International Journal of Latest Research in Engineering and Technology (IJLRET)
ISSN: 2454-5031
www.ijlret.com || Volume 11 - Issue 06 || June 2025 || PP. 32-42

Improving the Total Harmonic Distortion (THD) of the Output AC Voltage of Modular Multilevel Converter (MMC) in Grid-Connected Solar Power System

Nguyen Van Hiep[1,2*], Nguyen Tran Quoc Bao[1,2], Phan Quoc Dung[1,2]
[1]*Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology*
[2]*Vietnam National University – Ho Chi Minh City*
[*]*Corresponding Author*

Abstract: Modular Multilevel Converter (MMC) is an important component in grid-connected solar power systems due to its ability to generate high-quality output voltage, easy structure expansion, and efficient operation in large-power applications. Research on MMC focuses on improving the quality of output voltage and enhancing operational reliability, especially in renewable energy systems where output voltage and power often fluctuate depending on environmental conditions. This paper proposes a solution to improve the total harmonic distortion (THD) of the output voltage from MMC in grid-connected solar power systems. The solution integrates the Maximum Power Point Tracking (MPPT) algorithm to ensure optimal power exploitation from solar panels. At the same time, the paper focuses on analyzing the impact of the number of sub-modules in the MMC on the quality of the output voltage, including the level of harmonic distortion and operational stability. The main objective is to develop a suitable MMC design and control method to minimize THD, ensuring that the output voltage meets the strict standards of the grid-connected power system. In addition, the paper also discusses in detail the mechanism of integrating MPPT into the MMC, thereby highlighting the ability to optimize the system's operation under conditions of continuous changes in sunlight intensity. The testing process is carried out through simulation on MATLAB/Simulink software, in which the system parameters are surveyed to determine the relationship between the number of sub-modules and the quality of the output voltage. The research results provide useful information to guide the design of MMC for renewable energy systems, not only optimizing performance but also ensuring operational flexibility, suitable for the requirements of modern energy systems.

Keywords: Grid-connected solar power system, modular multilevel inverter, maximum power point, total harmonic distortion.

I. Introduction

In the context of renewable energy development, grid-connected solar power systems play an increasingly important role in providing clean and sustainable electricity. However, one of the major challenges in connecting solar power systems to the grid is the issue of power quality, especially the total harmonic distortion of the output voltage from the inverter.

Modular multilevel converter is one of the advanced technologies used in grid-connected solar power systems to convert direct current (DC) from solar panels into alternating current (AC) suitable for the grid. However, a notable problem is the generation of harmonics during the power conversion process, leading to unstable voltage quality, affecting the performance of the equipment and the grid system. Total harmonic distortion is an important index used to measure the distortion level of the output voltage wave. High THD can cause phenomena such as signal interference, reduce the life of the equipment and reduce the efficiency of the grid-connected solar power system. Therefore, improving the THD of the output voltage from MMC inverters is an urgent requirement to ensure power quality, improve system efficiency, and comply with the power quality standards and regulations of the connected grid. The problem of improving THD in grid-connected solar power systems can be achieved through many methods, such as optimizing control parameters, using harmonic filters or improving inverter design. However, choosing the most suitable and effective method is still a matter of research and development interest. Therefore, research on improving THD of output voltage from MMC inverters in grid-connected solar power systems is not only of theoretical significance but also brings practical applications, contributing to improving the quality of renewable energy and optimizing the performance of future solar power systems.

This paper presents the implementation of the design of a grid-connected solar power system combined with the MPPT algorithm to optimize the power obtained from solar radiation, then using an MMC inverter to convert DC voltage to AC suitable for grid connection. The main task of the research is to find the optimal number of MMC steps to improve the grid-connected output voltage, minimizing THD to match the grid standards. This is easily done by adding or removing the number of modules in the MMC [1], [2]. The features and efficiency of the MPPT algorithm and the operation of the grid-connected solar power system when the number of MMC steps changes are verified through a system simulated on Matlab/Simulink. The operation of the components, voltage quality... of the model will be comprehensively evaluated.

The rest of the paper is presented in an organized manner. In Chapter II, related studies are presented. Chapter III and Chapter IV present an overview of the system components and simulation results, respectively. Chapter V implements the controller proposal and finally the conclusion is presented in Chapter VI.

II. Related Works

Nowadays, MMC is increasingly asserting its role in optimizing performance and minimizing harmonic distortion, promising wide application in grid-connected PV systems and renewable energy conversion, so there have been many studies related to the above technique.

An advanced modulation method by triangular saturated common mode pulse width modulation (TSCMPWM) has been proposed, which is specially designed for grid-connected PV systems based on 3-phase 5-level MMC inverters [3]. The modulation signal of TSCMPWM is formed by adding triangular saturated common mode signal to the sinusoidal reference signal, which brings significant efficiency. This technique has new advantages over traditional modulation methods, when implemented, it will aim to minimize THD at the output (both voltage and current), as well as limit switching and conduction losses in the system.

For a modular multi-level high voltage direct current (MMC-HVDC) converter system, a new method is proposed to model and stabilize the system harmonics through the use of a passive circulating current filter (PCCF) [4]. The above technique has shown its effectiveness based on the analysis of harmonic stability from the Bode plots performed, compared with the time domain simulation results and FFT, thereby ensuring the accuracy and practical applicability in applications connected to renewable energy sources.

A power balancing strategy for a grid-connected single-phase H-bridge multilevel inverter with multiple independent PV arrays was also studied [5]. This control system operates based on energy data from the PV system, using a separate linear discrete voltage loop controller for each PV array, ensuring stability under all operating conditions. Thanks to its special structure, the staircase-shaped AC output waveform of this system achieves significantly lower THD than waveforms from two-level inverters, while reducing the need for output filters to comply with grid harmonization standards.

Another important component in the MMC system is the arm inductor (Larm). This inductor is designed to be connected in series with the phase converter, which plays a role in optimizing the circulating current ripple and minimizing higher harmonics [6]. This study shows that increasing the size of the arm inductor not only improves the total current THD response, but also has a positive impact on the output voltage waveform. Experiments and simulations have demonstrated that by adjusting the arm inductance, the MMC achieves more stable performance, especially when applying non-closed-loop PID control.

III. Grid-Connected Solar Power System and Modular Multi-Level Converter

A basic grid-connected solar power system is modeled and simulated using Matlab/Simulink software for studies on optimizing input power and improving output voltage quality. The structure of the system of basic elements is as follows:

- 34kW solar panel system is connected to a DC/DC boost converter combined with MPPT algorithm.
- Three-phase multilevel converter connected to R – L – C filter.
- 10kW AC load is connected to the AC bus.
- Transformer to step up the AC output voltage of MMC to connect to the 22kV grid.

In grid-connected mode, the solar system provides a stable DC voltage. The boost converter is controlled by the MPPT algorithm to provide maximum power. When the generated power is greater than the load demand, the surplus will be fed to the grid. Otherwise, the microgrid will receive power from the utility grid.

A. Maximum power control in solar panel system

The I-V characteristic of a photovoltaic cell changes with the irradiance of the cell. For each irradiance S, there will be a point on the I-V characteristic of the cell at which the cell reaches its maximum output power. If this is also the operating point of the photovoltaic system and the load, the efficiency of the system will be at its maximum. However, with a load with a fixed I-V characteristic, when the irradiance on the cell changes, the system may not operate at the maximum power point.

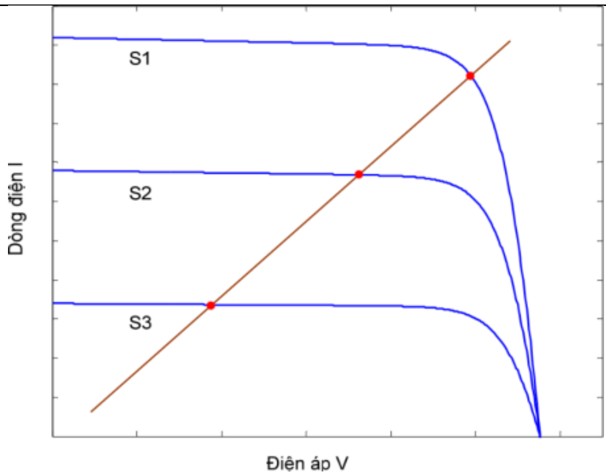

Figure 1: The operating point of the battery-load system varies with the insolation

From there, a control algorithm is needed to maximize the power output, which is the function of MPPT algorithms. In fact, many MPPT algorithms have been proposed, of which two algorithms are commonly used for conventional maximum power controllers: the perturbation and observation (P&O) algorithm and the incremental conduction (INC) algorithm. Currently, these two algorithms are widely used in commercial MPPT converters. The most special are the Hill-climbing algorithms due to their simplicity and high MPPT efficiency (up to 99%). In addition, the MPPT algorithm based on fuzzy logic is also receiving much attention in power electronics research, considered one of the most superior algorithms due to its ability to track the MPP point under rapidly changing radiation conditions [7].

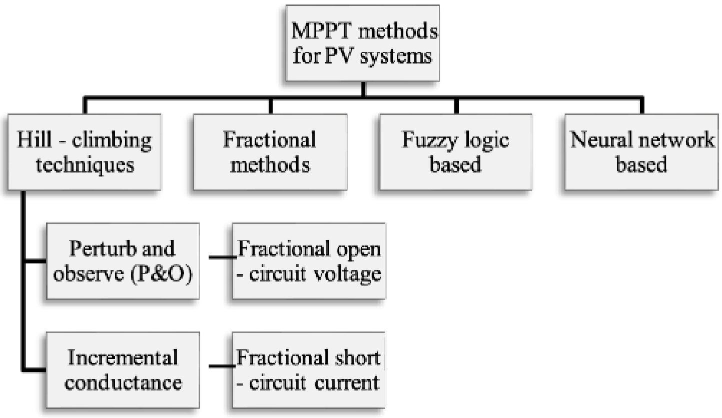

Figure 2: Popular MPPT algorithms for photovoltaic cells today

In this study, the P&O algorithm was chosen because of its advantages of being simple and easy to implement, with a short settling time. Although the P&O algorithm also has limitations such as not being able to track the MPP point during sudden solar radiation. However, after considering many factors, especially the test environment without many special fluctuations, the P&O algorithm is still a suitable choice.

*** Perturb and Observe (P&O) Algorithm**

The Perturb and Observe (P&O) algorithm is a form of Hill – climbing algorithm. The most basic form of the P&O algorithm works as follows:

Suppose that the PV array is operating at some point A on the $P_{PV} – V_{PV}$ curve, which is far away from the MPP. Point A can be either to the left or to the right of the MPP. In the P&O algorithm, a small voltage perturbation is applied. The operating voltage of the PV array is perturbed by a small change in ΔV and as a result the output power of the array changes by a measurable amount, ΔP.

- If ΔP > 0, then the perturbation of the PV array operating voltage has brought its operating point closer to the MPP. Thus, the next perturbation voltage will be in the same direction (same sign as the previous perturbation) and bring the operating point even closer to the MPP.
- If ΔP < 0, the operating point has moved away from the MPP, and the sign of the perturbation voltage needs to be reversed to bring the operating point towards the MPP.

The algorithm oscillates around the MPP point when entering the steady state. The magnitude of the perturbation voltage is kept very small to keep the voltage oscillation small. The P&O algorithm can be represented by the algorithm flowchart in Figure 3.

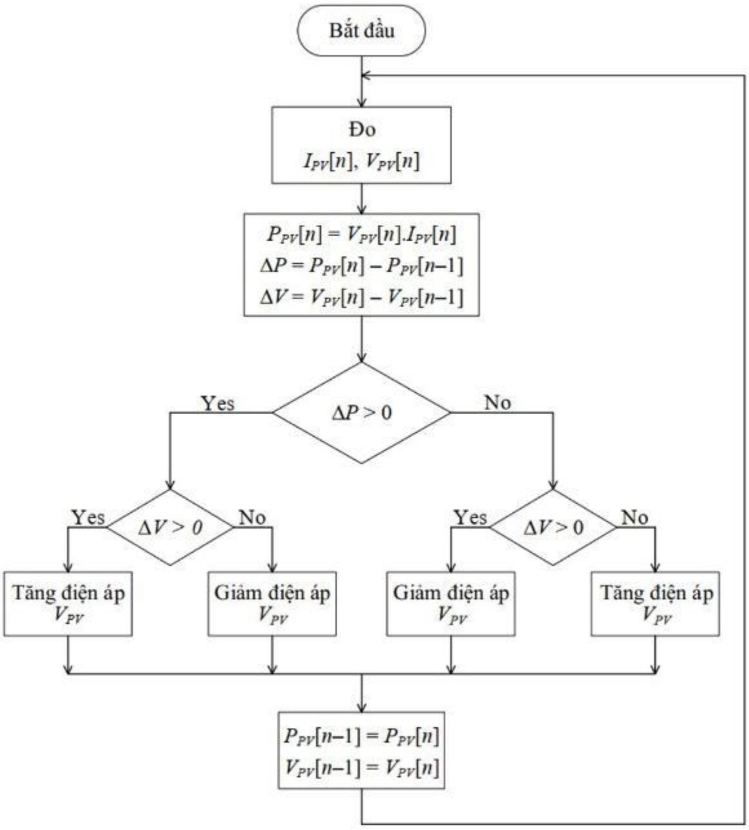

Figure 3: P&O algorithm flowchart

Algorithm explanation:

The MPPT controller will measure the current I and voltage V values, then calculate the deviation ΔP, ΔV and check:

- If ΔP x ΔV > 0 then increase the reference voltage value Vref.
- If ΔP x ΔV < 0 then reduce the reference voltage value Vref.

Then update the new values to replace the previous values of V, P and measure the parameters I, V for the next working cycle.

B. Proposed distributed control method for MMC [1]

Figures 4 and 5 show the control structure for the MMC inverter. In order to realize multi-level modulation at the voltage output, the carriers will be arranged in the range from 0 to 1. Figure 6 shows the arrangement of 4 carriers for one phase as an example. For the proposed structure, each module consists of 2 single-phase hemispherical units and a module controller to calculate and generate a carrier whose amplitude and position depend on the number of modules in one phase, the position of the module being calculated. The modules will exchange information about the position and total number of modules in the system, these signals are received from the front module and transmitted to.

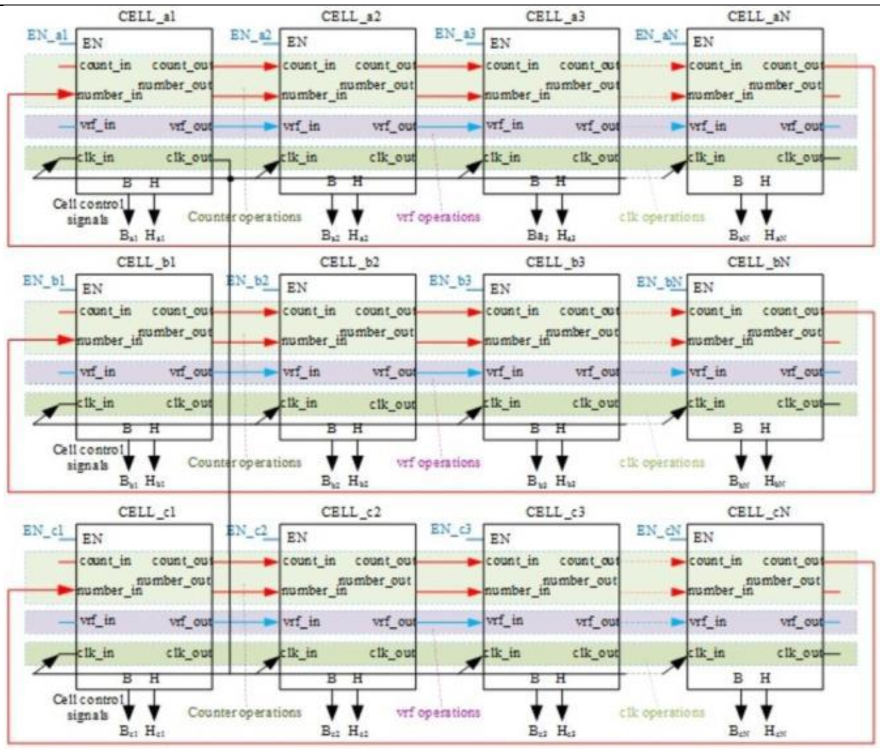

Figure 4: Flowchart of carrier modulation algorithm for PWM

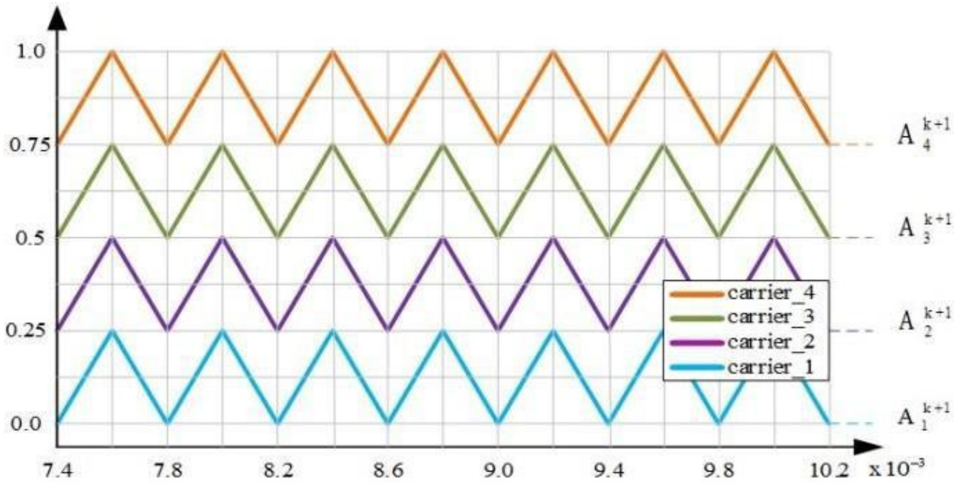

Figure 5: Carrier level update rule

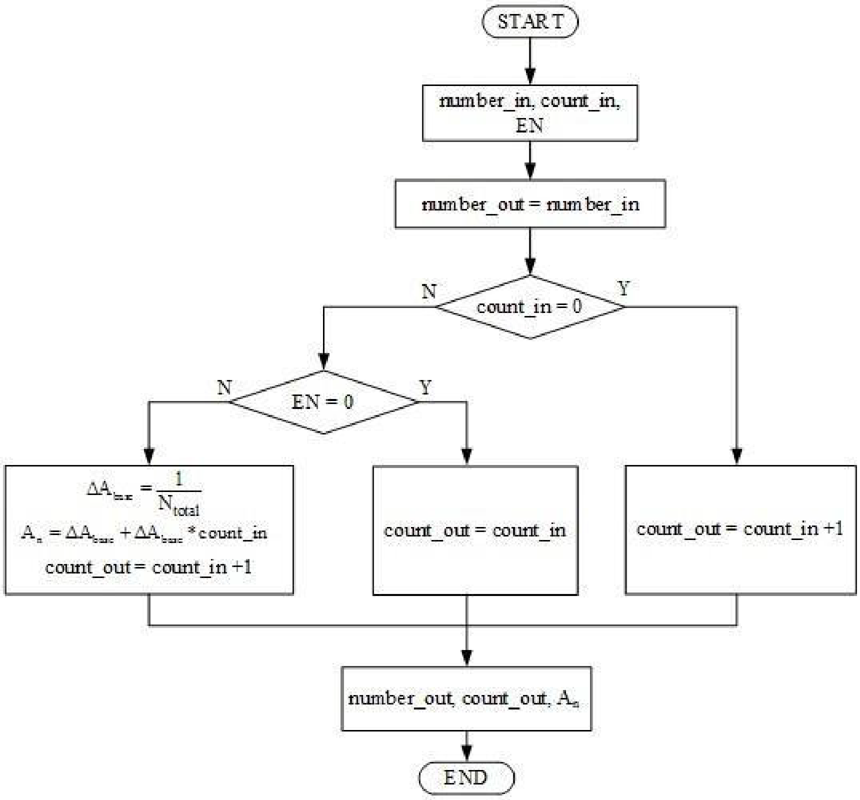

Figure 6: Flowchart of carrier modulation algorithm for PWM pulses

The proposed method is implemented using the formulas below. The implementation rule for module position numbering is very simple: at module n, at iteration k, the module n – 1 sequence number (named count_in) is read and incremented by one, which is assigned count_out. The same sequence is applied to all modules. Since the sequence number information line is just an open loop, the module at the first position has a value of 0 (no information). The information count of the last module is the total number of activated modules in the chain and it can be transmitted to all modules. The peak-to-peak amplitude of a carrier is calculated as ΔA_{k+1} and the level of the nth carrier is calculated as A_{k+1} using the internal variables of the module controller and there is no need to update the level information A_{n-1} (external variable) of the (n – 1)-th forward module as proposed in the traditional method, which increases the reliability of the processed data. The functions, meanings of the inputs, outputs and internal variables of a module are explained in Table 1. The algorithm flowchart of the improved DSA-LSC method is illustrated in Figure 6. The removal of any module is controlled by the enable signal (EN).

$$\text{count\_out}_n^{k+1} = \text{count\_in}_{n-1}^{k} + 1$$

$$\Delta A_{base}^{k+1}$$

$$A_n^{k+1} = \Delta A_{base}^{k} + \Delta A_{base}^{k} + \text{count\_in}_n^{k+1}$$

Input	
EN	Enable
count_in	Receive position information from the preceding module
number_in	Receive the total number of modules from the preceding module
vrf_in	Receive modulation signal from the preceding module
clk_in	Receive synchronization clock pulse from the preceding module
Output	
count_out	Transmit position information to the adjacent module
Number_out	Transmit the total number of modules to the adjacent module

Vrf_out	Transmit modulation signal to the adjacent module
clk_out	ransmit synchronization clock pulse to other modules
B,H	IGBT gate control signal
Internal variable	
ΔA_{base}	Peak-to-peak amplitude of the carrier level
A_n	n-th carrier level (low level)
N_{total}	Total number of activated modules

Table 1: Input/Output Functions of a Module

The survey model is a three-phase MMC, with a PWM modulator with 6 modules per phase. The simulation parameters are given in Table 1, the parameters used for simulation are suitable for systems with a capacity of less than 100kW and a low voltage of less than 500V.

To verify the system's operation, we performed the simulation on MATLAB/Simulink software. The task of the MPPT algorithm is to find the operating point to optimize the obtained power. To simplify the simulation and data collection process, the ambient temperature is kept constant at 25℃ and the solar radiation ranges from 100 to 1000 W/m2, with a step of ΔIr = 100 W/m2. Because using too low a number of sub-modules in MMC can lead to some important limitations, such as reducing the number of output voltage steps, which will increase harmonic distortion and reduce voltage quality. Therefore, the problem is only analyzed and evaluated in cases where the number of sub-modules in each phase is from 2 to 6, ignoring the case where MMC has only 1 sub-module. This also avoids problems related to device failure, if only one sub-module is active when a fault occurs it will affect the operation of the system.

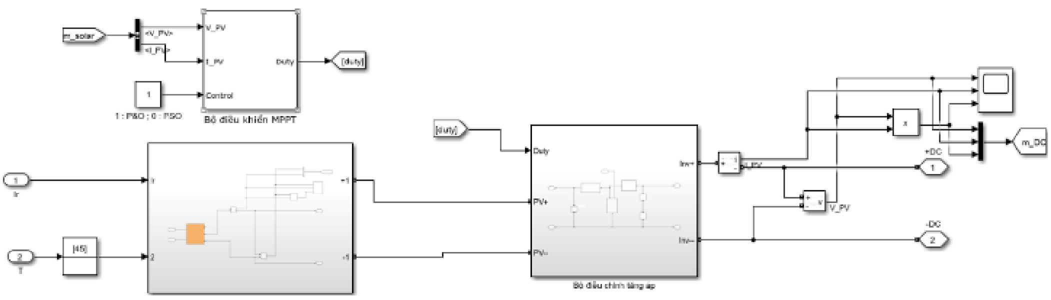

Figure 7: Solar panel system model combined with MPPT algorithm

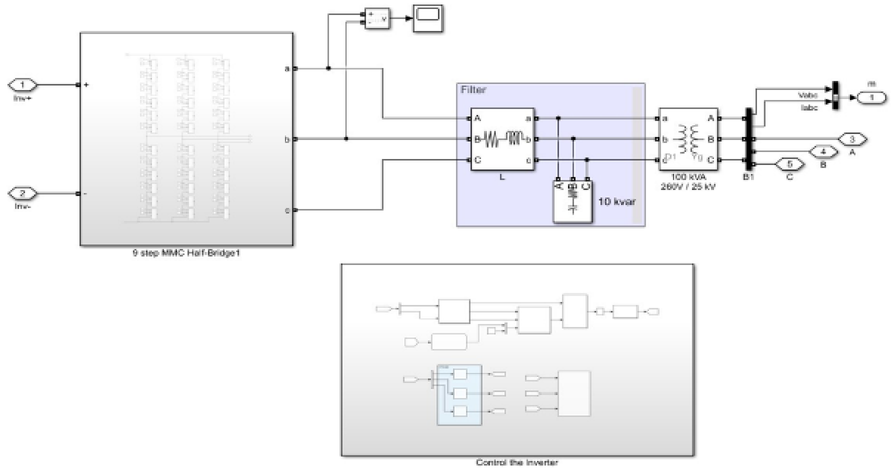

Figure 8: Grid-connected inverter model

IV. Simulation Results

A. Operation of MPPT algorithm

For the purpose of studying the change when using the P&O algorithm, the solar radiation is customized to vary from 0 → 1000 W/m². The power of the solar power system is optimized by the P&O algorithm depending on the irradiance level. Figures 9 and 10 show the curves of solar irradiance and PV system output power. The output power varies from 0kW to 34kW, closely following the solar irradiance level at a fixed ambient temperature.

- From 0-2s, the solar radiation is at 1000 W/m², then the system starts to operate so it takes some time to reach the steady state. It can be seen that during most of this time, the PV power increases to reach the MPP point, once reached, the algorithm maintains stability at this level.
- The remaining time is divided into 2s intervals corresponding to each different radiation level. It can be seen that the system operates quite stably and has few errors.

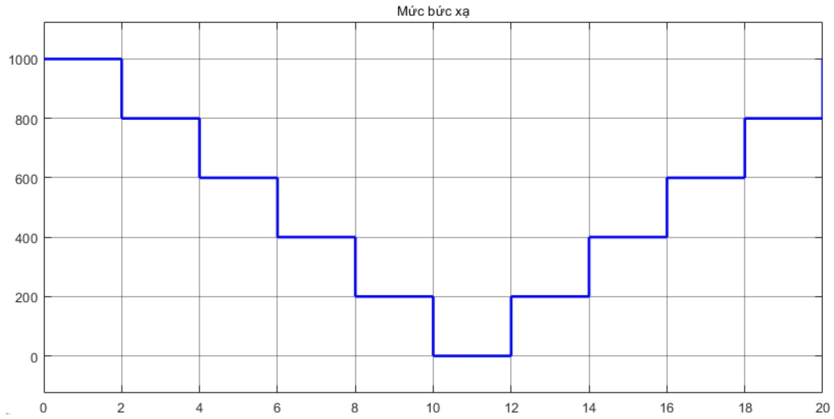

Figure 9: Solar radiation intensity

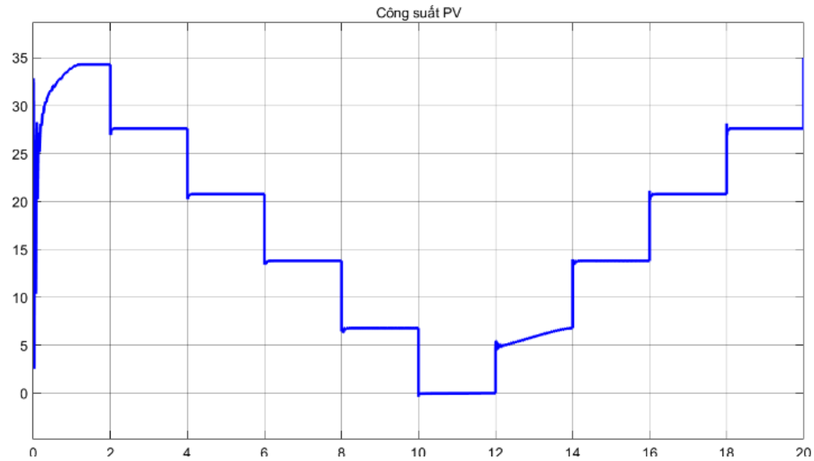

Figure 10: Solar power system capacity

The simulation results show that the solar panel system operates stably with high efficiency, in which the P&O algorithm demonstrates the ability to track the maximum power point effectively. The fast settling time shows the algorithm's good response to changes in solar radiation intensity. This not only ensures the optimization of the system's output power but also creates a solid basis for the investigation and evaluation of the performance of the multi-level inverter in the downstream stage, contributing to the goal of stability and efficiency in system operation.

B. Effect of module quantity on output voltage quality.

To investigate the output THD of the MMC, the solar radiation and the number of modules per arm of each phase are varied as mentioned in chapter III. Then the THD value of the voltage is measured for each case. The simulation results show that THD decreases gradually as the number of modules in the MMC increases, especially at low irradiance levels (100–300 W/m²). However, at higher irradiance levels (700–1000 W/m²), the THD value becomes stable, with smaller differences between cases. The number of sub-modules has a significant impact on THD. When using fewer sub-modules (such as 2 or 3), THD starts at a higher level and fluctuates more strongly with solar irradiance. In contrast, with a larger number of sub-modules (4, 5 or 6), THD is significantly lower and more stable, especially at high irradiance. This shows that increasing the number of sub-modules helps the system reduce harmonic distortion and maintain better power quality.

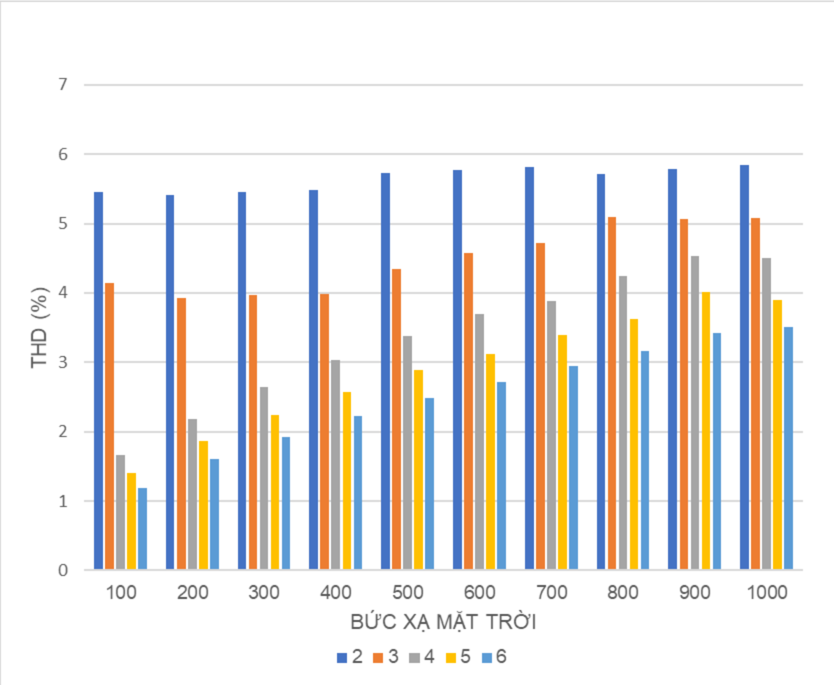

Figure 11: THD output voltage affected by solar radiation and number of modules in MMC

At low irradiance (100–300 W/m²), the difference in THD between the number of sub-modules is obvious, reflecting the important role of increasing the number of modules in low light conditions. However, at high irradiance (700–1000 W/m²), the influence of the number of sub-modules becomes less, as the system operates more stably in good light conditions.

It can be seen that the system with many sub-modules not only helps to reduce THD but also increases stability when the radiation changes. This is especially important in the design of solar power systems, to ensure high efficiency and optimal power quality, especially under conditions of strong radiation changes.

V. Using The Sub-Module Quantity Control Key

The MMC modeled in this study is a three-phase multilevel inverter consisting of two upper and lower arms, each arm containing 6 sub-modules. Therefore, when adding switches to close/open the sub-modules in each phase, this will directly affect the output voltage because it changes the number of voltage steps. The closing/opening of the sub-modules is performed simultaneously on the two arms and in all 3 phases, which means the number of sub-modules on each phase under each certain operating condition is uniform. From there, it is possible to study the influence of the number of active modules on the quality of the output voltage, especially THD.

Increasing the number of submodules per arm in an MMC multilevel converter results in a corresponding increase in the effective switching frequency. This is necessary to maintain the desired output voltage quality, as the system requires more switching events to balance the voltage across the submodules. This increase in switching frequency can lead to higher switching losses if not managed with an effective control strategy [8]. Although a larger number of submodules can improve the output voltage quality, it also increases the complexity of capacitor voltage management, leading to additional losses if not optimized[9]. Therefore, the controller needs to achieve two goals:

i. Maintain stable output voltage, THD does not exceed grid connection standard.
ii. The number of sub-modules is kept to a minimum to avoid power loss on the semiconductor switches as well as to simplify the control process for the system.

*** Control the number of sub-modules to optimize the output.**

From the results obtained in Chapter IV, it can be concluded that the larger the number of sub-modules (between 2 and 6), the lower the THD and the better the output quality. However, as mentioned above, the goal of this control is to maintain THD at an acceptable level for grid connection and at the same time minimize the number of modules to avoid power loss on semiconductor switches as well as simplify the control process for the system. In this problem, the allowable THD threshold is 5%. Therefore, it is necessary to control so that the number of operating sub-modules is the lowest under the condition that THD <= 5%.

From the results in Figure 11, it can be seen that the ideal number of active modules to achieve the requirement is 3 or 4. With solar radiation levels less than 800 W/m², the number of active modules is 4 and with radiation levels from 800-1000 W/m², the best number of active modules is 3. From there, an algorithm is built for the controller so that the system automatically measures the solar radiation level and turns on/off the sub-modules to achieve optimal results.

To verify the results of the above algorithm, a simulation was performed, in which the solar radiation changes over time with moderate and abrupt jumps.

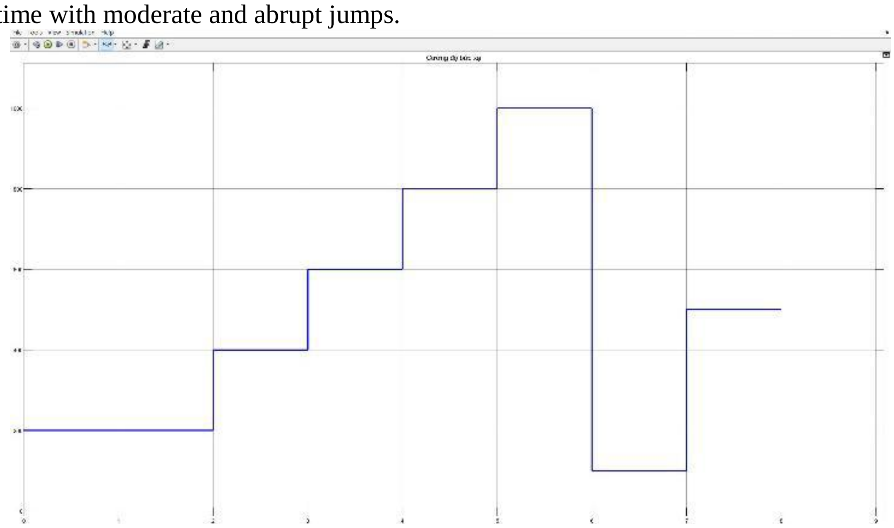

Figure 12: Surveyed solar radiation

Time (s)	Irradiance (W/m2)	THD (%)
0-2s	200	3.95
2-3s	400	3.91
3-4s	600	4.61
4-5s	800	4.13
5-6s	1000	4.64
6-7s	100	1.85
7-8s	500	3.81

Table 2: THD output voltage according to radiation levels

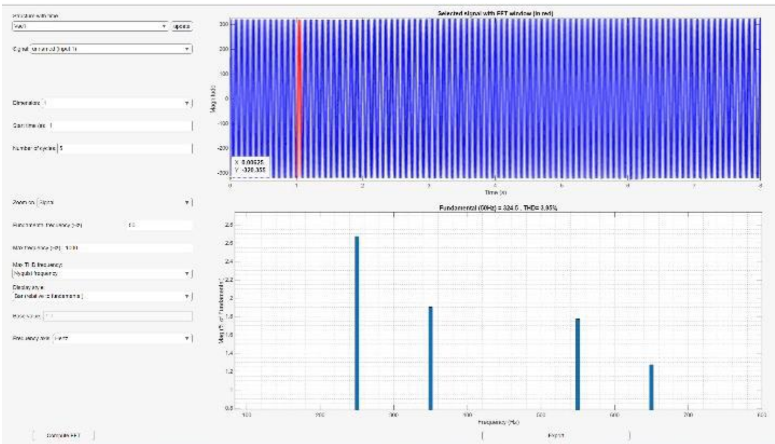

Figure 13: THD in the case of radiation is 200 W/m2

From the simulation results above, it can be seen that the system works well with the on/off controller of the sub-modules, the quality of the output voltage has a value close to the simulation results in Chapter III, and is always within the allowable threshold of less than 5% in both cases with small changes and sudden changes in solar radiation. The small deviation in value can be explained by the fact that the system needs time to establish when the radiation changes, so there will be deviations when surveying in a short time, if the survey time is increased, the error will decrease.

VI. Conclusion

The paper has studied and proposed solutions to improve the total harmonic distortion in grid-connected solar power systems using modular multilevel inverters (MMC). Simulation results on MATLAB/Simulink show that integrating the MPPT algorithm not only helps to optimize the power from solar panels but also ensures the quality of output voltage meets grid standards. At the same time, the number of sub-modules in the MMC is proven to be an important factor that directly affects the level of harmonic distortion and system performance.

Adjusting the number of modules in the MMC significantly improved the output voltage quality and reduced THD to an optimal level, meeting technical standards. The findings from this study provide an important basis for the design and control of modern grid-connected solar power systems, contributing to improving the efficiency of renewable energy and flexibility in system operation.

In the future, research can focus on directly investigating the losses on MMC, especially the switching losses and conduction losses, to propose methods for optimizing design and control. At the same time, evaluating the efficiency of the system under actual operating conditions with continuous changes in solar radiation intensity and load will also be a necessary direction, to ensure the comprehensiveness and higher practical application of the research results.

Acknowledgements

The study was funded by Ho Chi Minh City University of Technology – VNU-HCM under project number SVPFIEV-2024-ĐĐT-05. We would like to thank Ho Chi Minh City University of Technology, VNU-HCM for providing time and material resources for this study.

References

[1]. Dũng P Q, Công N P, Hòa T P, Tuyên N D, Hưng N D, Nhuận L A, "Điều khiển phân tán dịch mức sóng mang cho bộ biến đổi công suất liên kết dạng đa bậc trong lưới điện nhỏ dạng lai," Sci. Tech. Dev. J. - Eng. Tech.; 4(2):872-899.

[2]. Q. D. Phan, G. Gateau, M. Cousineau, L. Veit, R. De Milly, and M. Mannes-Hillesheim, "Ultra-fast decentralized self-aligned carrier principle for multiphase/multilevel converters," Proc. IEEE Int. Conf. Ind. Technol., vol. 2020-Febru, no. 1, pp. 517–522, 2020, doi: 10.1109/ICIT45562.2020.9067108.

[3]. S. Haq, S. P. Biswas, M. K. Hosain, M. A. Rahman, M. R. Islam, and S. Jahan, 'A Modular Multilevel Converter with an Advanced PWM Control Technique for Grid-Tied Photovoltaic System', *Energies*, vol. 14, no. 2, Art. no. 2, Jan. 2021, doi: 10.3390/en14020331.

[4]. B. Zhang and H. Nademi, 'Modeling and Harmonic Stability of MMC-HVDC With Passive Circulating Current Filters', *IEEE Access*, vol. 8, pp. 129372–129386, 2020, doi: 10.1109/ACCESS.2020.3009331.

[5]. J. Chavarria, D. Biel, F. Guinjoan, C. Meza, and J. J. Negroni, 'Energy-Balance Control of PV Cascaded Multilevel Grid-Connected Inverters Under Level-Shifted and Phase-Shifted PWMs', *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 98–111, Jan. 2013, doi: 10.1109/TIE.2012.2186108.

[6]. A. A. Gebreel and L. Xu, 'Power quality and total harmonic distortion response for MMC with increasing arm inductance based on closed loop-needless PID controller', *Electr. Power Syst. Res.*, vol. 133, pp. 281–291, Apr. 2016, doi: 10.1016/j.epsr.2015.12.024.

[7]. N. V. Tan, "Đánh giá hiệu quả các thuật toán MPPT P&O, INC và FUZZY LOGIC trong hệ thống pin năng lượng mặt trời", *TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ - ĐẠI HỌC ĐÀ NẴNG* vol 18 no 51, jan. 2020.

[8]. S. Huang, W. Liao, P. Liu, W. Tang, and S. Huang, 'Analysis and calculation on switching frequency and switching losses of modular multilevel converter with maximum sub-module capacitor voltage deviation', *IET Power Electron.*, vol. 9, no. 2, pp. 188–197, 2016, doi: 10.1049/iet-pel.2015.0418.

[9]. 'Review, Classification and Loss Comparison of Modular Multilevel Converter Submodules for HVDC Applications'. Accessed: Nov. 29, 2024. [Online]. Available: https://www.mdpi.com/1996-1073/15/6/1985.