

Original Paper

Research on Intelligent Control and Optimization Methods in Power Systems

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Abstract

As the scale and complexity of power systems continue to expand, traditional control and optimization methods are increasingly unable to meet the needs of modern power systems. Intelligent control and optimization methods, by introducing advanced artificial intelligence technologies, can better address complex issues within power systems. This paper explores the application of intelligent control and optimization methods in power systems, analyzing their basic principles, implementation methods, and practical application cases. The research aims to improve the operational efficiency and stability of power systems, providing theoretical support for the modern management of power systems.

Keywords

Power System, Intelligent Control, Optimization Methods, Artificial Intelligence, Operational Efficiency, Stability

1. Introduction

As a crucial component of national infrastructure, the security and stability of modern power systems are directly related to the normal operation of social and economic activities. With the continuous growth in power demand and the increasing proportion of renewable energy integration, the challenges faced by power systems are becoming more severe. Traditional control and optimization methods are limited in their ability to cope with the complex and variable environment of power systems. Intelligent control and optimization methods, by introducing artificial intelligence technologies, provide new approaches to solving complex problems in power systems. These methods, including those based on machine learning, deep learning, and reinforcement learning, can achieve intelligent control and optimization of power systems, improving operational efficiency, reducing operational costs, and enhancing system stability.

This paper delves into the application of intelligent control and optimization methods in power systems,

analyzing their basic principles, implementation methods, and practical application cases. The research aims to improve the operational efficiency and stability of power systems, providing theoretical support for the modern management of power systems. As technology advances, intelligent control and optimization methods will play an increasingly important role in power systems, bringing new opportunities and challenges to the power industry.

2. Intelligent Control Based on Machine Learning

2.1 Support Vector Machine (SVM)

Support Vector Machine (SVM) is a supervised learning algorithm widely used in classification and regression tasks. Its basic principle is to find an optimal decision boundary in a high-dimensional space to separate data into different categories. In power load forecasting, SVM can utilize historical load data to establish a model of the relationship between load and factors such as time and weather. Through this model, the future load demand at a certain moment can be accurately predicted, providing a reference for power system scheduling.

The accuracy of power load forecasting is crucial for the stable operation of power systems. In hot weather, power demand tends to increase significantly. The SVM algorithm, by learning from historical data, can predict this increase in demand in advance, allowing for reasonable power supply arrangements and preventing power outages due to shortages. Additionally, SVM can be used for anomaly detection by monitoring operational data in real-time to identify potential anomalies and take timely measures.

For instance, a power company used the SVM algorithm to forecast power load by analyzing past years' load and meteorological data, establishing a load forecasting model. This model demonstrated high prediction accuracy in practical applications, making the company's scheduling more efficient and reducing operating costs. Moreover, by predicting load peak periods, the company could prepare in advance to ensure the stable operation of the power system.

2.2 Random Forest (RF)

Random Forest (RF) is an ensemble learning method that constructs multiple decision trees and combines their prediction results for the final prediction. In power load forecasting, the RF algorithm can handle the impact of various changing factors on power demand and accurately predict future loads. RF's strengths lie in its robustness to data noise and strong generalization ability, making it perform well when handling complex power load data.

In practical applications within power systems, the RF algorithm, through comprehensive analysis of historical load data, weather data, holiday effects, and other factors, can accurately predict future load changes. For example, a power dispatch center used the RF algorithm for long-term load forecasting. By comparing the forecast results with actual loads, it was found that the RF algorithm had high accuracy in handling seasonal changes and holiday effects. This not only helped the dispatch center optimize power resource allocation but also significantly reduced dispatch pressure and operating costs.

Furthermore, the RF algorithm can be used for anomaly detection and fault diagnosis by learning from large amounts of operational data. RF can identify potential fault patterns and issue early warning signals promptly. This method effectively improves the operational safety of power systems, reduces power outages caused by equipment failures, and enhances the overall stability and reliability of the system.

3. Intelligent Control Based on Deep Learning

3.1 Convolutional Neural Network (CNN)

Convolutional Neural Network (CNN) is an important model in deep learning, primarily used for processing image data. Its basic principle is to extract different levels of features from input images through the combination of convolutional and pooling layers, and finally perform classification or regression through fully connected layers. In power systems, CNN can be used for image recognition and fault detection of power equipment by analyzing monitoring images to automatically identify equipment operating status and issue warnings.

For example, in substation equipment monitoring, numerous cameras are installed to monitor equipment status in real-time. By analyzing these monitoring images, CNN can identify normal and faulty states of equipment. When a fault is detected, the system automatically issues a warning signal, prompting maintenance personnel to check and address the issue promptly, thus preventing power outages caused by equipment failures.

A power company used the CNN algorithm to analyze monitoring images of substation equipment. By training on a large number of images under normal and faulty conditions, they developed a state recognition model. This model exhibited high recognition accuracy and robustness in practical applications, significantly improving equipment operational reliability and maintenance efficiency. Additionally, by automatically identifying and classifying fault images, maintenance personnel could quickly locate problems and take corresponding measures, reducing the impact of equipment failures on the power system.

3.2 Long Short-Term Memory Network (LSTM)

Long Short-Term Memory Network (LSTM) is a deep learning model suitable for processing time-series data. Its basic principle is to effectively solve the gradient vanishing and exploding problems that occur when traditional neural networks handle long-term dependencies by introducing memory cells and gating mechanisms. In power systems, LSTM can be used to process historical load data and electricity price data, achieving predictions of future power demand and market changes.

For instance, a power dispatch center used an LSTM model to forecast future power demand by analyzing historical load and electricity price data, establishing a power demand forecasting model. This model can accurately predict power demand changes over a period, providing reliable references for power dispatch, enhancing the flexibility and adaptability of power supply.

In the power market, LSTM is also widely used for electricity price forecasting. By analyzing historical

price data and market demand data, LSTM can predict future electricity price changes, helping market participants formulate reasonable trading strategies and avoid risks brought by price fluctuations. For example, a power trading platform used the LSTM model for electricity price forecasting. By improving prediction accuracy, the platform significantly reduced trading risks, enhancing market trading efficiency and stability.

Overall, deep learning-based intelligent control methods hold significant application prospects in power systems. These methods can not only improve system operational efficiency and reliability but also achieve intelligent management and optimization of various aspects of power systems, injecting new vitality into the development of the power industry.

4. Intelligent Control Based on Reinforcement Learning

4.1 Deep Reinforcement Learning (DRL)

Basic Principles:

Deep Reinforcement Learning (DRL) combines the advantages of deep learning and reinforcement learning. It is a method that optimizes decision-making strategies by interacting with the environment and obtaining feedback. DRL consists of two parts: an agent responsible for taking actions in the environment, and an environment that provides feedback through a reward or punishment mechanism. The agent evaluates each possible action through policy and value networks and selects the optimal action to maximize long-term rewards.

Application in Power Dispatch and Control Strategy Optimization:

In power systems, DRL can be used to optimize power dispatch and control strategies. For example, the management of distributed energy systems often involves multiple energy sources and loads, which traditional methods find challenging to handle. DRL can simulate various operating scenarios by establishing an agent, optimizing energy allocation and dispatch strategies through continuous trial and error, thereby improving system operational efficiency and reliability.

Case Study:

A city's power company introduced DRL technology to optimize its distribution network dispatch strategy. By simulating the operating environment of the power system, the agent learned how to reasonably allocate power resources during peak load periods. The results showed that the DRL-optimized dispatch strategy significantly reduced power losses and improved system stability. In practical applications, the company implemented DRL-optimized strategies, increasing the overall operating efficiency of the grid by about 15% and reducing the failure rate by about 20%.

4.2 Risk Management and Safety Assessment

Basic Principles:

Reinforcement learning's application in risk management and safety assessment mainly involves simulating various fault scenarios to evaluate system risks and develop response strategies. The reinforcement learning algorithm accumulates experience through continuous trial and error, better

responding to emergencies.

Fault Scenario Simulation and Response Strategies:

In power systems, reinforcement learning algorithms can test various fault scenarios by establishing a fault simulation environment and learn the best response measures. This approach helps system managers identify potential risks in advance and develop preventive and emergency strategies, enhancing the safety and stability of power systems.

Case Study:

A power dispatch center used reinforcement learning algorithms to simulate multiple power grid fault scenarios, including equipment failures, natural disasters, and human errors. Through these simulations, the system identified weak points in the grid and proposed corresponding improvement measures. The actual application results showed that reinforcement learning algorithms outperformed traditional methods in fault prediction and emergency response, increasing the response speed to sudden faults by 30% and reducing fault handling time by 25%.

5. Applications of Optimization Methods in Power Systems

5.1 Genetic Algorithm (GA)

Basic Principles:

Genetic Algorithm (GA) is an optimization method based on natural selection and genetic mechanisms. By simulating the biological evolution process, GA gradually optimizes the operating state of power systems to improve their economy and reliability. GA generates a series of candidate solutions through operations such as selection, crossover, and mutation, and evaluates these solutions' quality through a fitness function, ultimately finding the optimal solution.

Optimal Power Flow Calculation:

Optimal power flow calculation refers to the problem of minimizing power system transmission losses and optimizing voltage stability under various constraints. The application of genetic algorithms in optimal power flow calculation involves encoding, crossover, and mutation operations on variables in power flow calculations to effectively find the optimal operating state of the system.

Generator Unit Commitment Optimization:

Generator unit commitment optimization refers to the rational selection of generator unit combinations and output distribution under power demand and various operating constraints to achieve system economy and stability. GA optimizes the combination and output of generator units, minimizing the total system cost or losses, thereby improving system operational efficiency and economy.

Case Study:

A power system applied GA for optimal power flow calculation and generator unit commitment optimization. The results showed that GA effectively reduced system transmission losses and operating costs, improving the power system's economy and stability. Specifically, the system's total operating cost was reduced by about 10%, and transmission losses decreased by about 8%.

5.2 Particle Swarm Optimization (PSO)

Basic Principles:

Particle Swarm Optimization (PSO) simulates the foraging behavior of bird flocks and searches for the optimal solution by adjusting the position and velocity of particles. PSO is characterized by fast convergence speed and simple implementation, making it widely used in power system optimization.

Reactive Power Optimization:

Reactive power optimization refers to adjusting the parameters of reactive power compensation devices to keep the power system's reactive power within an appropriate range, thereby enhancing system stability and reliability. PSO continuously searches for the optimal parameter combination of reactive power compensation devices by adjusting particle positions and velocities, achieving optimal control of system reactive power.

Generator Unit Commitment Optimization:

In generator unit commitment optimization, PSO searches for the optimal generator combination and output distribution by adjusting particle positions and velocities, achieving system economy and stability optimization.

Case Study:

A power system applied PSO for reactive power optimization and generator unit commitment optimization. The results showed that PSO exhibited high efficiency and accuracy in handling these optimization problems. Specifically, the system's reactive power losses were reduced by about 12%, and generation costs decreased by about 10%.

5.3 Hybrid Intelligent Optimization Methods

Basic Principles:

Hybrid intelligent optimization methods combine the advantages of multiple optimization algorithms to solve complex optimization problems in power systems more effectively. By leveraging the strengths of different algorithms, hybrid intelligent optimization methods enhance system operational efficiency and reliability.

Combination of Genetic Algorithm and Particle Swarm Optimization (GA-PSO):

Hybrid Genetic Algorithm and Particle Swarm Optimization (GA-PSO) combine the global search capability of GA and the local search capability of PSO, allowing a more comprehensive search of the optimization space to find the optimal solution for the system.

Risk Management and Safety Assessment:

By combining the strengths of multiple optimization algorithms, hybrid intelligent optimization methods can more accurately assess system operational risks and develop corresponding risk response strategies to ensure the safe and stable operation of power systems.

Case Study:

A power system applied hybrid intelligent optimization methods for multi-objective optimization and risk assessment. The results showed that hybrid intelligent optimization methods performed excellently

in solving complex optimization problems, improving system economy, stability, and safety. Specifically, the system's overall operating efficiency increased by about 15%, and the accuracy of risk assessment improved by 20%.

6. Practical Application Cases of Intelligent Control and Optimization Methods

6.1 Applications in Smart Grids

Power Load Forecasting Model:

Smart grids achieve intelligent management of power systems by introducing deep learning-based power load forecasting models. Traditional power load forecasting methods mainly rely on historical data and simple statistical models, which are difficult to accurately predict complex load changes. In contrast, deep learning-based models can handle large amounts of multidimensional data, extract complex features, and achieve higher prediction accuracy.

A city's power company adopted a deep neural network-based power load forecasting model to optimize its power system management. This model utilized a large amount of historical load data, weather data, holiday data, and other external factors for training, establishing a complex neural network model. Through repeated training and optimization, the model could accurately predict future power demand changes.

In practical applications, this load forecasting model significantly reduced the peak-valley difference in the power system, making power dispatch more efficient. Specifically, by accurately predicting future load demand, the power company could adjust generation plans and power supply in advance, avoiding power waste or emergency dispatch due to incorrect load forecasts. Data showed that the city's power system's peak-valley difference was reduced by about 15%, significantly reducing dispatch pressure and operating costs. Furthermore, the improved accuracy of load forecasting enabled the power company to better arrange power production and distribution, avoiding power waste and emergency dispatch due to forecast errors, thereby enhancing the overall operational efficiency and economic benefits of the power system.

Intelligent Monitoring and Maintenance System:

Smart grids enhance equipment operational reliability, reduce outages caused by equipment failures, and improve overall system stability by installing intelligent sensors and IoT devices for real-time monitoring of power equipment status and using deep learning models to analyze data and detect faults and anomalies.

Specifically, intelligent sensors and IoT devices can collect various operational data of power equipment in real-time, such as voltage, current, temperature, and vibration. By transmitting these data to a central monitoring system, deep learning models can analyze them in real-time, identifying normal operating states and potential fault states of equipment. For example, when a device's temperature or vibration exceeds the normal range, the system immediately issues a warning signal, prompting maintenance personnel to check and address the issue promptly.

A power company achieved comprehensive monitoring of its substations and transmission lines by installing such an intelligent monitoring and maintenance system. The results showed that this system performed excellently in detecting equipment faults and abnormal operations. Specifically, the company's equipment failure rate decreased by about 20%, and outage incidents were reduced by about 15% through this intelligent monitoring system. Moreover, the ability to detect equipment problems in advance and address them promptly significantly improved maintenance efficiency and reduced maintenance costs.

6.2 Applications in Renewable Energy Integration

Reinforcement Learning in Wind Power Prediction and Dispatch Optimization:

With the increasing proportion of renewable energy integration, the volatility and uncertainty of power systems have significantly increased. To address this challenge, a wind farm introduced a reinforcement learning-based wind power prediction and dispatch optimization system, achieving efficient utilization and absorption of wind power.

Reinforcement learning optimizes decision-making strategies by interacting with the environment and obtaining feedback. The wind farm used reinforcement learning algorithms to train on data such as wind speed, wind direction, and historical power output, establishing a wind power prediction model. Through continuous learning and optimization of real-time data, the system can accurately predict short-term wind power output, providing reliable references for power dispatch.

In practical applications, the reinforcement learning system significantly improved wind power absorption capacity and economic benefits. Data showed that by optimizing wind power dispatch, the wind farm's wind power absorption capacity increased by about 20%, and the curtailment rate significantly decreased, with operating income increasing by over 15%. Moreover, by reasonably allocating load during high wind power output periods, the system reduced reliance on traditional thermal power, lowering overall carbon emissions. This reinforcement learning-based wind power dispatch optimization system not only improved wind power utilization but also enhanced the power system's adaptability to renewable energy volatility.

Wind Power Absorption Capacity and Economic Benefits Improvement:

Wind power, as an important renewable energy source, directly affects the overall efficiency of power systems. To improve wind power utilization efficiency, load must be reasonably allocated during high wind power output periods, reducing curtailment. By optimizing wind power dispatch, load demand can be reasonably arranged during high wind power output periods, ensuring maximum wind power utilization.

A wind farm significantly improved wind power absorption capacity and economic benefits by introducing a reinforcement learning-based wind power dispatch optimization system. Specifically, through real-time monitoring and prediction of wind power output, the system could reasonably allocate load demand during high wind power output periods, reducing reliance on traditional thermal power and significantly lowering carbon emissions. Moreover, by reasonably allocating load during

high wind power output periods, the curtailment rate during high wind speed periods was reduced by about 30%, and overall economic benefits increased by about 20%.

This reinforcement learning-based wind power dispatch optimization system not only improved wind power utilization but also enhanced the power system's adaptability to renewable energy volatility. In the future, with more renewable energy integration into the grid, similar intelligent control and optimization methods will play a greater role in ensuring power system stability and improving renewable energy utilization rates.

6.3 Applications in the Power Market

Electricity Price Prediction and Optimization Model:

In the power market, the operation, dispatch, and optimization of power systems are crucial. A power trading platform introduced a machine learning-based electricity price prediction and optimization model to achieve efficient management of market transactions and optimal allocation of power resources. The machine learning model utilizes a large amount of historical electricity price data, market demand data, and external factors affecting electricity prices (such as weather and policy changes) for training and prediction. By accurately predicting electricity prices, the trading platform can formulate reasonable trading strategies in advance, avoiding risks brought by market price fluctuations.

In practical applications, the machine learning model significantly improved the accuracy of electricity price predictions. Specifically, by analyzing historical data and market trends, the model could predict future electricity price changes in advance, helping market participants formulate reasonable trading strategies and avoid price fluctuation risks. Statistics showed that after applying the model, the power trading platform's electricity price prediction accuracy improved by about 25%, significantly reducing trading risks. Moreover, accurate electricity price predictions enabled power companies to better allocate resources, improving market trading efficiency and stability.

Optimization of Power Resource Allocation:

In power resource allocation, intelligent control systems use optimization algorithms to automatically adjust power production and distribution strategies based on power supply and demand conditions and electricity price predictions, ensuring optimal resource allocation. For example, through linear programming and genetic algorithms, the system can optimize the combination and operating states of generator units, reducing generation costs and improving generation efficiency.

A power trading platform achieved intelligent allocation of power resources by introducing optimization algorithms. In practical applications, the system automatically adjusted the operating states and load allocation of generator units based on power supply and demand conditions and market electricity price predictions, making power production and distribution more efficient. The results showed that through intelligent optimization methods, the platform's overall operating efficiency increased by about 18%, and generation costs decreased by 12%. Moreover, by optimizing the combination and operating states of generator units, the system could effectively reduce power losses

during peak load periods, improving overall economic benefits.

This machine learning and optimization algorithm-based power market management system not only improved market trading efficiency but also optimized power resource allocation, enhancing the power system's economic benefits and reliability. In the future, with continuous advancements in intelligent control and optimization technologies, the intelligent operation of power markets will further develop, providing strong support for stable power system operation and economic benefit improvement.

7. Conclusion

The application of intelligent control and optimization methods in power systems provides new ideas and methods for solving complex problems in modern power systems. By introducing advanced artificial intelligence technologies, power systems can achieve more efficient and reliable operations, meeting the growing power demand. In the future, with continuous technological advancements, intelligent control and optimization methods will play an increasingly important role in power systems, providing solid support for the intelligent and modern development of power systems.

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