Journal of Information Systems Engineering and Management
2025, 10(20s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

A Multilevel Inverter for Grid-Connected Photovoltaic Systems using Improved Moth Flame Optimization

Neelashetty Kashappa
Faculty, Electrical and Electronics Engineering department, Guru Nanak Dev Engineering College, Bidar, Karnataka, 585403, India
neelshettyk@gmail.com

ARTICLE INFO

Received: 18 Dec 2024

Revised: 30 Jan 2025

Accepted: 14 Feb 2025

ABSTRACT

In recent days, Renewable energy is rapidly growing, with solar energy being the most researched due to its sustainability, efficiency, and global adoption. Traditional approaches for grid-connected Photovoltaic (PV) systems have faced several challenges which include high Total Harmonic Distortion (THD) and low efficiency. Therefore, this research proposes five level Neutral Point Clamped (NPC)inverter optimized by Improved Moth Flame Optimization (IMFO) for grid connected PV systems. Initially, PV generator converts the absorbed sunlight into electrical energy where, multiple solar cells are connected in series and parallel to generate required DC power. Next, a Direct Current to Direct Current buck converter (DC-DC) with Incremental Conductance Maximum Power Point Tracking (IC-MPPT) method is employed where, IC MPPT is used for extracting the maximum power from PV generator and DC-DC buck converter for stabilising varying DC voltage. Further, Proportional Integral (PI) controller is employed for regulating DC voltage and controls Alternating Current (AC) power injection into grid by adjusting inverter switching patterns. To enhance the performance of PI, a IMFO is employed which optimized the parameters of PI controller. This obtained stable DC power is converted into AC power by the five level NPC inverter. Finally, an Inductor Capacitor (LC) filter is employed which filters the remaining harmonics and pure AC power is integrated in to grid. The proposed IMFO achieved better results in terms of K_p (0.0250) and K_i (0.0085) and THD (0.25) which attained very low THD when compared to existing Genetic Algorithm (GA).

Keywords: Direct Current, Incremental Conductance, Maximum Power Point Tracking, Neutral Point Clamped Inverter, Photovoltaic Systems, Proportional Integral Controller.

INTRODUCTION

In recent years, with the quick depletion of fossil fuels and the increasing global energy needs, renewable energy sources have recognized as a sustainable option to satisfy electricity needs while minimizing environmental effect [1]. Photovoltaic (PV) systems stand out among these sources for their ability to capture solar energy and convert it into electrical power, gaining considerable attention [2]. However, integrating PV-generated electricity into the utility grid calls for advanced power electronics, especially MLIs, which plays an important role in transforming DC power from solar panels [3] into grid-compatible AC power. With multilevel inverters chosen because of their better reduction of THD, developing high-efficiency inverters has become important to guarantee steady energy transmission and high quality [4]. They had utilized in large-scale industrial and utility applications as well as small-scale residential solar systems due to their highly scalable modular design [5]. Multilevel inverters are essential to accelerating the shift to clean and sustainable energy sources because they provide for a more dependable and efficient interface between solar PV installations and the electrical grid [6]. Additionally, modern optimization techniques, like Ant Colony Optimization (ACO), Artificial Bee Colony (ABC) and Cuckoo Search Algorithm (CSA) are being examine to boost the performance of multilevel inverters by upgrading control approaches [7] providing minimizing switching losses and optimal power tracking. Although multilayer inverters for grid-connected PV systems have several advantages, many problems prevent their general deployment. Harmonic distortion and power quality problems still cause major concerns since bad inverter performance led to excessive THD, therefore compromising grid stability [8].

Multilevel inverters had larger and heavier due to the extra components, which could influence the total weight and size of the PV system especially in space-limited installations. Another major difficulty in DC-link capacitors is voltage balancing since inappropriate voltage control could cause system inefficiencies and higher component stress [9]. Moreover, challenging are computational complexity and real-time control limits since multilevel inverters depend on advanced modulation and optimization strategies to provide seamless power conversion. Dealing with these challenges requires advanced optimization algorithms to fine-tune inverter parameters, improve efficiency, and enable real-time adaptive control. Advanced optimization strategies have been studied to enhance the dependability and efficiency of multilayer inverters in order to face these problems [10]. ACO mimics the foraging behaviour of ants to find the shortest path, making it effective in optimizing switching angles and reducing harmonics. Although ACO performs well in dynamic situations, it has sluggish convergence and large processing requirements. Because of its fast convergence, simplicity, and capacity to handle non-linear systems which make it appropriate for inverter control is extensively employed However, CSA [11] may get trapped in local optima and requires fine-tuning for optimal performance. The ABC technique is another promising method that certifies impactful power tracking, voltage management, and decreased power loss in multilevel inverters. It is modelled after the food-foraging behaviour of honeybees. ABC [12] offers great flexibility and adaptability, but it also uses more computing resources and occasionally causes premature convergence. These optimization techniques continue to evolve, supporting the development of grid-connected PV systems and ensuring maximum power extraction, reduced losses, and stable grid integration.

The main contribution of this research is demonstrated as

- Incremental Conductance Maximum Power Point Tracking (IC-MPPT) method is employed for extracting the maximum power from PV generator which updates the duty cycle of DC-DC buck converter to stabilise DC voltage.
- Improved Moth Flame Optimization (IMFO) is employed for optimizing the parameters of Proportional Integral (PI) controller which adjusts the spiral adaptation in solution spcae for quickly and effectively finding best K_i and K_p values to minimize error and improve stability.
- Five level Neutral Point Clamped (NPC)inverter is employed for converting the DC power into AC power which incorporated Sinusoidal Pulse Width Modulation (SPWM) technique for ensuring smooth transition among voltage levels and reduce THD.

The organization of this research is ordered as: section 2 determines literature review; section 3 explains the overall methodology, experiment results evaluated in section4, and the paper ends with summary which is presented in section 5.

LITERATURE REVIEW

Raihane Mechgoug*et al.* [13] introduced a grid-connected PV system by using five-level neutral point clamped (NPC) inverter for integrating the PV power into power grid. Initially, PV generator had captured solar energy and convert edit into DC power. To ensure steady voltage regulation, a DC-to-DC buck converter and MPPT were employed for optimizing the power output. This regulated DC power was supplied through a five-level NPC inverter that converted DC into AC power. After that, SPWM was incorporated for controlling the switching of the inverter. Finally, GA optimized PI controller was incorporated, that ensured voltage stability and reduced THD. The implemented five-level NPC inverter effectively reduced THD and improved power quality. However, the computational complexity of GA optimization process required more processing time and computational resources.

Shimi Sudha Letha *et al.* [14] suggested a fifteen-level inverter with reduced number of switches for harmonic elimination. The introduced fifteen-level inverter incorporates twelve switches in which eight switches for level generation and four for polarity generation. A Selective Harmonic Elimination (SHE) technique was employed for minimizing the THD and GA was employed for optimizing this SHE technique. The suggested fifteen-level inverter reduced THD, component and improved efficiency. However, the switching control and GA-SHE based optimization increased complexity that leads to more processing time.

Muhammad Sajid Iqbal et al. [15] demonstrated a 15-levelcascaded H-bridge multilevel inverter (CHB-PV) inverter by utilising an Artificial Neural Network (ANN). Initially, three isolated solar PV arrays were arranged with specific voltage of 1:2:4 for reducing number of switching devices requirement. After that, 15-level CHB-PV Generator had employed in which ANN control algorithm had designed for determining optimal switching angles for reduced THD. This ANN model had trained with single hidden layer consisting ten neurons and applied a ReLU activation function for effective training. The introduced 15-level CHB-PV generator effectively reduced THD but, failed to analyse the switching losses at higher frequencies. Himanshu Sharma *et al.* [16] introduced a 15-level CHB-PV generator for integrating both PV and Battery Energy Storage Systems (BESS) for enhance their efficiency and reliability. Firstly, a novel 15-level CHB-PV inverter with reduced switch count had designed for improving efficiency and reduce hardware complexity. After that, solar PV had integrated with BESS for stabilising power output and optimize energy utilisation. A reinforcement learning-based coordinated switching control had implemented for adjusting inverting operation during various solar irradiance conditions. The demonstrated 15-level CHB-PV inverter significantly reduced THD and improved power quality by employing Particle Swarm Optimization (PSO). However, 15-level CHB-PV inverter failed in testing the system under real-time grid conditions and it required high processing power for implementation. Madhu Andela *et al.* [17] suggested a fifteen level PV inverter with a reduced switch configuration to improve power quality in solar photovoltaic systems. This system resolves the challenges of conventional inverters which includes high switching losses and harmonic distortion. This method resolves by decreasing the number of switches while achieving higher voltage levels. Consequently, it uses only ten IGBT switches that are less than traditional diode-clamped, cascaded, or flying capacitor PV generators facilitates to reduce the system cost and complexity. Furthermore, simulations illustrate that the suggested PV inverter significantly lowers THD compared to 15-level, 31-level, and 63-level PV generators, resulting in improved efficiency and performance. Hence, the system integrates a solar photovoltaic source with DC-DC converters to generate multiple voltage levels which was suitable for off-grid applications.

PROPOSED METHOD

In this research, five level NPC inverter for grid connected PV Systems optimized by IMFO is proposed. Initially, PV generator converts the absorbed sunlight into electric energy where, multiple solar cells are connected in series and parallel to generate required DC power. Next, aDC-DC buck converter with NC MPPT method is employed where, NC MPPT is incorporated for extracting maximum power from PV generator and DC-DC buck converter for stabilising variable DC voltage. Further, PI controller is employed for regulating DC voltage and controls AC power injection into grid by adjustinginverter switching patterns. To enahance the performance of PI, a IMFO is empolyed which optimized the parameters of PI controller. This obtained stable DC power is converted into AC power by the five level NPC inveter. Finally, a LC filter is employed which filters the remaining harmonics and pure AC power is integrated in to grid. The Overall block diagram of proposed methodology is shown in figure 1. That consists of four main elements namely, PV generator, DC-DC buck converters, NPC five-level inverter and an LC filter. These four elements working and their contribution in this process is explained in further subsequent sections.

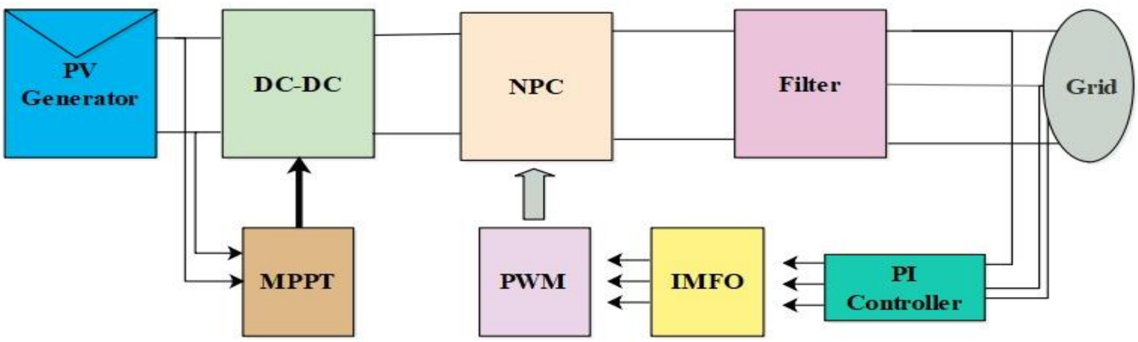

Figure 1. Overall Block Diagram of Proposed Methodology

Photovoltaic Generator

Here, the PV generator is a solar panel system that converts sunlight into electrical energy. It incorporates multiple solar cells which are connected together to form solar modules also known as arrays. These solar modules generate enough power to be used in different electrical applications, supplying a sustainable and consistent source of energy for powering industries, homes and buildings. Initially, the power produced at a singular solar cell is very low, so multiples cells are combined in series and parallel to obtain solar module that generates enough power. The one solar cell has a single diode with five parameters such as R_s, R_{sh}, I_{ph}, $I_0$and current voltage characteristics of solar cell is derived from diode equation and is given as shown in equation (1):

$$I_{Ph} - I_0\left(e^{\frac{q}{nAKT}}(V + R_s * I) - 1\right) - \frac{V+R_s*I}{R_{sh}} \quad (1)$$

Where, I represents the current provided by solar module, R_{sh} denotes the shunt resistance, I_0 is the saturation current which is a small leakage current that flows when there is no sunlight, I_{ph} denotes the photoelectrical current, R_s represents the series resistance, Ndenotes diode ideality coefficient and K denotes the Boltzmann's constant.

Equation (1) describes that parameters of solar module are directly related to solar panel parameters that are expressed as shown in equation (2), (3), (4) and (5):

$$I_{scpanel} = N_p I_{sc} \quad (2)$$

$$I_{opanel} = N_s I_0 \quad (3)$$

$$R_{spanel} = \frac{NS_s}{N_p} R_S \quad (4)$$

$$R_{P\,panel} = \frac{N_S}{N_P} R_P \quad (5)$$

Where, $I_{scpanel}$ denotes the total current depends on the number of parallel cells N_p, and I_{opanel} denotes total voltage depends on the number of series cells N_s, $R_{P\,panel}$ denotes the shunt resistance and if more cells are connected in shunt, then resistance decreases since, current has multiple paths to flow. R_{spanel} is the series resistance, if more cells are connected in series, resistance will increase this causes power losses inside the solar panel. These equations effectively described the relation among solar module parameters and individual solar cell parameters.

The photoelectric current (I_{ph}) is completely depended on temperature and irradiation that are expressed as mathematically, shown in equation (6), (7) and (8):

$$I_{ph} = \left(I_{ph,n} + K_l \cdot \Delta T\right) \cdot \frac{G}{G_n} \quad (6)$$

$$I_0 = \frac{I_{sc,n} + K_t \cdot \Delta T}{\exp\left(\frac{V_{oc,n} + K_v \cdot \Delta T}{A \cdot V_{th}}\right) - 1} \quad (7)$$

$$\Delta T = T - T_n \quad (8)$$

Where, I_{sc} represents the short circuit current during normal conditions that means $G_n = 1000w/m^2$,$T_n = 25^0$, T is the cells ambient, T_n denotes the nominal temperature, G denotes the current and G_n denotes the nominal irradiation, K_l denotes the coefficient of short circuits current temperature, $K_v$is the open circuit voltage and V_{th} denotes the thermal junction constant.

The obtained DC voltage is regulated by DC-DC buck converter and that is explained in the next step. The equivalent diagram of a solar cell is shown in figure 2.

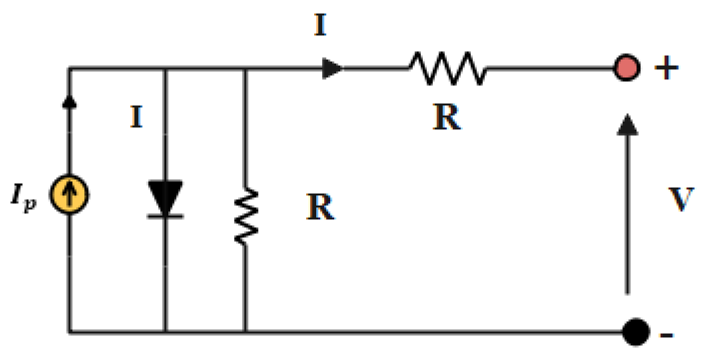

Figure 2. Equivalent Diagram of a Solar Cell

DC-DC Buck Converter

The DC voltage generated by PV generator is fed as input to DC-DC buck converter that stabilise the varying output voltage. Since, the output DC voltage from PV generator is fluctuates because, the solar radiation varies throughout the day. This unstable DC voltage cannot be directly passed to inverter or grid, to stabilize this voltage a buck converter is employed. The buck converter is the most commonly used DC-DC converter because its input voltage is lesser than its output voltage. Filters with capacitor and inductor combinations are commonly composed to improve converter performance. Consequently to, improve the effectiveness of solar panels, a MPPT technique is employed. The MPPT technique alters the current and voltage of a solar panel to extracts maximum power from it. There are several techniques are there to follow the Maximum Power Point (MPP), in this research, the IC method [18] is utilised because simple to use in real time and it is straightforward. The IC method was designed based on the observations of P-V characteristic curve which tries to enhance tracking time and energy production, even in environment with drastic temperature and irradiation changes. The MPP is calculated by utilising the relation among dI/dV and $-I/V$. If $dP/dV$is positive then MPPT lies on left side of recent position and if the dP/dV is negative then MPPT lies on right side. The IC method equation is computed as shown in equation (9) and (10):

$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} \quad (9)$$

$$= I + V\frac{dI}{dV} \quad (10)$$

Where, $\frac{dI}{dV}$ represents the incremental conductance, signifying how the current changes with respect to voltage, $-I/V$ is the instantaneous conductance of solar module at given operating point. MPP is obtained when $\frac{dP}{dV} = 0$ and as expressed in following equation (11), (12), (13) and (14):

$$\frac{dI}{dV} = -\frac{I}{V} (11)$$

$$\frac{dP}{dV} > 0 \text{ then } V_p < V_{mpp} \quad (12)$$

$$\frac{dP}{dV} = 0 \text{ then } V_p = V_{mpp} \quad (13)$$

$$\frac{dP}{dV} < 0 \text{ then } V_p > V_{mpp} \quad (14)$$

Here, equation (11) condition represents the MPP, equation (12) condition represents that voltage need to be increased to reach the MPP, equation (13) condition deos not required any voltage adjustment and equation (14) condition represents that voltage need to be decreased to reach the MPP. From this equations, clearly observes that MPPT algorithm decides either voltage should increase or decrease based on the conditions and it updates the duty cycle of DC-DC buck converter. Finally, converter regulates the output voltage and ensures maximum power is transferred. The obtained maximum power from this converter is given as input to PI controller that regulatesDC voltage and controls AC powerby adjustinginverter switching patterns for better synchronization and that is explained in the next step. The flow chart of incrementalconductance is shown in below figure 3.

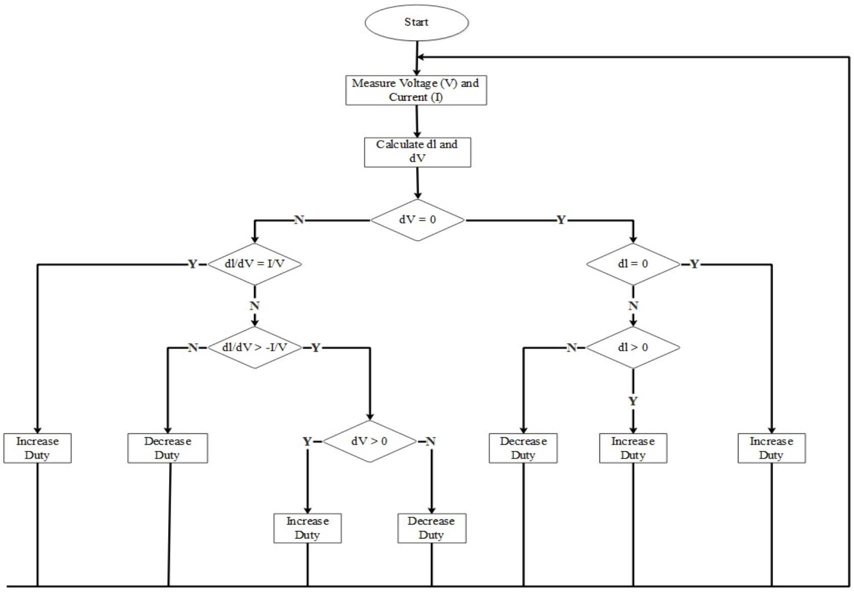

Figure 3. flow chart of Incremental Conductance

Proportional Integral Controller

The PI controller is employed before the inverter to regulate the DC-link voltage and controls AC power injection into grid. The employed PI controller is responsible for adjusting inverter switching patterns which leads to better synchronization. The PI controller is simple and easy to implement. The control of inverter output voltage always requires a closed loop since, PI controller continously compares the measured voltage and current with reference values which are set by MPPT.The error signal is integrated into PI controller, which adjusts the switching patterns of inveter by tuning K_i and K_p to minimize error and improve stability.The mathematical representation of PI controller is expressed as shown in equation (15):

$$u(t) = K_p . e(t) + K_i . \int_0^t e(t)dt \qquad (15)$$

Where, K_i and K_p are the parameters of PI controller, $e(t)$ is the error signal, , K_p is proportional gain that amplifies the error signal immeditately, K_i is the integral gain which eleminates steady state errors, $u(t)$ represents output control signal. It is difficult to define the PI controller transaction values so, IMFO algorithm is employed that optimize the PI controller parameters and it is explained in the further subsequent section.

Improved Moth Flame Optimization

The MFO [19] is a population based intelligent optimization algorithm that enables spiral flight of moths around flames. Notably, here flames and moths both are solutions of function and alteration among them is way we treat and update them in each iteration. The moths are search agents which moves throughout solution space and flames denotes the collection of optimal solutions discovered by moths. Here, each moth is a candidate (K_i ,K_p) pair. Let consider M and OM matrix that denotes the location of moth population and fitness values of individuals. Similarly, F matrix denotes flames location and OF denotes flames fitness value at current position. These matrices are defined as shown in equations (16) and (17):

$$M = \begin{bmatrix} m_{1,1} & m_{1,2} \cdots & m_1, d \\ \vdots & \ddots & \vdots \\ m_{n,1} & m_{n,2} \cdots & m_{n,d} \end{bmatrix}, OM = \begin{matrix} OM_1 \\ \vdots \\ OM_n \end{matrix} \qquad (16)$$

$$F = \begin{bmatrix} f_{1,1} & f_{1,2} \cdots & f_1, d \\ \vdots & \ddots & \vdots \\ f_{n,1} & f_{n,2} \cdots & f_{n,d} \end{bmatrix}, OF = \begin{matrix} OF_1 \\ \vdots \\ OF_n \end{matrix} \quad (17)$$

Where, n and d represents the number of moths and number of dimensions repectively. To simulate moth logarithmic spiralling mechanism towards a flame, its position needs to be updated and it is done by utilising following shown equation (18):

$$S(M_i, F_j) = D_i \cdot e^{bt} \cdot \cos(2\pi t) + F_j \quad (18)$$

Where, M_i represents $i-th$ moth, F_j denotes $j-th$ flame, D_i denotes exact ditance among M_i and F_j, b is a constant which affects logarthimic spiral shape, t denotes random number in [-1, 1]. When $t = 1$ describes that moth is far from flame and when $t = -1$ means that moth is near to flame and D_i is computed as shown in equation (19):

$$D_i = |F_i - M_i| \quad (19)$$

Equation (15) is a mathematical model of each moth flying to its equivalent flame. However, updating position of moth related to n various flames may reduce exploitation possibility of optimal solution. To overcome this limitation, an adaptive flame regulation mechanism is employed, that reduce number of flames NO_f with number of iterations as expressed in equation (20):

$$NO_f = round(N_{max} - I.\frac{N_{max}-1}{I_{max}}) \quad (20)$$

Throughout each iteration, flames are defined and organized based on their fitness values whenever flame list is updated. Then moths fly to the related flames to update their positions, based on position of optimal flame, based on best flame the first moth always updates its position, while the last moth according to the position of the worst flame. Finally in the last iteration, with respect to best flame moths update their positions. This process finds best K_i and K_p values but there still MFO has slower convergence and falls in local optima that leads to more processing time. To overcome this limitation, the MFO is improved by dynamically adjustingspiral adaptation and generating flames near to moth population will help in finding optimal value within low processing time and faster convergence. The updated spiral trajectory formula is computed as shown in equation (21):

$$D_i = |F_i - M_i| \times \exp(-b \times (\frac{D_i}{1+D_i})) \times \cos(2 \times \pi \times (\frac{t}{\max iteration})) \quad (21)$$

Where, b denotes the dynamic adaption parameter, t denotes present iteration number and cos function is utilised since, provides way to employ periodicity and oscillations into the spiral trajectory and balance exploration and exploitation effectively. This dynamic adjustment allows moths to move more effectively towards the flame and finds the best optimized K_i and K_p values quickly which are helpful in eleminating the errors and improve stability. The simultation setup of IMFO is illustrated in the following Table 1.

Table 1. Simulation set up of IMFO

Optimization	Parameter	Value
MFO	Constant Parameter (b)	1
	Population size	30
	Number of iterations	10
IMFO	Constant Parameter (b)	**0.5**
	Population size	**20**
	Number of iterations	**5**

From the Table 1, clearly observes that constant parameter (b)value decreased which means smaller (b) enhances the exploration capability of algorithm and alloes it for searching a wider are of solution space and avoid stucking in local optima. The number of population size and number of iterations also reduced which resulted inbetter convergence spped.Based on this optimized K_i and K_p values, the PI controller effectively adjusts the switching patterns and stabilise DC voltage and controls AC power injection into grid. This obtained stable DC current is fed as input to inverter for DC to AC conversion which is briefed in the next step. the navigation movement of moths MFOis shown in Figure 4.

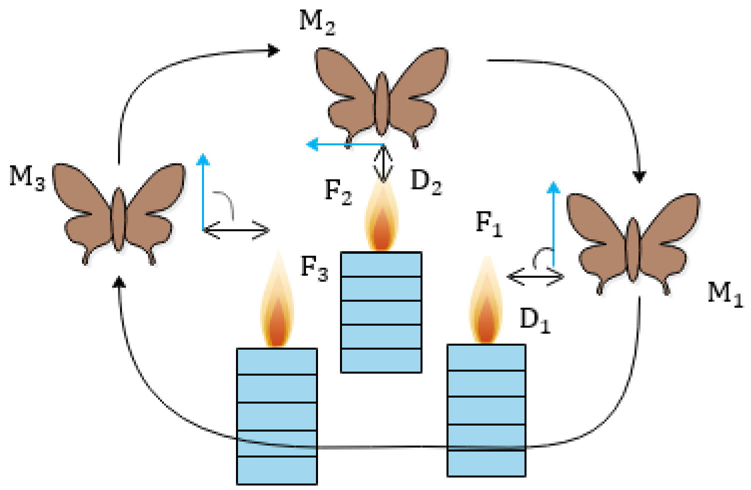

Figure 4. Navigation movement of moths in moth flame optimization algorithm

Five Level Neutral Point Clamped Inverter

The stable DC powerobtained after optimization is fed as input to five-level NPC inverter [20]. The employed five-level NPC inverter is an advanced MLI which is commonly utilised for high power applications. The three phase five-level NPC inverter contains three legs namely phase A, phase B and Phase C, each leg consits eight insulated-gate bipolar transistors (IGBT). There are six diodes per leg and four capacitors on the DC-link, initially, the DC link capacitors segregates the input DC voltage into various levels to faciliate multilevel voltage generation. After that, IGBT switches controls the power flow and regultage the voltage levels and clamping diodes helps in protecing the switches from overvoltage stress. Finally, this inverter generates five distinct output voltage levels which are $+V_{dc}$, $+V_{dc}/2$, $0V$, $-V_{dc}/2$ and $-V_{dc}$. This stepped waveform supports in reducing the harmonic distortion and improves the efficiency of power conversion. The inverter controls the switching of IGBTs in a control sequence inorder to obtain generated waveform closely related to sinsusoidal waveform. But to achieve high accurate sinusoidal waveform, the inverter utilised Sinusoidal Pulse Width Modultation (SPWM) technique that ensured smooth transition among voltage levels and reduce THD. The SPWM required $(N-1)$ triangular signals with similar frequency $f_p$and similar amplitude A_p. These triangular signals are associated for each phase with a reference signal of frequency f_{ref}. the modulation rate and frequency ration are expressed as shown in below equations (22) and (23):

$$m_a = \frac{A_{ref}}{(N-1)A_p} \tag{22}$$

$$m_f = \frac{f_p}{f_{ref}} \tag{23}$$

Where, $m_a$denotes the modulation rate, $m_f$denotes the frequency ratio. Here, value of m_a is less than 1 that represents a clean AC output with very low distortions and m_f is typically high that leads to smoother sinusoidal waveform with reduced THD. This clean AC powerstill holds some small harmonics, these are eliminated by LC filter and that is explained in next step.

LC Filter

The AC power obtained from five-level NPC inverter is given as input to LC filter which is placed at output of the inverter that ensures smooth and sinusoidal waveform. The LC filter is a passive low pass filter most commonly used in inverters for removing the unwanted distortions and high fequency harmonics. Initally, inductor smooths the current waveform by preventing current rapid changes and also prevents from high frequency switching ripples. Then capacitor divert high frequency harmonics to the ground and maintains a stable voltage waveform. After transmitting through the LC filter, the resultant ouptut obtained is a pure sine wave with very low THD, this warrants smooth grid integration without any instability. The obtained pure AC current is integrated into the grid.

RESULT

The proposed five level NPC inverter for grid connected PV Systems optimized by IMFO is implemented with a MATLAB/Simulink. For the experimental analysis, the software requirements such as windows 10 and MATLAB R2022b. The hardware requirements including Intel core i5 processor which is running at speed of 2.14 GHz and 16 GB of RAM.K_p, K_i, THD are utilized as the evaluation metrics.

Performance analysis

The performance evaluation of proposed IMFO is done with various traditional models by using evaluation metrics. The traditional models including CSA, ACO and ABC respectively, which are labelled as shown in table 2.

Table 2. Performance evaluation of proposed IMFO

Performance models	K_p	K_i
CSA	0.0122	0.0009
ACO	0.0125	0.0016
ABC	0.0175	0.0018
Proposed IMFO	**0.0250**	**0.0085**

From the table 2, it is clear that the proposed IMFO provided better results in terms of K_p (0.0250) and K_i (0.0085) when compared to traditional models Such as CSA, ACO and ABC. Further, the proposed IMFO is evaluated using THD and compared with the above-mentioned traditional models which are labelled as shown in table 3.

Table 3. Harmonic analysis of Proposed IMFO

Performance models	THD (%)
CSA	6.91
ACO	5.26
ABC	3.66
Proposed IMFO	**0.25**

From the table 3, the proposed IMFO achieved better results in terms of THD (0.25%) when compared with traditional models like CSA, ACO and ABC. The graphical representation of proposed IMFO, harmonic analysis is shown in figure 5.

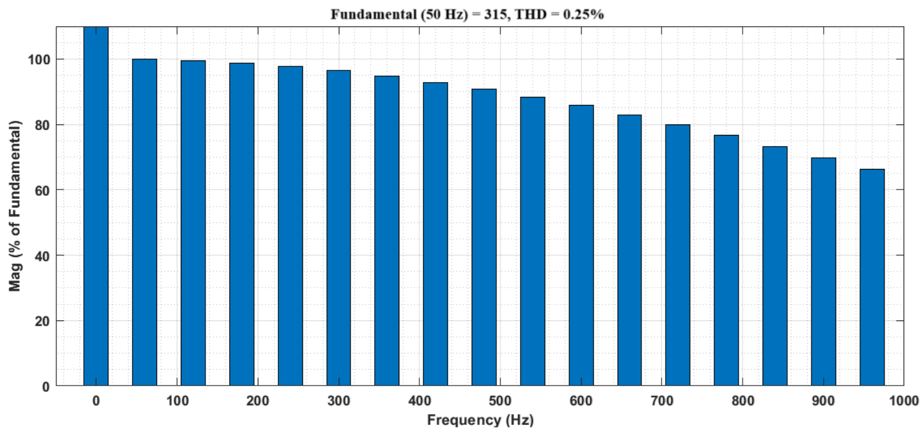

Figure 5. Harmonic analysis of IMFO

The graphical representation of output voltage after filtering is shown in figure 6.

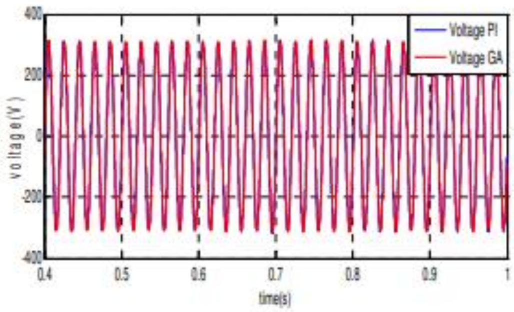

Figure 6. Output Voltage after Filtering

Comparative analysis

The comparative analysis of proposed IMFO is compared with existing GA [13] and evaluation is done by using evaluation metrics which is given in below table 4.

Table 4. Comparative evaluation of proposed IMFO

Comparative models	K_p	K_i
GA [13]	0.0218	0.0011
Proposed IMFO	**0.0250**	**0.0085**

Here, table 4 presents the comparative analysis of proposed IMFO is done by comparing with the existing method. The proposed IMFO achieved better results based on evaluation metrics of K_p (0.0250) and K_i (0.0085) when compared to existing GA [13] which attained K_p (0.0218) and K_i (0.0011) respectively. From the results, clearly observes that proposed IMFO found best values for K_p and K_i that minimized error and improved system performance. Further, IMFO is evaluated using THD and compared with existing GA [13], GA-SHE [14] and PSO [16] that are illustrated in the below given Table 4.

Table 5. Harmonic analysis of Proposed IMFO

Performance models	**THD (%)**
GA [13]	0.30
GA-SHE [14]	3.34
PSO [16]	6.46
Proposed IMFO	**0.25**

From the table 5, clearly observes that the proposed IMFO attained very low THD (0.25%) when compared with existing models GA [13] which achieved THD (0.30%), GA-SHE [14] (3.34%) and PSO [16] (6.46%) respectively.

SUMMARY

This research proposes IMFO for Grid-Connected Photovoltaic Systems. Firstly, PV generator is employed in which multiple solar cells are connected in series and parallel to generate required DC power. After that, a DC-DC buck converter with NC MPPT method is incorporated for stabilising variable DC voltage and extracting the maximum power from PV generator. A PI controller is employed which adjust the switching patterns of inverter for DC voltage and controls AC power injection into grid. Further, for enhancing the performance of PI, a IMFO is empolyed which optimized the parameters of PI controller. The obtained stable DC power is converted into AC power by employed five level NPC inveter. Finally, a LC filter is employed which filters the remaining harmonics and integrates this pure AC power in to grid. The proposed IMFO achieved better results in terms of K_p (0.0250) and K_i (0.0085) and lower THD value (0.25%) when compared to existing GA. In the future, by integrating adaptive control strategies, exploring hybrid optimization techniques will improve inverter efficiency, and enhance grid stability for large-scale photovoltaic power generation systems.

REFERENCES

[1] Xie, J., 2024. Application of optimized photovoltaic grid-connected control system based on modular multilevel converters. *Energy Informatics*, *7*(1), p.24.

[2] Elsanabary, A., Mekhilef, S., Seyedmahmoudian, M. and Stojcevski, A., 2023. A novel circuit configuration for the integration of modular multilevel converter with large-scale grid-connected PV systems. *IEEE Transactions on Energy Conversion*.

[3] Mondol, M.H., Rahman, M.A., Biswas, S.P., Islam, M.R., Kibria, M.F. and Muttaqi, K.M., 2023. A new integrated multilevel inverter topology for renewable energy transformation. *IEEE Transactions on Industry Applications*, *59*(3), pp.3031-3043.

[4] Khan, A.A., Minai, A.F., Husain, M.A. and Naseem, M., 2024. Multilevel inverter for renewable energy source-based grid integration. *Multilevel Converters*, pp.165-183.

[5] Santhi, R. and Srinivasan, A., 2023. An efficient AOA-RERNN control approach for a non-isolated quasi-Z-source novel multilevel inverter based grid connected PV system. *Energy*, *263*, p.125492.

[6] Rajesh, C.R., Meenalochini, P., Kannaiah, S.K. and Bindu, A., 2024. A hybrid control topology for cascaded H-bridge multilevel inverter to improve the power quality of smart grid connected system: NBO-RERNN approach. *Expert Systems with Applications*, *238*, p.122054.

[7] Boscaino, V., Ditta, V., Marsala, G., Panzavecchia, N., Tine, G., Cosentino, V., Cataliotti, A. and Di Cara, D., 2024. Grid-connected photovoltaic inverters: Grid codes, topologies and control techniques. *Renewable and Sustainable Energy Reviews*, *189*, p.113903.

[8] Iqbal, H., Tayyab, M., Rehman, H., Sarwar, A. and Hussan, M.R., 2024. 13 Level Switched-Capacitor Multilevel Converter with High Gain for Grid Connected Solar Photovoltaic Applications. *Multilevel Converters*, pp.147-163.

[9] Bansal, P. and Singh, A., 2024. Solar PV integrated simplified multilevel inverter configuration for power quality improvement using multilayer Gamma filter. *Electrical Engineering*, pp.1-17.

[10] Naderi, H., Ghaderi, N. and Abedini, M., 2024. Improving power quality and efficiency of multi-level inverter system through intelligent control algorithm. *Soft Computing*, pp.1-14.

[11] Srilakshmi, K., Kumar, A., Kondreddi, K., Krishna, T.M., Balachandran, P.K. and Gatto, G., 2024. Design of solar and energy storage systems fed reduced switch multilevel converter with flower pollination optimization. *Journal of Energy Storage*, *99*, p.113324.

[12] Kumar, D.G., Sireesha, N.V., Bhoopal, N., Gatla, R.K., Kotb, H., AboRas, K.M., Elrashidi, A., Alqarni, M., Ghadi, Y.Y. and Oubelaid, A., 2024. Application of soft computing algorithms for hybrid modular multilevel inverters. *Measurement: Sensors*, *31*, p.100999.

[13] Boucheriette, W., Moussi, A., Mechgoug, R. and Benguesmia, H., 2023. A multilevel inverter for grid-connected photovoltaic systems optimized by genetic algorithm. *Engineering, Technology & Applied Science Research*, *13*(2), pp.10249-10254.

[14] Joshi, Y., Letha, S.S., Bakhsh, F.I., Jaat, G.L. and Tilak, S., 2023. Harmonic elimination of a fifteen-level inverter with reduced number of switches using genetic algorithm. *IET Power Electronics*.

[15] Ghadi, Y.Y., Iqbal, M.S., Adnan, M., Amjad, K., Ahmad, I. and Farooq, U., 2023. An improved artificial neural network-based approach for total harmonic distortion reduction in cascaded H-bridge multilevel inverters. *IEEE Access*, *11*, pp.127348-127363.

[16] Anusha, G., Arora, K., Sharma, H., Thota, S.P., Joshi, G.P. and Cho, W., 2024. Control strategies of 15-level modified cascaded H-bridge PV GENERATOR with solar PV and energy storage system. *Energy Reports*, *12*, pp.2-26.

[17] Andela, M., Shaik, A., Beemagoni, S., Kurimilla, V., Veramalla, R., Kodakkal, A. and Salkuti, S.R., 2022. Solar photovoltaic system-based reduced switch multilevel inverter for improved power quality. Clean Technologies, 4(1), pp.1-13.

[18] Akoubi, N., Salem, J.B. and El Amraoui, L., 2022, March. Contribution on the combination of artificial neural network and incremental conductance method to MPPT control approachIEEE.

[19] Nandakumar, N. and Symon, V.T.P., 2024. An implementation of inertia control strategy for grid-connected solar system using moth-flame optimization algorithm. *Automatika*, *65*(1), pp.206-216.

[20] Boucheriette, W., Moussi, A., Mechgoug, R. and Benguesmia, H., 2023. A multilevel inverter for grid-connected photovoltaic systems optimized by genetic algorithm. *Engineering, Technology & Applied Science Research*, *13*(2), pp.10249-10254.