



Power Quality Enhancement in Hybrid Photovoltaic-Battery System with genetic algorithm Control of Three-Level NPC inverter

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ABSTRACT

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The hybrid system comprises key components, including a photovoltaic (PV) panel that generates electricity from sunlight and a battery energy storage (BES) unit that stores surplus energy for later use during low solar input or high demand. The generated power supplies a variable load with fluctuating energy needs, requiring efficient delivery. A DC link with a proportional-integral-derivative (PID) controller ensures voltage stability by adjusting control parameters to operating conditions. Additionally, a three-level NPC inverter, governed by genetic algorithm, manages power conversion and flow while minimizing Total Harmonic Distortion (THD).

1. INTRODUCTION

In recent years, the increasing demand for sustainable and efficient energy systems has led to significant advancements in hybrid power technologies [1][2]. Hybrid energy systems offer a promising solution by integrating various energy sources and storage mechanisms to provide stable and reliable power under varying environmental and load conditions[3]. This study focuses on a sophisticated hybrid system architecture that primarily incorporates a photovoltaic (PV) panel and a battery energy storage (BES) unit[4]. The PV panel plays a central role in harnessing solar energy and converting it into electrical power [5][6], while the BES serves as a vital reservoir, storing surplus energy for periods of low solar availability or heightened energy demand[7].

To accommodate fluctuating energy consumption patterns, the system is designed to supply a variable load that represents real-world electrical devices or applications with dynamic power requirements. Ensuring stable and efficient energy delivery in such a context necessitates advanced control strategies. For this purpose, the system employs a direct current (DC) link equipped with a proportional-integral-derivative (PID)

controller[8]. This controller is essential for maintaining voltage regulation, improving transient response, and reducing voltage fluctuations by continuously adjusting its parameters based on real-time operating conditions[9].

Furthermore, to ensure compatibility between the energy sources and the load, and to enhance the quality of power delivery, a three-level Neutral Point Clamped (NPC) inverter is integrated into the system. Unlike conventional inverters, the NPC topology offers improved efficiency and lower switching losses[10]. In this work, the inverter is controlled using a genetic algorithm, which enables adaptive and intelligent optimization of the inverter's operation[2]. One of the key objectives of this control approach is to minimize Total Harmonic Distortion (THD), thereby improving the overall power quality and efficiency of the hybrid system[11]. This article explores the integration of these components and highlights the impact of genetic algorithm-based control on system performance.

2. SYETEM DESCRIPTION

The integration of the solar source and battery, controlled through a Genetic Algorithm applied to the NPC, is illustrated in Figure 1.

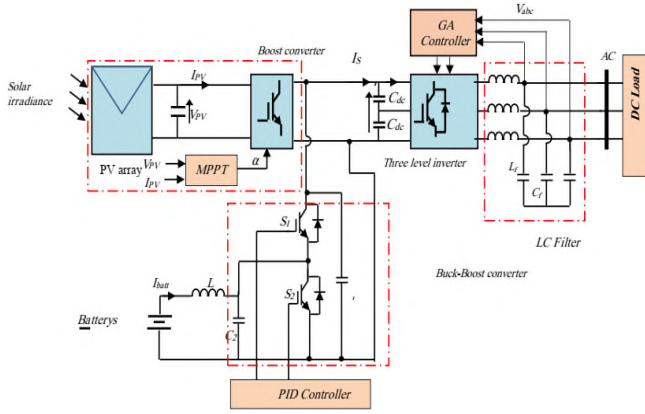


Figure. 1 Hybrid PV-Battery System with GA-Optimized NPC Inverter Control

2.1 Solar PV Array

Connected via a DC-DC boost converter with MPPT (e.g., P&O algorithm) to maximize power extraction.

Figure 2 provides a basic representation of the PV system [12]

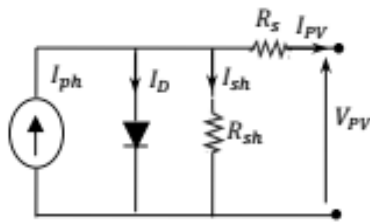


Figure. 2 PV cell's equivalent circuit.

In the single-diode model, the relationship between voltage (\$V_{PV}\$) and current (\$I_{PV}\$) at constant temperature and irradiance is given by Eq. (1) [5], applicable to a PV cell, module, and array.

$$I_{PV} = I_{ph} - I_D = I_{ph} - I_0 \left\{ \exp \left[\frac{(V_{PV} + R_s I_{PV})}{a} \right] - 1 \right\} - (V_{PV} + R_s I_{PV}) / R_{sh} \quad (1)$$

The values of \$R_{sh}\$ and \$R_s\$ are neglected in this study, simplifying Eq. (1) as follows [12].

$$I_{PV} = I_{ph} - I_0 \left\{ \exp \left[\frac{(V_{PV} + R_s I_{PV})}{a} \right] - 1 \right\} \quad (2)$$

2.2 Battery Energy Storage

Energy storage devices improve the reliability and efficiency of power distribution systems [13]. Among them, batteries are the most commonly used for electrical energy storage. Recently, many battery models have been developed, as noted in [14].

The equation for the model used in this study is given as follows

$$V_{bat} = V - R I_{bat} \quad (3)$$

Figure 3 shows the electric battery model.

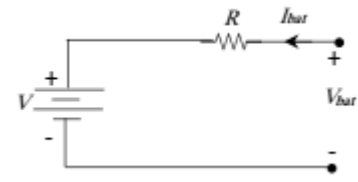


Figure. 3 Standard battery model

The state of charge (SOC) depends on the battery's charging and discharging over time, affected by power source and load changes, as shown in equation (4) [15].

$$SOC(t) = \begin{cases} SOC(t - \Delta t) + P_{bat} \frac{\eta_{ch}}{C_n V_{dc}} \Delta t \\ SOC(t - \Delta t) + P_{bat} \frac{1}{\eta_{dis} C_n V_{dc}} \Delta t \end{cases} \quad (4)$$

2.3 Three-Level NPC Inverter

A Three-Level NPC Inverter connects the DC link voltage to the system's load, controlling the load's voltage and frequency [16]. In this off-grid system, managing load voltage frequency and amplitude is essential. Figure 4 [17] shows the three-level inverter topology: when the upper switches (\$S_{k1}\$, \$S_{k2}\$) are ON, it outputs \$V_{dc1}\$; when the lower switches (\$S_{k3}\$, \$S_{k4}\$) are ON, it outputs \$-V_{dc2}\$; and a zero state occurs when the auxiliary switches \$S_{k3}\$ and \$S_{k4}\$ are activated [2][15].

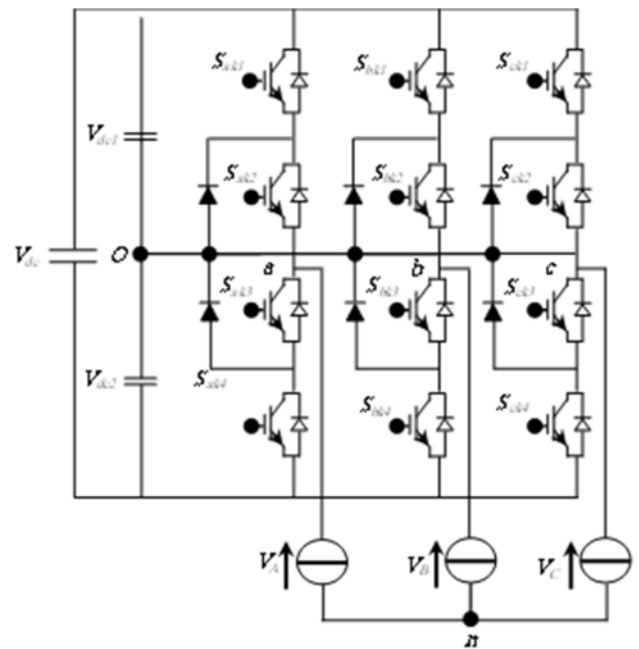


Figure. 4 Three phase three-level inverter NPC

The function \$F_{km}^b\$ of connection are given by [16][17].

$$\begin{cases} F_{k1}^b = F_{k1} \cdot F_{k2} \\ F_{k0}^b = F_{k3} \cdot F_{k4} \end{cases} \quad (5)$$

Leg voltage V_{A0}, V_{B0} and V_{C0} can be written as:

$$\begin{cases} V_{A0} = F_{11}^b \cdot V_{dc1} - F_{10}^b \cdot V_{dc2} \\ V_{B0} = F_{21}^b \cdot V_{dc1} - F_{20}^b \cdot V_{dc2} \\ V_{C0} = F_{31}^b \cdot V_{dc1} - F_{30}^b \cdot V_{dc2} \end{cases} \quad (6)$$

Simple output voltage is written as:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \left\{ \begin{bmatrix} F_{11}^b \\ F_{21}^b \\ F_{31}^b \end{bmatrix} V_{dc1} - \begin{bmatrix} F_{10}^b \\ F_{20}^b \\ F_{30}^b \end{bmatrix} V_{dc2} \right\} \quad (7)$$

3. Controller design

3.1 PID controller

The architecture of PID controller is revealed in Figure 5 [18].

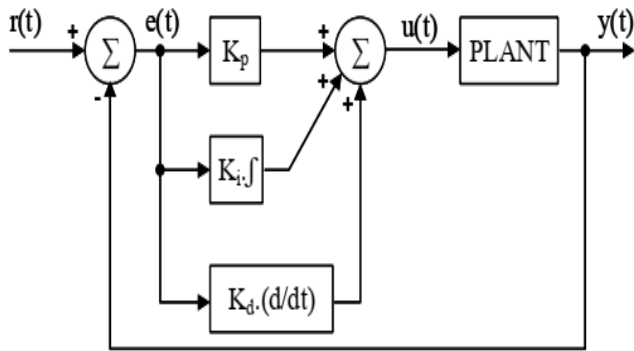


Figure. 5 Block diagram depiction of PID control system

$$G(s) = K_p + \frac{K_i}{s} + s \cdot K_d \quad (8)$$

$$G(s) = K_p \left(1 + \frac{1}{s \cdot T_i} + s \cdot T_d \right) \quad (9)$$

The PID controller responds quickly to output errors $e(t)$, but it cannot correct accumulated errors, leading to system output deviations [19][20]. The integral component is primarily responsible for eliminating these accumulated errors, though it may introduce delays, slowing the system's response and potentially causing oscillations. The derivative component accounts for the rate of change of the error, allowing the system to adjust preemptively and enhancing dynamic performance [21].

3.2 Design of a three-level NPC inverter using GenetiAlgorithm Control.

Evolutionary algorithms (EAs) solve both constrained and unconstrained optimization problems through five main steps. Among them, the genetic algorithm (GA) is one of the most widely used, as shown in the flowchart in Figure 6[22].

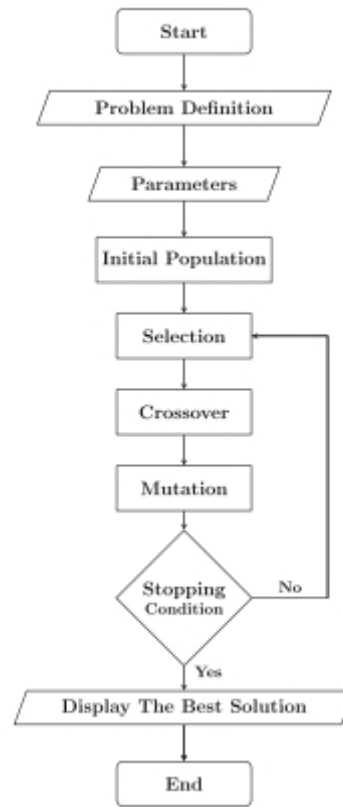


Figure. 6 Flowchart of the genetic algorithm

In this study, a genetic algorithm (GA) is proposed for the direct control of a three-phase, three-level Neutral Point Clamped (NPC) inverter, without relying on conventional controllers such as PID. The main objective is to optimize the switching angles or modulation vectors to generate an output voltage with minimal Total Harmonic Distortion (THD), while ensuring capacitor voltage balancing on the DC bus and reducing tracking error relative to a sinusoidal reference. The genetic algorithm is a stochastic optimization technique inspired by the principles of natural evolution[23]. It is particularly well-suited for complex, nonlinear optimization problems such as the control of multilevel inverters.

The GA-based optimization procedure consists of several key phases. The first is **initialization**, where a population of candidate solutions is randomly generated. Each individual $xi = [\theta_1, \theta_2, \dots, \theta_n] \in Rn$ represents a vector of switching angles within a half-period of modulation[24]. These angles must satisfy an ascending order constraint $\theta_1 < \theta_2 < \dots < \theta_n$, and lie within an admissible range, typically $\theta_i \in [\theta_{min}, \theta_{max}] \subset [0, \pi/2]$

Next, each individual is evaluated through a **multi-objective fitness function**, defined as:

$$ObjFun(x_i) = \alpha \cdot THD(x_i) + \beta \cdot E(x_i) + \gamma \cdot D(x_i) \quad (10)$$

where THD represents the total harmonic distortion of the output voltage, E is the RMS error between the generated and reference waveforms, and D represents the

voltage imbalance across the DC-link capacitors. The coefficients α, β, γ are weighting factors [23].

The **selection phase** uses a strategy such as roulette wheel or tournament selection to choose the best-performing individuals. Selected individuals are then subject to a **crossover operator**, which combines two parent vectors x_p, x_q to generate a new offspring x_c , according to:

$$x_c = \lambda \cdot x_p + (1 - \lambda) \cdot x_q, \lambda \in [0,1] \quad (11)$$

This crossover can be single-point or arithmetic, depending on the chosen encoding method. A **mutation operator** is then applied to introduce genetic diversity, randomly modifying one or more elements of x_c :

$$x_{c,j}^{new} = x_{c,j} + \delta, \quad \delta \sim U(-\epsilon, \epsilon) \quad (12)$$

where δ is a small uniformly distributed perturbation and j is a randomly selected index.

The evolutionary process continues for multiple generations until a stopping criterion is met, such as a maximum number of iterations or a minimum objective function value. At the end of the optimization process, the best individual provides the optimal switching angles to be applied in the inverter's modulation strategy[25]. This approach is fully model-free, making it robust against system uncertainties and nonlinearities in the inverter's dynamic behavior.

4. SIMULATION RESULTS AND DISCUSSION

The main parameters of the genetic algorithm and the electrical specifications of the three-level NPC inverter used in this study are summarized in Tables 1 and 2, respectively.

Table 1. Main parameters of genetic algorithm

Parameter	Value	Description
Population size	50	Number of individuals in each generation
Number of generations	20	Maximum number of iterations for evolution
Chromosome length	5-9 switching angles	Depends on the inverter level and harmonic order
Selection method	Tournament selection (size = 3)	Selects the best among 3 randomly chosen candidates
Crossover method	Arithmetic crossover	Creates offspring via linear combination of two parents
Crossover probability	0.85	High probability to promote genetic diversity
Mutation method	Uniform mutation	Randomly alters gene values within a defined range
Mutation probability	0.05	Prevents premature convergence by introducing variations
Termination criterion	Max. generations or convergence	Stops if improvement is below a threshold over several generations
Fitness function	Weighted sum: THD, error, imbalance	Multi-objective function as defined in Equation (10)

Table 2. Main Specifications of the Three-Level NPC Inverter

Parameter	Value	Description
DC-link voltage (VDCV_{\text{DC}})	600 V	Total voltage across both DC capacitors
Number of levels	3	NPC topology with three output voltage levels
Switching frequency	5 kHz	Carrier frequency for PWM or switching signal
Output phase voltage	± 450 V	Maximum positive and negative output levels
Modulation technique	SHE-PWM / GA-based	Selective Harmonic Elimination or GA-optimized modulation
Load type	Resistive (R)	Emulates a typical industrial
Filter type	LC	Used to reduce output voltage/current harmonics
Capacitor voltage balancing	Active or GA-based balancing	Ensures equal voltage across DC-link capacitors
Control objective	Minimize THD, voltage imbalance, tracking error	Achieved using the genetic algorithm

As shown in Figure 7, the genetic algorithm demonstrates a progressive improvement in fitness value over successive generations, confirming its effectiveness in optimizing the inverter switching strategy.

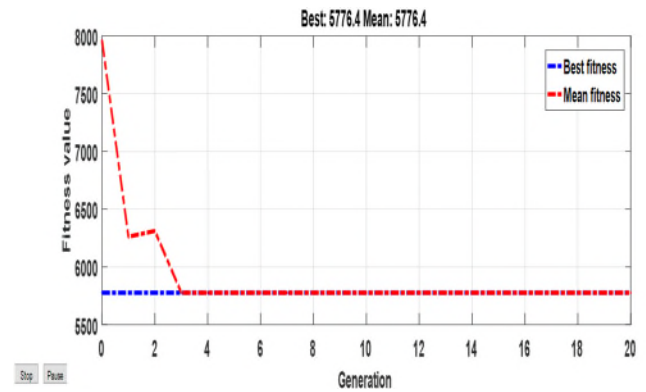


Figure. 7 The best obtained fitness curve through GA algorithm

Here, the control loop is implemented in Matlab/Simulink with a sampling time of $T_s = 10^{-5}$ s.

The optimal values obtained of the PID are $K_P = 2.75$, $K_I = 332.75$ and $K_D = 1.13$

The profiles of radiation and applied load in our simulation are presented in Figures 8 and 9 respectively.

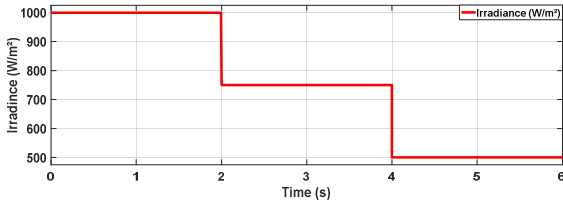


Figure. 8 Irradiance variations

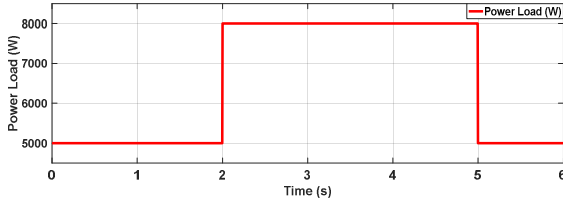


Figure. 9 Power load

Figure 10 depicts the DC bus voltage along with the two voltages Vdc1 and Vdc2 obtained using a PID controller. The illustrated Vdc link voltage is equal to the sum of the two voltages Vdc1 and Vdc2 and remains nearly constant.

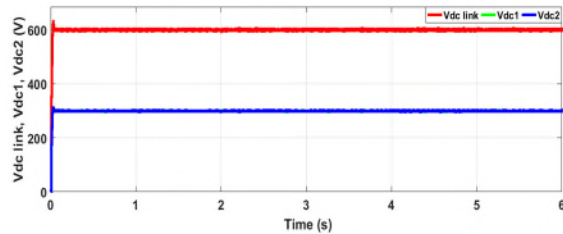


Figure. 10 Vdc link, Vdc1 & Vdc2

Figure 11 provides a summary of the powers generated by the various components comprising the PV system connected to the battery to supply a variable load as shown on the same graph.

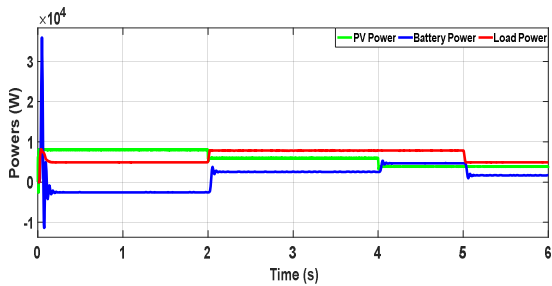


Figure. 11 Hybrid energy system powers

As shown in Figure 10, the PID controller maintains a constant DC-link voltage. Figure 11 further demonstrates the BBC controller's effectiveness, as it regulates battery charging and discharging to balance system power under different irradiance and load conditions. When AC load power exceeds PV power, the BBC controller discharges the battery to support the load, and it charges the battery when PV power exceeds load demand.

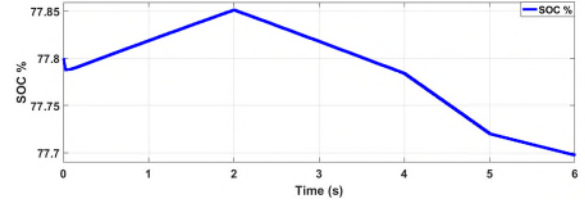


Figure. 12 Battery SOC

As shown in Figure 12, the SOC starts at 77.8%, initially decreases during the transition phase, then rises until 2 seconds (charging mode), and subsequently discharges until 6 seconds (discharging mode).

The load currents and voltages are purely sinusoidal, demonstrating the inverter control's effectiveness and the high quality of energy supplied, as shown in Figure 13 and Figure 15.

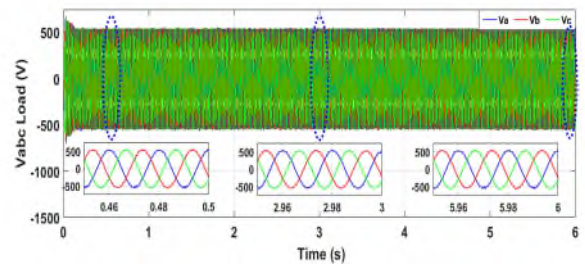


Figure. 13 Load output voltage

The spectral analysis of the load voltage reveals that the waveforms are distorted and have an acceptable harmonic distortion rate (THD=1.46% < 5%).

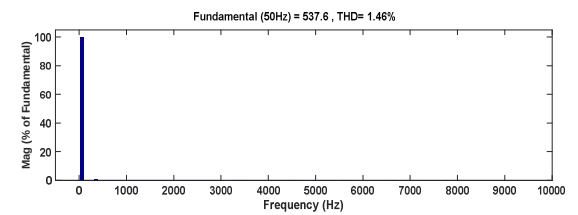


Figure. 14 Load output voltage

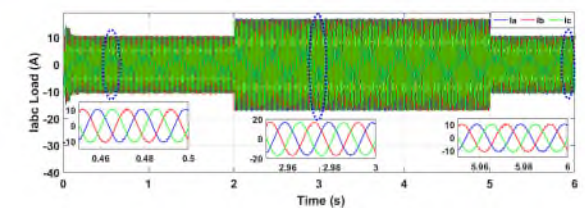


Figure. 15 Load output current

The line current ia is nearly sinusoidal with a low harmonic distortion rate THD equal to: 1.32 % < 5%.

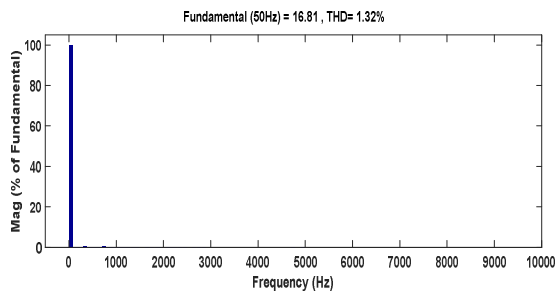


Figure. 16 Load output voltage

The proposed controller effectively minimizes harmonics and reduces ripple in the load currents and voltages. Two types of controllers were used: the genetic algorithm controller and the PID controller. The GA controller manages energy supply to balance demand and generation, while the PID controller ensures voltage stability by addressing voltage drops in the DC bus.

5. CONCLUSIONS

The article explores a photovoltaic (PV) system with battery storage that powers a variable load using a three-phase Neutral Point Clamped (NPC) inverter. To maintain stable power despite load fluctuations, a PID controller regulates the DC link voltage. Additionally, the three-phase NPC inverter is managed by a genetic algorithm controller (GAC) aimed at reducing harmonic distortion (THD), thereby improving power quality and enhancing the PV system's efficiency and performance.

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