

## Optimal Integration of Photovoltaic (PV) and Battery Energy Storage Systems in Power Distribution Using Hybrid Flower Pollination and $\beta$ -Hill Climbing

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**Abstract**—This study discusses the optimization of the placement and capacity of Photovoltaic (PV) and Battery Energy Storage System (BESS) units in the IEEE 33-bus distribution system using the Hybrid Flower Pollination Algorithm (FPA) and  $\beta$ -Hill Climbing ( $\beta$ HC) or HyFPA $\beta$ HC methods. The primary objective of this research is to enhance the performance of the distribution system by reducing power losses and improving the voltage profile. Based on the optimization results, three PV units with capacities of 749.3 kW, 577.5 kW and 620 kW were optimally placed at buses 8, 13 and 20, respectively, while one BESS unit with a capacity of 1112.4 kW was installed at bus 24. Simulation results indicate that the integration of PV and BESS significantly reduces the total system power losses from approximately 50 kW on several main feeders under the base condition (without Distributed Generation) to below 5 kW after optimization. In addition, the voltage profile improved from a minimum value of 0.92 p.u. to a stable range of 0.98–1.0 p.u. Furthermore, the integration of PV and BESS contributes to mitigating power fluctuations, enhancing energy efficiency, and improving the reliability of the distribution system operation. Therefore, the HyFPA $\beta$ HC method is proven to be effective in determining the optimal configuration of PV and BESS units to improve the technical performance of electrical distribution systems.

**Keywords**— *Battery Energy Storage System (BESS), Distributed Generation (DG), Hybrid Flower Pollination Algorithm (FPA) and  $\beta$ -Hill Climbing ( $\beta$ HC), Photovoltaic (PV), Placement and Sizing Optimization, Power Loss, Voltage Profile.*

### Introduction

The increasing demand for electrical energy necessitates an efficient, reliable, and environmentally friendly power system, considering the limitations of fossil energy sources and their associated carbon emissions[1]. The utilization of renewable energy based Distributed Generation (DG), particularly photovoltaic (PV) systems, has become a strategic solution to support the transition toward a sustainable energy infrastructure [2]. However, the fluctuating output of PV systems due to variations in solar irradiance and weather conditions poses

challenges to maintaining power system stability, thereby requiring the integration of Battery Energy Storage Systems (BESS) to balance power generation and consumption[3].

Determining the optimal location and capacity of PV and battery units is crucial, as improper placement can increase power losses, degrade voltage profiles, and lead to inefficient investment costs[4]. To address these challenges, intelligent optimization methods capable of handling the nonlinear and multi-objective characteristics of modern power system planning are required[5]. Various metaheuristic algorithms have been employed such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and the Flower Pollination Algorithm (FPA)[6], although the effectiveness of FPA may decline when dealing with highly complex objective functions. Therefore, combining FPA with the  $\beta$ -Hill Climbing ( $\beta$ HC) method offers a promising approach to enhancing convergence capabilities while avoiding local optima traps[7]. The Hybrid FPA $\beta$ HC (HyFPA $\beta$ HC) method is expected to yield more accurate and stable optimal configurations for PV–BESS placement in modern distribution systems[8].

### *Distributed Generation (DG) and Renewable Energy*

The concept of Distributed Generation (DG) refers to small to medium scale power generation systems that are directly connected to the distribution network or located close to the load point. DG offers several key benefits, including reduced power losses, enhanced reliability, improved voltage profiles, and

increased energy efficiency within the power system[9].

Over the past decade, the declining cost of solar modules and the implementation of green energy policies have made photovoltaic (PV) systems the most widely adopted form of DG[10]. However, the intermittent nature of PV systems, resulting from variations in solar radiation and weather conditions, leads to voltage fluctuations and power imbalances within the network[11].

The integration of a (BESS) serves as an effective solution to address these instabilities, as batteries can store excess energy during periods of high production and release it when demand increases or PV generation decreases. The integration of PV and BESS enables improvements in system capacity factor, voltage stability, and reductions in the operating costs of the distribution network[12].

#### Optimal Planning of PV–Battery Systems in Distribution Networks

Optimal DG planning involves determining the location and capacity of generation units (PV and BESS) to achieve specific objectives, such as:

- Minimization of system active power losses,
- Minimization of voltage deviation among buses,
- Minimization of the total system cost (Total Annual Cost, TAC), or
- Maximization of reliability index and energy efficiency[13].

This problem is generally formulated as a multi-objective nonlinear programming (MONLP) optimization problem with technical constraints of the distribution system. The complexity increases due to the involvement of uncertainties in PV power generation, load patterns, and energy prices. Various studies have evaluated efficient optimization methods for DG planning, including:

- Particle Swarm Optimization (PSO) demonstrates strong exploration capabilities but tends to converge prematurely to local optima[14].
- Genetic Algorithm (GA) performs well in multi-objective optimization but requires complex parameter tuning[15].

- Cuckoo Search (CS), Grey Wolf Optimizer (GWO), and Differential Evolution (DE) offer improved exploration capabilities but still face challenges in achieving convergence[16].

For these reasons, hybrid metaheuristic methods have been developed to combine the strengths of multiple algorithms, aiming to achieve an optimal balance between exploration and exploitation while accelerating convergence[17].

#### Flower Pollination Algorithm (FPA)

The Flower Pollination Algorithm (FPA) is a metaheuristic algorithm inspired by the natural process of flower pollination, developed by Xin-She Yang [18]. The fundamental principles of FPA consist of *global pollination* (using Lévy flight distribution) and *local pollination* (based on interactions among neighboring flowers).

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(g_* - x_i^t) \tag{1}$$

Where  $x_i^t$  is the  $I$  pollen or solution vector  $x_i$  at iteration  $t$ , and  $g_*$  is the best solution currently found among all solutions in the generation/iteration. The main advantage of FPA lies in its ability to explore a wide solution space through Lévy flight, making it effective in locating global optima [19]. However, several studies have shown that the standard FPA tends to be slow in the local exploitation phase and may suffer from premature convergence [20].

$$L \sim \frac{\lambda \Gamma(\lambda) \sin\left(\frac{\pi\lambda}{2}\right)}{\pi} \cdot \frac{1}{\delta^{1+\lambda}}, (\delta \gg \delta_0 > 0) \tag{2}$$

where  $\Gamma(\lambda)$  is the standard gamma function (2), and this distribution valid for large steps  $\delta > 0$ . Here  $\delta_0 = 0.1$  is used. Various modifications have been proposed, such as:

- Adaptive FPA (AFPA) with adaptive updates of the switch probability factor[21].
- Chaotic FPA, employing logistic maps to enhance population diversity[22].

- Hybrid FPA, integrating FPA with other algorithms such as PSO, CS, and DE to improve local exploitation performance[23].

*β-Hill Climbing (βHC) as a Local Search Operator*

The β-Hill Climbing (βHC) algorithm is a variation of Stochastic Hill Climbing, introduced to enhance the local exploitation capability of metaheuristic algorithms. In βHC, the search process employs a β-distribution to generate smaller and more directed steps toward the optimal region, thereby achieving a balance between exploration and exploitation[24].

$$x'_N = x_i \pm \cup (0,1) x bw \tag{3}$$

where  $j \in \{1,2, \dots, n\}$  is randomly selected, and  $b_w$  denotes the bandwidth from the new solution to the current solution. In case  $f(x') < f(x)$ , then  $x \leftarrow x'$ . Furthermore, subsequent research by Al-Betar *et al.* (2023) revealed that β-HC is effective as a local refinement operator in various hybrid algorithms, such as the Memetic Sine Cosine Algorithm, to strengthen the exploitation phase in the solution search process[25].

$$x'_i \leftarrow \begin{cases} x_r \cup (0,1) & rnd \leq \beta \\ x_i & otherwise. \end{cases} \tag{4}$$

where  $x_r \cup (0,1)$ . In case  $f(x') < f(x)$ , then replace the current solution with the new ones  $x \leftarrow x'$ . Thus, βHC plays a vital role as an adaptive local search mechanism capable of deepening exploitation without compromising the exploratory ability of hybrid algorithms.

*Hybrid Flower Pollination Algorithm and β-Hill Climbing*

The hybridization between the Flower Pollination Algorithm (FPA) and β-Hill Climbing (βHC), referred to as HyFPAβHC, combines the strong global exploration capability of FPA with the efficient local exploitation ability of βHC. In this mechanism, the initial population is optimized using the global pollination process of FPA, and the best solutions obtained are subsequently refined through βHC as a local improvement phase[26].

Alyasseri *et al*[27] demonstrated that the HyFPAβHC algorithm outperforms traditional methods in terms of:

- Convergence speed, Stability of results across iterations, and
- Global solution quality compared to FPA, GA, and PSO.

The application of this hybrid approach in the energy domain has shown promising results, including optimal planning of PV–BESS systems[28], [29] and the design of hybrid PV–wind–battery microgrids. With these characteristics, the HyFPAβHC method holds significant potential for application in the optimal planning of PV–BESS based Distributed Generation (DG), where achieving optimal solutions within a large and complex search space is essential[30].

**Research Methodology**

This study proposes a Hybrid Flower Pollination Algorithm and β-Hill Climbing (HyFPAβHC) to determine the optimal location and capacity of PV and BESS units in an IEEE 33-bus radial distribution system.

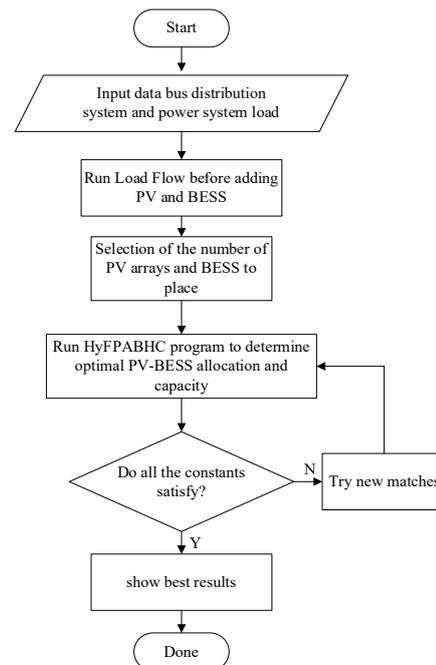


Figure 1. Hybrid FPA and βHC Research Diagram.

The primary objective of this research is to minimize power losses and voltage deviations within the distribution network. The implementation process is carried out using MATLAB R2020a, with the Backward-Forward Sweep (BFS) method applied for power flow analysis. The dataset employed is based on the standard IEEE 33-bus radial distribution system, which includes line impedance and load profile data. MATLAB serves as the main platform for network modeling, power flow simulation, and the implementation of the proposed optimization algorithm.

### Results and Discussion

The optimization results of PV and BESS placement and sizing in the IEEE 33-bus distribution system demonstrate a significant improvement in overall system performance, particularly in terms of power loss reduction and voltage profile enhancement.

Based on the optimization outcomes, three PV units are optimally installed at buses 8, 13 and 20 with capacities of 749.3 kW, 577.5 kW and 620 kW, respectively, while a single BESS unit is allocated at bus 24 with a capacity of 1112.4 kW.

Table 1. Optimization Result Data

Type of Unit	Bus Location	Capacity (kW)
Photovoltaic (PV)	8	749.3
	13	577.5
	20	620
Battery Energy Storage System	24	1112.4

The strategic placement of PV units enables the direct supply of active power to nearby loads, thereby reducing power flow from the main source and minimizing distribution line losses. The PV units located at buses 8 and 13 contribute to balancing power distribution in the central part of the network, whereas the PV installed at bus 20 improves the voltage profile at the end section of the system, which typically experiences the most severe voltage drops.

Meanwhile, the BESS at bus 24 plays a crucial role in mitigating power fluctuations caused by PV generation and providing reactive power support during peak load

conditions. The presence of BESS also helps maintain voltage levels within nominal limits and enhances the overall reliability of the distribution system.

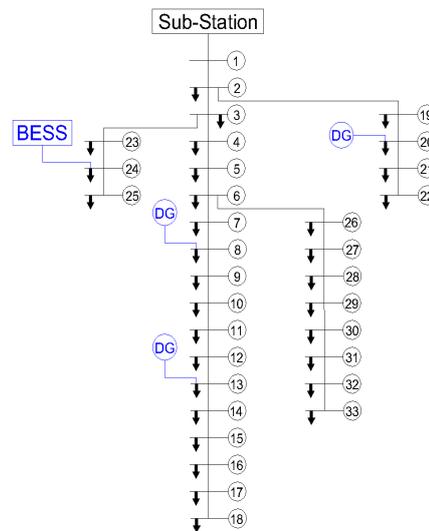


Figure 2. Optimization Results of PV and BESS Placement Locations

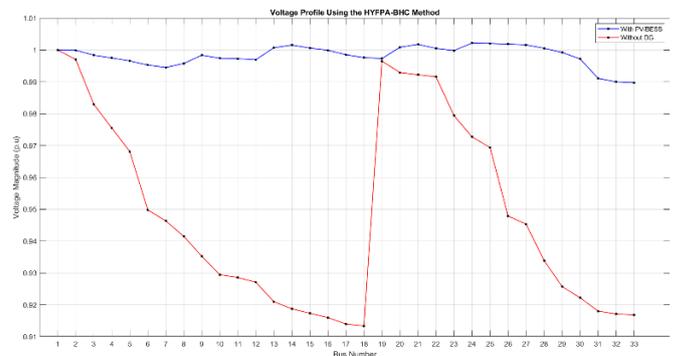


Figure 3. Voltage Profile Graph Before and After the Installation of PV and BESS

Figure 3 illustrates the voltage profile of the IEEE 33-bus distribution system obtained using the HyFPAβHC method under two conditions: without Distributed Generation (DG) and with the integration of PV/BESS. The horizontal axis of the graph represents the bus numbers ranging from 1 to 33, while the vertical axis indicates the voltage magnitude in per-unit (p.u.) values. Based on the optimization results, the integration of PV and BESS has a significant impact on improving the voltage profile of the IEEE 33-bus distribution system.

Under the condition without PV and BESS (red line), the voltage experiences a noticeable drop at several buses, with the lowest voltage reaching approximately 0.92 p.u. This condition indicates a considerable voltage decline resulting from full dependency on the main power source and the presence of high power losses along the distribution network. Under the condition with PV and BESS integration (blue line), the voltage profile exhibits a significantly higher level of stability, with voltage magnitudes consistently maintained within the range of 0.98 to 1.0 p.u. across all buses. This improvement indicates that the incorporation of distributed energy resources and energy storage systems enables the local supply of active and reactive power, thereby reducing the load on the main power source, minimizing power losses along the distribution lines, and maintaining overall system voltage stability.

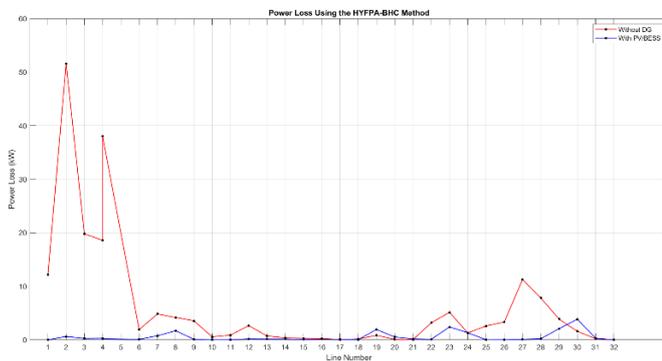


Figure 4. Power Losses Before and After the Installation of PV and BESS

Based on the graph entitled “Power Loss Using the HyFPAβHC Method” in Figure 4, a substantial reduction in power losses can be observed following the optimization process that integrates PV and BESS. Under the condition without distributed generation (red line), the highest power losses occur in the initial lines, particularly in line 2 and line 5, with losses reaching approximately 50 kW and 37 kW, respectively. This indicates that a significant portion of total power loss is concentrated in lines near the main source due to high current flow and uneven power distribution.

After applying the HyFPAβHC method to determine the optimal locations and capacities of PV and BESS, the power loss profile changes significantly. In the condition with PV and BESS integration (blue line), nearly all lines

exhibit much lower power losses, with most values falling below 5 kW. This demonstrates that the integration of distributed energy resources and energy storage systems effectively reduces current flow through the main feeders, thereby substantially decreasing active power losses.

From a technical perspective, the reduction in power loss results from the local power supply provided by PV-DG units, which can partially meet load demands near their installation points. Additionally, the BESS contributes to maintaining power balance and stabilizing energy flow within the system, leading to lower total current through the lines and, consequently, a significant reduction in losses.

### Conclusion

The optimization of PV and BESS placement and sizing on the IEEE 33-bus system using the HyFPAβHC method demonstrates clear performance enhancements. The integrated PV and BESS configuration maintains the voltage profile within 0.98–1.0 p.u., reduces active power losses, decreases the load on the main source, and stabilizes power fluctuations. These results confirm that HyFPAβHC effectively identifies an optimal PV and BESS arrangement that improves the efficiency, stability, and reliability of the distribution system.

### Acknowledgement

The author would like to express sincere gratitude to all parties who have provided support and contributions to the completion of this research. Special thanks are

extended to the institution and colleagues for their valuable feedback and technical assistance throughout the research and analysis process. Appreciation is also given to the developers of the IEEE 33-bus system for providing the data and technical references that made the study on the optimization of Photovoltaic (PV) and Battery Energy Storage System (BESS) placement and sizing possible.

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