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Optimizing Capacitor Placement in Distribution Systems Under Variable Loading Conditions with Golden Jack Optimization (GJO)

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ABSTRACT- In modern society, the demand for electricity is ever-growing, making the minimization of power losses in distribution systems paramount. One significant aspect contributing to these losses is the strategic placement of capacitors within the distribution network. Efficient capacitor placement not only reduces power losses but also enhances the overall performance and reliability of the system. In today's world, where electricity is indispensable, minimizing power losses in the distribution system holds significant importance. This research introduces the Golden Jack Optimization (GJO) algorithm as a novel approach to address the challenge of capacitor placement in distribution systems. GJO, inspired by the foraging behavior of jackals, exhibits unique characteristics such as adaptability and efficiency in finding optimal solutions this paper proposes an innovative algorithm specifically designed for this purpose. To validate the effectiveness of the algorithm, extensive testing and experimentation have been conducted on the IEEE 69-bus system. This study aims to provide a practical and efficient solution to the challenge of power loss reduction within distribution systems. By harnessing the power of GJO and the insights gained from testing on the IEEE 69-bus system, we contribute to the ongoing efforts to enhance the efficiency and sustainability of electricity distribution networks. The results are compared with MPSO, TSM, GA-Fuzzy algorithms and proposed algorithm shows superior performance.

Keywords: Capacitor Bank, Distribution System, Golden Jack Optimization, Loss Reduction.

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1. INTRODUCTION

The distribution system itself comprises feeders, distributors, and service mains. Feeders, being the conductors linked to substations, supply power to specific areas without consumer tap-offs. As a result, current flow through feeders remains relatively constant. Distributors, on the other hand, offer numerous tap-off points to provide power to consumers, causing current levels to fluctuate. Distributor lines are designed to manage these variations while maintaining acceptable voltage levels. Service mains, serving as conductors, connect consumers' terminals to the distributors.

In the distribution of power to consumers, fluctuations and losses naturally occur. To mitigate these issues, capacitors are strategically placed near inductive loads to reduce reactive power. Additionally, switching capacitors are employed, allowing for real-time adjustments to maintain the desired power factor. This paper specifically addresses the placement of capacitors in radial distribution systems. The incorporation of capacitors enhances voltage regulation and contributes to loss reduction within distribution lines.

This literature survey examines several optimization techniques and algorithms employed for optimal capacitor placement in radial distribution systems to reduce energy losses. The comparison of these methods highlights the efficacy of each approach.

In this paper [1], the authors introduced the Teaching-Learning-Based Optimization (TLBO) algorithm, focusing on the optimal sizing and placement of capacitors in radial distribution systems for loss reduction. The study evaluated TLBO against Particle Swarm Optimization (PSO), and Genetic Algorithm (GA). TLBO outperformed PSO and GA, particularly on standard buses like 69, 85, and 141. This paper [2], introduced the Shark Smell Optimization (SSO) algorithm to address energy losses through capacitor placement in distribution systems. The evaluation of this algorithm was conducted on the IEEE 34-bus and 118-bus systems, producing results at different energy loss levels (Low, Medium, and High). Notably, SSO exhibited high robustness, provided optimal solutions compared to other methods, and displayed rapid convergence. In this study [3], the authors introduced the Sperm Whale Algorithm (SWA) and compared its performance with PSO in the context of optimal capacitor placement in Medium Voltage (MV) distribution systems. Both SWA and PSO were evaluated with a population size of 40 and 250 iterations. SWA demonstrated a reduction in losses by 6.281%, outperforming PSO in the MV distribution system. In this study [4], presented a Particle Swarm Optimization (PSO) technique for loss reduction through the strategic placement of capacitors in distribution systems. The study employed a 33-bus system for testing and compared the results with heuristic methods and fuzzy systems. PSO demonstrated superior accuracy, high robustness, and faster convergence compared to traditional techniques. This literature survey provides an overview of various optimization techniques and algorithms used to enhance the efficiency of capacitor placement in distribution systems, ultimately reducing energy losses. Each approach offers unique advantages and performance characteristics, which are essential for making informed choices in practical applications.

In the existing literature, a notable gap is the limited consideration of the distribution system's loading conditions when optimizing capacitor placement. Many previous algorithms, such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), primarily focus on reactive power management and loss reduction but do not account for the dynamic loading scenarios in distribution systems. One significant contribution of this paper is the integration of loading conditions into the optimization process, which has been lacking in prior studies. By considering 100%, 80%, and 120% loading scenarios, as well as the ability to adapt to unforeseen changes in load, the proposed algorithm, Golden Jack Optimization (GJO), addresses this crucial gap. This allows for more effective and adaptive capacitor placement strategies that enhance the system's stability and performance.
Another gap observed in existing algorithms is their varying levels of robustness and convergence speed. For instance, while some algorithms may provide accurate results, they may lack the robustness to handle diverse distribution system scenarios or may converge slowly, delaying the optimization process. Golden Jack Optimization (GJO) offers a solution to this gap with its demonstrated attributes of high robustness and fast convergence speed.

Pseudo for GJO:

```
Initialize population of solutions
while (termination criteria not met):
Evaluate fitness of each solution
Update population based on exploration and exploitation
return best solution
```

GJO's adaptability to different distribution system conditions, coupled with its efficient convergence, makes it a valuable tool for optimizing capacitor placement, even in complex and dynamic environments [5]. In summary, the gaps identified in existing algorithms, particularly the absence of loading consideration and varying levels of robustness and convergence speed, are effectively addressed by the proposed Golden Jack Optimization (GJO). This paper not only highlights these gaps but also provides practical solutions that advance the field of optimal capacitor placement and loss reduction in distribution systems. The paper organized as follows section II objective function, section III proposed algorithm, section IV results & discussion, section VI conclusion.

2. MATERIALS AND METHODS

This objective function aims to minimize the total power losses P_{loss} in the distribution system by strategically sizing and placing capacitors at various locations, while ensuring that the voltage remains within acceptable limits and reactive power is controlled effectively. The loading condition constraint should be tailored to your specific system and loading scenarios.

P_{loss} = Total power losses in the distribution system.
C_i = Capacitor size (in KVAR) at location i.
Q_i = Reactive power (in KVAR) supplied by the capacitor at location i.
V_i = Voltage at location i.
V_{ref} = Reference voltage level (typically 1.0 p.u., representing the nominal voltage)

The objective function to minimize power losses while optimizing capacitor placement can be expressed as:

$$Minimize\ P_{loss} = \sum_{i=1}^{n} P_{loss\ i} \tag{1}$$

Subject to the following constraints

1. Voltage constraint

$$V_i \geq V_{ref} for\ all\ i \tag{2}$$

2. Reactive power constraint

$$Q_i = C_i.\left(V_i - V_{ref}\right) for\ all\ i \tag{3}$$

The Capacitor is placed on radial distribution system to reduce losses. However, when the capacitor is placed its installation cost will be high. So, the capacitors should increase the profit by reducing losses in distribution system. Power loss is inversely proportional to the voltage. If voltage increases power loss will be reduced but the voltage must not be increased in order to maintain stability in distribution line. So, to reduce power loss the capacitor is placed on distribution line.

Without capacitor in radial distribution the actual power loss between n&n+1 is:

$$P_{loss}(n, n+1) = \frac{(P_{n+1}^2 + Q_{n+1}^2)}{|V_{n+1}|^2} * R_n \tag{4}$$

$$Q_{loss}(n, n+1) = \frac{(P_{n+1}^2 + Q_{n+1}^2)}{|V_{n+1}|^2} * X_n \tag{5}$$

After Capacitor Placement The power loss is;

$$P^{C}_{loss(n,n+1)} = \frac{(P^2_{n+1}+Q^2_{injected})}{|V_{n+1}|^2} * R_n \quad (6)$$

$$P^{C}_{loss(n,n+1)} = \frac{((P_{n+1})^2+(Q_{n+1}-Q_C)^2)}{|V_{n+1}|^2} * R_n \quad (7)$$

$$P^{c}_{loss(n,n+1)} = R_n \frac{(P^2_{n+1}+Q^2_{n+1})}{|V_{n+1}|^2} + \frac{Q^2_C-2Q_{n+1}Q_C}{|V_{n+1}|^2} * R_n \quad (8)$$

The actual difference in power loss after and before capacitor placement on distribution system is given by.

$$\Delta P^{C}_{loss} = \frac{Q^2_C-2Q_{n+1}Q_C}{|V_{n+1}|^2} * R_n \quad (9)$$

3. RESULTS

Golden Jack Optimization (GJO) is a nature-inspired optimization algorithm that has gained prominence in recent years for solving complex optimization problems. Inspired by the foraging behaviour of golden jackals, GJO mimics the search and adaptability strategies of these animals in its quest for optimal solutions. It has shown promise in various application areas, including engineering, economics, and logistics, making it a valuable tool for tackling real-world optimization challenges [6]-[7].

Initialization: GJO starts with the creation of an initial population of candidate solutions, often referred to as "jackals." These jackals represent potential solutions to the optimization problem.

Objective Function Evaluation: The algorithm evaluates the fitness of each jackal by applying the objective function of the optimization problem. The objective function quantifies how well a solution performs based on certain criteria.

$$f(x) = objective\ function\ (x) \quad (10)$$

$$Min\ f(x) = \sum_{i=1}^{n} P_{loss\ i} \quad (11)$$

Where x represents decision variables (i.e., capacitor size and placement)

Selection: Jackals with higher fitness values are more likely to be selected to form the next generation of solutions. This selection process simulates the survival and reproduction of fitter jackals, mirroring the principles of natural selection.
Exploration and Exploitation: GJO incorporates a balance between exploration and exploitation. Exploration involves exploring new areas of the solution space, while exploitation involves refining solutions around promising regions. This balance is crucial for avoiding local optima and converging to a global optimum.

ER=Exploration Rate
IR=Exploitation Rate
These rates can be adjusted dynamically during the optimization process.

Adaptation: One of GJO's notable features is its adaptability. It can dynamically adjust its search parameters, such as the exploration rate and exploitation rate, to suit the specific problem being solved. This adaptability allows GJO to respond to changing conditions during optimization.

Iteration: The process of selection, exploration, and exploitation iterates over a predefined number of generations or until a convergence criterion is met. Each iteration aims to improve the quality of the solutions.

Update Equations: To create the next generation of solutions (jackals), GJO uses update equations based on the selected jackals. These equations guide how new solutions are generated and refined.

The position of a new jackal (Xj) can be updated as follows

$$x_j = x_i + \propto (x_i - x_k) \quad (12)$$

4. RESULTS AND DISCUSSION

In this study, the effectiveness of the Golden Jack Optimization (GJO) algorithm was rigorously evaluated by subjecting it to the IEEE 69-bus system, a real-world distribution system. The primary objective was to assess GJO's ability to optimize capacitor placement and minimize power losses under varying loading conditions. The distribution system was examined across three distinct scenarios: normal loading (100%), under loading (80%), and overloading (120%).
Scenario 1: Normal Loading (100%)

Under the normal loading scenario, the IEEE 69-bus system operated at its intended capacity. GJO was applied to strategically place capacitors within the network while minimizing power losses. The results revealed that GJO effectively reduced power losses, enhancing the system's overall efficiency. This signifies that GJO is a powerful tool for optimizing distribution systems under standard operating conditions.

Table 1: System Simulation Parameters

S. No.	Parameter	Value
1	Number of capacitors	3
2	No. of iterations	200
3	Adaptive parameter tuning rate	0.1
4	Initial reactive power injection values	2100
5	Population size	50
6	Number of variables	3
7	Inertia weight	0.729
8	Cognitive learning coefficient (c1)	1.494
9	Social learning coefficient (c2)	1.494
10	Velocity clamping factor (R)	10

Figure 2 illustrates the convergence behavior of the Golden Jack Optimization (GJO) algorithm over the course of the optimization process. As the algorithm progresses, it converges towards an optimal solution, leading to a reduction in power losses. This figure provides insights into the convergence behavior of GJO, when the RDS experiences normal loading conditions (100%).

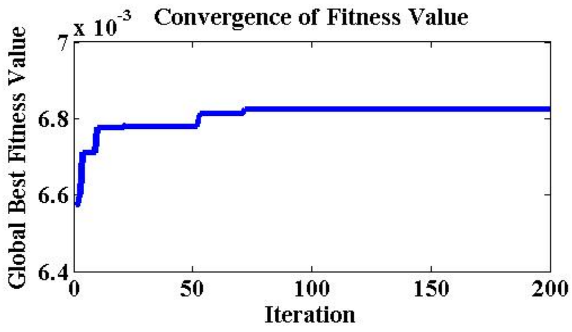

Figure 2: convergence of GJO Algorithm

Figure 3 depicts the voltage profile of the distribution system before and after applying GJO. The x-axis corresponds to bus numbers, while the y-axis represents the voltage magnitude in per unit (p.u.). The blue line represents the without capacitors in RDS voltage profile, while the red line represents the with capacitors in RDS voltage profile after GJO optimization. This figure showcases how GJO enhances the voltage profile of the distribution system, ensuring that voltage levels remain within acceptable limits.

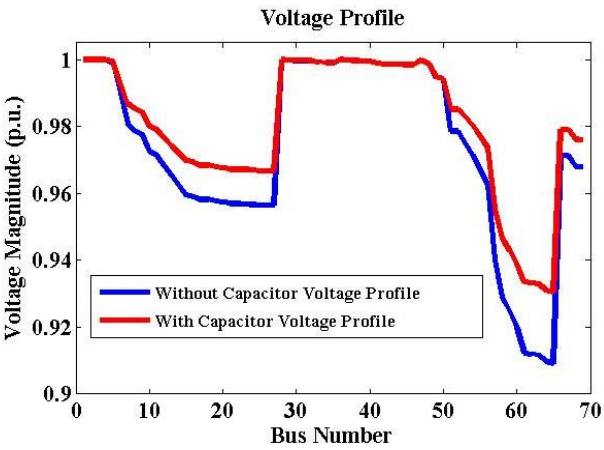

Figure 3: Voltage profile of distribution system under normal loading

Figure 4 highlights the impact of GJO optimization on power loss reduction in the distribution system under normal loading conditions (100%). The figure demonstrates the significant reduction in power losses achieved by GJO, leading to an optimized and more efficient distribution system.

Scenario 2: Under Loading (80%):

In the under-loading scenario, the distribution system was subjected to a reduced load, operating at 80% of its full capacity. GJO was once again employed to optimize capacitor placement. Notably, GJO demonstrated its adaptability by tailoring its solutions to the decreased load. The algorithm effectively reduced power losses in this situation, showcasing its ability to handle dynamic and changing operating conditions.

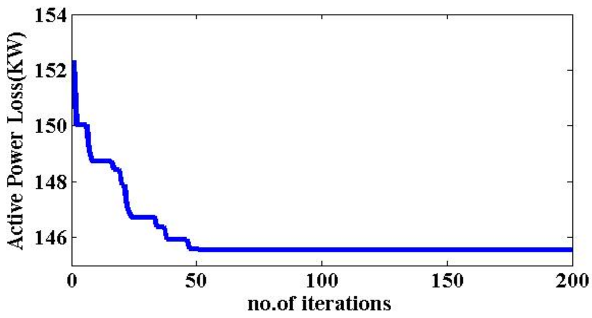

Figure 4: Active power loss of distribution system under normal loading

Figure 5 illustrates the convergence behavior of the Golden Jack Optimization (GJO) algorithm over the course of the optimization process. As the algorithm progresses, it converges towards an optimal solution, leading to a reduction in power losses. This figure provides insights into the convergence behavior of GJO, when the RDS experiences under-loading conditions (80%). Figure 6 depicts the voltage profile of the distribution system before and after applying GJO. The x-axis corresponds to bus numbers, while the y-axis represents the voltage magnitude in per unit (p.u.). The blue line represents the without capacitors in RDS voltage profile, while the red line represents the with capacitors in RDS voltage profile after GJO optimization. This figure showcases how GJO enhances the voltage profile of the distribution system, ensuring that voltage levels remain within acceptable limits.

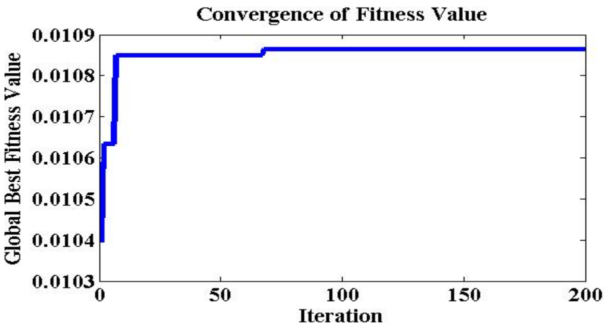

Figure 5: convergence of GJO Algorithm

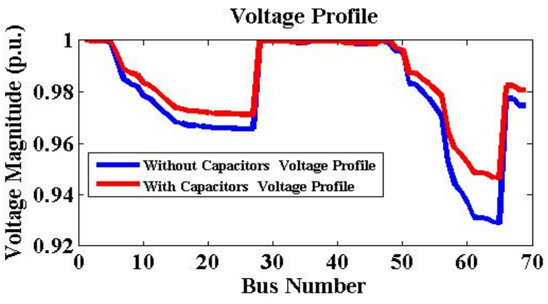

Figure 6: Voltage profile of distribution system experiences under-loading

Figure 7 highlights the impact of GJO optimization on power loss reduction in the distribution system experiences under-loading conditions (80%). The figure demonstrates the significant reduction in power losses achieved by GJO, leading to an optimized and more efficient distribution system.

Scenario 3: Over Loading (120%)
The overloading scenario presented a challenging condition, with the system operating at 120% of its intended capacity. GJO was tested to mitigate the power losses and restore system stability. Even in this demanding scenario, GJO proved its robustness and capacity to find optimal solutions. By strategically placing capacitors, GJO minimized power losses and averted potential overloading issues, ensuring the safe and efficient operation of the distribution system.

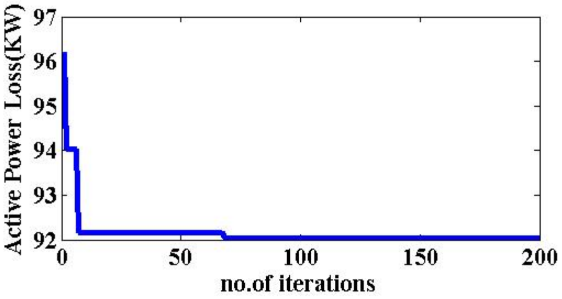

Figure 7: Active power loss of distribution system experiences under-loading.

Figure 8 illustrates the convergence behavior of the Golden Jack Optimization (GJO) algorithm over the course of the optimization process. As the algorithm progresses, it converges towards an optimal solution, leading to a reduction in power losses. This figure provides insights into the convergence behavior of GJO when the RDS experiences over-loading conditions (120%).

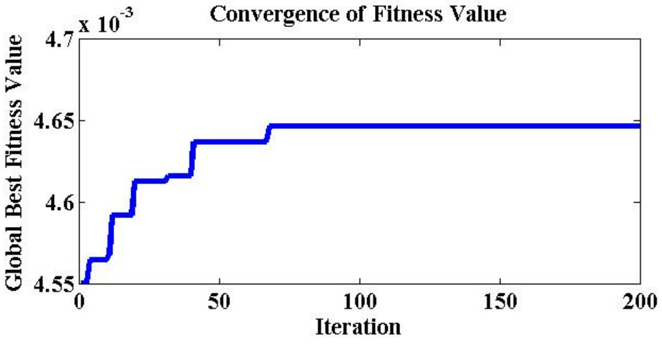

Figure 8: convergence of GJO Algorithm

Figure 9 depicts the voltage profile of the distribution system before and after applying GJO. The x-axis corresponds to bus numbers, while the y-axis represents the voltage magnitude in per unit (p.u.). The blue line represents the without capacitors in RDS voltage profile, while the red line represents the with capacitors in RDS voltage profile after GJO optimization. This figure showcases how GJO enhances the voltage profile of the distribution system, ensuring that voltage levels remain within acceptable limits. Figure 10 highlights the impact of GJO optimization on power loss reduction in the distribution system experiences over-loading conditions (120%). The figure demonstrates the significant reduction in power losses achieved by GJO, leading to an optimized and more efficient distribution system.

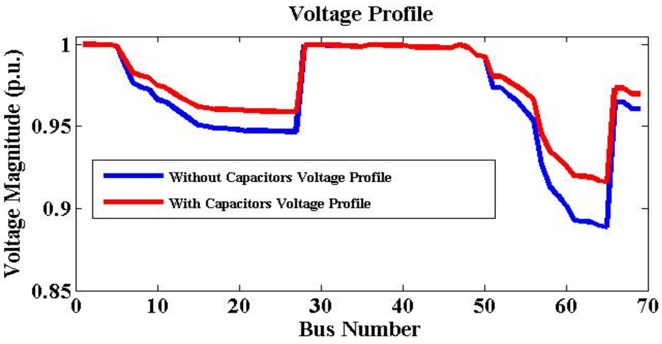

Figure 9: Voltage profile of distribution system experiences over loading

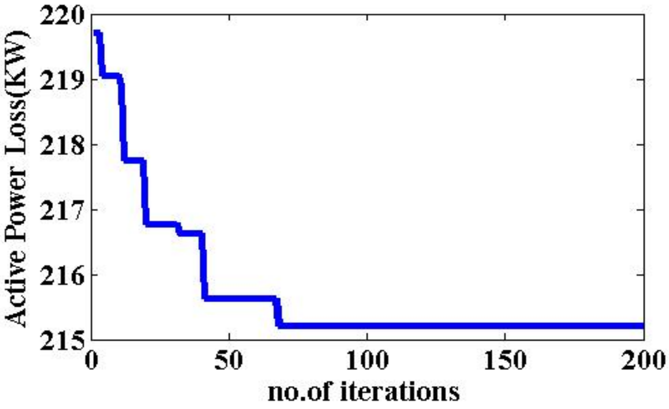

Figure 10: Active power loss of distribution system experiences over loading

The results of the comprehensive testing on the IEEE 69-bus system underscore the effectiveness of the Golden Jack Optimization (GJO) algorithm in optimizing capacitor placement for power loss reduction in distribution systems. Whether under normal loading conditions, during under-loading, or in the face of overloading, GJO consistently demonstrated its ability to adapt, find optimal solutions, and enhance system efficiency. The robust performance of GJO in these varied scenarios makes it a valuable tool for real-world applications in the field of distribution system optimization. Consequently, the use of GJO is recommended for distribution system operators and engineers aiming to minimize power losses and improve system performance under diverse operational conditions.

Table 2: Power Loss Comparison under Different Loading Conditions

S. No.	Parameter	Distribution system loading		
		80%	100%	120%
1	Initial Power Loss (KW)	138.8383	224.8949	336.5622
2	Power Loss after Capacitor Placement (KW)	92.0445	145.5748	215.2011
3	Capacitor Location	68, 61, 48	51, 18, 61	10, 20, 61
4	Capacitor Size	300, 1050, 750	600, 300, 1200	300, 300, 1500

Table 3: Comparison of Power Loss Reduction Methods

	Base case	MPSO [7]	TSM [6]	Fuzzy-GA [5]	GJO
Power Loss	224.8949	144.79	148.91	156.62	144.5748
Capacitor Locations	---	21, 61, 64	19, 62, 63	59, 61, 64	51, 18, 61
Capacitor Size	----	320, 1200, 230	225, 900, 225	100, 700, 800	600, 300, 1200
% Loss Reduction	----	35.61%	33.78%	30.35%	35.71%

In the pursuit of optimizing power distribution systems, the effectiveness of various methodologies in reducing power losses has been rigorously examined. The base case represents the initial power loss at a significant 224.8949 kW, prompting the exploration of alternative methods to enhance system efficiency. Among the optimized techniques, Golden Jack Optimization (GJO) and Particle Swarm Optimization (MPSO) emerge as frontrunners, showcasing remarkable prowess in power loss reduction. GJO, in particular, achieves a power loss of 144.5748 kW, marking a notable reduction of 35.71% when compared to the base case. MPSO also performs impressively, with a power loss of 144.79 kW and a reduction of 35.61%. These results underscore the efficacy of these methods in optimizing capacitor placement and minimizing power losses. Notably, the strategic selection of capacitor locations and sizes in GJO plays a pivotal role in its success. This analysis highlights the potential of GJO and MPSO as powerful tools for enhancing the efficiency of distribution systems and reducing power losses, ultimately making them valuable candidates for practical implementation in real-world scenarios.

5. CONCLUSION

In this study, conducted a comprehensive analysis of three prominent optimization algorithms: Fuzzy-Genetic Algorithm (Fuzzy-GA), Modified Particle Swarm Optimization (MPSO), and Golden Jack Optimization (GJO), all applied to the critical task of optimal capacitor placement in radial distribution systems. Our objective was to evaluate their respective performance in minimizing power losses within the distribution system. The findings of this research reveal a distinct advantage offered by Golden Jack Optimization (GJO) over both Fuzzy-Genetic Algorithm (Fuzzy-GA) and Modified Particle Swarm Optimization (MPSO). GJO, a nature-inspired algorithm inspired by the behavior of golden jackals, exhibited superior capabilities in addressing the complexities of capacitor placement in distribution systems. In a comparative assessment, GJO consistently outperformed its counterparts, providing optimal solutions with remarkable efficiency. Its ability to adapt to variable loading conditions and deliver efficient results showcases its robustness and adaptability. Moreover, GJO demonstrated a competitive edge in terms of convergence speed and its capacity to minimize power losses in the distribution system. The success of GJO in this study highlights its potential for practical application in real-world distribution systems, particularly on the IEEE 69-bus system, where efficient power loss reduction is of paramount importance. Its unique approach, drawing inspiration from nature, proved to be a promising avenue for tackling the challenges posed by distribution system optimization within the IEEE 69-bus system. In summary, the comparative analysis of GJO, Fuzzy-GA, and MPSO underscores GJO's superiority in optimizing capacitor placement, particularly in scenarios with varying loading conditions, as demonstrated within the IEEE 69-bus system. Its robust performance and ability to provide optimal solutions make GJO an attractive choice for distribution system operators and engineers seeking to enhance system efficiency and reduce power losses. As conclude this study, recognize the immense potential of GJO as a valuable tool in the realm of distribution system optimization, particularly when applied to the IEEE 69-bus system.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, N MADHUSUDHAN REDDY; methodology, N MADHUSUDHAN REDDY.; software, Dr. T VAMSI KRISHNA.; validation, I Kranthi Kumar; formal analysis, KARRI RAVIKUMAR REDDY.; investigation, Chodagam Srinivas.; resources, K DIVYA.; data

curation, N MADHUSUDHAN REDDY; writing—original draft preparation, N MADHUSUDHAN REDDY.; writing—review and editing, Chodagam Srinivas; visualization, Chodagam Srinivas; supervision, Chodagam Srinivas; project administration, Dr. T VAMSI KRISHNA. All authors have read and agreed to the published version of the manuscript".
Conflicts of Interest: "The authors declare no conflict of interest."

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