REDUCE HARMONIC FOR PHOTOVOLTAIC INVERTERS BY SPWM CONTROL METHODS VIA SIMULATION AND EXPERIMENT ASSESSMENT OF PHOTOVOLTAIC SYSTEMS

Trinh Trung Hieu[1], Nguyen Tho Hoang[2], Tran Ngoc Thien Nam[3], Van Trong Nhan[1], Duong Minh Quan[1*]
[1]*The University of Danang -University of Science and Technology,*
[2]*Vietnam Electricity - Power Transmission Company No.3,* [3]*Delta Electronic INC., Taiwan*

ARTICLE INFO

Received: 13/7/2023
Revised: 21/8/2023
Published: 22/8/2023

KEYWORDS

Control
Harmonic
Inverter
Photovoltaic
Power

ABSTRACT

The article explores the implementation of Sinusoidal Pulse Width Modulation (SPWM) control techniques to mitigate harmonic distortions in photovoltaic inverters. The researchers utilized a combination of simulation and experimental assessments to evaluate the effectiveness of these methods in photovoltaic systems. The study highlights the significance of harmonic reduction in photovoltaic inverters, as harmonic distortions can lead to power quality issues and impact the overall performance of the photovoltaic system. SPWM control methods are considered an efficient approach to minimize these distortions. To assess the performance of the SPWM control techniques, the researchers employed both simulation-based experiments and real-world experiments with actual photovoltaic systems. The simulation-based approach allowed them to model various scenarios and optimize the control methods under different conditions, while the real-world experiments provided valuable insights into the practical applicability of these techniques. The observed experimental results show that the proposed method has a lower level of output harmonic distortion than the previous control method, and at the same time, the practical value closely follows the reference value and complies with the operating standards of IEC and IEEE.

NGHIÊN CỨU GIẢI PHÁP ĐIỀU KHIỂN SPWM NHẰM GIẢM SÓNG HÀI CHO NGHỊCH LƯU QUANG ĐIỆN BẰNG PHƯƠNG PHÁP THỰC NGHIỆM VÀ MÔ PHỎNG

Trịnh Trung Hiếu[1], Nguyễn Thọ Hoàng[2], Trần Ngọc Thiên Nam[3], Văn Trọng Nhân[1], Dương Minh Quân[1*]
[1]*Trường Đại học Bách Khoa - Đại học Đà Nẵng,*
[2]*Điện lực Việt Nam - Công ty truyền tải điện 3,* [3]*Tập đoàn Điện tử Delta, Đài Loan*

THÔNG TIN BÀI BÁO

Ngày nhận bài: 13/7/2023
Ngày hoàn thiện: 21/8/2023
Ngày đăng: 22/8/2023

TỪ KHÓA

Điều khiển
Điều hoà
Biến tần
Quang điện
Năng lượng

TÓM TẮT

Bài viết tìm hiểu việc triển khai các kỹ thuật điều khiển chế độ rộng xung hình sin (SPWM) để giảm thiểu sóng hài trong bộ biến tần quang điện. Các nhà nghiên cứu đã sử dụng kết hợp các đánh giá mô phỏng và thử nghiệm để đánh giá hiệu quả của các phương pháp này trong các hệ thống quang điện. Nghiên cứu nhấn mạnh tầm quan trọng của việc giảm sóng hài trong bộ nghịch lưu quang điện, vì biến dạng sóng hài có thể dẫn đến các vấn đề về chất lượng điện năng và ảnh hưởng đến hiệu suất tổng thể của hệ thống quang điện. Các phương pháp điều khiển SPWM được coi là một cách tiếp cận hiệu quả để giảm thiểu những biến dạng này. Để đánh giá hiệu suất của các kỹ thuật điều khiển SPWM, các nhà nghiên cứu đã sử dụng cả thí nghiệm dựa trên mô phỏng và thí nghiệm trong thế giới thực với các hệ thống quang điện thực tế. Cách tiếp cận dựa trên mô phỏng cho phép họ lập mô hình các kịch bản khác nhau và tối ưu hóa các phương pháp điều khiển trong các điều kiện khác nhau, trong khi các thử nghiệm trong thế giới thực cung cấp những hiểu biết có giá trị về khả năng ứng dụng thực tế của các kỹ thuật này. Kết quả thực nghiệm quan sát được cho thấy phương pháp đề xuất có mức méo hài đầu ra thấp hơn so với phương pháp điều khiển trước đây, đồng thời giá trị thực tế bám sát giá trị tham chiếu và tuân thủ các tiêu chuẩn vận hành của IEC và IEEE.

DOI: https://doi.org/10.34238/tnu-jst.8328

[*] Corresponding author. *Email: dmquan@dut.udn.vn*

1. Introduction

Because conventional generation sources are gradually limited, renewable energy plays a significant role in ensuring energy security when the system is operating. The power electronics industry and converters are improving through the day, showing this energy's increasingly competitive cost and technology. Especially in the distribution system, small solar panel system is known as photovoltaics system in the form of rooftop increasingly taking up a large proportion of electricity generation [1], [2]. Still, the high penetration level of this type of energy also has many underlying causes of instability when connected to the system [3], [4]. Inverters help to convert solar energy into AC energy with high stability and easy inject to the distribution system. However, power quality can be degraded due to harmonics generated during conversion.

Some previous studies used a K-factor transformer as a filter to reduce harmonics [5], [6]. This solution increases the installation cost and is only effective with large power sources. Some previous studies have investigated advanced passive filters of form LCL, or LLCL integrated into converters to reduce high-order harmonics [7] – [9]. The effectiveness of this method has also been shown to reduce harmonics to an acceptable level. However, the fabrication cost of the converter will increase as well as the size. Therefore, it is necessary to study the control methods of the inverter and the source of harmonic problems in the converter.

There have also been many studies dealing with various control methods for the inverter to smooth the output responses of the converter. Converter control methods for improving output response stability without regard to whether there is any influence on the harmonics produced level [10], [11]. Moreover, most of these studies are simulations under standard conditions without outside physical effects like the natural environment, application for energy backup sour.

Evaluating inverter control methods in experimental conditions to prove their stable performance and observe the level of harmonics injected into the grid is necessary when the rooftop PV is a trend. Therefore, this study proposes a control method for the inverter and compares it with the current popular inverter method. The evaluation process is conducted through simulation and an empirical evaluation model. The inverter model is an H-bridge with less than 2kW, suitable for inverters applied to current rooftop PV. From there, the accuracy and high objectivity of the results in this study can be shown.

2. Advanced Inverter Control Techniques

2.1. SPWM for H-Bright inverter

SPWM is a PWM-based sinusoidal modulation method for inverters based on the requirement to provide a sine wave for AC load in output. The control signal transmitted to the semiconductor valves of the inverter is generated by changing the width pulses in proportion to the amplitude of the reference signal. In other words, the control signal is generated by comparing a sine control wave of frequency f_r and amplitude v_r with a carrier of frequency f_c and amplitude v_c.

The frequency of the carrier determines the switching frequency of valves, while the amplitude and frequency of the control wave decide for output voltage and frequency of the inverter, which is characterized by a m_a amplitude modulation:

$$m_a = \frac{V_r}{V_C} \tag{1}$$

For $0 \leq m_a \leq 1$, the control region is considered linear. Otherwise, $m_a > 1$ is considered nonlinear control region. Current control methods all give control wave values in the linear region [10] with the amplitude of the fundamental sine component of the phase voltage V_{AC} in the output waveform proportional to the modulation factor according to the formula

$$V_{AC} = m_a \times V_{DC} \tag{2}$$

Where: V_{DC} is the input voltage of the inverter.

Another important factor related to the quality of the inverter is the frequency modulation factor which is the ratio of the f_c to f_r. The m_f value is designed to have an even positive value [10]-[12]. Suppose m_f is a non-integer value, subharmonic components in the output waveform. If m_f is not an even number, the output waveform has a DC component and even harmonics. The value of m_f should be a multiple of two single-phase countercurrents.

$$m_f = \frac{f_C}{f_r} \tag{3}$$

2.2. Control method 1 – use HF Signal

Using an HF signal is a variant of the classic unipolar method. Instead of one triangular wave with an amplitude from -1 to 1, this method uses two alternating triangular waves to double the frequency. The control signal is fed into valves in both branches A and B of the H-bridge Inverter, shown in Figure 1. Branch A includes a pair of semiconductor valves S1 and S2, and branch B includes a pair of semiconductor valves S3 and S4. The signal is generated by comparing the control and carrier waves, as shown in Figure 2.

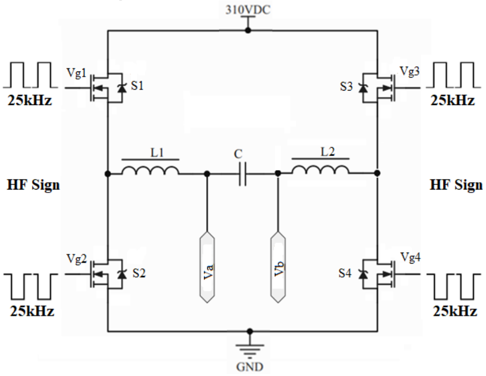

Figure 1. *H-bridge diagram and HF signal*

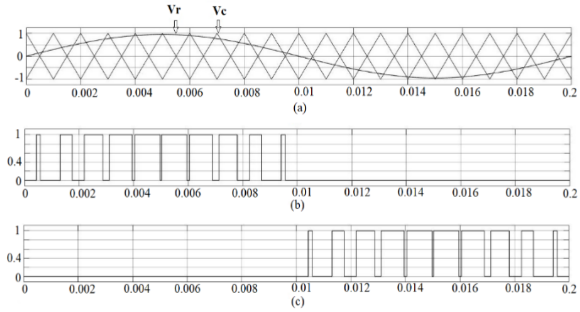

Figure 2. *Control Waveform Method 1*

2.3. Control method 2 – Combine HF sign and LF sign

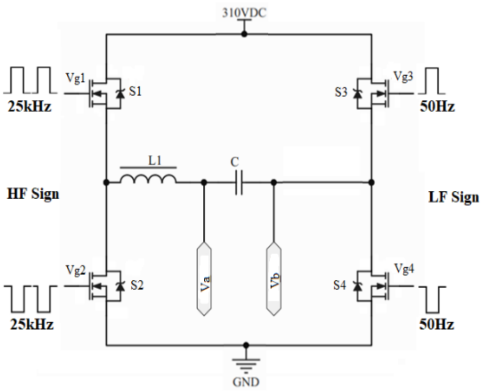

Figure 3. *H-bridge diagram using HF signal*

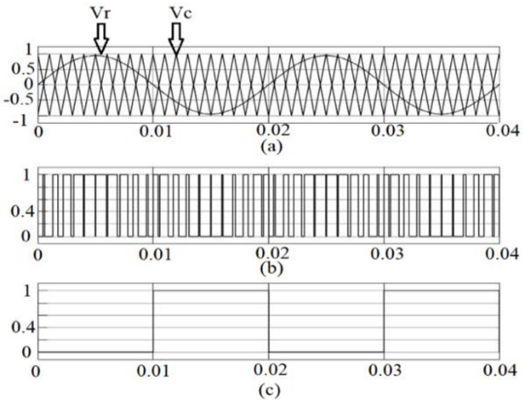

Figure 4. *Control waveform method 2*

In this method, logic gates are added to change the control waveforms so that the HF Signal feeds into the H-bridge A branch, and the other branch will be at 50Hz (LF Signal), as shown in Figure 3 and Figure 4. The advantage of the method compared with HF signal is to use only 1 filter coil on the high-frequency side, so the loss is smaller while the harmonics output load less.

Vg1 and Vg3 are the conduction impulses for valves S1 and S3, while the leading impulse S2 compensates for the conduction impulse S1 and is similar for S4 and S3.

2.4. Simulation Evaluations

2.4.1. Simulation model

The LCL type filter is designed as Figure 3 with the total inductance of the two inductors, L_1 and L_2, that should be less than 10% of the base inductor of the system to avoid large voltage drop [9], [10]. The current fluctuation I_{Ripple} is limited to 20% of rated current, from which inverter side inductor L_1 is selected based on a maximum allowable ripple of ΔI_{Ripple} current as in eq. (1).

Based on the theoretical diagram, the inverter is simulated in MATLAB/Simulink to evaluate the operability through the two mentioned control methods. The details of the pulse generator block, as Figure 5, send the signals to IGBT of H-bridge inverter in Figure 6 to operation. With control method 2, the case of using one filter coil in branch A (HF sign) and the case of using two filters are considered to show the advantages of the proposed control method. The simulation and experimental cases are summarized in Table 1.

Table 1. *Evaluation cases in simulation and experiment*

Case	Describe
1	Control method 1 with 2 inductor output filter
2	Control method 2 with 1 inductor output filter
3	Control method 2 with 2 inductor output filter

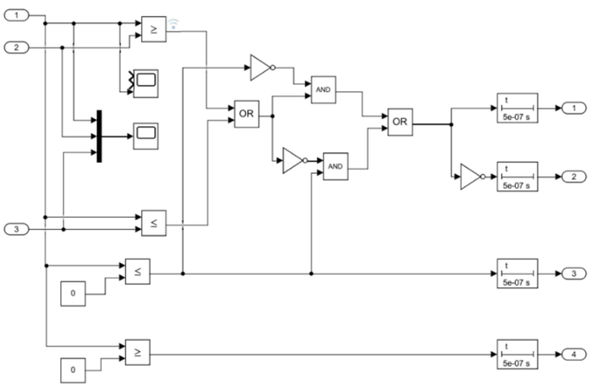

Figure 5. *Pulse Generator block*

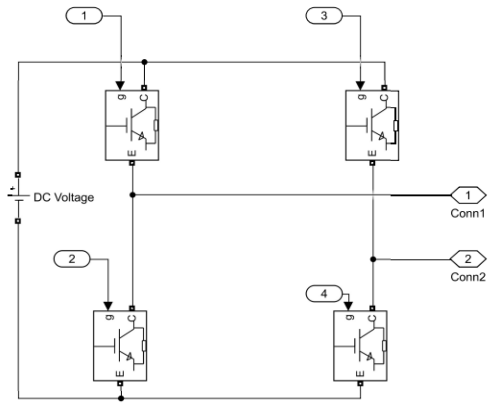

Figure 6. *IGBT module block*

2.4.2. Simulation results

The simulation results in case 1 are shown in Figure 7 and Figure 8. The current and voltage responses show that the output wave follows the standard sine form. The level of harmonics of the voltage is a little high, leading to the effects still oscillating in the form of sawtooth harmonics due to the triangular carrier wave f_c shown in Figure 8, while the level of electrical distortion is relatively low.

Detailed results of THD can be observed in Figure 8, with the total harmonic distortion of voltage and current of 4.77% and 2.46%, respectively. The degree of distribution of low-order harmonics (below 600 Hz, from 1st to 12th order) of voltage is lower than current, whereas high harmonic (above 600 Hz, from 12th to 20th order) of voltage has a difference discharge more than its current. That makes the obtained THD result of the voltage more significant.

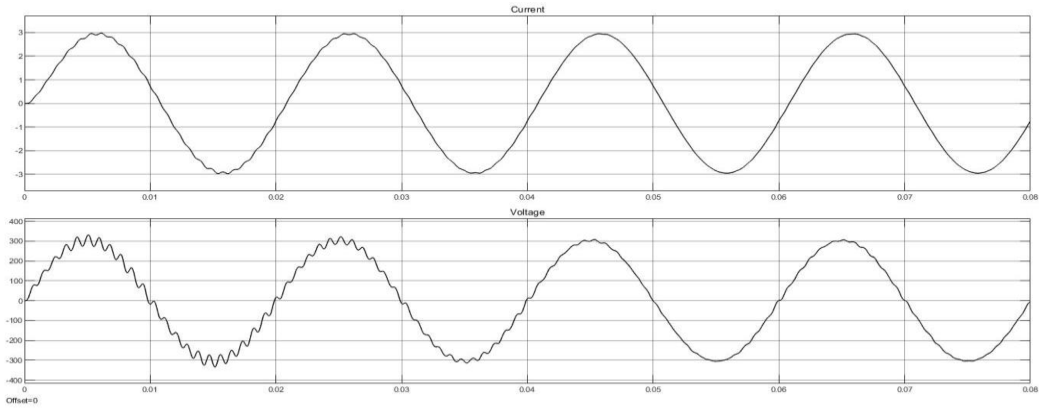

Figure 7. *Current (above)- Voltage (under) responses – Case 1*

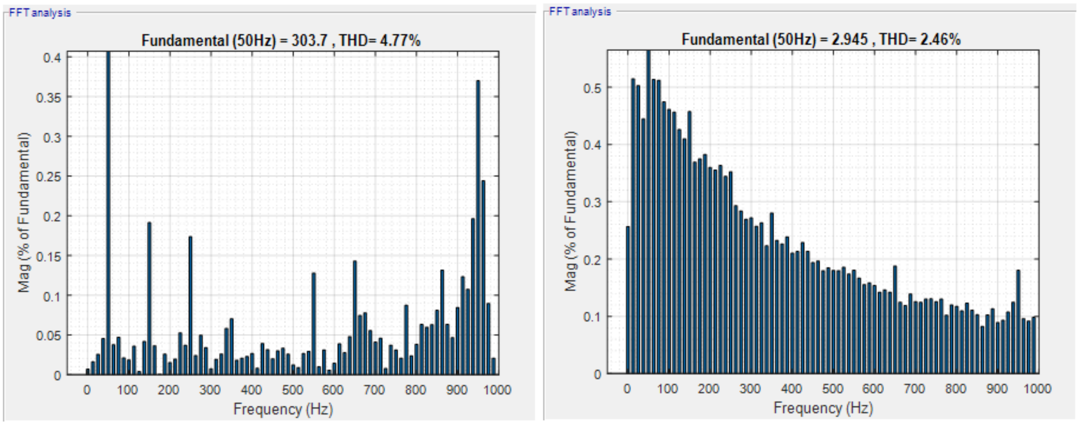

Figure 8. *THD of voltage (left side) and current (right side) - Case 1*

For case 2, with the responses investigated as in case 1, the voltage and current waves in Figure 9 show that there are still harmonics present, but to a lower level and a smoother waveform. Details of THD composition and similar results are also clearly shown in Figure 10, with voltage THD and current THD values of 3.26% and 2.33%, respectively.

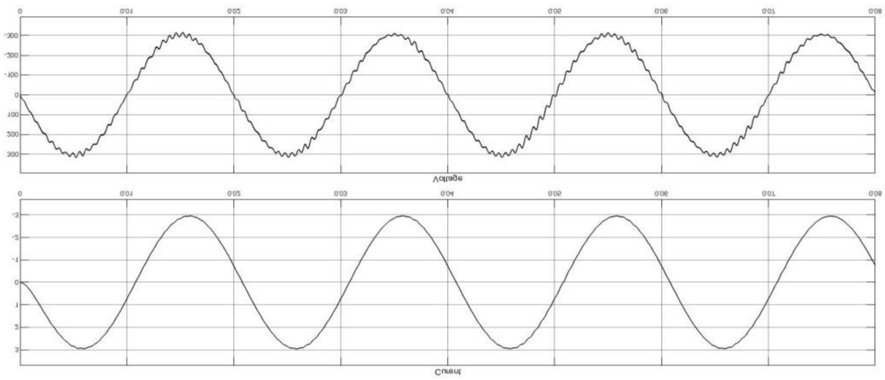

Figure 9. *Current (above)- Voltage (under) responses - Case 2*

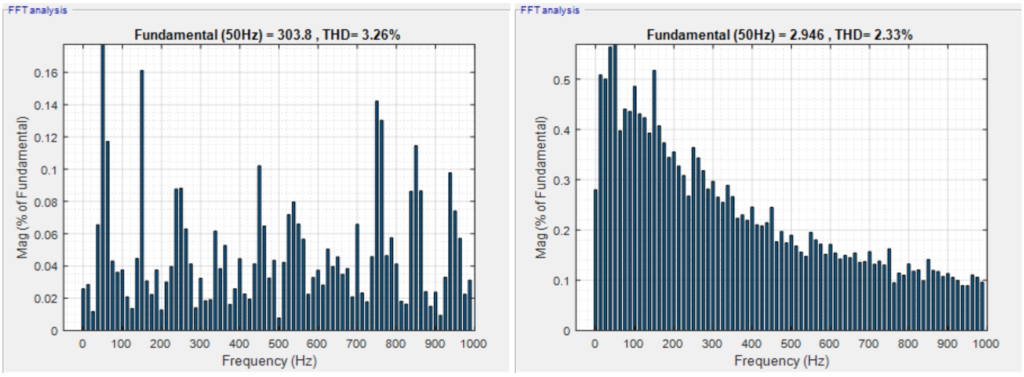

Figure 10. *THD of voltage (left side) and current (right side) - Case 2*

Compared with case 2, case 3 added one more filter coil inductor in branch B to be similar to case 1. The results of the obtained voltage and current waveforms are similar to case 2 with low distortion. Even the THD of voltage is better than the case of only a filter coil with a value of 2.98%, while the THD of current is only 2.39%, as shown in Figure 11 and Figure 12.

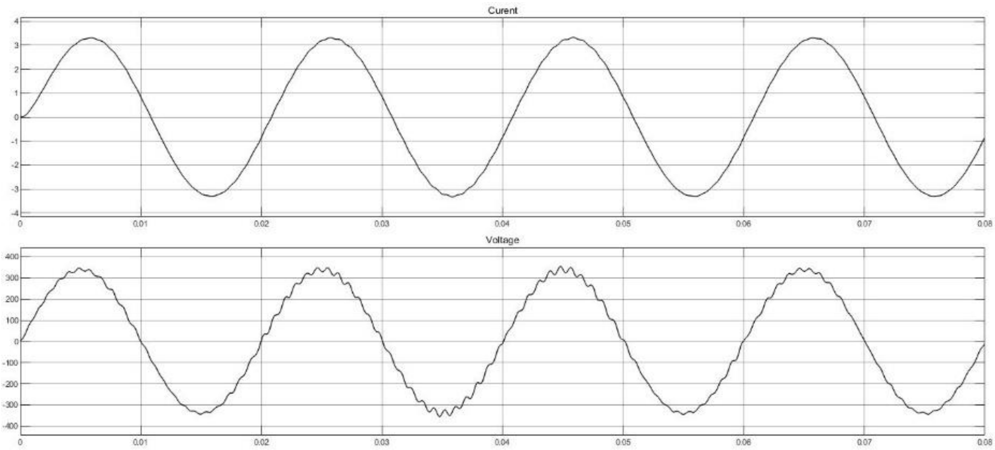

Figure 11. *Current (above) and Response Voltage (under) - Case 3*

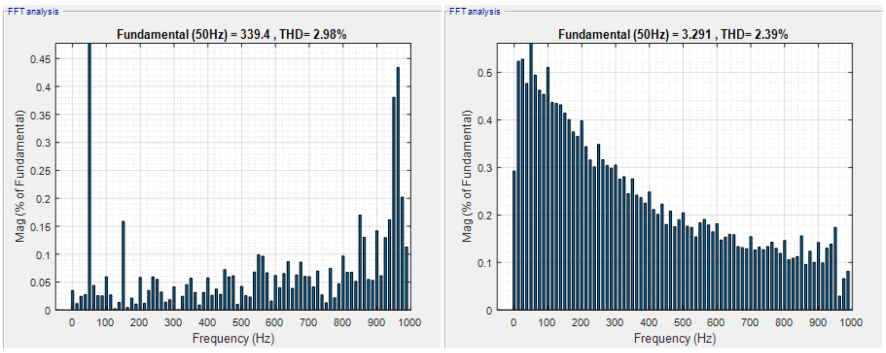

Figure 12. *THD of voltage (left side) and current (right side) - Case 3*

Table 2. *Simulation results*

	THD I (%)	THD V (%)
Case 1	2.46	4.77
Case 2	2.33	3.26
Case 3	2.39	2.98

The results in the simulation cases are summarized in Table 2. It is easy to see that the proposed control method when combining the HF signal and LF signal shows that the harmonic level from the inverter is significantly reduced while that of the inverter that the practical value is also much higher.

3. Experimental results and discussion

3.1. Integrated Filters for Grid-Tied Inverter

3.1.1. Experimental model

Based on the schematic block in Figure 13, the experimental model is designed and fabricated from the simulation progress in Figure 14. All three cases are designed based on equivalent parameters to ensure accuracy in the evaluation process. The test circuit uses the dsPIC33FJ16GS502 microprocessor to control the IGBT via an optoisolated drive circuit using the TLP250opto. The DC source uses a voltage of 310VDC from the photovoltaic system, hash rate is 25 kHz for HF Signal and 50 Hz for the LF signal, using a resistive load R=45Ω. The filter circuit has the value L=2.2 mH, C=4.7 uF, and coefficient m_a=0.9. To measure harmonic distortion, a multimeter Chauvin Arnoux CA.6116N was used, and Siglent SDS 1052DL+ oscilloscope with 50Mhz bandwidth, 50GSa/s sampling rate can get the data of the experimental model correctly.

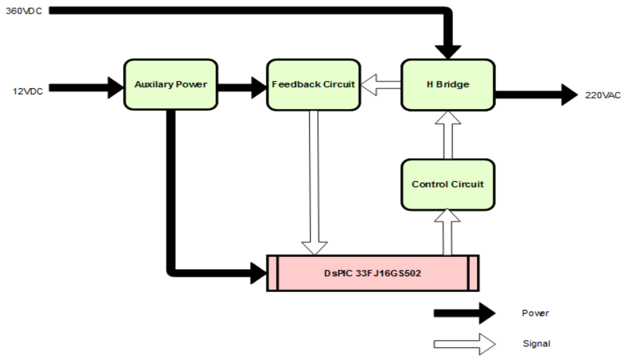

Figure 13. *Block diagram of experimental model*

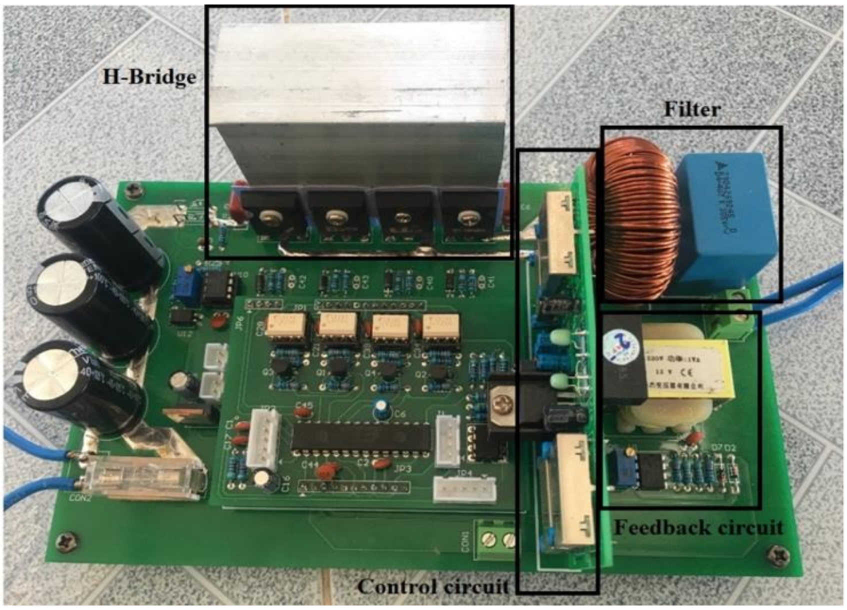

Figure 14. *Experimental model*

3.1.2. Results

The experimental process is performed with two scenarios: no-load and load. The results obtained with the control methods and the corresponding cases show that the output voltage responses from Figure 15 to Figure 17 are in standard sinusoidal form with very low distortion, and the output voltage frequency is around 50Hz.

Detailed experimental results are summarized in Table 3. Voltage harmonics at no-load and have loaded almost equivalent, but the current harmonics of method 2 give lower harmonic values than method 1 in both cases. The proposed solution shows the effectiveness of both the significant value and the THD ratio. For IEEE and IEC standards, the total harmonic distortion for the low voltage grid is less than 6.5%, the expected value is less than 5%, and the individual harmonic distortion is less than 3%.

Table 3. *Detail experimental results*

	Voltage THD at no-load (%)/$V_{No\ load}$	**Voltage THD at load (%)/V_{Load}**	**Current THD(%)/I_{Load}**
Case 1	1.2% / 209.7V	1.6% / 183.8V	4.7%/ 4.02A
Case 2	1.0% / 206.9V	1.3% / 182.8V	1.8%/ 4.11A
Case 3	1.1%/ 212V	1.4% / 186.1V	3.7%/ 4.16A

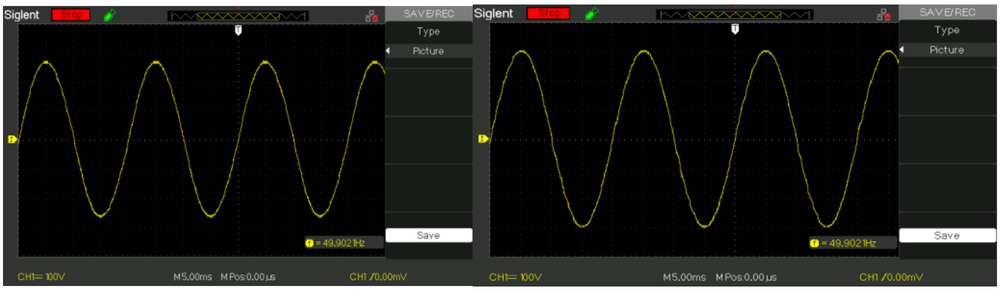

Figure 15. *Experimental voltage waveforms with no load (left) and load (right) – Case 1*

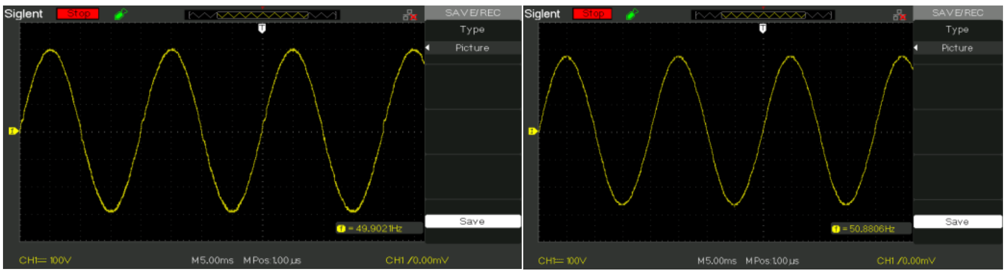

Figure 16. *Experimental voltage waveforms with no load (left) and load (right) – Case 2*

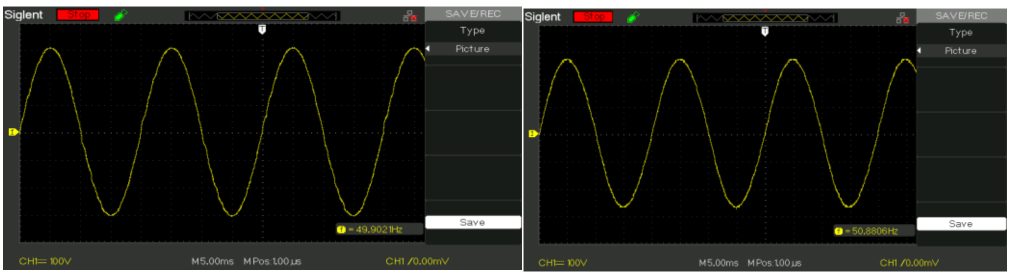

Figure 17. *Experimental voltage waveforms with no load (left) and load (right) – Case 3*

4. Conclusion

With the increasing penetration of solar energy nowadays, especially in rooftop PV, improving the inverter control method is essential to be studied in depth. Furthermore, simulation and experimental evaluations are required to ensure power quality when connected to the grid or supplied to the load.

This study investigates and proposes control methods for small inverters and, at the same time, verifies the ability to operate under the influence of actual physical conditions to ensure accuracy and objectivity. The results show that the experimental circuit coincides with the simulation results and that the control method affects the output THD and the efficiency of the proposed method.

However, the higher the rooftop solar system's installed capacity, the higher the inverter capacity is required. That will require solutions to stabilize the system, improve power quality, and need to be paid more attention to ensuring the safe operation of power systems.

Acknowledgements

This research was funded by the Ministry of Education and Training under project number CT 2022.07.DNA.06

TÀI LIỆU THAM KHẢO/ REFERENCES

[1] M. Q. Duong, N. Thien, N. A. M. Tran, G. N. Sava, and V. Tanasiev, “Design, Performance and economic efficiency analysis of the photovoltaic rooftop system,” *Rev. Roum. Scie. – Techn. Électrotechn. Et Énerg.*, vol. 64, no. 3, pp. 229–234, 2019.

[2] S. A. Tadjer and I. Habi, “Improvement of the Quality of Electrical Power by a Photovoltaic Generator Connected to the Grid,” *Rev. Roum. Sci. Techn. – Électrotechn. et Énerg*, vol. 61, no. 1, pp. 37-41, 2016.

[3] M. Q. Duong, N. T. N. Tran, and C. A. Hossain, “The Impact of Photovoltaic Penetration with Real Case: ThuaThienHue–Vietnamese Grid,” *International Conference on Robotics Electrical and Signal Processing Techniques (ICREST),* 2019, pp. 682-686.

[4] S. Das, P. K. Sadhu, B. Satpati, and A. K. Shrivastav, “An Innovative Harmonic Reduction Strategy to Ascertain the Stability of a GridConnected Photovoltaic System,” *Rev. Roum. Sci. Techn. – Électrotechn. et Énerg*, vol. 62, no. 2, pp. 165-169, 2017.

[5] Varschavsky, J. Dixon, M. Rotella, and L. Morán, “Cascaded Nine-Level Inverter for Hybrid-Series Active Power Filter, Using Industrial Controller,” *IEEE Transactions on Industrial Electronics*, vol. 57, no. 8, pp. 2761-2767, Aug. 2010.

[6] D. Martin, S. Goodwin, O. Krause, and T. Saha, “The effect of PV on transformer ageing: University of Queensland's experience,” *2014 Australasian Universities Power Engineering Conference (AUPEC),* 2014, pp. 1-6.

[7] S. Jayalath and M. Hanif, “Generalized LCL-Filter Design Algorithm for Grid-Connected Voltage-Source Inverter,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 3, pp. 1905-1915, March 2017.

[8] M. Q. Duong, V. T. Nguyen, A. T. Tran, G. N. Sava, and T. M. C. Le, “Performance Assessment of Low-pass Filters for Standalone Solar Power System,” *2018 International Conference and Exposition on Electrical and Power Engineering (EPE),* 2018, pp. 0503-0507.

[9] W. Wu, Y. He, and F. Blaabjerg, “An LLCL Power Filter for Single-Phase Grid-Tied Inverter,” *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 782-789, Feb. 2012.

[10] D. Zammit, C. S. Staines, and M. Apap, “Compensation techniques for non-linearities in H-bridge inverters,” *Journal of Electrical Systems and Information Technology*, vol. 3, no. 3, pp. 361-376, 2016.

[11] El-Hosainy, H. A. Hamed, H. Z. Azazi, and E. E. El-Kholy, “A review of multilevel inverter topologies, control techniques, and applications,” *2017 Nineteenth International Middle East Power Systems Conference (MEPCON),* 2017, pp. 1265-1275.

[12] J. Hu, C. Bi, K. Jia, and Y. Xiang, “Power Control of Asymmetrical Frequency Modulation in a Full-Bridge Series Resonant Inverter,” *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7051-7059, Dec. 2015.