



LC Filter Using Phase-Shifting Technique to Reduce Total Harmonic Distortion (THD) in Grid-Connected PV Systems

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Abstract

Recently, researchers are focused on photovoltaic (PV) energy as it has the potential to produce clean electricity and people are seeing it as an alternative to the energy produced by fossil fuels. People understand the importance of multilevel inverter, though still various issues regarding the application in PV must be tackled. The major one is connection to grid. The key point is high total harmonic distortion of grid current (ig). This paper employs a PS-PWM strategy, along with a phase-shifted MPPT algorithm featuring an LC filter and a multilevel H-bridge inverter configuration, with the aim of minimizing total harmonic distortion. The findings show that using this technique with the right value choice dedicated to the LC filter proposed and a suitable system controller allows a very significant reduction of the total harmonic distortion in current of grid (ig). The resulting inverter output waveforms are illustrated and Compared Based on the current of grid (ig) total harmonic distortion (THD). Every one of the setups we simulated in MATLAB Simulink.

Keywords: Photovoltaic; grid-connected multi-level H-bridge inverter; LC Filter; phase shifted MPPT technique; total harmonic distortion.

1. INTRODUCTION

There has been an increase in solar photovoltaics (PV) power generation system deployments. Similarly, the uptake of various renewable energy sources is also growing. Solar power could have a major impact on the power generation sector in future due to its potential. [1] The design of this grid-connected solar PV system shows a model employing maximum power point tracking (MPPT) on predictive control. This approach intends to increase the MPPT efficiency of the system. It contains a photovoltaic cell array, a DC-DC boost converter and three-phase voltage source converters. And Phase, and various controls such as Perturbation and Observe (P&O) algorithm, MPPT, Phase Locked Loop (PLL), dq transform, and Space Vector Pulse Width Modulation (SVPWM) [2]. The use of multi-level inverters coupled with a DC-DC boost converter in photovoltaic system applications is an economical topological choice, which It leads to reducing costs. The overall system efficiency is effectively measured. In addition, the integration of a boost converter makes it easier to track the maximum power point of the photovoltaic array, which improves overall system efficiency. In addition to that, improved grid current control, which reduce from the effect of the photovoltaic system on it [3]. Reflectors are characterized by multi-level with the ability to produce the harmonics, especially near the switching frequency. The overall harmonic voltage of the system is affected photovoltaic significantly, photovoltaic cells are powered, especially at high bus voltages close to photovoltaic access point by separating the harmonic energy flow and to understand the effect of photovoltaic power delivery capacity on voltage quality and line losses within the distribution grid electrical, it is possible calculation of harmonic losses [4]. In addition to furthermore, in scenarios where photovoltaic (PV) and wind turbine systems use a dual-fed induction generator coupled with a battery, adaptive reference voltage technology can be used to track the maximum power point. Even in the face of sudden changes in irradiance

conditions, this improved adaptive reference voltage remains stable, ensuring reliable monitoring of the maximum power point and improving energy capture and it can help reduce harmonics in the grid current connected to the photovoltaic system [5].

It is considered MPPT, or maximum power point tracking, technology is a major contributor to harmonic problems within photovoltaic systems connected to the grid and it can the sampling frequency used for MPPT parameters significantly affects the harmonic characteristics of the system. Then choosing a faster sampling rate enhances the efficiency of MPPT, like that it increases harmonic emissions and step size. With larger step sizes, there is a significant increase in output current harmonics. To address this challenge, the MPPT algorithm is modified to randomly select sampling rates within a narrow range, bridging the gap between fast and slow values, thus reducing the step size [6][7]. Advances in modern and innovative inverter designs have led to significant improvements in efficiency, size, weight, and reliability. Key features such as efficiency, cost-effectiveness, compactness, power quality, controllability, and accuracy have been emphasized. Research has demonstrated that the use of single-stage topologies in multilevel inverters is particularly effective in improving power quality [8]. Modular multilevel inverters (MMIs) are considered the optimal choice for connecting PV systems to the medium-voltage (MV) grid due to their numerous advantages, including improved power quality, increased efficiency, increased reliability, and scalability. However, MMIs are under continuous development and require further refinement to ensure safe deployment. Among the various combinations, the CHB and MMC families are considered the most suitable options for integration into medium and high voltage industrial networks [9].

This study is divided into three main phases. First, the propose a photovoltaic system design consisting of solar panels, each connected to an inverter to convert DC to AC. These inverters are then connected in parallel and connected to the grid using the phase-shifted modulation (PS-PWM) method, with the results analyzed in terms of total harmonic distortion (THD). In the second phase, the repeat the process, but using the creep method (MPPT phase shift), and monitor the results. In the final phase, the integrate an LC filter and evaluate the results. Finally, the compare and explain the differences between the two methods in terms of the levels of THD observed for each method. All procedures are performed using MATLAB simulations.

2. RELATED WORK

Multilevel topologies: Comparative studies indicate that the H-bridge variant is well suited to grid-connected PV applications with low THD [10], [11]. Modular multilevel inverters are considered for medium-voltage connection of PV plants, with CHB and MMC families regarded as the most suitable options for medium- and high-voltage networks [9].

Modulation-based harmonic reduction: Genetic-algorithm optimization of the switching angles has been reported to reduce THD relative to sinusoidal PWM [12], [13]. Phase-shifted techniques are widely used: a dual-layer PWM reference with a modified phase shift is reported to reduce unfiltered harmonics by about 50 % compared with conventional bipolar PWM [15]; a model-predictive scheme with space-vector phase-shifted PWM for a seven-level CHB shunt active filter is reported to reduce the THD caused by nonlinear loads by about 80 % [16]; PS-PWM moves the harmonics to multiples of the switching frequency in a nine-level inverter [20]; and APOD and POD carrier arrangements have been compared on a seven-level CHB inverter [21]. Parallel inverters with an optimal phase shift between them are another option [19]. Further work applies PWM or linear-quadratic regulation to H-bridge multilevel inverters [22], [23].

MPPT-related harmonics: The MPPT perturbation is a recognized source of DC-link ripple and interharmonics. Randomizing the MPPT sampling period within a narrow range reduces the effect of step size [6], [7]. Phase-shifting the DC-link voltage control between parallel converters mitigates interharmonics [17], and a phase-shifted MPPT applied to the cells of a CHB inverter cancels the oscillation of the overall DC voltage and the harmonics it causes [24].

Gap addressed: The studies above treat modulation, MPPT phase shifting and output filtering mostly separately. This paper applies PS-PWM, PS-MPPT following [24] and an LC output filter to the same three- unit CHB PV inverter and reports the THD of each stage under identical conditions. The PS-MPPT idea itself is taken from [24]; the contribution is the combined evaluation and the filter-sizing procedure.

3. PROPOSED SYSTEM

3.1 System description

Figure 1 shows the simulated system. Three PV units, each feeding one H-bridge cell, form a three- unit single-phase CHB inverter. The inverter output is connected to the grid through an LC output filter, as drawn in the Simulink model. Each unit uses a P&O algorithm to track its maximum power point traction the operating voltage is perturbed periodically and the change in output power decides the direction of the next perturbation. In the PS-MPPT method the phase of the perturbation of each unit is shifted with respect to the others so that the ripples they cause in the DC voltages partly cancel in the total DC voltage [24].

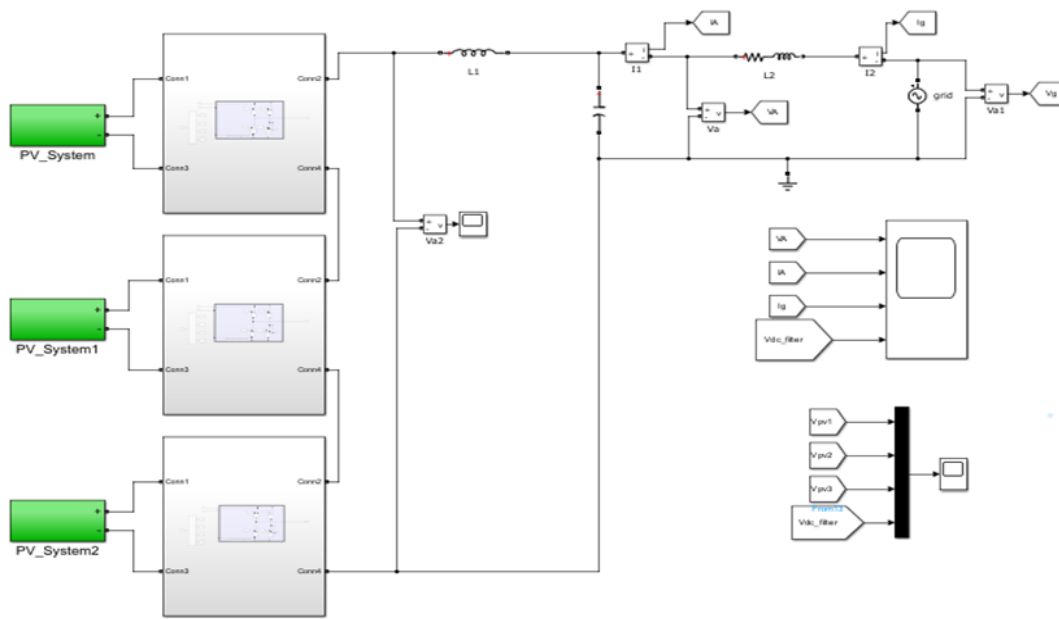


FIGURE 1: Simulink model of the proposed grid-connected PV system: three PV units with H-bridge cells and the LC output filter (PS-MPPT with LC filter).

3.2 Mathematical model

For a CHB inverter with N cells ($N = 3$ here), the output voltage is the sum of the cell voltages. With the averaged model,

$$v_o(t) = \sum_{k=1}^N v_k(t) = \sum_{k=1}^N m_k(t) \cdot V_{dc,k}(t) \quad (1)$$

where m_k is the modulation index of cell k and $V_{dc,k}$ its DC voltage. The total modulation index M_{total} produced by the current controller is distributed equally,

$$m_k(t) = \frac{M_{total}(t)}{N} \quad (2)$$

In PS-PWM, the carrier of cell k is displaced by:

$$\theta_{c,k} = (k - 1) \cdot \frac{\pi}{N}, \quad f_{o,sw} = 2N \cdot f_{sw} \quad (3)$$

For unipolar modulation (the displacement is $2\pi/N$ for bipolar modulation). The effective switching frequency at the output is then $2N \cdot f_{sw}$, i.e. 60 kHz for $N = 3$ and $f_{sw} = 10$ kHz.

The DC-link energy balance of each unit is:

$$C_{dc} \cdot V_{dc,k} \cdot \frac{dV_{dc,k}}{dt} = P_{pv,k} - v_k \cdot i_g \quad (4)$$

with $P_{pv,k} = V_{pv,k} \cdot I_{pv,k}$. The product $v_k \cdot i_g$ contains a component at twice the grid frequency (100 Hz), which is the main source of DC-link ripple and interacts with the MPPT perturbation. The P&O update of unit k is:

$$V_{ref,k}(n+1) = V_{ref,k}(n) + \Delta V \cdot \text{sign}\left(\frac{\Delta P_{pv,k}}{\Delta V_{pv,k}}\right) \quad (5)$$

PS-MPPT shifts the phase of the perturbation of each unit,

$$\varphi_k = (k - 1) \cdot \Delta\varphi \quad (6)$$

where $\Delta\varphi$ is the phase increment between adjacent unit. In the simulation reported here, $\Delta\varphi = \frac{2\pi}{3}$ for three units.

3.3 LC filter design

The output filter is described by:

$$L_f \cdot \frac{di_g}{dt} = v_o - v_c, \quad C_f \cdot \frac{dv_c}{dt} = i_g - i_{load} \quad (7)$$

And its cut-off frequency is:

$$f_c = \frac{1}{2\pi\sqrt{L_f \cdot C_f}} \quad (8)$$

The cut-off frequency is chosen above the low-order harmonics of the grid and well below the effective switching frequency, i.e. $10 \cdot f_g \leq f_c \leq 0.5 \cdot f_{o,sw}$. With $L_f = 3$ mH and $C_f = 20$ μ F, Equation (8) gives $f_c \approx 650$ Hz, which satisfies this condition ($500 \text{ Hz} \leq 650 \text{ Hz} \leq 30 \text{ kHz}$).

The DC-link capacitor is sized from the 100 Hz ripple. For a unit power P_k and a unit DC voltage $V_{dc,k}$, the amplitude of the voltage ripple is approximately

$$\Delta V_{dc,k} \approx \frac{P_k}{2 \cdot \omega_g \cdot V_{dc,k} \cdot C_{dc}} \quad (9)$$

where $\omega_g = 2\pi \cdot 50$ rad/s. For about 250 W per unit at a DC voltage of 124 V per unit, $C_{dc} = 3$ μ F gives a ripple amplitude of about 1 V (below 1 % of the unit voltage), whereas 3 μ F would give a ripple of the order of 1 kV, which is not physically meaningful. The DC-link capacitance is therefore taken as 3 μ F in Table 1.

3.4 Control Structure

The control system has two layers (Figure 2) and can be implemented in centralized or decentralized form. In the decentralized form, the primary controller receives the total DC voltage V_{total} and the reference voltage per unit $V_{ref}(k)$ from the secondary controllers over a low-bandwidth communication link. A proportional-integral (PI) voltage regulator acts on the sum of the references and produces the amplitude of the reference current i_d^* . The grid phase θ_g is obtained from a PLL and gives the grid-current reference. The grid current is regulated by a proportional-resonant (PR) controller (Equation 9) tuned at $\omega_0 = 2\pi \cdot f_g$, which outputs the total modulation index M_{total} . A sliding discrete Fourier transform estimates the grid-current phase, frequency and magnitude. The secondary controller of each unit performs the P&O MPPT by regulating the corresponding PV voltage.

$$G_{PR}(s) = K_p + \frac{2 \cdot K_r \cdot \omega_c \cdot s}{s^2 + 2 \cdot \omega_c \cdot s + \omega_0^2} \quad (10)$$

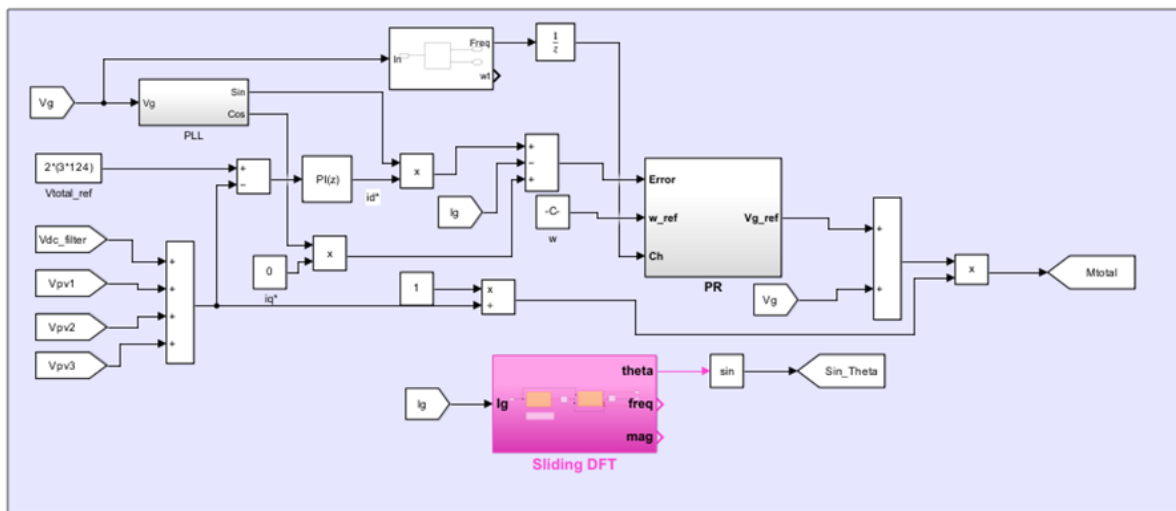


FIGURE 2: CHB single-phase photovoltaic inverter control system (DFT - Discrete Fourier Transform; PWM - Pulse Width Modulation; PI - Proportional Integration; PR - Proportional Resonance)

4. SIMULATION SET-UP

The system was simulated in MATLAB/Simulink with three PV units. Each unit is modelled from the manufacturer data of the PV module (Table 2) at standard test conditions (1000 W/m², 25 °C, IEC 60904). The simulation parameters are listed in Table 1. The same parameters are used in the three scenarios; only the PS-MPPT and the LC filter are switched on or off. Figure 3 shows the Simulink model of one PV unit with its MPPT.

TABLE 1: Simulation system parameters for DC link voltage

Parameter	value
Maximum power ($P_{\max}$)	249.86 W
DC-Link C_{dc} Capacitor	3 μ f
L_f inductor filter	3 mH
C_f filter capacitor	20 μ f
Switching frequency	10 KHz
Grid frequency	50 Hz
Grid voltage	220 V
MPPT step size	5 V

TABLE 2: Electrical parameters of the PV array (one unit).

Parameters	value
Series connected units per chain	4
Maximum power ($P_{\max}$)	249.86 watts
Voltage at MPP (V_{mpp})	31 volts
Currently in MPP (I_{mpp})	8.06 A
Open circuit voltage (V_{oc})	37.4 volts
Short circuit current (I_{sc})	8.55 A

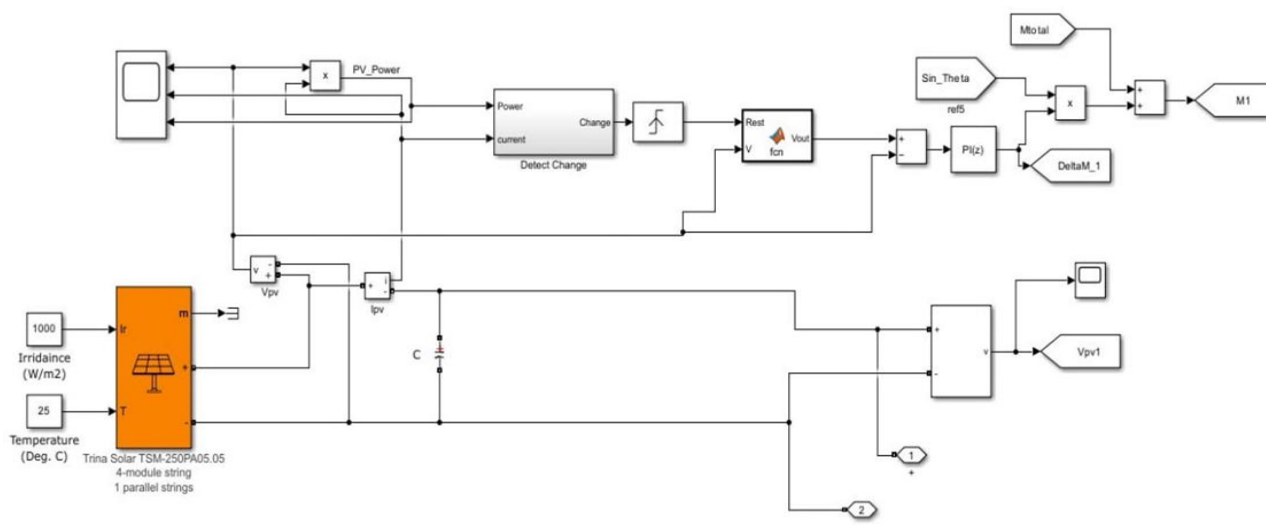


FIGURE 3: Simulink model of one PV unit with the P&O MPPT (Trina Solar TSM-250PA05.05, 4-module string, 1 parallel string).

5. RESULTS AND DISCUSSION

Three scenarios are compared. In all of them, the grid-current THD is computed from the FFT of a window of 10 fundamental cycles starting at 0.4 s, with a maximum frequency of 1000 Hz.

5.1 Scenario A: PS-PWM, (In Phase MPPT)

The grid current contains harmonic and interharmonic components and its THD is 5.70 % (Figure 4). The DC voltages show a visible ripple.

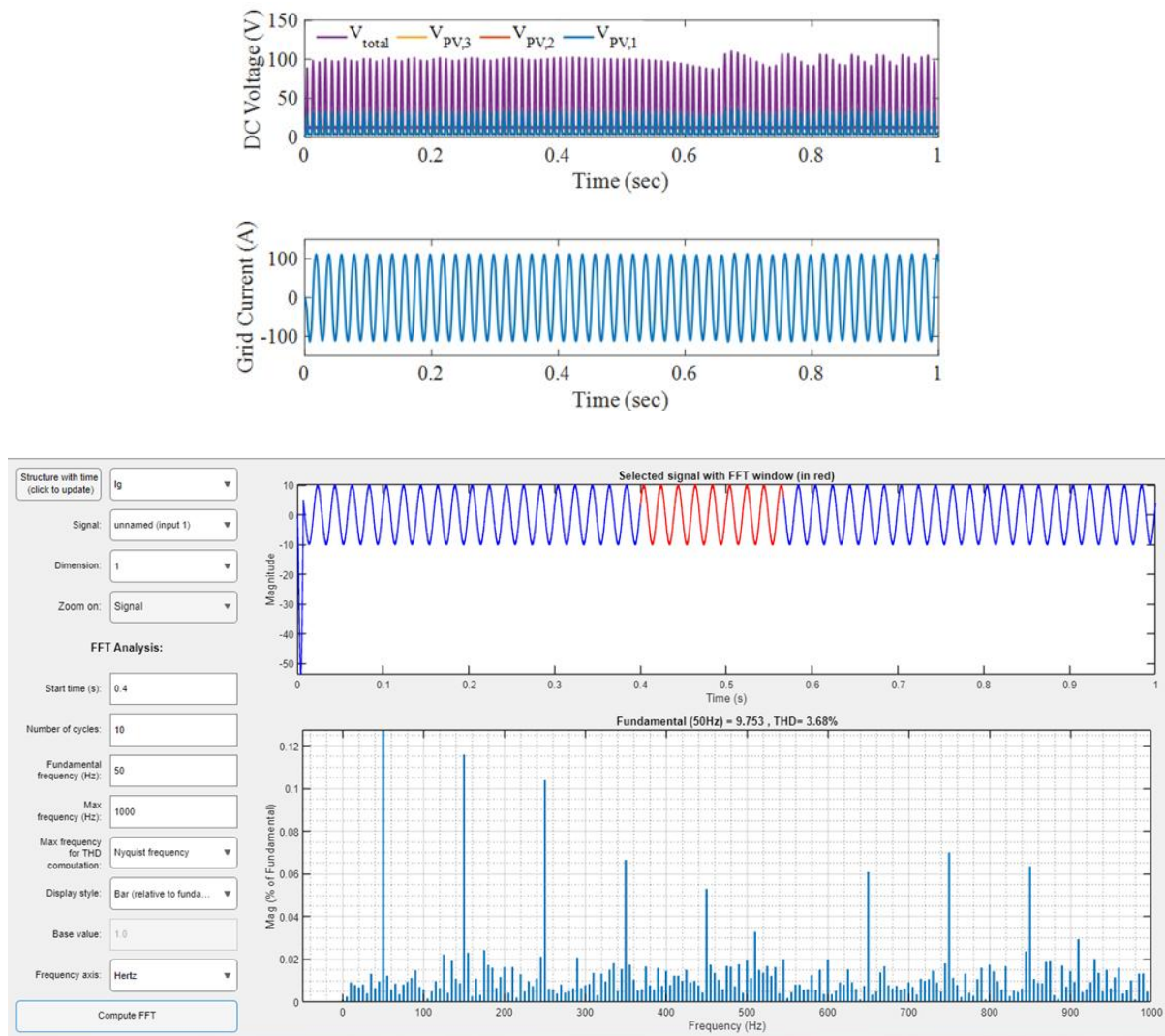
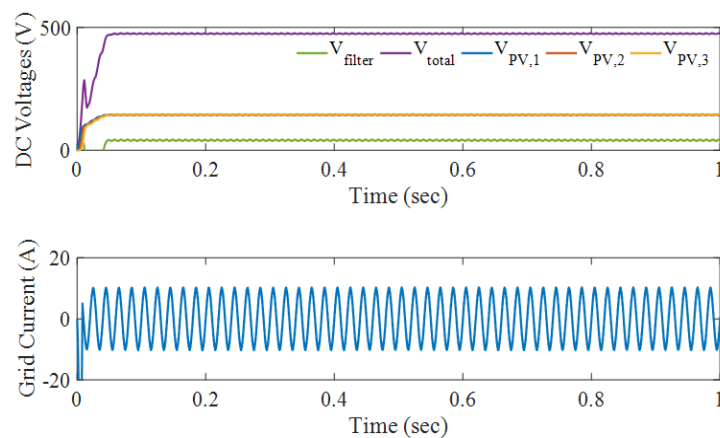


FIGURE 4: Scenario A. DC voltages, grid current and spectrum of the grid current (THD = 5.70 %).

5.2 Scenario B: PS-PWM with PS-MPPT

With the MPPT phase shift applied to the PV cells, the THD decreases to 3.68 % (Figure 5), a reduction of about 35 % relative to scenario A. This confirms that part of the distortion comes from the MPPT perturbations



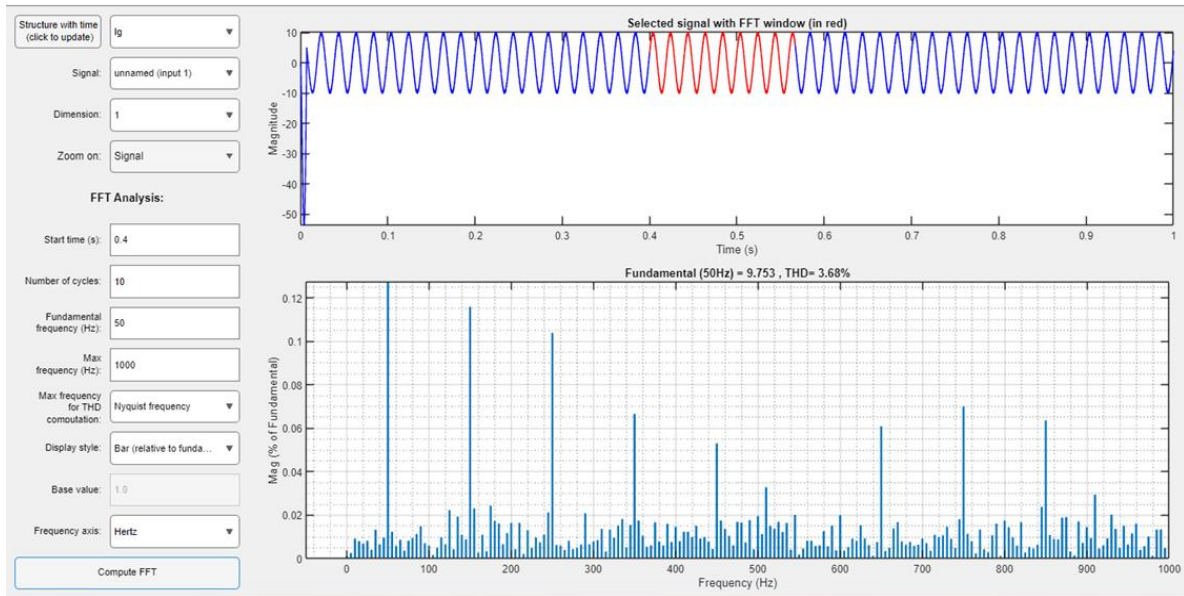


FIGURE 5: Scenario B. DC voltages, grid current and spectrum of the grid current (THD = 3.68 %).

5.3 Scenario C: PS-PWM And PS-MPPT with LC filter

Adding the passive LC filter to PS-MPPT lowers the THD to 0.69 % (Figure 6), a further reduction of about 81 % relative to scenario B and about 88 % relative to scenario A. The harmonic content near the switching frequency and its multiples is attenuated.

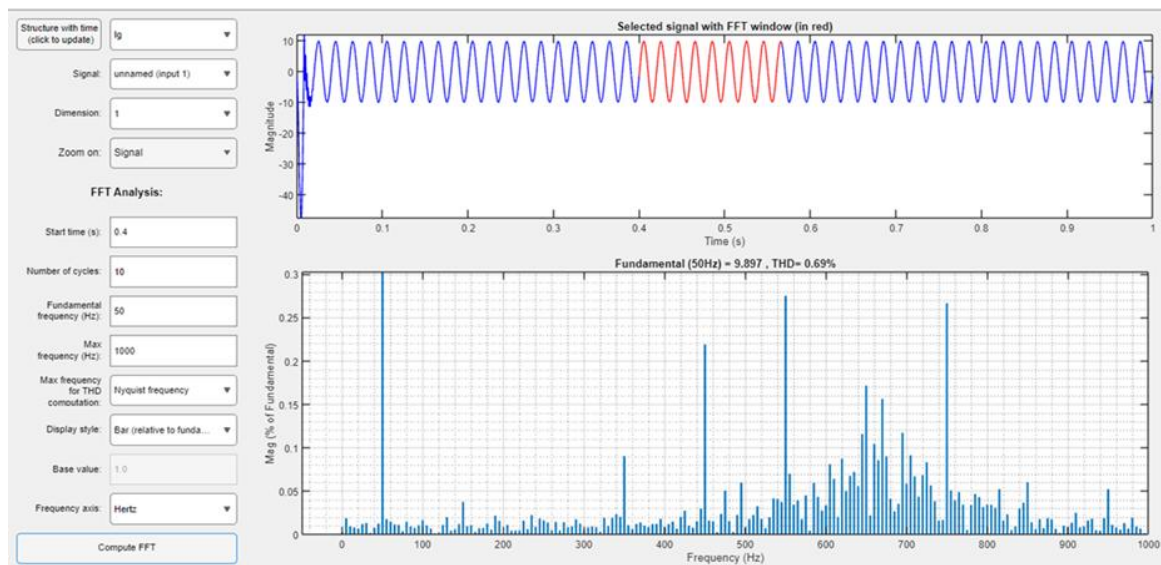
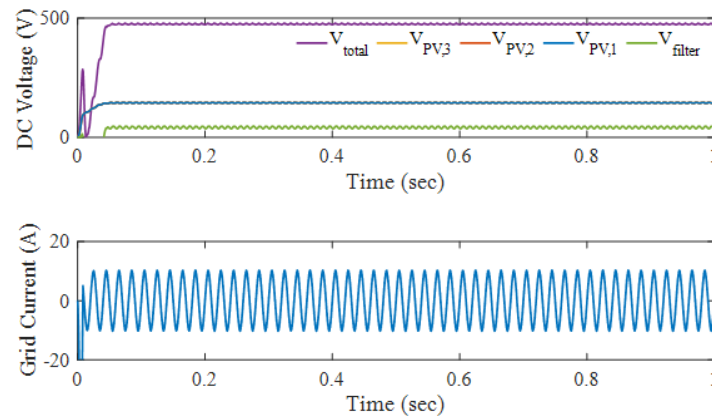


FIGURE 6: Scenario C. DC voltages, grid current and spectrum of the grid current (THD = 0.69 %).

Table 2: Grid-current THD in the three scenarios

Scenario	THD (%)	Reduction vs. A (%)
PS-PWM, (In Phase MPPT)	5.70	—
PS-PWM with PS-MPPT	3.68	35 %
PS-PWM And PS-MPPT with LC filter	0.69	88 %

5.4 Discussion and limitations

Both measures contribute. PS-MPPT acts on the source of the low-frequency distortion, the DC-link ripple caused by the MPPT perturbation, while the LC filter attenuates the components around the switching frequency. The THD of scenario C is far below the 5 % level commonly cited in IEEE Std 519 for current distortion, while scenario A is slightly above it; the applicable limit depends on the short-circuit ratio of the connection point and should be checked for the actual installation.

The study has limitations that should be kept in mind. The simulations are run at standard test conditions and a single operating point, so the behavior of PS-MPPT under changing irradiance, partial shading and load changes is not covered. The effect of the MPPT phase shift on the tracking efficiency has not been quantified, and the results have not been compared with other published methods. The generalization to other numbers of cells is not demonstrated: only $N = 3$ was simulated. These points are left for future work.

6. CONCLUSION

This paper evaluated PS-PWM, phase-shifted MPPT and a passive LC output filter on a three-unit single-phase CHB PV inverter in MATLAB/Simulink. The grid-current THD decreased from 5.70 % without MPPT phase shifting and without a filter, to 3.68 % with PS-MPPT, and to 0.69 % when the LC filter (cut-off about 650 Hz) was added, while the MPPT structure remained unchanged. The approach uses a standard P&O algorithm and a simple passive filter and is straightforward to implement in the simulated structure. Future work should include dynamic irradiance and load tests, a quantification of the tracking efficiency, a comparison with other harmonic mitigation methods and an extension to different numbers of units.

TABLE 3: Table of abbreviations

THD	Total Harmonic Distortion
(PV)	Photovoltaic
(ig)	Current of grid
(PS-PWM)	Phase-shifted pulse width modulation
(PS-MPPT)	Phase-shifted Maximum Power Point Tracking
LC filter	Inductance (L) & Capacitance (C) filter
(PLL)	Phase Locked Loop
(P&O)	Perturbation and Observe
DC	Direct Current
(SVPWM)	Space Vector Pulse Width Modulation
(MPPT)	Maximum Power Point Tracking
(MMIs)	Modular multilevel inverters
CHB	Cascaded H-Bridge (inverters type)
(SiC)	Silicon Carbide
(VSI)	voltage source inverter
(CSI)	current source inverter
(VSD)	variable speed drive
AC	Alternative Current
(SV-PM-PWM)	Space Vector and Phase-Shift Modulation
(PM-SCHM)	Pulse-Shifted H-bridge Multilevel inverter
(LQR)	Linear Quadrature Regulator
(LBC)	Low-Bandwidth Communication
(PI)	Proportional-Integral
(PR)	Proportional-Resonant
(VDC)	Voltage Direct Current

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