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Adaptive control strategies for enhancing the performance and stability of renewable energy systems

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ABSTRACT

The comparison done in this paper uses two control strategies for a solar-fed three-phase inverter, one with standard sinusoidal pulse width modulation (SPWM) and the other with unified space vector PWM (USPWM), equipped with adaptive voltage control (AVC) and a load current observer (LCO). A photovoltaic (PV) source feeds into a controlled DC link, which in turn supplies a DC voltage to the inverter powering an RL load. From the simulation, it is clear that although SPWM meets the output standards, it has increased total harmonic distortion (THD) and slower transient response. Alternatively, using USPWM control decreased THD to 3.01% and made the system respond in 11 ms, compared to 22 ms before. The new method provides better efficiency and better power quality when used with dynamic loads.

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1. INTRODUCTION

The global electricity demand is steadily increasing due to population growth, expanding urban development, technological advancements, and improved quality of life [1]. Most of the energy we produce, about 80% is derived from fossil fuels, which are finite resources that significantly contribute to environmental degradation. Because these resources are expected to run out soon, it is imperative to adopt sustainable and environmentally friendly energy sources [2]. The use of renewable energy sources (RES) such as solar, wind, and tidal energy is increasing due to their abundant availability, lower environmental impact, and long-term sustainability. Solar photovoltaic (PV) systems attract a lot of attention because they can be easily scaled, and their costs are rapidly declining [3], [4]. Nonetheless, combining these resources into the power grid presents several technical challenges. Because RES depends on the weather, its use can cause power to change, which may affect grid stability and power quality. To solve these problems, DC-DC converters and DC-AC inverters are employed between RES and the alternating current (AC) power system or loads [5], [6]. These converters ensure proper voltage and frequency regulation, reactive power compensation, and grid synchronization [7], [8]. In addition, these sources of power can cause harmonic distortion, result in switching losses, and result in electromagnetic interference, so good control and filtering approaches are required [9], [10]. To make sure electricity is provided consistently and stably. Voltage regulation gets harder in multi-phase inverters that power linear and non-linear RL loads when the load is changing. Proportional-integral (PI) controllers are standard, but they are designed only for particular circumstances and might not cope well with sudden changes in demand or the power supply [11], [12]. Consequently, it is becoming more important to use adaptive control systems capable of dynamically responding to power grid variations, maintaining voltage stability, and minimizing total harmonic distortion

(THD). load current observers (LCO), adaptive voltage controllers (AVC), and unified space vector PWM (USPWM) are some advanced techniques that could be useful in this area [13], [14]. This paper presents a comparative study of two control strategies. The conventional sinusoidal pulse width modulation (SPWM) and USPWM are integrated with adaptive voltage control and load current observation for a solar-fed three-phase inverter system. Both approaches are evaluated under identical conditions, focusing on key performance parameters such as transient response and THD.

2. SYSTEM CONFIGURATION

The system is set up to couple a solar photovoltaic (PV) source with a 3-Ø inverter by first using a boost converter for power conditioning. MATLAB/Simulink is used to model and simulate the entire configuration to assess the results of several control strategies when the load changes. All of these are part of the overall structure: a solar PV source, the system comprises a boost DC-DC converter, a 3-Ø inverter, and a balanced RL load. The boost converter takes the changing output from the PV array, steps it up, and maintains it as a steady voltage for the inverter. The inverter changes the stable DC voltage into a three-phase AC output, which is used to power different loads. Figure 1 shows the complete Simulink-based system layout comprising the PV input, boost stage, inverter, control mechanisms, and load.

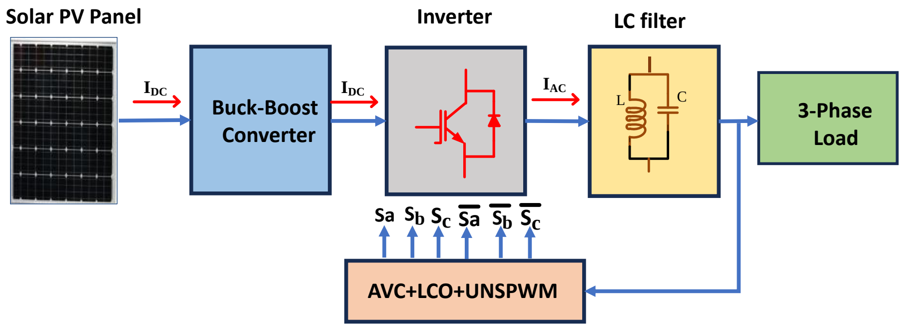

Figure 1. Solar PV system with AVC-based inverter control

2.1. PV source and boost converter

A solar photovoltaic (PV) array is the main energy source in the system's front end. A solar array's output when it receives standard irradiance conditions is modeled as a constant DC input in the simulation. Experts consider that the actual output voltage of a PV panel is close to 123 V. As the PV voltage is too low for proper three-phase inverter work, a boost DC-DC converter is put in place to raise it to a steady 400 V DC link.

It is the boost converter that helps maintain a steady voltage even when the sun's radiation and temperature change. A 0.15 mH inductor and a 500µF output capacitor are used so that the voltage remains stable and the ripple at the output is reduced. The PWM converter is used to switch the converter at a 10 kHz frequency, and the duty cycle is set manually or by a feedback system, depending on which simulation scenario is used.

The traditional boost converter steps up the PV voltage to a higher DC level required for inverter input [15]. The voltage gain of the boost converter in continuous conduction mode (CCM) is given by (1).

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

V_{in} is the input voltage from the PV panel; and V_{out} is the output voltage of the boost converter; D = duty cycle (0 < D < 1). It is because of the DC-DC conversion stage that the downstream inverter receives a reliable voltage, which helps produce high-quality three-phase AC output [16]. So, the boost converter is necessary to transform the unstable voltage from the solar panel into a steady middle voltage for converting AC later.

2.2. Three-phase inverter

After it is regulated by the boost converter, the DC voltage goes to a three-phase inverter, which changes it into usable three-phase AC to supply different electrical loads. Insulated gate bipolar transistor

(IGBT) switches are used for the inverter [17], which operates at a frequency of 10 kHz. Both the SPWM method and the USPWM with AVC and an LCO are used to control the inverter [18]. With SPWM, a sinusoidal reference wave and a triangular carrier are used to produce pulses, whereas USPWM adjusts the output of the inverter according to what is happening in the system and the reference value. Being set up this way, the models can be tested side by side under the same conditions.

3. CONVENTIONAL SPWM CONTROL STRATEGY

Power electronics often use the SPWM method because it is easy to implement and understand. A sinusoidal reference signal is compared with a high-frequency triangular carrier wave to produce switching pulses needed by the inverter [19]. Switching takes place at the intersection points, which helps the inverter produce a near-sinusoidal output voltage.

In the setup, the SPWM controller is used to power the three-phase inverter so that the AC output from the 400 V DC link is balanced and even. The modulation index is made less than 1 by keeping it below unity, and the frequency at which the switch is turned on and off is set to 10 kHz. SPWM inverter output is tested in the same conditions as the advanced control strategy, with both linear (RL) and nonlinear loads, as well as both balanced and unbalanced load configurations. Although SPWM does an okay job in steady-state operation, it struggles to handle unexpected loads and disturbances. Since it lacks adaptive control, the voltage may fluctuate more, and the THD may go up during sudden changes. So, SPWM is generally used where the load in the system is constant.

3.1. Proposed USPWM with adaptive voltage controller and load current observer

By incorporating USPWM along with an AVC and an LCO, the control strategy provides improved performance when the load is dynamic or irregular. By using this method, the author tries to settle the problems of SPWM by ensuring better voltage control, quicker reactions to sudden changes, and less THD. The AVC works in the dq-reference frame and automatically changes control factors to maintain the inverter output voltage close to its reference path [20]. It uses live data from the inverter voltage, the load, and various system variables to figure out the error signals. They are managed by model reference adaptive control, which constantly adjusts the control gains depending on the behavior of the system.

3.2. USPWM and dq transformation

Include the Park transformation equations (abc to dq) for AVC control.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120°) & \cos(\theta+120°) \\ \sin\theta & \sin(\theta-120°) & \sin(\theta+120°) \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

a) Reference current in dq-frame: The reference current vector for the inverter before filtering is given by (3) [21].

$$\mathrm{I}_{dq}^{\mathrm{ref}} = \mathrm{i}_{dq}^{*} \pm j\omega C_f \mathrm{v}_{dq} \quad (3)$$

Where: i_{dq}^{*} is the sensed or estimated load current using the LCO; C_f is the output filter capacitance; v_{dq} is the measured inverter output voltage in the dq-frame; and ω is the grid angular frequency.

b) Voltage error in dq-frame: The voltage difference between actual and reference voltages after the filter is given by (4) [22].

$$\Delta\mathrm{v}_{\boldsymbol{dq}} = \mathrm{v}_{dq}^{\mathrm{meas}} - \mathrm{v}_{dq}^{\mathrm{ref}} \quad (4)$$

c) Current error in dq-frame: The deviation between actual and target currents before the filter is computed as in (5).

$$\Delta\mathrm{i}_{dq} = \mathrm{i}_{dq}^{\mathrm{meas}} - \mathrm{i}_{dq}^{\mathrm{ref}} \quad (5)$$

d) Adaptive voltage control law: To dynamically adjust the control signal, the dq-axis reference voltage is calculated using a learning-based adaptive law [23].

$$\mathrm{v}_{dq}^{\mathrm{ctrl}} = \left(\sum_{n=1}^{N} \gamma_{dq,n} \cdot \mathrm{X}_{dq,n} + \mathrm{v}_{dq}\right) - \eta_{dq} \cdot \theta_{dq} \quad (6)$$

Where: $\gamma_{dq,n}$ is the adaptive gain for the n^{th} term; $X_{dq,n} = [v_{dq}, i_{ld}, i_{li}, 1]^T$ is the feature vector; v_{dq} is the output voltage vector; η_{dq} and θ_{dq} are design constants updated during adaptation; $N = 4$ in this case.

The adaptive gain $\gamma_{dq,n}$ evolves as (7).

$$\gamma_{dq,n}(t) = -\frac{1}{\phi_{dq,n}} \int_0^t \theta_{dq}(t) \cdot X_{dq,n}(t)\, dt \tag{7}$$

Here, $\phi_{dq,n}$ is a positive tuning factor, θ_{dq} represents the adaptive weight vector, and the integral enables continuous learning to match system dynamics.

This reformulated model ensures a clear adaptive mechanism where both the control gains and output voltages respond in real-time to changing load conditions, enabling low THD and fast dynamic response. The LCO calculates the load-side current using only data from the network. Inverter measurements are analyzed in a state-space observer model to find the present and voltage values [24]. The observer contributes to more precise control, mainly when there are fast changes in the load or unknown external disturbances. Using both AVC and LCO makes the inverter work more effectively by allowing real-time adjustments [25]. They make it possible to generate the reference voltage in the dq-frame, which the USPWM technique then changes into the switching pulses used by the motor. Unlike SPWM, USPWM relies on space vector modulation to create less harmonic output and better voltage use, mainly when the load conditions are unbalanced or nonlinear. The same simulation setup used for SPWM, maintaining identical circuit components and load conditions, has been employed to integrate the proposed controller. A comparative analysis of simulation results is conducted to evaluate its performance, focusing on voltage regulation, total harmonic distortion (THD), and transient response characteristics.

4. SIMULATION MODEL AND TEST SCENARIOS

This section describes the simulation model, system parameters, and test scenarios used to evaluate and compare the performance of the conventional SPWM controller and the proposed USPWM-based control strategy with AVC and LCO. Figure 2(a) illustrates the MATLAB/Simulink model that contains a solar PV source, perturb and observe (P&O) maximum power point tracking (MPPT) algorithm, boost converter, three-phase inverter, and RL load. The boost converter increases the PV output voltage of 123 V to a regulated 400 V DC link, which is regulated by the MPPT algorithm to guarantee maximum power extraction under varying irradiance conditions. The inverter operates using the SPWM method. This model would be used to compare the performance of the conventional SPWM technique under the same load conditions.

The results in Figures 2(b) and 2(c) show that the inverter voltage and current under RL load follow a sinusoidal shape when the SPWM controller is used, but the voltage has steady-state ripple and overshoot during transients. The settling time takes about 22 ms, which means the system takes its time to respond to sudden changes in load. On top of that, Figures 2(d) and 2(e) analyze the signal with FFT analysis, a voltage and a current THD are 9.24%, 5.97% suggesting significant amounts of low-order harmonics are present. Thus, the SPWM is not very effective at managing dynamic voltage and handling harmonic issues when connected to a reactance load.

4.1. Dynamic and harmonic analysis of the proposed control strategy

Inverter control techniques of a solar PV-fed system are compared and evaluated using a simulation model built in MATLAB/Simulink. First, an ordinary SPWM-based controller was used on a three-phase inverter with a balanced RL load. In an attempt to enhance performance, a Unified Space Vector PWM (USPWM) method combined with an AVC and LCO was subsequently implemented in Figure 3(a) (see Appendix). A DC-DC converter of 0.15 mH inductor, 500 µF capacitor, and 123 V DC PV source is used to provide 400 V DC. Comparative results clearly reveal that the proposed USPWM with AVC and LCO has a faster transient response, and also lower THD compared to SPWM, which justifies its superiority when subjected to the same testing conditions.

Using the suggested USPWM with AVC and LCO, the inverter output is steady and sine-shaped and can respond quickly to abrupt changes. Stabilization within 11 milliseconds after a load change occurs, making the system's transient response much better than that of SPWM. Figure 3(b) (see Appendix) shows the load voltage waveform of the inverter using the proposed USPWM with AVC and LCO, indicating a nearly sinusoidal voltage with negligible distortion. Figure 3(c) (see Appendix) depicts the load current waveform, which is smooth and synchronized with the voltage, demonstrating stable operation under the applied load. The FFT analysis of Figures 3(d) and 3(e) (see Appendix) proves that the voltage and current THD are 2.279% and 3.37% which is better, and shows that the power quality and robustness improve when the power is loaded with resistive loads.

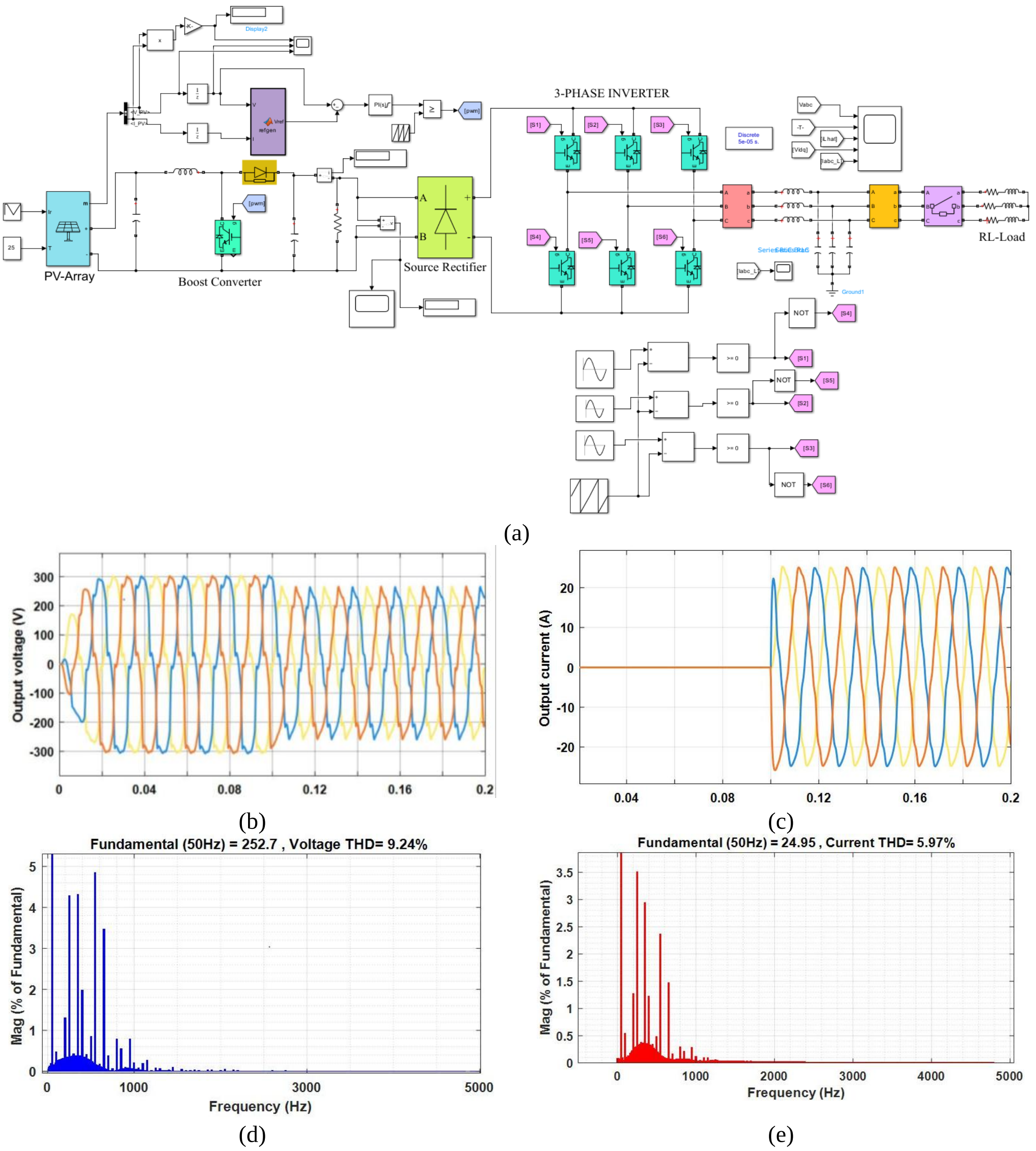

Figure 2. Simulation model of solar PV system using SPWM control: (a) system model, (b) load voltage waveform, (c) load current waveform, (d) voltage THD, and (e) current THD

5. CONCLUSION

The paper compares conventional SPWM with a USPWM scheme combined with an AVC and an LCO for a three-phase solar inverter. Using simulation, it was found that the new USPWM method greatly improves performance. Using USPWM + AVC + LCO, the voltage THD is reduced to 2.279%, lower than the 9.24% additionally, the current THD 3.37% reduced to compared to 5.97% achieved with SPWM alone. In addition, the time it takes for the system to settle down decreases from 22 ms (SPWM) to 11ms, showing a faster reaction to changes. With the implementation of the AVC and LCO, the voltage can be closely regulated, and the system quickly returns to normal when loads change, which makes it more resilient in unpredictable operating conditions. The results prove that using the suggested control strategy helps reduce harmonics and make the system work better during transient events. More work is planned for designing experiments and including advanced control methods for better results.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Sreedevi Kunumalla	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓
Durgam Rajababu		✓	✓			✓			✓	✓	✓	✓	✓	
A. V. V. Sudhakar	✓		✓	✓			✓		✓		✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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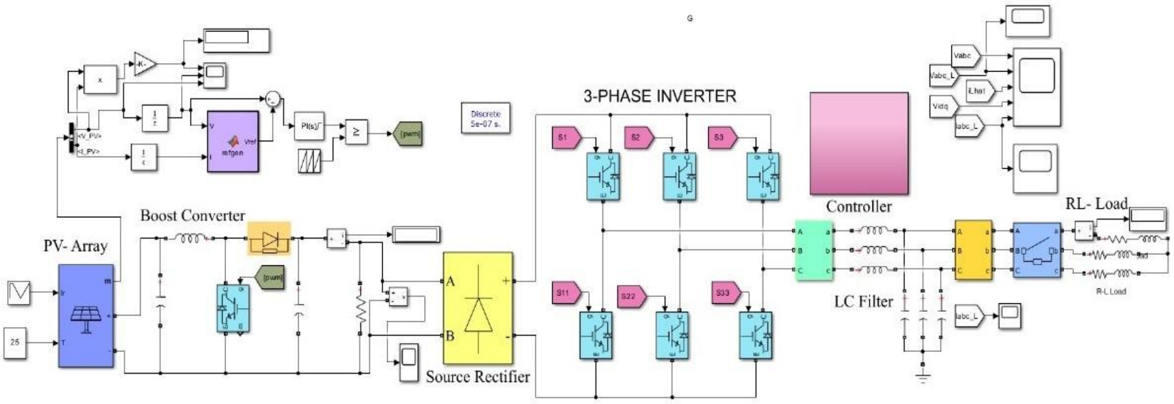
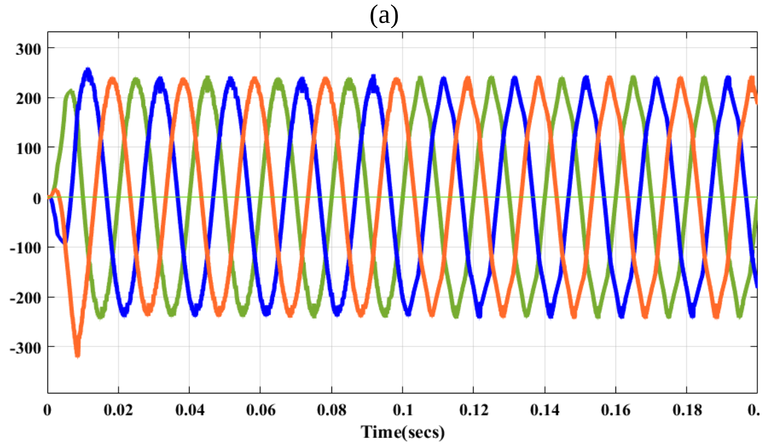
APPENDIX

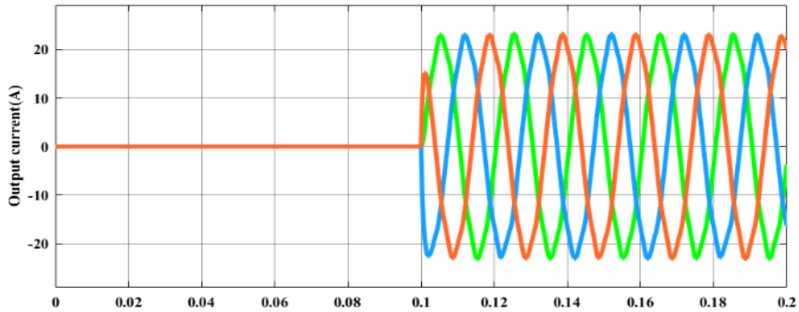


(a)

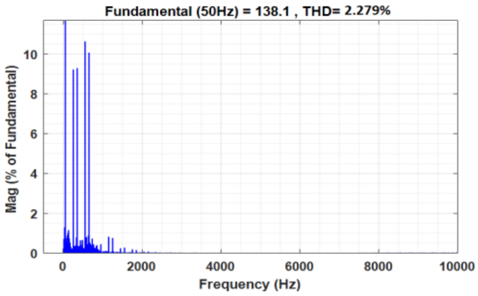


(b)

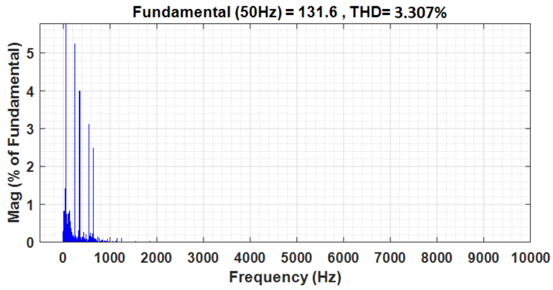
Figure 3. Simulation model of solar PV system using UVSPWM control: (a) system model and (b) load voltage



(c)



(d)



(e)

Figure 3. Simulation model of solar PV system using UVSPWM control: (c) load current waveform, (d) voltage THD, and (e) current THD (continued)

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