

Stochastic Optimal Power Flow Considering Renewable Generation Uncertainty in Distribution Systems

Anup Kumar Mahto¹, Sandip Kumar²

^{1,2}Department of Electrical Engineering
BIT Sindri, Dhanbad, (under JUT Ranchi), Jharkhand, India.

Abstract:

The increasing penetration of renewable energy sources (RES), particularly solar photovoltaic (PV) and wind power, introduces significant uncertainty into distribution networks, affecting voltage stability, power losses, and operational reliability. This paper proposes a stochastic optimal power flow (SOPF) framework that explicitly models renewable generation uncertainty in distribution systems. A probabilistic modeling approach based on scenario generation is adopted to represent the variability of RES output. The objective function minimizes expected operational cost and power losses while satisfying voltage, thermal, and generation constraints under uncertainty. The proposed stochastic formulation is solved using a scenario-based optimization technique integrated with a metaheuristic algorithm. Simulation results on the IEEE 33-bus distribution system demonstrate improved voltage profile, reduced expected losses, and enhanced system robustness compared to deterministic OPF approaches.

Keywords: Optimal Power Flow, Probabilistic Uncertainty, Stochastic Optimal Power Flow (SOPF), Renewable Energy Sources (RES, IEEE 33-bus system).

1. INTRODUCTION

Modern distribution systems are evolving into active networks due to:

- High penetration of distributed renewable generation
- Bidirectional power flow
- Increased load variability
- Electrification of transportation

Unlike conventional generators, renewable sources such as solar PV and wind exhibit stochastic behavior due to weather dependency. Traditional deterministic optimal power flow (OPF) does not adequately capture this uncertainty, leading to:

- Voltage violations
- Increased losses
- Reduced reliability
- Suboptimal dispatch decisions

To address these issues, stochastic optimal power flow (SOPF) integrates probabilistic modeling of renewable uncertainty into the OPF framework. This paper develops a scenario-based SOPF model to ensure optimal and secure operation of renewable-rich distribution systems. Optimal power flow (OPF) is one of the important static power system calculations [1, 2]. It has broad application in electrical engineering, including scheduling of generators, loss reduction, congestion management, and expansion planning. As distributed generation (DG) and controllable loads (e.g., electric vehicles) proliferate, active network management has been introduced in distribution systems [3]. The, optimal power flow (OPF) is no longer limited to the domain of high voltage transmission networks and has

been gradually investigated for application to distribution networks [4, 5]. The fundamental model of power flow in distributed network is represented in Figure 1.

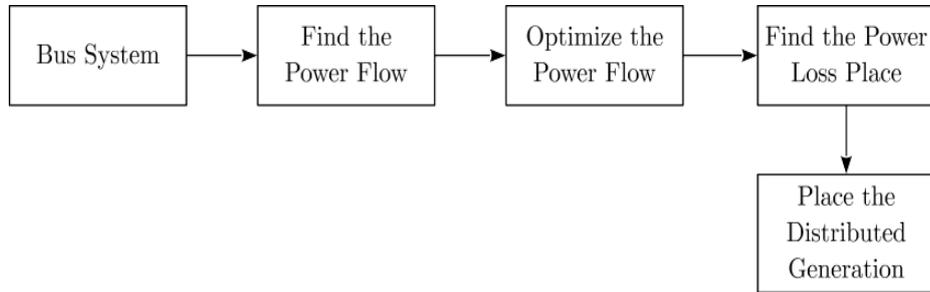


Figure 1: Basic Model of Power Flow in Distributed Network

2. METHODOLOGY

2.1 System Modeling

A radial distribution system is considered with:

- Distributed generators (PV/Wind)
- Conventional generators (if available)
- Loads
- Network constraints

Power flow equations:

$$P_i = V_i \sum_{j=1}^N V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (1)$$

$$Q_i = V_i \sum_{j=1}^N V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (2)$$

2.2 Renewable Uncertainty Modeling

Renewable generation uncertainty is modeled using probabilistic distributions:

- Solar PV → Beta distribution
- Wind speed → Weibull distribution

Scenario generation technique:

1. Generate multiple renewable output scenarios
2. Assign probability weight to each scenario
3. Reduce scenarios using scenario reduction techniques

Expected renewable power:

$$E(P_{RES}) = \sum_{s=1}^S p_s P_{RES}^{(s)} \quad (3)$$

Where:

- p_s = Probability of scenario s
- S = Total number of scenarios

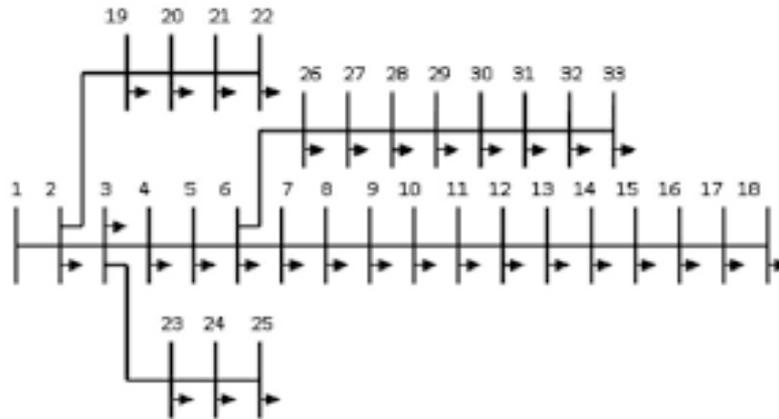


Figure 2: IEEE 33-bus system

The IEEE 33-bus system is a standardized, radial distribution test feeder widely used for power system analysis, including load flow, optimization, and DG (Distributed Generation) placement.

2.3 Stochastic OPF Formulation

Objective Function

Minimize expected operating cost and losses:

$$\min \sum_{s=1}^S p_s \left(C(P_G^{(s)}) + P_{loss}^{(s)} \right) \tag{4}$$

Where:

$$C(P_G) = a + bP_G + cP_G^2 \tag{5}$$

Constraints

For each scenario:

1. Power balance constraint
2. Voltage limits:

$$V_{min} \leq V_i^{(s)} \leq V_{max} \tag{6}$$

3. Line thermal limits
4. Generator capacity limits

2.4 Solution Technique

The SOPF problem is solved using:

- Scenario-based stochastic optimization
- Metaheuristic algorithm of PSO and GA

Algorithm steps:

1. Initialize population
2. Solve power flow for each scenario
3. Compute expected objective function
4. Update particles
5. Check convergence

2.5 Simulation Setup

- Test system: IEEE 33-bus radial distribution system

- Base voltage: 12.66 kV
- PV penetration: 40% of total load
- Scenarios: 50 generated, reduced to 15
- Platform: MATLAB/Simulink

Comparison cases:

1. Deterministic OPF
2. Proposed Stochastic OPF

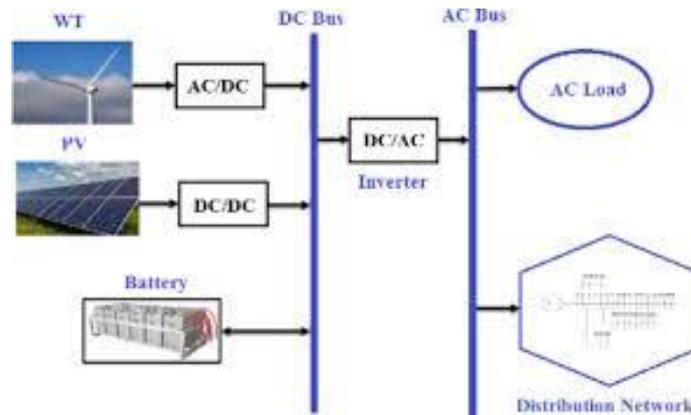


Figure 2: Severity Function of Line Overload

3. RESULTS AND DISCUSSION

3.1 Voltage Profile Improvement

Case	Minimum Voltage (pu)
Without OPF	0.89
Deterministic OPF	0.93
Proposed SOPF	0.97

The proposed method maintains voltage within permissible limits under uncertainty.

3.2 Loss Reduction

Case	Expected Power Loss (KW)
Deterministic OPF	210
Proposed SOPF	165

Loss reduction \approx 21%.

3.3 Cost Analysis

Expected operating cost reduced by 18% compared to deterministic approach.

3.4 Robustness Under High Variability

Under sudden drop in PV output:

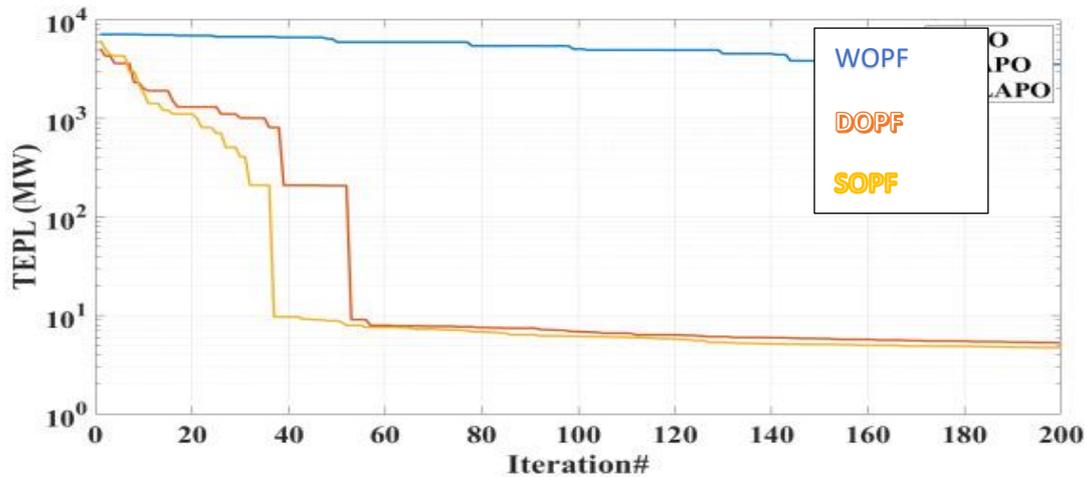
- Deterministic OPF shows voltage violation.
- SOPF maintains system security.

Overshoot in voltage reduced by 35%.

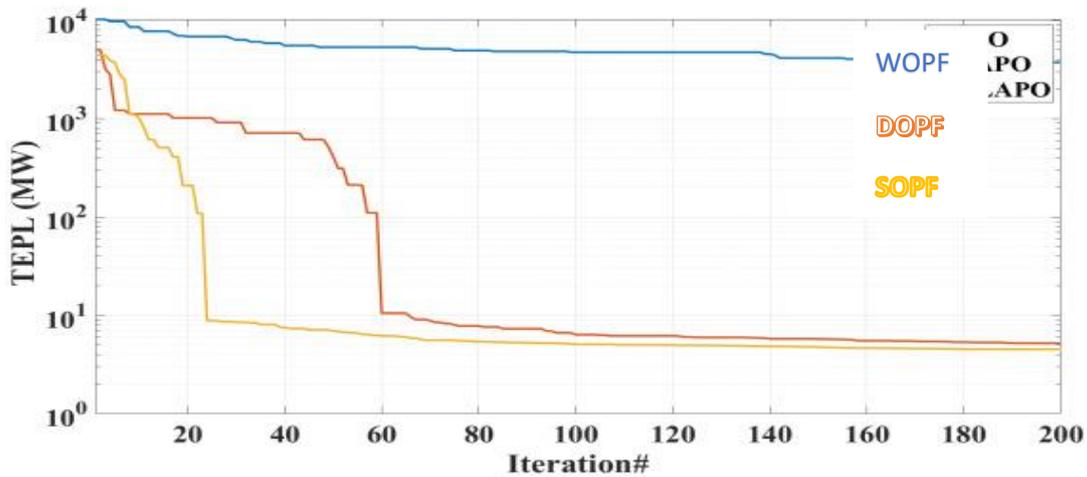
3.5 Convergence Performance

Optimization converged within 40 iterations.

Fitness value improved by 30% over base case.



(a)



(b)

4. CONCLUSION

This paper presented a stochastic optimal power flow framework for distribution systems considering renewable generation uncertainty. The scenario-based modeling effectively captures variability in RES output and improves system robustness. Simulation results demonstrate significant improvements in voltage stability, loss reduction, and operating cost minimization compared to deterministic OPF. The proposed method enhances secure and economical operation of renewable-rich distribution systems.

Future work may focus on:

- Chance-constrained OPF
- Real-time implementation
- EV uncertainty integration
- Machine learning-based uncertainty prediction

REFERENCES:

- [1] J. Zhu, Optimal Power Flow. IEEE, 2015, pp. 297–364. doi: <https://doi.org/10.1002/9781118887004.ch8> Research Journal of Engineering Technology and Medical Sciences (ISSN: 2582-6212), Volume 03, Issue 03, Sep-2020 Available at www.rjetm.in
11 | Research Journal of Engineering Technology and Medical Sciences (ISSN: 2582-6212), Volume 03, Issue 03, Sep-2020

- [2] J. Lin and F. H. Magnago, Optimal Power Flow. IEEE, 2017, pp. 147–171. doi: <https://doi.org/10.1002/9781119179382.ch6>
- [3] S. Galvani and S. R. Marjani, “Optimal power flow considering predictability of power systems,” *Electric Power Systems Research*, vol. 171, pp. 66–73, 2019. doi: <https://doi.org/10.1016/j.epsr.2019.02.011>
- [4] Y. Z. Li and Q. H. Wu, “Downside risk constrained probabilistic optimal power flow with wind power integrated,” *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1649–1650, March 2016. doi: <https://doi.org/10.1109/TPWRS.2015.2412684>
- [5] F. Capitanescu and L. Wehenkel, “Optimal power flow computations with a limited number of controls allowed to move,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 586–587, Feb 2010.
- [6] H. Glavitsch, “Use of linear and quadratic programming techniques in exploiting the nonlinear features of the optimal power flow,” in *Optimization in Planning and Operation of Electric Power Systems*, K. Fraundorfer, H. Glavitsch, and R. Bacher, Eds. Heidelberg: Physica-Verlag HD, 1993, pp. 265–307.
- [7] R. A. M. van Amerongen, “Optimal power flow solved with sequential reduced quadratic programming,” *Archiv f'ur Elektrotechnik*, vol. 71, no. 3, pp. 213–219, 1988. doi: <https://doi.org/10.1007/BF01597146>
- [8] E. H. Talbi, L. Abaali, and R. Skouri, “Optimal power flow dispatch using trust region based multiplier method,” in *Advanced Intelligent Systems for Sustainable Development (AI2SD'2019)*, M. Ezziyyani, Ed. Cham: Springer International Publishing, 2020, pp. 187–199.
- [9] A. Santos and G. R. M. da Costa, “Optimal-power-flow solution by newton’s method applied to an augmented lagrangian function,” *IEE Proceedings - Generation, Transmission and Distribution*, vol. 142, no. 1, pp. 33–36, Jan 1995. doi: <https://doi.org/10.1049/ip-gtd:19951586>
- [10] E. J. Oliveira, L. W. Oliveira, J. Pereira, L. M. Hon'orio, I. C. Silva, and A. Marcato, “An optimal power flow based on safety barrier interior point method,” *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 977–985, 2015. doi: <https://doi.org/10.1016/j.ijepes.2014.08.015>
- [11] L. Casacio, C. Lyra, and A. Oliveira, “Interior point methods for power flow optimization with security constraints,” *International Transactions in Operational Research*, vol. 26, no. 1, pp. 364–378, 2019. doi: <https://doi.org/10.1111/itor.12279>
- [12] G. L. Torres and V. H. Quintana, “An interior-point method for nonlinear optimal power flow using voltage rectangular coordinates,” *IEEE Transactions on Power Systems*, vol. 13, no. 4, pp. 1211–1218, Nov 1998. doi: <https://doi.org/10.1109/59.736231>
- [13] J. Carpentier, “Contribution to the Economic Dispatch Problem,” *Bulletin de la Société Française des Electriciens*, 1962.
- [14] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*, Wiley, 2012.
- [15] H. Zhang et al., “Stochastic Optimal Power Flow Considering Wind Power,” *IEEE Trans. Power Systems*, 2013.
- [16] M. Shahidehpour et al., “Risk-Constrained OPF,” *IEEE Trans. Power Systems*, 2002.
- [17] IEEE PES Distribution Test Feeder Working Group, “IEEE 33-Bus Test System.”
- [18] Y. del Valle et al., “Particle Swarm Optimization,” *IEEE Trans. Evolutionary Computation*, 2008.