HARMONIC CURRENTS ANALYSIS OF A 15 KW SINGLE PHASE ROOFTOP SOLAR POWER IN FUNCTION OF SOLAR IRRADIANCE AND PANEL TEMPERATURE IN VIETNAM

PHÂN TÍCH SÓNG HÀI DÒNG ĐIỆN CỦA HỆ THỐNG ĐIỆN MẶT TRỜI ÁP MÁI MỘT PHA 15 KW THEO SỰ BIẾN ĐỔI CỦA BỨC XẠ MẶT TRỜI VÀ NHIỆT ĐỘ TẤM PIN Ở VIỆT NAM

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Tóm tắt: Bài báo nghiên cứu tích toán sóng hài của hệ thống điện mặt trời áp mái một pha 15 kW theo sự biến đổi của bức xạ mặt trời và nhiệt độ tấm pin. Mô hình mô phỏng được xây dựng dựa trên bộ theo dõi điểm công suất cực đại sử dụng phương pháp nhiễu loạn và quan sát (P&O) và bộ điều khiển tỉ lệ cộng hưởng. Sóng hài được tính toán cho các trường hợp nhiệt độ tấm pin và bức xạ mặt trời khác nhau. Kết quả tính toán được so sánh với giới hạn về sóng hài dòng điện theo quy định tại Thông tư số 05/2025/TT-BCT ngày 01 tháng 02 năm 2025 của Bộ Công thương: Quy định hệ thống truyền tải điện, phân phối điện và đo đếm điện năng để đưa ra một số khuyến nghị.

Từ khóa: điện mặt trời áp mái, nhiệt độ, bức xạ mặt trời, MPPT, bộ điều khiển kiểu tỉ lệ - cộng hưởng, sóng hài

Abstract: This paper presents a study on the harmonic analysis of a 15 kW single-phase rooftop solar system under varying solar irradiance and photovoltaic (PV) panel temperature conditions. The simulation model is developed based on a Maximum Power Point Tracking (MPPT) algorithm employing the Perturb and Observe (P&O) method, integrated with a proportional-resonant (PR) controller. Harmonic distortion is evaluated across different operating scenarios influenced by changes in irradiance and panel temperature. The computed harmonic levels are then compared against the current regulatory limits on current harmonics as specified in Circular No. 05/2025/TT-BCT, dated February 1, 2025, issued by the Ministry of Industry and Trade: Regulations on Power Transmission, Distribution, and Energy Metering Systems. Based on the analysis, several recommendations are proposed to enhance compliance and system performance.

Keywords: rooftop solar, temperature, irradiance, MPPT, PR controller, harmonics

1. INTRODUCTION

In recent years, rooftop solar power has emerged as a key trend in Vietnam's renewable energy development strategy. The total installed capacity of rooftop solar systems exceeds 9,500 MWp, reflecting strong interest and investment from both the government and the public in this clean energy source.

Vietnam conditions are good for the development of rooftop solar energy, including high solar irradiance, rising electricity demand, and supportive government policies. Initiatives such as preferential electricity purchase prices for rooftop systems, and policies allowing individuals to install their own systems and sell surplus electricity to EVN (as outlined in Government Decree No. 135/2024/NĐ-CP dated October 22, 2024, on mechanisms and policies to encourage the self-production and self-consumption of rooftop solar power) have provided strong incentives for growth in this sector.

A typical rooftop solar power system comprises the following main components:

- Photovoltaic (PV) panels: Convert solar energy into direct current (DC) electricity.
- Inverter: Converts DC electricity from the PV panels into alternating current (AC) compatible with the power grid.
- Filter: Mitigates harmonic distortion.

Among these, the inverter plays a crucial role in energy conversion and system control. However, its inherent nonlinear characteristics are a primary source of harmonic distortion in RSP systems.

Harmonics are voltage or current components whose frequencies are integer multiples of the fundamental frequency (50 Hz in Vietnam). One of the major sources of harmonics is power electronic equipment, such as inverters used in rooftop solar systems. During the DC to AC conversion process, the non-linear switching behavior of the inverter introduces higher-order harmonics - commonly the 3rd, 5th, 7th, 11th, and beyond - into the system.

These harmonics can lead to serious technical issues, including:

- Increased equipment temperature: Harmonics elevate copper and stray flux losses in transformers, resulting in overheating and reduced equipment lifespan.
- Electromagnetic interference: Harmonics can interfere with the operation of nearby electronic devices.
- Grid instability: Harmonics may cause resonance phenomena, compromising the stability of the power system.
- Malfunction of protective relays: Harmonics can cause incorrect relay operation, potentially leading to unintended power outages.

Therefore, accurate harmonic analysis and assessment in rooftop solar power systems are essential to ensure power quality and system stability. Specific requirements include:

- Harmonic level assessment: Using tools such as power quality analyzers to measure and evaluate the Total Harmonic Distortion (THD) of voltage and current.
- Simulation and analysis: Employing simulation software such as PSCAD and MATLAB/Simulink to model and analyze harmonic generation and its impact on the system. This allows for prediction and implementation of effective mitigation strategies.
- Equipment selection and design: Selecting inverters and related components with harmonic mitigation capabilities—such as inverters with built-in harmonic filters or the installation of external harmonic filters.
- Compliance with standards and regulations: Ensuring system conformance to both international and national power quality standards, including IEEE 519, IEC 61000-4-7, and Circular No.

05/2025/TT-BCT dated February 1, 2025, issued by the Ministry of Industry and Trade: Regulations on Power Transmission, Distribution, and Electricity Metering Systems. This circular specifies maximum allowable voltage harmonic distortion on the grid (Table 1), mandates that power plants connected to the distribution network must not cause current harmonic distortion exceeding the limits in Table 2, and requires that electrical loads connected to the distribution network must comply with the limits defined in Table 3.

Table 1: Maximum permissible voltage harmonic distortion levels [1]

Voltage level	Total harmonic distortion (%)	Every harmonic distortion (%)
500 kV, 220 kV	3.0	N/A
110 kV	3.0	1.5
Medium voltage	5.0	3.0
Low voltage	8.0	5.0

Table 2: Maximum permissible current harmonic distortion levels for power plants [1]

Voltage level	Total harmonic distortion (%)	Every harmonic distortion (%)
110 kV	3.0	2.0
Medium and low voltage	5.0	4.0

Table 3: Maximum permissible current harmonic distortion levels for electrical loads [1]

Voltage level	Total harmonic distortion (%)	Every harmonic distortion (%)
110 kV	4.0	3.5
Medium voltage	8.0	7.0
Low voltage	12% if power ≥50 kW 20% if power <50 kW	10% if power ≥50 kW 15% if power <50 kW

One of technical challenges in rooftop solar systems is the continuously fluctuating nature of solar energy due to real-time environmental changes such as weather conditions, cloud coverage, and variations in solar irradiance. These fluctuations lead to corresponding changes in the level of harmonic generation. As a result, harmonic evaluation must be conducted under various operating conditions - including peak generation periods and scenarios with low internal load consumption - to ensure that the system consistently meets power quality standards under all circumstances.

This paper presents presents a study on the harmonic analysis of a 15 kW single-phase rooftop solar system using MPPT and PR controller under varying solar irradiance and photovoltaic panel temperature conditions. The structure of the paper includes 4 sections. The problem formulation is introduced in the second section; the third section presents simulation results and comments. Some conclusions are drawn in the last section.

2. PROBLEM FORMULATION

The structure of the rooftop solar power system connected directly to the grid consists of components as shown in Figure 1.

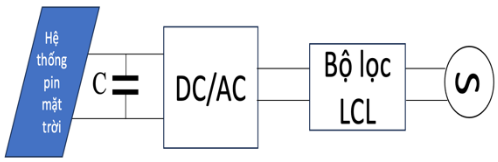

Figure 1: Structure of the modeling rooftop solar system

The studied rooftop solar panel system consists of 4 strings connected in parallel, with each string consisting of 10 panels connected in series.

Each panel has a maximum power of 350.364 W, 72 cells, an open-circuit voltage of 47 V, and a short-circuit current of 9.41 A.

Figure 2 represents the Voltage-Ampere characteristic, and Figure 3 represents the active power and voltage characteristic of the system.

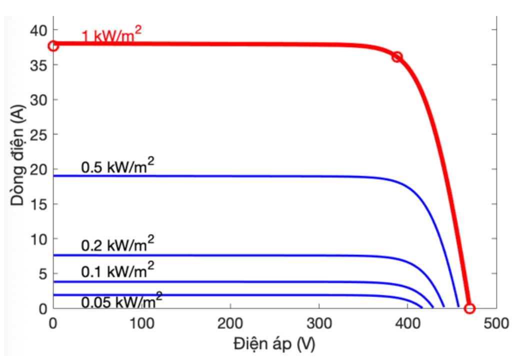

Figure 2: U-I characteristic of the rooftop solar power system at 25°C

Table 4 shows the maximum power values of the system at a temperature of 25°C. In the table, we can see that when the radiation is 1000 W/m² and the voltage is 388 V, the system reaches a maximum power value of 14,014 W.

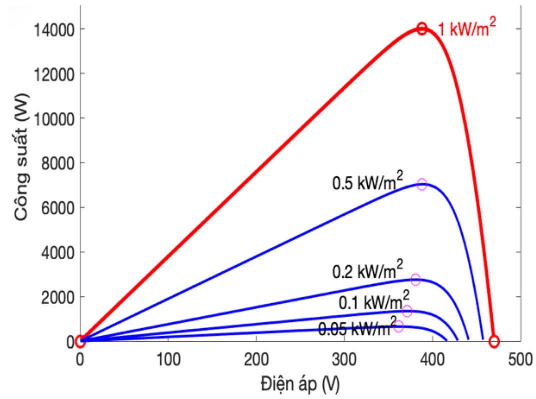

Figure 3: The P-V characteristic of the rooftop solar power system at 25°C

Table 4: Maximum power of the system in functionn of solar irradiance at a temperature of 25°C

Irradiance (W/m²)	50	100	200	500	1000
Maximum power (W)	652	1344	2756	7033	14014
Voltage (V)	361	371	380	388,4	388

The output voltage of the system is calculated by the Maximum Power Point Tracking (MPPT) controller based on the Perturb and Observe (P&O) method [2-6].

The DC/AC inverter has a rated power of 15 kW, using power semiconductor components with 3 terminals, specifically IGBT/Diode, and is controlled by Pulse Width Modulation (PWM) controllers as shown in Figure 4.

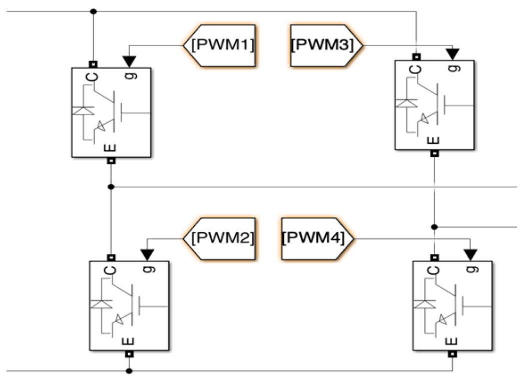

Figure 4: Structure of DC/AC inverter using IGBT/Diode controlled by PWM

To determine the phase angle of the control signal, the system uses a Phase-Locked Loop (PLL) [7-9]. The block diagram of the Phase-Locked Loop is shown in Figure 5.

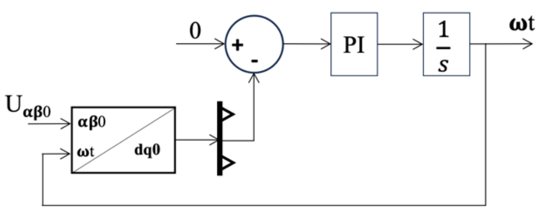

Figure 5: Block diagram of the Phase Locked Loop

The proportional-resonant controller is used to control the inverter. Its controller gain $G_{PR}(s)$ can be mathematically expressed as [10-14]:

$$G_{PR}(s) = K_P + K_R \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (1)$$

Where, K_P and K_R are the proportional and resonant gains, respectively; ω_0 is the fundamental frequency and ω_c is the cut-off frequency.

3. SIMULATION RESULTS

The solar power system model described above is simulated for solar irradiance levels of 400, 600, 800, and 1000 kW/m². For each irradiance level, simulations are conducted to calculate the Total Harmonic Distortion (THD) of the current at various PV panel temperatures of 25, 30, 35, 40, 45, 50, 55, and 60°C.

Figure 6 illustrates the voltage waveform of the grid and the current waveform at the position between the filter and the grid, with solar irradiance set to 1000 kW/m² and the PV panel temperature at 25°C. It is observed that the current and voltage waveforms are nearly in phase, indicating that the active power of the solar power system at the point of interconnection is predominantly real power. The power factor of the system is close to 1.0. In this scenario, the current waveform appears nearly sinusoidal.

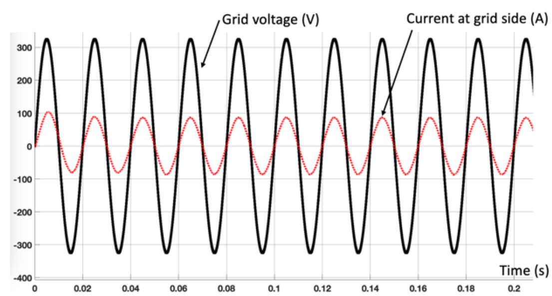

Figure 6: Grid voltage and current at grid side at 1000 kW/m², 25°C

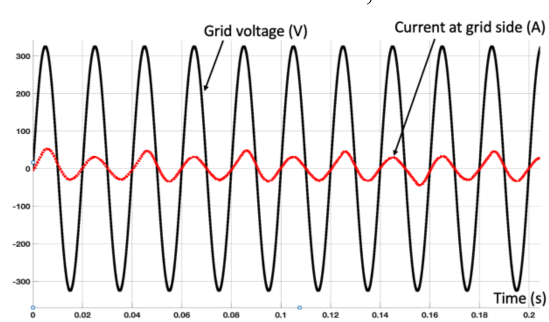

Figure 7: Grid voltage and current at grid side at 400 kW/m², 25°C

The THD values of the current from the system feeding into the grid, as the solar irradiance and PV panel temperature vary, are shown in Figure 8.

Figure 7 illustrates the current waveform at the position between the filter and the grid when the solar irradiance is 400 kW/m² and the PV panel temperature is 25°C. In this case, the current waveform is distorted. However, the grid voltage and current remain nearly in phase, meaning that the active power of the solar power system at the point of interconnection is still predominantly real power. Due to the reduced solar irradiance, the current amplitude is lower compared to the scenario with 1000 kW/m² irradiance.

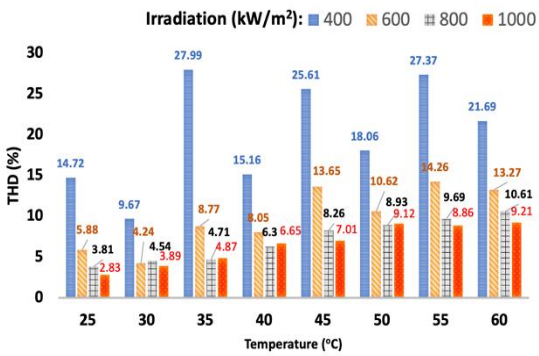

Figure 8: THD of grid side current in function of temperature and irradiance

The results shown in Figure 8 indicate the following:

- When the solar irradiance is 1000 kW/m² and the panel temperature is 25°C, the THD is 2.83%. The THD value increases as the temperature rises, reaching 9.21% when the panel temperature is 60°C.

- When the solar irradiance is 800 kW/m² and the panel temperature is 25°C, the THD is 3.81%. The THD value increases with temperature, reaching 10.61% when the panel temperature is 60°C.

- When the solar irradiance is 600 kW/m², the THD is at its minimum value of 4.24%, corresponding to a panel temperature of 30°C. The THD reaches its maximum value when the panel temperature is 55°C.

When the solar irradiance is 400 kW/m², the THD has its minimum value of 9.67%, corresponding to a panel temperature of 30°C. The THD reaches its maximum value, 27.99%, when the panel temperature is 35°C.

In the case where the rooftop solar system feeds power into the grid, according to Table 2, the maximum permissible THD value is 5%. This condition is met for solar irradiance levels of 800 and 1000 kW/m² with panel temperatures below 35°C. For a solar irradiance of 600 kW/m², the condition is satisfied when the panel temperature is approximately 30°C.

In the case where the rooftop solar power system does not feed power into the grid, according to Table 3, the maximum permissible THD value is 20% (assuming the load power is below 50 kW). This condition is satisfied for all the temperature scenarios considered when the solar irradiance is 600, 800, and 1000 kW/m². For a solar irradiance of 400 kW/m², the condition is satisfied when the panel temperature is 25, 30, 40, 45, or 50°C.

4. CONCLUSION

This paper presented the simulations of a 15 kW rooftop solar power system using a Proportional Resonant (PR) controller combined with a Maximum Power Point Tracking (MPPT) algorithm. The simulation results demonstrated that the system operates efficiently under various irradiance conditions; however, the output current waveform is significantly affected by solar irradiance and panel temperature. Notably, under low irradiance conditions, current distortion may exceed permissible limits, potentially impacting the quality of power fed into the grid. Therefore, the integration of additional harmonic mitigation solutions or adaptive control strategies should be considered to improve system performance and stability. This will be a future research direction.

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