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SMART GRID OPTIMIZATION THROUGH MACHINE LEARNING

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Smart Grid Optimization through Machine Learning: Enhancing Efficiency Reliability, and Sustainability of the Electrical Grid

Artificial intelligence (AI) is a significant development that promises to usher in a new era of scientific progress and technological advancement. AI brings to the table a wide range of beneficial capabilities and applications, which can be integrated into our electronic world and smart technology. Artificial intelligence uses machine learning, algorithms, and modeling to learn and make decisions based on provided data. *Machine learning* is an almost human-like technique wherein machines dramatically improve their performance as they learn from their mistakes or data. It is the learning process artificial intelligence takes to achieve near perfection in almost every action. Brown (2021) states, “Machine learning is a subfield of artificial intelligence, which is broadly defined as the capability of a machine to imitate intelligent human behavior (p.2). ”

An important artificial intelligence application is operating power grids more efficiently. A *power grid* is a network meant to deliver electricity to consumers; this includes generator stations, transmission lines, and towers (Štompf, 2020). All of these convert natural resources such as coal, oil, nuclear and natural gasses into electricity. In a technologically advanced society like ours, we have moved past the traditional power grids to obtain electricity by using *smart grids* that are operated with computers guided by artificial intelligence. Efficient communication between the power plant and the user enables utility companies to manage energy supply more effectively, resulting in reduced costs and improved reliability.

Incorporation of Machine Learning in Smart Grids

Artificial intelligence's machine learning helps create an efficient and reliable smart grid through predictive and adaptive maintenance, load balancing, energy optimization and fraud detection. Although smart grids can predict future energy demands by analyzing the data in real-time, machine learning can take it a step further and predict future maintenance, energy trends and equipment failures. This is useful as power loss is a major setback in supplying electricity to a large consumer base.

Integrated into the design of a smart grid is a two-way communication system known as advanced metering infrastructure (AMI). This two-way communication system collects metering information that contains cumulative kilowatt hour (kWh) usage, peak kilowatt demand, and voltage, found only in smart grids (Eaton, 2023). AMI is composed of smart meters, communication networks and data management systems that allows for two-way communication to take place. Similar to machine learning, AMI has many assets that are beneficial to the smart grid. "The system provides a number of important functions that were not previously possible or had to be performed manually, such as the ability to automatically and remotely measure electricity use, connect and disconnect service, detect tampering, identify and isolate outages, and monitor voltage" (SmartGrid, 2016, p. 4).

What Separates Machine Learning Grids From Others?

Normal power grids and smart grids have a load forecasting problem. Load forecasting is a complex multi-variable estimation problem whereby normal forecasting methods using numerical methods cannot provide accurate and reliable results as they can not track random trends. However, machine learning can provide accurate results with its algorithms to track random trends and predict future ones. The integration of machine learning allows AI to analyze past data from the system and learn from them. With the use of an AI algorithm, the system can predict future machine failures, and quickly undergo maintenance, which can reduce the cost of sudden emergency repairs due to its adaptivity in real-time data.

What Are Smart Grids?

Utility companies also face widespread price instability as consumer energy choices change frequently. Hence, reducing the costs of sudden maintenance and system repairs using predictive analytics models can heavily benefit utility companies. Smart meters are devices capable of accumulating detailed information on electricity consumption in order to lower bills and raise knowledge on the status of electricity. This data is obtained after the meter reads the rating of electricity fed into the grid, which is then used for a number of things, such as signals to the main system. Smart meters and sensors within a smart grid can transmit a signal with the time and date, which can be used to detect partial or complete power outages.

Smart grids created by energy agencies have many priorities that are still not fulfilled with the algorithm system. The top three priorities are demand response and consumer energy efficiency, wide-area situational awareness, and cyber security. Studies have shown that utility companies have recently paid more attention to achieving these goals by using smart devices with machine learning applications, which contain “various distributed computing algorithms to coordinate distributed components of their power systems”(Saqib 2020 p. 1). These algorithms used by Distributed Internet of Things (loT) devices and smart meters are capable of communicating, analyzing and operating their devices both independently and with others at high speeds. Smart meters heavily rely on machine learning techniques and are perceived to be implementing data science methodologies.

One of the valuable applications of artificial intelligence's machine learning is its predictive capabilities, which can analyze vast amounts of real-time data and anticipate power outages before they occur. This notifies operators of a potential outage giving them time to take measures to prevent them. These reliable systems can even distinguish home, street, and zonal outages. Smart grids are modernized electrical grids that moderate the generation, distribution and consumption of energy, but are still regulated by humans. Studies have shown that using machine learning techniques has been shown to yield superior outcomes in "highly-constrained optimization problems" (Sooriarachchi 2020, p. 2). This factor is determined by the capabilities of machine learning to adapt from previous data and be fully autonomous, taking many scenarios and factors into account to make a decision; it also takes into account the mistakes created from human error to regulate smart grids.

Predictive and Adaptive Machine Learning Applications

Adaptive capabilities not only benefit utility companies, but a consumer's daily life as well. Each consumer is granted a unique and personalized smart grid, tailored to their individual energy needs and consumption patterns. This allows the consumer more control and flexibility over their energy usage. AI-powered smart grid management and smart metering gives customers hourly evaluations of their energy usage, helping them to see where and when they use energy. It even gives consumers personalized suggestions to optimize their energy use and save money. The consumer can also manage their energy production, which can often be sold back to the power grid.

Load Balancing

While machine learning is capable of predicting future trends of electricity, this application can be taken a step further and used to optimize load balancing and storing energy. *Load balancing* is a set of techniques used by electrical power stations to store excess electrical power during periods of low demand. Having a grid incapable of load balancing could lead to a collapse of the grid, otherwise known as a *blackout*. In order to prevent blackouts, smart grids can use machine learning to analyze data on energy consumption patterns and predict future demands; this allows the system to have a general understanding of the future trends in electricity. It also allows the system to automatically adjust the distribution of energy to different areas based on the expected needs, ensuring that power is distributed efficiently and effectively, and even storing excess energy.

Furthermore, the integration of machine learning with smart grids can improve the efficiency, reliability and resiliency of the electrical grid, while also promoting the use of renewable energy sources and contributing to a more sustainable energy future. Similar to load balancing, AI can help distribute energy, and identify areas where energy efficiency can be improved through energy pattern analysis. This process of identifying and flagging inefficient appliances or spotlighting areas for insulation or other improvements can greatly reduce energy waste. Through machine learning energy grids can predict future electricity spikes or troughs, and algorithms can allow them to predict when renewable energy sources are available, such as wind and solar. *Deep learning*, a type of machine learning that enables a machine to process data like a human would, has been noted to be a potential tool for renewable energy sources. With the ability to “improve solar, and wind generation prediction accuracy based on large datasets,” deep learning can move past the typical numerical calculations made by power grids, and make decisions in even the most unstable and unpredictable environments (Zhang, 2018, p 2). This enables smart grid systems to be increasingly efficient, reliable, and cost-effective while reducing waste and minimizing environmental impact.

Energy Optimization

There are many scenarios that occur in a smart grid, which the human brain can not account for. Using a smart grid controlled by humans leaves room for human error, resulting in many mistakes in which managers are far too late to respond quickly to, and have to take safety precautions. This includes scenarios when less energy is available during high energy demands causing the frequency of the electric system to drop, and activating load-shedding plans to avoid power cuts. This results in the power plant switching off one by one, ending with a complete blackout, otherwise known as load shedding. Conversely, having too much electricity during low demand causes the electrical frequency to increase, then the power plant disconnects from the grid because the frequency range they operate at is far less than the frequency the plants are emitting. Machine learning could easily solve this problem by accurately predicting the trends of the energy consumption and equally balancing energy into designated areas for usage. The system could then store the excess electricity and later modulate electricity supply based on the data received. Machine learning algorithms can continuously monitor real-time data and adjust load balancing mechanisms as energy demands change. “Smart grids provide real-time tracking and displaying of energy system device conditions and efficiency through linkages and over large geographic areas, helping device operators and users recognize and optimize power system modules, actions and output” (Kumar, 2020, p. 2). With the help of machine learning, smart grids can not only distribute energy more efficiently and effectively, but lower the risk of over producing energy and power outages. Smart grids have yet to find the most optimal way of producing and transferring energy to homes and civil infrastructures. With machine learning's trial and error method, smart grids can find optimal energy usage through three main techniques.

Reinforcement learning is a training method in which an agent makes decisions through trial and error. They can be trained to make decisions in the context of energy usage, based on factors such as weather conditions, time of day, and energy prices. The machine would learn to make better decisions over time after seeing the graph statistics increase or decrease. Researchers have come up with a new type of reinforcement learning, known as deep reinforcement learning (DRL), combining deep learning with reinforcement learning (*rl)*. Researchers have noted a widespread deployment of advanced metering infrastructures and other monitoring systems that produce massive data and provide data basis for algorithm and model training in AI applications. "Therefore, DL RL, and DRL appear to be some of the enabling technologies for the future development and success of smart grids" (Zhang, 2018 , p 2). Another method would be generic algorithms, in which machines test possible solutions until an optimal solution is found. The machine could generate and test different energy usage patterns until it finds a desired pattern. The algorithm would generate different patterns by generating and combining different energy usage strategies, and evaluate the effectiveness of each pattern based on reliability, energy cost, and consumption. Lastly, a neutral network can be used to simply analyze data and identify patterns that work in the case of optimizing energy usage.

However, energy optimization in a smart grid is not limited to energy generation, but also to the distribution and consumption of energy in the network. The initial goal of smart grids was to create a more effective power grid, one with efficient transmission of electricity, faster restoration of electricity after power disturbances, lower costs for operators, and lower power costs for consumers. Soon after the creation of smart grids, optimizing energy quickly became one of the main goals as the Department of Energy and other energy agencies needed a way of balancing energy with demand, along with minimizing energy loss. Data accumulated from smart meters and other sensors can help machine learning algorithms predict future energy demands, forecast weather patterns, and adjust energy distribution accordingly - processes a normal smart grid or power grid can not accurately handle on their own. Machine learning is proving to be an invaluable tool in smart grid systems, not only for optimizing energy usage but also for improving fraud detection capabilities.

Fraud Detection and Prevention With Machine Learning

A high-tech power grid has its pros and cons, one of which is fraudulent activities. For many years, fraudulent activity has been a huge problem with smart grids, including energy and identity theft. Although smart grids have safety measures to prevent fraudulent activities, the risk of stolen data is still high. Normal algorithms in smart grids leave room for frauds and theft of electricity, costing tens of millions of dollars. With the integration of machine learning, detecting fraud can be more efficient. After analyzing countless fraudulent activities, machine learning can detect common abnormal behavior in the grid, such as energy theft, identity theft, false data injections, denial of service, and insider threats.

Energy theft is the most common fraud in smart grids; customers may tamper with the energy meters to underreport their energy usage. This results in lower energy bills for the customer, but increases prices for other customers. The second most common fraud is false data injections, where outside parties inject false data into the smart grid, which has the potential of disrupting the grid's operation or causing it to malfunction. Outsiders can manipulate data on energy production from a renewable energy source, such as solar energy or wind, to claim subsidies and tax credits.

The third common fraud is identity theft, where an attacker gains unauthorized access to a customer's account information to make changes to their energy usage or information. This can result in unauthorized changes to a customer's bill or create false energy use. Denial of service (Dos) attacks on the smart grid cause malfunctions or shut downs, which ultimately leads to disruptions in energy distribution. Insider threats are caused by trusted inside employees or contractors intentionally or unintentionally harming the grid system by manipulating data or stealing sensitive information.

Machine learning could help prevent such frauds through its adaptive fraud detection algorithms. After analyzing countless fraudulent activities, machine learning could refine its algorithms to accurately detect even the smallest bits of fraud in the system. Fraud detection is a prominent feature provided by AI as it helps to identify real users and prevent energy theft or meter tampering. Machine learning could potentially decrease the fraud rates in smart grids by identifying patterns and abnormalities in the system that indicate fraudulent behavior, improving the accuracy of the system, and attracting more customers. By detecting instances of fraud, machine learning can help utilities recover revenue lost to fraud and deter future instances of fraud, lowering the total amount of money lost to theft by a lot.

Machine Learning For The Future

Overall, machine learning can prove to be a beneficial addition to smart grids, including "i. Cutting energy waste, facilitating and accelerating the use of clean and renewable energy sources, and improving the planning, operation, and control of the power systems; ii. Information sharing and two-way communication; iii. Configuration of ownership and systems through energy suppliers; and iv. Net metering and related activities." (Sooriarachchi, 2020, p.). The integration of machine learning with smart grids can significantly enhance the reliability, efficiency and sustainability of the electrical grid. Machine learning in smart grids will be the first step in revolutionizing the energy industry. With the help of past data from users, smart grids will continue to improve its reliability and customer satisfaction, attracting more users, generating more data to be analyzed.

Conclusion

Through the analysis of data from smart meters and other sensors, machine learning algorithms can predict energy demand, forecast weather patterns, make fully automated decisions insensitive to the market structure, think beyond the scope of humans, and optimize energy distribution. Moreover, machine learning can enable utilities to perform predictive and adaptive maintenance, preventing potential power outages. This not only promotes the use of renewable energy sources but also contributes to a more sustainable energy positive future. Through the utilization of machine learning algorithms, smart grids can adapt to changing conditions and make proactive decisions to balance energy demand, reduce power outages, and detect fraudulent behaviors. The integration of machine learning in smart grids is undoubtedly the first step in revolutionizing the way we manage and distribute energy, leading to a more sustainable future.

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