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Optimal power flow and voltage stability enhancement in renewable energy integrated power systems using hybrid optimization techniques

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ABSTRACT

The increasing penetration of renewable energy sources such as photovoltaic and wind generation introduces uncertainty, voltage fluctuations and additional operational constraints in modern power systems. This paper presents a hybrid optimization framework for optimal power flow (OPF) and voltage-stability enhancement in a renewable-energy-integrated transmission network. The proposed framework combines a population-based search strategy with a local improvement stage to determine generator outputs, transformer tap settings and reactive-power support while satisfying network operating constraints. A standard IEEE test-system framework is considered for evaluation. The objective function simultaneously considers generation cost, active-power losses and voltage-deviation penalties. The methodology is designed to improve voltage profiles and reduce transmission losses while maintaining generator, line-flow and bus-voltage limits. The study also discusses the effect of renewable generation variability and reactive-power compensation on system security. The proposed approach provides a systematic basis for coordinated OPF and voltage-stability management and can be extended to larger practical networks.

Keywords: Optimal power flow, Power system, Voltage stability, Renewable energy, Reactive power, Transmission losses, Hybrid optimization, Smart grid

1. Introduction

Power systems are undergoing a significant transition due to the rapid deployment of renewable energy generation. Conventional synchronous generators provide controllable active and reactive power, whereas photovoltaic and many wind-generation units introduce variable operating conditions. Consequently, conventional OPF procedures must increasingly account for renewable uncertainty, voltage constraints and reactive-power flexibility.

Optimal power flow is a fundamental power-system optimization problem used to determine an economically and technically feasible operating point. The classical OPF problem minimizes an objective such as fuel cost subject to power-balance equations, generator limits, voltage constraints and transmission-line limits. In renewable-rich networks, the problem becomes more nonlinear because renewable generation changes the net load and can alter voltage stability margins.

Voltage stability is particularly important because inadequate reactive-power support can cause progressive voltage decline and, under severe conditions, voltage collapse. Coordinated control of generator reactive power, transformer taps and compensation devices can improve the operating margin. This paper therefore develops a combined OPF and voltage-profile optimization framework.

2. Research gap and objectives

Many OPF studies optimize generation cost while treating voltage performance as a secondary constraint. Other studies focus on voltage stability without fully coordinating economic dispatch and network losses. A practical framework should consider these objectives simultaneously, particularly when renewable generation varies.

The main objectives of this study are: (i) to formulate a multi-objective OPF problem for renewable-integrated networks; (ii) to include voltage-deviation and active-loss terms in the objective function; (iii) to coordinate active and reactive power controls; (iv) to evaluate the method on a standard IEEE test network; and (v) to establish a reproducible framework for future validation using real utility data.

3. Mathematical formulation

The proposed optimization determines the control vector $x = [P_g, Q_g, V_g, T, Q_c]$, where P_g and Q_g are generator active and reactive powers, V_g represents generator voltage set points, T represents transformer tap positions, and Q_c represents controllable reactive-power compensation.

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A weighted objective function is defined as:

$$\text{Minimize } F(x) = w \cdot C(P_g) + w \cdot P_{\text{loss}} + w \cdot V_D$$

where $C(P_g)$ is the generation-cost function, P_{loss} is total active-power transmission loss, and V_D is the voltage-deviation index. The weighting coefficients w_1 , w_2 and w_3 are selected according to the operational priority.

For a quadratic generator-cost model, $C(P_g) = \sum [a_i + b_i P_{gi} + c_i (P_{gi})^2]$. The active-power loss can be obtained from the AC power-flow solution. The voltage-deviation index is expressed as $V_D = \sum |V_i - V_{\text{ref}}|$, where V_{ref} is normally 1.0 p.u.

The equality constraints are the AC power-balance equations at each bus. The inequality constraints include generator active/reactive limits, bus-voltage limits, transformer-tap limits and thermal limits of transmission branches.

4. Proposed hybrid optimization framework

The proposed method uses two stages. In the first stage, a population-based optimizer explores the feasible operating region and identifies promising control vectors. In the second stage, a local improvement procedure refines the best candidates while enforcing power-flow constraints. A penalty function is applied to infeasible solutions.

For each candidate solution, an AC power flow is performed. If the power flow converges, the objective function is calculated from generation cost, active losses and voltage deviation. Solutions violating operational constraints receive a penalty. The process continues until the maximum number of iterations is reached or the improvement falls below a predefined tolerance.

The framework is suitable for implementation in MATLAB, Python or other power-system simulation environments. For a publication-quality study, the optimization should be repeated over multiple renewable-generation scenarios and compared against established OPF algorithms.

5. Test-system configuration

A standard IEEE benchmark network, such as the IEEE 30-bus system, can be used to validate the methodology. The benchmark contains generator buses, load buses and transmission branches and is

widely used for comparative power-system studies. Renewable generation can be introduced by replacing or supplementing selected conventional generation with photovoltaic or wind units.

Three representative operating scenarios are recommended: Scenario A—base loading with moderate renewable generation; Scenario B—high renewable output with lower conventional generation; and Scenario C—low renewable output with increased conventional generation. The same network constraints are retained for all scenarios so that the effect of renewable variability can be evaluated consistently.

6. Evaluation metrics

The following metrics should be reported: total active-power loss (MW), minimum bus voltage (p.u.), maximum voltage deviation (p.u.), total generation cost, number of constraint violations and convergence behavior. A voltage-stability indicator such as a voltage-stability index or minimum singular value may additionally be included. For a rigorous journal submission, numerical results should be generated from an actual simulation model rather than estimated values. This avoids unsupported performance claims and makes the work reproducible.

7. Illustrative results and Discussion

The expected behavior of the proposed framework is a reduction in voltage deviation and transmission losses compared with an unconstrained or single-objective operating point. During high renewable generation, the optimizer can reduce conventional generation and adjust reactive-power support to maintain acceptable voltage levels. During low renewable generation, conventional generators provide additional active and reactive support.

The voltage profile should be examined bus-by-bus, with particular attention to electrically weak load buses. A successful operating point should maintain all bus voltages within the selected operating range and keep branch flows below their thermal ratings.

A useful comparative table for the final study is shown below. The numerical entries must be populated from actual simulation runs before journal submission.

Method	Generation Cost	Loss (MW)	Min. Voltage (p.u.)	Constraint Violations
Base OPF	To be simulated	To be simulated	To be simulated	To be simulated
PSO-based OPF	To be simulated	To be simulated	To be simulated	To be simulated
Proposed Hybrid OPF	To be simulated	To be simulated	To be simulated	To be simulated

8. Renewable energy and reactive power coordination

Reactive-power management becomes increasingly important as renewable penetration increases. Inverter-based renewable resources can provide voltage support when their control capability and operating limits permit. The optimization framework can therefore include inverter reactive-power capability, shunt compensation and transformer tap settings as decision variables.

Coordinated control prevents one device from compensating excessively while another remains underutilized. Such coordination can improve voltage quality and reduce unnecessary reactive-power circulation.

9. Practical implementation

A practical implementation can follow these steps: develop the IEEE benchmark model; validate the base-case AC power flow; add renewable-generation models; define generator, voltage and branch constraints; implement the objective function; execute the hybrid optimizer; verify the final operating point using an independent AC

power-flow calculation; and perform sensitivity analysis for renewable output and load variation.

The final study should include convergence plots, voltage-profile plots, loss comparisons and a table of control-variable settings. Statistical results from multiple independent optimization runs should be reported when a stochastic optimizer is used.

10. Limitations

The proposed framework is an optimization methodology rather than a claim of measured utility performance. Benchmark-network results cannot automatically be generalized to a specific transmission utility. Renewable uncertainty, communication delays, protection constraints and detailed inverter controls may require additional modeling for field deployment.

11. Conclusion

This paper presented a hybrid optimization framework for coordinated optimal power flow and voltage-stability enhancement in renewable-energy-integrated power systems. By simultaneously consid

ering generation cost, transmission losses and voltage deviation, the framework provides a balanced operating strategy. The approach can coordinate conventional generators, transformer taps and reactive-power resources while respecting network constraints. Future work should incorporate probabilistic renewable forecasts, contingency-constrained OPF, dynamic voltage-stability analysis and validation on larger practical networks.

12. Future scope

Future research may extend the framework to N-1 security-constrained OPF, probabilistic OPF under renewable uncertainty, energy-storage coordination, flexible AC transmission systems, demand response, real-time optimization and machine-learning-assisted voltage-stability prediction.

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