Optimization of Power Stability Index and its Application in Load Shedding

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ABSTRACT

This paper presents a load shedding method to optimize the Power Stability Index (PSI), with the objective of enhancing the stability of microgrid power systems. In instances where the system encounters demand that exceeds its operational capacity, the loads in the power network are selectively curtailed to ensure that this index remains within acceptable limits. This approach ensures power balance, frequency stability, and a more efficient load-shedding process. To address this issue, the paper proposes a comprehensive PSI optimization method, where PSI is used not only as an evaluation metric but also as a key optimization variable to improve decision-making effectiveness. The Particle Swarm Optimization (PSO) algorithm is employed to determine the optimal load-shedding power that would satisfy operational constraints. This method leverages PSI to enhance the accuracy of load-shedding decisions and improve the adaptability and stability of the microgrid system under fluctuating load conditions. The effectiveness of the proposed method is validated on the IEEE 16-bus microgrid test system, thereby demonstrating its feasibility and efficiency.

Keywords-load shedding optimization; Power Stability Index (PSI); power system stability; power balance constraints; Particle Swarm Optimization (PSO)

I. INTRODUCTION

Microgrids have emerged as an optimal solution for electricity supply in remote areas, regions disconnected from the national grid, or areas requiring independent operation in emergency situations [1]. However, the stability of these systems can be severely compromised in the event of a fault, particularly during a voltage collapse [2]. Voltage collapse is a hazardous phenomenon that can lead to severe disruptions in power supply, even causing widespread blackouts. This phenomenon may occur due to factors such as generator loss [3], equipment failure [4], or sudden large load additions to the system [5]. When the load demand exceeds the power generation capacity, an imbalance between load power and supply power occurs, causing the voltage to drop below the acceptable levels, ultimately leading to a voltage collapse [6].

Recent studies have demonstrated the effectiveness of optimization algorithms such as the Genetic Algorithm (GA) [7], the Teaching Learning Based Optimization (TLBO) algorithm [8], and the Analytic Hierarchy Process (AHP) [9] in conjunction with stability indices such as the Voltage Stability Index (VSI) [10] for optimizing load shedding strategies. However, previous research [11] has only indirectly addressed load shedding through general system stability enhancement during faults or overload conditions.

The study by authors in [12] focuses on voltage stability in power systems integrating Squirrel Cage Induction Generator (SCIG) wind turbines. The authors utilized the minimization of the Fast Voltage Stability Index (FVSI) combined with Flexible AC Transmission Systems (FACTS) devices, such as STATCOM and SSSC, to maintain voltage stability and prevent collapse without requiring load shedding. Conversely, authors in [13] present an optimized load shedding method to prevent voltage collapse using the GA. This approach identifies critical load nodes and equipment to be shed to reduce power consumption below critical thresholds while minimizing shedding costs. However, GA has drawbacks, including long computation times and susceptibility to local optima. Recent studies have focused on developing optimization techniques to determine optimal load shedding strategies that minimize adverse system impacts. Among these, optimization using the PSI has gained significant attention. PSI assesses the impact of each load on system stability, providing a rational basis for determining shedding strategies [14]. Although several studies have employed PSI as a tool for evaluating load importance, they have not emphasized optimizing this index to enhance system performance [15, 16]. As a result, load shedding decisions have not reached optimal efficiency, as PSI has been used solely as a metric rather than an optimization parameter [17, 18].

To address this issue, this paper proposes a PSI-based optimization method where PSI is not only used for evaluation, but also serves as a component of the objective function and the main optimization variable to improve the efficiency of load shedding decision making. The PSO algorithm is applied to calculate the amount of shedding power such that the sum of the minimum PSI indices simultaneously satisfies the constraints. Unlike previous studies that only use PSI for load ranking, this approach utilizes the minimum PSI to refine load shedding decisions, thereby improving system adaptability and microgrid stability under load variations. The effectiveness of the proposed method is validated using an IEEE 16-bus microgrid test system.

II. METHODOLOGY

A. Power Stability Index and Mathematical Basis

PSI is a key metric for evaluating the stability of a power system based on the relationship between load power, curtailed power, and voltage parameters. To assess the voltage stability of all load buses, the PSI is examined in this study. A 2-bus system, as illustrated in Figure 1, is analyzed. The system is evaluated under two scenarios: with and without load shedding in the microgrid network.

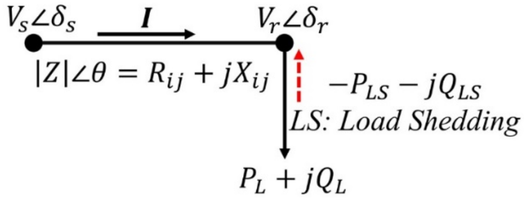

Fig. 1. Schematic of the 2-bus power grid and the impact of load shedding on PSI.

The relevant equations are as follows:

$$S_L = P_L + jQ_L = V_L I_L^* \tag{1}$$

$$\overline{V_L} = \overline{V_S} - \overline{I_L Z} \tag{2}$$

where: $$I_L = \frac{P_L - jQ_L}{V_L^*} \tag{3}$$

If the power grid undergoes a load shedding process, (3) is rewritten as follows:

$$I_L = \frac{(P_L - P_{shed}) - j(Q_L - Q_{shed})}{V_L^*} \tag{4}$$

Substituting I_L from (4) into (2):

$$\overline{V_L} = \overline{V_S} - \overline{\frac{\left[(P_L - P_{shed}) - j(Q_L - Q_{shed})\right].Z}{V_L^*}} \tag{5}$$

where P_{shed} is the curtailed power at customer load locations at bus *j*, *i* represents the sending bus, and *j* represents the receiving bus. R_{ij} is the resistance of the transmission line connecting buses *i* and *j*. P_L is the power consumption at bus *j*.

$$P_L - P_{shed} = \frac{|V_L||V_S|}{Z}\cos(\theta - \delta_S + \delta_L) - \frac{|V_L|^2}{Z}\cos(\theta) \tag{6}$$

$$Q_L - Q_{shed} = \frac{|V_L||V_S|}{Z}\sin(\theta - \delta_S + \delta_L) - \frac{|V_L|^2}{Z}\sin(\theta) \tag{7}$$

From (6):

$$|V_L|^2 - \frac{|V_L||V_S|\cos(\theta - \delta)}{\cos(\theta)} + \frac{Z(P_L - P_{shed})}{\cos(\theta)} = 0 \tag{8}$$

where $\delta = \delta_S - \delta_L$ is the phase angle difference between buses i and j, θ is the argument angle of the line impedance Z_{ij}, and V_L is the bus voltage and must be a real value. The discriminant (Δ) of the quadratic (8) is presented in (9).

$$\Delta = \left[\frac{V_S \cos(\theta - \delta)}{\cos(\theta)}\right]^2 - \frac{4Z(P_L - P_{shed})}{\cos(\theta)} \tag{9}$$

For (8) to have a valid solution for V_L, the condition $\Delta \geq 0$ must be satisfied, as expressed in (9).

$$\left[V_S \cos(\theta - \delta)\right]^2 - 4Z(P_L - P_{shed})\cos(\theta) \geq 0 \tag{10}$$

$$\text{where: } Z = \frac{R_{ij}}{\cos(\theta)} \tag{11}$$

In a microgrid network, due to the relatively low voltage levels and the characteristics of distribution networks, the R/X ratio is relatively high. As a result, the reactance X_{ij} can be neglected.

$$\left[V_S \cos(\theta - \delta)\right]^2 - \frac{4R_{ij}(P_L - P_{shed})\cos(\theta)}{\cos(\theta)} \geq 0 \tag{12}$$

$$\left[V_S \cos(\theta - \delta)\right]^2 - 4R_{ij}(P_L - P_{shed}) \geq 0 \tag{13}$$

$$4R_{ij}(P_L - P_{shed}) \leq \left[V_S \operatorname{Cos}(\theta - \delta)\right]^2 \tag{14}$$

$$PSI = \frac{4R_{ij}(P_L - P_{shed})}{\left[|V_S| \cos(\theta - \delta)\right]^2} \leq 1 \tag{15}$$

From (15), it can be observed that as the value of P_{shed} increases, PSI approaches zero (ideally, when $P_{shed} = P_L$, indicating a more stable system). In other words, the closer the PSI value of a bus is to zero, the more stable the bus becomes. It should be noted that in the PSI calculation formula, P_{shed} may include the curtailed power from customer loads or the curtailed power from Distributed Generation (DG), if present, at bus j [19, 20].

B. *Objective Function for Minimizing Power Stability Index*

The objective function for minimizing the total PSI is presented in (16).

$$H = \sum_{i=1}^{n} \sum_{j}^{n} PSI_j = \frac{4R_{ij}(P_{Lj} - P_{shed,j})}{\left[|V_i| \cos(\theta - \delta)\right]^2} \tag{16}$$

The calculation of PSI weighting is intended to indicate the relative stability of load buses. As the system operates at a high PSI, the probability of instability escalates due to large power transmission flows and significant voltage fluctuations. These phenomena may result in generator desynchronization. Conversely, when PSI has a low value, the system exhibits enhanced stability, with power and voltage fluctuations remaining within safe limits. Accordingly, this study evaluates the stability levels of buses and determines the amount of load shedding at each bus to minimize the total PSI. The closer P_{shed_j} approaches P_{Lj}, the closer PSI gets to zero. The variable is designated P_{shed_Lj} and each P_{shed_Lj} is constrained within the range $P_{load\_\min} < P_{shed\_Lj} < P_{load}$.

A crucial objective in load shedding control is to minimize PSI by adjusting P_{shed} to achieve a reasonable load reduction while ensuring stable system operation. This approach helps limit power fluctuations, prevent voltage collapses, and maintain a balance between power supply and consumption. Intelligent algorithms are employed to determine the optimal P_{shed_Lj} at each load bus, ensuring PSI minimization while satisfying the constraint conditions.

C. *Constraints in the Optimization Problem*

The optimization of the load-shedding strategy must comply with both technical and economic constraints to ensure the safe and efficient operation of the system. These constraints are defined in (17), (18), and (19).

$$0 < P_{shed,j} < P_{load,j} \tag{17}$$

$$V_{\min} \leq V_i \leq V_{\max} \tag{18}$$

$$\sum P_{gen} = \sum P_{load} - \sum P_{shed} + \sum P_{loss} \tag{19}$$

III. SYSTEM TESTING AND RESULTS

In this paper, the IEEE 16-bus microgrid system is applied to evaluate the PSI index and optimize load shedding to minimize the PSI. The system diagram is presented in Figure 2.

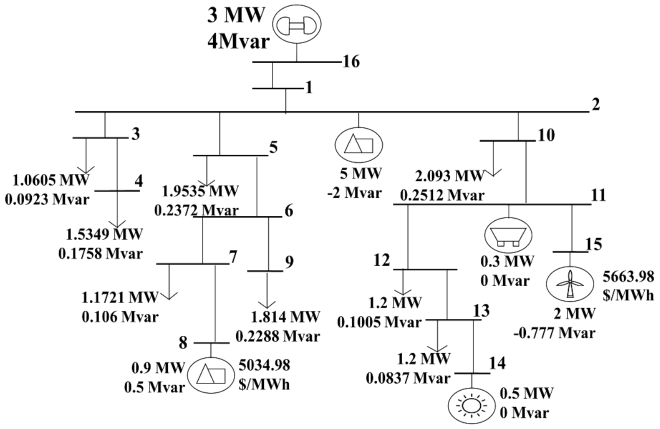

Fig. 2. IEEE 16-bus power grid system diagram.

A. *Input Parameters and Calculation Conditions*

The present study assumes that the IEEE 16-bus system has a time-varying load profile, as illustrated in Figure 3. The total load at each time interval is presented in Table I. Meanwhile, the system's generation capacity remains constant at 11.98 MW throughout the designated operation period. The load is distributed across the buses in the IEEE 16-bus system, with the rated values presented in Table II.

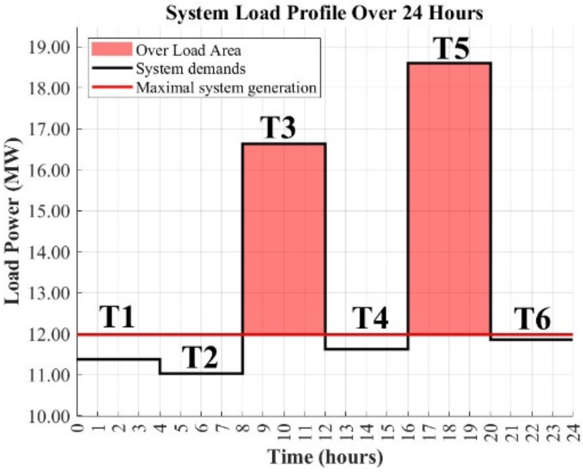

Fig. 3. IEEE 16-bus power grid system load profile of the IEEE 1-bus grid over 24 hours.

TABLE I. LOAD POWER OVER TIME

Time	t_1	t_2	t_3	t_4	t_5	t_6
Total load (MW)	11.38	11.02	16.63	11.62	18.59	11.86
Load level (%)	95	92	138	97	155	99

TABLE II. RATED LOAD VALUES AT EACH BUS

	Bus							
	3	4	5	7	9	10	12	13
Load (MW)	1.06	1.53	1.95	1.17	1.81	2.09	1.20	1.17
P_{shed_min} (%)	20	30	20	40	20	20	20	20
P_{shed_max} (%)	80	70	80	60	80	80	80	80

In scenarios where the aggregate power demand surpasses the generation capacity, the system may experience a power imbalance, increasing the risk of voltage collapse and frequency instability. This necessitates the implementation of load shedding to maintain frequency stability. The load reduction process is executed based on the PSI index, ensuring system stability improvement while preventing disruptions to critical loads (base loads).

The objective function, which is formulated in (16), is employed to address the load shedding optimization problem. The PSO algorithm is employed in this study to solve the PSI optimization problem. This method assists in determining the appropriate amount of load to shed, thereby ensuring the system's operational continuity during periods of peak demand or contingency events. The optimal load shedding strategy is designed to maintain system stability while meeting technical constraints.

B. Application of the Optimization Algorithm

PSO is a swarm intelligence-based algorithm that simulates the movement of particles in a search space to identify the optimal solution. Compared to traditional optimization methods, PSO offers several advantages, including fast convergence, reduced computational time, and the capacity for derivative-free optimization. These attributes render PSO well-suited for nonlinear problems, such as load shedding optimization, global optimization, and the avoidance of local minima traps. The operational process of the PSO algorithm is as follows.

```
##PSO algorithm operational process
Begin
Declare important parameters of PSO
    ($f$, $N$, $w$, $c1$, $c2$, $max\_iter$)
Initialization: Generate $N$ particles
    with random positions $x_i$ and velocities
    $v_i$
Evaluate the objective function $f(x_i)$
    for all particles
Set the individual best value $pbest_i$ =
    $x_i$ and the global best value $gbest$ =
    arg min $f(x_i)$
For each particle $i$, perform
    regression
Update the velocity $v_i$ and position $x_i$
Check if the condition for optimal $p_i$
    is satisfied
Check the stopping criterion to end
    the loop
Return the global best solution $gbest$
End
```

In each iteration, the PSO updates the velocity and position of each particle using the following equations:

$$v_i(t+1) = w \cdot v_i(t) + c_1 \cdot r_1 \cdot (pbest_i - x_i(t)) + c_2 \cdot r_2 \cdot (gbest - x_i(t)) \quad (20)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (21)$$

Following each update, the efficacy of the new solutions is evaluated based on the PSI index. The optimal load shedding scheme is selected as the one that minimizes PSI while satisfying system constraints. The termination of the algorithm occurs either when an optimal solution is found or after a predetermined number of iterations.

The optimal load shedding values are then applied to the system to assess the effectiveness of the optimization process. The PSI index is examined before and after load shedding to evaluate improvements in system stability. Furthermore, the minimum necessary load reduction is determined to avoid disruptions to critical loads. Voltage levels at buses and power flow through branches are also monitored to ensure that system constraints are not violated.

C. Results

The simulation was conducted on the IEEE 16-bus system, encompassing diverse test scenarios, to examine the impact of varying loads and load shedding on the PSI index. The PSI values both before and after the implementation of load shedding at the buses are shown in Table III. The convergence process of the PSO algorithm for the overloading periods is illustrated in Figures 4 and 5.

TABLE III. PSI SIMULATION RESULTS BEFORE AND AFTER OPTIMIZATION USING PSO

Bus *i*	**Bus *j***	**PSI (before)**	**PSI (after)**
2	3	0.042	0.036
3	4	0.107	0.030
2	5	0.048	0.041
6	7	0.009	0.006
6	9	0.036	0.031
2	10	0.082	0.070
11	12	0.009	0.008
12	13	0.055	0.020

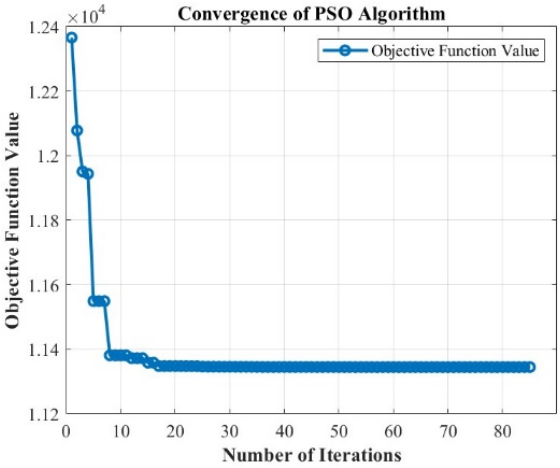

Fig. 4. Convergence process of the PSO algorithm during the 8 AM to 12 PM period.

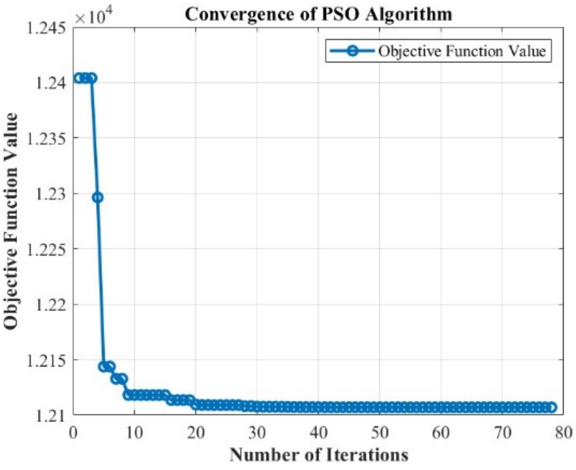

Fig. 5. Convergence process of the PSO algorithm during the 4 PM to 8 PM period.

After the application of PSO, the load shedding at each bus was optimized to ensure PSI stability. The optimal load shedding allocation for each bus is presented in Table IV.

To verify the effectiveness of the load shedding method, a simulation was conducted using PowerWorld version 22 GSO, considering two overload periods: 8 AM to 12 PM and 4 PM to 8 PM. In each time frame, a comparison of voltage and frequency parameters before and after load shedding was performed. The shedding time was 0.3 s after the load was increased.

TABLE IV. OPTIMAL LOAD SHEDDING ALLOCATION AT PEAK HOURS (8 AM TO 12 PM) AND (4 PM TO 8 PM) USING THE PSO ALGORITHM

Bus	Load shedding (kW) 8 AM - 12 PM	Load shedding (kW) 4 PM - 8 PM
3	850	850
4	1070	1070
5	120	1560
7	0.00	0.00
9	0.00	520
10	1670	1670
12	0.00	0.00
13	940	940
Total	4650	6610

The observed values indicate that both frequency and voltage levels exhibited significant improvement after the load shedding process compared to before implementation. Figures 6 and 7 show the voltage recovery at the buses after load shedding. Bus 3 and bus 13 have the highest recovery ratio due to the highest shedding ratio. In addition, the frequency value in Figure 8 shows that it also recovers to its rated value after load shedding.

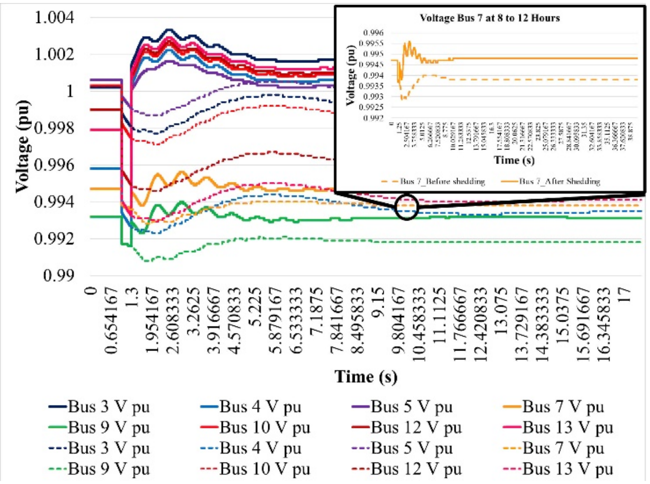

Fig. 6. Voltage at buses before and after load shedding (8 AM to 12 PM).

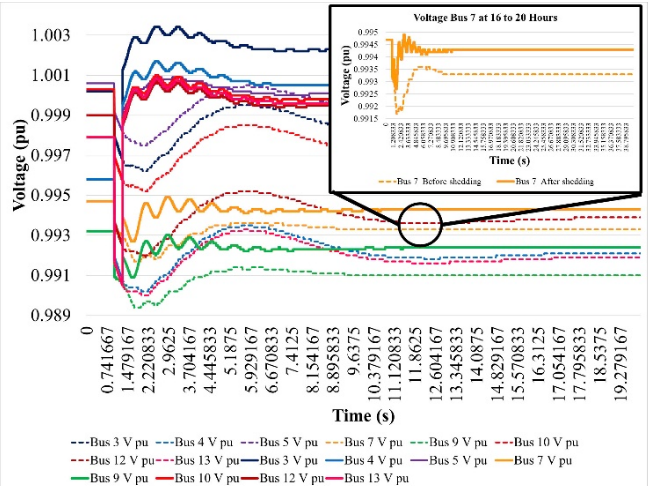

Fig. 7. Voltage at buses before and after load shedding (4 PM to 8 PM).

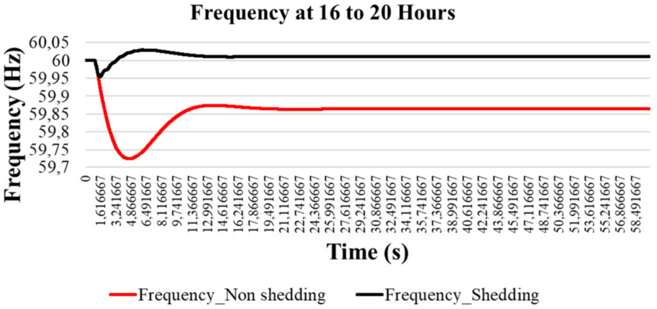

Fig. 8. Frequency values at bus 10 before and after load shedding.

Figure 9 demonstrates that the voltage stability characteristics at the load of bus 3 are enhanced following the implementation of load shedding.

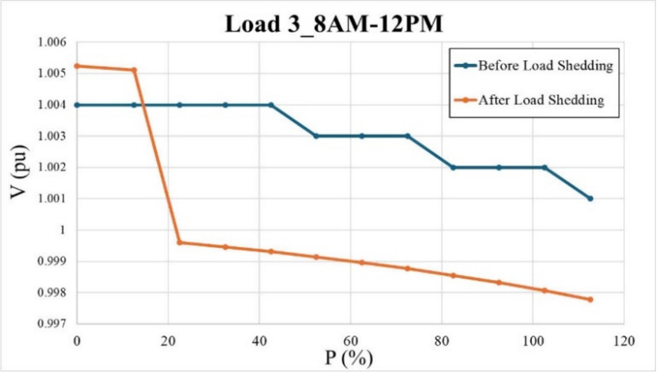

Fig. 9. Comparison of voltage stability characteristics at load 3 before and after load shedding.

IV. CONCLUSION

This research proposed a methodology for calculating the PSI index during the execution of load shedding activities and for optimizing this index using the PSO algorithm. In this study, the PSO algorithm is employed to calculate the optimal load shedding capacity at the load buses. This is achieved by minimizing the sum of the PSI indexes is minimal while satisfying the constraints. This contributes to enhancing the stability of the grid. In contrast to previous studies and similar works that employed PSI exclusively for evaluation and ranking of loads, this method utilizes the minimum PSI as a component of the objective function and the main optimization variable. This approach facilitates the refinement of load shedding decisions, thereby enhancing the adaptability and stability of the microgrid in the event of a change in the steady-state load. The results of the simulation on the IEEE 16-bus system demonstrate the effective optimization of the objective function which has been shown to reduce PSI and enhance system stability during periods of overload. This study contributes to improving the operational efficiency of microgrid power systems, especially in the context of increasing renewable energy integration and increasingly complex electricity demand. The algorithm exhibits fast convergence and high efficiency in solving optimization problems with constraints. Despite the demonstrated efficacy of PSO, its application is constrained by certain limitations. Therefore, future research can concentrate on integrating PSO with advanced algorithms such as hybrid PSO-GA or deep reinforcement learning.

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