Multi-Objective Optimization Technique to Enhance Microgrid Performance by Optimal Placement of DGs and UPFC

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***Abstract*—Demand for a reliable power supply and increasing renewable energy utilization have added complexity to the power systems. Flexible AC Transmission Systems (FACTS) devices are essential for improving voltage stability, lowering power losses, and improving system performance. In this paper, the IEEE 33-Bus distribution system is taken as a base model and modified as a microgrid by incorporating solar, wind, storage units as energy sources with the utility source. Unified Power Flow Controller (UPFC), is employed to study the impacts of FACTS devices on the proposed microgrid system performance. The same system is optimized for increasing the renewable share, minimizing active power losses by optimal placement of Distributed Generator (DG) and FACTS devices. Moreover, voltage stability and small signal stability are also considered during optimization. In this study, various optimization algorithms such as Multi-Objective Particle Swarm Optimization (MOPSO) and Non-dominated Sorting Genetic Algorithm (NSGA-II) are compared in order to find the best way to achieve optimal placement and control of DG and UPFC devices to enhance the system performance.**

***Index Terms*—FACTS Devices, Line losses, Microgrid, Renewable energy, Voltage stability.**

I. INTRODUCTION

The integration of renewable energy has led to an increase in the use of microgrids that combine dispersed generation, storage, and loads. However, the intermittent nature of solar and wind sources can cause voltage instability, frequency variations, and reactive power imbalance. FACTS devices such as Static Synchronous Compensator (STATCOM) and UPFC help solve these issues by providing reactive power support, voltage control, and better power flow management, thereby improving microgrid stability and reliability.

A review from 2009–2025 highlights the use of FACTS devices in renewable source integrated microgrids to address voltage instability, power losses, and reactive power issues. Devices like STATCOM, Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), and UPFC improve voltage support, power flow control, and the overall performance of the system. Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) are two common optimization methods that help find the best locations for DG and FACTS devices. Overall, FACTS devices make microgrids more stable, efficient, and reliable. The paper [1] looks at how FACTS controllers can improve power system stability and dampen oscillations when the system is heavily loaded. Paper [2] presents a STATCOM-based Icosφ control algorithm that aims to improve voltage stability and power factor correction in renewable-integrated systems. The paper [3] examines Static VAR Compensator (SVC), TCSC, and UPFC and finds that they improve voltage stability, increase transmission capacity, and lower losses. The paper [4] shows that STATCOM makes Doubly Fed Induction Generator (DFIG) based wind systems more stable and better able to handle faults. The paper [5] examines Optimal Reactive Power Dispatch (ORPD) techniques that employ FACTS and optimization methods to enhance voltage profiles, minimize losses, and augment system stability.

The paper [6] describes the use of FACTS devices such as STATCOM, UPFC and TCSC for voltage regulation and reactive power compensation. FACTS technology integration is useful in solving power quality, congestion, and variability of renewable energy. Document [7] discusses the Life Cycle Sustainability Assessment (LCSA) framework for evaluating energy systems based on their environmental, economic, and social sustainability. The study [8] outlines a methodology for assessing and evaluating the economic viability of energy systems throughout their entire lifecycle. The paper [9] discusses how FACTS devices can help connect renewable energy sources and make the grid more stable and efficient.

According to the research [10], there are four main types of FACTS modeling and optimization approaches: analytical, arithmetic, meta-heuristic, and hybrid. The study [11] proposes a dual-tiered multi-objective optimization framework for the optimal positioning of FACTS devices to enhance their stability and cost-efficiency. The study [12] examines ORPD strategies that integrate FACTS devices with sophisticated mathematical and fractional optimization techniques. The research [13] employs Whale Optimization Algorithm (WOA) based optimization to identify optimal locations for FACTS devices to enhance stability and save costs. The paper [14] discusses on how successfully FACTS devices maintain the voltage stable in power systems that employ renewable energy.

The paper [15] investigates the roles of FACTS devices in enhancing voltage stability and reducing power loss in multi-microgrid systems. They observed that superior outcomes are obtained using intelligent strategies (such PSO and GA) for placing and sizing these devices. The study indicates more attention on integration of multi-microgrid with FACTS for better performance of power system. The study [16] presents the importance of FACTS devices such as SVC, TCSC, UPFC and Distributed Power Flow Controller (DPFC) for power quality and grid stability improvement while incorporating renewable energy sources such as wind and solar. It also explores the possibility of improving FACTS technology through the use of power electronics, control methods, and Artificial Intelligence (AI). It ends by stating that FACTS devices are important for today’s stable and efficient power systems.

This paper [17] reviews the role of FACTS devices in reactive power compensation to improve voltage stability, reduce losses and enhance power flow control. The devices like TCSC, SVC, STATCOM and UPFC are compared. It highlights UPFC as most effective for high level applications while STATCOM is suitable for smaller systems.

This study [18] gives a review on the role of FACTS devices including STATCOM, SVC, TCSC, SSSC and UPFC in improving voltage stability in renewable integrated power systems. It points out that higher renewable energy leads to voltage instability and FACTS devices help in controlling reactive power and improving system performance. Studies suggest that STATCOM support is superior than SVC. In addition, control approaches include model predictive control and neural network are examined to improve efficiency.

The paper [19] employs optimization techniques for the automatic placement of FACTS devices to enhance system reliability and voltage stability. The paper [20] shows how to use improved particle swarm optimization (IPSO) to improve power flow and cable size methods for DC microgrids to work more efficiently. In the paper [21], optimal placement of FACTS devices for the improvement of static security of microgrids is presented. Some performance indices and optimization algorithms are introduced to reduce the voltage violations and increase the system reliability. The document [22] suggests a comprehensive planning framework for the design of a durable microgrid, considering technical, economic, and social factors. The FACTS devices are used to improve power flow control and stability. The research [23] indicates the need of proper placement of these devices through sensitivity analysis approaches to locate optimal positions to improve power flow and decrease losses.

The paper [24] explores the possibility of FACTS devices to assist in congestion relief, RE integration and grid performance improvement without costly infrastructure modifications, but also discusses challenges like cost and complexity and suggests future improvements to make these devices even more successful. This paper [25] discusses the enhancement of power quality and reductions in power systems by identifying the optimal location and size for a UPFC using sensitivity index analysis evaluating the total harmonic distortion, fine congestion, and active and reactive power losses. The method is practical, scalable, and cost-effective for modern power grid optimization.

In the work [26], the placement of FACTS devices in power system has been explored with the purpose to increase the loading limit of transmission line and also reduce the losses using Artificial Bee colony algorithm (ABC). In the study [27], various evolutionary techniques are proposed for optimal location and sizing of FACTS devices for minimization of transmission loss, enhancement of stability of power system. The paper [28] presents a full picture of the latest FACTS designs, new control approaches, and new technologies, including modular UPFCs. This research [29] has introduced a microgrid and its modeling with the real environmental data and the challenges of micro grid and power quality problems are noticed. Moreover, compensating methods using different control techniques, algorithms and devices against these problems are examined.

From the above literature review, UPFC is the best FACTS device for the proposed distribution microgrid. Therefore, the study suggests simultaneous optimal placement of distributed generators (DGs) and FACTS device (UPFC) in the microgrid so as to maximize Renewable Energy (RE) penetration and minimize line losses, and voltage stability and small signal stability also addressed during optimization.

II. METHODOLOGY AND PROBLEM FORMULATION

A. methodology

For this work, the IEEE 33-bus system is used as the base model and modified into a microgrid by integrating distributed generation sources such as solar, wind, and Solid Oxide Fuel Cell (SOFC) as storage units. The microgrid also includes a diesel generator as a constant source of power. For the optimization of the proposed microgrid, metaheuristic algorithms, namely NSGA-II and MOPSO, are selected. The system is optimized for renewable energy integration and line loss minimization through the strategic positioning of distributed generation sources (DGs) and UPFC.

The strategy for achieving the target is illustrated in Fig. 1. The literature study indicates that FACTS devices, including the Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC), have significance for enhancing the stability and performance of contemporary power systems. Based on this, UPFC is selected as the FACTS device for the enhancement of grid performance.

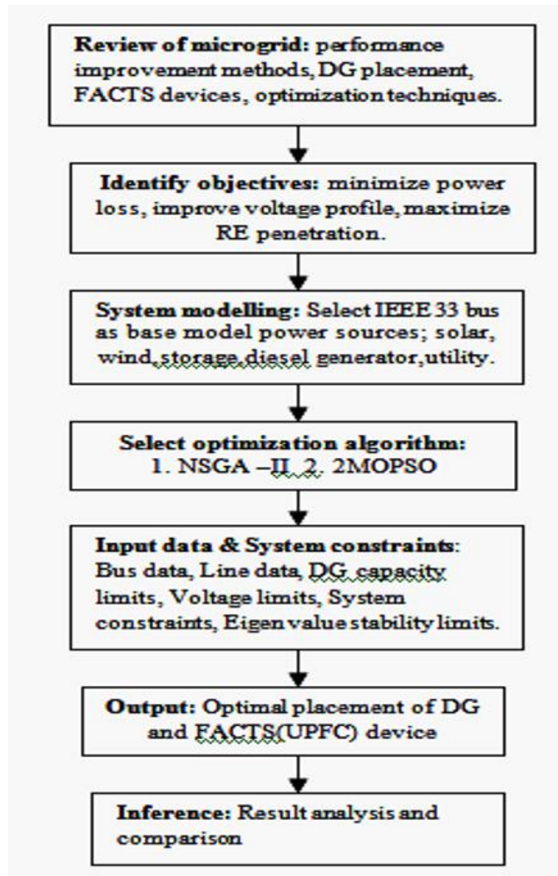

Fig.1: Methodology

B. Problem formulation

The goal of the suggested microgrid system is optimal use of renewable energy sources while keeping the system stable and minimizing power (line) losses through suitable placement of DGs and FACTS device. The optimization problem is structured with objective functions, incorporating both equality and inequality constraints. The objective functions seek to optimize renewable energy production while minimizing overall line losses within the system. The equality constraints provide the system's power balancing equations, and the inequality constraints show the limits on voltage and power generation sources that the microgrid can use.

The optimization problem is therefore formulated as follows,
The main objectives of the work are to maximize the renewable energy generation and minimize the network power loss.

$f_1 = \max(P_w + P_{spv})$ (1)
$f_2 = \min(P_{loss})$ (2)
Were, $P_{loss} = I^2R$

P_w = Wind power generation in MW
P_{spv} = Solar photovoltaic power generation in MW
P_{loss} = Total power (line) loss in each line of the system in MW

i) Equality Constraints
The equality constraints represent the power flow equations which ensure the balance between generated and consumed power at each bus of the microgrid.

Active Power balance equation
$P_k = \sum_{j=1}^{N}|V_k||V_j|[G_{kj}\cos(\theta_k - \theta_j) + B_{kj}\sin(\theta_k - \theta_j)]$ -(3)

Reactive Power balance equation
$Q_k = \sum_{j=1}^{N}|V_k||V_j|[G_{kj}\sin(\theta_k - \theta_j) - B_{kj}\cos(\theta_k - \theta_j)]$ -(4)
P_k = Active power at bus k
Q_k = Reactive power at bus k
V_k, V_j = Voltage magnitudes at buses k and j
G_{kj} = Conductance between bus k and j
B_{kj} = Susceptance between bus k and j
θ_k, θ_j = Voltage phase angles
N= Total number of buses in the system
These equations maintain the power balance in the microgrid network.

ii) Inequality Constraints
The inequality constraints represent the operating limits of voltage and power generation in the microgrid.

The voltage limits at each bus are specified as:
$0.9 \le V_k \le 1.1$ p.u.- (5)

This ensures that the bus voltage remains within the permissible operating range. The power generation from energy sources in the microgrid is limited by their installed capacity and operational constraints. The power generation limits for each source are shown below.

Solar: $0 \le P_{spv} \le 1$ MW - (6)
Wind: $0 \le P_{wind} \le 2$ MW - (7)
Storage: $0.2 \le P_{SOFC} \le 1$ MW - (8)
Diesel Generator: $0 \le P_{pv} \le 0.5$ p.u. - (9)

III. IEEE 33- BUS MICROGRID SYSTEM AND OPTIMIZATION STRATEGY

The microgrid system used in this study is developed by modifying the standard IEEE 33-bus distribution system. The Fig. 2 represents the IEEE-33 bus model. The IEEE 33-bus radial distribution system is adopted as the benchmark test feeder to validate the effectiveness of the proposed approach.

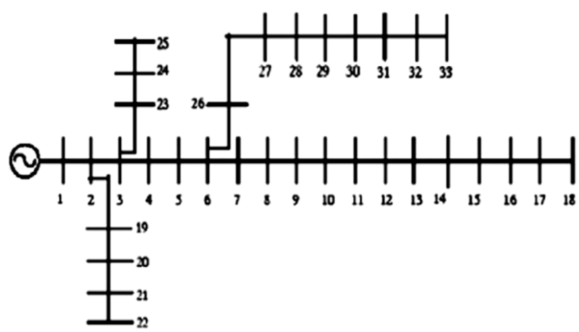

Fig. 2 IEEE33 bus standard system (base model)

The system consists of 33 buses and 32 lines and operates at a nominal line voltage of 12.66 kV with a base apparent power of 100 MVA. Bus #1 is selected as the slack bus, and bus # 2 to 33 are modeled as load buses. The total connected load of the system is 3.715MW and 2.3MVAr. The bus data and line data are extracted from the study presented in [31].

A) Optimization Strategy for the Proposed IEEE33 Bus Microgrid System.
In this work, the optimization problem is taken as multi objective optimization problem and solution is obtained by an algorithmic approach. The goal of the optimization technique is to enhance the share of renewable energy and reduce line losses by locating DGs and FACTS device (UPFC), in the right places by keeping bus voltage stability and small signal

stability within the margin. This study employs metaheuristic algorithms namely NSGA-II and MOPSO, along with a comparative evaluation of the presented algorithms.

i) NSGA-II Approach

These algorithms are selected due to their strong capability in handling multi-objective problems involving conflicting goals such as voltage stability, power loss minimization, and cost efficiency. In the proposed work, these algorithms are used to simultaneously minimize line losses, improve voltage profile, and maximize distributed generation (DG) penetration through proper placement of DGs and FACTS device. The proposed two algorithms use forward backward sweep method for the multi objective optimization for the best performance [32, 33].

NSGA-II is based on evolutionary principles and generates a well distributed pareto front using non-dominated sorting and crowding distance. It is a systematic method for solving multi-goal problems, initiating with a diverse group of possible solutions. These are evaluated against objective functions like maximizing RE share, reducing power loss, and enhancing voltage stability. Solutions undergo non-dominated sorting into Pareto fronts, using crowding distance to maintain diversity. Genetic operations selection, crossover, and mutation create new offspring solutions from parent and offspring populations. This iterative process continues until convergence or a stopping criterion is met, resulting in a Pareto front that illustrates the best trade-off solutions among the goals.

ii) MOPSO Approach

Microgrid optimization makes sure that system operates smoothly and efficiently by controlling power flow and resources well. This work utilizes MOPSO to determine the most advantageous sites for FACTS devices and DGs, consequently minimizing losses and improving voltage stability [34].

It is a version of the Particle Swarm Optimization (PSO) technique to assist in multiple objective problems. MOPSO uses swarm intelligence and particle movement to search for optimal solutions efficiently. First, it produces a swarm of particles, each one representing a possible solution in the search space. After that, these particles are examined with more than one objective function, such as minimizing line losses and maximizing RE share, through optimal location of DGs and FACTS device. Each particle maintains its personal best position (pBest), and a repository (archive) is used to store non-dominated solutions. From this repository, a global best (gBest) is selected to guide the swarm.

IV. RESULT AND DISCUSSIONS

The optimal operation of IEEE-33 bus microgrid without and with FACTS device is performed using NSGA-II and MOPSO algorithm. The best compromise solution obtained from the optimization represents an optimal balance between power generation, load demand, and loss minimization in the microgrid. The target is achieved without compromising the system stability in terms of voltage stability and small signal stability.

A) NSGA-II Optimization Result

The table 5.1 represents the analysis of result obtained by NSGA -II algorithm (without and with FACTS devices). The best locations of DGs and UPFC are provided within brackets with sources in the Table 1. Contributions from renewable sources (solar and wind), storage, and diesel generator are also maintained at consistent levels. With FACTS (UPFC), the line losses is 0.0165MW (0.4%) whereas, without UPFC the losses is 0.1035MW (2.5%). FACTS devices help reduce line losses by providing reactive power compensation, improving voltage profiles, and controlling power flow, reducing line current and associated I^2R losses. The best place to connect the UPFC at Bus #30 works because it increases power flow, lowers losses, and keeps the system in balance.

Table 1. Power flow Analysis of of optimized IEEE-33 Bus microgrid using NSGA-II method

Parameters	Without FACTS	With FACTS (UPFC, Bus #30)
Total Generation in MW	4.148	4.148
RE (Solar (Bus #14) + Wind (Bus# 30)) in MW	2.648	2.648
Storage (Bus# 24) in MW	1.000	1.000
PV (Bus 7) in MW	0.500	0.500

Total Load in MW	3.715	3.715
Line Loss in MW	0.1035 (2.5%)	0.0165 (0.4%)

i) Bus Voltage Analysis

The comparison of bus voltage achieved under different operating conditions is shown in the Fig. 3. The optimized microgrid with UPFC improves all the bus voltages except the slack bus. With the best location of UPFC voltages at all buses are within the limit and close to 1.00p.u. This is especially true for the weaker buses (Bus #26–33). In general, the profile gets smoother, with fewer voltage drops and a system that works better.

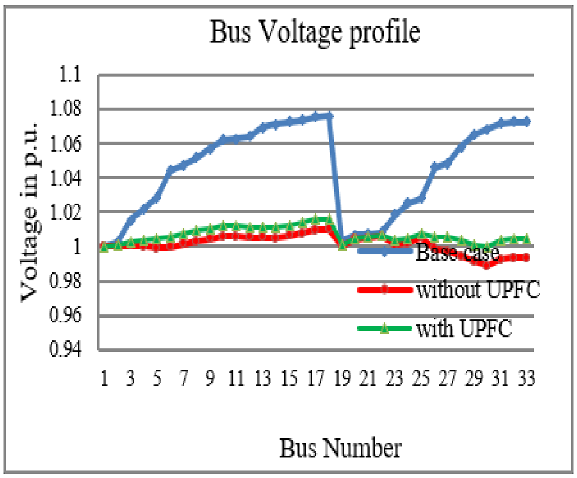

Fig. 3 Voltage Profile of Optimized IEEE-33 Bus microgrid using NSGA-II method

ii) Power Generation Analysis

The UPFC improves the performance and efficiency of the whole system. The overall line loss in the microgrid without UPFC is 0.1035 MW. This means that power is not being transferred efficiently and there are more line losses. The overall loss drops significantly to 0.0165 MW once the UPFC is added. This is because the UPFC adds 1.218 MVAR of reactive power at Bus #30. The power generation of various sources in the optimized microgrid is presented in Fig. 4 and the total RE share is 2.648MW (approx. 88% of total RE capacity). The UPFC actively controls both voltage magnitude and power flow, which minimizes reactive power imbalance and reduces current flow in the lines.

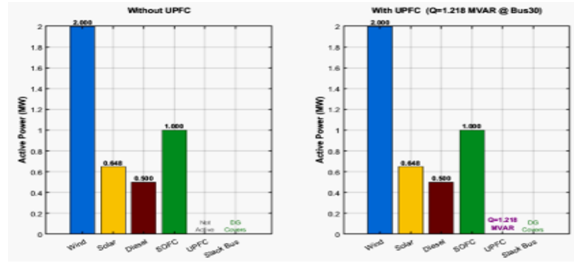

Fig .4 Power Generation Profile of Optimized IEEE-33 Bus microgrid using NSGA-II method (without and with UPFC)

The UPFC elevates the voltage at Bus# 30, and this enhances the overall voltage profile and reduces stress on the system. It ensures that no single segment of the network receives an excessive amount of power by distributing it more evenly across various generation sources, including wind, solar, diesel, and SOFC. The UPFC enhances microgrid performance by reducing the reactive power demand on the slack bus and improving transmission efficiency. This is an effective method to maintain voltage stability and reduce losses. The UPFC makes the energy system more reliable by making power distribution more efficient. This means that it can handle changes in demand and supply. So, it not only helps bring together renewable energy sources, but it also helps the microgrid have a smaller carbon imprint.

(iii) Stability Analysis

Stability analysis using eigenvalue distribution in the S -plane is used to evaluate the dynamic performance of the microgrid system. The location of eigenvalues determines whether the system is stable or unstable. The graphical representation of microgrid system stability after optimization (without & with FACTS) is given below in Fig. 5(a) and (b).

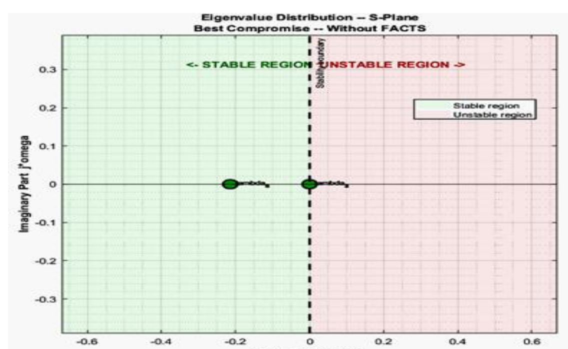

Fig.5 (a) Eigenvalue stability analysis of optimized microgrid using NSGA-II method (without UPFC)

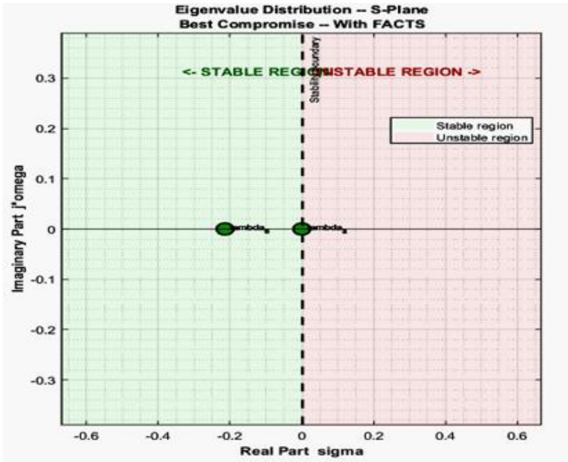

Fig.5 (b) Eigenvalue stability analysis of optimized microgrid using NSGA-II method (with UPFC)

Eigenvalue analysis demonstrates marginal stability before and after the installation of UPFC. This is because the UPFC is modeled for steady-state power flow regulation without specific dynamic or damping control methods. Hence its contribution to the small signal stability is minimal.

B) MOPSO Result Analysis

The reliability of microgrids is due to effective control of power flow and distributed resources. In this paper, the MOPSO algorithm is employed to validate the results obtained from NSGA-II method. The results obtained are the set of Pareto optimal solutions that provide optimal solution between power generation, load demand and minimizing power loss in the microgrid. The Table 2 represents the power flow report of MOPSO (without &with FACTS devices).

Table 2. Power flow Analysis of Optimized IEEE-33 Bus microgrid using MOPSO method.

Parameters	Without FACTS	With FACTS (UPFC, Bus# 30)
Total Generation in MW	4.189	4.189
RE (Solar (Bus #14) + Wind (Bus# 30)) in MW	2.694	2.694
Storage (Bus #24) in MW	0.995	0.995
PV (Bus #7) in MW	0.500	0.500
Total Load in MW	3.715	3.715
Line Loss in MW	0.1071 (2.56%)	0.0170 (0.41%)

The line loss without UPFC is 0.1071 MW (2.56%), while with UPFC, it is 0.017 MW (0.41%). This means that connecting the UPFC at Bus#30 makes the microgrid work better by enhancing power flow more efficiently, lowering losses, and improving the performance of the whole system. The outcomes obtained using MOPSO are fairly similar to the NSGA-II technique.

i) Bus Voltage Analysis

Fig.6 shows how the voltage profile changes with the solution of MOPSO technique. In this manner too all the bus voltages except slack bus improved after placing the UPFC at Bus#30. Here also the voltage profile becomes smoother with less voltage drop and enhancing system stability.

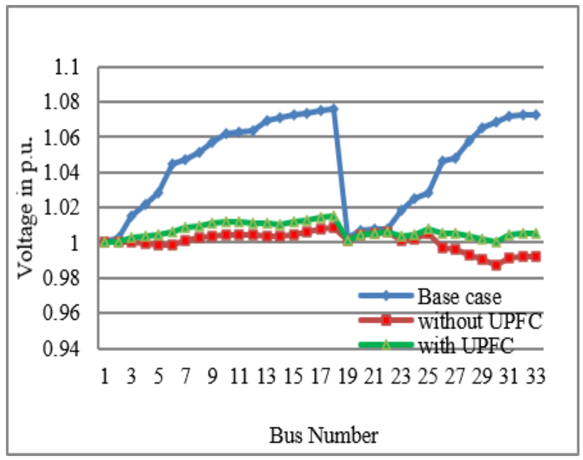

Fig.6 Bus voltage profile of Optimized IEEE-33 Bus microgrid using MOPSO method

ii) Power Generation Analysis

In MOPSO method, the total renewable energy share is 2.694 MW (approximately 90% of the total renewable energy capacity) without compromising system stability. The total real power loss in the base case (without UPFC) is 0.1071 MW, and after the UPFC is added, which injects 1.175 MVAR of reactive power at Bus #30, the total line loss drops to 0.0170 MW. This is because the UPFC effectively controls both voltage magnitude and power flow, which reduces reactive power imbalance and line currents, which lowers I^2R losses. Fig.7 shows the power delivered by different DGs, in both cases (without and with UPFC), using the MOPSO algorithm.

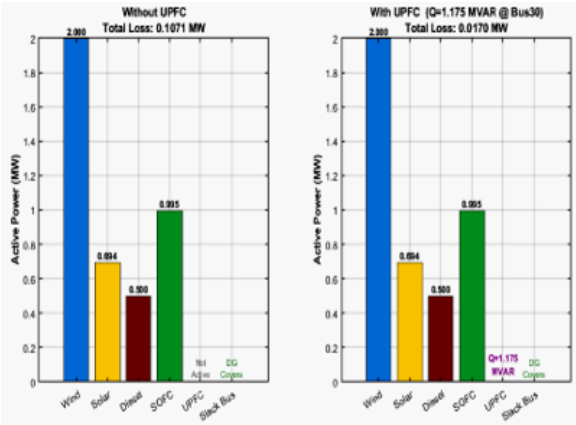

Fig .7 Power Generation Profile of microgrid using MOPSO method (without and with UPFC)

The UPFC also improves voltage support which improves the overall voltage profile and reduces stress on the system. The power generation from sources like wind, solar, diesel, and SOFC stays the same, which means that the improvement is due to better power flow control rather than changing generation. The UPFC is a good way to reduce losses and make voltage more stable because it makes transmission more efficient by lowering the reactive power load on the slack bus. This makes the microgrid more stable, balanced, and reliable.

(iii) Stability Analysis

Fig. 5.8 shows the small signal stability analysis of the optimized microgrid system with and without the UPFC device. The small signal stability behavior obtained using the MOPSO method is similar to that obtained using the NSGA-II method. In both cases, the system remains marginally stable.

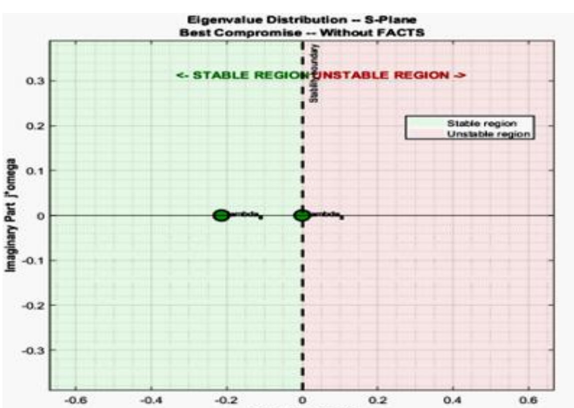

Fig.8 (a) Eigenvalue stability analysis of optimized microgrid (without UPFC)

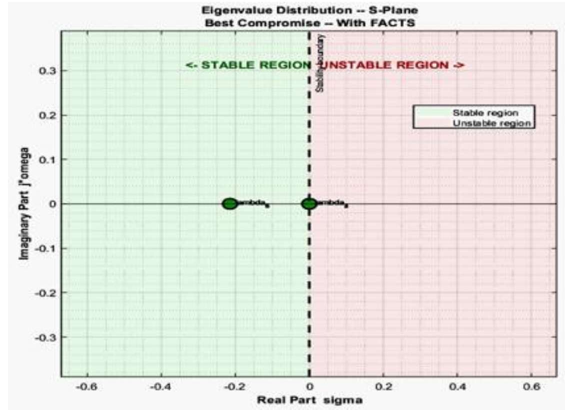

Fig.8 (b) Eigenvalue stability analysis of optimized microgrid (with UPFC)

The comparison between NSGA-II and MOPSO shows that both optimization algorithms effectively improve the performance of the microgrid system without disturbing the power balance. The generation, load, and contributions from renewable sources such as solar, wind, storage, and PV remain almost identical in both methods, indicating that the optimization focuses on enhancing system efficiency rather than altering generation distribution. Both algorithms successfully determine the optimal placement of the UPFC, ensuring better reactive power support and improved voltage stability across the network.

The comparison of the power flow reports obtained using NSGA-II and MOPSO techniques reveals a significant improvement in power loss reduction for both methods. In NSGA -II, the power loss decreases from 0.1035 MW (2.5%) to 0.0165 MW (0.4%), while in MOPSO, it reduces from 0.1071 MW (2.56%) to 0.017 MW (0.41%). Both methods provide power loss reduction; however, MOPSO performs slightly better in terms of percentage loss reduction and renewable energy contribution. Overall, both algorithms perform well in multi-objective optimization, enhancing the efficiency of the system.

V. CONCLUSION

The microgrid system improves sustainability and reduces dependence on conventional power generation; however, it also introduces significant operational challenges. In this work, the performance of the microgrid system is enhanced by integrating a FACTS device, namely the UPFC. The main aim of this paper is to minimize the line losses and optimize the penetration of renewable energy to the system by optimal placement of the FACTS device and DGs. Voltage stability and small signal stability are considered during the optimization process. Metaheuristic algorithms namely NSGA-II and MOPSO are used to achieve these objectives.

In this paper, the IEEE 33-bus system is modeled as a microgrid with solar, wind and energy storage systems. A FACTS device (UPFC) is added to improve the system performance. Bus #30 was found to be the best location for the UPFC to improve the power flow control and reduce the losses by effectively compensating the reactive power and regulating the voltage. Multi-objective optimization algorithms have been applied for the optimization of the location and size of the FACTS devices and DGs which led to improved voltage stability and minimum line losses satisfying the system constraints.

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