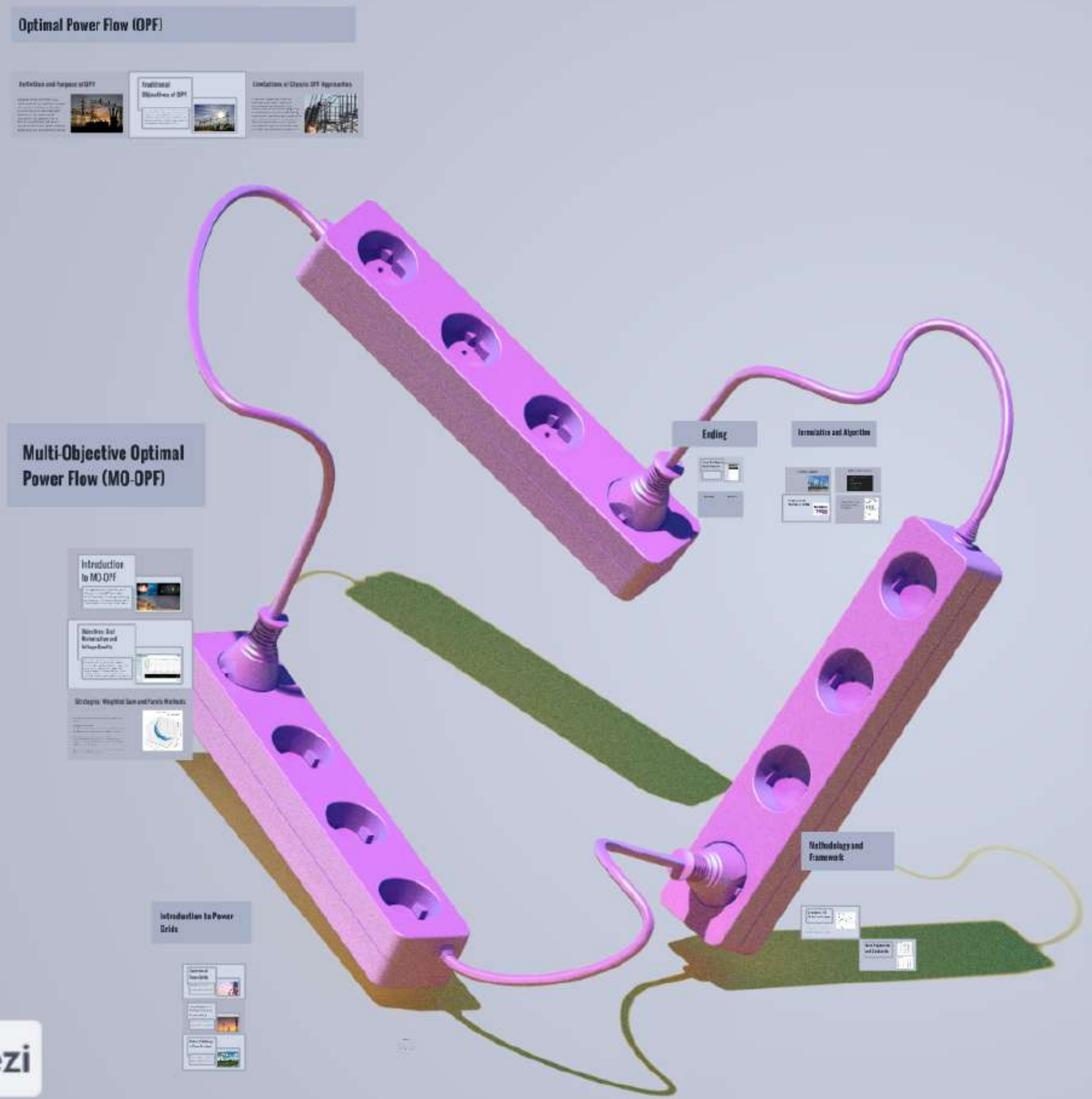

Multi-Objective Optimal Power Flow on the IEEE 14-Bus Test System

Balancing Cost and Voltage Stability in Modern Power Grids

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Overview of Power Grids

Power grids function as extensive networks connecting electricity generation sources to consumers. They encompass generation, transmission, and distribution systems, ensuring the reliable delivery of energy across vast distances.

Importance of Reliability and Economics

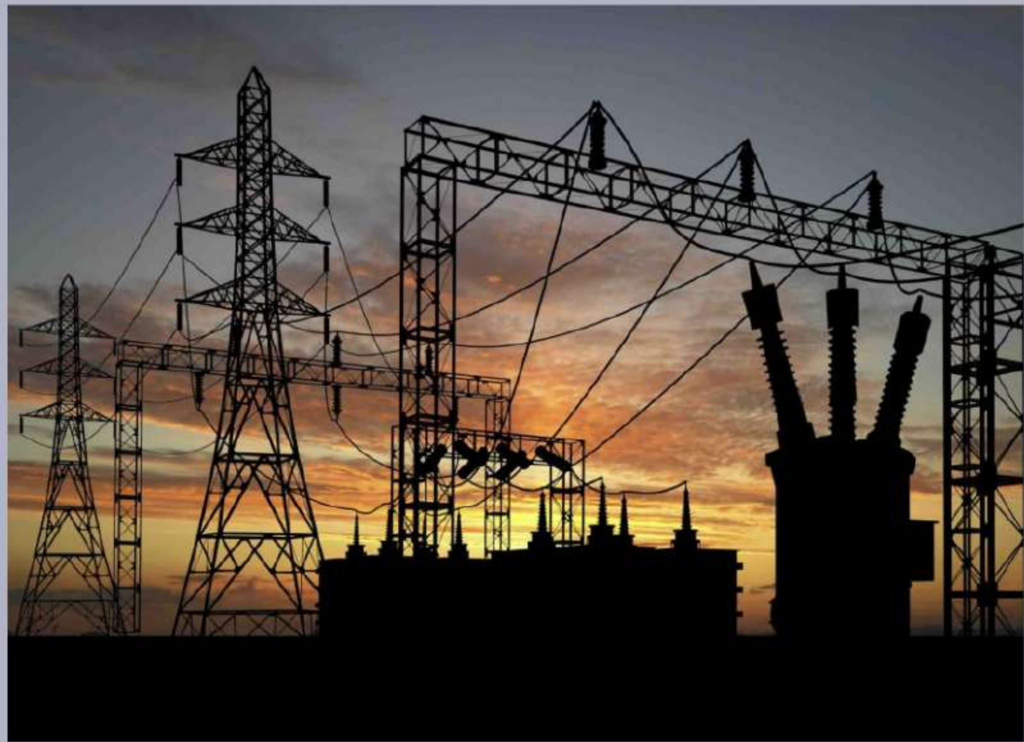
Reliability in power grids is crucial to ensure continuous electricity supply, while economic efficiency minimizes costs for consumers and operators. Balancing these factors is essential for sustainable energy practices.

Modern Challenges in Power Systems

Today's power systems face challenges such as stringent emission regulations, increased integration of renewable energy, and the need for enhanced reliability. These factors push grid managers to adopt advanced optimization methods.

Definition and Purpose of OPF

Optimal Power Flow (OPF) is a mathematical optimization problem that seeks to determine the most economical generation dispatch while ensuring operational constraints. Its purpose lies in facilitating efficient and secure operation of electric power systems, balancing cost, and system stability.



Traditional Objectives of OPF

The primary objective of the classic OPF is minimizing generation costs while adhering to system constraints, such as voltage limits and power balance equations. Traditional formulations focus primarily on economic efficiency, particularly emphasizing reduced operational costs without extensively addressing other aspects such as environmental impact or voltage stability.

Limitations of Classic OPF Approaches

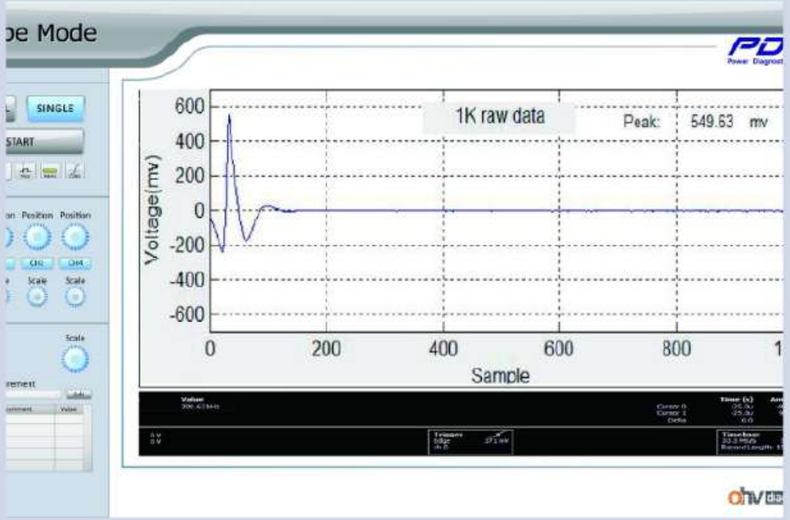
Classic OPF approaches often face challenges due to their inability to accommodate multiple objectives simultaneously, such as voltage quality or emission minimization. Additionally, conventional methods may struggle with real-world complexities, including non-linearities and uncertainties in power systems, leading to solutions that may not reflect optimal operational realities.

Introduction to MO-OPF

Multi-Objective Optimal Power Flow (MO-OPF) enhances conventional OPF by considering multiple conflicting objectives. This approach aims to navigate the dual challenges of reducing operational costs while ensuring voltage stability, critical for system reliability and power quality.

Objectives: Cost Minimization and Voltage Quality

The primary objectives of MO-OPF are to minimize overall generation costs, typically represented as a quadratic function of generator output, and to enhance voltage quality by reducing deviations from the ideal 1.0 per-unit voltage value. Balancing these objectives is crucial for improving overall system performance.



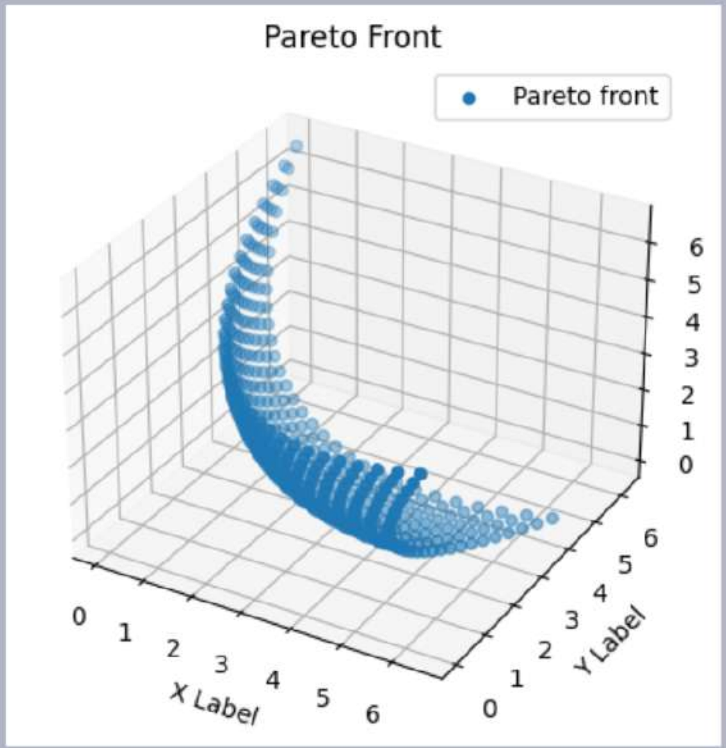
Strategies: Weighted Sum and Pareto Methods

To solve the MO-OPF problem, we explored two optimization strategies:

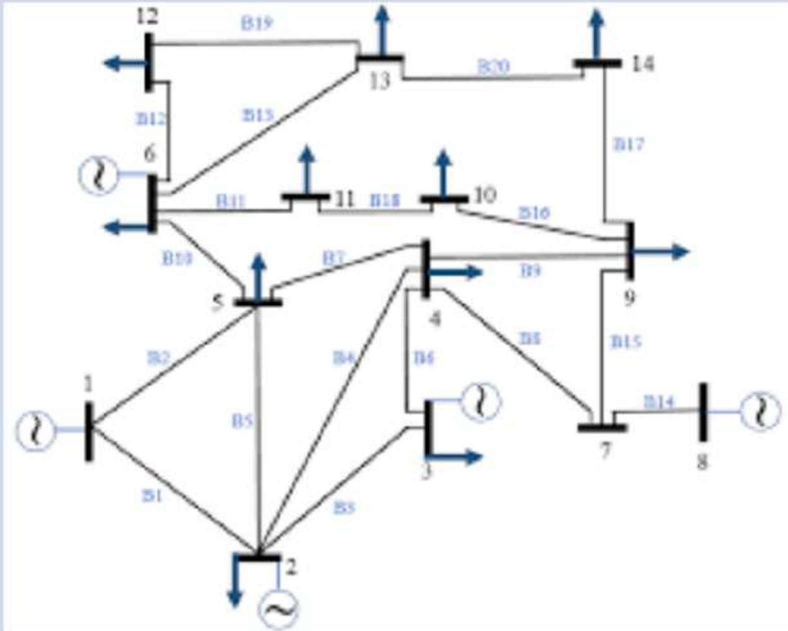
Weighted Sum Method
Combines cost and voltage deviation into a single objective using fixed weights. It is simple but requires predefined priorities.

Pareto Front Approach (Epsilon-Constraint)
Minimizes cost while varying limits on voltage deviation to generate a range of trade-off solutions. It avoids fixed weights and offers greater flexibility.

This dual approach allows comparison between fixed-priority and adaptive trade-off-based optimization.



Overview of IEEE 14-Bus Test System



The IEEE 14-bus system is a widely used test case in power system analysis, featuring **14 buses**, **5 generators**, and **20 transmission lines**. It includes a combination of load buses, generator (PV) buses, and a slack bus, representing typical operational conditions in a small-scale power network. Its structure captures essential features such as voltage limits, generator constraints, and network connectivity, making it suitable for studying optimal power flow under multiple ives.

Data Preparation and Constraints

The IEEE 14-bus system was imported from **MATPOWER's predefined case14 dataset. Key system components—such as bus data, generator limits, branch parameters, and cost coefficients—** were extracted and preprocessed. The **admittance matrix (Ybus) was constructed to model network connectivity, and generator cost data** was verified and completed to ensure quadratic cost functions for all five generators. Base MVA scaling was applied to normalize real and reactive power demands. Additionally, voltage and angle limits, as well as line flow capacities, were standardized to reflect realistic operational bounds. The data was stored in two Excel files.

branch_data.xlsx

1	From_Bus	To_Bus	G_pu	B_pu	S_max_MVA
2	1	2	4.999131601	-15.26308652	0
3	1	5	1.025897455	-4.234983682	0
4	2	3	1.135019192	-4.781863152	0
5	2	4	1.686033151	-5.115838326	0
6	2	5	1.701139667	-5.193927398	0
7	3	4	1.98597571	-5.068816978	0
8	4	5	6.840980661	-21.57855398	0
9	4	7	0	-4.781943382	0
10	4	9	0	-1.797979072	0
11	5	6	0	-3.967939052	0
12	6	11	1.955028563	-4.094074344	0
13	6	12	1.52596744	-3.175963965	0
14	6	13	3.098927404	-6.102755448	0
15	7	8	0	-5.676979847	0
16	7	9	0	-9.09008272	0
17	9	10	3.902049552	-10.36539413	0
18	9	14	1.424005487	-3.029050457	0
19	10	11	1.880884754	-4.402943749	0
20	12	13	2.489024587	-2.251974626	0
21	13	14	1.136994158	-2.314963475	0

bus_data.xlsx

1	Bus	P_Load_MW	Q_Load_MVAr	V_ref_pu
2	1	0	0	1.06
3	2	21.7	12.7	1.045
4	3	94.2	19	1.01
5	4	47.8	-3.9	1.019
6	5	7.6	1.6	1.02
7	6	11.2	7.5	1.07
8	7	0	0	1.062
9	8	0	0	1.09
10	9	29.5	16.6	1.056
11	10	9	5.8	1.051
12	11	3.5	1.8	1.057
13	12	6.1	1.6	1.055
14	13	13.5	5.8	1.05
15	14	14.9	5	1.036

Problem Formulation

The MO-OPF problem is formulated with the goal of minimizing two conflicting objectives: **total generation cost and voltage deviation from 1.0 per uni**t. The decision variables include bus voltage magnitudes, voltage angles, and real and reactive power outputs of generators. The system is subject to **nonlinear power flow equations, generator operating limits, voltage magnitude constraints, and line flow limits**. This formulation enables a realistic and constrained optimization setup for exploring **cost–voltage trade-offs**.

Mathematiical Formulation

$$\min_{x} \left[f_1(x) = \sum_i (a_i P_{g_i}^2 + b_i P_{g_i} + c_i), \quad f_2(x) = \sum_i (V_i - 1)^2 \right]$$

subject to:

$$P_{g_i} - P_{d_i} = \sum_j V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij})$$

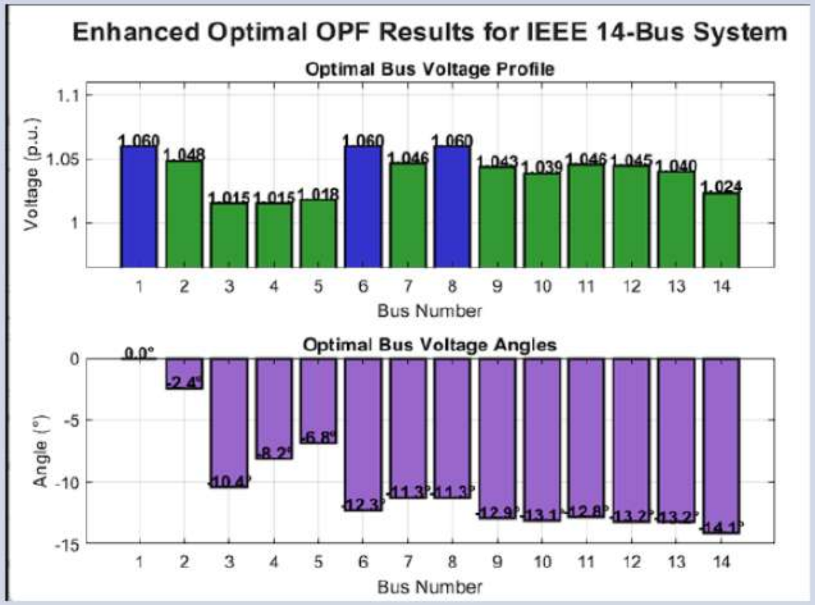
$$Q_{g_i} - Q_{d_i} = \sum_j V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij})$$

$$P_g^{\min} \leq P_g \leq P_g^{\max}, \quad Q_g^{\min} \leq Q_g \leq Q_g^{\max}$$

$$V^{\min} \leq V \leq V^{\max}, \quad |S_{ij}| \leq S_{ij}^{\max}$$

$$\theta_{\text{slack}} = 0$$

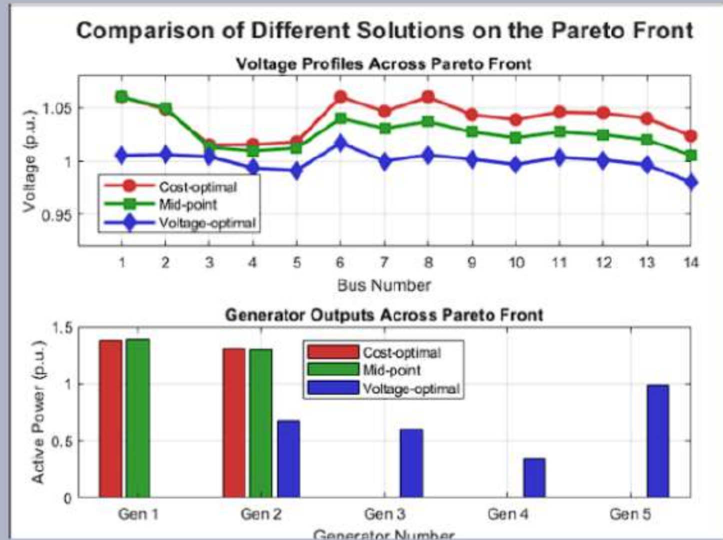
Implementation of Weighted Sum Method

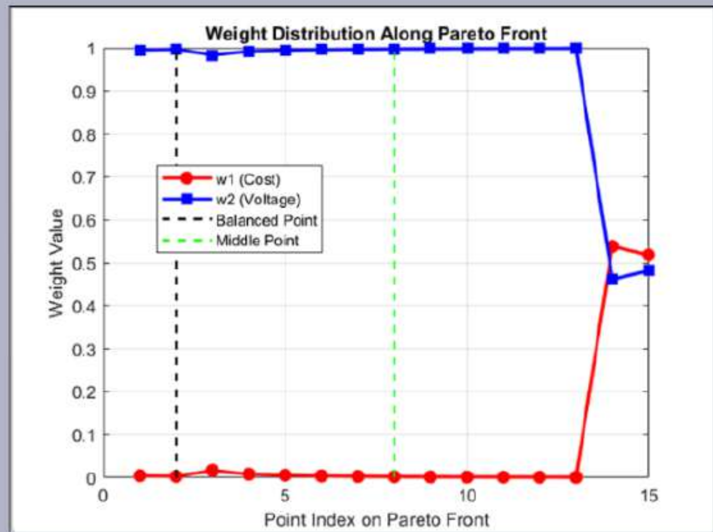


The fixed weights method was implemented by combining generation cost and voltage deviation into a single objective, with weights set to 0.7 for cost and 0.3 for voltage deviation. Optimization was performed using MATLAB's fmincon solver, subject to all standard OPF constraints including power balance, voltage and generator limits, and line flow restrictions. The approach resulted in a minimum generation cost of 54.27 and a voltage deviation metric of 0.0257, indicating a well-balanced solution. All bus voltages remained within operational limits, with major generation contributions from Buses 1 and 2, and a smooth voltage angle transition from 0° at the slack bus to –14.1° at the far end of the network.

Implementation of Pareto Front Analysis

To overcome the limitations of fixed weights, the Pareto front method was implemented using the epsilon-constraint approach, where voltage deviation was bounded by gradually varying limits while minimizing generation cost. Optimization was carried out using MATLAB's fmincon across a series of 15 epsilon values, generating a range of Pareto-optimal solutions. This process revealed a clear trade-off: as voltage deviation constraints were relaxed, generation cost decreased, while voltage deviation increased. The best solution achieved a cost of 54.30 and a voltage deviation of 0.0133, demonstrating flexibility in exploring operating points. The results confirm that this method provides a broader and more adaptive decision space, free from the need to predefine weight preferences.





Future Directions for MO-OPF Research

Future research should focus on integrating additional objectives such as emissions reductions and renewable energy sources into the MO-OPF framework. Exploring advanced algorithms and multi-faceted data analytics will enhance decision-making capabilities in complex power systems.

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Conclusion

This study demonstrated a multi-objective approach to optimal power flow on the IEEE 14-bus system, targeting both generation cost and voltage stability. The fixed weights method provided a simple and efficient solution but required prior weight selection. In contrast, the Pareto front method revealed a full spectrum of trade-off solutions, allowing greater flexibility in decision-making. The comparative analysis highlights the value of Pareto-based optimization in supporting more adaptive and informed operational strategies for modern power systems.