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Overview of wind power intermittency: Impacts, measurements, and mitigation solutions

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HIGHLIGHTS

- The impacts of wind power intermittency on power system are summarized from different aspects.
- The measurements of wind power intermittency are reviewed based on numerous studies.
- New definitions and metrics are proposed to measure intermittency.
- The mitigation solutions for intermittency are concluded from different aspects.
- The further studies about wind power intermittency are discussed.

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ABSTRACT

Environmental issues and the prospect of an energy crisis inspire humans to exploit wind power. However, with the increase of wind power penetration level, operating power systems securely and reliably is a serious challenge due to the inherent nature of wind power intermittency. Wind power intermittency has been the major barrier for large scale wind power integration. This paper reviews past research on wind power intermittency, including its impacts on power system, how it is measured, and mitigation solutions. It has been found that as wind power integration increase, the system reverses and costs consequently increase, while the system reliability and CO_2 reductions decrease. In order to mitigate wind power intermittency, studies on intermittency measurements and mitigation solutions are necessary. Existing measurements of wind power intermittency are summarized firstly. Considering the limitations of existing methods, new definitions and metrics are proposed based on our study. Then, various wind power intermittency mitigation solutions are comprehensively reviewed, including wind farms, generation-side, demand-side and energy storage. In the final part of this paper, the further work on wind power intermittency is discussed in detail. In summary, wind power intermittency can be effectively mitigated using various technological and managerial approaches based on an in-depth understanding of intermittency.

Contents

Abbreviations: AI, annual installed wind capacity; AGC, Automatic Generation Control; ACE, Area Control Error; ACPS1D, Average CPS1 Drop; AC, alternating current; BES, battery energy storage; CI, cumulative installed wind capacity; CDEs, CO_2 emissions; CPS, control performance standards; CHP, combined heat and power; CAES, compressed air energy storage; DFIG, doubly fed induction generator; DSM, demand-side management; DR, demand-side response; DC, direct current; ESSs, energy storage systems; FIT, Feed-In-Tariff; FSIG, fixed speed induction generator; FC, fuel consumption; GPM, gravity power module; HPs, heat pumps; HES, hydrogen energy storage; HTS, high-temperature superconductors; LOLP, loss of load probability; Li-ion, Lithium Ion; MFD, Maximum Frequency Deviation; MACE, Maximum ACE; MCPS1D, Maximum CPS1 Drop; NWP, Numerical Weather Prediction; NiCd, Nickel Cadmium; NaS, Sodium Sulphur; NGCC, natural gas combined-cycle; PDF, probability density functions; PEVs, plug-in electric vehicles; PHS, pumped hydroelectric storage; SMES, superconducting magnetic energy storage; SC, super capacitor; TVA, Tennessee Valley Authority; THD, total harmonic distortion; TES, thermal energy storage; WPD, wind power density; ZnBr, Zinc Bromide.

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1. Introduction

With issues of energy crisis and environmental pollution becoming increasingly serious, the development of renewable energies (e.g. solar energy, wind energy, biomass energy, geothermal energy) has become the primary consensus and key strategy for countries worldwide [1]. Among all the renewable energies, wind power has now firmly established itself as a mainstream option for mankind [2]. There are three main reasons that wind power is utilized worldwide. First, the wind resource is inexhaustible. Statistical data show that the total onshore wind resource is more than 1 trillion kilowatts. Potential electricity from wind is estimated at about 840 petawatt-hours [3]. Second, the environmental benefits of wind power are numerous [4], including remission of air pollution and nearly no water consumption. The greatest environmental benefit of wind power is the reduction of carbon dioxide emissions [5,6]. In 2013, the total existing wind farms contributed to about 372 million tons reduction of annual carbon dioxide emissions [6]. Finally, increasingly mature technologies are lowering the cost of wind energy [4,7,8].

A series of support mechanisms and policies have been implemented to promote the development of wind power. These policies include taxation incentives [9,10], investment subsidies [11], renewable portfolio standards [12–14], fixed premium systems [15,16], and so on [17–20]. Table 1 presents a summary of wind power policies in different countries. Because of the aforementioned advantages and policy support, the global growth of wind power has been surprisingly rapid in past decades. By the end of 2015, the total cumulative global installed capacity reached 432,419 MW as shown in Fig. 1 [21], which is about 25 times of the installed capacity in 2000. It is anticipated that, by the end of 2030, the installed wind capacity will reach 2000 GW, supplying about 16.7–18.8% of the total electricity produced worldwide [6]. Denmark generated 42.1% of its electricity from wind turbines in 2015 [22]. The goal of Denmark government is producing 50% of all electricity from wind by 2050 [23].

Regionally, the development of wind power in China has increased exponentially in the past decades. The total cumulative installed wind capacity reached 91.42 GW at the end of 2013, ranking first in the world [25]. The cumulative installed capacity has increased 115-fold from 2005 to 2015, as depicted in Fig. 2. China generated 5618 TW h of electricity between January and November 2015. Wind generation provides 186 TW h, accounting for 3.3% of total generation (up from 2.8% in 2014) [26,27]. According to the Chinese wind power development roadmap of 2050, the total installed capacity will reach 200 GW, 400 GW and 1 TW by 2020, 2030 and 2050, respectively. Wind power will then provide 17% of the national electricity demand and become a major power source [28].

Despite rapid developments in wind power, wind power integration and consumption are not optimistic. Wind power curtailment is frequently. As shown in Fig. 3, the average utilization hours[1] of wind power is 1728 h in 2015, reaching the lowest point in the past six years. During the same period, the curtailment (The wind turbines are shut off factitiously despite normal wind flow) rate of wind power[2] is 17%. The curtailment rate of wind power is highest in Gansu Province, 8.2 TW h of wind electricity are curtailed. The curtailment rate is 39% [26].

Wind power intermittency is one of the main factors behind wind power curtailment [29–31]. Wind speed, which is intermittent in space and time, is the primary force driving wind turbines. Therefore, electricity generated by wind turbines is generally highly intermittent. In other words, wind power is not always available when needed. Wind power cannot be scheduled and controlled as thermal, nuclear and hydroelectric plants [32]. As a result, large scale wind power penetration will lead to impacts on power system operational security and stability and,

[1] Average utilization hours $= \frac{\text{The total power generation of wind power}}{\text{The installed capacity of wind power}}$

[2] Curtailment rate of wind power $= \frac{\text{Wind power generation curtailment}}{\text{Wind power generation curtailment} + \text{Actual wind power generation}}$