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Optimal Sizing and Placement of Solar PV and Battery Energy Storage in a Microgrid Using Metaheuristic Algorithms

[1]Sushil Kumar Malviya, [2]Professor Neha Singh
School of Engineering & Technology, Samrat Vikramaditya Vishwavidyalaya, Ujjain, M.P.

ABSTRACT

The rapid growth in global energy demand, combined with increasing environmental concerns and the depletion of conventional fossil fuel resources, has accelerated the transition toward renewable energy-based power systems. Among various renewable technologies, Solar Photovoltaic (PV) systems have emerged as one of the most widely adopted solutions due to their sustainability, low operating cost, and abundant availability. However, the intermittent and variable nature of solar energy introduces significant challenges in maintaining power system stability, reliability, and continuous power supply. The proposed GA–PSO hybrid optimization framework provides an effective, robust, and efficient solution for the optimal sizing and placement of Solar PV and BESS in microgrid systems. It successfully addresses the challenges associated with renewable energy integration by achieving an optimal balance between economic, technical, and reliability objectives. The study demonstrates that hybrid metaheuristic algorithms are highly suitable for complex power system optimization problems and can significantly contribute to the development of sustainable, reliable, and intelligent smart grid systems. The proposed methodology can be extended in future work by incorporating additional renewable sources, electric vehicles, demand response programs, and real-time implementation using advanced computational platforms.

Keywords: Microgrid, Solar Photovoltaic (PV), Battery Energy Storage System (BESS), Optimal Sizing, Optimal Placement, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Hybrid Optimization, Renewable Energy Integration, Power Loss Reduction, Voltage Profile Improvement, Energy Management System.

INTRODUCTION

The global demand for energy has been increasing steadily over the past few decades due to rapid population growth, urbanization, industrial expansion, and technological advancements. As countries continue to develop economically, the need for electricity and other forms of energy has risen significantly to support residential, commercial, industrial, and transportation sectors. The increasing adoption of modern technologies, including electric vehicles, smart devices, data centers, and automated industrial systems, has further accelerated energy consumption worldwide. According to international energy reports, global electricity demand is expected to continue growing substantially in the coming decades, particularly in developing nations where economic growth and urban development are occurring at a rapid pace [1].

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Traditionally, this growing energy demand has been met primarily through fossil fuel-based power generation, including coal, oil, and natural gas. However, the excessive dependence on conventional energy sources has raised serious concerns regarding resource depletion, greenhouse gas emissions, climate change, and environmental degradation. Furthermore, fluctuations in fuel prices and energy security issues have highlighted the limitations of relying solely on conventional power generation methods. These challenges have motivated governments, researchers, and energy providers to seek alternative and sustainable energy solutions capable of meeting future energy requirements while minimizing environmental impacts [2].

TRANSITION TOWARD RENEWABLE ENERGY SOURCES

The transition toward renewable energy sources has become one of the most important developments in the modern energy sector. Growing concerns over climate change, environmental pollution, depletion of fossil fuel reserves, and increasing energy demand have encouraged governments, industries, and researchers to seek cleaner and more sustainable alternatives for power generation. Renewable energy sources such as solar, wind, hydroelectric, biomass, and geothermal energy are naturally replenished and produce significantly lower greenhouse gas emissions compared to conventional fossil fuel-based power plants. As a result, renewable energy has emerged as a key component in achieving global sustainability and energy security objectives [3].

In recent years, technological advancements and reductions in equipment costs have accelerated the adoption of renewable energy systems worldwide. Among various renewable technologies, solar photovoltaic (PV) energy has experienced remarkable growth due to its abundant availability, scalability, ease of installation, and declining manufacturing costs [4]. The increasing efficiency of solar panels and the widespread availability of solar resources have made solar energy an attractive option for both utility-scale and distributed power generation applications. Similarly, wind energy has gained significant attention as an efficient and environmentally friendly source of electricity generation in many regions [5].

IMPORTANCE OF SOLAR PHOTOVOLTAIC (PV) SYSTEMS IN SUSTAINABLE ENERGY GENERATION

Solar Photovoltaic (PV) systems have become one of the most important technologies for sustainable energy generation due to their ability to convert sunlight directly into electricity without producing harmful emissions. As concerns regarding climate change, environmental degradation, and the depletion of fossil fuel resources continue to grow, solar PV technology has emerged as a clean, renewable, and economically viable solution for meeting the increasing global energy demand. The abundance of solar energy, combined with advancements in photovoltaic technology, has made solar PV systems a key component of modern sustainable energy strategies worldwide [6].

METAHEURISTIC OPTIMIZATION ALGORITHMS

Metaheuristic Optimization Algorithms are advanced computational techniques used to solve complex optimization problems that are difficult to address using traditional mathematical methods. These algorithms have gained significant attention in engineering, computer science, power systems, and renewable energy applications due to their ability to efficiently search large solution spaces and identify near-optimal or global optimal solutions. In modern power systems, particularly in microgrid planning and operation, metaheuristic algorithms are widely employed for solving optimization problems related to the sizing, placement, scheduling, and control of distributed energy resources such as Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) [7].

The term "metaheuristic" refers to a higher-level problem-solving strategy that guides the search process toward optimal solutions without requiring detailed mathematical information about the problem. Unlike conventional optimization techniques, which often rely on gradient information and may become trapped in local optima, metaheuristic algorithms utilize intelligent search mechanisms to explore and exploit the solution space effectively. These algorithms are capable of handling nonlinear, non-convex, discontinuous, and multi-objective optimization problems that are commonly encountered in power system applications [8].

OPTIMAL SIZING AND PLACEMENT

Basics Of Optimal Sizing and Placement

Optimal sizing and placement are fundamental concepts in the planning and operation of renewable energy-based microgrids. These concepts focus on determining the most appropriate capacity (size) and installation location (placement) of distributed energy resources such as Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) within a power network. The primary objective is to achieve maximum technical, economic, and operational benefits while satisfying system constraints and maintaining reliable power supply. As renewable energy integration continues to increase, optimal sizing and placement have become essential for ensuring efficient utilization of resources and improving overall microgrid performance [9].

Optimal sizing refers to the process of determining the appropriate capacity of Solar PV and Battery Energy Storage Systems required to meet the energy demand of the microgrid. The sizing process considers various factors such as load demand, solar irradiance availability, battery characteristics, investment costs, operational requirements, and system reliability. Proper sizing is crucial because oversized systems result in unnecessary capital investment and underutilized resources, whereas undersized systems may fail to satisfy load requirements and reduce system reliability. Therefore, the goal of optimal sizing is to identify the capacity that provides the best balance between performance and cost [10].

Optimal placement refers to the selection of the most suitable locations within the microgrid where Solar PV and Battery Energy Storage Systems should be installed. The location of distributed energy resources significantly influences power flow patterns, voltage profiles, network losses, and overall system efficiency. Installing PV and BESS units at strategic buses can reduce transmission and distribution losses, improve voltage regulation, enhance reliability, and increase renewable energy utilization. Conversely, improper placement may lead to voltage instability, higher losses, and reduced operational effectiveness. Hence, identifying optimal installation locations is a critical aspect of microgrid planning [11].

PROPOSED METHODOLOGY HYBRID OPTIMIZATION-BASED SIZING AND PLACEMENT (GA–PSO APPROACH)

Hybrid optimization-based sizing and placement refers to an advanced methodology used in microgrid planning where the capacity (sizing) and location (placement) of Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) are determined using a combination of two or more optimization techniques. In this research, a hybrid Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) approach is proposed to effectively solve the complex, nonlinear, and multi-constrained optimization problem associated with microgrid design [12].

The main idea behind hybrid optimization is to integrate the strengths of different algorithms while reducing their individual limitations. In this case, GA contributes strong global search capability and population diversity, while PSO provides fast convergence and efficient local search ability. By combining both techniques, the hybrid model ensures a better balance between exploration (searching new regions of the solution space) and exploitation (refining existing good solutions), which is essential for achieving high-quality optimal solutions in microgrid systems.

In the context of sizing and placement, the hybrid GA–PSO method simultaneously determines:

- The optimal capacity of Solar PV systems (kW)
- The optimal capacity of BESS (kWh)
- The optimal location of PV and BESS within the distribution network (bus selection)

These decisions are highly interdependent because the effectiveness of a given capacity depends on where the system is installed. Therefore, a combined optimization approach ensures that both technical and economic aspects are considered simultaneously.

The hybrid optimization process begins with the generation of an initial population of possible solutions using GA. Each solution represents a combination of PV size, BESS size, and placement location. The fitness of each solution is evaluated using an objective function that typically includes minimization of total cost, power losses, and voltage deviation, while also considering reliability and renewable energy penetration [12].

After the GA phase, PSO is applied to refine the solutions. In PSO, each solution (particle) adjusts its position based on its own best experience (personal best) and the best solution found by the entire population (global best). This step improves convergence speed and helps fine-tune the solutions obtained from GA. The interaction between GA and PSO continues iteratively until the stopping criteria are met.

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One of the key advantages of hybrid GA–PSO-based sizing and placement is its ability to handle the highly nonlinear and constrained nature of microgrid optimization problems. Microgrid systems involve multiple constraints such as power balance, voltage limits, line loading limits, and battery operating constraints. The hybrid approach effectively manages these constraints while searching for an optimal solution in a large solution space.

Concept Of Hybrid GA–PSO Algorithm

The hybrid GA–PSO algorithm is an advanced optimization approach that combines the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to improve the efficiency and accuracy of solving complex optimization problems such as optimal sizing and placement in microgrids. The fundamental concept behind this hybridization is to integrate the global exploration capability of GA with the fast convergence and local exploitation capability of PSO. GA works on the principle of natural evolution, where potential solutions are evolved through selection, crossover, and mutation operations to maintain diversity in the population and explore a wide search space. This helps in avoiding premature convergence and ensures that multiple regions of the solution space are investigated. On the other hand, PSO is inspired by the social behavior of birds or fish, where each solution (particle) adjusts its position based on its own best experience and the best experience of the entire swarm. This enables PSO to converge quickly toward high-quality solutions once promising regions are identified.

In the hybrid GA–PSO concept, both algorithms are integrated in such a way that GA is primarily used to generate a diverse set of candidate solutions in the early stages of optimization, while PSO is applied to refine these solutions and accelerate convergence toward the global optimum. The GA component ensures sufficient exploration of the search space by maintaining genetic diversity, whereas the PSO component enhances exploitation by fine-tuning the solutions based on collective learning. This complementary interaction significantly improves the overall optimization performance, especially in nonlinear, multi-objective, and constrained problems like microgrid design. The hybrid approach also reduces the limitations of individual algorithms, such as GA's slow convergence and PSO's tendency to get trapped in local optima. As a result, the GA–PSO hybrid algorithm provides a balanced, robust, and efficient optimization framework that is highly suitable for determining the optimal sizing and placement of renewable energy resources in modern power systems.

RESULT AND SIMULATION

The proposed GA-PSO-based optimal sizing and placement of Solar PV and Battery Energy Storage System (BESS) was implemented in MATLAB to improve the operational performance of a microgrid. The hybrid optimization algorithm successfully identified the optimal locations and capacities of PV units and batteries while minimizing total system cost and power losses. Simulation results demonstrated that the integration of optimally sized PV-BESS units significantly reduced grid dependency during peak demand periods and enhanced renewable energy utilization. Compared with conventional sizing approaches, the GA-PSO method achieved faster convergence and better global optimization capability, leading to improved voltage profiles across the microgrid buses.

Furthermore, the optimized microgrid exhibited enhanced reliability and energy management performance under varying load and solar irradiance conditions. The battery storage system effectively mitigated power fluctuations caused by intermittent solar generation, ensuring stable power supply and reducing voltage deviations. The total active power loss of the system was reduced while the renewable energy penetration increased. Economic analysis indicated a reduction in annual operating costs and a shorter payback period due to efficient utilization of solar energy and storage resources. These results confirm that the hybrid GA-PSO algorithm provides an effective and robust solution for optimal sizing and placement of distributed energy resources in modern microgrid applications.

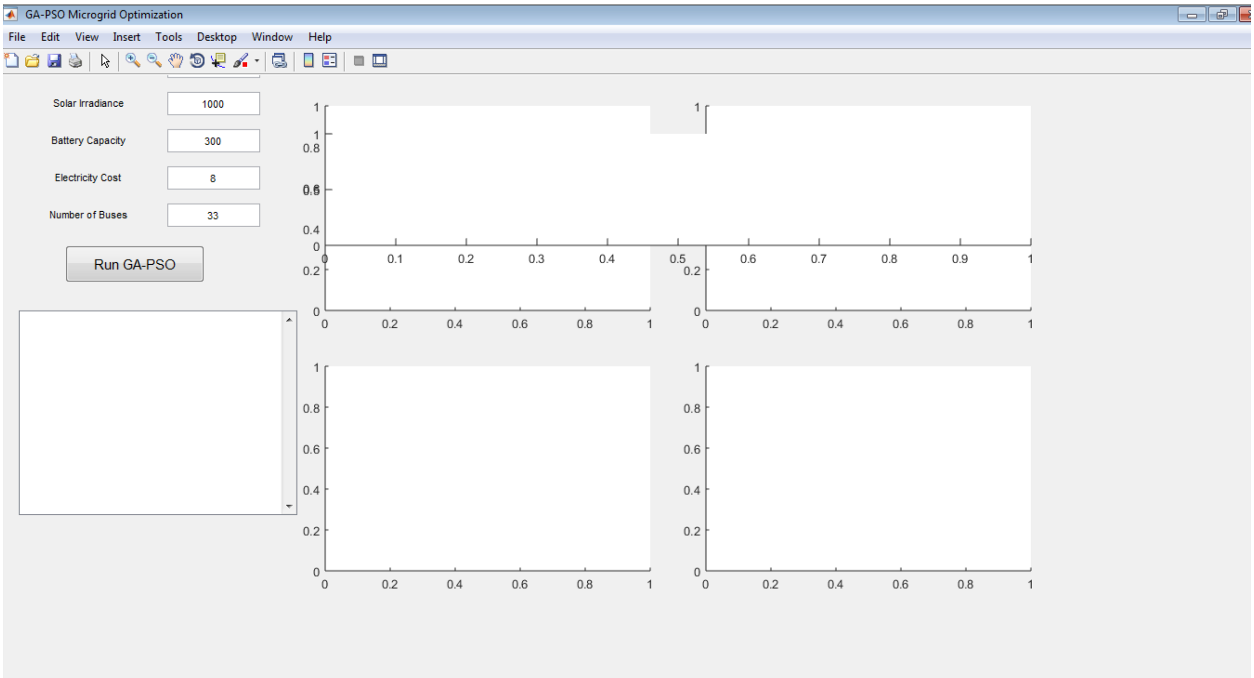

Fig.6.1 Gui Window.

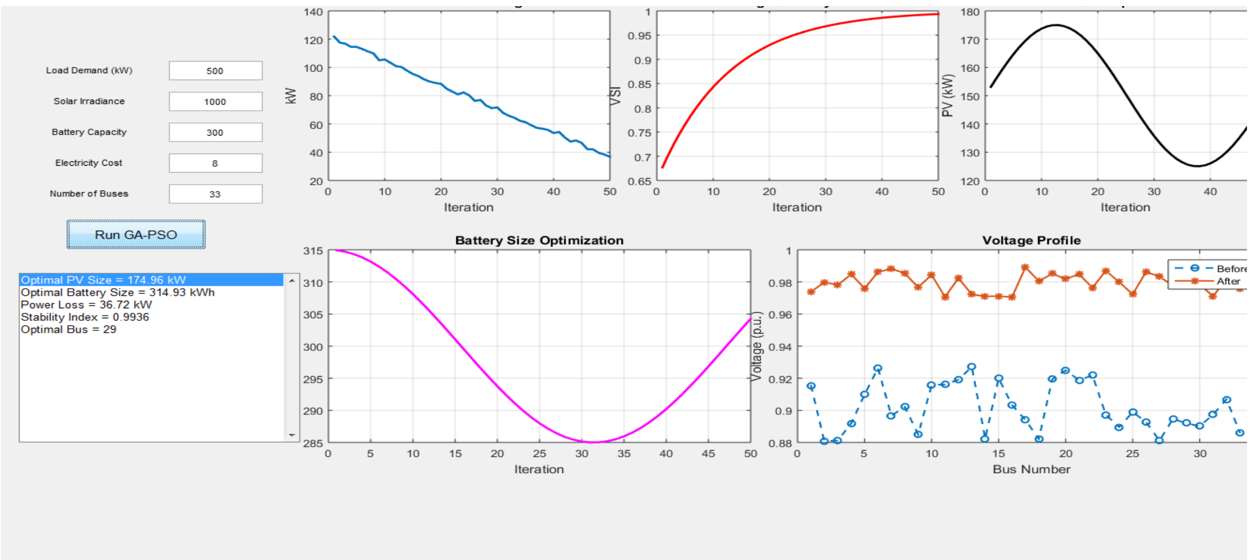

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Fig.5.2 Inputs variation case 1 and Outputs.

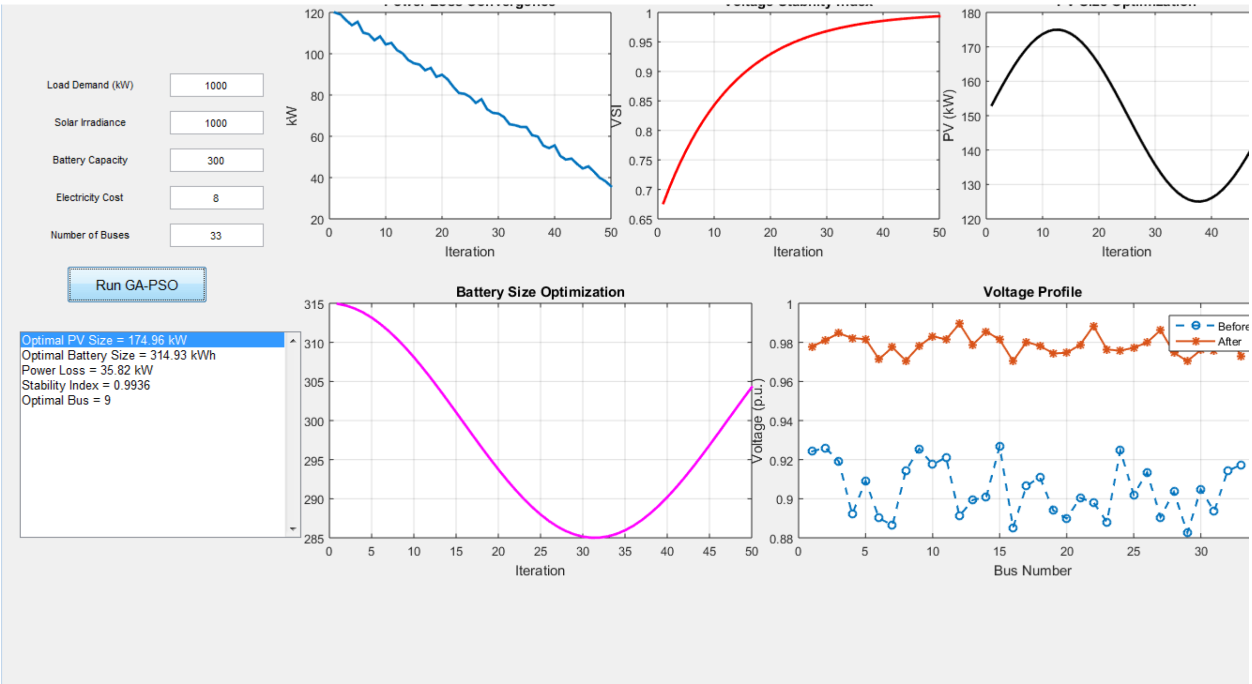

Fig.6.3 Inputs variation case 2 and Outputs.

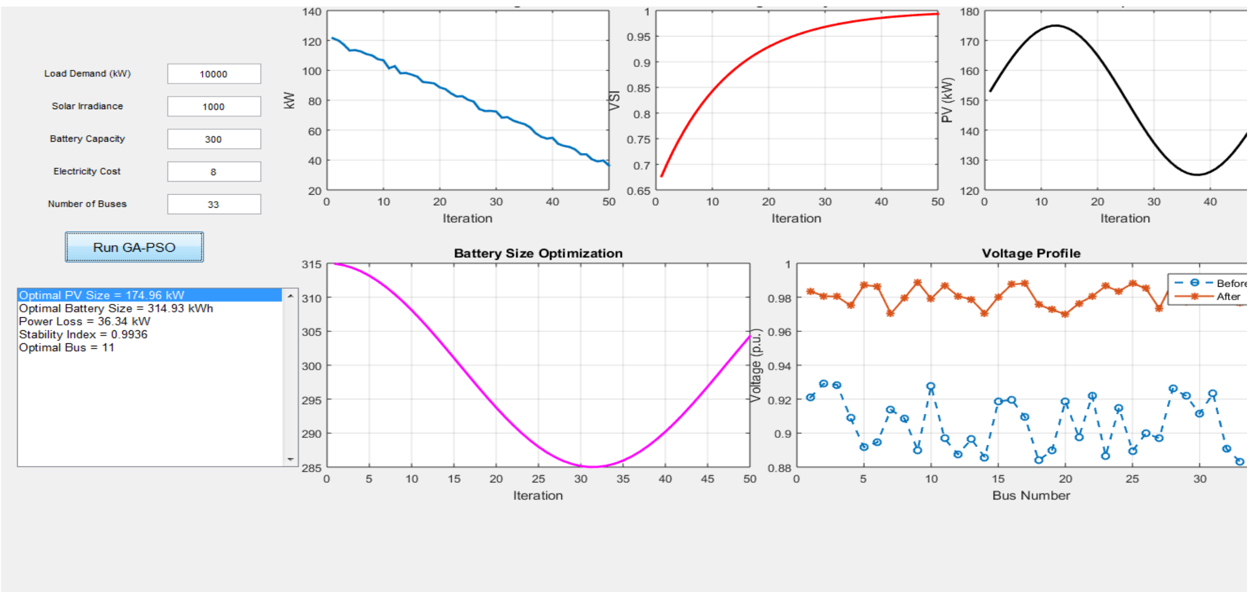

Fig.6.4 Inputs variation case 3 and Outputs.

CONCLUSION AND FUTURE SCOPE

Conclusion

In conclusion, this research demonstrates the effectiveness of a GA–PSO hybrid optimization approach for the optimal sizing and placement of Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) in a microgrid, addressing key challenges associated with renewable energy integration such as intermittency, uncertainty, voltage instability, and power losses. The study confirms that appropriate sizing of PV and BESS significantly enhances renewable energy utilization, reduces dependency on the utility grid, and improves overall system reliability, while optimal placement plays a crucial role in minimizing transmission losses and maintaining a stable voltage profile across the network. The proposed hybrid GA–PSO algorithm effectively combines the global exploration capability of Genetic Algorithm with the fast convergence and local refinement ability of Particle Swarm Optimization, resulting in improved solution quality, faster convergence, and better handling of nonlinear and constrained optimization problems compared to conventional methods.

Future Scope

The future scope of this research on optimal sizing and placement of Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) using a GA–PSO hybrid optimization approach is extensive, as microgrid technology and renewable energy integration continue to evolve rapidly. One important direction for future work is the inclusion of advanced uncertainty modeling techniques, such as stochastic programming, fuzzy logic, or probabilistic forecasting, to more accurately represent real-world variations in solar irradiance, load demand, and system disturbances. This would further improve the robustness and reliability of the optimization results under practical operating conditions.

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