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Calculation of Optimal Switching Angles for Three Phase MLI Using Particle Swarm Optimization Algorithm

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Abstract:

In renewable energy sources (RESs), the multilevel inverter is essential because it provides an economical and highly effective way to convert DC from photovoltaic (PV) sources into high AC voltages. Furthermore, a novel technology is really significant as it enhances power generation efficiency and allows PV systems to be seamlessly integrated into the grid, which promotes the wider adoption of RES and a sustainable future. Through determining the ideal switch angles in this study, the particle swarm optimization (PSO) algorithm is applied. The reduced switches multilevel inverter output load voltage with the minimum capacity of total harmonic distortion (THD) is the basis for selecting these angles. The method is being used for the nonlinear equations related to the switching angle computation. In this experiment, the DC source is an isolated, irregular photovoltaic panel feeding a three phase 25-level inverter with fewer switches and sources. Both theoretical research and simulation are conducted using Matlab/Simulink for a multilevel inverter 12-switches/phase, where the input DC voltages are organized as (1:1:5:5)Vdc for each phase. The THD of the 25-level output voltage and current are 1.78% and 0.19%, respectively. The designed system explains its effectiveness for producing the required output voltages at different modulation indexes.

Keywords: *Renewable energy sources, MPPT algorithm, multilevel voltage source inverter, selective harmonic elimination, particle swarm optimization, THD.*

1 Introduction

The modular architecture, low dv/dt, and better efficiency of the multilevel inverter (MLI) result in nearly sine-wave output voltage waveforms and minimal harmonic distortion, making it a very beneficial device for medium and high-voltage applications. There are several unique issues associated with traditional MLI topologies, including cascaded H-Bridge inverter (CHBMLI), diode clamped (DCMLI), and flying capacitor (FCMLI). The FCMLI grapple with complicated voltage control and higher magnitude, whereas the CHBMLI needs many isolated DC sources to get lower total harmonic distortion (THD). The DCMLI uses a lot of diodes and extensive power flow control. Depending on the usage of isolated DC sources, MLIs are more separated into asymmetric and symmetric structures. These traditional methods are examined, and improvements are suggested to increase MLI act for different power applications (Rodriguez J. et al 2007). Higher output voltage levels in symmetric MLI topologies necessitate multiple equal amplitude input DC sources. Asymmetric MLIs, on the other hand, accomplish greater levels with fewer input sources of different magnitudes, which lessens the requirement for several separated DC sources, a typical drawback in conventional inverter types (Ali R. A., et al, 2024). There are several advantages when renewable energy sources (RESs) are joined into the electricity grid. The aforementioned factors include lowering the strain that increasing load demand is placing on the present power grid, decreasing blackouts caused by greater power consumption, lowering network limits on power delivery capabilities, and lowering the challenges involved in constructing more transmission and distribution lines (Gupta and Jain 2014). Given that the amount of power produced by renewables changes during the day, it is imperative to optimize energy collecting. The output power of solar arrays is dependent on solar radiation and its intensity. The control methods of these systems must thus respond correctly to changes in these parameters (Bughneda A., Salem

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M., Richelli A., Ishak D., and Alatai S., 2021), (Ali R. A, Abdulghafoor A. A., and Antar R. K., 2023). PV array systems cannot function at maximum power point tracking (MPPT) unless the input current and voltage at the output are adjusted. PV panels' fluctuating voltage and low output voltage quality are controlled by DC-DC step-up converters in solar power systems. The consistent voltage and frequency needed for the grid connection are produced by a DC-AC (single or three-phase) inverter, which enhances the power quality of the system (Subudhi B. and Pradhan R. 2013), (Ali R. A., Abdulghafoor A. A., and Antar R. K., 2024).

In 2020 (Salman M., et al 2020), the goal of the research is to reduce THD in CHBMLIs while maintaining computational efficiency and system simplicity. It draws attention to the difficulties of solving intricate nonlinear transcendental equations while using selective harmonic elimination (SHE) to reduce low-order harmonics. In order to effectively reduce THD, the authors suggest using a genetic algorithm (GA) to improve switching angle selection. MATLAB used to construct and simulate a 5-level inverter to compare the outcomes of the suggested GA approach with conventional step modulation. The results showed a decrease in THD from 17.88% to 16.74%, along with notable drops in the third and fifth harmonics. All things considered, the GA method enhanced power quality by producing an output that was almost sinusoidal under varied loads when paired with an LC filter. In 2024 (Nasser A. M., et al, 2024), authors investigated a three-phase half CHBMLI control algorithm for PV systems using modified sinusoidal pulse width modulation (SPWM). Unlike existing approaches that need numerous carriers, the suggested solution requires just three signals: one modulating signal, one triangle waveform, and one carrier that simplifies the controller. The THD, which is successfully lowered to 6.8%, is the goal of the gray wolf optimization (GWO) method, which is used to optimize switching angles. In 2024 (Yabalar and Ercelebi 2024), another article presented a hybrid optimization technique that combines teaching learning-based optimization with the whale optimization algorithm for SHE in a three-phase multilevel inverter with a reduced switch topology. This method of adjusting switching angles significantly decreases harmonics of the 11-level inverter. Simulations and experimental findings show that this hybrid methodology has better output voltage quality and performance than previous techniques, emphasizing its potential for harmonic reduction in multilevel inverters. In 2023 (Jayakumar T., et al, 2023), the suggested study used a less switching devices 31-level inverter that optimized using the Artificial Bee Colony (ABC) method to analyze pulse width modulation for SHE in a solar system. It uses the GWO algorithm for effective power extraction and a high-gain DC-DC SEPIC converter to keep the output voltage steady. In order to minimize the higher order harmonics, multi-carrier modulation is used. In 2021 (Chew W. T., et al, 2021), the grasshopper optimization algorithm (GOA), which uses selective harmonic minimization pulse width modulation to optimize switching angles in CHBMLIs was designed. According to simulation findings on a three-phase, nine-level CHBMLI, GOA is able to eliminate low-order harmonics and provide a staircase AC output by properly managing variable modulation indices. In comparison to the evolutionary algorithm, GOA finds optimum solutions across a wider range and achieves greater global minima dependability than the Newton-Raphson approach. In general, the outcomes confirm that GOA works well for this use case. In 2024 (Ali R. A., et al, 2024), the study minimizes THD by implementing a 31-level inverter utilizing FPGA and the Practical Swarm Algorithm (PSA), yielding outcomes that meet IEEE requirements. With simulation and real-world results closely matching, Particle Swarm Optimization (PSO) was utilized to successfully handle nonlinear equations and uneven DC sources.

According to literature, a PSO algorithm is adopted to select the best angles for SHE in a suggested 25-level inverter with 12-switches topology, as shown in Figure 1.

2 System Description

2.1 PV system

Solar panels and arrays of PV cells turn light into electricity. Different cells function as diodes and produce electron-hole pairs whenever they come into contact with light. The n-p junction of the diode creates movements of holes and electrons in the electric material, which are driven out into an external circuit by the interface potential. Leaked current at n-p junctions and cell parallel resistance are the causes of thermal losses (Tazi K., et al, 2017). Weather and day temperature conditions, and the sun position all affect solar irradiation. Output current and voltage are significantly fluctuating as a result of each of these parameters, which results in non-linear behavior. A boost converter uses a MPPT technique to achieve maximum power in order to mitigate this matter (Qasim and Velkin 2021).

The PVs, diodes, are made from pn-type semiconductor materials. Upon exposure to sunlight, the PVs generate an electrical current. For PV modules to provide enough voltage and power, several solar cells linked in parallel and series are often needed (Chen Y. M, et al, 2007). Figure 2 shows a forward-biased parallel diode coupled to a current source (Kumari and Kumar 2018). The PV cells with the effect of irradiation (Ir) and temperature (T) are used as input DC sources of the MLIs. To confirm MPPT got from the PVs, the step-up converter switches was switched using the MPPT technique. The suggested PV cell with the boost model circuit is shown in Figure 2. The MPPT algorithm built based on Perturb-Observation (P&O) method depends on the measured PVs voltage and current. Figure 3 shows the depended P&O algorithm flowchart (Qasim and Velkin 2020).

2.2 Configuration of system components

The three-phase circuit design for the 25-level inverter seen in Figure 4 consists of four PV array circuits, four boost converters with their MPPTs, and twelve switches for each phase. The converter acts as DC sources with unequal values and structure (1:1:5:5)V_{dc}. The MLI circuit is designed to provide an output voltage ranging from +12V_{DC} to -12V_{DC}.

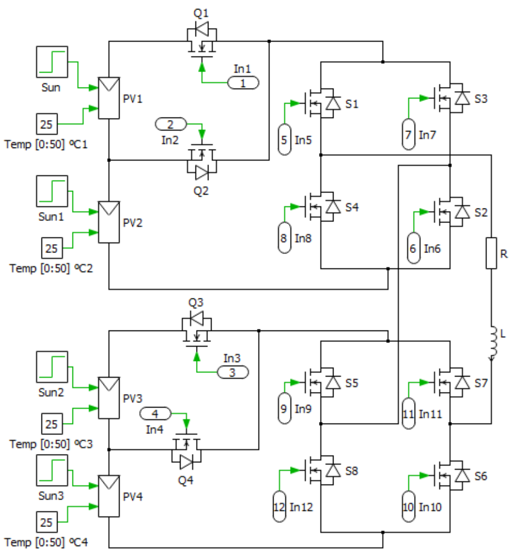

Figure 1. The suggested 25-level inverter circuit per phase.

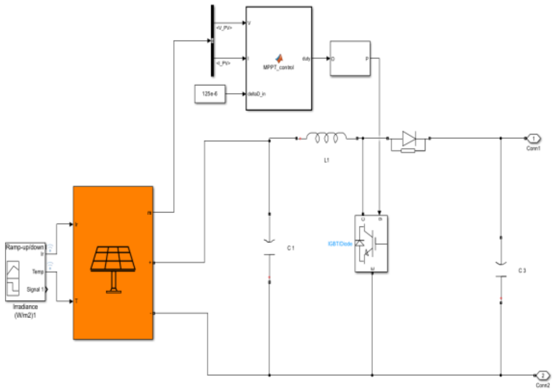

Figure 2. PV with DC boost converter model circuit

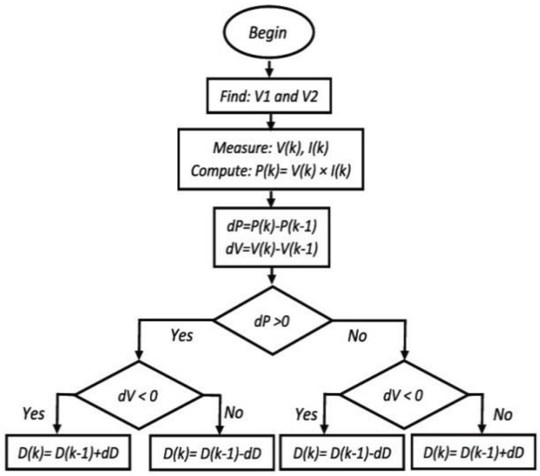

Figure 3. The P&O algorithm flowchart (Colak I., Kabalci E, Bayindir R., 2011)

3 Methodology

Controller of the suggested MLI depends on the switching angles being specified. The output voltage and current of MLI circuit may be controlled using a variety of modulation methods. Classify modulation schemes into two groups according to the frequency of switching can be done (Neralwar K. S., Meshram P., and Borghate V., 2016), (Muthuramalingam A., Balaji M., Himavathi S., 2006). The control circuit is uncomplicated and reliable, as each leg has its own trigger circuit representing 12 pulses, equal to the number of leg switches. Each pulse value is obtained through an algorithm that calculates the optimal value for each pulse. The phase angle between each two phases, 120 degrees, is added to the calculated value. Figure 5 shows the designed controller circuit.

3.1 Selective Harmonic Elimination

The harmonic removal approach is an offline method that uses calculated angles to remove low order harmonic components and regulate the fundamental component. Switching angles are computed depending on many nonlinear equations to minimize low order harmonics (Rao and Rao 2021). Artificial intelligence (AI) techniques are mostly applied as an optimization technique to address engineering challenges (Mohammed L., 2022). Furthermore, low-cost digital signal processors may be used to quickly build this AI. Several optimization techniques are employed in different contexts, including differential evolution, PSO, GA, and Bee Algorithm (Vijaya A. N., et al, 2021). The objective functions used by these algorithms take nonlinearity in low-order harmonic equations into account. Most researchers use different goal functions to eliminate low harmonic orders (Espinosa C. A. L., et al, 2012). A number of approaches have been put out over time to deal with the harmonic elimination issue. The PWM approach of selective harmonic removal allows for the expression of the output waveform by Fourier expansion (Krikor K. S., et al, 2008). The m-level converter's Fourier series expansion and the output voltage expression are provided by:

$$Bn = \sum_{i=1,2,3,\dots}^{m} \frac{4V_{dc}}{n\pi} \cos(n\alpha_i) \quad (1)$$

$$V(t) = Bn * sin(n\alpha_i) \quad (2)$$

The power switch angles must be calculated to minimize voltage and current distortion as minimum as possible (Ozpineci B., et al, 2005). The magnitude of the modulating signal to the overall DC input voltage is indicates as the modulation index (Mi), which represents as (Ghasemi N., et al, 2011):

$$Mi = \frac{V1}{S*Vdc} \quad (3)$$

It is possible to eliminate all low order harmonics by resolving equations (2) and (3).

$$\begin{Bmatrix} V1 = \frac{4Vdc}{\pi}[cos\alpha_1 + cos\alpha_2 + \cdots + cos\alpha_m] = Mi \\ V3 = \frac{4Vdc}{3\pi}[cos3\alpha_1 + cos3\alpha_2 + \cdots + cos3\alpha_m] = 0 \\ \vdots \\ Vn = \frac{4Vdc}{n\pi}[cosn\alpha_1 + cosn\alpha_2 + \cdots + cosn\alpha_m] = 0 \end{Bmatrix} \quad (4)$$

Where S is dc source number, V_1 is the fundamental voltage value, V_{dc} is dc source value, α_m is switching angle, and V_n is the output voltage for the n^{th} harmonic. In single-phase, n = 1,3, 5, 7 … ∞, but in three-phase system, the triple harmonics are removed. The following condition must be met by the switching angles (Kennedy and Eberhart 2002).

$$0<\alpha_1<\alpha_2<\alpha_3<\cdots\alpha_{12}<90 \quad (5)$$

3.2 Particle Swarm Optimization

The optimization approach known as PSO was introduced by (Kennedy and Eberhart, 2002). Search areas with many dimensions are typically utilized for the PSO algorithm (Davis L., 1991). In nature, insect swarm behavior serves as the model for the PSO computational method. The PSO algorithm and GA optimization are comparable. The particles transfer about the search space, with each possible solution being randomly assigned a velocity vector. Every particle utilizes the tracing in individually of its directs inside the search space, linking it to the finest solution found up to that point. "pbest" (present best) is another name for this number. Comparably, a value designated as "best" is likewise tracked in the same manner. The overall algorithm tracks the general value and location that each particle in the population has achieved up to that moment, which is referred to as (global best) "gbest". To summaries, particle swarm optimization involves using the variation in velocity (acceleration) of individual particles to the variable (gbest) at each temporal step. Using these random values, a random term is used to assign acceleration. These terms are created for the acceleration to (pbest) and (gbest) (Eberhart, and Kennedy 1995). The objective function's variables are randomly chosen. The variables (pbest) and (gbest) are numbered as a result of the iterations. The following formulas are then used to number the velocity vector V for the variable θ:

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$$V_{(n+1)}=WVn + k_1\, ran(P_{best} - X_n) + k_2\, ran(G_{best} - X_n) \quad (6)$$

$$X_{(n+1)}=X + V_{(n+1)} \quad (7)$$

The new particle's velocity may be determined using Eq. (6). This updated number is determined by the pace at which you were previously moving, the distance between your present location and your best position (individual experience), and the best experience of the swarm (group). The particle's new location is mentioned in Eq. (7). The weight of inertia, or W value, varies depending on the kind of issue and each criterion when the coefficients k1 and k2 are selected between 1 to 2. Selecting a larger W number, however, makes the scan go more smoothly. Selecting a lower number, however, modifies the current search area. Finding the overall optimal value fast and selecting an acceptable inertial weight value can lead to increased expertise. The expressed fitness value (FV) is set regarding to equation (10).

$$FV(\alpha 1, \alpha 2, \ldots, \alpha_m) = \left[\frac{(h3)^\wedge 2 + (h5)^\wedge 2 + (hn)^\wedge 2}{\text{abs}(h1)}\right]^\wedge 1/2 \quad (10)$$

Where h_1 is the fundamental component, and h_n is the amplitude of the n^{th} harmonic with n odd number of (5, 7 up to 25).

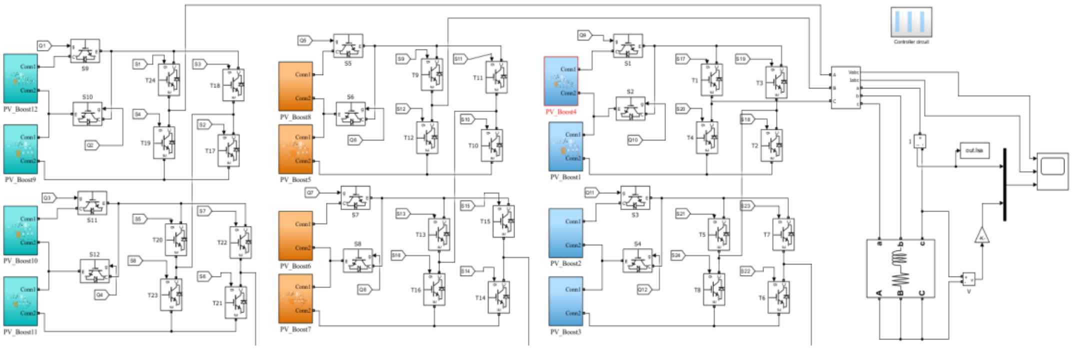


Figure 4. Model three-phase circuit of the 25-level inverter.

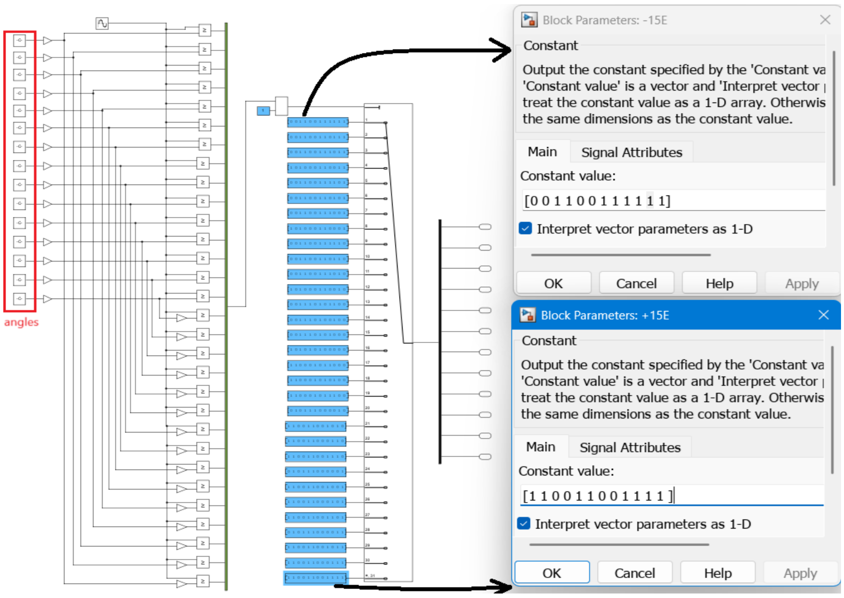


Figure 5. the control circuit of the 25-level inverter per phase.

4 Results and Discussion

The suggested 25-level inverter system is tested with PV panels data as shown in Table 1 and inductive load R=100Ω and L=200mH. The PV with DC converter circuits is built to give voltage of 30Vdc with the structure is (1:1:5:5)Vdc. Figure 6 illustrates the determined power, current, and voltage of the used PV panel. Figure 7 explains the P-V and I-V characteristics of the PVs used in this study. While Figure 8 illustrates the output pulses outcomes from MATLAB simulation that used to drive the inverter switches for phase A. Figure 8 indicated to the best designated switch angels in degree at variable modulation index for the three-phase 25-level inverter. Figure 10 demonstrations the THD values for three-phase regarding to the modulation index. Figure 11(a) displays the phase voltage and current of the three-phase 25-level inverter at modulation index (0.95) with angles of α_1 =1.45°, α_2 = 8.56°, α_3 = 13.16°, α_4 =19.32°, α_5 = 20.11°, α_6 = 23.52°, α_7 = 29.12°, α_8 = 40.67°, α_9= 44.19°, α_{10} = 58.71°, α_{11} = 67.12°, and α_{12} = 88.71°. Figure 11(b) shows the Fast Fourier transform analysis of the 25-level voltage and current at modulation index of (0.95). The THD magnitudes of the line output voltage and current are 1.786% and 0.198%, respectively. Through the results shown in the figures and the values of the optimal angles obtained through the PSO algorithm, it can be said that the proposed circuit has given accurate and ideal results at different Mi values close to one. This is clearly evident depending on the THDs for both voltage and current waveforms.

Table 1. The PV panel 25-Level inverter.

Components	Symbols	Value
1Soltech 1STH-215-P	PV1&PV2 PV3&PV4	1 Series x 1 parallel 5 Series x 3 parallel
Maximum power	P_{Max}	213.15W
Open Circuit Voltage	Voc	36.3V
Short –Circuit Current	Isc	7.84A
Voltage at maximum power point	Vmp	29V
Current at maximum power point	Imp	7.35A

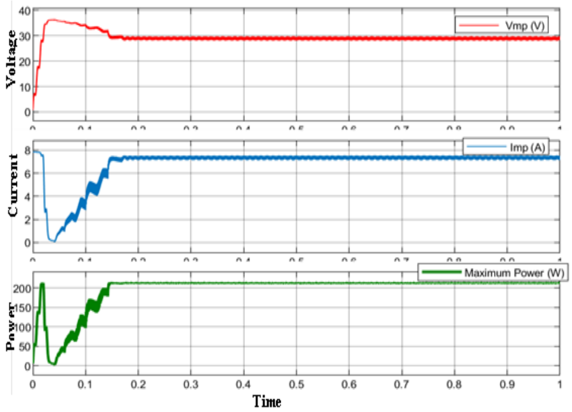
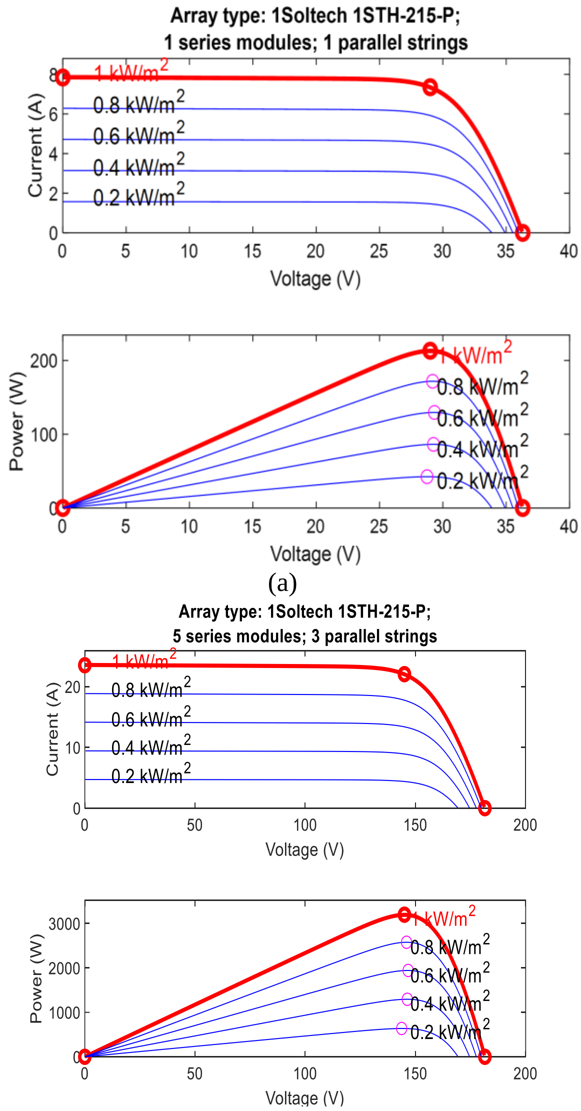


Figure 6. Voltage, current, and power of the selected PV for phase A.



(a)

(b)

Figure 7. The P-V and I-V features of (a) PV1, PV2 and (b) PV3, PV4 arrays.

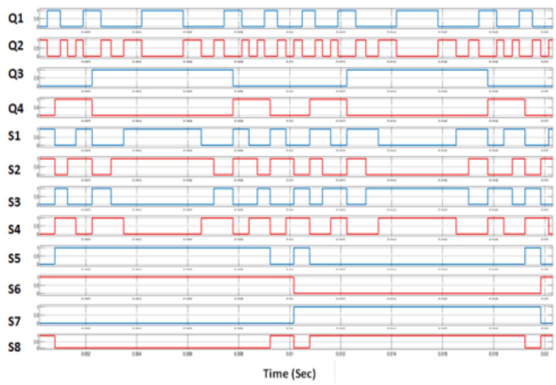


Figure 8. The output pulses pattern to drive the inverter switches for phase A.

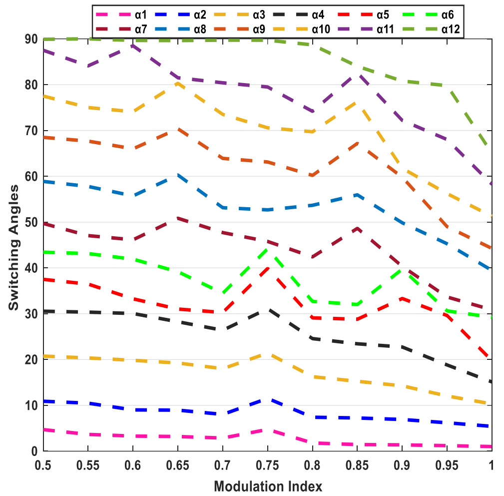


Figure 9. Different switching angles and modulation index of the three-phase 25-level inverter.

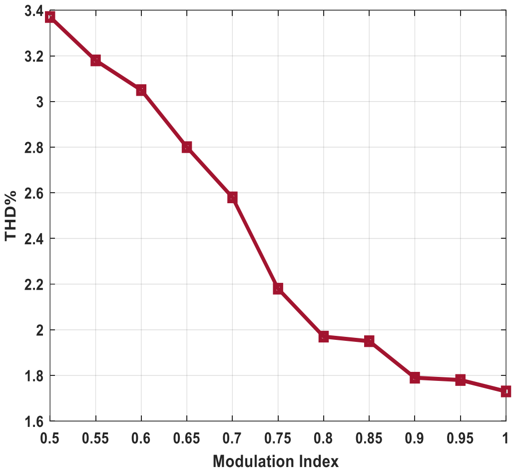
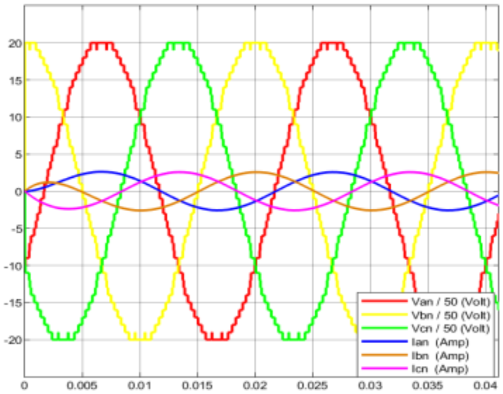
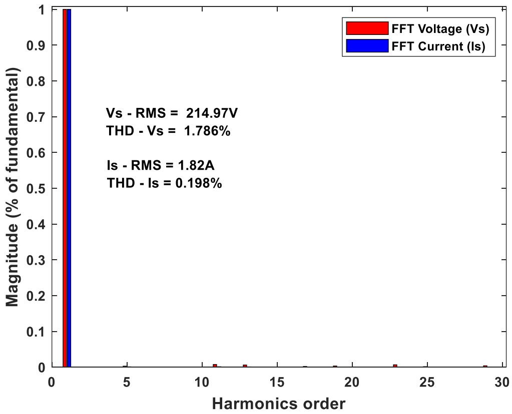


Figure 10. THD of the three-phase 25-level output voltage at different modulation index.



(a)



(b)

Figure 11. (a) three-phase 25-level line voltage and current waveforms and (b) their FFT analysis at modulation index (0.95).

5 Conclusions

This paper examines the best angles to minimize the lower harmonics in the output voltages of the three-phase 25-level inverter. The SHEPWM approach has been developed for this reason. Non-linear transcendental equations are created in this case of implementation. A sophisticated PSO method is employed to solve these nonlinear equations. These algorithms may solve nonlinear equations and, using an offline procedure, provide a solution of ideal switching angles. This method might be used to remove lower frequency information, particularly the fifth and seventh harmonics. The PSO algorithm validation is used and given a low THD values. The computed THD values of the output line voltage and current are 1.78% and 0.19%, respectively. These values fall within the IEEE519-2014 standards range. Thus, in terms of accuracy and harmonic distortion, the suggested PSO algorithm produces the best possible outcome. In the future, the suggested paradigm may be applied in real-time experimentally verification.

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