The Resilience and Stability of Smart Grids Under a High Proportion of Renewable Energy

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Abstract. This article gives a systematic review concerning the resilience and stability of smart grids with the integration of high-proportion renewable energy. The central proposition is that the large increase of variable, intermittent, and low inertial, like wind and solar, renewable energy sources causes problems for grids. This article adopts methods like reviewing, analyzing techniques and conducting case studies to look into some technologies like multi-timescale collaborative optimization scheduling, virtual synchronous generator, multi-energy complementary system and AI forecasting technology. Examining projects such as Hubei Suizhou’s 100% renewable county grid, South Africa’s AI dispatch system, it can be seen they have improved renewable energy insertion, enhanced grid self-repair capabilities and improved frequency stability. In this paper, the main innovation lies in the synthesis of the resilience and stability framework and using the recent engineering validation to provide support. Future studies can also look more at the technical bottlenecks and system plan improvements so that innovation will be driven to markets that support the future power system.

Keywords: Smart grid; renewable energy; power electronic converter grid connection; resilience; stability.

1. Introduction

The global energy sector is going through a big change toward being more sustainable, and there are plans to use lots of renewable energy. But at the same time, the large amount of volatile, intermitting wind and solar being put into power grids can make grids less stable and resilient. These are all connected through power electronics converters without the inertia of the conventional generator which causes the frequency to become unstable and voltages to fluctuate. and worse is increasing severe weather increases grid exposure [1].

In reply, large part of study efforts goes towards improving smart grid resilience - the system can hold up against, fit into, and bounce back from troubles and stability - keep voltage and frequency within reasonable bounds; Major tech development is multi-energy complementation sys plus A I - based preditions for variance. For stability multi-timescale scheduling and VSG mimic key, inertial responses A practical verification comes from the world pilots such as hubei Suizzhou China high-renewable County Grid, South Africa AI driven dispatch System.

However, there are still some difficulties: problems such as long-term storage technology and technical issues caused by a complex system due to distributed "prosumers" and imperfect markets.

The paper presents a review regarding the resiliency and stability of smart grids with a large proportion of renewables. It analyses the two-sided influence of renewables, it is clear about the important improving technologies and the most central steadiness ways, and it investigates using case studies. And then it points out lasting issues and future trends to back the development of lasting power systems.

2. The Dual Impact of Renewable Energy on The Power Grid

2.1. Multifaceted Negative Impacts

First, the overwhelming majority of renewable energy sources may have a negative impact on the stability of smart grids. It may be influenced by some factors, such as the environment, resulting in unstable supply, which is also known as "indirectness" and "variability" [2].

2.1.1 Specific Questions and Examples

The first influencing factor is weather. For example, it is difficult for solar power to generate electricity efficiently on cloudy days. Furthermore, in winter, with shorter days and lower solar altitudes, power generation capacity is significantly lower than in summer. Secondly, some power generation output may be unstable, exhibiting a fluctuating trend. For example, tidal power has four tidal cycles per day (two high tides and two low tides). During high and low tide periods, the water velocity is zero, and power generation ceases. Consequently, the output power exhibits intermittent pulses[3].

2.2. Positive Potential

2.2.1 Some Environmental Advantages

Renewable energy has many advantages in smart grids. For example, compared with traditional fossil fuels, renewable energy releases almost no greenhouse gas emissions. Therefore, it will cause less pollution to the environment. Secondly, renewable energy comes from nature and is a reusable energy that will not be exhausted. Therefore, it can have high flexibility and reduce energy supply risks.

2.2.2 Potential

Renewable energy has great potential in smart grids. For example, on the supply side, with the increase in population and government subsidies, renewable energy has begun to develop rapidly in recent years. For example, data shows that china's renewable energy has increased by 15.2% year-on-year from January to July 2025. The algorithm predicts that renewable energy has great development potential. The model GM (1, 1) can be used for prediction [4]. The final conclusion is that renewable energy can meet the demand for emergency peak-shaving reserve power.

2.2.3 Possible Future Development and Application

With the development of renewable energy, some technologies may become the key to solving the instability of the power system and ensuring energy supply. For example, The integration of energy storage systems enables charging during off-peak hours and discharging during peak hours, thereby shaving peak demand and enhancing supply reliability., the system can be charged during off-peak hours and discharge during peak hours to support the grid load, reducing dependence on generators, further reducing consumption and providing more electricity, thus ensuring the continuity and reliability of the power supply system.

3. Key technologies for enhancing the resilience and stability of power grids

3.1. Try to combine the Research of Smart Grid and Renewable Energy and the Technical System Related to these two Technologies

Smart grids can address the problem of intermittency through intelligent technologies, such as research on the joint operation of renewable energy and energy storage equipment, which includes methods to increase the utilization rate and reduce electricity costs. For example, the use of multi-energy complementary systems to combine various renewable energy sources with different geographical distribution characteristics to output them more reasonably and achieve more efficient goals. For example, in Qinghai and other regions, an integrated base for wind power and water storage power generation can be built. By utilizing its complementarity, when the wind is insufficient, flexible hydropower generators can be started to supplement it, and when the wind is excessive, water can be pumped to store energy.

3.2. Application of Prediction Technology

Accurate forecasting techniques can be employed to mitigate this uncertainty to increase efficiency [5]. They can also use some relatively mature technologies to make predictions, such as wind power prediction technology. This technology refers to achieving balance and stability of the power system by predicting the wind power in the next few minutes, or developing some new energy storage technologies, such as energy storage systems (ESS) [6].

4. Core methods to ensure stability

4.1. Stability

Due to the intermittent and fluctuating characteristics of renewable energy, its dispatch and management become more difficult. Therefore, traditional power system stability analysis methods face new challenges. Renewable energy generation is uncontrollable and may cause grid frequency and voltage fluctuations, or even system instability [7].

Stability refers to the ability of the grid to maintain synchronous operation and voltage and frequency within a safe range under various disturbances (such as load fluctuations and generator failures). Its core is to maintain the dynamic balance of the system and avoid cascading failures or collapse caused by disturbances. Grid stability is mainly divided into two types: static and dynamic (as shown in Table 1). Dynamic stability studies the dynamic response and recovery process of the grid after a major disturbance, while static stability studies the self-adjustment and recovery capabilities of the grid when encountering minor disturbances [8].

Table 1. Dynamic and static stability difference

	Concept	**Definition**	**Time scale**	**Disturbance type**
1	Static stability	The ability of the system to maintain a stable operating point (voltage, frequency) under small disturbances or slow changes, focusing on steady-state equilibrium analysis.	Steady state (seconds to minutes)	Slow load fluctuations and gradual output of renewable energy
2	Dynamic stability	The system's ability to restore synchronous operation through dynamic adjustment after a large disturbance (such as short circuit or power outage), focusing on transient process analysis.	Transient (milliseconds to seconds)	Sudden failures, rapid power fluctuations

4.2. Optimized operation

4.2.1 Multi-timescale collaborative optimization scheduling

In the event of extreme weather, natural disasters, system overload, abnormal operation, physical damage to network components, and deviation from standard operating parameters, the physical and cybernetic infrastructure of smart grids may exhibit unpredictable behavior [9].

As for the static stability of the power grid, since the uncertainty of renewable energy output varies at different time scales, a single dispatching strategy is difficult to cope with. Therefore, it is crucial to establish a multi-time scale collaborative optimization dispatching framework covering day-ahead, intraday, and real-time. A typical three-stage dispatching optimization model is shown in Table 2.

Table 2. Typical three-stage scheduling optimization model

1	**Day Ahead**	Based on the forecast of wind and solar output in the next 24 hours, a power generation plan and backup plan with the goal of optimal economic efficiency are formulated, and the output curve is submitted to the market.
2	**Intraday rolling scheduling**	15- minute cycle , using more accurate ultra-short-term forecast data . This phase primarily utilizes faster-responding resources (such as gas-fired units and pumped hydro storage) to balance forecast errors and reduce the pressure on real-time dispatch.
3	**Real Time Scheduling**	On a time scale of minutes or even seconds, rapid adjustment resources such as battery energy storage and demand-side response are used to smooth out instantaneous fluctuations in wind and solar output, ensure the stability of grid frequency and interconnection line power, and achieve precise power balance.

This multi-stage collaborative model can give full play to the advantages of different flexible resources, gradually absorb uncertainties, and effectively improve the overall operating efficiency and stability of the system.

4.2.2 Virtual Synchronous Generator (VSG)

VSG is the most representative advanced strategy in grid-connected control, which mainly guarantees the dynamic stability of the power system. Since the grid-connected converter lacks rotating parts, many traditional synchronous generators (SG) have been replaced by grid-connected converters. This leads to a significant reduction in the inertia of the system, a significant reduction in the anti-interference ability of the system, and a significant reduction in the frequency stability of the system [10]. VSG embeds the second-order mathematical model of the synchronous generator (rotor motion equation and excitation equation) in the control algorithm of the converter, enabling it to accurately simulate the inertia, damping, and other key dynamic characteristics of the synchronous generator [11]. When the grid frequency or voltage is disturbed, VSG simulates the rotational inertia of the synchronous generator to slow down the system frequency change rate and prevent instability caused by rapid frequency drop; suppresses subsynchronous oscillations or low-frequency oscillations caused by the grid connection of new energy through virtual damping coefficients to avoid power angle loss; responds to frequency deviations autonomously through primary frequency regulation and restores power balance; and improves grid voltage stability through primary voltage regulation. Therefore, energy storage or renewable energy units based on VSG control can autonomously and quickly provide active or reactive power support, just like synchronous generators, effectively suppressing frequency and voltage fluctuations and improving the "active support" capability of the power grid. Distributed power sources, including energy storage, wind power, photovoltaics, and electric vehicles, usually use inverters to connect to the distribution network, which provides a good application scenario for VSG technology. Among them, the combination of VSG technology and energy storage systems (especially battery energy storage) can provide fast and flexible frequency regulation and voltage regulation services for the power grid, which is an effective means to ensure the stable operation of the power grid in microgrids and weakly connected areas [12].

5. Typical case analysis

A number of representative smart grid construction projects have emerged at home and abroad, which demonstrate the innovation and application of grid resilience and stability technology in a high proportion of renewable energy environment. Through in-depth analysis of these cases, valuable experience can be provided for the development of smart grids in the future.

5.1. Typical cases in China

China has made significant progress in smart grid construction, and the following typical examples illustrate China's latest achievements in grid resilience and stability technology in the context of a high proportion of renewable energy access:

Hubei Suizhou Guangshui High Proportion New Energy County Power Grid: The project has built the first 100 megawatt 100% new energy power system with long-term independent operation. Its core technologies include independent networking of new energy and collaborative control of source, grid, load and storage, achieving a very high proportion of renewable energy grid connection and consumption. The system has a power supply area of 418 square kilometers, serving a population of more than 200,000 people, and has an installed capacity of 244MW of new energy, while the maximum load is only 61MW. The project solves key technical problems such as stable control and fault protection of high-proportion new energy grids through flexible load regulation, distributed energy storage optimal configuration and intelligent scheduling algorithms, and provides replicable solutions for similar county power grids.

Guizhou distribution network self-healing system: Guizhou Power Grid Company carried out the construction of an intelligent distribution network transformation demonstration area in Wudang District, Guiyang City, and implemented intelligent transformation of 84 distribution network lines, achieving three 100% breakthroughs in the distribution network ring rate, "self-healing" coverage rate and convertible power supply rate. The system can automatically isolate fault sections in the event of a fault and restore power to non-fault areas within 2 minutes, reducing the processing time by more than 50% compared to traditional times. This technology greatly improves the power supply reliability and fault response speed of the distribution network, reducing the power outage time for users.

5.2. Typical foreign cases

Many countries in the world have also carried out active exploration in the construction of smart grids, and these projects provide an important reference for the construction of our country's new power system:

AI intelligent dispatching system in Gauteng, South Africa: China Zhidian and South African National Power Company (Eskom) have implemented the "Intelligent Power Distribution + AI Dispatching Pilot Project". Through the deployment of intelligent sensor networks and self-developed AI load scheduling algorithms, the project has significantly improved the response ability of new energy sources such as wind power and photovoltaic during peak and valley periods, achieved a 36% increase in wind and solar grid-connected capacity, increased the utilization rate of local new energy to 78%, and reduced carbon emissions by more than 1.2 million tons per year. The project demonstrates the important role of artificial intelligence technology in new energy dispatch and grid optimization.

Malaysia Flexible DC Cross-Island Interconnection Project: In view of Malaysia's multi-island and uneven energy distribution, China Zhidian has built a 320-kilometer submarine flexible DC channel with a total installed capacity of 3.5GW. The project will complement East Malaysia's abundant hydropower resources and West Malaysia's photovoltaic wind power, and is expected to reduce the use of nearly 850,000 tons of standard coal per year. This cross-regional flexible DC interconnection technology provides an effective solution for renewable energy consumption in island countries and geographically complex regions.

6. Challenges and future directions

Although smart grid technology has made significant progress in improving renewable energy access and ensuring grid stability, it still faces many challenges. Accurately identifying these challenges and grasping future trends is critical to building new power systems.

6.1. Main challenges

In the context of a high proportion of renewable energy access, the resilience and stability of smart grids face the following three main challenges:

Technical bottleneck challenges: The randomness and volatility of renewable energy are inherent characteristics, which leads to the need for a refined supply and demand balance between randomly fluctuating load demand and power sources. The decline of system inertia is another prominent problem, and the stability of system frequency is facing a severe test after the traditional synchronous generator is replaced by power electronic equipment. In addition, the lack of long-term energy storage technology also restricts the consumption of a high proportion of renewable energy, and there is currently a lack of cost-effective large-scale energy storage solutions to solve the problem of multi-day or even seasonal energy balance.

System planning and operation challenges: With the widespread application of distributed power generation, multiple loads, and energy storage, a large number of user-side entities have both power generation and consumption attributes, becoming "prosumers". This has changed the terminal load characteristics from the traditional rigid and pure consumption type to the flexible, production and consumption type. The evolution of power system structure from centralized to distributed has increased the complexity of system operation control. The transformation of distribution networks from passive networks to active networks requires new planning and design and operation management methods.

Market mechanism and policy challenges: The existing electricity market mechanism cannot fully reflect the market value of flexible and regulated resources, and various types of markets such as auxiliary service market, spot market, and capacity market need to be continuously improved and effectively connected and integrated. The aggregation and sharing mechanism of energy data has not yet been perfected, and how to achieve effective use of data without infringing on user privacy still needs to be further explored. In addition, the lack of international cooperation standards also restricts the global promotion of smart grid technology, and there are differences in technical standards and regulatory policies in different countries, which increases the difficulty of cross-border energy interconnection.

6.2. Future trends

In the face of the above challenges, smart grid technology and application show the following important development trends:

Digital technology deep empowerment: cloud computing, big data, Internet of Things, mobile Internet, artificial intelligence, blockchain, edge computing and other "cloud big things move intelligent chain edge" technologies will be widely used in all aspects of the power system. These technologies can realize the collaborative operation of massive dispersed objects and the accurate perception and adjustment of the complex operating state of the system. Artificial intelligence technology will play an important role in load forecasting, equipment condition monitoring, fault diagnosis, and scheduling optimization. Digital twin technology will build a virtual power grid corresponding to the physical power grid, realize accurate mapping and advanced simulation of operating states, and support rapid decision-making and autonomous response.

Hierarchical zoning collaborative architecture: In the future, the power system will present a hierarchical zoning structure of "flexible backbone network, intelligent distribution network, and extensive microgrid". The backbone network realizes the optimal allocation of resources on a large scale through flexible AC and DC transmission technology. the distribution network has evolved in the direction of active, collaborative and intelligent; Microgrids and virtual power plants have become important forms of aggregating distributed resources. This architecture can achieve a combination of "local balancing and global optimization", which not only improves system reliability but also reduces operating costs.

Market mechanism improvement and innovation: Auxiliary service markets, spot markets, capacity markets and other types of markets will continue to improve and effectively connect and integrate to better reflect the market value of flexible and regulating resources. The linkage between green electricity trading and the carbon market will gradually increase, such as the "Green Electricity-RMB Settlement Pilot" in Buenos Aires, Argentina, which demonstrates a new model of cross-border green electricity trading. New market players such as virtual power plants and load aggregators will promote the large-scale integration of decentralized resources and participate in market transactions, and improve system regulation capabilities.

7. Conclusion

This paper systematically reviews the research progress on the resilience and stability of smart grids in the high-renewable scenario. Firstly, it analyzes the dual role of the impact of renewable integration. From the side of renewable energy integration, it will bring certain difficulties to the grid frequency and grid voltage stability due to its characteristics of volatility and intermittency, with low inertia; On the other hand, it is clean, renewable, and can be used sustainably. But on the other hand, it’s renewable, sustainable, and environmentally friendly. Secondly introduces the main technology points about efficiency improvement such as the technology of multi-energy complementary system, the algorithm of the accurate prediction of the system etc to enhance the flexible and reliable of the grid also mention the basic method of grid stabilization, based on multi-scale coordinated optimal scheduling method, and in combination with VSG, it can be solved as a static and dynamic stable problem; through some ordinary domestic and foreign methods to show the engineering practical effect of the theoretical technology. fourthly, to recognize existing technological bottleneck points as well as operation flaw points of systems and market mechanism barrier points; and also anticipate trends like empowering by digital technology and hierarchical cooperation and market innovation.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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