Smart Grid Automation Technology and Artificial Intelligence Co-optimization

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Abstract. With the popularization of energy transition throughout the world and the dual carbon agenda, smart grid, which is the heart of new power system, has an ever-growing scarce requirement on the intensive fusion of automation technology and artificial intelligence. The intelligent grids and their intelligence level are also greatly enhanced by artificial intelligence and its ability to schedule the work, address any faults and allocate resources of the smart grid because of its robust data processing, pattern recognition, and optimization features of the grid decision-making systems. This paper is dedicated to the synergistic optimization of automation and artificial intelligence in smart grids, and one of the priorities is the possible artificial intelligence functioning in the areas of fault diagnostics, renewable energy integration as well as load prediction and resource scheduling. Through the implementation of deep learning tools like LSTM to forecast short-term loads, uniting blockchain technology to ensure credible data exchange and optimization of the scheduling process, and thorough investigation of the consumer behavior of electricity consumption in order to increase the efficiency of resource distribution. The goal is to develop a more adaptable, dependable, and effective smart grid scheduling and operation structure which will offer theoretical foundation and technical aid in the process of intelligent transformation of the grid.

Keywords: Smart grid, artificial intelligence, automation.

1. Introduction

As the pace of the global energy transition process continues to increase, the imperative characterized by the goal of the dual carbon has become one of the driving forces in enhancing the rationalization of energy structure and power system transformation. Here, smart grid as one of the essential infrastructures of developing a new power system is becoming more and more dependent on deep involvement in the automation technology and artificial intelligence to solve numerous problems generated by the high ratio of renewable energy access, the rise of diversified loads, and the rise in the complexity of systems operation. The artificial intelligence technology, its high levels of data processing, pattern recognition and optimization decision making capability offers new solutions to schedule, operate, fault and resource allocation of the smart grids, increasing the level of intelligence and the optimization of the power grid.

The proposed paper is devoted to the joint optimization of the smart grid automation technology and artificial intelligence, and especially to the discussion of the possibilities of artificial intelligence application in color-blindness areas of fault detection, integration of renewable energy sources, load prediction, and distribution of resources. With the help of the deep learning models, including LSTM short-term load forecasting, and the development of the technologies like blockchain to share the trustful information and optimize the schedule, the study will take a look under the hood of the user electricity consumption patterns, to optimize the resource allocation technique. The work will also seek to develop a more adaptable, effective, and trustworthy intelligent grid scheduling and operation architecture offering theoretical frameworks and technological foundation to the intelligent transformation of the grid promotion.

2. Overview of Smart Grid and Artificial Intelligence

2.1. Artificial Intelligence Technology and the Power Grid

The characteristics of artificial intelligence are: learning (continuously improving knowledge and algorithms, usually referred to as machine learning), recognition (identifying situations and processes based on past similarities), and action (taking actions autonomously) [1]. Artificial intelligence relies on its data processing capabilities, pattern recognition abilities, and intelligent decision-making capabilities, providing important support for the intelligent upgrade of the power grid. AI technologies such as machine learning, deep learning, and computer vision are widely used in the dispatch control, equipment operation and maintenance, and user service processes in the power grid, improving the efficiency and reliability of system operations. The overall goals of smart grids include optimal resource utilization, higher energy efficiency, greater system reliability, enhanced system security, and providing users with economic power distribution [2]. Artificial intelligence technologies are key tools to help achieve the overall goals of smart grids.

2.2. Research Background and Significance of the "Dual-carbon" Goal

Incorporating "peak carbon dioxide emissions and carbon neutrality" into the overall layout of China's ecological civilization construction, green and low-carbon energy development is the key to achieving the 'dual carbon' goals. The power industry has the highest level of emissions in the energy industry, and it is the main direction for China's future carbon emission reduction efforts. To achieve the goals of carbon peak and carbon neutrality, it is necessary for the power system to accelerate the high proportion of renewable energy access and build a clean, low-carbon, safe, and efficient energy system. In this context, the deep integration of artificial intelligence technology with smart grids presents great potential. Its high consistency and overall optimization capabilities enhance the efficiency and reliability of grid operation, injecting core power into the continuous upgrade and innovative development of automation technology. This has significant practical significance for the construction of a clean, low-carbon, safe, and efficient new energy system.

2.3. Research Status at Home and Abroad

Google DeepMind has developed an Artificial Neural Network (ANN) model in the international scene to predict the future average Power Usage Effectiveness (PUE) the ratio between the total building energy consumption and the IT energy consumption. Since 2018, the AI system has been driving cooling systems directly with the exception of human intervention only when it is necessary and has been implemented in several Google data centers [3]. Google DeepMind has been working with the UK National grid to solve a wind power forecasting and optimization project, with the aim of trying to make the grid more adaptable to changes in renewable energy using the deep learning technology. Japan has been working on investigating the advantages of AI tools since the late 1980s, and thus, Japanese power companies, manufacturing companies, and university researchers began collaborating with each other in their research and development [4]. State grid corporation of China is also proactively encouraging the adoption of AIs in the automated scheduling process in the domestic sector. They have created an AI-driven intelligent scheduling assistant decision-making system which allows making predictions related to the loads and errors even more precise. These examples show that the technology of AI is slowly becoming a significant fundamental ingredient of the current operation and management of power grids.

2.4. Key Technological Challenges

Despite the numerous advantages of artificial intelligence to the power grid, numerous problems remain in the practical implementation of this method. This includes randomness and fluctuation of the output power of renewable sources of energy like wind and solar energy that subjects the grid to strain as long as it is running steady. The vagaries of the energy storage systems add complexity to the scheduling process whereas the challenge of trying to know the extreme weather events, and precisely estimate the grid exposure and the vulnerability poses technical challenges [5]. High impedance faults (HIFs) are detected and the results are a gyre threat to grid security and stability [6]. The size and diversity of intelligent terminal devices are another problem that makes modeling more problematic in power generation, loads, and DC transmission systems and therefore complicate the traditional controller design [7]. Communication differences and slowing delays during runtime will cause a drop in system stability. Moreover, one should not overlook the security control concerns of the automation technology, among which one may note the risk of data leakage, network intrusion, and the design of redundancy of the system.

3. Application Modes of Artificial Intelligence in Smart Grids

3.1. Data-Driven Intelligent Perception and State Evaluation

The smart grid is based on the principles of real-time perception and proper evaluation of large volumes of multi-source and heterogeneous data. In this mode, artificial intelligence technologies have the functions of intelligent sensory organs and analytical brains, specifically machine learning and deep learning. By conducting intensive mining of the data of the SCADA systems, PMUs (phasor measurement units), smart meters, and meteorological data, AI models can be used to achieve real-time grid operation status and ultra-short-term prediction of the grid operation status. As an example, the recognition of the infrared images of the devices using Convolutional Neural Networks (CNN) can be used to provide early warnings of fault of the major equipment used, like the transformers and the circuit breakers, in combination with a time series analysis method, AI can sense the tendencies of the movements of the lines and voltages on different nodes that may present a hazardous situation, which will assist the operator in making decisions, as well as make the traditional response at risk into the pre-warning.

3.2. Model-based Predictive Analysis and Optimization Decision

Facing the strong uncertainty of renewable energy and load, traditional analysis methods based on physical models have shown weakness. Artificial intelligence has opened up a new paradigm of "data-driven modeling" and "intelligent optimization decision-making". In this mode, AI predicts the behavior of complex systems by constructing high-precision data models. As mentioned earlier, the application of LSTM networks in short-term load forecasting is a typical example of this mode. Moreover, the end result of prediction and optimization algorithms may be part of a closed-loop process to make decisions. In the case of AI agents, applying Reinforcement Learning algorithms it is possible to figure out how to optimize the timing of all activities in a wide range of operating conditions (unit combination, reactive power optimization, and demand side response) in a dynamic equilibrium between economic and security concerns by playing against the power grid simulation environment.

3.3. Autonomous Response Coordination Control and Fault Handling

The highest-level application pattern is to achieve the system's autonomous response and coordinated control, aimed at enhancing the self-healing capability and operational resilience of the power grid. In this mode, artificial intelligence serves not only as an analysis tool, but also as the "smart central" of the control system. When faults occur in the power grid, the AI system can quickly and accurately diagnose and locate faults (such as dealing with high impedance faults HIFs) based on multiple sources of information, and autonomously generate and execute isolation and non-fault area power restoration strategies. Furthermore, in the distribution network, with the help of multi-Agent cooperative technology, various smart terminals can autonomously manage local energy and globally optimize interactions under the coordination of AI algorithms, effectively addressing the control challenges brought by the plug-and-play distributed power sources, and establishing a truly flexible and reliable meshed power supply network.

4. Intelligent Grid Architecture and Technical Implementation

4.1. Hierarchical Architecture of Smart Grid Dispatching

With the goal of "dual-carbon", the rapid construction of a new power system has been prompted, leading to a significant increase in the complexity of grid dispatch due to the integration of a high proportion of renewable energy sources. This addresses issues such as low integration degree, slow response, and lack of intelligence in traditional dispatch systems. Long Short-Term Memory (LSTM) networks, as a special type of recurrent neural network (RNN) with the ability for long-term learning, are suitable for time series modeling and forecasting [8]. Reference can be made to the AI-based grid dispatch system architecture proposed by An Guangpei et al., which builds a collaborative optimization framework with a core consisting of three layers: "decision-function-application". In this architecture, the decision layer relies on the LSTM-TS hybrid model to collect and preprocess multi-source data on unit output, load, and equipment status, and utilizes deep learning technology to conduct grid state estimation and dispatch strategy generation. The intelligent monitoring, learning, decision-making, execution, and interaction modules built in the function layer assist in the closed-loop control of the entire process of data identification, fault diagnosis, to task generation, and the application layer directly interacts with the business scenarios and initiates the dispatch instruction execution and anomaly handling process to accomplish data-based, online and intelligent dispatch tasks [9]. The advantages of the hierarchical architecture of artificial intelligence are completely illustrated by its benefits in time series prediction, local optimization and intelligent decision-making. Experimental performances of the simulation indicate that the system can improve channel blocking resilience and job scheduling effectiveness, which provide valuable technical assistance to construct a fresh generation of the intelligent grid dispatch system that is very dependable and efficient.

4.2. Intelligent Power Grid Distribution Automation

The power system of the intelligent grid has an automation dispatch that is indispensable in the technical assistance of the efficient and reliable work of the power system. The development of the distribution automation has been in three phases; component automation, local automation, and system intelligence. China is now under intelligent distribution system phase, which involves applying the computer communication, automatic control, and smart monitoring as a support of autonomous predictions, fault diagnosis, rapid self-healing capabilities of the distribution system. The intelligent data acquisition devices, automatic reclosers, load control devices, etc. are important parts of dispatch automation system, which collaborate with one another to constitute a meshed power supply system and a dual power backup mode effective to increase the reliability of power supply and fault responsiveness. This system allows real-time control of the line operation condition, automatic load control, and identification of faults remotely with the help of the big data analysis, and allows decreasing manual intervention and enhances the efficiency of operations. The distribution automation system construction streamlines the grid organization, improves the system security and cost and preconditions the harmonization of intelligent grid and artificial intelligence technologies, which forms one of the major aspects of achieving the transformation to intelligent power systems.

4.3. Intelligent Technology Optimization

In the field of intelligent technology optimization, the wide application of artificial intelligence in electrical automation control plays an important role in the effective operation of smart grids. Through the application of advanced algorithms and software technology, artificial intelligence technology optimizes the electrical automation control in a more efficient and reliable way, and achieves certain effects in the process of production and system structure optimization.

With the development of time, intelligent technology has changed the traditional design mode of electrical engineering based on manual experience, and realized computer-aided design. This design method greatly shortened the design cycle, improved design accuracy and reduced the total number of connections of the system through the integrated control computer. This method reduced the line load and improved the stability of the entire power grid [10]. The changeability and dispersion of wind and photovoltaic power, as well as the limitation of the transmission capacity of the inter-area power transmission, caused the frequent congestion of the grid. This brought great challenges to the power system. Titz et al. (2023) built an explainable machine learning model based on artificial intelligence to predict the redispatch and balancing transactions in the German transmission system. Different from previous studies, the model used multiple features to train the model, including wind power, photovoltaic power, hydropower, loads, electricity prices and cross-border power flows. The model used the SHAP (SHapley Additive exPlananations) method to quantitatively explain the driving or mitigating effect of various factors on the congestion and revealed the causality of the grid operation to alleviate the redispatch demand [11]. The application of data analysis of artificial intelligence technology in distribution automation can make prediction analysis and factor analysis of power grid status more efficient and accurate. Furthermore, the intelligent operation based on artificial intelligence technology, such as remote control, scheduled operation and multi-terminal cooperation, can enhance the ability of the system to deal with emergencies. By quickly cutting off power outage, switching backup equipment and analyzing fault root cause, the grid self-healing ability and operation effect are enhanced [13]. Therefore, artificial intelligence technology optimizes the electrical automation control process and content and lays a solid technical basis for the automated management and coordinated control of smart grids.

5. The Advantages and Necessity of Artificial Intelligence in Smart Grids

5.1. Advantages of Artificial Intelligence Optimization

The smart grid automation system that employs the application of the artificial intelligence technology has several advantages and the advantages are broadly witnessed in two fronts namely high consistency and high integrity.

To begin with, artificial intelligence has a high level of consistency. In a complicated and dynamic power grid operating environment, the conventional ways of control are usually erratic when subjected to outside disturbances or internal change in parameters which leads to unreliable control outcomes. Nevertheless, the artificial intelligence-based control systems can continuously extract the features and learn the patterns of a large amount of data with the help of machine learning and deep learning algorithms, and obtain the specific prediction and decision-making. Artificial intelligence systems can be used in dealing with load forecasting, fault diagnosis, and real-time scheduling to ensure the consistency and reliability of response strategies, which oversees the performance variation due to human or environmental influences, increasing the stability and controllability of power grid operation.

Artificial intelligence has improved the overall system, and as an integrated system including power generation, transmission, distribution, and consumption, traditional automation methods generally focus on local optimization and it is difficult to achieve global coordination. Artificial intelligence technology, with its powerful data processing and pattern recognition capabilities, can conduct comprehensive analysis and management optimization from the overall level of the system. For example, by building an intelligent decision support platform that combines neural networks with expert systems, artificial intelligence technology can achieve unified control of energy flow, information flow, and control flow in the power grid, improving the overall operational efficiency of the network, enhancing the coordination of multi-energy access, and improving the system's ability to resist interference and recover.

5.2. The Necessity of Artificial Intelligence Integration for the Upgrading of Automation Technology

In the conditions of the paradigm of energy transition and diversification of electricity demand, the complete introduction of artificial intelligence into the smart grid automation system is becoming an invariable trend in the technological revolution. To make technological innovation viable in solving new challenges and development opportunities in a sustainable manner, there is a need to foster the profound advancement of artificial intelligence and classical automation control. As an escalating number of renewable sources are brought to the large scale, the charge load of electric vehicles grows at a pace significantly faster than it is increasing, and user-side interactions become stronger, the grid structure has also come to be more complex. Refinement and adaptive control are becoming hard to attain using traditional control methods. The AI technology is also capable of dealing with uncertainty with high strength and may develop to meet new modes of operation and changes in the external environment by the use of reinforcement learning, intelligent optimization algorithms among other mechanisms to ensure that the grid system continues to be advanced and adaptive throughout the process of technological iteration.

One of the sources of the sustained technological leadership and the management of innovation is the integration of artificial intelligence. The automation technology should be holistically improved to be no longer perception-response, but prediction-adaptation, in the building of smart grids. Artificial intelligence increases the level of intelligence in the state perception of systems and fault management, and also changes the nature of control strategies of voltage control, reactive power management, demand side response, and other factors fundamentally. The advent of AI technology can assist in creating the new generation of grid automation systems that have the self-learning and self-decision-making features, which will become the main technical support of the automation systems development towards efficiency, cleanness, and reliability.

6. Conclusion

The paper is dedicated to the collaborative optimization of smart grid automation technology and artificial intelligence, and more specifically, the potential of artificial intelligence application in load forecasting, fault diagnosis, resource scheduling, and other important factors. Since the smart grid is the backbone of the modern energy system, the automation degree of the smart grid depends on the collaborative optimization of the artificial intelligence technology. Artificial intelligence exhibits a great degree of consistency and benefits in system integrity on the technical scale, which is a key engine towards enhancing automation systems to intelligence, flexibility, and independence. In the wake of growing complexity and ambiguity of the future grids, the tightening of the belt to grid operational efficiency alongside grid security with intensification of the integration and deployment of the artificial intelligence and grid automation technology is poised to form a firm base toward a clean, low-carbon, intelligent energy system construction. The overall adoption and profound use of artificial intelligence in smart grids have become an unavoidable direction towards technological improvements and sustainable development of the industry.

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