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Voltage Control Strategy for Large-Scale Wind Farm with Rapid Wind Speed Fluctuation

Xi Cai [1], Zhangbin Yang [1], Pan Liu [1], Xueguang Lian [1], Zhuang Li [2], Guorong Zhu [2,*] and Hua Geng [3]

[1] China Three Gorges Construction Engineering Corporation, Chengdu 610095, China; cai_xi@ctg.com.cn (X.C.); yang_zhangbin@ctg.com.cn (Z.Y.); liu_pan5@ctg.com.cn (P.L.); lian_xueguang@ctg.com.cn (X.L.)
[2] School of Automation, Wuhan University of Technology, Wuhan 430070, China; 334881@whut.edu.cn
[3] Department of Automation, Tsinghua University, Beijing 100084, China; genghua@tsinghua.edu.cn
* Correspondence: zhgr_55@whut.edu.cn

Abstract: In large-scale wind farms, the voltage fluctuations caused by the uncertainty of wind speed at the turbine terminals pose a pressing challenge. This article presents a localized voltage control strategy tailored toward rapid adjustments in turbine terminal voltage in wind turbine generators. Based on relative voltage observation, this strategy achieves voltage coordination between the high and low ends of the transformer in wind turbine generators. Firstly, the overall structure of the wind farm and the characteristics of terminal voltage are analyzed. Secondly, the principles and feasibility of the relative voltage control strategy are examined. Finally, the effectiveness of the proposed control strategy is validated through simulation results from a specific wind farm. The results demonstrate its capability to achieve a fast and stable voltage dynamic response within the wind farm based on local information, thus mitigating the risk of voltage out of limit.

Keywords: wind farm; local reactive power regulation; voltage stability; local voltage observation

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1. Introduction

Against the backdrop of global efforts to achieve peak carbon emissions and carbon neutrality, wind power, as a low-carbon and clean energy technology, has been receiving policy support and market favor, leading to a steady expansion in installed capacity and operational scale [1]. However, inherent characteristics of wind power generation, particularly the volatility and unpredictability of wind speeds, present challenges to the management of voltage stability in wind turbine generators. Fluctuations in wind speeds directly cause fluctuations in turbine terminal voltage, and inherent impedance in the distribution system can also lead to voltage variations, especially for remote wind turbine generators, posing risks of voltage out of limit [2]. To maintain the stability of wind turbine generators and the entire power system, precise control of turbine terminal voltage is crucial. This importance is further highlighted in situations of rapid wind speed changes [3]. Real-time monitoring and dynamic adjustment technologies, such as advanced reactive power control strategies, voltage regulation devices, and intelligent management systems, must be employed to achieve stable control of turbine terminal voltage. This approach not only ensures the reliable operation of wind turbine generators but also enhances the overall efficiency and safety of the power grid. This method contributes to the achievement of carbon neutrality goals [4].

Currently, the prevailing solutions for voltage control in large-scale wind farms rely on centralized control architectures, which optimize overall operational efficiency. However, these architectures face challenges such as high computational loads and communication pressures, particularly in rapidly changing wind speeds where quick adaptation becomes difficult. Reference [5] proposed a reactive power and voltage coordinated control method based on deep reinforcement learning. By establishing the optimal reactive power flow model and training it with a reinforcement learning algorithm, the voltage stability can be effectively improved, and the model solving performance is better. However, the paper does not mention the computational complexity problems that may exist in the practical application of this method, and the computational efficiency in large-scale wind farms needs to be further verified. In reference [6], major innovations in the strategy proposed in this paper compared to existing research include hierarchical control of coordinated capacitors/inductors and DFIGs, avoidance of wind curlews, and droop control based on local voltage measurement for fast response. This paper does not fully consider the influence of the wind farm internal network on control strategies, which may need further study.

In [7], a coordinated reactive power and voltage control strategy based on the tabu search algorithm is proposed to solve the problem that the spatial dimension of the optimal solution of multiple turbines in wind farms is too high and it is difficult to accurately control the reactive power output of single turbines. However, this strategy does not fully consider the practical factors such as communication delay and control error in actual engineering, so it needs to be tested and verified in actual wind farms. In references [8–10], a coordinated reactive power control method based on voltage sensitivity for on-line voltage safety enhancement is proposed. The influence of the control method on the system stability is not discussed, which is one of the important indexes to evaluate the control method.

Decentralized control, or distributed control, can alleviate the computational burden on the central controller but imposes higher requirements on the stability of local communication and may introduce data transmission delays. Therefore, in the case of rapid wind speed fluctuations, it is necessary to utilize the local information of wind turbine units for fast voltage control. A distributed control strategy is proposed in [11], designating some wind turbines as leaders, receiving the voltage information of common coupling points, calculating the required reactive power, and realizing coordinated operation among all wind turbines through a diffusion algorithm, thus realizing reactive power coordination and voltage regulation of common coupling points. However, there is a lack of coping mechanisms for communication network failures. This paper does not discuss how to ensure the reliable operation of the control system when the communication network fails. Based on the multi-time-scale characteristics of reactive power control devices in wind farms, a hierarchical reactive power optimization control strategy is proposed in [12]. Compared with the traditional voltage/reactive power control strategy, this strategy coordinates different control phases over multiple time frames. While the article mentions the ability of the intraday optimization control phase to adjust reactive power output based on real-time monitoring data, it does not discuss in detail how to acquire and process these data quickly and accurately. Reference [13] presents a distributed optimal voltage control (DOVC) scheme based on the analytic target cascade (ATC) method for large-scale VSC-HVDC connected wind farm clusters. But this paper does not consider the influence of communication constraints on distributed control. In practice, communication constraints will affect the control effect, which needs to be considered. References [14–16] propose a modeling method for multiple wind farms based on an improved Gaussian mixture model. They further present a two-layer probabilistic reactive power optimization algorithm to develop a voltage control strategy for integrating multiple wind farms into the power system. Although the Nataf transformation algorithm based on estimation proposed in these papers simplifies the calculation process, its accuracy may be insufficient compared with the accurate integral algorithm. In references [17–19], a robust optimization-based hierarchical voltage control strategy for wind farms is introduced to enhance voltage control effectiveness. The calculation of the robust optimization model is large, and the calculation efficiency needs to be improved to meet the needs of practical applications. Moreover, the reliability of communication in wind farms is not considered in these papers, and communication failures may lead to control failures in practical applications. This strategy addresses the challenges of uncertainty in active power output within wind farms and the differences in response time among reactive power regulation devices, which can hinder effective voltage control in the system.

In summary, this paper proposes a fast local voltage control approach for wind turbine units in wind farms, considering the rapid fluctuations in wind speeds. First, taking a direct-drive permanent magnet synchronous generator (PMSG) as an example, this paper introduces the decentralized control structure of a wind farm and its turbine terminal voltage characteristics. Secondly, a relative voltage control strategy is proposed within the decentralized framework. This strategy improves the voltage distribution along the feeder lines within the wind farm. This paper presents a reactive power compensation method based on local relative voltage error observation. Based on the known structure and parameters of the power grid, a method of local relative voltage error observation is presented in this paper. This method makes use of the voltage transfer characteristic, so that each compensation node can track the voltage amplitude of the previous node, to realize the voltage regulation without centralized reactive power command. This method improves the dynamic performance of voltage regulation in wind farms and realizes local reactive power compensation without remote communication. Finally, a simulation model is built in MATLAB/Simulink 2023a to validate the feasibility and effectiveness of the proposed control approach.

2. Wind Farm Topology and Terminal Voltage Characteristics

2.1. Overall Wind Farm Topology

There are various types of wind farm structures, including ring topology, tree topology, mesh topology, and radial topology, among which radial wind farm topology is the most common. As shown in Figure 1, this topology offers simple wiring, high operational reliability, and convenient monitoring and maintenance.

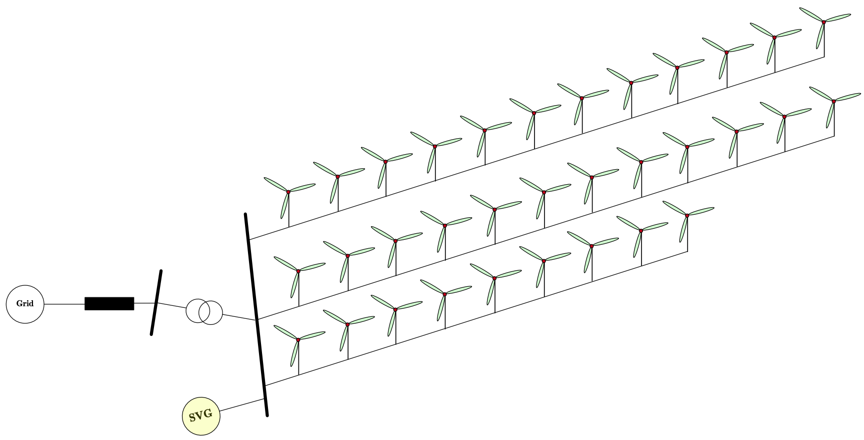


Figure 1. Topology of an actual radial wind farm.

This wind power generation facility utilizes permanent magnet direct-drive synchronous generators, with a rated voltage of 690 volts for each generator unit. All units are connected to the 35 kV feeder lines through matching box-type transformers. The generated power from the units is then centrally collected via this distribution system and converged at the grid connection point of the wind farm. At this point of connection, the electrical energy is transmitted to the regional power grid through the wind farm's main transformer. To ensure effective integration with the grid, meet the voltage requirements at the grid connection point, and accommodate the operational control needs of the power grid, the wind farm's grid connection point is equipped with high-capacity centralized reactive power compensation devices.

The Static Var Generator (SVG) for reactive power compensation at the wind farm's grid connection point is primarily used to meet the requirements of voltage stability and power quality in the electrical system. The output power of wind farms is influenced by natural factors such as wind speed, leading to volatility and uncertainty. This can result in fluctuations in the reactive power demand within the grid. SVGs are capable of quickly and accurately controlling the output of reactive power, thus maintaining voltage stability in the grid. SVGs have a rapid response capability, allowing them to switch from absorbing to providing reactive power within milliseconds, which is crucial for dealing with sudden events in the grid (such as load surges, faults, etc.). In summary, the use of SVGs for reactive power compensation at wind farm grid connection points is to ensure the stable, efficient, and reliable operation of the grid while improving power quality and economic benefits [20–26].

The traditional centralized control remains the mainstream control method adopted by wind farms today. In this approach, the controller at the wind farm's central station receives the status information from each turbine, processes and calculates this information, and then distributes the calculated power reference values to individual turbines based on certain principles. However, the computation at the central station in a centralized control system is relatively complex and time-consuming, making it unable to meet the requirements of fast control over turbine terminal voltage. Additionally, the establishment of long-distance communication between the central station controller and the turbines comes with high costs. With the expansion of wind farms, the computational and communication reliability requirements for the central station controller also increase in a centralized control architecture. Relying solely on the central controller to send instructions cannot meet the demands of fast control of turbine terminal voltage.

In contrast to the traditional centralized control in wind power systems, in distributed control, the controllers of each turbine collect data information such as power and voltage from their own units. Then, they independently calculate the power reference values for their respective units and update the status information.

2.2. Voltage Characteristics between Wind Turbines in a Wind Farm

In Equation (1), P is the active power, Q is the reactive power, R is the box variable resistance, and X is the box variable reactance. The amplitude and phase angle of nodes A and B are represented as $U_a\angle\theta_a$ and $U_b\angle\theta_b$. The feasibility and accuracy of the proposed method rely on the parameters of the cable lines and the detected voltage and current. After the construction of a wind farm, the data for the short-circuit ratio, no-load current, and load losses for the transformers in the field, as well as the lengths and positions of all cables and transformers, are fixed. Therefore, under normal operating conditions, the parameters are known.

$$U_a\angle\theta_a = (U_b + \frac{P\cdot R + Q\cdot X}{U_b} + j\frac{P\cdot X - Q\cdot R}{U_b})\cdot\angle\theta_b \quad (1)$$

3. Relative Voltage Control Strategy

Relative voltage control is a locally based strategy for rapid control of generator terminal voltage, capable of quickly damping voltage fluctuations caused by rapid changes in wind speed, without the need for instructions from a centralized controller. As shown in Figure 2, the wind turbine is connected to the feeder line through a transformer substation, with Side A as the low-voltage side and Side B as the high-voltage side. From an energy flow perspective, since Side A is the energy-emitting end and flows through the transformer to the high-voltage Side B, it is evident that the potential at Side A is higher that at than Side B. As analyzed earlier, the internal parameters of the transformer substation and the line parameters are known. Therefore, if the voltage at Side A is measured, the voltage at Side B can be calculated. The calculated voltage can then be used as a reference to control the amplitude of the voltage at Side A, ensuring that the voltage magnitudes at both Side A and Side B are the same. This effectively reduces the generator terminal voltage, thus mitigating the risk of the voltage exceeding limits. Furthermore, since the control conditions are determined based on local information through calculations, there is no need for control instructions from a centralized controller.

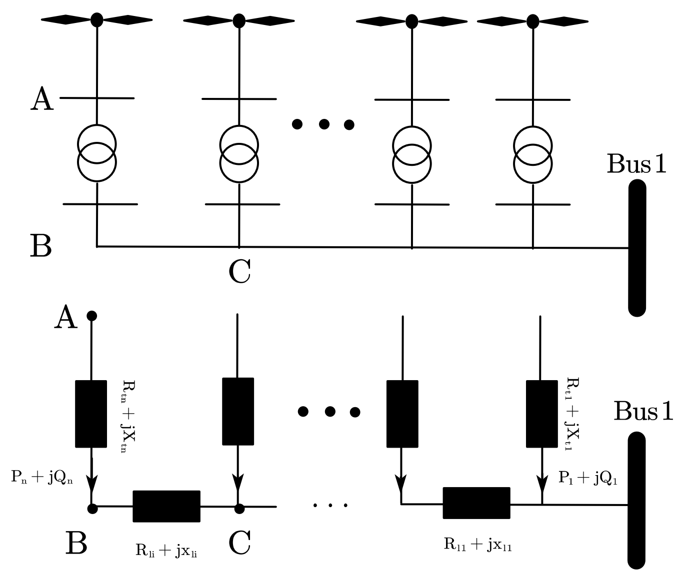


Figure 2. Equivalent model of wind turbines under a certain feeder in a wind farm.

3.1. Relative Voltage Control Target

The control objectives include the voltage at the point of common coupling (PCC) and the voltage at the wind generator terminal. The PCC voltage is influenced by wind power variations and grid voltage disturbances. As the reference voltage for the wind farm, the stability of the PCC voltage is crucial. Additionally, since the wind power needs to be injected into the grid through a series of transformers and feeder lines, the variations in wind power may alter the voltage distribution characteristics along the transmission path, leading to fluctuations in the generator terminal voltage. Maintaining the stability of the terminal voltage ensures that the generator remains connected to the grid. The equivalent model of the wind turbine generator is illustrated in Figure 3.

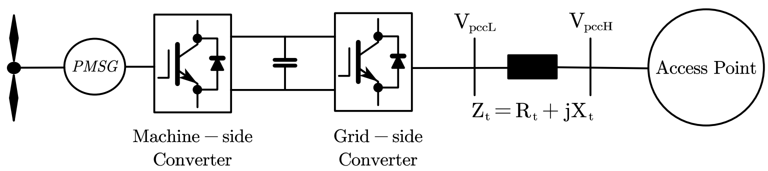


Figure 3. Wind turbine equivalent model and voltage characteristics.

Because wind turbines feed wind power into the grid through a series of transformers and feeders, changes in wind power can alter the voltage distribution along the transmission line, which can affect the stability of the generator terminal voltage. To ensure that the wind turbine does not disconnect from the grid, it is necessary to ensure the stability of the terminal voltage. Therefore, the terminal voltage stability constraint can be expressed as

$$U_{mref} - U_{merr} \leq U_m \leq U_{mref} + U_{merr} \tag{2}$$

where U_m is the generator terminal voltage, U_{mref} is the reference voltage, and U_{merr} is the error value. The rated capacity of the reactive power compensator determines whether the desired voltage level can be maintained. Given that the capacity of the grid is typically much larger than that of the wind farm, when the compensation capacity of the reactive power compensator is insufficient to meet the demand, voltage fluctuations caused by the grid cannot be fully compensated by the wind farm. In such cases, the voltage loop operates in saturation mode, resulting in uncontrollable voltage stability issues at various nodes within the wind farm and exacerbating the instability of voltage fluctuations. Therefore, a relative voltage control method based on local information for reactive power regulation has been proposed.

Considering the rapid fluctuations in wind speed that can cause voltage fluctuations at the generator terminal, it is possible for the voltage at the wind turbine generator terminal to exceed its limits. By monitoring the voltage and utilizing the remaining capacity of the grid-side converter of the wind turbine generator, reactive power can be absorbed from the grid to achieve a nearly uniform voltage level at both ends of the transformer substation, thereby reducing the risk of voltage exceeding limits.

3.2. Relative Voltage Observation Method

The relative voltage refers to the voltage value at the preceding node of the adjacent nodes in the feeder line within the wind farm. It can be derived from the voltage transfer function in Equation (1), using the voltage value at the preceding node and the parameters of the feeder line. This value serves as the reference voltage for the generator terminal voltage node:

$$U_{pccH} = \sqrt{(U_{pccL} - \frac{P_{pccL} \cdot R + Q_{pccL} \cdot X}{U_{pccL}})^2 + (\frac{P_{pccL} \cdot X - Q_{pccL} \cdot R}{U_{pccL}})^2} \quad (3)$$

Since the parameters of a wind farm remain relatively constant after construction, the information required to generate the reference voltage is locally observable. Theoretically, based on this reactive power compensation method, the voltages of all nodes, compensating devices, and generators within the wind farm can be maintained at the same level. Additionally, this strategy eliminates the need for remote communication and complex scheduling, relying solely on local observations to achieve fast and coordinated voltage control. By setting the reference voltage as the observed voltage at the preceding node, even if the voltage at the point of common coupling (PCC) deviates from the rated value, the voltages of all critical nodes within the wind farm will be controlled to the same value. This relative voltage control strategy ensures that the compensator does not exceed its reactive power capacity during the regulation process and allows the PCC voltage to be adjusted back to the rated value through other control methods.

4. Simulation

Taking a specific wind farm as an example, this paper validates the feasibility and effectiveness of the proposed relative voltage control. As shown in Figure 1, the wind farm consists of three feeder lines and 33 wind turbine generators, each with a rated power of 1.5 MW. Feeder lines A and B have 12 wind turbine generators each, while feeder line C has 9 wind turbine generators. The specific parameters are detailed in Table 1. The remaining parameters of the wind turbine generators can be found in reference [27].

Table 1. Wind farm model parameters.

Parameter	Value
Wind farm base capacity/MW	49.5
Feeder reference voltage/kV	33
PMSG rated capacity/MW	1.5
Rated frequency/Hz	50
Rated wind speed/(m/s)	12

4.1. Internal Operating Conditions of a Wind Power Plant under Simulated Wind Speeds

The wind speed in a particular wind farm is depicted in Figure 4. Considering the rapid fluctuations in wind speed that can cause voltage fluctuations at the generator terminals of wind turbine units, there is a risk of voltage out of limit. This paper proposes the use of relative voltage control for local control of wind turbine units to mitigate the risk. In Figure 5a, the distribution of generator terminal voltages for a specific wind turbine on each feeder line at the point of common coupling (PCC) is shown without the implementation of relative voltage control. From the distribution of generator terminal voltages on each feeder line, it can be observed that the generator terminal voltages of wind turbine units increase with the distance from the point of common coupling due to the impedance of the transmission lines on the feeder lines.

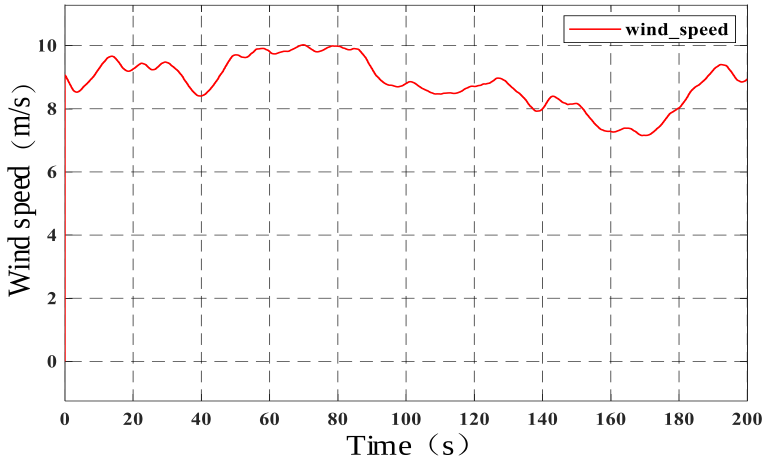
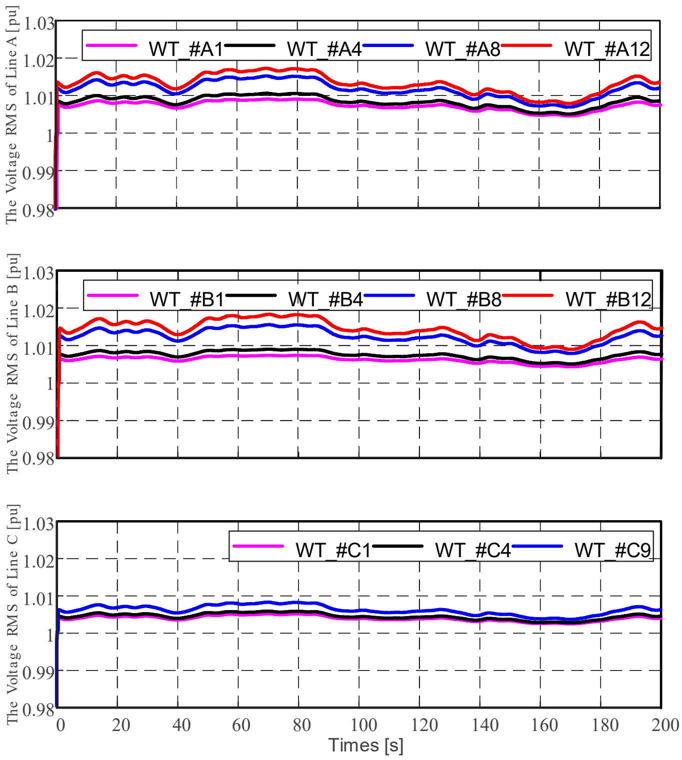
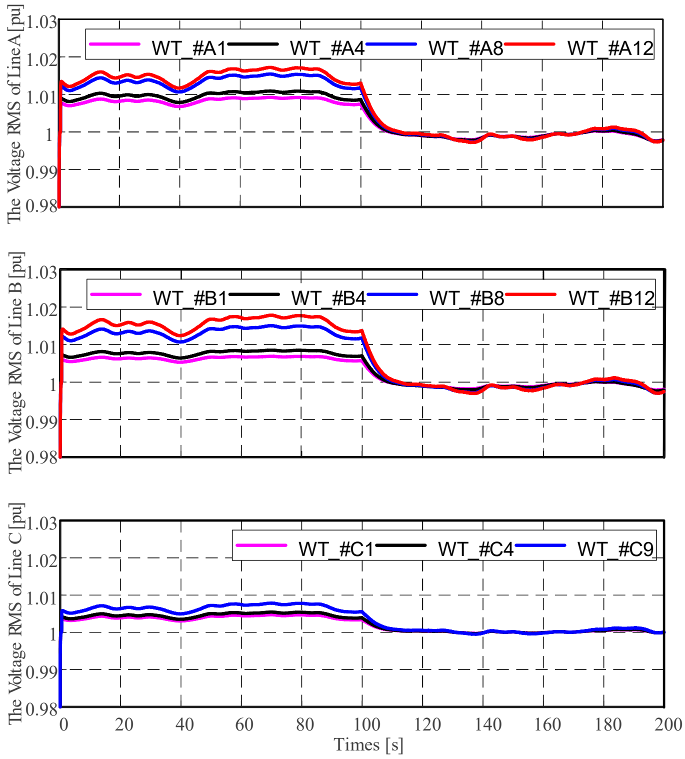


Figure 4. The wind speed acting on a certain wind turbine inside the wind farm.



(a)

Figure 5. *Cont.*



(**b**)

Figure 5. Terminal voltage of wind turbines at each feeder in the wind farm: (**a**) Voltage values on each feeder without relative voltage control; (**b**) voltage values on each feeder after relative voltage control.

4.2. Application of Relative Voltage Control Strategy

The simulation results of this control strategy are presented in Figure 5b. It can be observed that after 200 s, the implementation of the relative voltage control strategy leads to a decrease in the generator terminal voltages of each feeder line to around 1 p.u., achieving a rapid suppression of voltage fluctuations. Therefore, reactive power compensation under relative voltage control is proven to be effective.

In traditional reactive power compensation strategies, the absolute value of the voltage at the point of common coupling (PCC) is used as the reference. Under this control mode, if the wind farm only needs to meet the voltage requirements at the PCC, the absolute value control will only compensate for the voltage drop caused by the active fluctuations of the wind turbine generators and will not actively support the reactive power consumption of the grid. However, with the application of relative voltage control, slight voltage fluctuations can occur in wind turbines, which align with the voltage fluctuations of the grid under normal operating conditions.

To achieve global voltage control in the wind farm, this system incorporates a parallel SVG reactive power compensation device at the PCC. A comparison in Figure 6 reveals that the energy source for voltage regulation in relative voltage control is provided by the reactive power compensation device, and it does not affect the energy flow at the point of grid connection. The wind turbine needs to adjust the voltage, so it needs to absorb energy. In order to avoid affecting the voltage balance of the grid, the energy required for relative voltage control is provided by an SVG, as shown in the figure. Due to the delay in control signals, conventional control methods result in significant voltage fluctuations at the PCC. By leveraging local reactive power compensation based on relative voltage observation, wind farms can achieve global control without centralized dispatch. This method demonstrates strong advantages in terms of faster compensation and more stable voltage regulation.

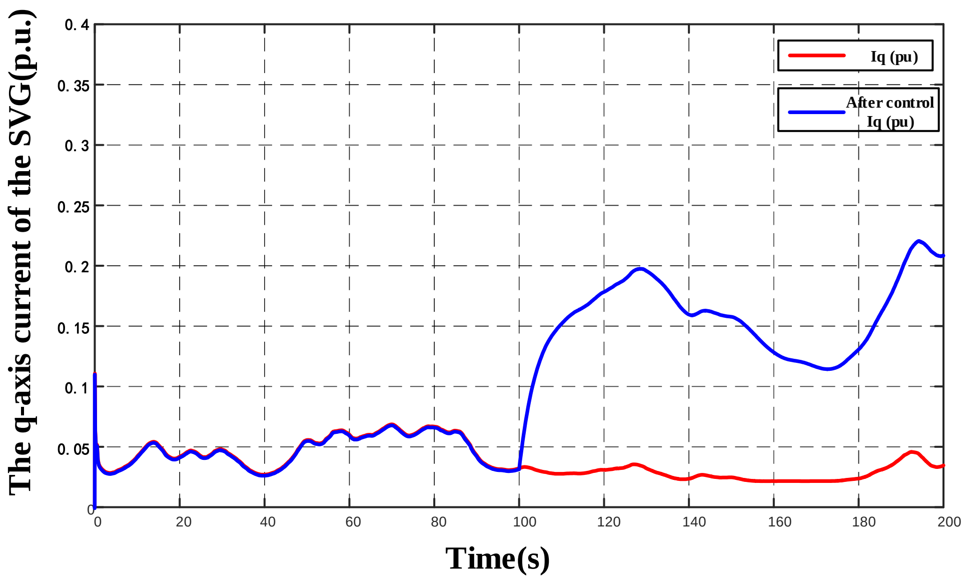


Figure 6. Comparison of the power generated by the reactive power compensation device before and after the relative voltage control.

5. Conclusions

The voltage dynamic response and stability issues in wind farms are gradually becoming important in the field of renewable energy generation. This paper proposes a voltage relative control method based on local reactive power compensation. Currently, there are significant challenges in the upper-level data processing and transmission delay for reactive power compensation in wind farms. This method addresses the situation where the total power capacity of the wind farm is much smaller than that of the grid, and it compensates only for the local voltage fluctuations caused by the active power fluctuations of the wind turbine units. Since the network parameters are known, local voltage and current information can be observed locally through calculations. Therefore, the proposed strategy can achieve global voltage control and reactive power allocation without the need for an upper-level computing center and can provide faster and more stable dynamic responses without the need for long-distance interconnection. Finally, the effectiveness of the proposed voltage coordination control is validated through simulation examples conducted in a real wind farm. As shown in Figure 5, significant improvements in voltage fluctuation are observed after implementing relative voltage control, with the compensating voltage magnitude being around 0.01 p.u. If the reference voltage on the high-voltage side of the transformer is 35 kV, the risk of voltage exceedance within the wind farm is significantly mitigated. This enhances the dynamic performance of internal voltage regulation in wind farms and achieves local voltage regulation without the need for remote communication. From the point of view of the reactive power emitted by SVG as shown in Figure 6, the increase of about 0.2 means that the reactive power required by a wind farm representing 33 fans is relatively large. In future work, further research can be conducted on how to quickly provide the energy required by SVGs.

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References

1. Global Wind Energy Council. Global Wind Report 2022 14 March 2023. In *Linear Networks and Systems*; Chen, W.-K., Ed.; Wadsworth: Belmont, CA, USA, 1993; pp. 123–135.
2. Bebars, A.D.; Eladl, A.A.; Abdulsalam, G.M.; Badran, E.A. Internal electrical fault detection techniques in DFIG-based wind turbines: A review. *Prot. Control. Mod. Power Syst.* **2022**, *7*, 18. [CrossRef]
3. Wigner, E.P. Theory of traveling-wave optical laser. *Phys. Rev.* **1965**, *134*, A635–A646.
4. Gao, H.; Wang, J.; Liu, Y.; Wang, L.; Liu, J. An improved ADMM-based distributed optimal operation model of AC/DC hybrid distribution network considering wind power uncertainties. *IEEE Syst. J.* **2020**, *15*, 2201–2211. [CrossRef]
5. Wang, H.; Wang, L. Research on Voltage Coordination Control Strategy of Wind Farm Based on Hierarchical MPC. *Electr. Drive* **2022**, *52*, 9. [CrossRef]
6. Tan, H.; Li, H.; Xie, X.; Yang, T.; Zheng, J.; Yang, W. Reactive-voltage coordinated control of offshore wind farm based on deep reinforcement learning. In Proceedings of the 2021 3rd Asia Energy and Electrical Engineering Symposium (AEEES), Chengdu, China, 26–29 March 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 407–412.
7. Yang, S.; Wang, W.; Liu, C.; Huang, Y. Coordinative Strategy for Reactive Power and Voltage Control of Wind Farms Cluster Considering Wind Power Fluctuation. *Proc. CSEE* **2014**, *34*, 4761–4769. [CrossRef]
8. Li, S.; Zhou, N.; Xing, L.; Zhang, Z.; Zhang, Z.; Fang, Q. Hierarchical Voltage Control of a Wind Farm Based on Droop Control. In Proceedings of the 2020 5th Asia Conference on Power and Electrical Engineering (ACPEE), Chengdu, China, 4–7 June 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 432–436.
9. Ren, X.; Wang, H.; Wang, Z.; Wang, Q.; Li, B.; Wu, H.; Yang, J.; Wang, W. Reactive voltage control of wind farm based on tabu algorithm. *Front. Energy Res.* **2022**, *10*, 902623. [CrossRef]
10. Liu, J.H.; Cheng, J.S. Online voltage security enhancement using voltage sensitivity-based coherent reactive power control in multi-area wind power generation systems. *IEEE Trans. Power Syst.* **2021**, *36*, 2729–2732. [CrossRef]
11. Chattopadhyay, D.; Bhattacharya, K.; Parikh, J. Optimal reactive power planning and its spot-pricing: An integrated approach. *IEEE Trans. Power Syst.* **1995**, *10*, 2014–2020. [CrossRef]
12. Su, H.-Y.; Hong, H.-H. A stochastic multi-objective approach to pilot bus selection for secondary voltage regulation. *IEEE Trans. Power Syst.* **2020**, *35*, 3262–3265. [CrossRef]
13. Nguyen, T.T.; Kim, H.M. Leader-following diffusion-based reactive power coordination and voltage control of offshore wind farm. *IEEE Access* **2020**, *8*, 149555–149568. [CrossRef]
14. Wang, M.; Liao, K.; Yang, J. Hierarchical Voltage/Var Optimization Control of a Wind Farm. In Proceedings of the 2021 IEEE 16th Conference on Industrial Electronics and Applications (ICIEA), Chengdu, China, 1–4 August 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 195–200.
15. Huang, S.; Wu, Q.; Zhao, J.; Liao, W. Distributed optimal voltage control for VSC-HVDC connected large-scale wind farm cluster based on analytical target cascading method. *IEEE Trans. Sustain. Energy* **2019**, *11*, 2152–2161. [CrossRef]
16. Xu, Y.; Korkali, M.; Mili, L.; Chen, X.; Min, L. Risk assessment of rare events in probabilistic power flow via hybrid multi-surrogate method. *IEEE Trans. Smart Grid* **2019**, *11*, 1593–1603. [CrossRef]
17. Tamraz, M. Mixture copulas and insurance applications. *Ann. Actuar. Sci.* **2018**, *12*, 391–411. [CrossRef]
18. Xu, Y.D.; Yuan, Y. Analysis of aggregated wind power dependence based on optimal vine copula. In Proceedings of the 2019 IEEE Innovative Smart Grid Technologies-Asia, Chengdu, China, 21–24 May 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1788–1792.
19. Asadollah, S.; Zhu, R.W.; Liserre, M. Analysis of voltage control strategies for wind farms. *IEEE Trans. Sustain. Energy* **2020**, *11*, 1002–1012. [CrossRef]
20. Shen, Y.; Liang, L.; Zhang, B.; Liu, Y.; Li, Y. Hierarchical Control Strategy for Wind Farm Based on Improved Sensitivity Algorithm. *Proc. CSU-EPSA* **2020**, *32*, 28–33+41. [CrossRef]
21. Karthikeya, B.R.; Schütt, R.J. Overview of wind park control strategies. *IEEE Trans. Sustain. Energy* **2014**, *5*, 416–422. [CrossRef]
22. Li, L.; Yang, C.; Xu, H.; Yan, Q.; Zhou, S.; Yang, H. Coordinated Voltage Control for Offshore Wind Farm Equipped with SVG and Energy Storage. In Proceedings of the 2022 12th International Conference on Power and Energy Systems (ICPES), Guangzhou, China, 23–25 December 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 800–804.
23. Wei, Z.; Runqing, B.; Yong, Z.; Chen, L. Research on application of SVG for reactive power control in wind farm. In Proceedings of the 2012 Power Engineering and Automation Conference, Wuhan, China, 18–20 September 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 1–3.
24. Zhang, Y.; Xie, X.; Song, P.; Liu, H.; He, T. Suppression methods for low frequency oscillation of wind farm considering SVG minimum output dead zone. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Xiamen, China, 3–5 September 2018; IOP Publishing: Bristol, UK, 2018; Volume 192, p. 012043.
25. Zhou, Z.; Mastoi, M.S.; Wang, D.; Haris, M. Control strategy of DFIG and SVG cooperating to regulate grid voltage of wind power integration point. *Electr. Power Syst. Res.* **2023**, *214*, 108862. [CrossRef]

26. Chen, J.; Chang, Q.; Hao, X.; Li, P.; Li, H. Analysis of medium-frequency oscillation based on bifurcation theory and joint modelling of SVG and direct-drive wind turbine. *Int. J. Electr. Power Energy Syst.* **2024**, *155*, 109660. [CrossRef]
27. Zhao, Y.; Chai, J.; Sun, X. Relative Voltage Control of the Wind Farms Based on the Local Reactive Power Regulation. *Energies* **2017**, *10*, 281. [CrossRef]