Battery Supported Solar PV Panel Based Multilevel Inverter with Optimal PI Controller Using Hybrid GA-PSO Algorithm

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Abstract. In recent years, multilevel inverters (MLIs) have found major applications in motor control and renewable energy systems (RES). Solar photovoltaic (PV) arrays have varied output voltages and require the support of battery energy storage systems (BESS) to maintain controlled output. The use of modular MLI configurations in multiple solar PV units makes it easier to regulate the output voltage waveform and reduce total harmonic distortions (THDs). In this work, we propose a 15-level MLI configuration with a reduced number of switches for battery-supported solar PV applications. To reduce the THDs of the inverter and improve control, we propose a hybrid optimization algorithm that combines the benefits of a genetic algorithm (GA) and particle swarm optimization (PSO). The simulation results show good output performance with low THD levels.

Keywords: Multilevel Inverter · Optimization · Photovoltaic Systems · Energy Storage Devices

1 Introduction

Solar PV technology has experienced substantial growth due to declining costs and technological advancements, resulting in improved efficiency and reliability. New solar PV products and solutions, such as flexible solar panels, building-integrated photovoltaic (BIPV), battery-integrated solar PV systems, etc., have emerged as a result of these developments. Inverter technology is crucial in PV systems, especially battery-integrated solar PV systems, as it affects the overall efficiency and reliability of the system. Multilevel inverters are being widely researched and used to address the challenges such as power quality, energy efficiency, and harmonic distortion [1]. MLIs were first introduced in 1975 and are widely used in medium-voltage and high-power applications like electrical motor drives, energy storage systems, and FACTS [2]. The most widely used MLI configurations are Neutral Point Clamped (NPC) inverters or Diode-Clamped MLI (DC MLI), Flying Capacitor MLI (FC MLI) [3, 4], and Cascaded H-Bridge MLI (CHB MLI)

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[5]. However, traditional MLI topologies require a large number of power components, which increases their cost and complexity. To address this issue, Reduced Switch MLI (RS MLI) topologies have been developed to improve reliability and reduce cost and loss by reducing the number of components. RS MLIs are divided into three categories: symmetric RSS MLI, asymmetric RSA MLI, and modified RSM MLI that can be used in both grid-tied and standalone applications.

Multiple new topologies for RS MLIs have been proposed in recent years [6–10], focusing on further minimizing the number of components and switches, improving energy conversion efficiency and power density, and producing a smooth sinusoidal waveform with a high number of levels. Several symmetric and asymmetric MLI topologies have been developed that operate with different number of switches and dc sources, with some featuring cascaded H-bridge configurations and others employing modularized and multi-modular converter structures [6–8]. Asymmetric CHB-MLI structures are used to increase the number of levels but can lead to uneven voltage stress on switches, which affects reliability. Cascaded MLI structures are popular due to their simple control structure and lack of the need for diodes and capacitors, but they require multiple DC sources and have a high number of switches, which increases cost and complexity. Hybrid and asymmetrical cascaded structures aim to reduce the number of input DC voltage sources, but they require specific algorithms and separate driver and protection circuits for each switch, which also significantly increases the cost and complexity [9, 10].

An appropriate controller for the developed MLI helps improve the efficiency, power quality, and stability of the MLI system. Various controllers and control strategies developed and used for MLIs include Proportional-Integral (PI) controllers, Model Predictive Control (MPC), Space Vector Modulation (SVM), and Pulse Width Modulation (PWM) techniques. PI controllers are commonly used in MLIs to regulate the output voltage by adjusting the duty cycles on the switches. The integration function in the PI controller helps eliminate steady-state errors, and the proportional function improves the system's response time. Optimization techniques have become increasingly popular for solving complex, nonlinear problems in various practical applications [11]. While classical numerical techniques are useful for linear problems, they have limited practical application due to the highly nonlinear nature of real-time problems. This has led to the development of advanced optimization algorithms inspired by natural phenomena [12, 13], which are better equipped to provide solutions for complex computational problems. In this work, we use a hybrid optimization technique combining the benefits of genetic algorithm and particle swarm optimization. This controller is implemented for a battery-supported solar PV system with a 15-level multilevel inverter configuration.

2 MLI for Battery Supported PV Systems

2.1 Battery-Supported PV Systems

The proposed system combines a battery with a solar photovoltaic array to power a load using converters and a multilevel inverter. In Fig. 1, the system's block diagram is displayed. Two separate sources, one from the battery system and one from the solar PV array, make up the inverter's input. DC link and DC/DC converter guarantee the efficient

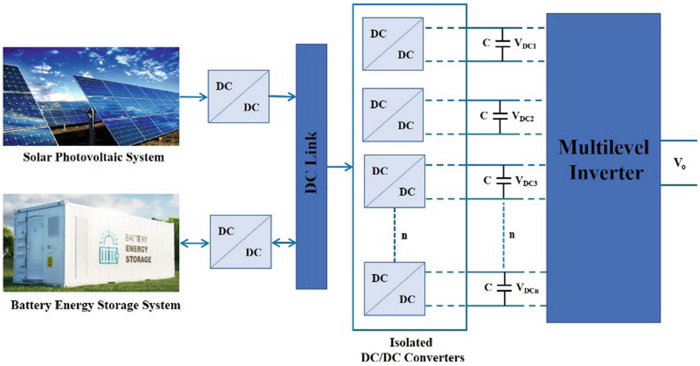

Fig. 1. Overall Block diagram of the battery-supported PV system connected to MLI.

and flexible integration of several renewable energy sources. The PV arrays are equipped with a boost converter and a maximum power point tracking (MPPT) controller, which employs the Perturb and Observe (P&O) algorithm. This algorithm adjusts the PV array's operating point in small increments before measuring the power output. If there is an increase in power output, the operating point is adjusted further until the peak power point is reached.

The battery system considered in this paper has a bidirectional converter that regulates the flow of energy between charging and discharging. The voltage is controlled by generating PWM pulses and applying them to the inverter's input terminals. The battery system provides a consistent source of power to supplement the intermittent nature of solar power, resulting in a more stable power supply system overall.

2.2 Modified 15-Level Cascaded H-Bridge MLI with Reduced Switches

A Cascaded H-Bridge Multilevel Inverter with fewer switches, shown in Fig. 2, has been considered as an adaptation of asymmetric structures. This topology employs three DC voltage sources and ten switches. It is possible to generate a staircase voltage pattern by using the proper switching sequence. This modified MLI requires fewer components than all other modified cascaded topologies currently in use. This reduced-switch configuration provides several benefits, including reduced complexity, increased reliability, and increased efficiency. It has the benefit of only requiring controlled switches and no diodes or capacitors. This modified topology is expected to outperform other topologies in terms of performance, making it a promising solution for applications requiring a dependable and efficient power conversion system.

3 Optimized MLI Control

3.1 PI Controller

The Proportional Integral controller is widely used in industrial applications due to its simplicity, ease of design, and low cost. It is effective in minimizing forced oscillations and steady-state errors, but its integral mode can have a negative impact on the system's

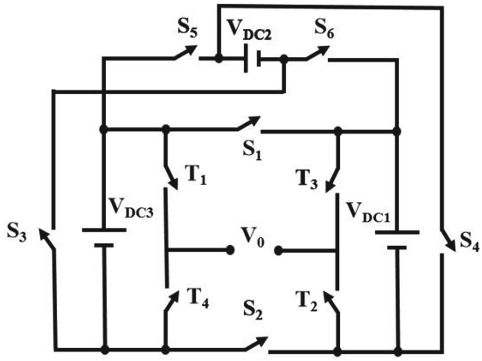

Fig. 2. Modified 15-level Cascaded H-Bridge MLI with reduced switches.

response time and overall stability. To address this issue, the derivative mode can be added to the PI controller to predict the error's behavior and improve the controller's reaction time. The controller is represented by the equation:

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{1}$$

where K_p is the proportional gain, and K_i is the integral gain.

Changing the coefficients and control parameters of the PI controller can significantly affect its performance. The PI controller remains a popular choice in many industrial applications [14, 15]. The main objective of the controller is to optimize the efficiency of the overall system. Moreover, the PI controller can reduce steady-state error and enhance system performance by minimizing peak overshoot. The K_p and K_i are considered as decision variables in the optimization problem, with THD as the objective function to be minimized.

3.2 Hybrid GA-PSO Algorithm for Controller Optimization

The hybrid GA-PSO algorithm for PI controller optimization can be performed in series or parallel. This paper uses series hybridization where only one population is generated for both PSO and GA. PSO algorithm updates the population's velocity and position based on the personal best (p_{best}) and global best (g_{best}). The updated positions are evaluated, and selection is performed based on the new population's stored p_{best} and g_{best} values. This ensures that each particle preserves its best position, and the entire population also maintains its global best value, thereby eliminating the drawback of GA in preserving its best positions. Crossover and mutation are then performed. The overall flow of the proposed hybrid PSO-GA algorithm for PI controller parameter selection is shown in Fig. 3.

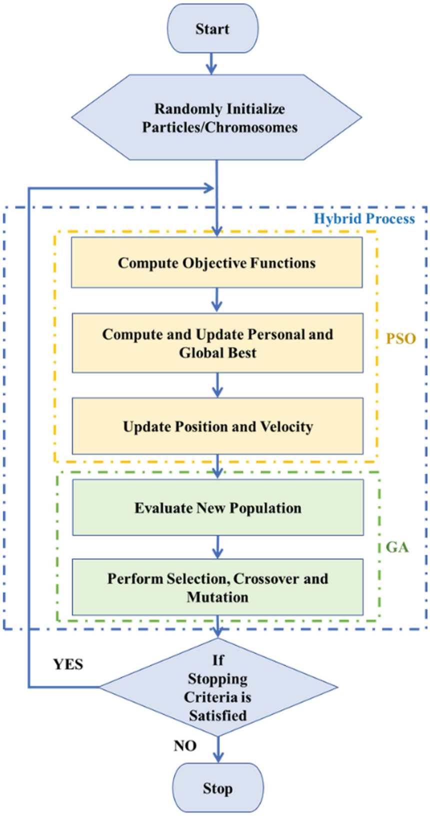

Fig. 3. Flowchart of GA-PSO algorithm.

4 Results and Discussion

The proposed 15-level multilevel inverter is modeled in MATLAB/SIMULINK, and the proposed GA-PSO algorithm for the inverter control is written in MATLAB code. The algorithm takes the output voltage and current measurements from the simulation in Simulink and performs the search for the best optimal K_p, K_i values. These values help in the generation of appropriate gate pulses for the inverter switches. The reference waveform and carrier waveform for the generation of 15 levels in the inverter are shown in Fig. 4. These signals help in producing the output inverter voltage with 15 levels, as shown in Fig. 5.

The simulation parameters used are listed in Table 1. The PV array is composed of multiple panels with the different number of parallel strings and series strings. The maximum power point tracking voltage and current of each PV module is used, and the maximum power output of each panel is rated at 120W.

The results of the harmonic analysis of the four inverter topologies are displayed in Figs. 6 and 7. The THD comparisons are based on the proposed 15-level configuration

Table 1. Simulation Parameters.

Parameter	Value
Fundamental frequency	50 Hz
Carrier frequency	2.5 kHz
RL Load	45 Ω, 55e-3 mH
PV Array, Parallel Strings	4
PV Array, Series Strings	7
PV Module, Maximum Power	120 W
PV Module, MPPT Voltage	17.33 V
PV Module, MPPT Current	6.93 A

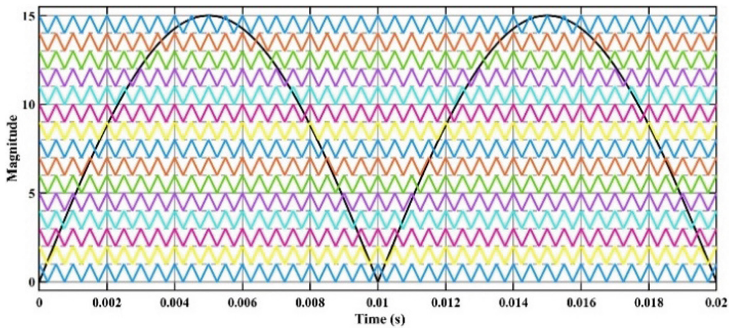

Fig. 4. Inverter Output Voltage waveform PWM carrier and reference waveform.

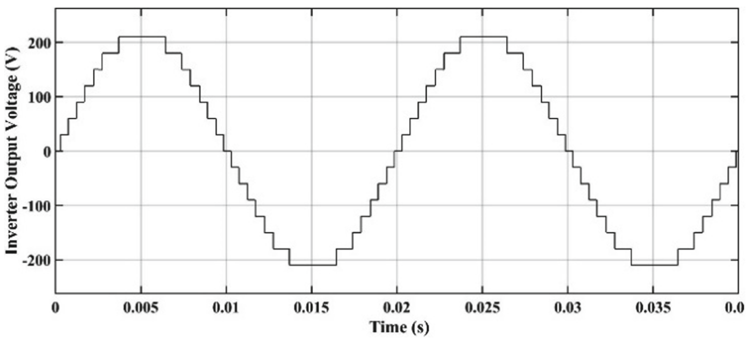

Fig. 5. Inverter Output Voltage waveform.

connected to an RL load, which demonstrates significantly lower THD when operated with the proposed GA-PSO algorithm with a THD of 4.45% reduction from 6.53%.

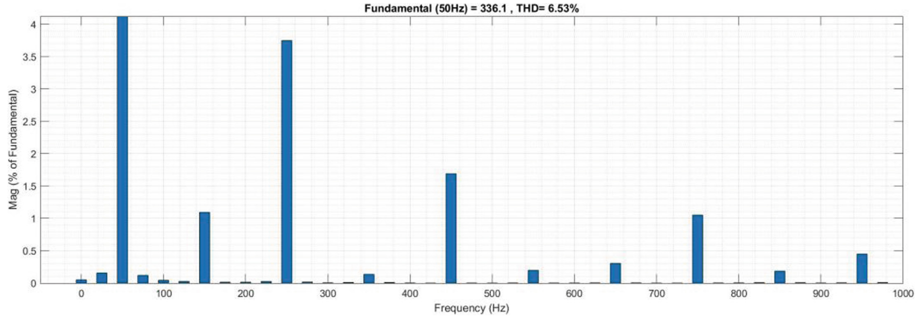

Fig. 6. THD of Inverter output voltage waveform without GA-PSO algorithm.

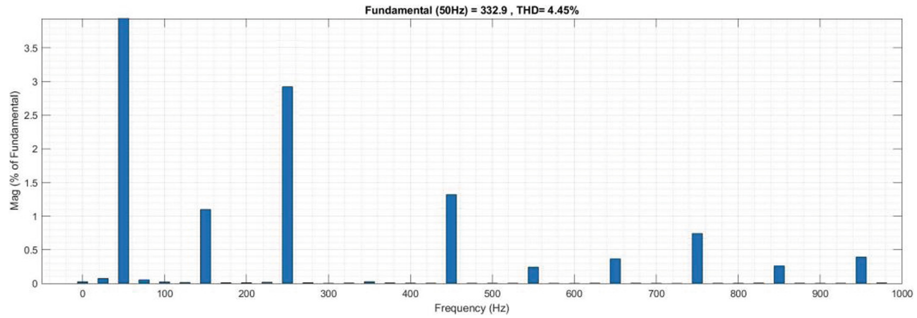

Fig. 7. THD of Inverter output voltage waveform with GA-PSO algorithm.

5 Conclusion

This work presents a 15-level multilevel inverter for a battery-supported solar PV system. This inverter configuration is a modified cascaded H-bridge inverter with reduced switches. A GA-PSO algorithm is proposed for the inverter control. The simulation results show that the inverter was able to effectively reduce harmonics and exhibit good performance when used with solar PV arrays of varying voltage outputs. The modular structure of the inverter design reduces the complexity of increasing levels and can be applied in a wide range of renewable energy applications, making it more accessible and affordable. Future research will investigate the proposed inverter design for use in hybrid renewable energy systems and various operating conditions.

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