International Journal of Engineering Research-Online
A Peer Reviewed International Journal
Articles available online http://www.ijoer.in; editorijoer@gmail.com

Vol.8., Issue.2, 2020
March-April

RESEARCH ARTICLE

ISSN: 2321-7758

A COMPARATIVE EVALUATION OF DISTRIBUTED GENERATION TECHNOLOGIES WITH EMPHASIS ON WHEELING POWER AND MARGINAL COST IMPLICATIONS

Hitesh S. Baria[1], Pradip C. Parmar[2]
[1]Lecturer, Electrical Engineering Department
[2]Lecturer, Electrical Engineering Department, The M.S. University of Baroda
E-mail: baria.hiteshs-polyeed@msubaroda.ac.in, parmar.pradipc-polyeed@msubaroda.ac.in

DOI: 10.33329/ijoer.8.2.23

ABSTRACT

This paper presents a comprehensive evaluation of various Distributed Generation (DG) technologies, including wind, solar, fuel cells, and microturbines, with respect to their technical efficiency, cost-effectiveness, and environmental impact. The analysis is extended to examine the influence of DG on wheeling power and locational marginal cost (LMC) using standard IEEE 30-bus and 9-bus systems.

Using MATLAB-based simulations and the Newton-Raphson load flow method, the effect of DG on system lambda values, line loading, and optimal power flow (OPF) is observed. Results indicate that strategic placement of DG units significantly enhances network performance, enables efficient wheeling, and reduces operational costs. The paper also introduces a rule-based wheeling mechanism based on system lambda, supporting economically sound DG transactions in open power markets.

Keywords: Distributed Generation, Microturbines, Solar PV, Fuel Cells, Wheeling Power, Locational Marginal Cost, Economic Dispatch, IEEE 30-bus System, Load Flow Analysis, Newton-Raphson.

1. Introduction

The global power sector is witnessing a paradigm shift from centralized power generation to distributed energy systems. This change is driven by technological advancements, economic competitiveness of renewable energy sources, and the rising need for flexible, resilient, and cleaner power systems. Distributed Generation (DG) technologies—such as solar photovoltaics (PV), wind turbines, microturbines, and fuel cells—enable localized power production close to the load centers, thereby reducing transmission losses and enhancing system reliability.

DG systems can operate in both grid-connected and islanded modes, offering a broad range of applications from backup supply and peak shaving to primary generation and combined heat and power (CHP). Compared to conventional power plants, DG technologies are modular, faster to deploy, and have relatively lower environmental impact.

One of the significant economic advantages of DG is its impact on system operation cost and marginal pricing. By injecting power locally, DG reduces the burden on transmission lines and shifts the system marginal cost (lambda) downwards. This makes DG not only a technical enhancement but also an economic lever in modern power markets.

Another crucial aspect of this transformation is the concept of wheeling power—transferring electricity from a DG owner to a consumer through a third-party transmission system. Wheeling arrangements involve economic, regulatory, and technical considerations, especially in open-access environments where multiple producers and consumers interact. The evaluation of marginal cost across buses helps identify optimal wheeling paths and supports locational pricing strategies.

This paper aims to:

- Compare and evaluate multiple DG technologies based on their performance, cost, and environmental impact.
- Analyze the impact of DG on marginal cost and power flow using IEEE 9-bus and IEEE 30-bus systems.
- Develop a simple rule-based framework for wheeling contracts using marginal cost (lambda) and line loading information.

Simulation results demonstrate that the thoughtful integration of DG technologies improves power system economics, voltage stability, and supports efficient power transactions in deregulated energy environments.

2. Literature Review

The role of Distributed Generation (DG) in modern power systems has been widely studied, with research covering optimal placement, sizing, impact on system losses, voltage profiles, and economics.

Corpaneto et al. presented a method for loss allocation in unbalanced systems using Branch Current Decomposition and RCLP techniques. Their work, though foundational, was limited to a 13-bus system and did not account for renewable-based DG or cost implications. In contrast, this paper integrates wind and solar DG and focuses on their economic impacts.

A significant body of literature focuses on optimization algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE) for DG sizing and placement. For instance, Singh et al. used GA to minimize losses in 16, 37, and 75-bus systems. Their approach, however, emphasized technical parameters without linking to wheeling or locational pricing mechanisms.

Other studies addressed wheeling pricing by incorporating transmission system operating costs through optimal power flow (OPF) models. One such work evaluated time-of-use pricing across 14 and 30-bus IEEE systems using the MINOS package. While comprehensive in cost analysis, these models did not include actual DG-based injections or marginal cost variations due to renewable sources.

Real-time digital simulation environments have also been employed to assess protection and reliability issues arising from DG integration. Hautakangas et al. modeled a medium-voltage distribution network with a wind-based DG unit using RTDS and dSPACE simulators. While technically robust, their study focused on fault response rather than economic dispatch or wheeling.

In terms of economic modeling, other works developed tools to estimate network losses and DG impacts using load profiles and simulation engines like IPSA. These tools were applied to real utility topologies but did not include marginal cost tracking or wheeling contract analysis.

Locational Marginal Pricing (LMP), commonly used in transmission networks, has been proposed for use in distribution networks to incentivize optimal DG placement. A study modeling a rural Uruguayan network demonstrated significant price differences across buses, justifying nodal pricing mechanisms. This paper extends such an approach by applying lambda-based analysis to IEEE test systems and integrating wheeling rules.

In summary, most existing works treat DG either as a technical enhancement or as an isolated optimization problem. Few combine economic dispatch, wheeling feasibility, and comparative technology assessment in a single framework. This paper fills that gap by:

- Comparing technologies (solar, wind, fuel cells, microturbines)
- Studying DG's effect on system lambda and wheeling opportunities

- Proposing a rule-based contract framework for power exchange

3. Methodology

This study adopts a simulation-based approach to analyze the performance of Distributed Generation (DG) technologies from both technical and economic perspectives. The methodology includes modeling of multiple DG technologies, load flow analysis, and evaluation of marginal cost variations and wheeling feasibility within standard IEEE test systems.

3.1 IEEE Test Systems Used

Two widely accepted standard systems are used:

- **IEEE 9-Bus System:** A simplified network suitable for conceptual testing and initial verification of DG impact.
- **IEEE 30-Bus System:** A practical distribution network with multiple generation and load buses, widely used for optimal power flow (OPF) and economic dispatch studies.

In both systems, DG units are introduced at buses with notable voltage drops or higher load concentrations.

3.2 DG Technologies Evaluated

The following DG technologies are analyzed and compared:

1. **Solar Photovoltaic (PV):** Low-maintenance, clean energy source with variable output based on irradiance.
2. **Wind Turbine (Induction-based):** Suitable for moderate- to large-scale installations; output varies with wind speed.
3. **Fuel Cells (PEM/PAFC types):** High efficiency and suitable for continuous base load applications, though cost is high.
4. **Microturbines:** Compact units used for combined heat and power (CHP) in commercial settings.

Each DG source is modeled as a PQ bus in the simulation with realistic ratings and output profiles.

3.3 Load Flow Analysis

The Newton-Raphson Load Flow (NRLF) method is implemented in MATLAB for solving bus voltages and power flows. The process includes:

- Input of system data (bus, branch, generation).
- Specification of power injections and load demands.
- Iterative calculation of bus voltages using:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j)$$

- Termination based on power mismatch below 0.0001 p.u.

3.4 Marginal Cost and Economic Dispatch

The economic dispatch problem is modeled using a quadratic cost function:

$$C_i(P_i) = a_i + b_i P_i + c_i P_i^2$$

The optimal dispatch condition is:

$$\frac{dC_i}{dP_i} = \lambda \quad \forall i$$

Where λ is the system marginal cost. By observing λ across buses before and after DG integration, its economic impact is quantified.

3.5 Wheeling Framework

To analyze wheeling transactions, the following steps are followed:

1. Line flow data is extracted from the NRLF results.
2. Buses with available generation and deficient load are identified.
3. Wheeling is permitted if:
   - Line loading < 90%
   - λreceiver < λsender
   - Path is loop-free and voltage stable

Based on this analysis, rules for basic wheeling contracts are proposed. Power can be transacted between third-party entities without stressing the network or increasing losses.

4. Results and Discussion

Simulation results were obtained by running load flow analysis and economic dispatch calculations on the IEEE 9-bus and 30-bus systems, both with and without DG integration. The comparative analysis focuses on system performance, cost optimization, voltage stability, marginal cost distribution, and wheeling feasibility.

4.1 Impact on System Losses and Voltage Profile

DG units were strategically placed at load-intensive or voltage-sensitive buses (e.g., Bus 7, 11, and 24 in the 30-bus system). Their impact was immediately observable:

- **Real Power Loss Reduction:**
  - Without DG: 18.2 MW (IEEE 30-bus)
  - With DG (solar + wind): 12.4 MW
- **Voltage Improvement at Weak Buses:**

Bus	Voltage Without DG (p.u.)	Voltage With DG (p.u.)
24	0.935	0.969
27	0.937	0.972
30	0.939	0.974

These improvements were consistent in both test systems, confirming that DG placed near load centers reduces voltage drops and transmission losses.

4.2 Effect on System Marginal Cost (Lambda)

The base case lambda for the 30-bus system was computed at:

- **λ (without DG):** 6.83 ₹/kWh
- **λ (with DG):** 5.42 ₹/kWh

This reduction indicates a decrease in overall system generation cost, validating the cost-effectiveness of DG.

Marginal cost variations across the network also showed a flattening effect with DG, improving economic uniformity and enabling better pricing decisions for energy contracts.

4.3 Technology Comparison

The DG technologies were ranked based on overall contribution to efficiency, environmental impact, and cost savings:

Technology	Cost (₹/kWh)	Efficiency (%)	Emission Level	Notes
Solar PV	6.0–7.5	15–20	Zero	Ideal for peak shaving, daytime
Wind Turbine	4.5–6.5	25–35	Zero	Good in windy regions
Fuel Cell	8.0–10.0	35–60	Very Low	High cost, clean & reliable
Microturbine	6.5–8.5	25–30	Moderate	Suited for CHP applications

While solar and wind offered best environmental performance, fuel cells proved better for reliability and continuous load.

4.4 Wheeling Path Evaluation

Based on line flow and lambda data, wheeling transactions were found feasible in the following cases:

- **DG at Bus 11 wheeling power to Bus 27**
  - Line loading: 65%
  - $\lambda 27 < \lambda 11$
  - No looped paths
- **DG at Bus 24 wheeling to Bus 30**
  - Enabled by underutilized line 24–25–30
  - Voltage stable
  - Reduced burden on main feeders

Rules derived from these observations included:

1. Wheeling allowed if line loading < 90%
2. Prefer paths where receiving bus has lower lambda
3. Maintain voltage within 0.95–1.05 p.u.
4. Limit wheeling to 30% of line capacity to maintain stability

4.5 Visualization

The voltage profile improvement and marginal cost reduction were plotted using MATLAB.

5. Conclusion

This study offers a comparative and integrative analysis of Distributed Generation (DG) technologies, focusing on their impact on system performance, economics, and wheeling feasibility. Using IEEE 9-bus and 30-bus test systems, we demonstrated that the strategic placement of solar, wind, fuel cell, and microturbine-based DG leads to substantial improvements in power system operation.

The key conclusions are as follows:

1. **System Loss Reduction**: Integration of DG near load centers consistently reduced total real power losses by more than 30%.
2. **Voltage Profile Improvement**: Critical load buses that previously suffered from low voltage were stabilized well within permissible limits with the addition of DG.
3. **Economic Advantage**: The system marginal cost (lambda) decreased significantly with DG, validating its economic viability in cost-sensitive environments.
4. **Technology Selection**: Among all evaluated technologies, wind and solar were found most cost-effective and environmentally friendly, while fuel cells offered superior reliability.
5. **Wheeling Potential**: A rule-based framework was successfully developed using line flow and lambda data, enabling third-party power transactions in a deregulated market without compromising system reliability.

The integration of DG, when planned and executed based on marginal cost and load sensitivity, not only enhances grid performance but also paves the way for smart, decentralized power networks. Future work may include the modeling of dynamic pricing, real-time control of DG units, and the incorporation of storage technologies into the wheeling model.

6. References

[1]. Corpaneto, E. et al., "Loss Allocation in Distribution Systems Using Branch Current Method," IEEE Transactions on Power Systems, 2019.

[2]. Singh, R., "Optimal Placement of DG using Genetic Algorithm," IJEEE, Vol. 25, No. 4, 2018.

[3]. Hautakangas, S. et al., "Protection Issues in Distribution Networks with DG," IEEE PES, 2017.

[4]. UK DG Programme, "Modelling Network Losses due to DG Penetration," DTI Report, 2019.

[5]. Kundur, P., *Power System Stability and Control*, McGraw-Hill, 1994.

[6]. IEEE PES Task Force, "IEEE 30-Bus and 9-Bus Test System Specifications," Technical Reports.

[7]. Sharma, V., "Locational Marginal Pricing in Distribution Networks," Springer Energy Systems, 2019.