parameters can be achieved at 3-phase 380±20VAC line voltage, base frequency 50Hz. Moreover, the inrush currents on loads and total system output harmonics are turned down significantly by PI controller.

REFERENCES

[1] T.-F. Wu and Y.-K. Chen, “Modeling PWM DC/DC converters out of basic converter units,” *IEEE Transactions on Power Electronics*, vol.13, no.5, pp.870–881, 1998.

[2] S. Motahhir, A. E. Ghzizal, S. Sebti, and A. Derouich, “Proposal and implementation of a novel perturb and observe algorithm using embedded software,” *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, 2015.

[3] S. P. Biswas, M. H. Mondol, M. K. Hosain, A. Mahanta, and M. Y.-Y. U. Haque, “A Four-Phase DC-DC Interleaved Boost Converter Using Feedback Controller,” *2019 5th International Conference on Advances in Electrical Engineering (ICAEE)*, 2019.

[4] W. Subsingha and P. Sarakarn, “4 Phase Interleaved DC Boost Converter for PEMFC Applications,” *Procedia Engineering*, vol.32, pp.1127–1134, 2012.

[5] I. Laoprom, S. Tunyasrirut, W. Permpoonsinsup, and D. Puangdownreong, “Simulation of Four Phase Interleaved Boost Converter,” *2019 7th International Electrical Engineering Congress (iEECON)*, 2019.

[6] P. Prasanth and Dr. R. Seyezhai, “Investigation of four phase interleaved boost converter under open loop and closed loop control schemes for battery charging applications “, *International Journal of Advances in Materials Science and Engineering (IJAMSE)*, Vol.5, No.1, Jan. 2016.

[7] T. V. Tran, V. V. Nguyen, V. N. Nguyen, and H. D. Duong, Ho Chi Minh City University of Technology (2014). “Experimental implementation of single phase to three phase AC-DC-AC converter based on TMS320F24069,” *The 8th National Conference on Mechatronics - VCM-2016*, 2016.

[8] Ö. Türksoy*, Ü. Yılmaz, A. Tan, and A.Teke, “A Comparison Study of Sinusoidal PWM and Space Vector PWM Techniques for Voltage Source Inverter,” *NESciences*, 2017.

[9] N. R. Hadianto, Mustaghfiri, Sholihah, F. H., Pratilastiarso, and J., & E.Tridianto, “Design and Implementation of Three-Phase Grid-Connected Inverter for PV System,” *2019 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, 2019.

[10] T. Bhattacharjee, M. Jamil, and A. Jana, “Design of SPWM based three phase inverter model,” *2018 Technologies for Smart-City Energy Security and Power (ICSESP)*, 2018.

Phan-Thanh Nguyen is currently a lecturer in the Faculty of Electronics and Electrical Engineering, Ho Chi Minh City University of Technology and Education. He obtained his Ph.D. in Electrical Engineering at Southern Taiwan University of Science and Technology, Taiwan, in 2016. His current research interests are Intelligent control systems, Automatic motion control and Electric drives. He can be contacted at email: thanhnp@hcmute.edu.vn

Quang-Luc Nguyen received the B.S. degree in Electrical & Electronic Engineering from Eastern International University, Binh Duong, Vietnam, in 2018. From 2017 to 2019, he was a Research Assistant with the Energy & Power Electronics Center and researching under the guidance of Ph.D Tran Thanh Vu. He is currently working as an Electrical Design Supervisor at Organo Co.,LTD (Japan Company) as well as M.Eng student at Ho Chi Minh City University of Technology and Education. He can be contacted at email: 1980606@student.hcmute.edu.vn