

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

Sushil Kumar Malviya, Professor Neha Singh

School Of Engineering and Technology, Vikram University, Ujjain University in Ujjain,
Madhya Pradesh

ABSTRACT

An essential consideration for a microgrid's cost-effectiveness is the size of its renewable energy sources. A collection of RES, a storage system, converters, and loads make up the grid-connected hybrid renewable energy system. The operating area needed by the type of DG technology is one variable used in this article to determine the DG sizing, while all potential candidate buses in the various AC/DC micro-grid system zones are another variable, taking into account the HPC losses in the system. A hybrid AC/DC MG system is created to optimize the size and designing using different renewable energy sources. To evaluate the proposed approach, Metaheuristic Algorithms is implemented on aforementioned micro-grid systems and the obtained results are verified with other Particle swarm optimization in the synopsis.

Keywords: Optimization, Cost Minimization, Microgrid, GA Optimization, Sizing

I. INTRODUCTION

The global transition towards sustainable energy systems has accelerated the adoption of distributed energy resources (DERs), particularly photovoltaic (PV) systems and battery energy storage systems (BESSs), within microgrid architectures [1,2]. Microgrids, especially those operating on direct current (DC), have emerged as a promising solution for integrating renewable energy sources, enhancing energy efficiency, and improving grid resilience [3,4]. The increasing penetration of renewable energy, driven by policy incentives and technological advancements, has necessitated the development of advanced methods for optimal sizing and operation of PV and BESS units in microgrids [5,6].

Optimal sizing of PV and BESS units is a critical aspect of microgrid design, directly impacting system reliability, economic performance, and environmental sustainability [7,8]. Oversizing leads to unnecessary capital expenditures, while undersizing can result in increased grid dependency and reduced self-sufficiency [9]. Traditional sizing approaches often rely on deterministic or rule-based methods, which may not adequately capture the stochastic behavior of renewable generation and load profiles. Recent research has emphasized the importance of probabilistic and data-driven techniques to address these uncertainties.

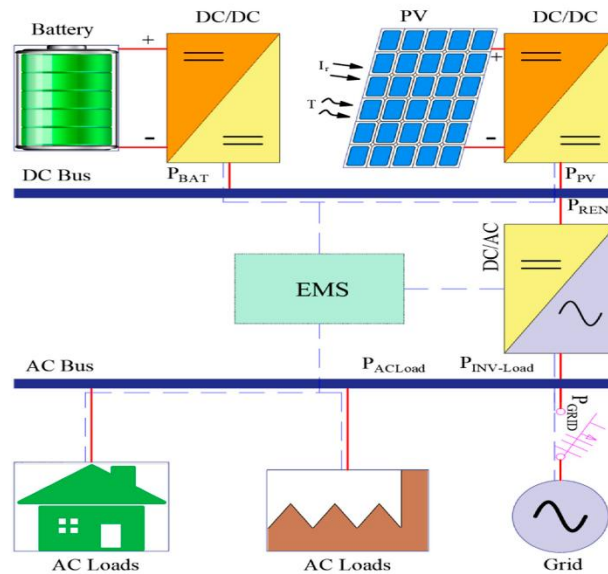


Fig.1.1 Optimization of PV and Battery Energy Storage Size in Grid-Connected Microgrid

II. METAHEURISTIC OPTIMIZATION

The integration of advanced forecasting methods, particularly those based on artificial intelligence (AI) and machine learning (ML), has significantly improved the accuracy of load and generation predictions in microgrids [4,5]. Among these, Long Short-Term Memory (LSTM) networks have demonstrated superior performance in modeling complex temporal dependencies in energy consumption data [6,7]. LSTM networks, a type of recurrent neural network (RNN), are capable of learning long-term patterns and trends, making them well-suited for short-term and long-term load forecasting applications. The application of LSTM-based forecasting in microgrid optimization has been shown to enhance demand-side management, reduce operational costs, and improve system reliability.

In addition to advanced deep learning models such as LSTM, traditional machine learning approaches like the Multi-Layer Perceptron (MLP) have also been widely used for load forecasting in energy systems. MLPs, as feedforward artificial neural networks, are capable of modeling nonlinear relationships between input features and target variables and have been applied to short-term and long-term load prediction tasks in various microgrid studies [2]. While MLPs offer simpler architecture and faster training compared to recurrent models, their ability to capture temporal dependencies is limited, which can affect forecasting accuracy in highly variable energy environments.

In addition to load forecasting, the optimal sizing of PV and BESS units has been extensively studied using a variety of optimization techniques. Metaheuristic algorithms such as genetic algorithms (GA), particle swarm optimization (PSO), and ant colony optimization (ACO) have been widely employed to solve the multi-objective optimization problems associated with microgrid design [3]. These methods enable the simultaneous consideration of economic, technical, and environmental objectives, facilitating the identification of Pareto-optimal solutions [2]. Hybrid approaches that combine AI-based forecasting with metaheuristic

optimization have also been proposed, further enhancing the robustness and adaptability of microgrid sizing strategies [7].

III. HYBRID ENERGY SYSTEMS (HESS)

As global energy demands rise and environmental concerns escalate, the urgent need for sustainable energy solutions has brought renewable-based hybrid energy systems into focus [1]. The depletion of fossil fuels and the increase in fuel prices further underscore the necessity of transitioning to renewable energy sources, particularly solar and wind power. However, the intermittent nature of these resources poses significant challenges in maintaining a stable power supply [2].

Hybrid energy systems (HESs) offer a promising alternative by integrating renewable sources with energy storage and backup generation. By utilizing battery storage to capture excess energy during peak production periods, HESs enhance reliability by providing backup power when renewable output is low or demand is high. Diesel generators can also serve as supplementary power sources when battery reserves are depleted. Microgrids (MGs), which incorporate distributed energy resources, such as solar panels, wind turbines, energy storage systems, and generators, provide localized solutions that address the limitations of centralized power grids. These systems improve energy resilience, efficiency, and sustainability while allowing for independent or grid-connected operation, thereby reducing carbon emissions.

Recent advancements in renewable technologies and energy management systems have made microgrids increasingly economically feasible. They can seamlessly transition between grid-connected and islanded modes, optimizing energy generation and minimizing reliance on fossil fuels. Hybrid microgrid systems (HMSs), which combine renewable generation, storage, and backup components, ensure a reliable and continuous power supply. However, optimizing these systems for residential or community applications requires careful consideration of factors such as renewable variability, energy demand patterns, and system sizing to achieve a balanced supply–demand relationship. While HESs integrating solar and wind sources demonstrate greater reliability and cost-effectiveness than single-source systems [3,4], optimizing these configurations remains complex due to the stochastic nature of renewable resources and fluctuating energy demands. The integration of components such as battery storage and diesel generators is essential for managing these fluctuations and maintaining operational efficiency [5,6].

HYBRID MICROGRIDS

Hybrid microgrids, which integrate various energy sources such as solar, wind, and traditional fossil fuels, have emerged as a viable solution for addressing contemporary energy demands sustainably. The effective sizing of these microgrids is paramount for optimizing performance, enhancing reliability, and minimizing operational costs. This literature review aims to explore the methodologies and findings in the domain of hybrid microgrid sizing, emphasizing the diverse approaches, inherent challenges, and prospective research directions. The methodologies employed for sizing hybrid microgrids can be categorized into several key groups:

Software Tools: A considerable number of studies have leveraged software tools such as HOMER, HOMER Pro, PVSYST, and HOGA for the optimization of MGs [8,9]. These tools facilitate the design process by enabling users to model various configurations and conduct economic analyses. However, a significant limitation is their lack of transparency; users often find it challenging to intuitively select system components or access the underlying calculations and algorithms [10,3].

Deterministic Methods: Approaches including iterative, analytical, numerical, and graphical techniques are also widely utilized. Although these methods are generally straightforward, they can be time-intensive due to the exhaustive simulations required to cover all possible configurations. For instance, one study highlighted that, while analytical models can produce accurate results, they necessitate considerable computational resources and time to analyze different scenarios [1].

Metaheuristic Algorithms: Recent advancements have seen the adoption of metaheuristic algorithms for optimizing HMSs configurations. Techniques such as genetic algorithms, particle swarm optimization, and social spider optimization have been effectively applied to address complex sizing challenges. For example, a study [4] employed social spider optimization (SSO) to determine the optimal sizing of an HRES integrated into a microgrid in the Al-Jouf region of Saudi Arabia. This research evaluated configurations that included photovoltaic (PV) systems, wind turbines (WT), batteries, and diesel generators (DGs), with a focus on the cost of energy (COE) as the fitness function. Another noteworthy study utilized the grasshopper optimization algorithm (GOA) to ascertain optimal system configurations in Yobe State, Nigeria, encompassing PV systems, WTs, battery storage systems, and DGs [5]. The objective was to minimize the COE while ensuring system reliability. Additionally, a novel bonobo optimizer (BO) was introduced to optimize off-grid HRES designs in Saudi Arabia, concentrating on minimizing annualized system costs (ASCs) and enhancing power reliability [6].

IV. RESEARCH MOTIVATION

Providing access to reliable, affordable energy, and clean energy by adopting microgrid system is important for countries looking to achieve their sustainable development goals as the extension of the grid is capital and time expensive. These microgrids are small electrical power systems that connect several electricity users to some distributed power generators and energy storage systems, which are mainly interconnected by power converters and can be made of renewable energy sources or hybridized with fossil fuel generators. Hybrid solar system, wind turbine, and energy storage system are used for grid electrification applications, and they are good for applications in hot climates. However, due to the CO₂ emission, delivery cost and rising price of diesel fuel, renewable energy sources are more and more popular in microgrid development, especially in remote areas. Both wind and solar power sources are intermittent as they depend on weather and climate changes; however, hybridizing the two sources can overcome this drawback.

Due to the depletion of traditional energy, as well as the increasing emphasis of many countries in the world on environmental issues, an pro-environment and flexible way for power

generation is needed urgently to solve these problems. Distributed generation (DG) can be connected with the actual situation of each place, generate electric power flexibly and efficiently, so it has been attached importance to and has become the new focus in power system research. Introduction of distributed generation source (DGs) to distribution network impacts on the structure and operation of distribution network, namely nodes voltage, power flow, short-circuit current, reliability of distribution network. The DG advantages can be divided into technical, economical and environmental benefits. Technical advantages[7] are included wide ranges of benefit such as efficiency, grid reinforcement, power loss reduction, reliability, eliminating or deferring the upgrades of power system, improving load factors and voltage profile and thus increased power quality. The economical advantages are entailed the reducing of transmission and distribution operating cost, to save the fossil fuel and decreasing in electricity price. Environmental advantages are covered the reductions in emission of greenhouse gases and also sound pollutions. Several techniques have been proposed in determining the optimal location of DG. The major objective of DG placement techniques is to minimize the losses of power systems. However, many researchers have applied the evolutionary computational methods for finding the optimal DG location. The Genetic Algorithm [10], Fuzzy Systems and Tabu Search are more commonly used. This synopsis includes Optimal Power Flow using NR method, Evolutionary Computational Method such as Genetic Algorithm.

V. PROBLEM IDENTIFICATION

The increasing integration of solar photovoltaic (PV) systems and battery energy storage in microgrids introduces significant challenges related to their optimal sizing and placement. Improper allocation of PV and battery units can lead to higher investment costs, increased power losses, voltage instability, and underutilization of renewable energy resources. Traditional analytical and deterministic optimization methods often struggle to handle the nonlinear, multi-objective, and constrained nature of microgrid planning problems, especially under variable load demand and intermittent solar generation. Therefore, there is a critical need for an efficient optimization approach that can simultaneously address economic, technical, and operational constraints to achieve reliable and cost-effective microgrid operation.

VI. LITERATURE REVIEW

Mehmet Kurtoğlu et al.[1] Battery energy storage systems (BESSs) play a significant role in increasing the performance of solar photovoltaic (PV) systems by reducing the adverse effects of intermittency of power generated by solar PV systems. Over the past decade, the integration of BESS technology with solar PV systems has gained significant attention in residential applications, electric vehicle charging stations, and large-scale grid-connected systems. Although numerous studies on solar PV-integrated BESS, a review that holistically covers all key aspects such as DC-DC converter topologies, maximum power point tracking (MPPT) methods, optimization approaches, and energy management systems (EMSs) is still missing.

Chukwuemeka Emmanuel Okafor et al.[2] This study presents a simulation, optimization, and assessment of economic impacts of a grid-connected solar PV system with electric vehicles (EVs) and various battery energy storage systems (BESS) for distribution network systems.

Four optimization algorithms—Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Direct Search Optimization (DSO), and Grey Wolf Optimizer (GWO) were deployed in determining the optimal parameters for energy storage deployment in the distribution networks integrated with EVs and solar photovoltaic (PV) systems. Two real-world distribution network systems were modeled for time-based (quasi-dynamic) simulations: the 30-bus South African distribution network and the 49-bus distribution network of Baghdad City, Iraq.

Thuan Thanh Nguyen et al.[3] Optimal operation of battery energy storage system (BESS) in the microgrid systems is an effective solution to exploit the efficiency of highly uncertain renewable energy sources. This article presents a model for optimal operation of BESS in the microgrid system using a metaheuristic algorithm to reduce the cost of electricity purchased from the grid. The microgrid model includes grid source, load, photovoltaic system (PVS), wind turbine (WT) and BESS that are built using the Simulink model based on model predictive control. The data of load, radiation, wind speed, and electricity price are updated every 15 min. At each interval during the day, the coyote algorithm (COA) is adjusted to find the optimal power for the BESS. The considered cases include the microgrid without BESS, the microgrid with BESS operated using the heuristic approach based on power difference between generation sources and load demand, and the microgrid with BESS operated to minimize energy costs using the COA and particle swarm optimization (PSO) algorithms.

Ali Chebabhi et al.[4] The integration of photovoltaic (PV) system with battery energy storage system (BESS) in standalone DC microgrids provides significant advantages including direct DC coupling, reduced conversion stages and power losses, and enhanced power quality and system efficiency. However, complex dynamic interactions among DC-bus voltage, BESS current, and PV characteristics create substantial control challenges under system uncertainties and disturbances such as parameter variations, irradiance fluctuations, and load changes. To address these challenges, this paper proposes a novel optimized active disturbance rejection control (ADRC) strategy for simultaneous regulation of the DC microgrid voltage and BESS current. The key innovation consists in replacing the traditional extended state observer-based ADRC with an optimized generalized super-twisting extended state observer (OGSTESO), which delivers faster convergence, superior disturbance estimation accuracy, and enhanced robustness.

Riwa Q. Momani et al.[5] This paper presents a cost-optimal sizing framework for Battery Energy Storage Systems (BESS) in grid-connected microgrids using the Artificial Rabbits Optimization (ARO) algorithm. The main objective is to minimize the total operational cost of the microgrid by optimally determining the size of the BESS under real-world constraints, including dynamic pricing, varying load, and renewable energy availability. The proposed model incorporates technical and economic considerations, including depth-of-discharge limits, initial battery state-of-charge (SOC), and different wind turbine models. Three operational scenarios are evaluated: without BESS (Case A), and with BESS initialized at 20 %, and 100 % SOC (Cases B, and C).

Chandransh Singh et al.[6] Hydrogen energy plays a crucial role in decarbonizing global energy systems due to its clean and flexible nature, making it a vital element in future microgrids. However, integrating microgrids with high penetration of Renewable Energy Sources (RESs) into distribution networks introduces challenges such as increased power losses and voltage deviations. This paper presents a comprehensive framework to address these challenges through dynamic network reconfiguration.

Binaya Kumar Malika et al.[7] The transformation of the traditional distribution system into a microgrid concept of upgradation requires assessing and planning for infrastructure that delivers electricity with improved management, higher reliability, and security, along with economical energy consumption pricing and environmentally friendly energy generation. Several key factors, including demand forecasts, planning policies, condition monitoring, proper infrastructure integration, and reliability standards, significantly influence the planning process. The distribution generation (DG) placement and sizing, along with energy storage devices (ESD), play a critical role in distribution system planning, affecting not only the existing operational performance but also the future expansion of the network and handling uncertainties for a reliable and secure power supply and management.

Mohd Bilal et al.[8] Designing and sizing standalone microgrids integrating Solar PV, wind turbines (WT), diesel generators (DG), and battery energy storage systems (BES) involves balancing reliability, economic feasibility, and environmental sustainability. Conventional optimization methods often fail to achieve these objectives effectively, highlighting the need for hybrid approaches. In this context, this paper presents a hybrid optimization methodology for designing and sizing standalone microgrids incorporating Solar PV, WT, DG, and BES, with a focus on environmental sustainability.

Wenjuna Liao et al.[9] The article focuses on the combined application of distributed generation, cutting-edge energy storage, and electric vehicles in cooperative microgrids, which are an essential part of intelligent electricity distribution networks. The paper presents the innovative use of a recompression supercritical CO₂ (S-CO₂) Brayton cycle with an ejector as a storage system to absorb the fluctuations of renewables and to extend system flexibility. The given optimization framework is capable of figuring out the best location and the right capacity of the microgrids, and, besides, it can perform a 24-h dynamic scheduling of electric vehicle charging rates. The electric vehicle uncertainties, including fleet size, travel distance, and stochastic charging behavior, are explicitly incorporated. Simulations of the IEEE-30 bus system validate the considerable technical and economic advantages.

Tilak Giri et al.[10] The rapid adoption of electric vehicles (EVs) globally demands expanded charging infrastructure; however, their unplanned integration into radial distribution systems (RDS) often causes voltage instability, high power losses, and system inefficiencies. This study optimizes the placement and sizing of solar photovoltaic-battery system (PV-BESS) in Nepal's 30-bus Byasi feeder to mitigate these issues.

VII. CONCLUSION

This review paper presented a comprehensive analysis of optimal sizing and placement of Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) in microgrids using

metaheuristic optimization algorithms. The study highlighted the growing importance of renewable energy integration in modern power systems to improve energy efficiency, reliability, economic performance, and environmental sustainability. Different metaheuristic techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), Ant Colony Optimization (ACO), Whale Optimization Algorithm (WOA), Firefly Algorithm (FA), and Hybrid Optimization approaches were critically reviewed for solving complex nonlinear optimization problems associated with microgrid planning.

The review identified that optimal sizing and placement significantly influence power loss reduction, voltage profile improvement, operational cost minimization, reduction in greenhouse gas emissions, and enhancement of system stability. Among the reviewed techniques, hybrid and adaptive metaheuristic algorithms demonstrated better convergence characteristics, faster computational performance, and improved global search capability compared to conventional optimization methods. Furthermore, the integration of BESS with Solar PV was found to effectively mitigate intermittency issues, enhance energy management, and improve the reliability of standalone and grid-connected microgrids.

The paper also discussed various objective functions and constraints considered by researchers, including economic cost, reliability indices, emission reduction, state of charge constraints, power balance, and network operational limits. It was observed that the effectiveness of optimization techniques depends on system configuration, load uncertainty, renewable generation variability, and algorithm parameter selection.

Finally, the review concludes that metaheuristic-based optimization methods provide robust and flexible solutions for optimal PV-BESS planning in microgrids. However, future research should focus on real-time optimization, uncertainty modeling, artificial intelligence-assisted hybrid algorithms, multi-objective energy management, cyber-secure smart microgrids, and integration of electric vehicles and demand response programs to achieve more intelligent, sustainable, and resilient energy systems.

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