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Local utilization of wind electricity in isolated power systems by employing coordinated control scheme of industrial energy-intensive load

Siyang Liao, Jian Xu*, Yuanzhang Sun, Yi Bao

The School of Electrical Engineering, Wuhan University, Wuhan 430072, China

HIGHLIGHTS

- Coordinated control scheme of energy-intensive load for system frequency regulation.
- Quantitative analysis of energy-intensive load active power regulating range.
- Hardware-in-the-loop testbed is designed to test the control time delay.
- Energy-intensive load automatic control for wind power fluctuation smoothing.

ARTICLE INFO

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ABSTRACT

This paper presents a demand side frequency control scheme in the isolated power system for wind power local utilization. The industrial isolated power system driven by self-owned coal-fired generators and wind farms is both economical and environmentally-friendly. However, the system frequency stability issue is critical due to the lack of power support from the bulk power system. For the isolated power system, the participation of energy-intensive loads in frequency regulation is vital for frequency stability, especially when large scale wind power is integrated in the system. The coordinated control scheme by the saturable reactor and the generator exciter is investigated to realize the energy-intensive load automatic control based on the energy-intensive load model. The coordination of the two control measures significantly enlarges the energy-intensive load regulation range. Energy-intensive load can be regulated to eliminate the power imbalance in the isolated power system together with traditional frequency regulation methods. The hardware-in-the-loop (HIL) testbed is designed to verify the control effect of the proposed coordination method. Time delay of the control method is simulated in this testbed, making the experimental result more practical in the actual power system. Simulations have been carried out in the RTDS-based HIL testbed, verifying that frequency stability of the isolated power system can be maintained by the proposed coordinated control scheme.

1. Introduction

The development of renewable energy such as wind power and solar power has grown rapidly in recent years. According to the Global Wind Report 2016 released by Global Wind Energy Council (GWEC), the global installed capacity of wind power was increased by 54,600 MW in 2016, of which 23,328 MW was in China, accounting for 42.7% of the new-added global installed capacity of wind power in 2016 [1]. As of the end of 2016, China's cumulative wind power installed capacity had reached 128 GW, and the wind power generation had reached 185.1 TWh. The proportion of wind power generation to total power generation also increased from 0.7% in 2010 to 4.0% in 2016. The rapid development of wind power has brought enormous economic and environmental benefits to society and effectively solved the energy shortage problem [2]. However, on the other hand, due to the uncertainty of the output power of wind power, it also poses a serious challenge to the operation and dispatching of the power grid [3,4].

As reported in the “2016 China Wind Power Review and Outlook” released by Chinese Renewable Energy Industries Association, the deserted wind power generation in China amounted to 49.7 TWh annually, accounting for 17.1% of the total wind power generation [5]. It is pointed out in the report that wind power integration capacity is still the bottleneck for China’s wind power industry development. The main reason for the wind curtailment is the lack of peaking generators to deal with the uncertainty of wind power [6]. Most wind power clusters are centrally integrated to the western and northern China which are far

* Corresponding author.
E-mail address: xujian@whu.edu.cn (J. Xu).

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away from load centers in Eastern and Southern China [7]. Moreover, flexible power sources, such as gas turbines and pumped storage power stations, only reach 7.0% and 2.4% of the renewable energy installed capacity in the area installed with large scale wind power [8].

Constructing a long distance power transmission line to transmit the wind power from the energy resource center to the load center is the most direct solution [9,10]. However, the construction cost is high. Additionally, technical issues such as low frequency oscillation and voltage instability may be caused by the long distance power transmission [11,12]. Consequently, Chinese government clearly put forward that energy-intensive loads should be constructed in the energy source center to alleviate the burden of wind power transmission.

There are two modes to locally utilize of wind power by energy-intensive loads. One is in the grid-connecting mode, in which energy-intensive loads are powered by wind farms and the bulk power system. The other is in the isolated operation mode, in which energy-intensive loads are powered by wind farms and self-owned generators. It is much more difficult for the isolated power system to operate stably due to the lack of the power support from the bulk power system [13–15]. However, for some areas that are far from the bulk power system, it costs more to construct the long distance tie-line so the isolated operation mode is more economically feasible. Besides, in China, the bulk power system also charges industry customers the reserve fees when the tie-line is constructed. The reserve fees can also be saved when the isolated operation mode is chosen. Motivated by this, the high energy-consuming loads owner would like to construct the isolated power system driven by the self-generation power plants and wind farms for the production. While this power supply mode results in significant reduction for electricity cost with high efficiency of wind power utilization, the frequency stability of the isolated power system is the most critical issue to be solved [16].

Many researches have discussed the frequency stability and frequency regulation issue of the isolated power system. Building an equivalent model to describe the frequency dynamics of the isolated power system is an effective way to research the frequency stability issue [17–21]. Because of small inertia, frequency deviation may occur in sub-second when power imbalance exists. In Ref. [17], a widely used system frequency response (SFR) model is proposed to describe the system frequency dynamics. The isolated power system is equivalent to a single generator so that the frequency dynamics can be expressed analytically when power disturbance occurs. Based on the SFR model, Ref. [18] proposes a simplified model to calculate the maximum frequency deviation of the isolated power system even when different generation technologies with very different governors are present in the power system. With increasingly more new energy integrated in the isolated power, the system inertia decreases correspondingly, making it more difficult to maintain the system frequency stability [19,20]. Ref. [21] presents a frequency dynamics and stability analytical method of the wind farm integrated power (WFIP) system, and points out that the integration of wind power in isolated power systems leads to increase of dips/peaks in frequency.

Based on the above research, a frequency control method for the isolated power system has also been researched in several existing literatures. In Ref. [22], the under frequency load shedding method is researched based on the SFR model aiming at the frequency stability issue. In Ref. [23], rate of change of frequency (*ROCOF*) is adopted to estimate the magnitude of the disturbance, and an adaptive approach is introduced to under frequency load shedding. However, under frequency load shedding is only effective to the generator tripping or load tripping scenario. For continuous power disturbance caused by wind power fluctuation, this method is not effective.

Equipping with diesel generators or the energy storage system (ESS) has also been researched aiming at the frequency stability of the isolated power system [24–27]. Comparing with under frequency load shedding, the power output of diesel generators or ESS can be regulated continuously to smooth the wind power fluctuation. In Ref. [24], the optimal sizing and operating policy of the energy storage system are presented for small isolated grids. Ref. [25] proposes the control method of the ultra-capacitor for frequency stability enhancement in small-isolated power systems using the index *ROCOF*. Ref. [26] further integrates the superconducting magnetic energy storage with battery to achieve the ability of not only performing a good frequency regulating function but also extending the battery service time. In Ref. [27], an actual isolated power system driven by a wind park and a pumped storage system is introduced. The operation and maintenance cost parameters of the isolated power system are estimated and the the economic sensitivity analysis is performed. However, these methods are only effective when the load capacity and the wind power installed capacity are small [28]. While for the industrial isolated power system with large wind power installed capacity and large load capacity, maintaining the frequency stability entirely depending on diesel generators or ESS is not economical.

This paper presents a new wind power local utilization mode that the industrial isolated power system is driven by wind and coal power for energy-intensive load production. Energy-intensive loads have great potential to consume large scale wind power because its capacity is of tens or hundreds of megawatts class. By constructing an isolated power system, both the high costs of the tie line construction and reserve fees can be saved. Consuming large scale wind power brings both economic and environmental benefits to production. As a consequence, energy-intensive load owners have a strong willing to construct the hybrid coal-wind industrial isolated power system. However, compared to the other kinds of loads, energy-intensive loads require higher reliability for production. Due to its huge load capacity, traditional frequency regulation methods such as the under frequency load shedding or equipping with the ESS may not work in many scenarios.

How to make full use of the regulation potential of energy-intensive loads has also aroused concern from several researchers [29–31]. Since energy-intensive load accounts for the vast majority of loads in the isolated power system, regulating the energy-intensive load active power to participate in frequency regulation is a direct method. Ref. [29] analyzes the regulation potentials of demand-side management in high energy-consuming enterprises in Germany in terms of economy and technical feasibility, and points out that high energy-consuming load can provide peak regulating capacity for the grid. Ref. [30] studies the application feasibility of demand-side management in the Indian electrolysis industry, and proposes a dispatching method for electrolytic energy-intensive load considering the time-of-use pricing. In Ref. [31], model of energy-intensive load is built to participate in power system scheduling to gain a win–win situation. However, these researches mainly focused on the peak load management in the balancing markets in the longer time scale, which is not suitable for the frequency stability issue in the isolated power system. An aluminum load control method by regulating the saturable reactor is proposed in Ref. [32] so that the aluminum load can participate in frequency regulation when needed. However, the active power regulation capacity of this method is limited because there is a regulation limitation of the saturable reactor. Based on the voltage dependency characteristic of the aluminum load, the system voltage will be regulated by the generator excitor when conventional system frequency regulation capacity is not enough [33]. Based on this, a time-varying load-damping control method is proposed in Ref. [34] to decrease frequency deviation in the transient process. However, when large power disturbance occurs, the system voltage has to be regulated significantly to eliminate power imbalance. Both the voltage quality issue and the voltage stability index are affected under this condition.

Additionally, time delay is another key issue in the isolated power system frequency control. Due to small inertia, the frequency transient process of the isolated power system is at sub-second level [35,36]. In the previous research, time delay is usually set as a constant. The dardware-in-the-loop testbed is a proper way to verify the effectiveness of the control scheme with the full consideration of the time delay in