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Enhancing the Operational Reliability of Grid-Interactive Hybrid Microgrids: Challenges and Solutions

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ABSTRACT

The growing demand for decentralized and resilient power systems, supported by advancements in generation and storage technologies, has driven the development of hybrid microgrids. Among various operational challenges, voltage unbalance in low-voltage, three-phase hybrid microgrids remains a critical issue, as it adversely affects system performance, equipment lifespan, and power quality. This unbalance primarily arises from uneven single-phase load distribution, non-linear loads, and faulty equipment.

Conventional mitigation methods often depend on network parameters that are not directly measurable by inverters, require additional hardware, or rely heavily on communication between distributed generators. To overcome these limitations, this study proposes a perturb-and-observe-based voltage unbalance mitigation strategy for four-leg inverter systems interfacing distributed generators with low-voltage microgrids. The method injects a negative-sequence current at the inverter's point of connection and iteratively adjusts system parameters to minimize voltage unbalance. A dedicated control strategy is developed to implement this technique using three-dimensional space vector modulation.

Additionally, optimization techniques are employed to determine the optimal placement of inverters to reduce total voltage unbalance and active power losses. Simulation results on unbalanced radial distribution systems validate the effectiveness and robustness of the proposed approach.

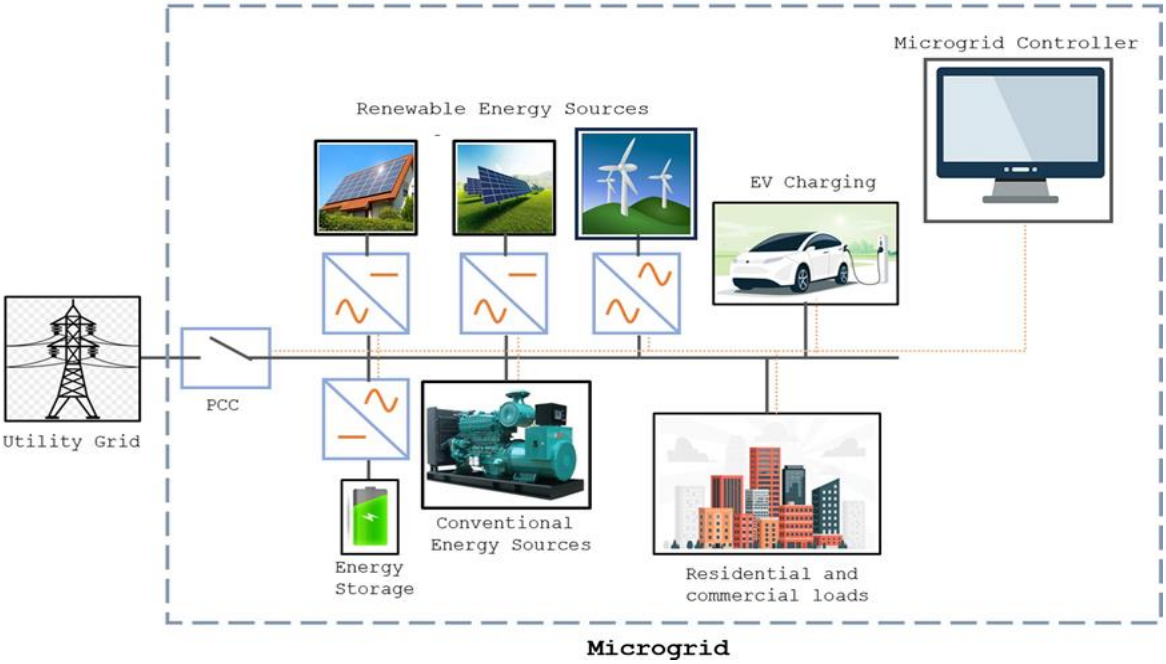
Keywords: Hybrid-Microgrid, Voltage Unbalance, Active power, Distributed Generators,DER.

1.Introduction

1.1 Microgrid

A traditional electrical grid is a centralized power distribution network that supplies electricity over a large geographical area—often an entire region or country. In such systems, power is generated at large-scale plants and transmitted over long distances to consumers through extensive transmission and distribution networks.

In contrast, a microgrid is a localized, small-scale power distribution system capable of operating either independently (islanded mode) or in coordination with the main grid (grid-connected mode). It typically serves confined areas such as neighbourhoods, campuses, islands, or industrial parks, integrating various Distributed Energy Resources (DERs) including renewable sources, energy storage systems, and conventional generators. The main differences between a traditional grid and a microgrid lie in their scale, autonomy, and the deployment of distributed generation.



1.2 Basic Components of a Hybrid Microgrid

A hybrid microgrid comprises several key components that enable efficient, flexible, and reliable power generation, storage, and distribution:

- Distributed Energy Resources (DERs):
  DERs encompass decentralized energy technologies such as generators, storage systems, and demand-response mechanisms. They enhance grid flexibility, renewable integration, and resilience.

  - Distributed Generators (DGs): Include renewable sources like solar PV, wind, hydro, and biomass, as well as conventional diesel or gas generators.
  - Energy Storage Systems**:** Technologies such as batteries, flywheels, supercapacitors, and pumped hydro store excess energy and stabilize supply.
  - Electric Vehicles (EVs): Function as both loads and storage units, enabling vehicle-to-grid (V2G) interactions.
- **Power Conversion Systems:**
  Inverters, rectifiers, and converters ensure compatibility between various energy sources and loads, managing AC/DC power flow within the microgrid.
- **Microgrid Controller:**
  The controller manages generation, storage, and consumption using real-time data, control algorithms, and communication infrastructure to maintain stability, frequency, and voltage
- **Grid Interconnection:**
  Microgrids connect to the utility grid at the Point of Common Coupling (PCC), allowing bidirectional power exchange. Some systems operate off-grid, without a PCC.
- **Loads and Consumers:**
  These include residential, commercial, or industrial users and their electrical equipment. The growing number of EVs represents a significant and dynamic load.

1.3 Modes of Operation of a Microgrid

Microgrids operate in two primary modes: grid-connected and islanded.

Grid-Connected Mode

- Power Exchange: The microgrid imports or exports power depending on internal demand and generation balance.
- Grid as Backup: The utility grid provides support when local generation is insufficient, ensuring continuity of supply.
- Synchronization: The microgrid must align its voltage and frequency with the utility grid using control mechanisms such as grid-support inverters.
- Power Quality: It must maintain voltage and frequency within acceptable limits, contributing to overall grid stability.
- Regulations and Tariffs: Operation adheres to import/export tariffs and net-metering policies, ensuring fair energy exchange.

Islanded Mode

- Energy Self-Sufficiency: The microgrid relies solely on internal DERs and storage to meet demand.
- Autonomous Operation: Advanced control and energy management systems maintain stability and reliability.
- Islanding Detection and Protection: Protection schemes such as anti-islanding relays ensure safe disconnection and reconnection.
- Load Shedding and Prioritization: Non-critical loads may be shed to balance supply and demand during shortages.

- Reconnection: Synchronization and protection mechanisms ensure safe transition back to grid-connected mode.

1.4 Advantages of Hybrid Microgrids

- Enhanced Resilience: Maintain power supply during grid outages, supporting critical infrastructure.
- Localized Generation: Reduce transmission losses and enhance efficiency by producing power close to consumption points.
- Renewable Integration: Enable efficient use of distributed renewable sources and support EV integration.
- Cost Savings: Lower transmission costs, enable energy trading, and support demand response programs.
- Grid Support and Independence: Provide ancillary services such as voltage regulation and frequency control, and enable energy autonomy for communities.

2 Microgrid Control

Microgrid control structures are classified as centralized or decentralized, with a hierarchical control architecture often adopted to balance both. The hierarchy consists of three levels: primary, secondary, and tertiary control.

- **Primary Control:**
  The fastest level, responsible for stabilizing voltage and frequency, sharing real/reactive power, and ensuring plug-and-play operation of DERs.
- **Secondary Control:**
  Operates at a slower pace to restore voltage and frequency deviations, maintain power quality, and provide setpoints for primary controllers.
- **Tertiary Control:**
  The slowest level, managing power exchange with the main grid while optimizing economic operation through load forecasting, price analysis, and generator dispatch planning.

2.1 Causes of Voltage Unbalance in Microgrids

Voltage unbalance in microgrids can arise from several factors:

- Uneven Distribution of Single-Phase Loads:
  Connecting single-phase loads unevenly across the three phases leads to unequal current and voltage distribution, causing phase unbalance.
- Non-Linear Loads:
  Devices such as variable speed drives and electronic equipment draw non-sinusoidal currents that introduce harmonics and uneven phase currents, resulting in voltage unbalance.
- Faulty Equipment:
  Malfunctioning components—such as open or shorted transformer windings or faulty generator connections—can cause unequal phase voltages.

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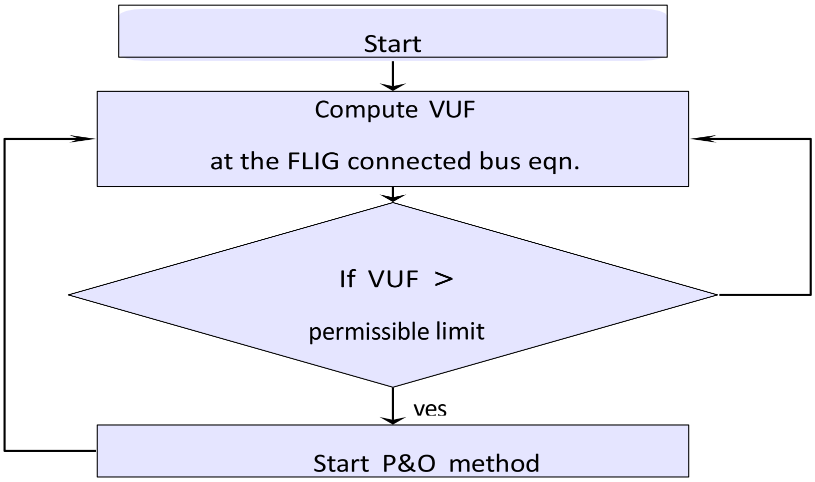
- Grid Disturbances:
  External grid faults, voltage sags/swells, or sudden load changes can disturb balanced conditions and create voltage unbalance in the microgrid.

2.2 Effects of Voltage Unbalance in Microgrids

Voltage unbalance adversely affects microgrid performance and equipment reliability in several ways:

- Increased Equipment Stress:
  Unbalanced voltages cause uneven heating and mechanical stress in electrical equipment, accelerating ageing and increasing failure risk.
- Reduced Efficiency:
  Motors and other devices operate less efficiently under unbalanced conditions, leading to higher losses, lower power factor, and increased operational costs.
- Equipment Malfunctions:
  Sensitive electronic devices may experience erratic operation or damage due to unequal phase voltages, compromising system reliability.
- Poor Power Quality:
  Voltage unbalance contributes to harmonic distortion, flicker, and voltage fluctuations, degrading overall power quality.
- System Instability:
  Persistent voltage unbalance can cause voltage drops, surges, and instability in protection and control systems, affecting microgrid reliability.

The flowchart for the developed method is shown in Fig



ISSN: 2320-3714
Volume: 4 Issue: 2
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3.0 Case Study I: 25-Bus System

The first test system considered is a **4.16 kV, 25-bus unbalanced radial distribution network**, as shown in *Fig.*

Optimal Placement of a Single FLIG

The effect of installing a single Four-Leg Inverter-based Generator (FLIG) on real power loss and the System Voltage Unbalance Factor (SVUF) is analyzed.

Initially, without any FLIG installation, the system parameters are as follows:

- SVUF: 8.34
- Reactive power loss: 167.28 kVAR
- Real power loss: 150.12 kW

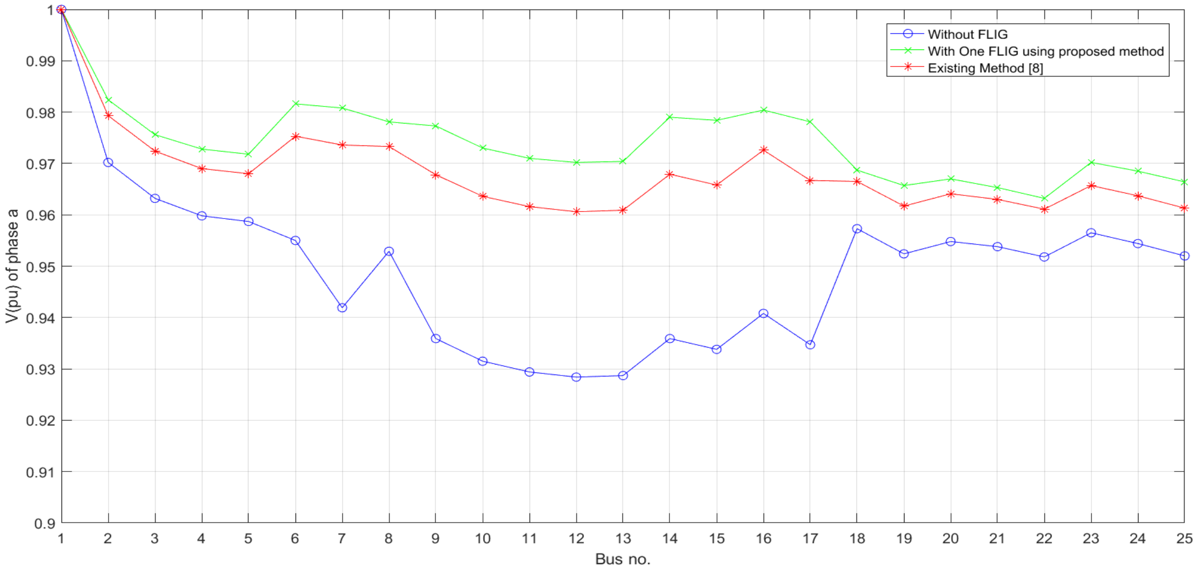
Using the weighted-factor-based Multi-Objective Particle Swarm Optimization (MOPSO) technique, the optimal FLIG placement is determined to be at Bus 7, with an optimal rating of 1890 kW. After installation, the results show significant improvement:

- SVUF: reduced to 2.49
- Reactive power loss: reduced to 76.22 kVAR
- Real power loss: reduced to 67.67 kW

For comparison, Bhimarasetti *et al.* installed a 1945 kW Distributed Generator (DG) at Bus 7. Their approach resulted in an SVUF of 5.45, reactive power loss of 87.35 kVAR, and real power loss of 79.58 kW.

The proposed method achieves a 74.06% reduction in SVUF, 54.43% reduction in reactive power loss, and 54.94% reduction in real power loss compared to the existing method.

Figures illustrate the voltage profile comparison for single-FLIG placement. The proposed FLIG-based approach with voltage unbalance compensation significantly improves voltage profiles while substantially minimizing SVUF and power losses, demonstrating its effectiveness and superiority over the referenced method.



Non-dominant solutions for placement of one FLIG in the 25-bus URDS

Location	FLIG Size (kW)	Reactive Power Loss (kVAR)	Real Power Loss (kW)	SVUF
3	2830	72.78	73.29	2.35
6	2296	76.41	71.57	2.37
7	1890	76.22	67.77	2.49

4.0 Case Study II: IEEE 13-bus system

The second test system is the standard 4.16 kV IEEE 13-bus URDS illustrated in Fig. This system has three-phase, single-phase, and two-phase buses. As FLIGs can only be integrated into three-phase buses, their placements are also restricted to the three-phase buses. Single-phase and two-phase buses are excluded from SVUF computations. The total load of the system is 3466 kW and 2101.59 kVAR.

Optimal placement of one FLIG

Without any FLIG installed, the SVUF, reactive power loss, and real power loss for the IEEE 13-bus URDS are 14.32, 433.44 kVAR, and 147.39 kW, respectively. For the placement of one FLIG using the weighted factor-based MOPSO, the optimal location obtained is bus 7 (or 12 with the switch closed). Fig. 4.12 shows the objective function's plot at various buses. With one FLIG installed, the SVUF, reactive power loss, and real power loss are reduced to 8.54 (-40.36%), 154.44 KVAR (-64.37%), and
59.47 kW (-59.65%), respectively.

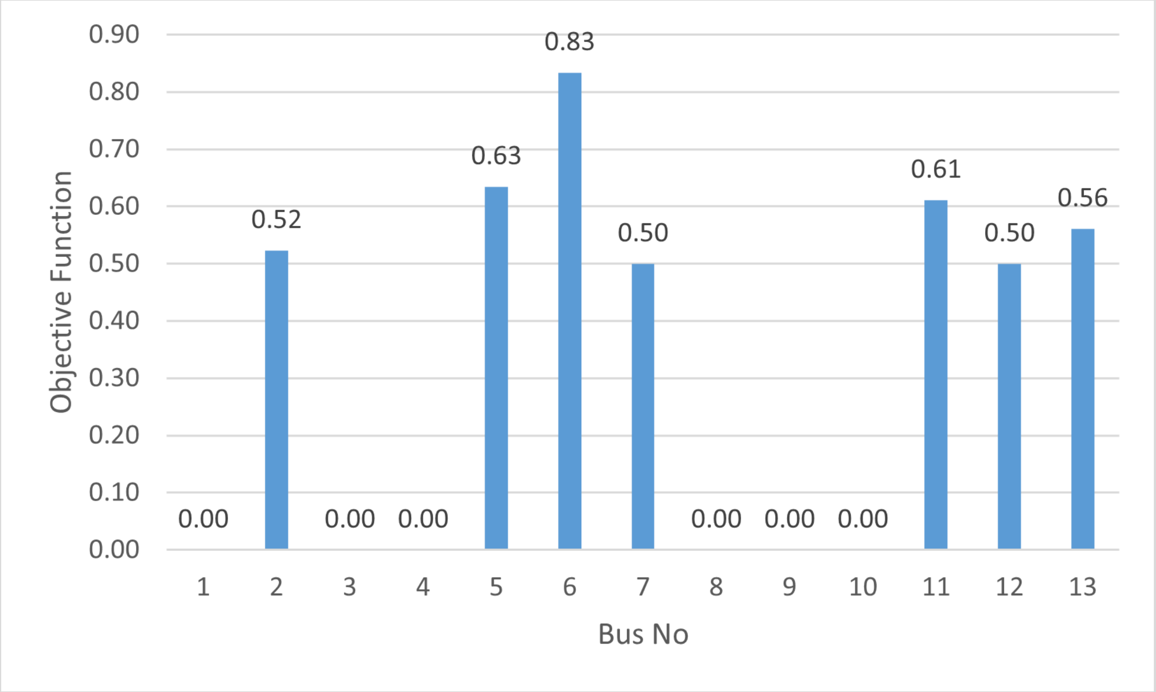


Fig. Plotting of objective function for placement of one FLIG in the 13-bus URDS using weighted factor-based MOPSO

Using Pareto-based MOPSO to place one FLIG results in obtaining three non- dominant solutions. The numerical results are presented in Table, while the Pareto front of these solutions is illustrated in Fig. Placing the FLIG at bus 7 yields a minimum real power loss of 59.47 kW, while placing it at bus 2 yields a minimum SVUF of 6.2. The best-compromised solution is achieved by placing the FLIG on bus

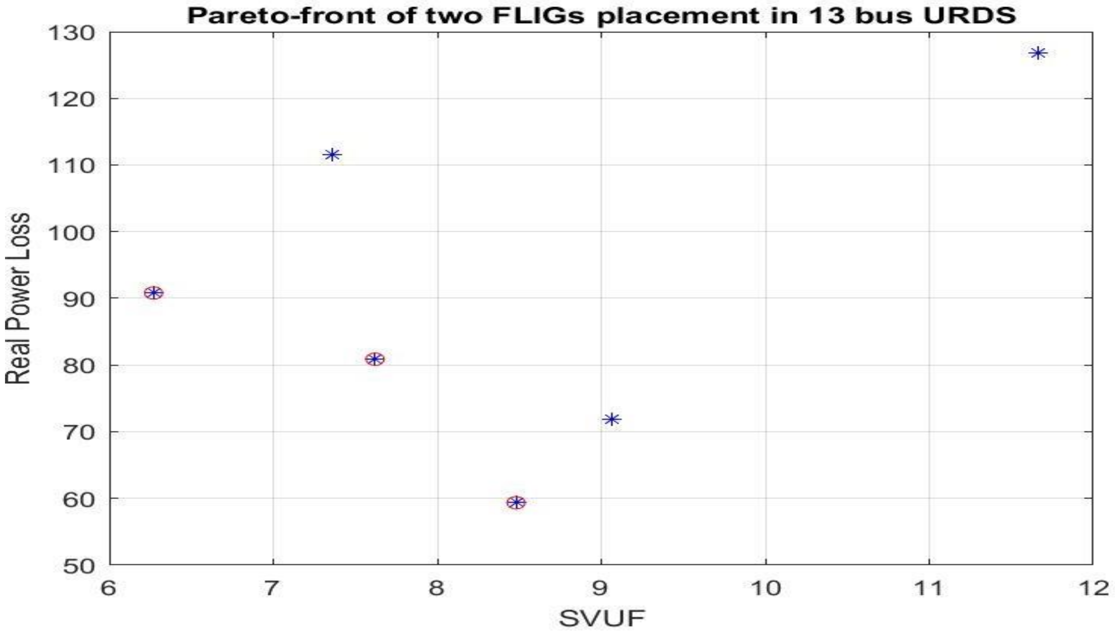


Fig. Pareto front for placement of one FLIG in the 13-bus URDS

Table Non-dominant solutions for placement of one FLIG in the 13-bus URDS

Location	FLIG Size (kW)	Reactive Power Loss (kVAR)	Real Power Loss (kW)	SVUF
2	3232	251.97	90.42	6.2
7	3232	154.44	59.47	8.54
11	2178	214.98	80.88	7.62

Optimal placement of two FLIGs

Using weighted factor-based MOPSO, buses 2 and 7 are found to be the optimal locations for two FLIGs placements. Fig. 4.14 displays the objective function values for the installation of these two FLIGs. The total SVUF observed are 1.03, with reactive power loss at 134.89 kVAR and real power loss at 55.12 kW. These values represent a significant reduction in SVUF, reactive power loss, and real power loss by 92.81%, 68.86%, and 62.5%, respectively. Table. 4.6 presents a comparison of the results for each test scenario.

Three alternatives for the placement of two FLIGs were identified using the Pareto method. The Pareto front of non-dominant solutions is shown in Fig. 4.15, and Table. 4.7 presents the corresponding numerical outcomes. The placement of two

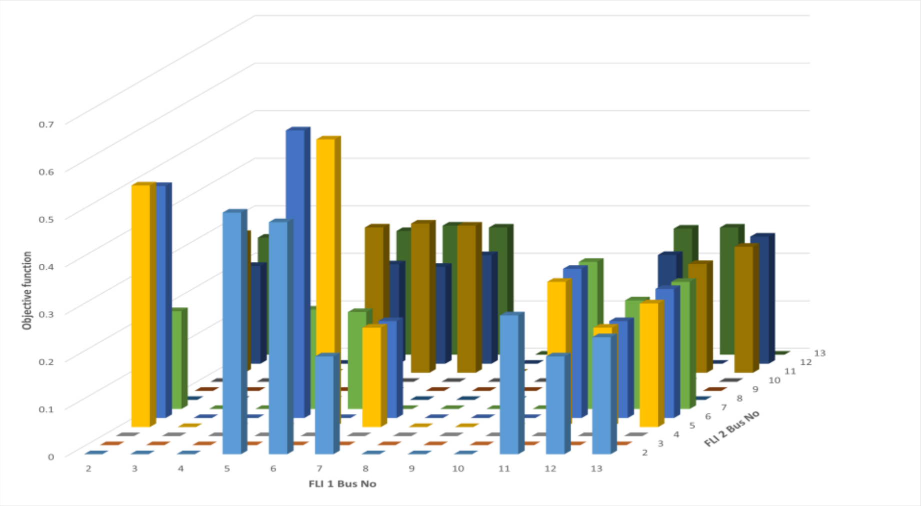


Fig. Plotting the objective function for the installation of two FLIGs in the IEEE 13-bus system using the weighted factor-based MOPSO.

Table: Comparison of results for placement of FLIGs in the 13-bus URDS

	Without FLIG	With One	With Two
Location	—	FLIG 7	FLIGs 2 & 7
DG size (kW)	—	3232	934 & 2449
Real Power Loss (kW)	147.39	59.47	55.12
Reactive Power Loss (kVAR)	433.44	154.44	134.89
SVUF	14.32	8.54	1.03

FLIGs at buses 6 and 7, with capacities of 582 kW and 2518 kW respectively, yields the minimum real power loss. This solution results in an SVUF of 1.95, a reactive power loss of 131.44 kVAR, and a real power loss of 51.99 kW. Placing FLIGs at buses 2 and 7, with capacities of 934 kW and 2449 kW respectively, yields the maximum reduction in SVUF. In this solution, the observed SVUF is 1.03, with reactive power loss at 134.89 kVAR and real power loss at 55.12 kW. The best-compromised solution involves placing two FLIGs of 632 kW and 2825 kW at buses 5 and 7 respectively. This solution results in an observed SVUF of 1.27, a reactive power loss of 136.67 kVAR, and a real power loss of 55.08 kW.

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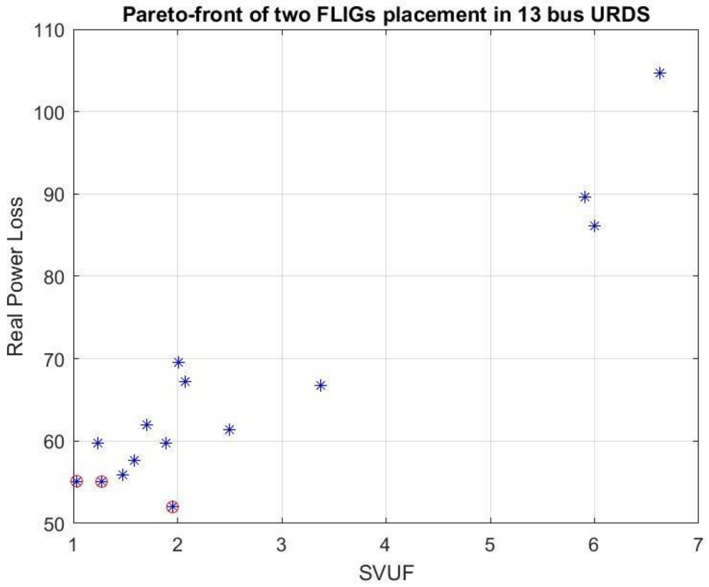

Fig. Pareto front for placement of two FLIGs in the 13-bus URDS Table

Non-dominant solutions for placement of two FLIGs in the 13-bus URDS

Location	FLIG Sizes (kW)	Reactive Power Loss (kVAr)	Real Power Loss (kW)	SVUF
2 & 7	934 & 2449	134.89	55.12	1.03
5 & 7	632 & 2825	136.37	55.08	1.27
6 & 7	582 & 2518	131.44	51.99	1.95

5.Conclusion and Recommendation:

Voltage unbalance is one of the most critical operational challenges in low-voltage microgrids. It primarily arises from the unequal distribution of single-phase loads among the three phases. Additional contributors include unbalanced three-phase loads and faulty electrical equipment, which further aggravate system imbalance.

A review of the existing literature reveals several methods for mitigating voltage unbalance. Conventional solutions, such as the use of active shunt or series filters and STATCOMs, can effectively improve voltage balance but are often costly and underutilized. Other approaches involve unequal power injection into heavily loaded phases or drawing additional power from lightly loaded ones; however, these methods require complex hardware configurations. Techniques based on demand response management have also been proposed but rely heavily on consumer participation, limiting their practical applicability.

Some advanced strategies involve the injection of negative sequence current through inverter-based distributed generators (DGs). Nevertheless, most of these approaches require additional hardware, sensor networks, or communication links among DGs, increasing system cost and complexity.

Considering these limitations, this work proposes a simple, reliable, and cost-effective unbalance voltage compensation technique suitable for four-leg inverter-interfaced distributed generators (FLIGs). The method does not require additional hardware or communication infrastructure, making it easy to implement with existing systems.

The proposed technique mitigates voltage unbalance by injecting negative sequence current at the inverter's point of connection. The reference negative sequence current is generated by summing two orthogonal components of the negative sequence. The system is perturbed in four orthogonal directions, and the corresponding Voltage Unbalance Factors (VUFs) are observed. The inverter control is then adjusted toward the condition with the minimum observed VUF, and the perturb-and-observe (P&O) process continues iteratively until the system stabilizes near the optimal point.

A dedicated control strategy is designed to implement this compensation mechanism, along with a detailed guideline for developing a three-dimensional space vector modulation (3D-SVM) model in MATLAB/Simulink. Notably, the effect of optimal FLIG placement on VUF reduction in a microgrid has not been thoroughly explored in previous studies.

To address this, Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO) algorithms are employed to determine the optimal placement and sizing of FLIGs, aiming to minimize both active power loss and system voltage unbalance factor (SVUF). Simulation results confirm the effectiveness of the proposed approach.

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