Proceedings of Business and Economic Studies, 2025, Volume 8, Issue 4
http://ojs.bbwpublisher.com/index.php/PBES
Online ISSN: 2209-265X
Print ISSN: 2209-2641

Exploring Optimization Strategies for Island Power Grid Line Layout Oriented Towards Large-Scale Distributed Renewable Energy Integration

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Abstract: The construction of island power grids is a systematic engineering task. To ensure the safe operation of power grid systems, optimizing the line layout of island power grids is crucial. Especially in the current context of large-scale distributed renewable energy integration into the power grid, conventional island power grid line layouts can no longer meet actual demands. It is necessary to combine the operational characteristics of island power systems and historical load data to perform load forecasting, thereby generating power grid line layout paths. This article focuses on large-scale distributed renewable energy integration, summarizing optimization strategies for island power grid line layouts, and providing a solid guarantee for the safe and stable operation of island power systems.

Keywords: Island power grid; Line layout; Optimization strategy; Distributed renewable energy; Large-scale

Online publication: September 10, 2025

1. Introduction

Renewable energy technologies continue to evolve, and the cost of renewable energy generation has been significantly reduced. Accelerating large-scale and distributed renewable energy integration into island power grids has become an inevitable trend, bringing greater challenges to island power grid line planning. At present, domestic island power grid line planning has achieved certain results. However, with the steady integration of large-scale distributed renewable energy, the limitations of traditional methods based on historical experience and expert judgment for planning line layouts have become increasingly evident. It is difficult to accurately grasp the power grid's operational status after renewable energy integration, which seriously threatens the stability and safety of power grid operations. How to further optimize and improve has become a top priority.

1.1. Island power load forecasting

Due to their geographical specificity, island power grids belong to independent or semi-independent power systems. They have strong load fluctuations, small power supply radii, and the advantage of high renewable energy utilization rates. In the future, with the integration of large-scale distributed renewable energy, island power grids will face many new challenges in supply and demand balance. As a fundamental aspect of power grid planning, power load forecasting essentially collects historical data and information for multi-dimensional analysis to predict future electricity demand over a period of time. This provides support for subsequent renewable energy capacity allocation, line regulation, and power grid topology design [1].

The power load on island grids includes commercial, residential, public facility, and industrial electricity consumption. Some islands are primarily focused on tourism, and during the peak season, a large influx of tourists increases the demand for electricity on the island. During the low season, the electrical load on the island decreases, resulting in significant seasonal fluctuations in power load. Other islands are mainly focused on industries such as fisheries processing, where production electricity consumption exhibits intermittent and cyclical characteristics, greatly increasing the complexity of the island's power load.

By collecting power load data from different regions of the island and using normalization methods, data cleaning and conversion are achieved using the following formula:

$$x_{norm} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

In the formula, x_{norm}, x_{max}, x_{min}, x represent normalized data, the maximum value of the dataset, the minimum value, and the original load data, respectively. Data normalization emphasizes scaling features to the same numerical range. Combining the operating characteristics of the island's power system and forecasting goals, regression prediction methods are used to forecast the island's power load, using the following formula:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \tag{2}$$

In the formula, ε, β_i, Y, X_i represent the error value, regression coefficient, predicted power load of the island, and influencing factors, respectively. Based on the above formulas, the power load on the island can be accurately predicted, providing a reliable data basis for subsequent power system planning and operation on the island.

2. Analysis of large-scale distributed renewable energy access points

2.1. Planning objectives for access points

In the planning and design of island power grid lines, it is necessary to consider the selection of large-scale distributed renewable energy access points. Whether the access point selection is reasonable relates to the stability and reliability of the power system operation. Specific planning needs to meet the following objectives: (1) Maximize renewable energy consumption: Placing access points in the crossover area between renewable energy-rich areas and load-intensive areas can effectively avoid excessive line losses due to long transmission distances; (2) Improve grid resilience: Adopting multi-point decentralized access to the island grid and establishing an "N-1" redundant structure can effectively avoid cascading failures caused by single-point failures, minimizing the risk of large-scale power outages [2]; (3) Optimize economy: Comprehensive consideration of renewable energy equipment investment, lifecycle operation and maintenance costs, and line renovation costs.

2.2. Access potential evaluation

The large-scale distributed access of new energy on islands requires a full understanding of the spatial distribution characteristics of resources in the region, as shown in **Table 1**.

Table 1. Spatial distribution characteristics of island resources

New energy type	Key Metrics	Data acquisition method
Photovoltaics	Inclined surface irradiance and shadow occlusion	Satellite remote sensing + drone aerial photography modeling
Wind power	Annual average wind speed at 50m height	LIDAR wind tower + meteorological reanalysis data
Wave energy	Significant wave height, energy flux density	Ocean buoy monitoring + numerical simulation

A two-tier evaluation framework is adopted to establish a quantitative model for assessing the potential of large-scale distributed new energy access on islands. The formula for calculating the maximum technical development capacity of photovoltaic systems is as follows:

$$P_{\max}^{PV} = \eta \bullet A_{roof} \bullet G_{tilt} \bullet PR \quad (3)$$

In the formula, η represents inverter efficiency, PR denotes the performance ratio, $P_{\max}^{PV}$ stands for the maximum technical development capacity of the photovoltaic system, A_{roof} represents the actual available roof area, G_{tili} signifies irradiance on the inclined surface, and PR is the performance ratio.

In addition, a comprehensive evaluation index system is established to comprehensively evaluate the feasibility of access point selection from the dimensions of energy matching degree, ecological sensitivity, return on investment, and fault ride-through capability [3]. Based on the modified NSGA-II algorithm for the access point location model, the objective function minimizes (f_1 represents the total investment cost of lines, f_2 denotes the expected grid loss, and f_3 signifies the voltage fluctuation variance). An adaptive penalty function is employed for power flow limit constraints. The specific formulas are as follows:

(1) Economic objective function formula:

$$f_1 = \sum_{k \in \Omega L} c_k^{line} \cdot l_k \cdot x_k + \sum_{k \in \Omega DG} c_i^{DG} \cdot P_i^{\max} \cdot y_i \quad (4)$$

In the formula, x_k and y_i indicate whether line k is constructed and whether node i is connected to new energy, respectively. c_k^{line}, l_k, and c_i^{DG} represent the unit length line cost, line length, and new energy unit capacity cost, respectively.

(2) Power stability objective function formula:

$$f_3 = \frac{1}{N} \sum_{i \in \Omega N} [\frac{1}{T} \sum_{t \in T} (V_i(t) - \overline{V}_i)^2] \quad (5)$$

In the formula, $\overline{V}_i$ represents the rated voltage, and N denotes the number of nodes.

(3) Power flow formula:

$$\begin{cases} P_{ij} = P_j + r_{ij} \dfrac{P_{ij}^2 + Q_{ij}^2}{V_i^2} + \sum k : j \to kP_{jk} \\ Q_{ij} = Q_j + x_{ij} \dfrac{P_{ij}^2 + Q_{ij}^2}{V_i^2} + \sum k : j \to kQ_{jk} \\ V_j^2 = V_i^2 - 2(r_{ij}P_{ij} + x_{ij}Q_{ij}) + (r_{ij}^2 + x_{ij}^2) \dfrac{P_{ij}^2 + Q_{ij}^2}{V_i^2} \end{cases} \quad (6)$$

*Applicable to all lines i→j.

The specific algorithm flow is shown in **Figure 1**.

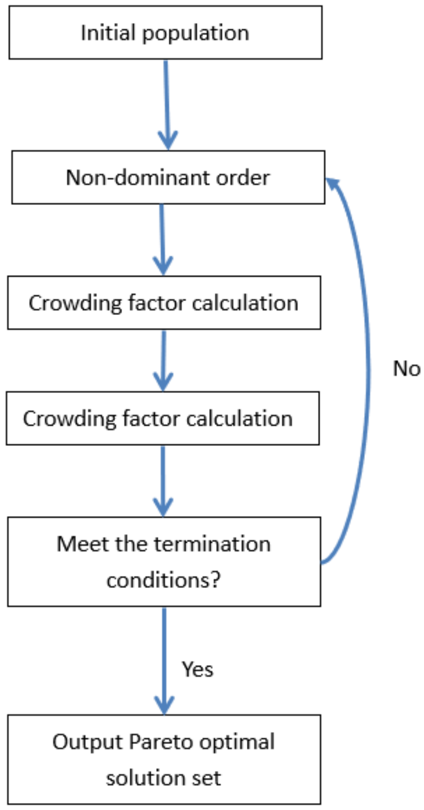

Figure 1. Algorithm flow

After distributed new energy is integrated into the island power grid, it is connected to the island distribution network in a distributed manner, with real-time monitoring and adjustment, so that the new energy generation facilities can be smoothly integrated into the grid, thereby improving the operational stability of the island power grid.

3. Optimization strategy for large-scale distributed new energy access to island power grid line layout

Based on selecting appropriate large-scale distributed new energy access points, it is necessary to plan the island power grid line layout reasonably to achieve full integration of large-scale new energy [4].

3.1. Optimization of line layout objectives and constraint systems

The optimization of island power grid line layout should tightly focus on the triple objectives of safety, economy, and low carbon emissions. A multi-objective optimization model is established as follows:

(1) Economic objective

$$F_1 = \sum_{i \in \Omega L} (C_{line}^i \cdot L_i \cdot \delta_i) + \sum_{i \in \Omega DG} C_{DG}^i \cdot P_{DG}^{j\max}) \quad (7)$$

In the formula, δ_i ranges from 0 to 1, indicating whether construction is carried out; C_{line}^i, L_i, and C_{DG}^i represent the unit length line cost, line length, and new energy unit capacity cost, respectively.

(2) Safety objective

$$F_2 = \sum_{t=1}^{T} \sum_{k \in \Omega L} I_k^2(t) \cdot R_k \cdot \Delta t \quad (8)$$

In the formula, $I_k(t)$ and R_k denote the current and resistance of line k during time period t, respectively.

(3) Low-carbon objective

$$F_3 = \frac{\sum_{t=1}^{T} \sum_{j \in \Omega D} P_D^j(t) \cdot \Delta t}{\sum_{t=1}^{T} P_{load}(t) \cdot \Delta t} \times 100\% \quad (9)$$

Using the weighted sum method, the multi-objective problem can be transformed into a single-objective optimization analysis:

$$\min(\lambda_1 \frac{F_1}{F_1^{base}} + \lambda_2 \frac{F_2}{F_2^{base}} - \lambda_3 \frac{F_3}{F_3^{base}}) \quad (10)$$

In the formula, F_i^{base} it represents the target value of the baseline scenario.

Based on optimizing the line layout objectives, corresponding constraints should be determined to ensure the feasibility and practicality of the line layout optimization plan. Specific analyses can be conducted from perspectives such as topological structure constraints, line capacity, environmental, and engineering constraints.

(1) Electrical safety constraints:

Power Flow Equation: $P_G - P_L = V\sum V(G\cos\theta + B\sin)\theta$ (11)

(2) Topological constraints:

Radial Operation Equation: $N_{branch} = N_{node} - 1$ (12)

The island power grid operates in a radial configuration:

$$N_{branch} = N_{node} - N_{source} \quad (13)$$

Formula N_{source} represents the number of main power source nodes.

The line capacity refers to the maximum current value that a power grid line can carry under normal operating conditions. By constraining the line capacity, it can be ensured that the later line current value does not exceed the rated capacity, avoiding overload failures. In each line l_i, the flowing current I_t should not exceed the maximum allowed current.

In terms of environmental and engineering constraints, it is required that the power grid line layout maintains a buffer distance of not less than 500m from ecological protection areas such as coral reefs and mangrove forests; in coastal areas, the line salt fog corrosion level is not less than C4, meeting the requirements of ISO 9223 standard; if the slope of the construction area exceeds 30°, overhead construction of lines is not allowed [5].

3.2. Establishment of a multi-agent collaborative optimization framework

Focusing on a two-tier and multi-agent optimization framework. The upper planning layer includes government entities and power grid companies. The former sets the minimum renewable energy penetration rate (≥ 40%) and carbon emission quotas; adheres to the goal of maximizing return on investment and prepares reasonable main grid framework plans. The lower operational layer includes distributed power clusters and load aggregators. The former uses consensus algorithms to draw output curves, while the latter adjusts demand-side response based on electricity price signals [6].

3.3. Line impedance matching and dynamic reconstruction technology

Calculating line capacity based on the distribution of renewable energy access points. Some offshore wind power transmission lines are suitable for choosing cross-linked polyethylene insulated cables with lap joints, which have a 1.8 times higher current carrying capacity compared to conventional cables; in areas with severe salt fog corrosion, tin-plated copper core wires are suitable, and anticorrosive additives are added to the insulation layer [7]. Combining the fluctuation of renewable energy output, the line is equipped with adjustable reactors and static var generators. Once the peak photovoltaic output causes abnormal voltage rise in the line, the static var generator can absorb excess reactive power; voltage fluctuations caused by wind power output fluctuations can be dynamically adjusted by reactors to adjust line impedance. The quantitative relationship formula between line parameters and renewable energy capacity is as follows:

$$Z_{line} = \frac{R + jX}{S_{DG}^{\max}} \leq K_{stab} \tag{14}$$

In the formula, K_{stab} represents the system stability coefficient, and the impedance optimization is achieved by reasonably adjusting the wire cross-sectional area. Additionally, combining the extreme climate that island lines may encounter, the adaptability design of the lines is optimized. In some areas frequented by typhoons, the line is suitable for choosing a structure combining tension towers with optical cable composite overhead ground wires. The towers can withstand wind speed impacts of 45m/s, and anti-pollution flashover composite insulators are selected; waterproof and sealed structures are used for high-humidity island cable joints, filled with silicone insulating materials to enhance the extreme climate adaptability of island power grid lines [8–10]. Even in case of abnormalities, different warning mechanisms can be triggered according to the level of emergencies, and a three-level trigger mechanism can be established for the power grid, as shown in **Table 2**.

Table 2. Three-level event trigger mechanism

Level	Type	Response action
Level 1	Typhoon Red Warning	Switch to islanding mode - energy storage priority
Level 2	Load surge >20%	Activate smart soft open point (SOP)
Level 3	Renewable generation forecast deviation >15%	Adjust OLTC tap position and implement reactive power compensation

3.4. Simulation verification

A certain island in the South China Sea has a total area of 58 km², with a peak power load of 32 MW, installed new energy photovoltaic capacity of 18 MW, wind power capacity of 9 MW, and energy storage of 15 MWh. The island mainly uses 10 kV overhead lines, with an average load rate of 78%.

The IEEE 34-node distribution system is adopted, which includes 33 lines and 34 nodes, with a rated voltage of 24.9 kV and a total load of 4.8 MW + 2.0 Mvar. Photovoltaic power stations are connected to nodes 6, 12, 18, 25, and 30, while a wind turbine is connected to node 29, increasing the new energy penetration rate to 45%. The impedance of coastal lines is increased by 20%, and the reactance of mountain lines is increased by 15%. Specific parameters are shown in **Table 3**.

Table 3. Key parameter table

Parameter category	Original value	Island adaptation value
Peak Total Load	4.8 MW	6.2 MW
Average Line R/X Ratio	1.2	1.5
Allowable Voltage Deviation	±5%	±10%
Short-Circuit Capacity	12 MVA	18 MVA

After optimizing the island's power grid layout using the planning method described in this paper, the overall cost has been reduced from 87.6 million yuan to 72.3 million yuan. The annual average network loss rate has dropped from 6.8% to 4.1%, the new energy consumption rate has increased from 72.3% to 88.6%, and the fault recovery time has been reduced from 45 minutes to 19 minutes.

4. Conclusion

In summary, new energy generation has a small environmental impact and relatively clean generation methods. With continuous updates and upgrades in new energy generation technology, generation costs have significantly decreased. Therefore, promoting large-scale distributed new energy access to island power grid systems has become a major area of new energy application. However, due to the randomness and intermittency of new energy sources, certain hidden dangers are posed to the stable operation of island power grids. Island power grid systems should comprehensively consider the demand for new energy grid connection, coordinate the economy, safety, and low carbon emissions of the power grid, and optimize the layout of lines, thereby improving operational efficiency and creating more ideal economic benefits.

Disclosure statement

The authors declare no conflict of interest.

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