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Original Article

Optimization of Sizing and Location of UPFC for Voltage Profile Improvement Using Particle Swarm Optimization and Fuzzy Logic Controller

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Abstract *- This project addresses the critical challenge of enhancing voltage profiles in power systems through the optimal placement and sizing of Unified Power Flow Controllers (UPFCs) using a synergistic combination of PSO and FLC. The study focuses on Electrical 14 and 30 Bus systems as benchmark test cases for validation and verification. The proposed methodology formulates an objective function encompassing both voltage deviation and power losses, emphasizing a holistic optimization approach. Particle Swarm Optimization is employed to efficiently explore the solution space, seeking the optimal locations and parameters of UPFCs. The UPFCs' parameters are* dynamically *adjusted in real-time through the integration of a Fuzzy Logic Controller, which is adept at handling uncertainties and nonlinearities inherent in power systems.*

Keywords *- UPFC (Unified Power Flow Controller), Voltage profile improvement, Particle Swarm Optimization (PSO), Fuzzy Logic Controller (FLC), Power system optimization.*

1. Introduction

The stability and reliability of modern electrical power systems are paramount for the seamless functioning of our technologically advanced society. A critical aspect of maintaining the health of power grids is ensuring an optimal voltage profile throughout the network. Voltage deviations, whether they are too high or too low, can lead to a range of problems, including equipment damage, inefficient energy transfer, and even power outages.

Unified Power Flow Controllers (UPFCs) have emerged as a powerful solution to address voltage profile issues by dynamically controlling the flow of power within the network. This research investigates the crucial task of determining the optimal sizing and location of unified power flow devices to enhance the profile of voltage using a combination of (PSO) and (FLC) [10].

Power systems have become increasingly complex due to factors such as the integration of renewable energy sources, varying loads, and changes in network topology. Traditional methods for voltage profile improvement often fall short in adapting to these dynamic conditions. Therefore, there is a growing need for sophisticated optimization techniques that can intelligently place and size UPFC devices within the grid to mitigate voltage problems effectively. This observation introduces a singular approach that leverages the strengths of each PSO and FLC [8]. PSO is a population-primarily based optimization algorithm inspired by the collective behavior of birds and fish. It excels in searching for the most fulfilling solutions in massive, complex solution areas.

Fuzzy good judgment controllers, alternatively, are regarded for his or her adaptability and ability to cope with unsure and obscure statistics. By means of combining those two techniques, we intended to locate the premiere locations and sizes for UPFC devices that could reply dynamically to voltage variations, providing real-time voltage profile development [9].

The research focuses on a comprehensive power system model, encompassing diverse load scenarios, various network topologies, and contingency situations. Through extensive simulations and performance evaluations, we aim to demonstrate the superior capabilities of the proposed PSO-FLC approach in effectively improving voltage profiles. By reducing voltage deviations and minimizing power losses, this methodology promises to enhance the efficiency, reliability, and resilience of electrical grids, ultimately contributing to a more sustainable and robust power infrastructure [9].

2. Literature Review

Voltage profile improvement in electric power structures is an essential concern to ensure the stability, reliability, and efficiency of the grid. Unified Power Flow Controllers (UPFCs) have won sizable attention as a viable answer for voltage control due to their capability to adjust energy flow dynamically. This section reviews the prevailing literature on UPFC applications and optimization strategies, highlighting the constraints of modern methods and the rationale for integrating Particle Swarm Optimization (PSO) and Fuzzy Logic Controllers (FLC) in these studies [2].

2.1. UPFC Applications

UPFCs, part of Flexible AC Transmission System (FACTS) devices, have demonstrated their effectiveness in voltage control and power flow management. The literature reveals various UPFC applications, including:

Voltage Profile Improvement: UPFCs can alleviate voltage deviations and enhance the overall voltage profile by injecting or absorbing reactive power.

Line Flow Control: They can control power flow in transmission lines by adjusting the series and shunt compensation.

Transient Stability Enhancement: UPFCs contribute to the transient stability of the power system by controlling voltage and power flow during disturbances.

Loss Minimization: UPFCs can help reduce power losses by optimizing the power flow distribution.

The integration of Particle Swarm Optimization (PSO) and Fuzzy Logic Controllers (FLC) holds promise for addressing these limitations [4]. PSO offers the ability to efficiently search for optimal UPFC locations and sizes in complex solution spaces. On the other hand, FLC introduces adaptability and robustness to the control strategy, allowing UPFCs to respond effectively to changing grid conditions and uncertainties. The synergy between PSO's optimization capabilities and FLC's adaptability makes this integrated approach a promising solution for enhancing voltage profiles and overall grid performance.

This paper presents an algorithm to solve the multi-objective Optimal Reactive Power Dispatch (ORPD) problem in an unbalanced bus system. Unlike the traditional ORPD problem, load ability maximization, voltage profile enhancement, loss minimization, and ATC enhancement are achieved under unbalanced conditions. Here, ORPD is effectuated by determining the optimal location and size of the UPFC using a hybrid version of GA and FF. Experimental results on the benchmark IEEE test bus systems demonstrate the ORPD performance of the proposed algorithm over the traditional algorithms under unbalanced conditions. Moreover, the proposed algorithm is proved for its performance in maintaining a better trade-off among multiple objectives, even under overloading conditions. The analysis also includes an investigation of the sensitivity of the algorithm against the overloading conditions of the bus system. Finally, the experimental results confirm that the proposed algorithm is superior to conventional algorithms like GA, PSO, a hybrid version of GA-PSO, and the traditional FF algorithm [4].

In the context of the optimal location and sizing of UPFC for voltage profile improvement, the proposed PSO-FLC approach aims to overcome the shortcomings of traditional methods and provide a more effective and adaptive solution. This research leverages the strengths of both PSO and FLC to optimize UPFC placement and control, ensuring improved voltage profiles and grid stability under varying operating conditions [6].

This literature review provides an overview of the existing research on UPFC applications, optimization techniques, and the rationale for the proposed PSO-FLC approach in the context of voltage profile improvement. It establishes the need for a more adaptive and efficient solution in addressing voltage control challenges in modern power systems [5].

In this paper, a heuristic technique based optimal location of UPFC to improve the performance of the power system is proposed. Here, the maximum power loss bus is identified as the most suitable location for fixing the UPFC. Generator outage affects the power flow constraints such as power loss, voltage, real and reactive power flow. Generator outage at different buses is introduced and the performance of the system is analyzed. The optimum location has been determined using the Artificial Bee Colony algorithm (ABC) under this condition.

By connecting UPFC at the optimal location given by the ABC algorithm, the power loss in the system is reduced, and the voltage profile is improved. The proposed work is implemented in MATLAB and tested on the IEEE 30 bus system. Initially, the single generator outage is introduced at different buses in the system, and afterwards double generator outage is introduced. In these conditions, the voltage profile and the power loss are analyzed at normal conditions, outage conditions and after connecting UPFC, whose location is given by the proposed ABC algorithm. The performance of this algorithm is evaluated by comparing the results with those of different techniques. The comparison results demonstrate the superiority of the proposed approach and confirm its potential to solve the voltage stability problem [7].

PSO is a well-known optimization algorithm that is easy to implement and has a good convergence rate. It mimics the social behavior of birds flocking or fish schooling, making it effective for solving nonlinear and complex optimization problems. This method is widely used in power systems for optimizing the location and sizing of devices like UPFC. It demonstrates good performance in enhancing the voltage profile and minimizing power losses.

However, PSO can sometimes suffer from premature convergence, especially in highly complex search spaces, and it requires careful tuning of parameters like cognitive and social coefficients. The FLC technique has so many advantages, and it can handle imprecision and uncertainty effectively, making it suitable for real-world power systems with variable conditions and it does not require a precise mathematical model, which simplifies implementation.

The FLC technique is used to control the reactive power and voltage profile by adjusting the UPFC parameters based on fuzzy rules, and it provides robust performance under varying load conditions. The design of the fuzzy rule base and membership functions can be complex and time-consuming. The Performance of FLC heavily depends on the expertise of the designer in creating effective fuzzy rules.

2.2. Integration of PSO and FLC

Existing Work: Most studies focus on either PSO or FLC individually.

Gap: Limited research on the hybridization of PSO and FLC to leverage the strengths of both methods for optimizing UPFC parameters.

Proposed Research: Explore the integration of PSO and FLC to achieve better optimization results, such as improved convergence speed and handling of uncertainties.

2.3. Comparative Analysis of Optimization Techniques

Existing Work: Comparisons between PSO and other optimization techniques (like Genetic Algorithm and Differential Evolution) are available, but comprehensive comparisons involving FLC are scarce.

Gap: Lack of detailed comparative studies on the effectiveness of FLC versus PSO in the context of UPFC optimization for voltage profile improvement.

Proposed Research: Conduct a thorough comparative analysis of PSO and FLC (and their hybrid) in optimizing UPFC parameters, focusing on voltage profile enhancement and loss minimization.

3. Unified Power Flow Controller

A Unified Power Flow Controller (UPFC) is the most widely used controller among information devices [10]. The UPFC offers simultaneous control of actual and reactive power float and voltage values at exclusive buses. Several constant kingdom fashions are available for UPFC to be carried out in electricity along with the glide utility based totally on the Newton-Raphson algorithm. A few are decoupled UPFC version, injection UPFC model and comprehensive NR UPFC version. Modern-day Injection model of UPFC is used. The fundamental schematic diagram of UPFC, as proven in Figure 1.

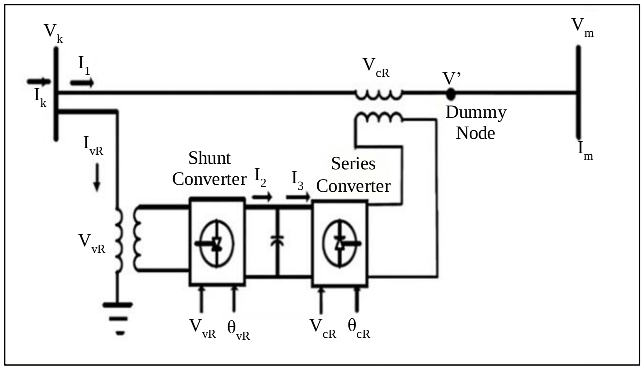

Fig. 1 UPFC schematic diagram

The fundamental configuration of a UPFC is hooked up among the sending-quit Vs and the receiving-stop Vr. The UPFC includes a combination of a series tool and a shunt tool, the DC terminals of which can be connected to a commonplace DC link capacitor.

The Existing version may be included with the Equal Current Injection (ECI) strength to go with the flow model without problems. By the ECI set of rules, implementation of electricity waft calculations is plenty quick and précis. The equal current injection model is shown in Figure 2.

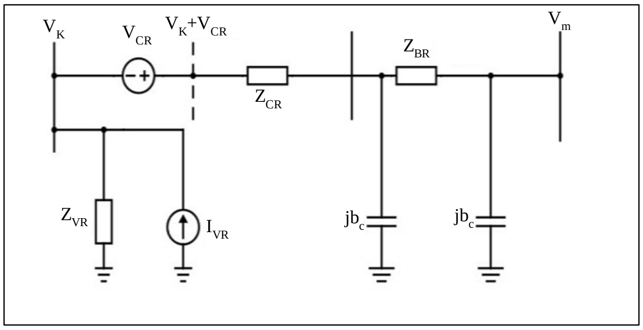

Fig. 2 Equal Current Injection (ECI) model

According to Figure 2 with the ECI model as follows in equations,

$$I_{VR}=\frac{V_{VR}}{Z_{VR}} \quad (1)$$

$$P_{CR}=P_{VR} \quad (2)$$

$$S_{VR}=V_K I^* \quad (3)$$

$$=V_K\left(\frac{V_K-V_{VR}}{Z_{VR}}\right)$$

$$=\frac{|V_K|^2}{Z_{VR}^*}=-V_K\left(\frac{V_{VR}}{Z_{VR}}\right) \quad (4)$$

According to the Newton-Raphson algorithm, the ECI mismatch equation with the UPFC version can be written. The real power transmitted over the line from the sending to the receiving bus becomes,

$$P_S=-P_S=\frac{V_R V_S}{X}Sin(\emptyset) \quad (5)$$

$$Q_S=\frac{V_S^2}{X}-\frac{V_R V_S}{X}Cos(\emptyset) \quad (6)$$

The power losses on the line are given by,

$$P_{Loss}=P_S+P_R=G(V_S^2-V_R^2)-2V_SV_RGCos(\emptyset)$$

$$Q_{Loss}=P_S+P_R=B(V_S^2-V_R^2)-2V_SV_RBCos(\emptyset)$$

Where, G is conductance, B is susceptance. $\emptyset=\emptyset_S-\emptyset_R$ called power angles.

4. Optimal Placement of UPFC Using Fuzzy Approach

Fundamental goals to be taken into consideration at the same time as designing a fuzzy logic to discover the most efficient placement of UPFC are,

- Minimization of the power loss.
- Preserving voltage within the permissible limits.

A Fuzzy Inference System (FIS) containing a tough and rapid of rules is then used to determine the UPFC placement suitability of each node inside the device.

In the first step, load go along with the float solution for the unique machine is required to reap the real and reactive strength losses. Another time, load waft answers are required to acquire the electricity loss reduction with the useful resource of compensating the complete reactive masses at each node of the transmission system. The loss discounts are then linearly normalized into [0, 1] variety, with the fine loss discount having a value of one and the lowest cost being zero. The strength loss index value for the nth node may be located via the usage of the equation below.

$$PLI(n)=\frac{LR(n)-LR(min)}{LR(max)-LR(min)}$$

For the high-quality ideal placement of UPFC through using the fuzzy logic controller and its rules to determine the suitability of a node for UPFC set up are formed. Rules desk for fuzzy as given in Table 1.

Table 1. Fuzzy rules

AND		**Voltage**				
		L	**LM**	**M**	**HM**	**H**
PLI	L	LM	LM	L	L	L
	LM	L	LM	HM	M	L
	M	HM	H	LM	L	HM
	HM	HM	LM	M	LM	L
	H	L	HM	L	LM	LM

FLCs use linguistic variables and fuzzy rules to make decisions based on input data and provide crisp output values. Fuzzy logic controller rules are a fundamental component of FLCs. These rules define how the controller should respond to different combinations of input variables. The fuzzy rule base is a set of if-then rules that guide the decision-making process [9]. Each rule combines linguistic terms from the input variables to produce a fuzzy output. A rule typically takes the form: “IF (input variable A is term X) AND (input variable B is term Y) THEN (output variable is term Z).” For example,

- If PLI is H and voltage is L, the UPFC SI is L
- If PLI is M and voltage is LM, the UPFC SI is H
- If PLI is LM and voltage is M, the UPFC SI is HM

Here, L is Low, H is High, M is medium, LM is low medium, and HM is high medium.

5. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a popular optimization technique inspired by the social behavior of birds and fish, where individuals in a group (particles) cooperate and communicate to find the best solution to a problem. PSO is often used to solve optimization problems, search for the global optimum in a search space, and is particularly well-suited for continuous and multi-dimensional optimization problems. The fitness or objective function is evaluated for each particle. The objective function quantifies how good or bad a solution is with respect to the optimization problem's goals. Each particle has several properties, including its position and velocity. These properties are initially assigned random values.

- Position: $X_i=(X_{i,1},X_{I,2}\ldots\ldots X_{i,n})\in R^n$
- Velocity: $V_i=(V_{i,1},V_{I,2}\ldots\ldots V_{i,n})\in R^n$

Each particle maintains its individual best position,

$$P_i=(P_{i,1},P_{i,2}\ldots\ldots P_{i,n})\in R^n$$

$P_{best(i)}=f(P_i)$ and swarm maintains its global best (G_{best}), $P_g\in R^n$

$$Gbest=f(P_g)$$

In a swarm, by updating the location and pace by the following formulas, we will get a private first-class function (i.e. Pbest), and an international nice role (i.e. gbest). The debris aims to attain the gbest particle by using the subsequent formulae. The original Velocity update equation is as follows,

$$V_i^{(k+1)} = v_i^k + C_1\,\text{rand}_1\,(p_{\text{best } i} - X_i) + C_2\,\text{rand}_2\,(g_{\text{best } i} - X_i)$$

With rand_1, rand_2, C_1, C_2: Acceleration constant.

In each iteration (or generation), particles adjust their velocity and position based on their past experiences and the experiences of their neighbors in the population. Two key factors determine the velocity and position updates:

Cognitive Component (Personal Best): Each particle remembers its own best-known position (personal best) and tries to move toward it.

Social Component (Global Best): Each particle also considers the best-known position among all particles in the population (global best) and tries to move toward it.

Two acceleration constants control the balance between these two components, often denoted as cognitive and social acceleration coefficients (usually represented as c1 and c2). Figure 3 shows the flow chart of particle swarm optimization.

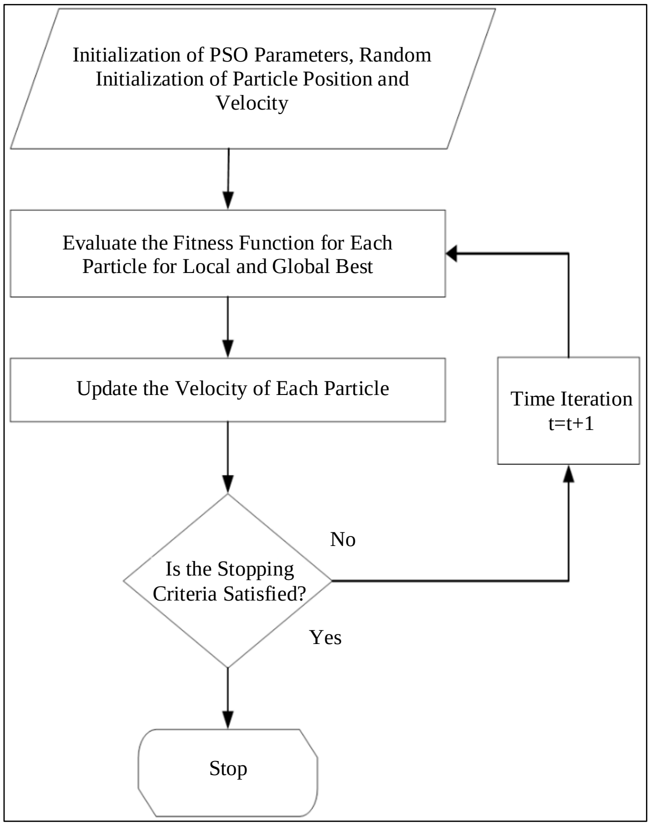

Fig. 3 Flowchart of Particle Swarm Optimization

The particle position update equation is as follows,

$$X_i^{k+1} = X_i^k + V_i^{k+1}$$

Inertia weight:

$$V_i^{(k+1)} = Wv_i^k + C_1\,\text{rand}_1\,(p_{\text{best } i} - X_i) + C_2\,\text{rand}_2\,(g_{\text{best } i} - X_i)$$

Weight update equation is as follows,

$$W = w_{max} - ((w_{max} - w_{min})*t)/T$$

Considered constraints are as follows,

$$V_i^{min} \leq V_i \leq V_i^{max}$$

$$X_i^{min} \leq X_i \leq X_i^{max}$$

The swarm behavior of particles adjusting their positions and velocities in response to their personal and global experiences allows PSOs to explore the search space effectively and converge toward optimal or near-optimal solutions. The major advantages of PSO are its simplicity and ease of implementation, making it a popular choice for optimization problems in various domains, such as engineering, machine learning, and finance. However, the performance of PSO can be influenced by the choice of parameters (e.g., acceleration coefficients) and the initialization of particles, so tuning these parameters is often required to achieve good results for specific problems.

6. Results

The IEEE 14 bus system [10] is made up of 20 transmission lines, 5 generator buses (numbers 1, 2, 3, 6, and 8), and 9 load buses (numbers 4, 5, 7, 9, 10, 11, 12, 13, and 14). The various load scenarios, such as 85, 100, and 110%. Table 2 displays the ideal placement on load buses, the UPFC rating, and the actual power losses following the UPFC placement for various load scenarios using PSO. Figure 4 shows the IEEE-14 radial bus system.

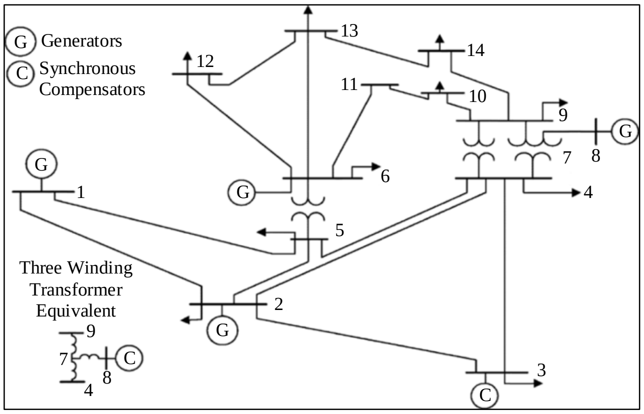

Fig. 4 IEEE-14 bus system

Table 2 shows results for the IEEE-14 bus system with placement of UPFCs with PSO-FLC for various places at distinctive loading conditions.

Table 2. Results for the IEEE-14 bus system

Loading Conditions	Losses without UPFC (MW)	UPFC Location	PSO-FLC	
			Angle	Losses with UPFC (MW)
85% Loading	9.2588	4 5	7.5820 8.5950	9.225
100% Loading	13.3938	5 14	7.5820 8.5950	13.2742
Overloading (110%)	16.7223	9 14	7.5820 8.5950	16.4393

Figure 5 suggests voltage profile earlier than and after placement of UPFC under loading (85%) situations for IEEE-14 bus system. From this voltage profile, it is clearly shown that the placement of UPFC at bus-4 and bus-5 will provide optimal results, and by this, the total losses are reduced to 9.225 MW.

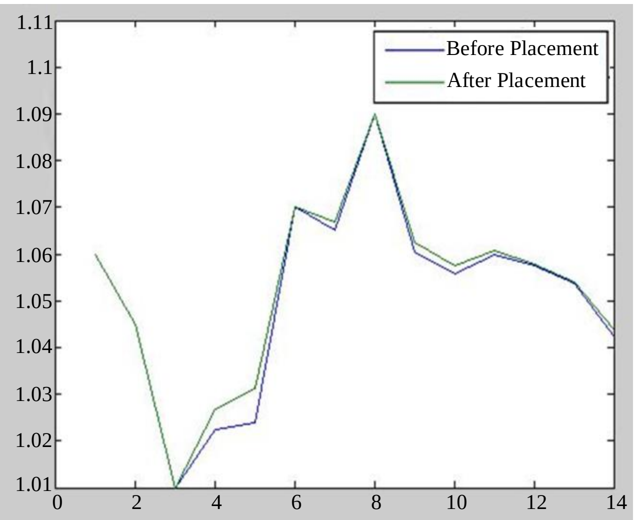

Fig. 5 Voltage profile earlier than and after placement of UPFC (85% loading)

Figure 6 shows the voltage profile earlier than and after placement of UPFC beneath loading (100%) conditions for the ieee-14 bus system. From this voltage profile, it is clearly shown that the placement of UPFC at bus-5 and bus-14 will provide optimal results, and by this, the total losses are reduced to 13.2742 MW.

Figure 7 indicates the voltage profile earlier than and after placement of UPFC overloading (110%) situations for the IEEE-14 bus system. From this voltage profile, it is clearly shown that the placement of UPFC at bus-9 and bus-14 will provide optimal results, and by this, the total losses are reduced to 16.4393 MW.

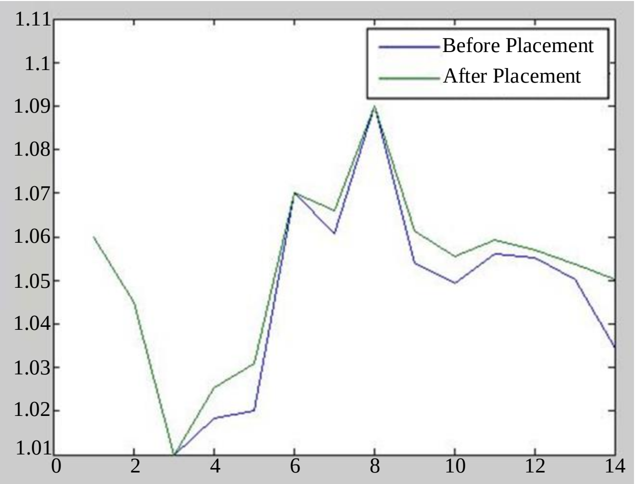

Fig. 6 Voltage profile before and after placement of UPFC (100% loading)

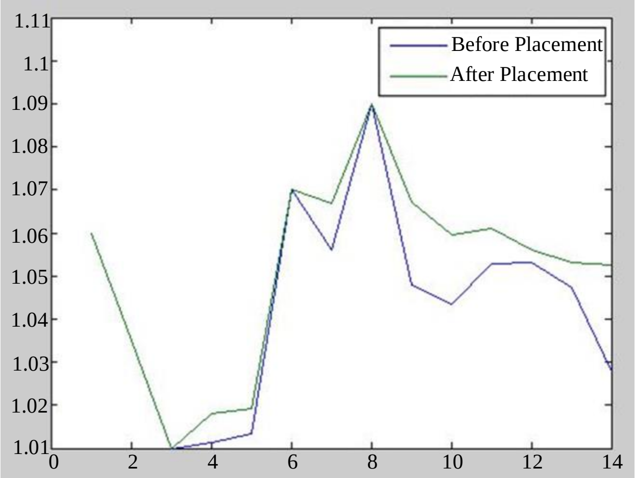

Fig. 7 Voltage profile before and after placement of UPFC (110% loading)

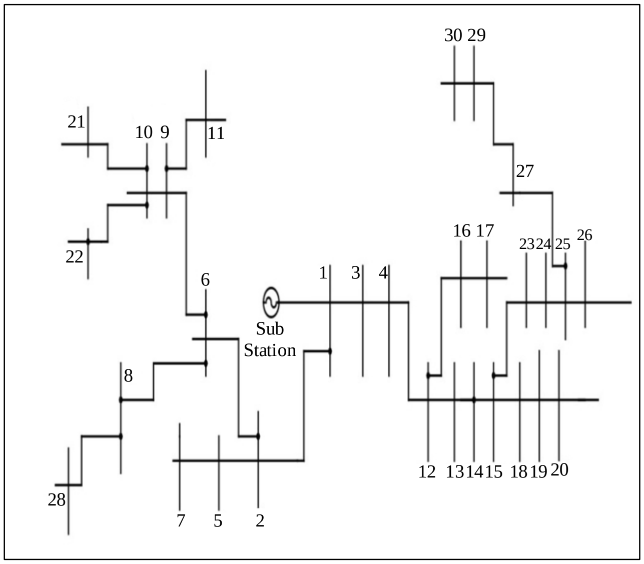

Fig. 8 IEEE-30 bus system

There are six generator buses (bus numbers 1, 2, 5, 8, 11, and 13) in the IEEE 30 bus system [10], 24 load buses (bus numbers 3, 4, 6, 7, 9, 10, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 and 30), and 41 transmission lines. Varying load circumstances, such as 85, 100, and 110%. For various load scenarios utilizing PSO, Table 3 displays the ideal position on load buses, the UPFC rating, and the real power losses following UPFC deployment. Figure 8 shows the IEEE 30 radial bus system. Table 3 indicates the consequences for the IEEE-30 bus system with UPFCs with PSO-FLC for various locations at distinct loading conditions.

Table 3. Results for the IEEE-30 bus system

Loading Conditions	Losses without UPFC (MW)	UPFC Location	PSO-FLC	
			Angle	Losses with UPFC (MW)
85% Loading	12.1131	7 21 26	0.5650 1.2980 2.8520	12.0155
100% Loading	17.5280	21 24 30	0.5650 1.2980 2.8520	17.3568
Overloading (110%)	21.9318	21 24 30	0.5650 1.2980 2.8520	21.6473

Figure 9 indicates the voltage profile before and after placement of UPFC under loading (85%) situations for the IEEE-30 bus system. From this voltage profile, it is clearly shown that the placement of UPFC at bus-7, bus-21 and bus-26 will provide optimal results and by this, the total losses are reduced to 12.0155 MW.

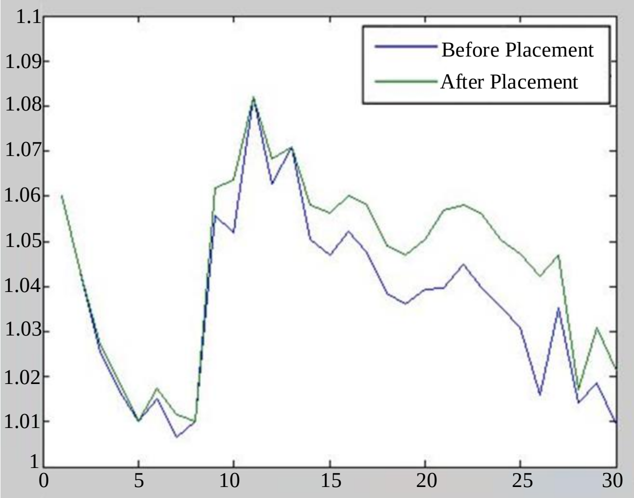

Fig. 9 Voltage profile before and after placement of UPFC (85% loading)

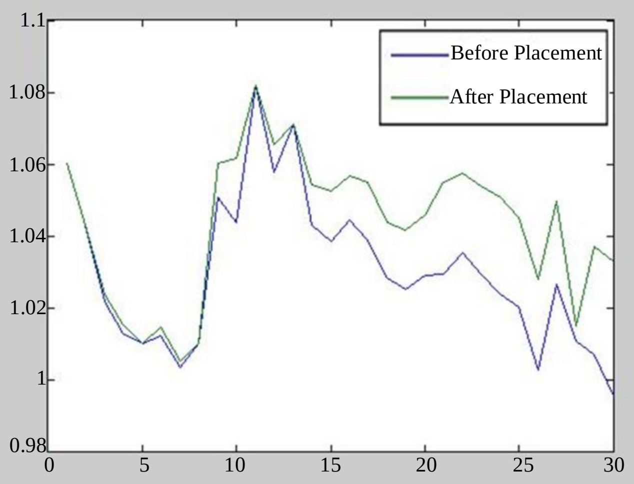

Fig. 10 Voltage profile before and after placement of UPFC 100% loading

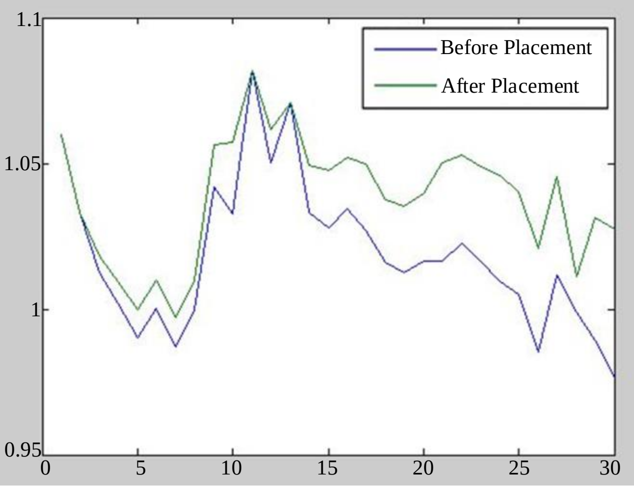

Fig. 11 Voltage profile before and after placement of UPFC (110% loading)

Figure 10 suggests a voltage profile earlier than and after placement of UPFC under 100% loading situations for the IEEE-30 bus system. This voltage profile clearly shows that the placement of UPFC at bus-21, bus-24 and bus-30 will provide optimal results, and by this, the total losses are reduced to 17.3568 MW.

Figure 11 suggests a voltage profile earlier than and after placement of UPFC overloading (110%) situations for IEEE-30 bus devices. From this voltage profile, it is clearly shown that the placement of UPFC at bus-21, bus-24 and bus-30 will provide optimal results, and by this, the total losses are reduced to 21.6437 MW.

7. Conclusion

The combination of fuzzy and PSO has been used on this mission to reduce energy loss and enhance the voltage profile in transmission devices. Numerous premier locations are obtained by means of the UPFC suitability index from the fuzzy technique. Optimum sizes for the respective places are received by way of using PSO. The result for IEEE-14 and IEEE-30 buses indicates that the power loss is reduced, and the voltage profile is maintained inside distinct limits under distinct load conditions like mild load, regular load and overloading instances.

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