Study on Type Selection of 1000kV Compact Transmission Lines (Postprint)

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Date: 2019-03-05T00:00:00+00:00

Abstract

The amount of natural power transmitted by a transmission line and the natural power per unit cross-sectional area constitute two important reference indicators affecting transmission line economics. In the selection of ultra-high voltage (UHV) transmission lines, beyond these two indicators, electromagnetic environmental constraints such as conductor surface electric field intensity, radio interference, and audible noise must also be considered. Compact transmission technology can effectively increase both the line' s natural power and its natural power per unit cross-sectional area, while simultaneously improving the surrounding electromagnetic environment. This paper applies compact transmission technology, considers practical engineering constraints including economic performance and electromagnetic environment in UHV line selection, establishes a multi-objective mathematical model with multiple nonlinear constraints, and obtains UHV transmission line configurations with conventional symmetric sub-conductor arrangements. By comparing the obtained configuration with conventional UHV line configurations, a line configuration with superior economic performance and electromagnetic environment is identified. Furthermore, this paper employs a particle swarm algorithm to optimize the aforementioned configuration through asymmetric sub-conductor arrangement, further reducing electromagnetic parameters such as radio interference and audible noise around the line, obtains line configurations with asymmetric sub-conductor arrangements for each phase, and finally validates the obtained configuration through simulation using the finite element method.

Full Text

Preamble

A Study of Conductors Selection Types in 1000kV Compact Power Transmission Line

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Abstract: The natural power transmission capacity of a line and the natural power per unit cross-sectional area are two important indicators for evaluating transmission line economics. In ultra-high voltage (UHV) transmission line selection, electromagnetic environmental constraints such as conductor surface electric field strength, radio interference, and audible noise must also be considered. Compact transmission technology can effectively increase both the natural power and natural power per unit cross-sectional area while improving the electromagnetic environment around the line. This paper applies compact transmission technology to UHV line selection, considering both economic factors and electromagnetic environmental constraints, to establish a multi-objective nonlinear optimization model with multiple constraints. The model yields conventional UHV transmission line configurations with symmetric sub-conductor arrangements. Comparison with conventional UHV line selections reveals a configuration with superior economic and electromagnetic performance. Furthermore, particle swarm optimization is employed to optimize the asymmetric arrangement of sub-conductors in the selected configuration, further reducing electromagnetic parameters such as radio interference and audible noise around the line. Finally, finite element method simulations validate the obtained configuration.

Keywords: Ultra-high voltage, compact power transmission technology, electromagnetic environment, conductor selection types, finite element analysis method

1 Introduction

Compact transmission technology optimizes conductor arrangement to reduce line wave impedance and decrease conductor surface electric field strength, thereby achieving the goals of increasing natural power transmission capacity, reducing line corridor width, and improving the electromagnetic environment around the line [1-5]. The Soviet Union previously applied compact transmission technology to optimize the conductor arrangements of 330kV and 500kV lines [6], and China has conducted related research on 500kV and 750kV compact transmission lines [7-8]. However, studies on applying compact transmission technology to 1,000kV UHV AC transmission line conductor selection remain relatively scarce both domestically and internationally.

This paper proposes a selection method for 1,000kV UHV AC transmission line conductors that aims to improve natural power and natural power per unit cross-sectional area while considering practical engineering constraints such as conductor surface electric field strength, radio interference, and audible noise. A multi-objective nonlinear optimization model with inequality constraints is established to transform the conductor selection problem into a mathematical framework. Solving this model yields an initial optimal conductor configuration, which is then compared with commonly used UHV transmission lines to identify a superior option in terms of natural power, natural power per unit cross-sectional area, and electromagnetic environment.

2 Conductor Selection Methodology

2.1 Initial Scheme Selection

Based on investigations of 500kV and 750kV compact AC lines and 1,000kV conventional UHV transmission lines, combined with design experience, several candidate initial schemes were identified and are presented in Table 1 .

2.2 Establishing the Conductor Selection Model

During the initial scheme selection process, a multi-objective model was established to enhance line natural power and natural power per unit cross-sectional area. The specific model is as follows:

$$Pn0 = \frac{6\varepsilon_0 n v_B r K_{ut} U_p}{E_{per}}$$

$$Pn = \frac{6\varepsilon_0 n v_B r K_{ut} U_p^2}{E_{per}}$$

where $Pn0$ and Pn represent the natural power per unit cross-sectional area and total natural power, respectively; ε_0 is the permittivity; n is the number of sub-conductors; v_B is the phase matrix; r is the conductor radius; K_{ut} is the conductor effective utilization coefficient; U_p is the phase voltage; and E_{per} is the conductor surface limit field strength. Other parameters are detailed in reference [6].

When establishing the solution model, practical engineering constraints including audible noise, radio interference, and maximum sub-conductor surface electric field strength must also be considered. The constraint conditions are shown in equation (2):

$$12m \leq L \leq 16m$$

$$15.0 \leq S/d \leq 18.0$$

$$L_{AN} \leq 55dB(A)$$

$$E_{imax} \leq 0.88 E_0$$

$$E_{lin} \leq 55 dB(\mu V/m)$$

where L is the inter-phase distance; d is the sub-conductor diameter; S is the splitting spacing, all representing structural dimension constraints. L_{AN} denotes audible noise; E_{lin} denotes radio interference; and E_{imax} is the maximum sub-conductor surface field strength, all representing electromagnetic environment constraints.

Using Matlab as the computational platform, the above candidate schemes were solved to obtain their optimal solutions, presented in Table 2 .

Analysis of Table 2 reveals the following patterns: (1) Increasing the number of bundles can increase line natural power while substantially improving natural power per unit cross-sectional area. (2) With the same number of bundles, the equilateral triangular arrangement yields higher natural power and natural power per unit area. (3) Increasing sub-conductor radius can increase natural power, but simultaneously decreases natural power per unit cross-sectional area.

Based on this analysis and considering practical engineering constraints, increasing bundle numbers creates significant difficulties for construction and maintenance. Therefore, the number of sub-conductors should not be excessive. The model solutions yield two candidate schemes: 10-bundle equilateral inverted triangle arrangement with sub-conductor radius $r = 16.08$ mm, splitting spacing $S = 408.89$ mm, and inter-phase distance $L = 14.9$ m; and 12-bundle equilateral inverted triangle arrangement with sub-conductor radius $r = 13.33$ mm, splitting spacing $S = 376.88$ mm, and inter-phase distance $L = 13.1$ m.

Incorporating engineering practicality, the initial candidate schemes are: (1) Phase conductors using 10×LGJ-500/35 in equilateral inverted triangle arrangement, inter-phase distance 14.9 m, splitting spacing 400 mm, with the lowest phase conductor at an average height of 20 m above ground; (2) 12×LGJ-400/35 in equilateral inverted triangle arrangement, inter-phase distance 13.1 m, splitting spacing 375 mm, with the lowest phase conductor at an average height of 20 m above ground.

2.3 Selection of Optimal Conductor Configuration

Through investigation of 1,000kV UHV conventional transmission lines, this study compares the 8×LGJ-500/35 conductor with 400 mm splitting spacing used in the UHV AC demonstration project with typical ZBSI and ZMP1 towers, and the 8×LGJ-630/45 conductor with 400 mm splitting spacing used in the 1,000kV Huainan-Shanghai double-circuit line with typical SK301 towers [9].

These three typical tower configurations are compared with single-circuit compact equilateral inverted triangle arrangements of 10×LGJ-500/35 and 12×LGJ-400/35 as candidate schemes for optimization.

Using Matlab as the computational platform, the electromagnetic environment parameters for each candidate scheme were calculated and are presented in Table 3 .

Analysis of Table 3 shows that compared with conventional 8-bundle single-circuit lines, the UHV single-circuit compact transmission lines with equilateral inverted triangle arrangements (both 10×500 and 12×400 configurations) significantly reduce the width of regions where magnetic induction strength and field strength exceed 4 kV/m, while substantially increasing natural power and power transmission per unit corridor width. The 10×500 and 12×400 UHV compact configurations increase natural power by approximately 29% and 40%, respectively, compared to the conventional ZBS1 tower arrangement, with unit corridor transmission capacity 3.8 and 4.1 times greater.

Although the 10×500 configuration has a larger inter-phase distance that may increase tower investment, the increased number of bundles in the 12×400 configuration results in greater total tower weight [10-11]. Additionally, construction and hardware installation for 12-bundle conductors are more difficult than for 10-bundle conductors, leading to higher overall investment. Considering transmission capacity increase, line investment reduction, and construction difficulty, the 10×500 conductor arrangement proves superior.

3 Sub-Conductor Asymmetric Arrangement Optimization

3.1 Objective Function

To further reduce sub-conductor surface electric field strength and improve the line's electromagnetic environment, this paper employs particle swarm optimization to optimize the sub-conductor arrangement of the selected configuration.

The optimization aims to achieve uniform distribution of electric field strength across sub-conductors. Therefore, a function reflecting the non-uniformity of sub-conductor surface electric field strength is introduced as the objective function (3):

$$f = \frac{E_{max} - E_{min}}{E_{aver}}$$

where E_{max} is the maximum surface electric field strength of the phase conductor; E_{min} is the minimum; and E_{aver} is the average. A smaller f value indicates more uniform sub-conductor surface electric field distribution. Since 1,000kV UHV single-circuit compact transmission lines should meet the same environmental protection requirements as conventional UHV lines [1-2,14-17], the constraints for objective function (3) are identical to equation (2).

3.2 Optimization Method Analysis

When a sub-conductor moves away from the geometric center of the phase conductor, the shielding effect from adjacent sub-conductors weakens, increasing its own surface electric field strength while decreasing that of adjacent sub-conductors. Conversely, when a sub-conductor moves closer to the geometric center, the shielding effect from adjacent sub-conductors strengthens, reducing its own surface electric field strength while increasing that of its neighbors. Therefore, for sub-conductors with surface electric field strength below the average value, they can be positioned relatively farther from the phase conductor center, while those above the average can be positioned relatively closer.

3.3 Analysis of Conductor Surface Electric Field Before and After Optimization

Based on the conductor selection scheme, the spatial arrangement of sub-conductors before optimization is shown in Figure 1 [Figure 1: see original paper]. After optimization (with sub-conductor radius, conductor height above ground, inter-phase distance, and conductor type remaining unchanged), the optimized arrangement is shown in Figure 2 [Figure 2: see original paper].

Figure 3 [Figure 3: see original paper] compares the sub-conductor surface electric field strength distribution before and after optimization. The results show that before optimization, the distribution is highly non-uniform, with a maximum surface field strength of 24.67 kV/cm and minimum of 20.68 kV/cm—a 19.31% difference. After optimization, the maximum is 23.79 kV/cm and minimum is 22.33 kV/cm—only a 6.54% difference. This demonstrates that modifying sub-conductor arrangement significantly reduces electric field strength non-uniformity.

3.4 Comparison of Electrical Parameters Before and After Optimization

Since the optimized arrangement substantially reduces sub-conductor surface electric field strength non-uniformity, the maximum surface electric field strength decreases, consequently reducing radio interference and audible noise levels associated with conductor surface electric field strength, as shown in Table 4 .

4 Finite Element Method Simulation of Transmission Line Electric Field Strength

To verify the accuracy of Matlab simulation results, this paper employs finite element analysis to calculate conductor surface electric field strength for comparison with Matlab computational results.

4.1 Ansys-Based Transmission Line Model Development

A two-dimensional model of the 1,000kV single-circuit compact transmission line was developed using Ansys for finite element analysis. The mesh subdivision of the line model is shown in Figure 4 [Figure 4: see original paper].

4.2 Finite Element Simulation Results Analysis

Detailed simulation of the optimal configuration using finite element analysis yields the maximum sub-conductor surface electric field strength. The Ansys analysis result for Phase B electric field strength in the optimized arrangement is shown in Figure 5 [Figure 5: see original paper].

The Ansys simulation indicates a maximum sub-conductor surface electric field strength of 22.87 kV/cm, while the Matlab result shows 23.79 kV/cm. Comparison reveals the Ansys result is slightly higher, with a 3.8% error between the two results—satisfactory for engineering requirements. This confirms that the Matlab analytical method provides accurate calculations of maximum sub-conductor surface electric field strength.

5 Conclusions

Research on UHV AC compact transmission line conductor selection and sub-conductor arrangement optimization yields the following conclusions:

(1) The UHV AC compact transmission line configuration using 10×LGJ-500/35 conductors in equilateral inverted triangle arrangement with 400 mm splitting spacing and 14.9 m inter-phase distance demonstrates high economic efficiency and engineering practicality.

(2) The optimized conductor arrangement offers significant research value, substantially reducing sub-conductor surface electric field strength non-uniformity, markedly decreasing audible noise and radio interference levels, and improving the electromagnetic environment around the conductors.

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Note: Figure translations are in progress. See original paper for figures.