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Grid Resilience and Energy Storage: Leveraging Machine Learning for Grid Services and Ancillary

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Abstract: This paper reviews the multiple roles of machine learning in improving the resilience of power grids, especially in applying new energy storage technologies. Energy storage technologies, such as compressed air energy storage, flywheel energy storage, and superconducting coil energy storage, significantly improve the power grid's ability to respond to load fluctuations and emergencies through intelligent control and optimisation of machine learning algorithms. This not only helps to optimise energy dispatch and improve the operational efficiency and flexibility of the grid but also significantly improves the stability and reliability of the grid so that it is better able to meet future challenges and needs.

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Introduction

In the current power system, the resilience of the grid infrastructure has become an important issue related to life safety and daily life. Faced with the frequent occurrence of extreme natural disasters such as hurricanes and floods, the power grid's resilience has become the focus of research. Grid resilience, that is, the ability of the grid to prevent, withstand and quickly recover loads in the face of extreme events with low probability but high losses, is an emerging discipline in the field of infrastructure security. Traditional resilient power grids rely primarily on fossil-fuel generators and hydroelectric units, but extreme events in recent years have shown their inadequacies and risks. Diesel generators are idle for a long time, and the utilization rate of resources is low, especially when dealing with small probability events.

New energy storage technologies are changing the electricity market landscape to integrate renewable energy and release clean energy effectively. By providing grid assistance services or participating in demand response, new energy storage technologies can be financially compensated and can be connected to the grid in real time, becoming an effective, resilient resource in emergency situations.

In the context of the deepening reform of the power market, new energy storage technology has achieved commercial operation in the field of automatic generation control (AGC) FM due to its fast response and flexible location layout. From Beijing, Tianjin, Tang, and Shanxi to Guangdong, its application has gradually expanded to the whole country. Not only limited to frequency modulation auxiliary services, but new energy storage technology also involves new energy fields such as peak regulation, supporting wind power and photovoltaic power generation, and its installed capacity and the role of backup sources in the grid are steadily increasing.

However, in the face of the background and key challenges of the NYISO market, such as the complexity of market participation thresholds, technical standards and market rules, new energy storage technologies must be further adapted and optimized. Data analytics and machine learning technologies play an important role in optimizing the operation and efficiency of new energy storage technologies through accurate load prediction, anomaly detection and real-time response. Lai et al. (2024) propose a framework called FTS that aims to find a faithful time sieve. The framework combines time series data analysis and machine learning techniques to improve the accuracy and predictive power of time data, providing a new solution for the trust of time data.

Machine learning algorithms, such as time series analysis and deep learning models, can help predict power demand fluctuations, optimize energy scheduling, and improve the grid's response speed and flexibility, improving the grid's resilience and reliability to meet future challenges and demands. This paper aims to explore how to optimize the application of new energy storage technologies in the NYISO market through data analysis and machine learning techniques to achieve more sustainable and efficient power system operation.

2. Related Work

2.1. Different Types of Energy Storage Technologies and Their Characteristics

(1) Introduction

Since the 1990s, Italy and Switzerland have used pumped energy storage to store electricity for over 100 years. One solution for the current peak and valley problems in the power system is to build pumped energy storage power stations. This type of hydropower station works by using a certain amount of water as an energy carrier and then converting it into electricity to supply the power system. It can store excess electric energy during the low load and high-water periods. The working principle is to draw water from the lower reservoir to the upper reservoir and save the electric energy as potential energy. This excess electrical energy can be transported to the power system during the peak load and dry season of the power system. In summary, the pumped energy storage power station has a dual identity, which can be used as a power user to store off-peak energy, but also as a hydropower station to provide peak load power.

(2) Characteristics

Its advantage is that, after long-term development, the technology is quite mature, has a certain reliability and large capacity, but is limited by the reservoir capacity. If pumped energy storage and wind power system cooperate, and combined with thermal power units, establish a combined wind-water-fire unit containing pumped energy storage, it can save the limited regulation resources of pumped energy storage, improve the effectiveness of the standby response of thermal power units, and avoid the frequent start and stop of thermal power units.

Its disadvantage is that it is seriously limited by geographical location, and there must be a suitable location for the construction of high and low reservoirs. In addition, there is a certain amount of energy loss in the process of pumping and generating electricity, and under the constraints of geographical location, it is usually impossible to get close to the load center. Wang et al. (2024) investigated AI-generated text detection and classification methods based on BERT deep learning algorithm. Their research demonstrates the potential of BERT in text processing, particularly in processing generated text data, achieving significant performance improvements.

In addition to power loss, if the system cannot work properly due to a major accident, the pumped energy storage power station cannot play a role. For example, when the magnetic loss occurs under the condition of pumping phase regulation, the existing magnetic loss protection has defects, and the unit excitation cannot be switched in time, which is not conducive to the stable operation of the system.

2.2. Compressed Air Energy Storage

In the 1950s, compressed-air energy storage plants appeared, which could store cheap electricity and then deliver it to the power system during peak demand. Its working principle is to drive the compressor by means of excess electric energy during the power load low period, so that the air can fill the underground gas storage, and when it needs to be used, the stored air can be released to drive the generator to generate electricity. Its working principle is similar to pumped energy storage, which was first applied to pneumatic tools, as long as it has sufficient scale, it can effectively solve the problem of peak-valley difference. The key is to find suitable places to store compressed air, such as exhaust mines and caves with better sealing. Yang et al. (2024) optimized the detection of diabetic retinopathy using the initiation-V4 and dynamic version of the Snow Leopard optimization algorithm. Their research shows that combining efficient deep learning networks and optimization algorithms can significantly improve the accuracy and efficiency of disease detection.

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At this stage, only a few countries in the world have successfully built demonstration compressed air energy storage power stations. Getting rid of dependence on fossil fuels such as natural gas, which can provide heat sources, and large caverns, while improving system efficiency, is a key issue for the wide application of compressed air energy storage.

2.3. Flywheel Energy Storage

Flywheel energy storage (battery) Built-in motor can be used as generator and electric motor. When the electric energy is stored, it can play the role of the motor and realize the flywheel acceleration. When the power is output, it can play the role of a generator to supply power to external facilities and reduce the speed of the flywheel; When the flywheel stops working, the system maintains minimal loss operation. It mainly relies on the acceleration and deceleration of the flywheel to complete the charge and discharge, the application of variable speed constant frequency power electronics technology, so the output energy frequency will not change.

(1) Introduction

In addition, the flywheel unit can also be used as a unit unit, which can be combined with actual needs, resulting in a device with greater power and can be installed around the load. This usage can be combined with the actual demand to complete the corresponding expansion, but also to ensure that the power does not lose. The flywheel energy storage system has excellent effect on the frequency regulation and control of the power grid, which can effectively improve the frequency stability of the power grid and ensure the reliability and security of the power grid operation.

Huang et al. (2024) conducted a tumor segmentation study using image enhancement methods. They explored how to improve the accuracy and clarity of tumor areas by enhancing image quality, providing a new technical approach for medical image analysis.Under normal circumstances, carbon fiber materials are used to make flywheels, because the actual speed can reach 40 000 to 500 000 r/min, which is not the speed of flywheels made of other materials. In addition, it is not only light in weight, but also high in strength, which effectively reduces the weight of the system, and the energy loss, especially the friction loss, in the charging and discharging process is also significantly reduced. Magnetic bearings are selected for both motor and flywheel, which have the advantage that the suspension state can effectively reduce mechanical friction. The two operate in a vacuum container, effectively reducing air friction. In this case, the flywheel battery can achieve a net efficiency of about 95%.

(2) Characteristics

For experts and scholars in the field, their research focuses on the development of composite materials and superconducting magnetic levitation technology. The former can effectively increase the energy storage density and reduce the volume and weight of the system; The latter is currently the most important way to reduce losses.

2.4. Magnetic Field Storage (Superconducting Coil Storage)

Magnetic field energy storage refers to the input of current into the inductor to store magnetic field energy. It is connected with the power system using the converter, and the converter has the characteristics of fast and efficient.

The superconducting coil has a high energy storage efficiency because it does not exist any resistance in the operating state. In addition, superconducting coils have a higher current and energy storage density than conventional coils. Not only that, it also has a very fast response speed because it is restricted only by the control loop time constant and the converter switching time, which is especially suitable for transient states such as transient processes of power systems. Liu et al. (2024) conducted a study on hazardous flight weather prediction based on machine learning techniques. They have developed a model that accurately predicts the dangerous weather conditions that flights may face, improving flight safety and punctuality.

The disadvantage is that it must be configured with cryogenic equipment, and even the operation of high-temperature superconducting coils cannot be separated from the temperature of liquid nitrogen. There are still many difficulties in the application of superconducting coil energy

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storage technology, and a lot of research needs to be carried out, including its cost, production materials, properties and so on. If the excitation coil is optimized, the maximum vertical magnetic field can be weakened, the critical current can be increased, and the utilization rate of the superconducting strip can be improved.

2.5. Electric Field Energy Storage (Supercapacitor Energy Storage)

Electric field energy storage refers to the storage of electric energy by means of the charge storage capacity of the capacitor. The disadvantage of traditional capacitors is that the capacitance is too small, so it can only be applied to the field of weak current and high voltage pulse technology. After the advent of supercapacitors, they can be used in the field of energy. Supercapacitors, as the name suggests, have a super large capacitance, the dielectric constant of their dielectric is extremely high, can make small volume capacitors, the unit is farad, compared to ordinary capacitors, orders of magnitude significantly increased.

Liu et al. (2024) conducted a study on flight accident prediction based on backpropagation neural networks. Their research uses neural network models to analyze the potential impact factors of flight accidents, providing a data-driven predictive tool for aviation safety management.Based on the above characteristics, supercapacitor energy storage will be widely used in transportation and energy. For example, the supercapacitor energy storage and photovoltaic system are combined into a hybrid cascade photovoltaic inverter; the supercapacitor energy storage unit can not only calm the active power fluctuations but also expand the output voltage regulation range of the photovoltaic unit by outputting reactive power, which is conducive to the stable operation of the photovoltaic system and improve the reliability of power supply. For example, the supercapacitor energy storage system is applied to the DC side of the permanent magnet direct drive wind power system, and the appropriate control strategy can improve the low voltage crossing ability of the wind power unit.

2.6. Rechargeable Battery Energy Storage

Rechargeable battery energy storage is also known as "secondary battery" or "battery"; its essence is electrochemical energy storage. In the past, due to factors such as price and energy storage density, rechargeable battery energy storage was not considered in the field of energy storage. However, with the continuous development of science and technology, rechargeable batteries have been increasingly widely used, and it has become an indispensable energy storage device in independent power stations such as wind and solar power.

There are many kinds of rechargeable batteries, among which the most common is lead-acid batteries, which are currently represented by sealed maintenance-free lead-acid batteries. At the same time, alkaline batteries are constantly being upgraded, and nickel-metal hydride batteries have gradually replaced traditional nickel-cadmium batteries. Comparing lead-acid and alkaline batteries, it can be found that the characteristics of the former include having a relatively large capacity, a relatively strong structure, and being able to charge and discharge multiple times. Its disadvantage is that it is more expensive, which makes it unable to be widely used in the energy sector. Lead-acid batteries are in urgent need of a technological revolution in lightweight, long life, low cost, fast charge and other aspects, and the future must learn from advanced technologies and advanced concepts of various disciplines such as material science and electronic technology to obtain a place in the increasingly fierce competition.

3. Application of Data Analysis and Forecasting in the NYISO Market

3.1. Data collection and Processing: Introduces the Data Source and Collection Method

Data is the key to driving power market decisions and optimising operations. In the NYISO market, data sources include historical power usage, weather, market trading data, etc. These data are obtained through various collection methods, such as smart meters, weather sensors, and market trading platforms. They are cleaned, converted and stored to ensure the accuracy and availability of data.

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For example, smart meters provide accurate load information to the NYISO market by collecting and transmitting users' electricity consumption data in real-time. These data help predict load fluctuations and support market operators in making real-time power scheduling and optimisation decisions, improving market efficiency and stability.

2. Time series analysis and forecasting: load forecasting and market demand forecasting using machine learning technology

Time series analysis and forecasting are key techniques for using historical data to predict future electricity demand and market behaviour. In the NYISO market, machine learning algorithms such as ARIMA and LSTM are widely used in load and market demand forecasting. These algorithms can identify and exploit underlying data patterns and trends to improve the accuracy and precision of predictions. For example, an LSTM (Long Short-Term Memory) neural network model can predict electricity demand in the coming hours or days based on historical load data and relevant market factors, such as weather changes and holiday effects. Such accurate forecasting can help market participants optimise energy buying and selling strategies, reduce costs and improve market efficiency.

3.3. The Role of Data-Driven Decision-Making in Improving the Efficiency of Market Participants

Data-driven decision-making is the key to greater efficiency and flexibility in the NYISO market. Market participants can more accurately predict market trends, optimise energy allocation, and even participate in real-time market transactions through analysing and mining big data. This decision-making approach not only reduces operational risk but also improves the competitiveness and profitability of market participants. Optimise trading strategies with real-time market data and machine learning algorithms. Market participants can effectively enhance their efficiency and market share in the NYISO market by adjusting their energy supply and purchasing strategies promptly based on predicted market demand and price trends to maximise profits or meet customer demand.

4. The Role of Machine Learning in Improving Grid Resilience

4.1. Intelligent Control and Optimization: How can Machine Learning be Used to Optimise the Operation of Energy Storage Systems

Machine learning is essential in optimising the operation of energy storage systems. Machine learning algorithms can predict future load demand and energy supply by analysing historical and real-time sensor data. For example, reinforcement learning algorithms dynamically adjust energy storage systems' charging and discharging strategies to maximise system efficiency and stability. This intelligent control can reduce energy costs and improve the grid's response to load fluctuations and emergencies. In general, intelligent microgrids in some cities achieve optimal utilisation of distributed energy resources by deploying machine learning-based energy management systems. For example, an intelligent microgrid project in California uses reinforcement learning algorithms to optimise the coordinated operation of photovoltaic power generation, energy storage systems, and load management. Based on real-time weather prediction and load demand, the algorithm adjusts the operation strategy of the system to improve energy efficiency and ensure the stability of the power grid. This intelligent control and optimisation enable the microgrid to quickly adjust energy supply in the face of sudden changes in weather or sharp increases in power demand, effectively improving the resilience and reliability of the overall grid.

4.2. Application of Reinforcement Learning in Intelligent Microgrid and Distributed Energy Management

Reinforcement learning, a technology that can learn optimal behaviour by interacting with the environment, is significant for intelligent microgrids and distributed energy management. In these complex energy systems, reinforcement learning algorithms can adjust energy distribution and load management strategies based on real-time data to optimise the system's operational efficiency and responsiveness. For example, by interacting with smart meters and smart home devices, reinforcement learning algorithms can learn and predict a user's energy consumption patterns and then adjust the energy distribution of individual nodes in the microgrid to maximise user satisfaction

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and system stability. In an intelligent microgrid project in Germany, researchers used algorithms based on deep reinforcement learning to manage multiple distributed energy resources within a region, including wind, solar, and electric vehicle charging stations. The algorithm predicts energy demand and supply in the next few hours by collecting and analysing real-time energy production and consumption data. It dynamically adjusts the operation mode and charge and discharge strategy of individual energy devices within the microgrid. This intelligent management not only improves energy utilisation efficiency but also significantly reduces the system's operating costs. It can quickly adapt to and respond to market fluctuations or emergencies, ensuring the stability and reliability of regional energy supply.

4.3. Discuss the Potential of Machine Learning in Real-Time Response and Reducing the Risk of Power Outages

Machine learning has great potential for real-time response and reducing the risk of power outages. By establishing predictive models based on big data and intelligent algorithms, potential failures and load overload in the power system can be identified so that preventive measures can be taken or power distribution strategies can be adjusted in real-time. This data-driven real-time monitoring and response capability can significantly improve the stability and reliability of the grid and reduce the socio-economic impact of power outages. A power company in the United States used machine learning algorithms to analyse historical data and real-time monitoring data to build a predictive model to predict possible points of failure and overloads on power lines. By monitoring factors such as line temperature, load changes and weather conditions, the model identifies potential risks and alerts them in advance for overhaul or adjustment. This predictive and real-time response system significantly reduces the risk of power outages, improves the reliability and stability of the power system, and reduces the impact of service outages on customers and enterprises, saving many maintenance costs and human resources for power companies.

The above-detailed description of the different roles of machine learning in enhancing Grid Resilience shows its importance and practical application value in modern power systems.

Conclusions

As a key supporting technology of renewable energy, energy storage technology has effectively realised the integration with wind and photovoltaic energy through the intelligent management of machine learning and promoted the development of the power system in a more sustainable direction. Future research and technological innovation will focus on increasing energy storage density, reducing costs, and optimising system efficiency to support power systems' more comprehensive application and development.

While machine learning shows great potential in power grid resilience, it faces challenges such as complex market entry barriers, inconsistent technical standards and opaque market rules. Future research should focus on optimising the application of machine learning algorithms in the power market to improve prediction accuracy and real-time response capability and promote the widespread application and sustainable development of energy storage technology in power systems.

In summary, data analytics and machine learning have played an essential role in facilitating the development of the NYISO market in a more sustainable and efficient direction. By optimising the intelligent management of energy storage technology, the power system can better adapt to future challenges and needs, providing solid technical support and guaranteeing the large-scale integration of renewable energy.

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