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A Review of Renewable Energy and Power System Integration

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Abstract: Wind and solar energy are two examples of the renewable energy that nations around the world are accelerating their development of in response to global climate change and energy scarcity. However, current power networks face new difficulties as a result of these energy sources' volatility and intermittency. Based on the existing literature and data, this article reviews the latest research advances in the integration of renewable energy sources (such as solar and wind) with conventional power systems. The paper discusses the main technical challenges faced in the integration process, including intermittency, stability and other issues. At the same time, this paper discusses the development of demand response, load management, machine learning, energy storage technology and smart grid technology, of which smart grid technology is the main content of this article review. The purpose of this paper is to summarize the existing smart grid technology, explain the help of smart grid for renewable energy grid connection, and provide a reference direction for future research. Finally, according to the existing policies, the paper looks forward to the future and believes that the share of renewable energy in the future grid will be increasing.

Keywords: Renewable Energy, Solar Energy, Smart Grid.

1. Introduction

Electricity is an indispensable resource in today's life, and about 800 million people in the world still do not have access to it. As Galvin states in the article, low income, energy inefficiency and high fuel prices are the main causes of energy poverty [1]. Large-scale adoption of renewable energy generation, is an important way to address energy poverty [2]. These energy sources are characterized by high sustainability, relatively low environmental impact. Solar power generation depends on the intensity of the sun's illumination. Therefore, many factors, such as the change of day and night, weather conditions and seasonal changes, can affect the efficiency of power generation [3]. When the light is sufficient, the solar power generation system has large power generation, high power generation efficiency, and relatively high-power generation power. But in the night or cloudy days and other solar lights are insufficient, not only does the total amount of power generation drop sharply, but the power generation is also at a low level. Wind power is sensitive to changes in wind speed. When the wind speed is small, the output power of the wind turbine is very low.

When the wind speed is too high, the wind turbine may also be shut down to protect the equipment. Based on these practical phenomena, it can be concluded that renewable energy, led by solar energy

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and wind energy, has a high dependence on the environment and is not controllable. Compared with traditional fossil energy, renewable energy has no stable output capacity and cannot be adjusted according to the power grid's demand for electricity consumption. Such randomness and intermittancy will lead to the imbalance of power supply and demand [4]. As a result, the frequency fluctuation of the power grid will fluctuate when it is connected to the traditional power grid [5]. Such intermittency and volatility will make the power generation of the power generation facilities on the supply side of renewable energy unstable and unable to provide stable reactive power for the grid [6].

For a complete power system, renewable energy changes the traditional power system from a few large power plants to a broad group of users of the power model. Power generation facilities are often distributed far from the load center, such as remote mountain or coastal areas rich in wind energy resources. This geographical imbalance makes the power system need to build more transmission lines and substation facilities to transfer electric energy to the load center [7]. Moreover, because of the intermittent and fluctuating characteristics of renewable energy generation, the power supply reliability of the power system is greatly affected. As of 2017, the total installed capacity of solar energy in the world reached 398 GW, and that of wind energy reached 546 GW [5]. To balance demand and supply, demand response and load management techniques have been proposed [8]. Demand response balances power supply and demand by dynamically adjusting users' demand for electricity. Especially when the supply of renewable energy is insufficient or excess, through different pricing or incentive policies, reduce or increase the power load to ensure the stability of the power grid and improve the reliability of the power grid. According to the different locations of different projects in the power system, it is classified as follows: based on market (wholesale and retail markets), based on motivation (reliability and economy), based on system (dispatchable and non-dispatchable) [8]. Load management is the reduction of grid stress by optimizing load distribution in the power system. For example, during peak usage hours, it is possible to balance power demand and reduce grid stress by scheduling adjustable loads, such as industrial equipment or electric vehicle charging. This management method not only improves the operation efficiency of the power grid, but also saves the cost of electricity consumption for users [9].

Breakthroughs in next-generation energy storage technologies will be key to the energy system balancing the volatility of renewables [10][3]. In the future, in addition to the continuous optimization of lithium battery technology, solid-state batteries, as a representative of a new generation of energy storage technology, are gradually becoming a research hotspot. Solid-state batteries are considered to be expected to replace current liquid batteries due to their high energy density, safety and long cycle life. Flywheel energy storage is a high-power density, short-time response energy storage technology, suitable for frequency regulation, short-time voltage stability and other scenarios. The flywheel energy storage system stores kinetic energy through a high-speed rotating flywheel, and quickly releases or absorbs energy to adjust when frequency fluctuations or short-time voltage problems occur in the power grid. Supercapacitor is also a high-power density energy storage technology with extremely high charge and discharge speed, but its energy density is relatively low, which is suitable for application in scenarios that need to release energy quickly, such as instantaneous voltage regulation of power systems or energy recovery systems in rail transit. The development direction of ultracapacitor technology in the future is to increase its energy density to broaden its application scenarios in power grids [10].

In addition to demand response, load management and energy storage technology, smart grid can balance power supply and demand to a certain extent and reduce the impact of power fluctuations on power grid stability through real-time monitoring and dynamic adjustment of power flow, so smart grid is also considered to be a key technology to complete the integration of renewable energy and power system. The following will mainly discuss the application and advantages of smart grid technology in the integration process of renewable energy (solar energy and wind energy) and

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traditional power systems. How to use these technologies to solve the problem of renewable energy generation. The purpose is to summarize the relevant technologies and provide a feasible direction for the research of renewable energy grid connection.

2. Smart grid

2.1. Smart grid technology overview

Smart grid is a comprehensive system integrating modern information technology, communication technology and power technology. Its goal is to achieve more flexible supply and demand management, reduce energy consumption, and adapt to large-scale access of renewable energy while improving the efficiency of the power system [11-12]. Through real-time data collection and dynamic adjustment, smart grid enables the power system to conduct more accurate scheduling of power load and generating capacity, so as to cope with the instability caused by intermittent energy such as solar and wind energy [13-9].

2.1.1. Advanced Metering Infrastructure (AMI)

AMI, one of the core technologies of smart grid, is mainly used for real-time data acquisition and remote control at the client end [11]. AMI system includes smart meter, data management system and communication network, which can accurately record the electricity consumption of each user and provide real-time electricity consumption information transmission and two-way communication [14-11]. Through smart meters, power companies can monitor the changes in power demand of users in real time and adjust the load according to demand-side management strategies [11].

2.1.2. Distribution System Automation (DSA)

DSA, is another important technology in the smart grid, aiming to improve the monitoring and operation efficiency of the distribution system through automation equipment and control technology. DSA can realize the functions of real-time monitoring, fault location and automatic recovery of the distribution network, reduce manual intervention and improve the flexibility and stability of the power system [15]. In the context of renewable energy access, the role of DSA is particularly prominent. The volatility of solar and wind power generation will directly affect the voltage and power balance of the distribution network, and through DSA, the distribution company can automatically adjust the power flow when the wind speed changes or the solar radiation decreases, ensuring voltage stability on the load side. At the same time, DSA can carry out reactive power compensation and load adjustment according to the real-time status of the distribution network, optimize the operating efficiency of the distribution network, reduce transmission and distribution losses, and further enhance the grid's adaptability to intermittent energy.

2.1.3. Energy Management System (EMS)

EMS is a key tool for power system scheduling and management. It is mainly aimed at optimizing the scheduling of the power system. This optimization is mainly achieved by monitoring the operational status of power generation, transmission, distribution, and consumption. EMS plays an irreplaceable role in the integration of renewable energy. It can achieve reasonable scheduling of different power generation amounts in the power system through real-time data collection and analysis. In the scenario where renewable energy is connected to the power grid, EMS can dynamically dispatch and optimize power generation management based on weather forecast, generation prediction and load demand [16]. When the power generation of solar energy and wind energy fluctuates greatly, EMS can automatically call the energy storage system or peak power supply

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to maintain the balance of the power system. Through the real-time optimization of EMS scheduling, the utilization rate of renewable energy is improved, the waste of power generation is reduced, and the stable operation of the power system is ensured.

2.1.4. Machine learning(ML)

ML is also being applied [17]. ML is a form of data-driven programming that automatically learns programs based on examples. ML models fall into three main categories, including supervised ML, Unsupervised ML, and enhanced ML.

Supervised learning: Power systems and intelligent energy systems provide input-output pairs for ML algorithms, which learn the functional mapping from input to get the desired output, also known as a regression process. This technique plays a key role in data and load forecasting. A typical example is supervised vector machine (SVM) learning models used to analyze power data generated by distributed generation and conventional generators [17][18].

Unsupervised learning only needs to provide input data to the ML algorithm and does not need to provide corresponding output or the learning process does not depend on the output. It then clusters into groups based on the similarity of the data. This allows you to find data groups or patterns that might not otherwise be obvious. An integrated grid-based energy system cluster can be used to optimize the energy distribution of nodes for optimal energy distribution. In this way, unsupervised power data can be processed quickly [17][19].

Reinforcement Learning(RL): Unlike the first two types of learning, RL has no fixed data set, a feature that has caused it to receive a lot of attention in the energy field. As power systems become more complex, so do security and uncertainty issues. Compared with model predictive control (MPC) methods, RL has a wider application because of its better sequential decision-making ability (for risk measures and uncertainties) [17][20].

2.2. Advantages of smart grid technology for the integration of renewable energy

Through the collaborative application of the above technologies, smart grid has greatly improved the power system's ability to adapt to renewable energy. Firstly, smart grids can quickly respond to changes in solar and wind power generation. This is thanks to its real-time monitoring and dynamic adjustment functions. This reduces the impact of intermittent power generation on the frequency and voltage stability of the power grid [13-9]. Secondly, AMI and EMS effectively reduce the risk of power supply and demand imbalance and improve the utilization efficiency of renewable energy through demand-side management and load adjustment. At the same time, the automatic control and self-healing capabilities of DAS and EMS ensure the rapid recovery of the distribution network in case of failure and enhance the reliability of the power system [12]. Smart grid technology is not only suitable for power systems with large-scale renewable energy access but can also help distributed energy systems better integrate [12]. For example, distributed photovoltaic power generation systems can be dynamically matched with the electricity demand of users through smart grid technology to reduce the loss of grid-connected electric energy. With the further development of smart grid technology, its role in the integration of renewable energy and power systems will be more important.

3. Policy and market reform outlook

The evolution of policies and market mechanisms is a key factor driving the further development of renewable energy and smart grid technologies.

Compared with traditional power generation, the cleanliness and sustainability of renewable energy generation are the main advantages for future development. This advantage is limited by technology, resulting in very high power generation costs. To encourage the total installed capacity of renewable energy, China adopts the economic subsidy measures of feed-in tariff and the measures of cross-regional price diversification [21]. The strategy of feed-in tariff refers to that the power grid provides a fixed electricity price to the owners of renewable energy generation facilities such as solar power plants, so as to ensure that the electricity generation income is constant and ensure that the renewable energy generation facilities such as solar power plants can make profits from it. Diversification of prices across regions can be seen as the optimal method of feed-in tariff subsidies. In recent years, with the development of technology, the cost has dropped significantly, so the feed-in tariff subsidy has also dropped significantly. Because of the mismatch between energy supply and demand in some regions, the feed-in tariff subsidy has evolved from a national unified price to a cross-regional diversified price to encourage solar power generation in the central and eastern regions [21]. The improvement of the carbon market mechanism is also an important direction of future energy policy reform. By establishing and expanding the carbon trading system, more economic incentives can be provided for renewable energy generation projects. Especially in the context of tightening carbon emission caps, the rising price of carbon trading will encourage traditional high-emitting companies to increase their investment in clean energy and promote greater integration and utilization of renewable energy.

Future energy market mechanisms need to be more flexible to accommodate the widespread use of distributed energy and storage technologies. Traditional power market rules are often based on centralized power production and a single demand side, while the future market will gradually evolve to a multi-energy complementary and two-way trading model. Specifically, the electricity market needs to provide more access opportunities for distributed energy and storage, allowing small power generation facilities, energy storage systems as well as individual users to participate in power trading. For example, users install small solar power generation facilities in their homes, and after meeting individual demand for electricity, sell excess electricity to the grid [21]. For the power grid, this method reduces the cost of transmission and distribution. For individuals, it reduces the cost of purchasing electricity and gives them an extra income with government subsidies. This approach further promotes the localization and flexibility of energy production and consumption.

4. Conclusion

Solar energy and wind energy, as representatives of renewable energy, have been widely promoted around the world because of their environmental protection and sustainable advantages. However, its random and intermittent power generation characteristics also bring serious challenges to the stability of the power system, the reliability of power supply and the transmission and distribution of power. Fluctuations in grid frequency and voltage, reduced reliability of supply, and adaptability of transmission and distribution systems are all problems that must be dealt with when renewable energy is connected on a large scale. To address these challenges, smart grids have been proposed as a future solution. As a solid foundation for large-scale integration of renewable energy, mainly solar and wind, into the traditional power grid, smart grid applications are based on AMI, DSA and EMS. Their integrated application is of great help to the power system to adapt to the randomness and intermittency of new energy generation, and greatly improves the stability and reliability of the power system. However, it cannot be ignored that the rapid development of renewable energy has put forward many technical challenges to the power system. To maximize the challenges of intermittence and volatility, power quality issues and policy and economic barriers brought about by the use of new energy sources, great advances have been made in power electronics technologies such as demand response, load management, virtual power plants and new energy storage technologies led by lithium batteries, flywheel energy storage and supercapacitors. At the same time, the promotion of government policies and market mechanisms is also an important help to solve these problems. Through the dual drive of technology and policy, the future power system will be able to better integrate renewable energy and realize the optimization and transformation of the energy structure. The future energy system will depend on technological innovation, advances in storage technology, and reforms in policy and market mechanisms. By further promoting the development of smart grid and energy storage technology and improving the market mechanism, countries around the world can achieve a higher proportion of renewable energy integration, thus laying a solid foundation for tackling climate change and achieving the sustainable development goals of energy.

References

[1] Galvin, Ray, ed. Inequality and energy: how extremes of wealth and poverty in high income countries affect CO2 emissions and access to energy. Academic Press, 2019.

[2] Pagliaro M, Meneguzzo F. Distributed generation from renewable energy sources: ending energy poverty across the world[J]. Energy Technology, 2020, 8(7): 2000126.

[3] Rabaia M K H, Abdelkareem M A, Sayed E T, et al. Environmental impacts of solar energy systems: A review[J]. Science of The Total Environment, 2021, 754: 141989.

[4] Zhou S, Wang Y, Zhou Y, et al. Roles of wind and solar energy in China's power sector: Implications of intermittency constraints[J]. Applied energy, 2018, 213: 22-30.

[5] Mokeke S, Thamae L Z. The impact of intermittent renewable energy generators on Lesotho national electricity grid[J]. Electric Power Systems Research, 2021, 196: 107196.

[6] Qian Kejun, Yuan Yue. Distributed Generation Technology and Its Influence on Power System [J]. Power System Protection and Control, 2007(13):25-29.

[7] Honarmand M E, Hosseinnezhad V, Hayes B, et al. An overview of demand response: From its origins to the smart energy community[J]. IEEE Access, 2021, 9: 96851-96876.

[8] Kataray T, Nitesh B, Yarram B, et al. Integration of smart grid with renewable energy sources: Opportunities and challenges — A comprehensive review[J]. Sustainable Energy Technologies and Assessments, 2023, 58: 103363.

[9] Tan K M, Babu T S, Ramachandaramurthy V K, et al. Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration[J]. Journal of Energy Storage, 2021, 39: 102591.

[10] Dileep G. A survey on smart grid technologies and applications[J]. Renewable energy, 2020, 146: 2589-2625.

[11] Butt O M, Zulqarnain M, Butt T M. Recent advancement in smart grid technology: Future prospects in the electrical power network[J]. Ain Shams Engineering Journal, 2021, 12(1): 687-695.

[12] S. S. Sayali, M. P. Thakre, S. Chandrakant, A. M. Jain and M. Ganesh, "Functionality of Smart Grid with RE Enables the Generation of Solar Energy: Opportunity to Come, " 2020 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), Chennai, India, 2020, pp. 1-7, doi: 10.1109 / ICPECTS49113.2020. 9337019.

[13] Abdullah A A, El-Den B M, Abo-Al-Ez K M, et al. Security management for an advanced metering infrastructure (AMI) system of smart electrical grids[J]. Applied Sciences, 2023, 13(15): 8990.

[14] Kashem M. Muttaqi, Jamshid Aghaei, Velappa Ganapathy, Ali Esmaeel Nezhad.

[15] Technical challenges for electric power industries with implementation of distbution system automation in smart grids, Renewable and Sustainable Energy Reviews, Volume 46, 2015, Pages 129-142, ISSN 1364-0321, https://doi. org/10.1016/j.rser.2015.02.013.

[16] Vuddanti S, Salkuti S R. Review of energy management system approaches in microgrids[J]. Energies, 2021, 14(17): 5459.

[17] Ahmad T, Madonski R, Zhang D, et al. Data-driven probabilistic machine learning in sustainable smart energy/ smart energy systems: Key developments, challenges, and future research opportunities in the context of smart grid paradigm[J]. Renewable and Sustainable Energy Reviews, 2022, 160:112128.

[18] Donti P L, Kolter J Z. Machine learning for sustainable energy systems[J]. Annual Review of Environment and Resources, 2021, 46(1): 719-747.

[19] Sharmila P, Baskaran J, Nayanatara C, et al. A hybrid technique of machine learning and data analytics for optimized distribution of renewable energy resources targeting smart energy management[J]. Procedia Computer Science, 2019, 165: 278-284.

[20] Perera A T D, Kamalaruban P. Applications of reinforcement learning in energy systems[J]. Renewable and Sustainable Energy Reviews, 2021, 137:110618.

[21] Li J, Huang J. The expansion of China's solar energy: Challenges and policy options[J]. Renewable and Sustainable Energy Reviews, 2020, 132: 110002.