Research on the stability of grid-connected wind and solar power generation

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Abstract. This paper mainly introduces multiple strategies to enhance the stability of wind and solar power grid integration. Firstly, considering the impact on the environment, mechanical energy storage systems such as FESS, PHES and CAES are introduced and analyzed. These energy storage systems cope well with wind and solar demand fluctuations. Then three kinds of GFM control techniques are introduced. For VF control, single-loop control leads to better stability of the grid. VOC is one of the more efficient in terms of power sharing and synchronization speed. Finally, three types of uncertainty that need to be considered in VPP are introduced, such as the uncertainty of renewable energy, the uncertainty of market price and the uncertainty of load demand. Considering the uncertainty of renewable energy, two VPP optimization methods are given to improve the stability of power grid. This paper hopes to consider the possibility of combining these methods in future VPP research.

Keywords: Grid integration, Solar energy, Wind energy, Virtual power plant, Renewables control.

1. Introduction

Climate issues have attracted worldwide attention due to the repeated incidence of adverse weather conditions and the threat of increased global warming. These climate problems are exacerbated by the increasing amount of greenhouse gases such as carbon dioxide in the air, which are emitted by burning coal, oil and other fuels [1]. In order to deal with this problem, countries around the world adopted the Paris Agreement in 2015, which aims to cut carbon emissions by 80% by 2050 [2], with renewable energy generation being the main way. Renewable energy sources (RESs) in the world (e.g. Wind and solar energy) of installed capacity continues to grow [3]. In fact, the installed capacity of wind energy in the world rose from 420GW in 2015 to 900GW in 2022, while that of solar energy rose from 230GW in 2015 to 1,050 GW in 2022, as shown in fig.1 and 2 [3]. To achieve carbon peaking and carbon neutrality, the installed capacity of solar and wind power will still maintain rapid growth in China [3, 4].

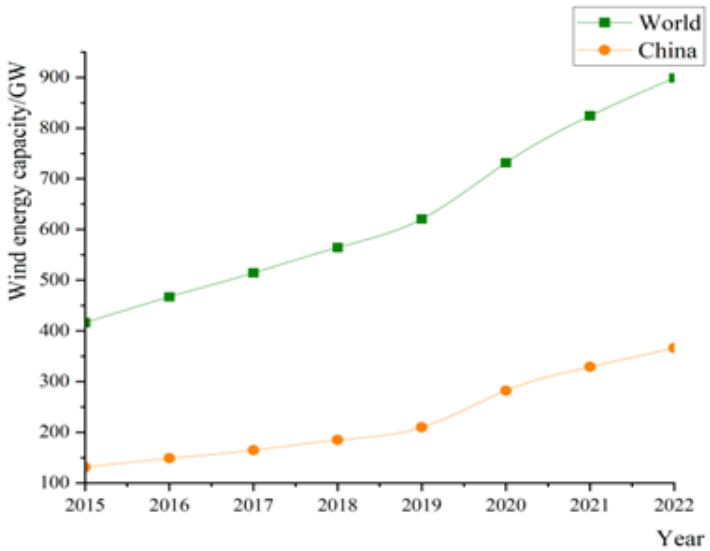


Figure 1. Installed capacity of wind energy in the world and China [2]

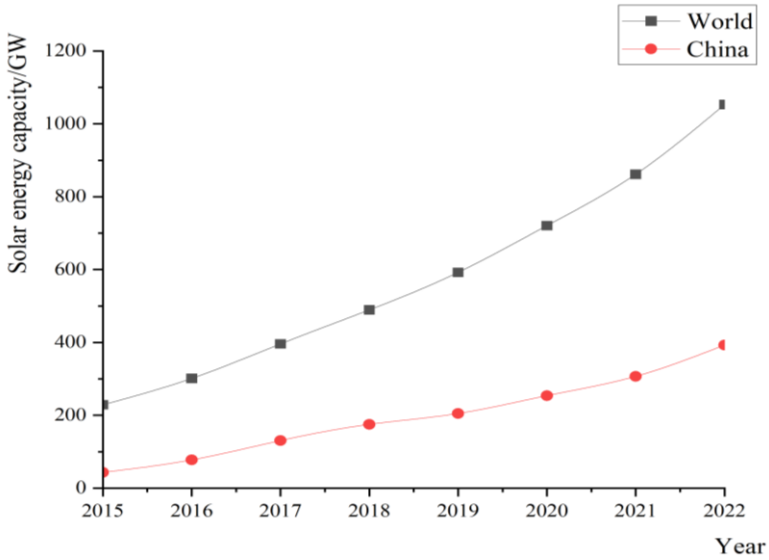


Figure 2. Installed capacity of solar energy in the world and China [2]

However, the intermittency and uncertainty of wind and solar power generation have brought challenges to the stability and security of the grid, such as frequency variation, voltage fluctuation, and harmonics [5]. There are many researchers have carried out related research. Some studies have considered the operation of the grid after large-scale RESs are connected to the grid, and concluded that it can be used through the integration of diverse energy sources, especially wind and solar energy.

Energy storage absorbs energy during peak generation and outputs energy during peak demand [6]. Research shows that energy storage can well alleviate the intermittency of wind and solar energy [7]. RES has high permeability, which will aggravate the instability of the power grid when it is integrated into the power grid [8]. Some studies have proposed new grid-forming (GFM) control strategies to bolster the robustness of grid-connected inverters for RES, aiming at the problems of traditional grid-connected control methods for grid-connected converters [8].

Virtual power plant (VPP) is a system that manages multiple power supply types, which can coordinate and optimize distributed power supply effectively to bolster the stability of power grid [9]. However, VPP always leads to a part of energy loss, so the best scheduling model should be determined according to different requirements. There has been a lot of research on the optimal scheduling model of VPP recently [10]. The optimal scheduling of VPP needs to consider various uncertainties, such as the intermittences of renewables, the variability of market prices and different load demands [11].

There have been many reviews of the research on the stability of renewable energy grid connection, as mentioned above. This paper focuses on the methods to improve the stability of wind and solar power grid connection, and summarizes recent optimization methods for virtual power plants considering different uncertainties. This paper hopes to consider the possibility of combining these methods in future research on VPP.

2. The stability of wind and solar power grid connection

2.1. Mechanical energy storage systems

Energy storage systems (ESS) flexibly respond to fluctuations in renewable energy demand to improve the stability of renewable energy grid connection [7]. Considering on environmental impact considerations, mechanical energy storage systems (MESS) are relatively low [7]. Its main divided into three kinds, flywheel energy storage system (FESS), pumped hydro energy storage (PHES) and compressed air energy storage (CAES). Hybrid energy systems can increase the utilizations of renewable energy [7]. In particular, solar and wind power are the most typical ones, which can be coupled to different MESS.

2.1.1. Flywheel energy storage system

FESS holds energy in a kinetic state based on the rotational mass of the flywheel [7]. FESS mainly consists of four parts, bearing system, flywheel, motor generator and power converter [12]. Flywheel as an energy buffer, can effectively reduce peak power [7]. The different shapes of the flywheel indicate the utilization rate of the material, expressed by the shape factor (K) [7]. Equation (1) (2) shows that the energy stored by the flywheel is affected by inertia, speed and shape [7].

$$E_f = \frac{1}{2} J_f \tag{1}$$

$$\frac{E_f}{m} = K \frac{\sigma_{max}}{\rho} \tag{2}$$

Where E_f is the energy stored by the flywheel, J_f is the moment of inertia of the flywheel, ω is the rotational speed, m is the mass, σ_{max} is the maximum stress, ρ is the density of the flywheel [7].

2.1.2. Pumped hydro energy storage and compressed air energy storage

PHES is a kind of MESS based on the gravitational potential energy of water to store energy. It is divided into three components, pump, hydro turbine and upper reservoir [7]. There are many feasibility studies and optimization methods for PHES, which are widely concerned around the world [13]. It can be seen from equation (3) that the energy stored in the upper reservoir is affected by the amount of water stored and the height of the waterfall [14].

$$E_w = \frac{V \times \rho \times g \times H \times \eta}{3.6 \times 10^6} \tag{3}$$

Where E_w is the stored energy of upper reservoir, ρ is the water density, g is the gravitational acceleration, H is the water-head height, η is the overall efficiency of the hydro turbine unit [14].

CAES is the compression of air into a high-pressure state in an underground storage chamber to store excess energy [7]. It consists of five components: compressor, cooler, pressure vessel, regenerator, turbine and generator. Recently, a new hybrid wind-solar-compressed air energy storage system has been proposed, based on the isothermal compressed air energy storage system [15]. It has a relatively good energy efficiency [15].

2.2. GFM control

GFM converters are currently a viable solution for improving the stability of interconnected power grids. It is fundamentally different from the grid-following (GFL) converters [16]. GFM converters can be represented as controlled voltage sources, while GFL converters are considered current sources [16]. GFM control is to control and adjust the frequency by directly controlling the output voltage [16]. GFM converters have different control structures. The existing researches on GFM control can be roughly divided into three categories: constant voltage/frequency (VF) control, GFM control based on power synchronization loop (PSL) and GFM control based on a new virtual oscillator controller (VOC) [8].

VF control is usually applied in closed systems instead of the active power grids, such as island grids and passive power grids, due to the constant voltage source of VF control [8]. VF control is usually divided into two types, single-loop and multi-loop control [8]. The study has compared the two and concluded that the use of single-loop control will make the power grid have higher stability [17].

In order to be applied to active grids, the influence of other voltage sources needs to be considered in GFM control [8]. PSL-based GFM control can regulate active and reactive power in the grid [8]. PSL primarily simulates the characteristics of grid-connected synchronous generators [8]. Considering the different structures of PSL, PSL-based GFM control includes droop control, power synchronization control (PSC), and synchronous power controllers (SPC), etc. The droop control and PSC are similar, both based on the sagging characteristics of SG. The difference between the two

makes little difference to the results [8]. SPC has a second-order overdamped system, which solves the problem of SG's fixed frequency control in power grid [8].

The virtual oscillator controller (VOC) is based on the synchronization phenomenon in the coupled oscillator network, and its converter can independently generate sinusoidal voltage by simulating the dynamics of the nonlinear oscillator [8]. Compared to PSL-based GFM control, VOC has more efficient power sharing and synchronization speed [8].

3. VPP

3.1. Classification of uncertainties

VPP is environmentally friendly and can well coordinate traditional energy and renewable energy in the energy management system to make the system operate efficiently. In addition, it can coordinate the distribution of energy sources in different regions [11]. VPP is usually combined with conventional power plants (CPP), wind farms (WPP), photovoltaic generators (PV), energy storage systems (ESS), electric vehicles (EV), and demand response (DR) [11]. The structure of VPP is flexible, and its optimal scheduling needs to take into account different uncertainties [11]. A review of relevant studies has given sources of uncertainty, such as renewable power uncertainty, market price uncertainty and load demand uncertainty [11]. For the uncertainty of renewable energy sources, the intermittency and variability of wind and solar are mainly considered [11]. For example, the wind speed required for wind power generation is affected by environmental factors such as terrain, weather, and temperature, and the solar radiation required for photovoltaic power generation is affected by time changes and weather. This kind of intermittent and random energy grid connection will have some impact on the stability and security of the power grid [11].

3.2. Solutions for optimizing through the lens of renewable energy uncertainty

In the past studies, some optimization strategies have been recommended to deal with the uncertainty of renewable energy [11].

Monte Carlo simulation (MCS) is a widely used stochastic programming method that is used to analyze and quantify uncertainty. The method assumes the probability distribution function (PDF) of the input parameters and selects the output parameters according to statistical analysis [11]. A study has assumed Weibull and Gamma distributions for the PDFS of wind speed and solar irradiances, while giving a two-stage mathematical programming approach to deal with the uncertainty of the given different scenarios [18].

Robust optimization (RO) is an effective method to solve uncertain problems under the condition of partial information missing [11]. The aim of this method is to find the best solution under the worst condition [11]. Compared with MCS, RO does not require the PDF of input parameters, so it can be calculated more efficiently, so it can be used to analyze power dispatching decision-making problems. For example, in [19], a VPP scheduling model based on price-influenced demand response and incentive-oriented demand response is proposed to analyze the uncertainty of wind and solar power generation by introducing RO theory.

4. Conclusion

This paper mainly introduces multiple strategies to enhance the stability of wind and solar energy grid connection. The first is energy storage, taking into account the environmental impact, introducing and analyzing mechanical energy storage systems such as FESS, PHES and CAES. These energy storage systems are well equipped to cope with fluctuations in demand for wind and solar. Then GFM control technologies were introduced, such as VF control, PSL-based GFM Control and VOC. For VF control, single-loop control makes the power grid have better stability. Compared to PSL-based GFM control, VOC is relatively more efficient in terms of power sharing and synchronization speed. Finally, it introduces the types of uncertainties that need to be considered in VPP, such as the

uncertainty of renewable energy, the uncertainty of market price and the uncertainty of load demand. Aiming at the stability of grid connection of renewable energy, two VPP optimization methods dealing with the uncertainty of renewable energy with examples are given. This paper hopes to consider the possibility of combining these approaches in future VPP studies.

References

[1] Viteri, J. P., Henao, F., Cherni, J., et al. Optimizing the insertion of renewable energy in the off-grid regions of Colombia. Journal of Cleaner Production, 2019, 235: 535 - 548.

[2] Fragkos, P., van Soest, H. L., Schaeffer, R., et al. Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. Energy, 2021, 216: 119385.

[3] Our World in Data. Renewable Energy. Retrieved on September 25, 2024, retrieved from https: //ourworldindata.org/renewable-energy.

[4] Hu, H., Jing, Z., Guo, Q., et al. Evaluation Approach for Wind and Solar Complementarity Considering Output Fluctuation and Intermittency. Modern Electric Power, 2024.

[5] Xu, T., Gao, W., Qian, F., et al. The implementation limitation of variable renewable energies and its impacts on the public power grid. Energy, 2022, 239: 121992.

[6] Ahmed, F., Al Kez, D., McLoone, S., et al. Dynamic grid stability in low carbon power systems with minimum inertia. Renewable Energy, 2023, 210: 486 - 506.

[7] Mahmoud, M., Ramadan, M., Olabi, A. G., et al. A review of mechanical energy storage systems combined with wind and solar applications. Energy Conversion and Management, 2020, 210: 112670.

[8] Zhang, H., Xiang, W., Lin, W., et al. Grid forming converters in renewable energy sources dominated power grid: Control strategy, stability, application, and challenges. Journal of modern power systems and clean energy, 2021, 9: 1239 - 1256.

[9] Alahyari, A., Ehsan, M., Mousavizadeh, M. A hybrid storage-wind virtual power plant (VPP) participation in the electricity markets: A self-scheduling optimization considering price, renewable generation, and electric vehicles uncertainties. Journal of Energy Storage, 2019, 25: 100812.

[10] Li, Q., Wei, F., Zhou, Y., et al. A scheduling framework for VPP considering multiple uncertainties and flexible resources. Energy, 2023, 282: 128385.

[11] Yu, S., Fang, F., Liu, Y. Uncertainties of virtual power plant: Problems and countermeasures. Applied energy, 2019, 239: 454 - 470.

[12] Li, X., Palazzolo, A. A review of flywheel energy storage systems: state of the art and opportunities. Journal of Energy Storage, 2022, 46: 103576.

[13] Javed, M. S., Ma, T., Jurasz, J., et al. Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. Renewable Energy, 2020, 148: 176 - 192.

[14] Koko, S. P., Kusakana, K., Vermaak, H. J. Optimal power dispatch of a grid-interactive micro-hydrokinetic-pumped hydro storage system. Journal of Energy Storage, 2018, 17: 63 - 72.

[15] Ji, W., Zhou, Y., Sun, Y., et al. Thermodynamic analysis of a novel hybrid wind-solar-compressed air energy storage system. Energy Conversion and Management, 2017, 142: 176 - 187.

[16] Rosso, R., Wang, X., Liserre, M. Grid-forming converters: Control approaches, grid-synchronization, and future trends—A review. IEEE Open Journal of Industry Applications, 2021, 2: 93 - 109.

[17] Du, W., Chen, Z., Schneider, K. P., et al. A comparative study of two widely used grid-forming droop controls on microgrid small-signal stability. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019, 8: 963 - 975.

[18] Tajeddini, M. A., Rahimi-Kian, A., Soroudi, A. Risk averse optimal operation of a virtual power plant using two stage stochastic programming. Energy, 2014, 73: 958 - 967.

[19] Ju, L., Tan, Z., Yuan, J., et al. A bi-level stochastic scheduling optimization model for a virtual power plant connected to a wind–photovoltaic–energy storage system considering the uncertainty and demand response. Applied energy, 2016, 171: 184 - 199.