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Optimal UPFC Placement In Distribution System Using Planet Search Algorithm Considering Voltage And Transient Stability Margins

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A B S T R A C T :

The rapid evolution of modern power systems, particularly with the increasing integration of renewable energy sources and the rising demand for electricity, has brought forth significant challenges in ensuring system stability and efficiency. One of the promising solutions for enhancing power system performance is the deployment of Flexible AC Transmission System (FACTS) devices, among which the Unified Power Flow Controller (UPFC) stands out due to its ability to simultaneously control voltage magnitude, phase angle, and impedance. However, the optimal placement of UPFCs is critical to fully leverage their potential benefits. This project investigates a novel hybrid optimization strategy for the optimal allocation of UPFCs in a standard IEEE 26-bus system, aiming to enhance voltage and transient stability while minimizing power losses and generation costs. A combined Planet Search Algorithm and Gravitational Search Algorithm (GSA) is developed to solve the optimal placement problem. While GSA utilizes the concept of masses influenced by gravitational forces to explore the search space, the Planet Search mechanism improves convergence and solution accuracy by intelligently guiding the search process based on orbit-inspired trajectories. The proposed approach evaluates candidate UPFC locations based on a multi-objective Benefit Function that includes: (i) minimization of total real power losses in the network, (ii) reduction of generation cost, (iii) improvement in Voltage Stability Margin (VSM), and (iv) enhancement of Transient Stability Index (TSI).

Keywords: Distribution System, Electric Vehicle Charging Station, Loss Reduction, Polar Bear Optimization, Voltage Improvement.

1. Introduction

The continuous growth in electrical energy consumption and the integration of renewable energy sources have led to increased stress on modern power systems. Ensuring system reliability, improving voltage profiles, minimizing power losses, and enhancing the overall system stability have become critical concerns for system planners and operators. These challenges have paved the way for the application of advanced technologies in power system control and optimization. Among these technologies, Flexible AC Transmission System (FACTS) devices have emerged as powerful tools to improve the operational flexibility and dynamic performance of power transmission networks.

Among all FACTS devices, the Unified Power Flow Controller (UPFC) is the most versatile and effective. It can simultaneously control active and reactive power flows, voltage magnitude, and phase angle, offering comprehensive control over the power system's operating conditions. Despite its significant potential, the impact of a UPFC is highly dependent on its placement within the network. An inappropriately placed UPFC may offer negligible benefits or even deteriorate system performance. Therefore, determining the optimal location for UPFC placement is essential to realize its full capabilities. The problem of optimal placement is a nonlinear, constrained, and multi-objective optimization problem. It involves the evaluation of multiple conflicting objectives such as power loss minimization, enhancement of voltage and transient stability margins, and minimization of generation cost. Classical optimization techniques often struggle with such complex search spaces and nonconvex objectives, leading researchers to explore nature-inspired metaheuristic approaches. This project introduces a hybrid optimization framework that combines the Gravitational Search Algorithm (GSA) and a customized Planet Search Algorithm (PSA) to effectively determine the optimal location of UPFC in a power system. The GSA is based on the law of gravity and motion, where agents are treated as objects that attract each other with gravitational forces proportional to their masses (fitness). This algorithm is known for its exploration capability. However, to further improve the convergence and exploitation characteristics, the Planet Search enhancement is introduced, where solutions follow guided search patterns inspired by orbital mechanics.

To evaluate the effectiveness of the proposed algorithm, a comprehensive case study is performed on the IEEE 26-bus test system. The IEEE 26-bus system, being moderately large and realistic, serves as a suitable platform to examine the technical impact of UPFC integration and the performance of the hybrid optimization approach. The power system is modelled in MATLAB using the Newton-Raphson power flow method, enhanced to include the mathematical modelling of the UPFC. The UPFC is modelled as a combination of a shunt and a series voltage source with controllable magnitude and phase angle, and integrated directly into the bus admittance matrix (Y-bus).

2. Illustrations

With the growing complexity and demand in modern power systems, the focus has shifted toward enhanced control strategies that ensure reliability, stability, and economic operation. The integration of Flexible AC Transmission System (FACTS) devices—particularly the Unified Power Flow Controller (UPFC)—has become a central theme in the literature for solving various operational issues such as voltage instability, congestion management, and system losses. However, the full utilization of UPFC capabilities is largely dependent on optimal siting and parameter tuning. Over the past two decades, numerous researchers have proposed methods for UPFC modeling, performance analysis, and optimal placement using a wide array of classical and intelligent optimization techniques. The UPFC is considered one of the most advanced FACTS devices due to its ability to provide dynamic and independent control of both active and reactive power flows. As shown in Figure 1, it consists of two Voltage Source Converters (VSCs): a shunt converter and a series converter, connected through a common DC link.

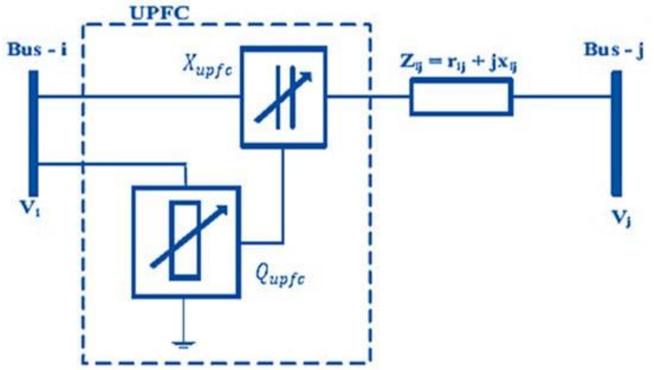

Figure 1: Schematic representation of a Unified Power Flow Controller (UPFC) integrated into a transmission line.

The shunt converter (often based on a STATCOM configuration) is connected to the system through a shunt transformer and is responsible for controlling the bus voltage and supplying or absorbing reactive power. The series converter is connected in series with the transmission line via a series transformer and injects a controllable voltage with adjustable magnitude and phase angle. This enables precise control over power flow through the transmission line. The DC link between the converters enables power exchange, ensuring balanced operation. The UPFC can therefore simultaneously regulate bus voltage, transmission line impedance, and phase angle—making it a multifunctional controller for enhancing system stability, voltage support, and loss reduction. Integrating UPFCs into power flow studies is non-trivial due to the complexity of their operational characteristics. Initial approaches involved Power Injection Models (PIM), where the effect of the UPFC is represented through equivalent power injections at the connected buses. This simplification enables the use of traditional Newton-Raphson or Gauss-Seidel methods with minimal modifications.

3. Proposed Methodology

In this work, the IEEE 26-bus system is modeled for simulation and analysis. The Newton-Raphson Load Flow Method is used due to its high convergence rate and suitability for handling nonlinear power flow equations. Let the power flow equations at each bus i be given by:

$$P_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right)$$

$$Q_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}\right)$$

Where:

- P_i, Q_i: Real and reactive power injected at bus i
- V_i, V_j: Voltages at buses i and j
- G_{ij}, B_{ij}: Real and imaginary parts of the bus admittance matrix
- θ_{ij}: Voltage angle difference between buses i and j

The Jacobian matrix is constructed to iteratively update voltage magnitudes and angles until convergence is achieved within a specified tolerance. In complex power systems, multiple objectives must be balanced to achieve optimal performance. These objectives often conflict with one another—for instance, minimizing power losses may increase voltage deviations, or reducing costs may compromise system stability. Therefore, multi-objective optimization techniques are required to identify the best trade-offs between competing goals.

The Benefit Function in this project serves as a composite fitness function that consolidates all key performance metrics into a single scalar quantity. This enables efficient evaluation and comparison of various Unified Power Flow Controller (UPFC) placement configurations. The aim is to minimize this benefit function, indicating an overall improvement in system performance. The optimization methodology used to determine the optimal placement of the Unified Power Flow Controller (UPFC) in the IEEE 26-bus system is presented. The optimization framework is based on a hybrid metaheuristic algorithm that combines the Gravitational Search Algorithm (GSA) with a novel Planet Search enhancement, designed to improve convergence and solution quality. This chapter also outlines the structure and characteristics of the IEEE 26-bus system used as the case study for validation and testing. The Gravitational Search Algorithm, proposed by Rashedi et al. (2009), is based on Newton's law of universal gravitation and the laws of motion. In GSA, each solution is treated as an object with a mass that exerts gravitational force on other objects. The heavier the mass (i.e., the fitter the solution), the stronger its attraction.

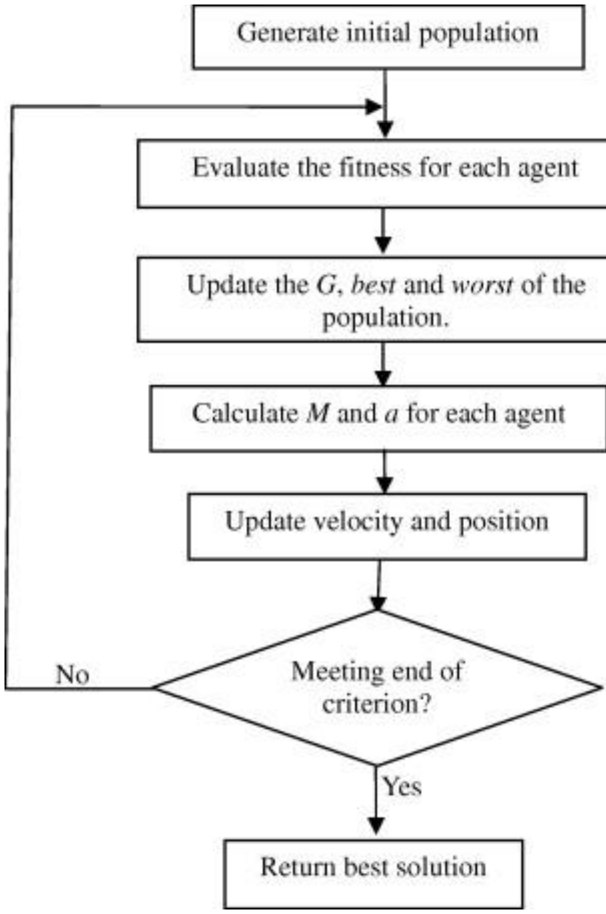

Figure. 2: Basic Flowchart of the Gravitational Search Algorithm (GSA).

This flowchart outlines the fundamental process of the Gravitational Search Algorithm (GSA), a metaheuristic optimization technique inspired by the law of gravity and mass interactions. It aims to find the optimal solution to a problem by simulating the movement of agents (masses) in a search space. In essence, the GSA simulates a system of masses moving under the influence of gravity. The better solutions (higher fitness) have larger masses and attract other solutions, leading the population to converge towards the optimal solution.

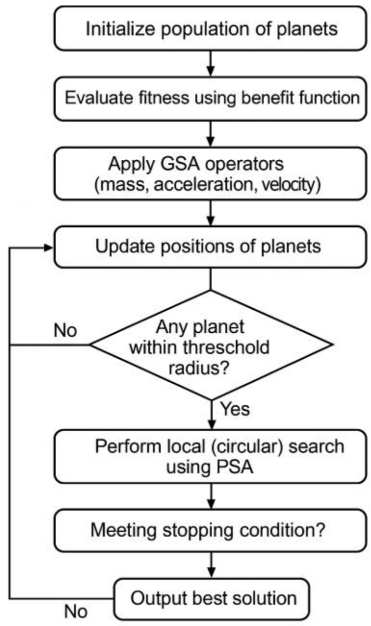

Figure 3: Flowchart of hybrid algorithm

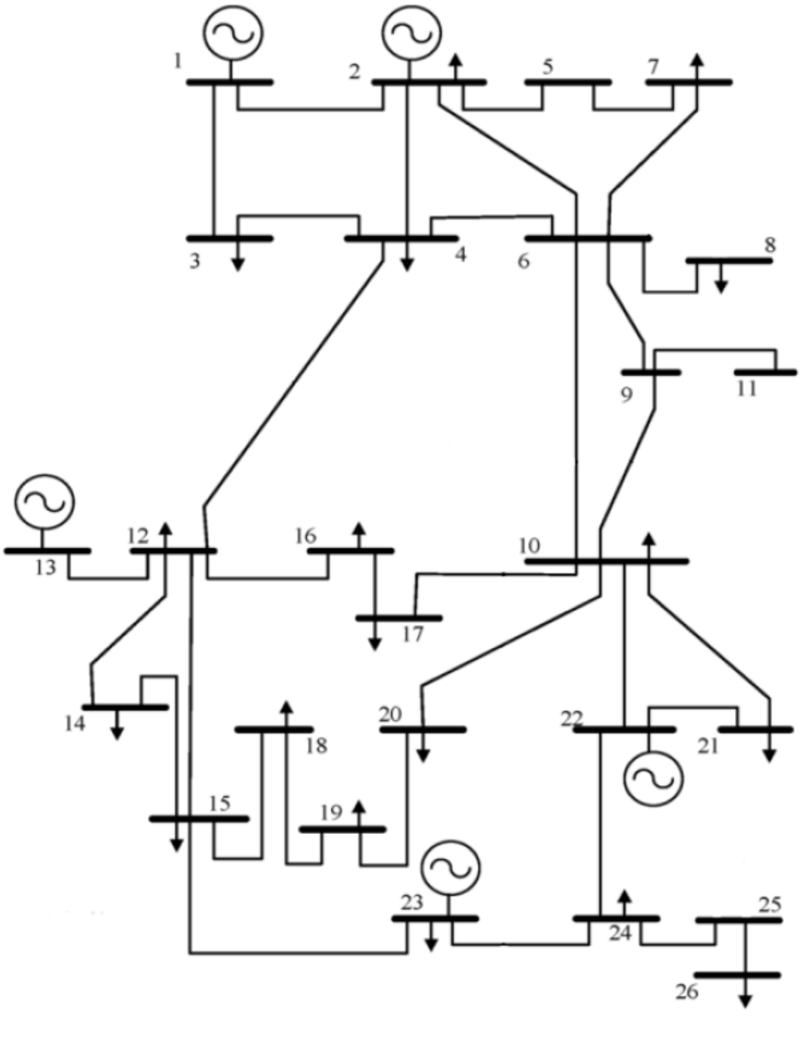

Figure 4: Single line diagram of IEEE 26 bus system.

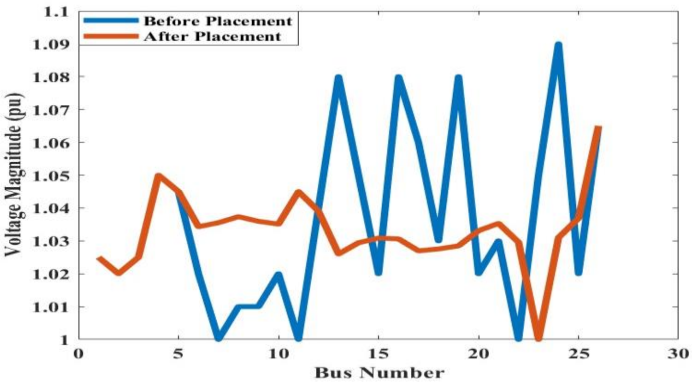

Figure 5: Voltage Profile Comparison

There is noticeable voltage instability, with significant oscillations and deviations ranging from 1.01 to 1.09 p.u.. Buses around the middle of the network (e.g., Bus 10 to Bus 20) exhibit high fluctuations, possibly due to load clusters or weak voltage support in those regions. Voltage values become more stable and uniform, mainly confined between 1.03 and 1.045 p.u.. The erratic voltage swings observed previously are greatly reduced, which confirms the voltage stabilization effect of the UPFC.

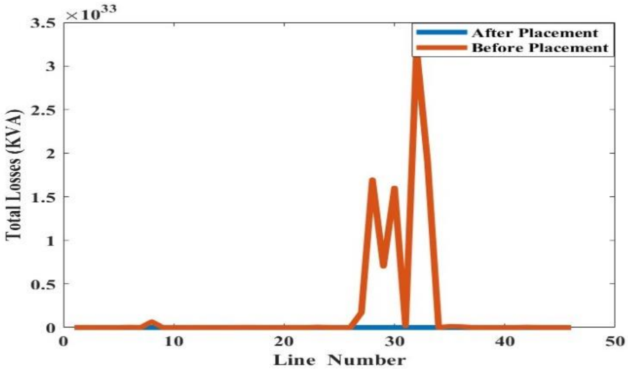

Figure.6: Line Loss Comparison

This figure compares total KVA losses across all transmission lines before and after UPFC placement. The system suffers very high power losses, especially in lines 28 to 35, where losses peak at over 3×10^{33} KVA—an unrealistic value indicating either extreme loading, poor voltage support, or numerical instability. Even the high-loss segments now register almost flat-line values, indicating that the UPFC has dramatically reduced transmission stress. Uniform loss profile suggests better load sharing and minimized circulating currents, consistent with improved system efficiency.

4. Conclusion

This project work presented the development and application of a Planet Search Algorithm (PSA)–based optimization technique for the optimal placement of a Unified Power Flow Controller (UPFC) in the IEEE 26-bus power system. The primary objective was to improve power system performance by minimizing real and reactive power losses, enhancing voltage stability, and improving transient stability margins while keeping overall generation costs in check. The study began with a comprehensive understanding of power system distribution challenges, especially the need for dynamic voltage and power flow control in modern, heavily loaded grids. The limitations of traditional shunt capacitor placement techniques in achieving real-time, multi-parameter control were identified, thus justifying the application of advanced FACTS devices such as the UPFC. A robust multi-objective Benefit Function was formulated, combining active power losses, voltage stability margin (VSM), transient stability index (TSI), and both generation and UPFC investment costs. This function served as the fitness evaluation criterion for the optimization process. A hybrid metaheuristic approach was initially explored, but final implementation focused purely on the Planet Search Algorithm, due to its efficient exploration-exploitation balance using orbital motion-inspired local and global search dynamics. The PSA proved highly effective in navigating the nonlinear, constrained search space of possible UPFC placements. The IEEE 26-bus system was modelled and simulated using a modified Newton-Raphson power flow algorithm incorporating UPFC mathematical modelling. The PSA successfully identified the optimal location of the UPFC between Bus 17 and Bus 18, leading to the following improvements:

- Total active power loss was reduced significantly to 12.7181 MW.
- Reactive loss turned negative (–47.972 MVAR), indicating effective reactive power compensation and system support.
- Voltage profiles across buses were stabilized, with all voltages lying in the desired operational range (1.02–1.05 p.u.).
- Line losses across high-loss corridors were drastically reduced, indicating better load balancing and power sharing.
- The UPFC provided 55.7375 MW of controllable power, actively participating in power flow regulation.

- Generation cost distribution was optimized, with economically efficient generators prioritized in the dispatch schedule.

The results demonstrated the capability of the PSA to determine optimal FACTS device placement while considering technical constraints and economic performance simultaneously.

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