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Research on Resource Planning and Transmission Line Optimization System of US Power Grid Based on GIS Technology

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Abstract: *Based on the background of the key regions of energy development and utilization in the United States, this study proposed a grid resource planning and transmission line optimization system based on geographic information System (GIS) technology to address the problems of power resource management and power transmission capacity limitation. The system uses the spatial information processing and visualization advantages of GIS technology, combines the abundant renewable energy (such as wind and solar energy) and traditional energy (such as natural gas and coal) in the United States, and builds a set of efficient power resource management platform. The platform uses SuperMap engine and SQL Server database as data architecture, which can realize the comprehensive management of power grid resources, feasibility analysis of renewable energy development, and optimal planning and design of transmission lines. Taking "Texas Power Grid +500kV transmission and transformation project" as a practical case, the applicability of the system in transmission line design and optimization is verified, and the broad application prospect of the system is demonstrated in improving the decision-making efficiency and resource allocation in the power industry. This study not only provides a strong technical support for the sustainable development of smart grid in the United States, but also provides a scientific basis for the government to formulate energy policies and resource allocation.*

Keywords: *Geographic information system, Power resource management, Transmission line optimization, Energy development*

1. Introduction

The vast size and complex geographical environment of the United States lead to significant differences in the distribution and demand of electricity resources in different regions. Through the application of GIS (Geographic Information System) technology, researchers can accurately grasp the relationship between power grid facilities and the natural environment, and in-depth analysis of the spatial layout of power resources, so as to optimize the power transmission path, ensures efficient transmission and rational use of energy. By analyzing all kinds of geospatial data, GIS technology provides data support for power grid planning and helps to realize the optimal plan of resource allocation.

With the continuous economic growth of the United States, especially driven by the process of industry and urbanization, energy demand is increasing year by year, and the contradiction between electricity supply and demand is becoming more prominent. The traditional power network planning method is limited by technical means, and it is difficult to cope with the complex and changing needs at present, while GIS technology breaks through this limitation. By integrating geographic information such as terrain, height, and land use, GIS enables more refined and intelligent power grid planning. With this technology, the researchers can effectively avoid the environmental impact and social problems that may occur in the construction of the power grid, while optimizing the selection of power transmission lines, reducing resource waste, reducing construction costs, and improving the reliability and economic benefits of the power grid system.

The optimal design of transmission lines is always one of the key problems in the grid planning of the United States. Due to the vast territory of some parts of the United States and the long distance of power transmission, the choice of power transmission lines is not only affected by the terrain and natural environment, but also closely related to energy transmission efficiency, construction costs and

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safety. Through GIS technology, researchers are able to analyze the natural conditions and geographical barriers in different regions in detail, so as to design the optimal power transmission lines. At the same time, GIS can also be used to dynamically monitor the running status of the line, provide real-time feedback and early warning, and ensure the stability and safety of power transmission.

This study is not only innovative and valuable academically, but also provides a scientific basis for the rational allocation of power resources in the United States and supports the sustainable development of regional economy. In the context of promoting the construction of intelligent infrastructure, the intelligent and optimized planning of the power grid has become an important measure to promote energy transformation and green development, and GIS technology has played a key role in this process, helping the United States to maintain a leading position in the global energy competition.

2. Relevant Research

With the continuous expansion of power system scale, grid resource planning and transmission line optimization are facing more complex challenges. G Zhang proposed an innovative method [1] to optimize the layout strategy of 220kV transmission line monitoring equipment by combining meteorological disaster probability, climatic characteristics, historical fault data and GIS information. This method can realize intensive monitoring of frequent fault areas and sparse monitoring of rare fault areas, so as to improve the allocation efficiency of monitoring equipment, and has significant reference value for the planning of power grid resources in the United States.

KLi's research focuses on inspection and maintenance in complex environments, and proposes a task assignment and path planning framework based on multi-UAV technology [2]. By applying the improved bidirectional ant colony algorithm and the discrete Honey badger algorithm, the framework solves the task assignment problem under windy conditions, and optimizes the path planning of UAs with the improved honey badger-fly algorithm. This method significantly improves the efficiency and accuracy of transmission line inspection, and provides an advanced solution for the optimization of power grid inspection system.

For power transmission line planning, Feng J introduces a multi-objective optimization path selection method for stepping ring grid networks. Through the construction of virtual topological nodes and the collaborative optimization of multiple objective functions [3], this method effectively improves the comprehensive effect of line planning and provides a more scientific optimization strategy for power grid line planning.

In terms of transmission line condition monitoring, J Chen used association rule algorithm to analyze historical state data in depth [4] and built a transmission line state recognition model based on this. By combining the random forest algorithm, the model achieves an assessment accuracy of more than 90% and verifies its applicability on large-scale data sets, providing cutting-edge technical support for power grid resource planning.

M Li proposed a general and efficient optimization design method for mesh transmission lines [5]. This method can quickly and accurately characterize the characteristic impedance and propagation constant of network transmission lines, and provide effective design guidance, which significantly improves the design efficiency and accuracy.

Y Hu's research focuses on improving the current diffusion performance of concrete pile for transmission tower foundation [6]. He proposed the method of placing flexible graphite grounding electrode on the inner wall of pile, and verified by finite element analysis that this method can significantly improve the current density distribution and reduce the grounding resistance, especially in the construction restricted area, the use of vertical grounding electrode can save a lot of land area, providing an important reference for the design of grounding structure.

The Wireless grid monitoring model (WiGriMMA) proposed by MN Birje uses agent technology to monitor the status and movement of wireless devices [7], so as to realize effective resource planning and avoid device overload. Simulation tests show that the model is superior to the traditional grid monitoring model in terms of resource availability, equipment status and operation execution rate, which provides a new idea for power grid resource planning.

H Zhao proposed an intelligent fault diagnosis and response method based on GIS maps and the Internet of Things, which combined automatic fault diagnosis, data analysis, panoramic display and

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response optimization functions to improve the intelligent management level of power grid system and provide an efficient solution for power grid resource planning and transmission line optimization in the United States.

These research results not only provide technical support for power grid resource planning and transmission line optimization, but also lay a solid foundation for future power grid construction and management.

3. GIS Technology Is Applied to the Design of Power Grid Planning System

3.1 The U.S. Government Is Pushing for Smart Grid Measures

The decentralization of the power grid management system in the United States has increased the complexity of power grid planning, construction and operation, resulting in increased difficulty in transmission network coordination, which is not conducive to the safe and stable operation of large power grids. Despite measures taken in recent years, such as the establishment of Independent System operators (ISOs) and regional transmission organizations (Rtos), it is still difficult to effectively solve the problem of decentralized dispatch management, as shown in Figure 1. In addition, the mismatch between the rapid development of renewable energy and the lagging construction of the transmission grid further restricts the long-distance transmission of energy. Based on this background, it is particularly necessary to apply GIS technology to carry out research on the resource planning and transmission line optimization system of the US power grid, so as to improve the coordination and operation efficiency of the power grid and help the efficient transmission of renewable energy.

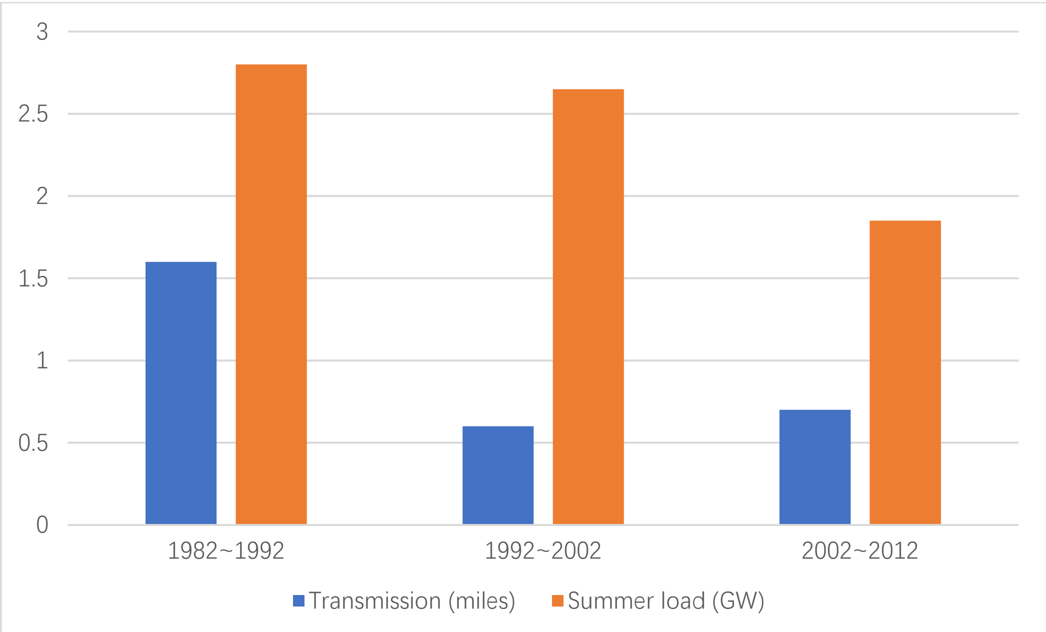

Figure 1: Comparison of historical growth of transmission and generation capacity in the United States

In the stage of system structure and design, the whole system needs to be deeply analyzed to clarify the function and interaction of each component. The core task of this phase is to decompose a complex system into a number of basic components and study how these components work together to achieve a predetermined goal. Through this process, the development team can identify the key requirements of the system and evaluate its economic, technical, social, and organizational viability. In order to ensure that the design can meet the actual needs, the team conducted a detailed requirements survey to clarify the specific needs and expectations of users, so as to avoid potential problems caused by changes in requirements. In doing so, combined with the American Recovery and Reinvestment Act (ARRA 2009) $4.5 billion for the U.S. Department of Energy, which focuses on smart grid investment subsidies and funding for demonstration projects, as shown in Table 1, and covers personnel training, grid security planning, management support, and standards system development needs. This paper ensures that the new system can effectively address the shortcomings in the resource planning and management of the U.S. power grid.

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Table 1: Main uses of smart grid funds provided by ARRA 2009 in the United States

Direction of fund allocation	Budget Allocation (US$ billion)
Smart grid construction subsidy project	34.00
Smart Grid Pilot Project	6.20
State Power Management Support Projects	0.44
State Electric Safety and Planning Support Programs	0.395
Regional Power Security Planning Support Project	0.08
Energy assessment and interstate power transmission corridor planning	0.60
Smart grid interconnection standard system	0.10
Talent training and training programs in the power industry	1.00

After the introduction of EISA 2007 and ARRA 2009, the United States vigorously promoted the construction of smart grids, and launched key support programs and demonstration and promotion projects. In 2009, the U.S. Department of Energy (DOE) issued a solicitation announcement, planning to invest $3.4 billion and $620 million, respectively, with funding support of up to 50%. Because the number and amount of the first applications far exceeded expectations, the Department of Energy ended the original project submission phase early. In October of the same year, then-President Barack Obama announced 100 government-funded projects that were expected to generate $4.7 billion in private capital investment. In November, Energy Secretary Steven Chu announced 32 smart-grid demonstration projects that together have attracted more than $1 billion in private investment. Together, the two initiatives have invested a total of $4.02 billion and generated $5.7 billion in social capital, with annual smart grid investments expected to reach $3.2 billion between 2010 and 2012. In terms of capital flow, it is mainly concentrated in cross-field technology integration, transmission and distribution grid construction, energy storage system and other fields, Table 2 and 3 are shown below.

Table 2: Funding for the Smart Grid Support Program

Project	Funding / $100 million
Integrated technology integration engineering	21.5
Advanced Metrology Infrastructure (AMI)	8.18
Distribution network	2.54
Power transmission system	1.48
User terminal system	0.32
Industrial manufacturing	0.26
Total	34.29

In terms of the allocation of funds, the $3.429 billion investment in the Smart Grid Support program went primarily to integrated engineering ($2.15 billion), advanced metering systems ($818 million), distribution networks ($254 million), transmission systems ($148 million), customer end equipment ($32 million), and industrial manufacturing ($26 million). At the same time, $620 million of the demonstration program is mainly invested in regional smart grid technology integration demonstration projects ($435 million) and energy storage technology projects ($185 million). In order to ensure the return on investment of enterprises in smart grid projects, the US government has also introduced a tariff adjustment policy. In July 2009, the Federal Energy Regulatory Commission (FERC) issued a Smart grid policy statement that allows utilities to recover part of their investment costs through a short-term rate adjustment mechanism, and in December, FERC approved Pacific Gas & Electric's (PG&E) rate increase application for the first time to meet the funding needs of smart grid construction.

Table 3: Funds for smart grid demonstration and promotion projects

Project	Funding / $100 million
Regional-level smart grid technology demonstration project	4.35
Electric energy storage technology project	1.85
Total	6.20

3.2 Database Design

In the database design of this study, the project provides important basic data for this study. When constructing the power grid resource planning and design platform, the system design relies on the spatial database and the attribute database, which are the core parts of the platform, and the ground code and administrative code are precisely compiled according to the national standards.

In this system, SuperMap SDX+ is selected as the data engine for spatial data processing, which is an integrated spatial data engine with efficient storage, access, query and update functions. SuperMap SDX+, as an important part of SuperMap GIS platform, can support the comprehensive management of various spatial data, including vector data, raster data and their attribute information. Its advanced storage technology and high performance make it ideal for GIS projects of different sizes and desktop applications, especially when working with complex spatial data sets.

In the process of establishing spatial data, due to the large amount of data involved in the power grid resource planning and design platform, the processing process is particularly complicated. Paper topographic maps are scanned to generate electronic images. These paper maps may be deformed and crumpled due to environmental factors, such as humidity and temperature changes, so it is necessary to keep the drawings as flat as possible during scanning to reduce errors. After scanning, the image will be geometrically corrected to correct deviations due to paper distortion. Accurate geographical coordinates are ensured by using high precision software for geometric correction.

The image is vectorized, and all necessary spatial elements such as residential points, protected areas, and roads are extracted and entered into the system. In SuperMap Desktop software, after vectorization, the data is stored in SDD format, and all spatial elements and attribute information are recorded accordingly. Topology processing stage needs to solve the topology errors that may occur in the data set editing process, such as redundant nodes, false nodes, duplicate lines, etc. These errors may affect the accuracy of the data, so the system uses SuperMap Desktop software for detailed topological processing to ensure the integrity and consistency of the final data.

In the establishment of the attribute database, the system is responsible for managing a variety of attribute information, including the number, height, longitude and latitude of the wind tower and other detailed data, the name of the wind farm and the unit to which it belongs, the voltage level of the substation, and the detailed data of the tower such as voltage level and project name. These data are managed by Microsoft SQL Server 2008, and the relational database structure is used to ensure the integrity and reliability of the data, which provides a full range of support for power grid resource planning and design.

4. Implementation of the US Power Grid Planning Platform

4.1 System Platform Design and Implementation

In the process of model training, multiple algorithms of supervised learning and unsupervised learning, such as support vector machine (SVM), random forest (RF) and deep neural network (DNN), are combined to improve the prediction accuracy and stability of the model. By constructing a complex neural network architecture, we are able to extract deep features from nonlinear data, which significantly improves the recognition accuracy of fatigue states. The cross-validation and hyperparameter optimization techniques applied in the training further improve the performance of the model and effectively prevent the occurrence of overfitting.

In the verification phase, this study comprehensively evaluated the model by using performance evaluation indexes such as confusion matrix, ROC curve and F1 score. These assessments not only provide insight into the accuracy, sensitivity, and specificity of the model, but also validate the reliability and stability of the system through tests in real-world environments. The system has excellent performance in actual operation, can effectively monitor the fatigue state of the crew, and provide timely warning information.

After the application of this system, the safety of the crew's working environment has been significantly improved, which provides a scientific basis for shipping enterprises to optimize the crew's work arrangement and rest system. Going forward, we plan to continue to optimize the system to further improve its accuracy and adaptability, and to promote the further development and application expansion of crew fatigue management technology.

In the field of wind resource analysis, accurate assessment of wind energy potential is a key task. Existing Wind resource assessment software, such as WAsP (Wind Atlas Analysis and Application Programme), developed by the Technical University of Denmark, is mainly designed for flat terrain in Europe, which can lead to significant calculation errors when faced with complex terrain in the United States. To address this challenge, the platform has developed a wind resource assessment module for

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complex terrain in the United States. The module uses C# programming language, combined with complex algorithms to calculate various wind resource parameters, including the continuity and integrity of data, thus ensuring the accuracy and reliability of the evaluation results. In actual operation, the platform can deeply process the wind speed data (provided in TXT format) collected by the weather station and the wind field measurement tower, calculate and display a variety of wind resource parameters. The final results are presented in charts and tables to support subsequent wind farm assessments and micro-site selection, providing strong support for achieving maximum social and economic benefits. Through the analysis of actual wind farm data, such as the wind resource data of the White Flag Wind Farm in 2012, the system can process wind speed data at different altitudes from 10 meters to 70 meters, and generate detailed reports on the daily and annual changes in wind speed and wind power.

4.2 System Test and Result Analysis

In this study, we conducted an in-depth test of the system's wind resource assessment and transmission line planning modules to evaluate their performance and accuracy in practical applications. For the Wind Resource Assessment module, we used wind speed data from U.S. electric fields from weather stations and wind towers. The test validated the ability of the system to process wind speed data from altitudes of 10 meters to 70 meters, and was able to accurately calculate daily and annual wind speed trends. Compared with the actual wind field data, the error of the calculated results is within the acceptable range, which indicates that the system can maintain a high level of calculation accuracy under complex terrain conditions. In addition, the system can clearly present the wind resource analysis results through charts and tables, providing reliable support for wind farm evaluation and micro-site selection.

In the test of the transmission line planning module, we have carried out a detailed analysis. At the beginning of the test, the system uses topographic maps, administrative zoning maps and various vector data to initially draw up the power transmission lines. The test results showed that the system successfully avoided important facilities and protected areas. In the route evaluation stage, the system evaluates the impact of the route on the communication lines, railways and other facilities along the route, and revises the route accordingly. The final line planning diagram accurately reflects the actual design requirements. The whole route is 785.615 kilometers with 50 turns, which is in line with the design specifications. The system effectively deals with obstacles such as mineral areas, lakes and roads, and carries out necessary buffer processing to ensure the economy and reliability of the line.

In summary, the system shows excellent performance in wind resource evaluation and transmission line planning. The wind resource evaluation module shows efficient data processing ability and accurate calculation results when processing actual wind speed data, which provides strong support for resource evaluation and optimization of wind farms. The transmission line planning module combines various geographical and environmental data to generate a reasonable line scheme, which provides a strong technical support for the optimal allocation of power resources. Future work will focus on further optimizing system functionality for more complex geographic and environmental conditions, while increasing support for emerging technologies and data sources.

5. Conclusion and Prospect

By developing a GIS-based power grid resource planning and design platform, this paper proposes an effective solution to the shortage of information management and the difficulty of power delivery in power grid resource planning. Through the application of SuperMap Objects component GIS technology and Microsoft SQL Server 2008 database, the platform has achieved remarkable results in wind resource assessment and transmission line planning. The wind resource evaluation module accurately calculates the parameters of wind resources, providing strong support for the evaluation and location of wind farms, while the power transmission line planning optimizes the allocation of power resources on the basis of meeting the safety and economic requirements. Although the research has demonstrated the efficiency and stability of the platform, the future needs to further improve the transmission line planning theory, develop mobile applications, pay attention to environmental protection, and improve the visualization of the system using B/S architecture and cloud GIS technology. These work will further enhance the intelligence and efficiency of the system, and provide more comprehensive support for power grid resource management.

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