Research on Key Technologies for Static Weather Forecasting of Xinjiang Power System Based on Machine Learning and Multi source Numerical Model Fusion

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ABSTRACT Xinjiang's power system is characterized by a vast service area, complex terrain, long transmission corridors, widely distributed substations, and a high proportion of renewable generation. Static and stable weather, marked by low wind speed, inversion, and weak diffusion conditions, can intensify risks such as pollution flashover, icing accumulation, subsequent line galloping, renewable output fluctuation, and regional load imbalance. To improve power-oriented stagnant weather forecasting, this study integrates machine learning with multi-source numerical model fusion. ECMWF, GRAPES, and WRF data are standardized, bias-corrected, and downscaled to a unified high-resolution grid, then combined with ground observations, reanalysis data, grid equipment records, and fault histories. A power-specific stagnant weather index system is constructed, and machine-learning models, including random forest, gradient boosting, LSTM, and attention networks, are used for fusion forecasting. The resulting products support grid-based and line-level forecasting for dispatching, maintenance, and risk warning. The study directly contributes to electromagnetic insulation safety, high-voltage transmission reliability, and power-system electromagnetic environment management.

INDEX TERMS atmospheric stagnation,power system,machine learning,electromagnetic insulation,transmission line

I. INTRODUCTION

A. RESEARCH BACKGROUND AND SIGNIFICANCE

1) Research Background

XINJIANG is a vital energy hub. The local power grid is characterized by long-distance transmission, large capacity, ultra-high voltage, AC/DC hybrid connections, and a high proportion of renewable energy integration. With the large-scale integration of wind and photovoltaic power, the sensitivity of the power system to meteorological conditions has significantly increased, and stable weather has become one of the key meteorological factors affecting the safe operation of the power grid. Static and stable weather is characterized by low surface wind speeds and strong temperature inversions, which facilitate the accumulation of moisture and the formation of heavy fog or rime. While these "calm" conditions do not directly trigger high-energy line galloping, they provide the critical "incubation period" for non-uniform ice or rime accretion on conductors. This ice buildup changes the aerodynamic profile of the lines; when the stagnant period ends and wind speeds increase slightly (even within a 4–7 m/s range), the previously accreted ice induces aerodynamic instability, leading to icing-induced galloping (dancing). Therefore, forecasting the stagnant period is a vital precursor for predicting subsequent mechanical failures. At the same time, it can cause sudden changes in output of photovoltaic power plants during sunrise and sunset periods, long-term low output of wind power, and uneven distribution of regional loads, seriously threatening the safety of main equipment and power supply reliability of the power grid [1,2].

The current electricity meteorological forecasting generally adopts a single numerical model product, which has obvious limitations in the complex terrain of Xinjiang. Firstly, there is a deviation between the initial field of the numerical model and the physical processes of the boundary layer, and the forecasting ability of weak systems such as static and stable weather is insufficient; Secondly, the spatial and temporal resolution of the forecast is low, making it difficult to support the grid based and line level defense needs of the power grid; Thirdly, the forecast products are aimed at general meteorology and are not deeply coupled with power equipment failures and power grid operation risks; Fourthly, there are multiple single point forecasts and insufficient regional coverage, resulting in weak continuous forecasting capabilities along long-distance transmission lines [3].

In recent years, machine learning has shown outstanding advantages in nonlinear fitting, multi-source information fusion, feature extraction, etc. It can effectively correct numerical model errors and improve the accuracy of extreme and weak weather system forecasting. The integration of multi-source numerical models such as ECMWF, GRAPES, WRF, and machine learning to construct a specialized static and stable weather forecasting technology system for the Xinjiang power system has become an urgent need to enhance the meteorological disaster prevention capability of the power grid [4].

2) Research significance

Theoretical significance: To construct a framework for electric power meteorological forecasting that integrates multi-source numerical models and machine learning, propose methods for identifying, extracting, and predicting static and stable weather in complex terrain areas, improve the theoretical system of electric power meteorological forecasting, expand the application boundaries of machine learning in the field of energy and power, and provide new theoretical and technical paths for high-precision and specialized electric power meteorological forecasting [5,6].

Practical significance: Significantly improve the accuracy and lead time of static and stable weather forecasting for the Xinjiang power grid, achieve line level, grid based, and hourly refined forecast output, provide accurate meteorological support for pollution flashover prevention and control, icing warning, new energy power prediction, equipment status maintenance, and scheduling operation optimization, reduce the risk of power grid failures, minimize power outage losses, and ensure the safe and stable operation of large-scale energy bases and reliable power transmission [7].

B. CURRENT RESEARCH STATUS AT HOME AND ABROAD

1) Research on Monitoring and Identification of Steady Weather Conditions

A large amount of research has been conducted both domestically and internationally on the definition, index construction, and spatiotemporal distribution characteristics of static and stable weather. A relatively mature discrimination index has been formed in the field of general meteorology. However, there is relatively little research on the definition, threshold, and impact mechanism of static and stable weather for the power system, and a unified evaluation system for static and stable weather for power specific use has not yet been formed [8].

2) Research on the Application of Numerical Models in Power Meteorology

Numerical models such as WRF, ECMWF, and GRAPES have been widely used for predicting wind speed, temperature, humidity, ice cover, and pollution storms. However, under complex underlying surface conditions such as mountainous areas, basins, and Gobi in Xinjiang, the simulation of boundary layer processes shows significant deviations, and the ability to forecast weak forcing systems such as stable weather is insufficient.

3) Application Research of Machine Learning in Meteorological Forecasting

Machine learning can effectively correct numerical model errors and improve the accuracy of forecasting factors such as temperature, wind speed, humidity, and radiation. Existing research has mostly focused on conventional meteorological elements, and research on integrated forecasting of comprehensive weather events such as electricity scenarios and stable weather is still weak [9].

4) Research on Meteorological Disaster Warning in Power System

The existing meteorological warnings are mostly aimed at serving the public, and are not closely integrated with the characteristics of power grid equipment faults, operational risks, and dispatch strategies. The correlation mechanism between stable weather and pollution flashover, icing, and dancing is unclear, and the refinement, practicality, and pertinence of warnings need to be improved.

5) Review of Research Status

Overall, there are four obvious shortcomings in existing research: firstly, the insufficient utilization of multisource numerical model fusion and the lack of complementary information capabilities; Secondly, machine learning models have not been specifically optimized for the characteristics of stable weather and power faults; Thirdly, there is a lack of a dedicated static and stable weather indicator system for the Xinjiang power grid; The fourth issue is that the combination of forecasting products with power grid dispatching, equipment operation and maintenance, and risk warning services is not closely integrated. This article conducts systematic research on the above issues [10].

C. RESEARCH CONTENT AND TECHNICAL ROUTE

1) Research Content

1. Establish a specialized static and stable weather indicator system for the Xinjiang power system;
2. Establish standardization and fusion preprocessing techniques for multi-source numerical model data;
3. Optimize machine learning models suitable for predicting stable weather conditions;
4. Build a multimodal machine learning fusion forecasting model;
5. Develop grid based and line level refined forecasting products;
6. Conduct comprehensive empirical testing and business application analysis;
7. Form a complete technical system and application standards.

2) Technical roadmap

Following the route of "data acquisition standardization processing feature optimization model construction fusion forecasting product development empirical testing business application", using multi-source numerical models, ground observations, reanalysis data, power grid equipment data, and fault records as inputs, with machine learning as the core, a high-precision forecasting model is constructed to output static and stable weather products that meet the needs of the power grid [11].

D. PAPER STRUCTURE AND CHAPTER ARRANGEMENT

The full text consists of seven chapters: Chapter 1 is the introduction; Chapter 2 is about relevant theories and data foundations; Chapter 3 is about the construction of a static and stable weather indicator system for power specific applications; Chapter 4 discusses the fusion and preprocessing techniques of multi-source numerical model data; Chapter 5 is a machine learning based static and stable weather fusion forecasting model; Chapter 6 is empirical analysis and business application; Chapter 7 is the conclusion and outlook.

II. RELATED THEORIES AND DATA FOUNDATION

A. BASIC THEORY OF STEADY WEATHER

Quiet and stable weather refers to a weather state where the horizontal transport and vertical exchange capacity of the atmosphere is weak, the atmospheric structure is stable, the near ground wind speed is low, and there is a high risk of temperature inversion and fog. The core elements include near ground wind speed, wind direction stability, boundary layer height, inversion intensity, relative humidity, temperature dew point difference, pressure gradient, etc. Steady and stable weather has the characteristics of long duration, uneven spatial distribution, strong locality, and high risk of triggering equipment failures, making it an important weather type with high incidence in autumn and winter seasons in Xinjiang [12].

B. FUNDAMENTALS OF MULTI SOURCE NUMERICAL MODELS

This article adopts three mainstream numerical model products: ECMWF, GRAPES, and WRF. ECMWF has high accuracy and long lead time; GRAPES is a domestically produced independent model with strong regional adaptability; WRF can achieve high-resolution nested simulation of regions. There are differences in spatial resolution, temporal resolution, physical processes, and forecasting elements among the three modes, which have significant complementarity and provide a basis for integrated forecasting. Please refer to Table 1 for details [12].

TABLE 1. Basic Information of Multi-source Numerical Models

Model Name	Spatial Resolution	Time Resolution	Forecast Range	Strength in Xinjiang Region
ECMWF	$0.25^\circ \times 0.25^\circ$	1 hour	0–72 h	High accuracy, stable long-term forecast
GRAPES	$0.1^\circ \times 0.1^\circ$	1 hour	0–48 h	Good regional adaptability
WRF	1–3 km	1 hour	0–24 h	High-resolution local simulation

C. MACHINE LEARNING RELATED THEORIES

The machine learning models used include decision trees, random forests, gradient boosting trees, long short-term memory networks, attention mechanism networks, fusion models, etc. Machine learning can process high-dimensional, nonlinear, and non-stationary sequences, automatically mine complex mapping relationships between meteorological elements and stable weather, and achieve deviation correction and accuracy improvement of numerical models [13].

D. OPERATING CHARACTERISTICS OF XINJIANG POWER SYSTEM

The Xinjiang power grid has the characteristics of long transmission lines, wide coverage areas, significant differences in terrain, high proportion of new energy, large scale of external transmission, and frequent changes in operation modes. The impact of calm and stable weather on the power grid is mainly reflected in the increased risk of pollution flashover, worsening of line icing, decreased and fluctuating output of new energy, abnormal local loads, decreased insulation performance of equipment, and increased difficulty in emergency response [14].

E. DATA SOURCES AND TYPES

The research data includes multi-source numerical model data, ground meteorological observation data, high-altitude detection data, reanalysis data, power grid equipment ledger data, transmission line fault data, new energy output data, load data, geographic terrain data, etc. The data covers the entire Xinjiang region, with long time series and high spatial density, which can support model training and validation [15].

F. DATA QUALITY CONTROL METHODS

Establish a unified data quality control process, including outlier removal, missing value filling, consistency testing, spatiotemporal matching, format standardization, element normalization, etc., to ensure the reliability and stability of model input data [16].

III. CONSTRUCTION OF STATIC AND STABLE WEATHER INDICATOR SYSTEM FOR XINJIANG POWER SYSTEM

A. DEFINITION OF ELECTRICITY SPECIFIC STATIC AND STABLE WEATHER

Based on the climate characteristics of Xinjiang and the laws of power grid faults, the term 'Power-Related Stagnant Weather (PRSW)' is defined as a weather condition during the operation of the power grid, characterized by low ground wind speed, stable atmosphere, weak diffusion ability, and the risk of transmission line pollution flashover, icing, dancing, insulation degradation, and fluctuations in new energy output. This definition is guided by the safety of the power grid and differs from general meteorological calm weather [17].

B. PRINCIPLES FOR SELECTING INDICATORS

The selection of indicators follows the principles of scientificity, systematicity, operability, sensitivity, electricity correlation, and data availability, ensuring that the indicators can accurately reflect the intensity of static and stable weather and its impact on the power grid [18,19].

C. CONSTRUCTION OF STEADY WEATHER INDICATOR SYSTEM

Build a three-tier indicator system, including the target layer, criteria layer, and indicator layer.

Target layer: Comprehensive index of static and stable weather for power specific use.

Criteria layer: dynamic conditions, thermal conditions, humidity conditions, layering conditions, terrain influence conditions [20].

Indicator layer: Near ground wind speed, wind speed coefficient of variation, inversion intensity, boundary layer height, relative humidity, temperature dew point difference, pressure gradient, terrain height, terrain undulation, etc. See Table 2 for details.

TABLE 2. Power-oriented Static Stability Weather Index System

Category	Index Name	Unit	Low Risk	Medium Risk
Dynamic Condition	Near-surface wind speed	m/s	>3	1–3
Thermal Condition	Inversion intensity	°C	<0.5	0.5–1.5
Humidity Condition	Relative humidity	%	<70	70–85
Stratification Condition	Boundary layer height	m	>300	150–300

D. DETERMINATION OF INDICATOR THRESHOLD

Based on historical stable weather events and power grid failure cases in Xinjiang, statistical analysis, sensitivity analysis, and fault matching methods were used to determine the classification thresholds for each

indicator. The stable weather was divided into four levels: none, mild, moderate, and severe, corresponding to different levels of power grid risk.

E. CALCULATION OF COMPREHENSIVE INDEX OF STEADY WEATHER

By combining Analytic Hierarchy Process and Entropy Weight Method for weighting, the comprehensive index of static and stable weather is calculated to achieve a quantitative expression of the intensity of static and stable weather, providing a unified label and target for subsequent forecasting models.

F. RATIONALITY VERIFICATION OF INDICATOR SYSTEM

By testing historical typical events, spatial distribution, fault correlation, and regional adaptability, it is verified that the indicator system is scientific and reasonable, and can accurately identify static and stable weather processes that affect power grid safety.

IV. MULTI SOURCE NUMERICAL MODEL DATA FUSION AND PREPROCESSING TECHNOLOGY

A. ANALYSIS OF CHARACTERISTICS OF MULTI SOURCE NUMERICAL MODE DATA

Compare the forecasting performance of ECMWF, GRAPES, and WRF in the Xinjiang region, analyze the deviation characteristics and spatiotemporal distribution patterns of different models in factors such as wind speed, temperature, humidity, and boundary layer height, and clarify the advantages and disadvantages of each model.

B. STANDARDIZATION PROCESSING OF MULTI-SOURCE DATA

To address the inherent scale mismatches between ECMWF (0.25°), GRAPES (0.1°), and WRF (3 km), a Bilinear Interpolation method is employed to downscale the coarser global models (ECMWF and GRAPES) to a standardized 3 km x 3 km Lambert Conformal Conic grid matching the WRF domain. Temporal alignment is achieved through linear interpolation to reach a synchronized 1-hour resolution. Elevation-based bias correction is applied during the spatial downscaling process to account for Xinjiang's complex topography.

C. MULTI MODE DEVIATION CORRECTION METHOD

Adopting regional, temporal, and elemental bias correction strategies to eliminate pattern system errors, improve the quality of basic data, and provide high-quality input for machine learning models.

D. MULTI SOURCE DATA FEATURE LAYER FUSION

Construct a feature fusion framework to extract pattern statistical features, spatial distribution features, temporal evolution features, and terrain matching features, forming a high-dimensional and strong representation fusion feature set to enhance the model's ability to recognize stable weather conditions.

E. SPACE MATCHING BETWEEN POWER GRID EQUIPMENT AND METEOROLOGICAL DATA

Establish geographic coordinate mapping for transmission lines, substations, and new energy power stations, map grid meteorological data to equipment points, achieve accurate matching between “lines grid” and “sites grid”, and support equipment level forecasting.

F. PREPROCESSING PROCESS AND AUTOMATION IMPLEMENTATION

Building an automated preprocessing process, including data acquisition, verification, calibration, fusion, matching, storage, and output modules, can achieve business stable operation and meet real-time forecasting needs.

V. A STATIC AND STABLE WEATHER FORECASTING MODEL BASED ON MACHINE LEARNING AND MULTIMODAL FUSION

A. OVERALL MODELING FRAMEWORK

Construct a four layer fusion forecasting framework consisting of “multimodal input feature fusion machine learning correction model integration forecast output”, fully leveraging the physical foundation of numerical models and the fitting advantages of machine learning.

B. SAMPLE CONSTRUCTION AND LABEL GENERATION

Using the comprehensive index of stable weather as a label, construct supervised learning samples with multiple time inputs and single/multiple time outputs, covering different seasons, regions, and intensities of stable events to ensure sample balance and representativeness.

C. FEATURE SELECTION METHOD

Using correlation analysis, importance scoring, mutual information method, and recursive feature elimination for feature optimization, redundant information is removed, model complexity is reduced, and forecasting efficiency and generalization ability are improved.

D. MACHINE LEARNING MODEL CONSTRUCTION AND OPTIMIZATION

Construct random forest, gradient boosting tree, long short-term memory network, and attention network models separately, and optimize the structure for the persistence, locality, and weak signal characteristics of stable weather, including time windows, hidden layers, activation functions, loss functions, training strategies, etc.

E. MULTI MODEL INTEGRATED FORECASTING

Adopting strategies such as weighted voting, mean fusion, and optimal selection for multi model integration, further reducing single point errors and improving forecast stability and reliability.

F. MODEL EVALUATION INDICATORS

A comprehensive evaluation is conducted using ACC, FAR, and POD. Additionally, both RMSE and MAE are utilized to provide a nuanced view of error distribution: RMSE is sensitive to large outliers which represent critical failure in extreme weather alerts, while MAE provides a steady measure of average forecast deviation. To demonstrate the true skill of the proposed Integrated Model, the results are compared against a Persistence Forecast (PF) baseline, which assumes weather remains constant over the forecast lead time. Please refer to Table 3 for details.

TABLE 3. Evaluation Indicators of Prediction Model

Indicator	Full Name	Evaluation Criterion
ACC	Accuracy	The higher, the better
RMSE	Root Mean Square Error	The smaller, the better
MAE	Mean Absolute Error	The smaller, the better
FAR	False Alarm Rate	The smaller, the better
POD	Probability of Detection	The higher, the better

G. MODEL INTERPRETABILITY ANALYSIS

Using methods such as feature importance, partial dependency graph, and contribution analysis, explain the decision-making logic of the model and enhance its credibility and acceptance in the power industry.

VI. EMPIRICAL ANALYSIS AND BUSINESS APPLICATION

A. OVERVIEW OF THE RESEARCH AREA

The total area of Xinjiang is 1.66 million square kilometers, with terrain divided into mountainous areas, basins, Gobi, oases, etc., and significant differences in climate. The research area covers all 14 prefecture level cities, all 750kV/220kV/110kV transmission lines, substations, wind farms, and photovoltaic power stations, which are typical representatives.

B. EXPERIMENTAL SETUP

The training set uses historical data from multiple years, while the test set uses independent annual data. The time resolution is hourly, and the spatial resolution is gridded. The forecast lead time is 1-72 hours, meeting the needs of power grid scheduling and operation and maintenance.

C. ANALYSIS OF MULTI MODE FUSION EFFECT

After the fusion of multi-source models, the accuracy of various meteorological element forecasts has significantly improved, and the deviations of key elements such as wind speed, humidity, and boundary layer height have been significantly reduced, providing high-quality input for subsequent forecasts.

D. COMPARISON OF PREDICTION RESULTS OF MACHINE LEARNING MODELS

All machine learning models are significantly better than a single numerical model, and the ensemble model performs the best. The accuracy of the comprehensive forecast of static and stable weather is high, with low rates of missed and false reports. It has outstanding warning capabilities for moderate and severe static and stable weather, as shown in Table 4 for details.

TABLE 4. Prediction Performance Comparison of Different Models

Model	ACC	RMSE	MAE	POD	FAR
Persistence Forecast (Baseline)	0.612	0.425	0.310	0.584	0.416
Single ECMWF	0.721	0.315	0.246	0.702	0.298
Random Forest	0.824	0.223	0.174	0.815	0.185
LSTM	0.846	0.201	0.156	0.833	0.167
Integrated Model (Proposed)	0.897	0.152	0.118	0.892	0.108

E. PERFORMANCE ANALYSIS OF REGIONAL FORECASTING

The model performs well in northern, southern, eastern Xinjiang, mountainous areas, and basins, with the most significant improvement in complex terrain areas, solving the problem of large prediction bias in traditional models under Xinjiang terrain.

F. PERFORMANCE ANALYSIS OF SEASONAL FORECASTING

The model performs best during the high incidence period of static and stable weather in autumn and winter, with strong ability to capture sustained static and stable weather processes, which can effectively support the seasonal prevention and control focus of the power grid.

G. VERIFICATION OF FORECASTING EFFECTIVENESS FOR POWER GRID EQUIPMENT

Comparing the forecast results with historical pollution flashover, icing, and dancing faults, the forecast results are highly consistent with the occurrence of faults, which can identify high-risk periods and areas in advance and have high warning effectiveness.

H. DEVELOPMENT OF BUSINESS BASED FORECASTING PRODUCTS

Develop five types of business products: static and stable weather grid forecast map, static and stable weather profile along the line, static and stable weather duration forecast, power grid risk level warning, and new energy power meteorological correction products.

I. APPLICATION IN POWER DISPATCHING

Provide meteorological input for daily planning, intraday adjustments, new energy power forecasting, and load forecasting of the power grid, improve planning accuracy, and reduce operational risks.

J. APPLICATION IN EQUIPMENT OPERATION AND MAINTENANCE

Support equipment status maintenance, pollution zone level adjustment, anti pollution flash control, icing warning, and optimized line inspection, achieving a transition from “passive repair” to “active defense”.

K. APPLICATION BENEFIT ANALYSIS

Through practical application, the number of failures caused by stable weather has significantly decreased, equipment downtime has been shortened, the accuracy of new energy forecasting has been improved, and scheduling operations are safer and more economical, resulting in significant comprehensive benefits.

VII. CONCLUSION AND PROSPECT

A. CONCLUSION

1. We have established the first dedicated static and stable weather indicator system for the Xinjiang power system in China, which enables the transformation of static and stable weather from a general meteorological definition to a power risk oriented approach, and can accurately identify high-risk static and stable weather in the power grid.

2. A complete data processing technology has been established for standardizing multi-source numerical models, correcting deviations, and fusing feature layers, which solves the problems of spatiotemporal inconsistency and large systematic deviations in multi-source data and significantly improves the quality of basic data.

3. A static and stable weather forecasting method combining machine learning and multi-source numerical models has been proposed. The model accuracy is significantly better than that of a single numerical model, and it has strong adaptability to complex terrain. The forecast lead time, spatiotemporal resolution, and warning capability fully meet the needs of the power grid.

4. We have developed grid based, line level, and hourly operational forecasting products, forming a practical, operational, and scalable technical system that has achieved significant results in the actual application of the Xinjiang power grid, effectively enhancing the grid's ability to defend against meteorological disasters.

5. A complete key technology chain covering “data model product application” has been formed, which can provide demonstration and reference for power meteorological forecasting in other regions of the country.

B. INNOVATION POINTS

1. For the first time, a power specific static and stable weather indicator system for the Xinjiang power grid has been constructed, achieving precise coupling between meteorological conditions and power grid risks.

2. Propose a forecasting framework that deeply integrates multi-source numerical models with machine learning, significantly improving the forecasting ability of weak weather systems in complex terrains.

3. Achieve precise matching between power grid equipment and meteorological grids, and provide line level and equipment level refined forecasting support.

4. Form a full process business oriented technical system that can be directly embedded into the power grid dispatch and operation and maintenance system, with strong engineering practicality.

C. OUTLOOK

1. Further integrate satellite remote sensing, radar, and ground Internet of Things observation data to build an integrated observation and forecasting system for space, sky, and earth.

2. Deepen the research on the mechanism of static and stable weather and power grid faults, and establish a more refined fault probability prediction model.

3. Promote research on ultra short term and real-time forecasting technology to support second/minute level power prediction and rapid dispatch of new energy.

4. Build a cross regional and integrated power meteorological forecasting platform to achieve nationwide promotion and application.

5. Combining big model technology to enhance the intelligence, automation, and decision support capabilities of forecasting.

AUTHOR CONTRIBUTIONS

Conceptualization –Dagui Liu, Xu Jie, Bin Zhang and Wei Shi; methodology – Dagui Liu, Xu Jie, Bin Zhang and Wei Shi; investigation – Dagui Liu, Xu Jie, Bin Zhang and Wei Shi; writing-original draft preparation – Dagui Liu, Xu Jie, Bin Zhang and Wei Shi. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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