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Abstract. In recent years, due to the severe global energy crisis, the development of renewable energy has gone faster and faster. As integrated large-scale power grids have far-reaching impacts that undermine the stability and self-sufficiency of small regions, the gradual advancement of distributed microgrids and their integration with renewable energy generation have given rise to a series of microgrid technologies. The most representative among these is the photovoltaic-wind-storage microgrid. However, constrained by the instability and intermittency of wind and solar power generation—characteristics that lead to fluctuating electricity output—photovoltaic-wind-storage microgrids face challenges in meeting stable power demand due to their inherent instability and isolation during operation.This paper aims to analyze and compare existing literature and research on photovoltaic-wind-storage microgrids. Through a comprehensive analysis of optimization schemes such as microgrid energy storage, time-of-use pricing, and energy storage technologies—integrating literature reviews, experimental comparisons, and synthetic analyses—it proposes conclusions with reference value for optimizing the stability of photovoltaic-wind-storage microgrids. These insights aim to promote their sustainable development and enhance operational stability.

INTRODUCTION

In recent years, due to the excessive use of fossil energy, a series of environmental problems and energy crises have emerged. The sustainable development of the environment has received increasing attention worldwide. At the same time, although the old-fashioned integrated power grid is easy to regulate the overall power supply, it has a global impact in major events such as earthquakes and system failures, which is not conducive to the stability of regional power supply. All these reasons have led various countries to start researching the development of photovoltaic-wind-storage microgrid systems. Initiated by countries including the U.S., Japan, and European nations, multiple microgrid demonstration projects have been successfully established [1]. However, since most countries focus their research and development goals on environmentally friendly, distributed energy control, and energy utilization, there is a shortage of research on the stability of such microgrids at present. But due to the environmental constraints of wind and solar energy, the photovoltaic-wind-storage microgrid may not be able to ensure stable power supply in actual use. Therefore, the research on the stability of the photovoltaic-wind-storage microgrid is also an important research direction in the future.

This paper mainly studies the power operation stability of photovoltaic-wind-storage microgrids in actual operation. Through the analysis of existing research results, a theoretical scheme for optimizing stability is obtained. This study aims to propose feasible solutions to improve the stability of photovoltaic-wind-storage microgrids to enhance their stability in actual operation.

THEORETICAL FOUNDATION ANALYSIS

System Architecture Analysis

Microgrid systems consist of devices such as energy storage devices, distributed power sources, and loads [2-5]. Structurally, there are two main types of microgrids: simple microgrids and complex microgrids [6]. Simple microgrid consists of load and photovoltaic power generation, but due to its simple structure, it has a large instability; complex microgrid consists of electric loads and a variety of distributed power sources, and at the same time, in order to improve the regulation and stability of the system, equipped with the deployment of the energy storage system, which is able to regulate the distribution of energy according to the specific situation, and it has a good stability. According to the scale and access mode, the microgrid has a total of five different operation modes: general wind and general light, strong wind and strong light, strong wind and weak light, weak wind and weak light and weak wind and strong light [6]. In actual operation, The strategic integration of wind turbine systems with energy storage architectures can be used to achieve the effect of "shaving peaks and replenishing depletion".

This paper focuses on the DC microgrid system (Figure 1). In fact, according to the different ways of power supply, the microgrid system also has two types of AC microgrid and AC/DC microgrid [7], but due to the DC microgrid is more stable than the AC microgrid, the loss of energy is small, and nowadays the advantage is even greater [8], photovoltaic power generation and distributed power sources such as wind power generation have a more DC portion, and the docking is more convenient in the actual operation; and at present, In China's power sector, the prevalence of strong DC and weak AC systems drives the higher practicality of DC microgrids. Therefore, the DC microgrid is more practical, so this paper does not study the other two microgrids for the time being.

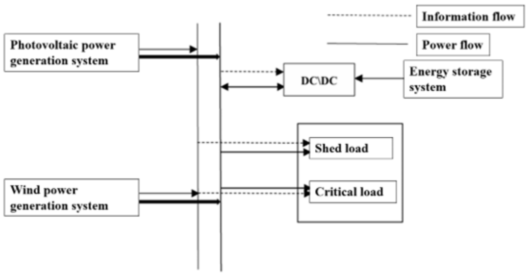

FIGURE 1. Typical structure diagram of DC microgrid

Wind Energy

Wind power generation technology is already quite mature and is currently a mainstream renewable energy source. The main process of wind power generation is: wind energy - mechanical energy - electrical energy. The wind turbine starts to rotate under the drive of wind force, overcoming the inherent friction of the unit and doing work to achieve the conversion of wind energy to electrical energy. However, in actual power generation applications, wind power generation is completely dependent on the natural environment and is completely influenced by natural wind, which has great instability. Therefore, it is an important unstable factor in a micro-grid system.

Solar Energy

Solar photovoltaic power generation is a very popular renewable energy industry in recent years and has great potential. Photovoltaic power generation mainly relies on the photovoltaic effect of semiconductor devices, converting solar energy into electrical energy through a series of reactions in solar cells.

The principle of this process is roughly as follows: Sunlight shines on the semiconductor device, causing electrons in the battery to enter the free-moving electrons and holes, causing positive and negative charges to repel and accumulate, forming an electric potential difference and generating electrical energy.

Solar photovoltaic power generation has developed various technologies with comprehensive benefits, such as fish-photovoltaic complementarity etc. The industrial prospects are excellent, but in actual operation, it is similar to wind energy, being subject to solar radiation and having instability. Therefore, it is also an unstable factor in the wind-solar-storage micro-grid system.

Energy Storage

Energy storage mainly relies on batteries such as lithium-ion batteries and storage batteries to store generated energy. This process involves the mutual conversion of electrical energy and chemical energy. Energy storage technology is crucial in the wind-solar-storage micro-grid system and can play a role in regulating the overall situation in certain cases.

For example, on sunny days with abundant solar radiation or cloudy days with strong wind, a large amount of excess electricity generated can be stored in batteries through energy storage technology. When there is insufficient solar radiation, no wind, or during peak electricity consumption, the stored electricity can be released to achieve stable power supply. In the wind-solar-storage micro-grid system, to improve system stability, the perfect deployment of energy storage technology is an important part, which is conducive to improving overall stability.

ANALYSIS OF THE IMPACT OF TIME-SHARING TARIFFS ON STABILITY

In the energy supply of wind and solar storage microgrids, the demand side of the demand for electricity by its season, the crowd and other different bias in a regular basis, for example: for the working population, the peak of electricity consumption in the morning and evening; for the retired people, the whole day of the electricity is more uniform; in the winter may be the morning and evening heating large amount of electricity, in the summer before and after the noon of the refrigeration and the large amount of power consumption. The energy sources of wind and solar storage microgrid are mainly photovoltaic power generation and wind power generation. Photovoltaic power generation is time-sensitive, with weak solar radiation in the morning and evening, resulting in low power generation; the sun's altitude angle is the greatest around noon (14:00), with the strongest solar radiation, resulting in the most power generation (the weather conditions in this scenario are sunny). Alternatively, wind energy production is not time-sensitive and can be generated whenever there is wind. In terms of microgrid energy sources, the overall trend is less generation in the morning and evening and more around noon, so energy management based on microgrid generation has a place in maintaining microgrid stability. It is a good means to ensure the stability of power supply by dividing time-sharing tariffs by generation capacity, ensuring that users use more power when the generation capacity is high and less power during the rest of the day. Ziwan Ma used the algorithm of fuzzy C-means to come up with a better scheme of time-sharing tariff [6].

Ziwan Ma divides the electricity load into peak, valley and flat parts by fuzzy C-mean and determines the reference tariff for each time period, thus guiding the users to use electricity at different time periods, shaving peaks and leveling valleys, and achieving the purpose of economic optimization of the system [9]. Also according to the literature [10], the load data of 24h in a month is given, and the three types of time periods are clustered by fuzzy C-mean, and then according to the value of the affiliation matrix, the time-sharing reference tariff table is obtained [6], which divides the one-day electricity consumption time period into three sections: peak (7-8; 18-22), flat (8-18) and valley (22-0; 0-7), and the reference tariffs are 0.5054, 0.425, and 0.12, respectively, 0.425 and 0.12 yuan/degree.

By dividing the tariff into time slots, the user side can follow the energy law of the supply side and use less electricity when the generation is low and more when the generation is high, thus ensuring the stability of power supply to a certain extent, which is a more feasible option.

ANALYSIS OF THE IMPACT OF ENERGY STORAGE CAPACITY SELECTION ON STABILITY

Energy storage plays a crucial role in wind-solar-storage microgrids, storing the excess electricity when the generation is high and discharging when the generation is low to ensure the stability of the system. However, considering the economic cost of energy storage technology and the lifespan of infrastructure, the energy storage capacity is an aspect that needs to be comprehensively considered. Li Peng, Yu Jiancheng, and others analyzed and studied the selection of energy storage capacity for wind-solar-storage microgrids [11]. This study first determined the basic parameters: based on engineering practice, determine the installed capacity of wind power generation and photovoltaic power generation in the microgrid system, as well as the size and nature of the load connected to the microgrid system. Then, clarify the boundary constraints and data prediction: respectively determine the boundary constraints of the microgrid system in grid-connected mode and "island" mode, and obtain the simulation prediction data of distributed power generation and load prediction data through simulation software. For example, in the grid-connected mode, assuming the power factor of wind and solar energy systems is nearly unity, reactive power is disregarded, based on the power generation capacity and regional meteorological conditions, obtain the predicted data of active power of wind and photovoltaic power generation and the predicted data of active power of the microgrid load; in the island mode, analyze based on the output characteristic curves of distributed power sources and loads. Next, according to the simulation prediction data of the grid-connected mode and the island mode, calculate the electricity difference between the generated power and the load demand in the same period. Based on the electricity difference of the microgrid system under the grid-connected mode and related constraints, calculate the energy storage equipment capacity requirement under the grid-connected mode; based on the expected operating time of the microgrid system to maintain its voltage and frequency in the island mode and the electricity difference, calculate the energy storage equipment capacity requirement in the island mode. Incorporating capacity requirements for energy storage systems in both grid-connected and island operation modes, a calculation of microgrid energy storage capacity is performed.

The method proposed by Li Peng, Yu Jiancheng, and others for selecting the energy storage capacity of the wind-solar-storage microgrid system based on the injected boundary constraints can accurately select the energy storage capacity of the wind-solar-storage microgrid system. This method provides a scientific basis for engineering construction and ensures the reliable operation of the wind-solar-storage microgrid system, improving the technical and economic feasibility of microgrid system construction. Under typical day conditions, it is calculated that the energy storage capacity under the grid-connected mode is not less than 48.07 kWh, to meet the 1-hour operation needs of the island. As determined by the analysis, the storage capacity for energy should be at least 40.09 kWh. Considering comprehensively, the energy storage capacity of the microgrid system is determined to be 60 kWh, and the power of the inverter is selected not less than 15 kW. To improve the stability of the microgrid system, a better solution is proposed, which is conducive to improving the stability of the microgrid system [11].

EXAMINING HOW ENERGY STORAGE TECHNOLOGIES AFFECT STABILITY PERFORMANCE

Equally important in wind and energy storage microgrids are energy storage technologies. Traditional energy storage technology can be divided into four categories: chemical energy storage, mechanical energy storage, thermal energy storage and electromagnetic energy storage [12]. Electrochemical energy storage and electromagnetic energy storage due to the development of more mature research, has been used on a large scale; as a representative of mechanical energy storage pumped storage due to its large scale, high construction costs and harsh natural environment requirements, is not suitable for deployment in small-scale distributed microgrids; thermal energy storage technology is currently mainly compressed air energy storage, high technical and environmental requirements, so it is not suitable for deployment in the microgrid.

Chemical energy storage mainly relies on batteries to store energy, the more popular batteries have several categories: lithium-ion batteries, lead-acid batteries, liquid current batteries and sodium-ion batteries. Considering the wide applicability and practicality, this paper only compares and analyzes lithium-ion batteries and lead-acid batteries.

Lithium-ion battery by its small size, low self-discharge rate, no memory effect, and charging and discharging efficiency, fast response speed, to meet the microgrid "that is, charging and discharging, according to the rapid" energy characteristics, very suitable for deployment in the wind and light storage microgrid; and for the current most widely used energy storage battery, high security. The disadvantage is that the use of organic electrolyte, there is a risk of thermal runaway. In practice, the technology route is mainly lithium iron phosphate (LFP) and lithium ternary (NCM and NCA).

Lead-acid batteries are traditional energy storage batteries with low cost, high reliability, abundant production raw materials, mature manufacturing process, low maintenance costs, stable performance, which can guarantee the stability of microgrid energy supply, and have been widely used in solar energy storage systems and other fields. However, due to its large size, heavy weight, low mass specific energy, high self-discharge, short service life defects, is not conducive to the long-term development of the microgrid and the economy, while the use of the battery in the process of heavy metal pollution, which is contrary to the development of wind and light storage microgrids of the original intention (environmental sustainability).

Through the above comparison, this paper believes that lithium-ion batteries are more suitable for the current wind power storage microgrid system, which can reduce the cost and improve the stability of the system while guaranteeing the energy supply.

CHALLENGES AND OPTIMIZATION ANALYSIS

Challenges Faced

One of the main challenges faced by the photovoltaic-wind-storage microgrid is the intermittent and fluctuating nature of wind and solar energy. Wind power generation depends on wind speed, which is unstable, resulting in fluctuating power output; solar power generation is affected by weather and time, and cannot generate electricity at night or on cloudy days. These characteristics make it difficult for the microgrid to provide a stable power supply, leading to a power supply-demand imbalance and affecting system stability.

The current cost of energy storage technology is high, and its large-scale application is limited. The indicators such as battery lifespan, charging and discharging efficiency, and energy density also need to be improved.

The photovoltaic-wind-storage microgrid includes various distributed power sources, energy storage devices, and loads. The dynamic characteristics of each part vary greatly. Moreover, due to the different output characteristics of different power sources, the charging and discharging strategies of energy storage devices also need to be matched with power sources and loads and other equipment. In both grid-connected and islanded microgrid operations, control strategy modifications are necessary, and the control system is required to have stringent reliability and real-time performance.

Optimization Measures

Integrate advanced meteorological prediction technology and multi-source data to build a high-precision wind energy and solar power generation prediction model to reduce power prediction errors. In response to prediction results, dynamic optimization of energy storage charging/discharging strategies is employed to balance supply-demand volatility and minimize dependence on traditional power networks.

Use model predictive control and distributed optimization algorithms to coordinate the operation of power sources, energy storage, and loads within the microgrid in real time. Through rapid power regulation and two-way interaction mechanisms, stabilize system voltage and frequency, and enhance the collaborative economic efficiency with the main grid.

Provide financial subsidies and tax reductions to lower the construction and operation costs of the microgrid. Promote direct power supply and flexibility resource trading models, establish time-of-use pricing mechanisms, guide users to use electricity rationally, and enhance the system's peak-shaving capacity.

CONCLUSION

This paper finds that there is still a huge space in improving the stability of wind and energy storage microgrid systems, which can be optimized from many aspects. Therefore, efforts can be made in the division of time-sharing tariffs, The optimization of energy storage capacity distribution and storage technologies. The whole day is divided into three time periods, guiding residents to use less electricity when generating less power to ensure that there is always a surplus of energy storage, and at the same time letting residents use more electricity when generating more power to get the maximum utilization rate of electricity; optimize the configuration of energy storage so that the microgrid system storage capacity of 60 kWh, and at the same time selecting the power of the inverter is not less than 15 kW, in order to improve the overall stability; in addition, the lithium-ion battery as the core of the original energy storage is also is favorable to improve the overall stability of operation.

The main contribution of this paper is to provide several directions and suggestions for improving the stability of wind power storage microgrids, and to provide relevant technology developers with optimization directions for reference, which is conducive to operators to optimize the existing power generation fluctuation situation, and to improve the overall durability and stability of the operation of wind power storage microgrids.

The current study tends to be idealized, not through the construction of a specific model to verify the real feasibility of the optimization scheme, and gives a few optimization directions have limitations, future research should be through the construction of a specific model, the relevant recommendations of this paper into a specific model for experimental verification to prove the feasibility. In the specific put into use, can also be installed in the microgrid through the addition of smart meters and SCADA and other systems as the feedback end, and then through the specific response end to make the relevant countermeasures.

REFERENCES

1. Y. Li, Y. Yang, and G. Chang, "Current status and prospect of research application of microgrid technology in China," China Electric Power 2016, **S1**, 159-163+170 (2016).
2. R. H. Lasseter, A. Akhila, C. Marnay et al., "Consortium for electric reliability technology solutions white paper on protection issues of the microgrid concept," CERTS White Paper (2002). Available: http://certs.lbl.gov
3. R. H. Lasseter, A. Akhila, C. Marnay et al., "White paper on integration of distributed energy resources: the CERTS microgrid concept," LBNL-50829, Lawrence Berkeley National Laboratory (2002)
4. MicroGrids Consortium, "European research project MicroGrids," EU Contract ENK5-CT-2002-00610 (2006). Available: http://microgrids.power.ece.ntua.gr
5. MoreMicroGrids Consortium, "European research project more MicroGrids," EU Contract SES6-019864 (2009). Available: http://microgrids.power.ece.ntua.gr
6. Z. Ma, "Energy optimization management of off-grid wind-solar-storage complementary microgrid," Ph.D. dissertation, Hubei University for Nationalities (2022).
7. R. F. Zhao, "Research on control strategy of optical storage DC microgrid," M.S. thesis, Beijing Jiaotong University, Beijing, China (2014).
8. L. Qiao and H. Bao, "Research and analysis of microgrid experimental system," Science and Technology Innovation 2012, **24**(37) (2012).
9. X. Xi, "Design of wind-solar complementary power supply system for Zhongshan Station in Antarctica," M.S. thesis, Taiyuan University of Technology, Shanxi, China (2018).
10. J. Zhang, "Research on coordinated control strategy of multiple power sources for wind-solar-storage microgrid," M.S. thesis, North China Electric Power University, Hebei, China (2013).
11. P. Li, J. Yu, F. Chi et al., "Selection method of energy storage capacity for wind, light and storage microgrid system based on injected boundary constraints," in Proc. 2012 Power Communication Management and Smart Grid Communication Technology Forum, Tianjin, China, 62-65 (2013).
12. Y. Jia, "Development status of hybrid system of wind, light and storage," Science and Technology Wind 2018,28(127) (2018).