International Journal of Control and Automation
Vol.7, No.2 (2014), pp.85-98
http://dx.doi.org/10.14257/ijca.2014.7.2.09

Centralized Reactive Power Control for a Wind Farm under Impact of Communication Delay

Zhuo Chen[1], Zhenghang Hao [2] and Shuijie Qin [3]

[1]*Department of Mechanical Engineering, Guizhou University, Guiyang, 550025, China*
[2] *State Grid XJ Group Corporation, Xuchang, 461000, China,*
[3] *The key Laboratory for Photoelectric Technology and Application, Guizhou University, Guiyang, 550025, China*

ee.chenz@gzu.edu.cn, haozhenghang@163.com, shuijie.qin@gmail.com

Abstract

Generally, a wind turbine may have inferior reactive power dynamic performance where constant power control is adopted by a wind farm equipped with doubly fed induction generators (DFIGs). As a result, power system disturbance may incur grid faults where the wind farm cannot provide enough reactive power to the grid. This paper proposes a novel reactive power control strategy with centralized management for a wind farm. The real-time signal representing the voltage at a specified remote location -- a point of common coupling (PCC), is taken into account as an increment of the given value of the reactive power before being transmitted into each wind turbine by the distributed communication networks. In order to implement real-time regulation with reactive power output to the entire wind farm, this signal is meanwhile fed into the control loop in the rotor-side converter. Considering the issue of widely geographical distribution for each individual wind turbine, this paper studies the impact of communication delay on the system performance. As simulation results showing, in both of the cases of grid faults and wind speed fluctuation, the system with this control strategy can provide reactive power complement and keep the bus voltage stable. By using frequency domain analysis, this research also explores that different delay time may result in control failure due to multi-frequency harmonic incurred in the cases of long-term delay.

Keywords: *DFIG, wind farm, reactive power control, delay*

1. Introduction

Wind power has become one of the most important and promising sources of renewable energy that can partially solve the energy crisis and environmental dilemma we are confronting today. With the rapid development of manufacturing technology and power electronic technology, the trend has been moved from installations with a few wind turbines to the equipments of large wind farms with more than hundreds of MW of capacity. In China, the penetration of wind power into electricity networks is increasing and many large wind farms mainly employ doubly-fed induction generator (DFIG). However, a critical issue was observed. When the power grid is subjected to serious disturbance, wind turbine generators

ISSN: 2005-4297 IJCA

(WTGs) in the wind farm are not able to regulate reactive power dynamically because WTG is usually controlled to operate in the condition of constant power factor. Thus, the situation may result in the residual voltage is so low that the cascading trip-off of WTGs failures occur, which directly impacts on the wind farm normal operation and threatens the grid safety. Therefore, studying how the wind farm participates in the grid voltage regulation and how to take full advantage of the ability of reactive power regulation of wind turbines are the effective ways to suppress voltage fluctuation, and to maintain voltage stability of the point of common coupling (PCC) and to insure safe running of electrical power system.

Reactive power control has been proposed by many researchers as the main control approach to excavate the ability of reactive power regulation of WTGs. The transient reactive voltage control model for the wind farm has been simplified as single-generator-to-load model and was studied principally, confirming that fault ride-through capability can be significantly improved by transient reactive voltage control [1]. The novel control strategies of grid-side convertor have been proposed in the two studies [2-3] to achieve reactive compensation during grid fault. Crowbar control strategy has been considered in the reactive power control to improve both fault adaptability and ride-through capability [4-7]. The control scheme of optimal tracking secondary voltage in the wind farm has been raised to control the voltage of regional pilot nodes [8]. When the wind farm was connected to strong grid, some of the issues, including loss of reactive power absorbed by the grid and the limitation of active and reactive power output capability, were emerged. Aims at the issues, the control strategies have been presented to compensate reactive power for the nearest node in the grid [9]-[10].The published literature [11] have emphasized the importance of the coordination control between voltage and reactive power. Meanwhile, the coordination controller for a DFIG-based wind farm has been designed [12-13]. The coordination controller was able to adjust the voltage and reactive power of PCC continuously and realize the maximum saving for compensation equipments investment. Moreover, combining the coordination voltage control scheme with the method of mounting hardware circuits (capacitors, SVCs etc.) could still achieve good results [14]. For improving the voltage stability of the grid and the wind farm, the scheme which decreases the negative sequence voltage via injecting negative-sequence current into the grid has been proved effective [15].

These studies show that, adjusting the control strategy reasonably for WTGs is able to effectively improve capability of reactive power. However, previous studies haven’t mentioned how to resolve the distributed control of remote signals. Meanwhile, none of these studies have considered how to solve the delay problem caused by remote control and the problem of control reactive power for WTGs connected with the weak grid.

The novel contributions made in this study can be summarized as follows: A centralized reactive power control scheme is proposed for the DFIG-based wind farm, which enable each wind power generator to change transient reactive power contribution and to mitigate voltage fluctuation of PCC during transient grid faults and variable wind condition. Moreover, delay issue is an important issue faced by design of the controller due to the long distance between wind power generators and the control platform. Therefore how various delay times impact on the control effect is discussed and analyzed.

This paper is organized as follows: Section 2 reviews the rotor-side control system of DFIG and discusses two methods of additional reactive power control. A centralized control strategy of reactive power for the wind farm is designed to improve the stability of voltage at PCC in Section 3. The Influence of communication delay on the effect of the centralized reactive power control is analyzed in Section 4 and validated by means of simulations in Section 5. Finally Section 6 draws the conclusions.

2. Reactive Control Schemes of DFIG

In the present scheme, the rotor of DFIG and the grid are generally tied by two back-to-back voltage source inverters. Converter is able to achieve the decoupling of stator active and reactive power, making the converter equipped with the ability of dynamic reactive power output. However, this ability is restricted by constant power factor control mode in engineering application. Therefore, additional means of reactive power control can be adopted to fully excavate the dynamic reactive regulation of WTG.

2.1. Autonomous Control System of DFIG

The converter connected with the rotor winding is named as rotor-side converter. The control system of the converter is usually adopted as double closed-loop structure with power control loop and current control loop.

Figure1 illustrates the schematic diagram of autonomous rotor-side control system. idr and iqr are respectively the rotor currents of d and q axles. Vdr and Vqr are respectively the rotor voltages of d and q axles. △Vdr and △Vqr means voltage compensation of d and q axles for coupling elimination respectively. Pstator and Pref are respectively the stator active and active reference value. Qstator and Qref are respectively stator reactive power and reactive power reference value. Among these values, reference value Qref depends on the request of the reactive power exchange between DFIGs in steady-state operation and electrical grid. If the grid needs WTGs to provide reactive voltage support owing to reasons like fault and so on, the original set value Qref cannot meet the demand which DFIGs export transient reactive power to ensure the grid voltage stability.

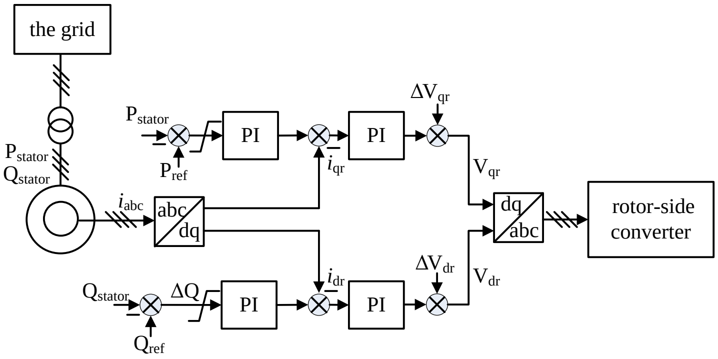


Figure 1. Control system of rotor-side converter of DFIG

2.2 Two Schemes of Additional Reactive Control

In order to make DFIG provide reactive power support during the grid voltage fluctuation, the stator reactive power reference value Q_{ref} must be modified dynamically to follow the voltage change. In Figure 2, it is shown that the feedback signal U_f is amplified and filtered. Parameters determined by the amplification and the filter are gain K and time constant T_a. Then, the additional reactive signal Q_{ad} is obtained and added to the node for comparing Q_{stator} and Q_{ref} in the reactive power control system. Next, Q_{ad} together with Q_{ref} reestablish the new reactive power reference value. After that, to achieve transient reactive power regulation, the control system relies on the new value to adjust the stator reactive output.

According to the signal U_f obtained from different locations, two schemes are proposed as follows.

Scheme 1: when signal U_f is derived from the stator voltage of WTG, the situation is named as local control.

Scheme 2: when U_f is derived from the voltage of PCC, the situation is named as global control.

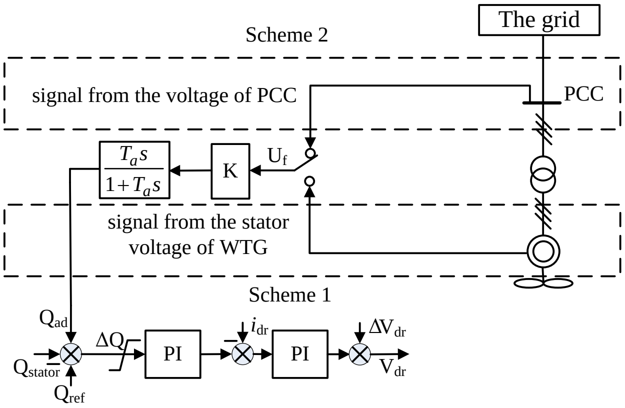


Figure 2. Additional reactive power control

In principle, the purpose of the two control schemes mentioned above is to suppress PCC voltage fluctuation. However, application effect shows that the two schemes are different.

The simulation system shown in Figure 3, which is used to illustrate the difference of control effect between local control and global control, consists of two 1.5MW DFIGs (G1 and G2) connected to an infinite bus via two 220kV transmission lines. Bus B1 is the point of common connection (PCC). And, it is the common bus connected the wind farm substituted by G1 and G2. The parameters of DFIG is seen Appendix. The values of the transmission lines resistance and reactance are R=0.36Ω/km, X=0.4Ω/km, R_l=0.2Ω/km, X_l=0.32Ω/km, while transmission lines length are L_1=2.5km, L_2=6km, L_3=180km. Because G1 and G2 are located in different place in the wind farm, the lines length L_1 and L_2 are not equal. During the time is between 5s and 125s, the wind speed first rises from 10m/s to 14m/s, then falls to 8m/s. There are simulation curves of bus B1 voltage shown in figure4 when the local control and global control are adopted respectively.

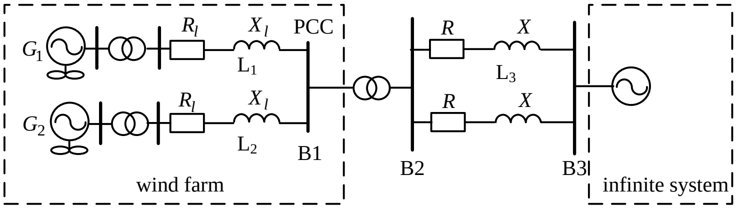


Figure3. Test system of additional reactive control

Figure 4 shows that although the decoupling control of autonomous system of DFIG makes the voltage fluctuate at small range with wind speed varying, it is still easy to find that the effect of global control is superior to local control. This is because that the DFIGs are not only highly scattered in different areas in the wind farm and the electrical distance between each DFIG and PCC is different, but also each DFIG owns respective different operating characteristics. Even if the generator terminal voltage could be constant via adopting additional control method, it is difficult to guarantee that the voltage of bus B1 is stable.

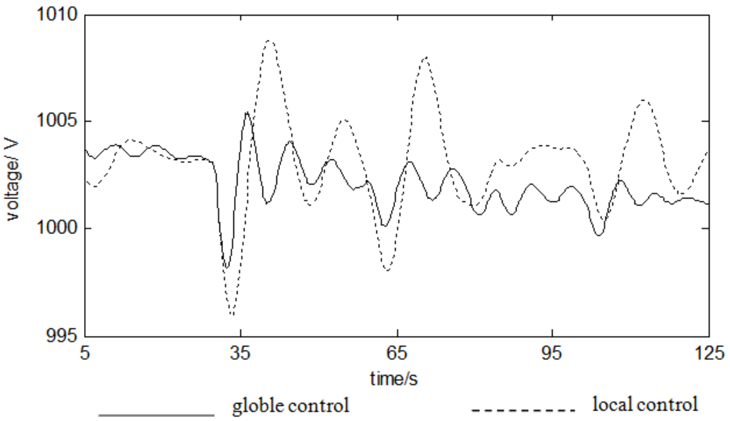


Figure 4. Bus B1 voltage curves for local control and global control during wind speed fluctuation

Therefore, this paper, taking the common bus voltage as control objective, adopts the method of global control to implement additional reactive power control of each unit in wind farm.

3. Centralized Control Strategy of Reactive Power for Wind Farm

Because each wind turbine capacity is relatively small, the reactive power regulation of one wind turbine cannot bring obvious variation to the total power of the wind farm and PCC voltage. Therefore, reactive power adjustment of the wind farm must be combined with multi wind turbine generator power regulation to complete.

The centralized reactive control strategy of the wind farm shown in Figure5 adopts the logical structure combined by the wind turbine autonomous control method (see Figure1) and the global control scheme (see Figure2). Firstly, the additional controller collects the common bus voltage of the wind farm as the control signal. Then, the signal is transmitted to the integrated control platform for processing. After that, the platform outputs the additional control signal of the wind farm reactive power to the reactive regulation loop of each wind turbine by communication optical fibers in order to modify the reactive power reference. At the same time, the process can make each wind turbine regulate its reactive power following the new reference result in the change of the total output for the wind farm. By this way, the goal of the coordination between entire wind farm and grid voltage will be able to achieve.

In this control system, the original function of the autonomous controller will remain unchanged and will not be weakened by the feedback signal. Moreover, increasing or decreasing the power output of each WTG, reactive power of the wind farm will be simultaneously regulated to lead to the reduction of the bus voltage fluctuation. Therefore, as long as the control platform can balance between the autonomous control system with the additional reactive control system and coordinate the software of each control subsystem, the centralized reactive power control scheme can be applied in the practical engineering.

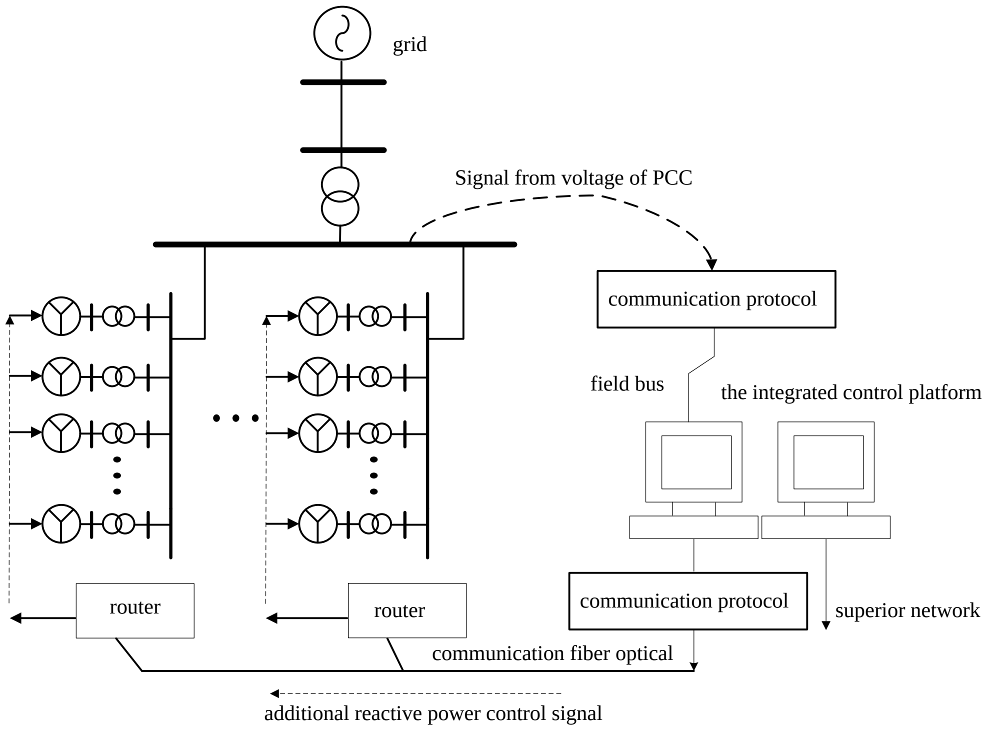


Figure 5. Centralized control system for wind farm

4. The Influence of Delay on the Centralized Reactive Control for Wind Farm

Because WTGs are distributed in broad area, the control signal must be transmitted through long distance transmission lines. Therefore, it is needed to discuss the influence of delay on the control effect. Taking the communication delay into account, the additional reactive control system of the WTG i is shown in Figure6. $H_i(s)$ includes the links such as amplification and filter (see Figure 2).

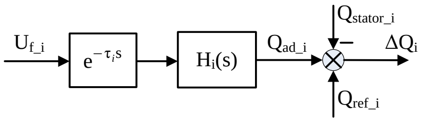


Figure 6. The influence of communication delay on the control system

If the communication delay time of the i WTG is τ_i, the influence of the delay will be mainly reflected in that the delay link $e^{\tau_i s}$ was introduced in the feedback channel of the s domain. In other words, the expression of the delay occurs as the frequency shift of the feedback signal which is proportional to delay time τ_i. Moreover, the frequency shift is manifested as the variation of signal power spectral density. Because the regional difference among the autonomous control systems results in the generation of various delays and then causes the change of signal power spectral density, after the control signal is processed and transmitted by the long distance the undesired frequency components which may decline the quality of the grid voltage will be introduced and will affect the frequency of the common bus voltage.

Therefore, once the centralized reactive power control strategy is employed, the influence of communication time delay should be paid more attention and the effective means to reduce delay should be taken into consideration so as to guarantee that the transient reactive power of the wind farm can be effectively regulated and the wind farm can friendly interact with the gird.

5. Simulation Analyses

The simulation platform MATLAB7.6/SIMULINK is used to provide the simulation of the control effects on a power system. The test system given in Figure 7 is made up to the wind farm and the infinite system connected by the double-circuit transmission lines with 180km long. The wind farm consists of 80 DFIGs with rated power as 1.5MW. The parameters of DFIGs and the transmission lines are in the same as those parameters employed in Section 2.2.

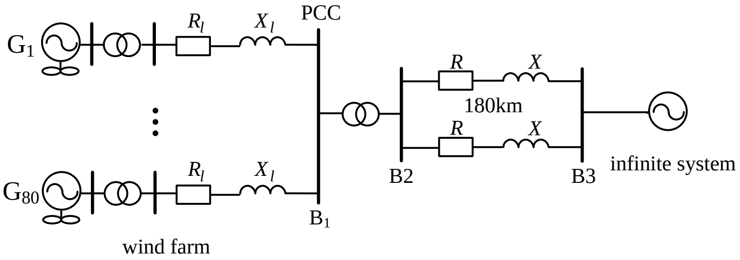


Figure 7. Simulation system of centralized control for the wind farm

5.1 The Influence of Centralized Control on Common Bus Voltage during the Fluctuation of Grid Voltage

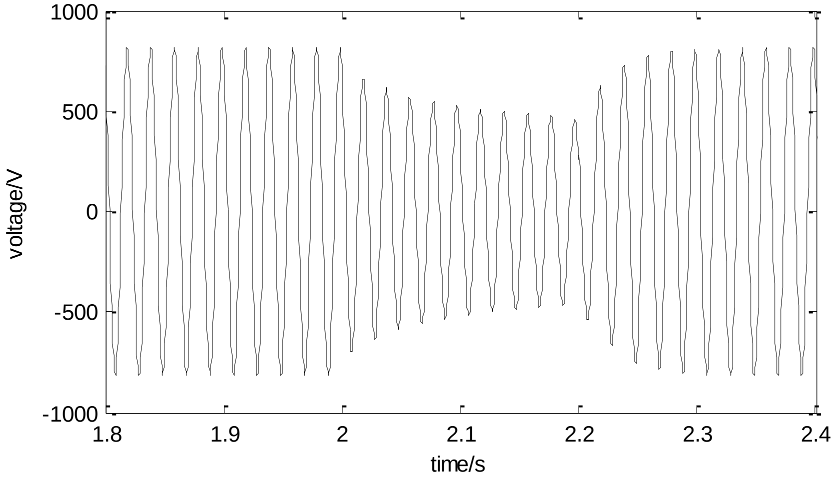
If the grid voltage drops by 40% when t=2s and fault time is 0.2s, figure8 shows the simulation results of the voltage at the common bus B1 changes with time. As shown in Figure 8 (a), it is easy to be found that bus B_1 of phase A voltage lowers by 30% during gird fault. However, after adopting the additional reactive centralized control strategy proposed in this paper and taking the common bus voltage as control goal, the amplitude of the common bus voltage as shown in Figure 8 (b) just drops by 10%. Additionally, it is shown in Figure 9 that the wind farm provides the transient reactive support depending on the action of the control strategy during the fault period. Thus, the transient reactive support effectually suppresses the voltage dips. Meanwhile, the fact that the degree of voltage dips mainly relies on the capacity of the WTG should be recognized. The greater the capacity is, the stronger the ability to suppress the voltage dips.

Because applying the centralized control strategy is taking industrial communication networks as its technical base, the problem of communication time delay should not be avoided. To confirm that the influence of various delay time on the centralized control effect is significantly different, bus B1 voltage of phase A is calculated in the following two conditions and recorded in Figure 10

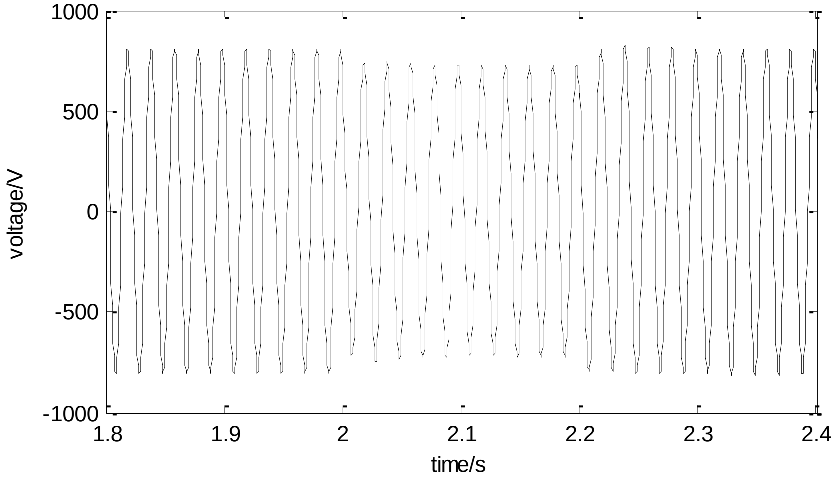
Condition 1: the communication delay time of 40 WTGs in the wind farm shown in figure7 is set to10ms.

Condition 2: the communication delay time of 40 WTGs in the wind farm shown in figure7 is set to 20ms.

When delay time is 10ms during the grid fault, the wind farm can provide enough reactive to make voltage only dip by around 12%. Its effect is close to no delay (see Figure 8(b)). However, when the delay time increases to 20ms, although the voltage amplitude drops by no more than 12% during the fault, the voltage amplitude at any other time no longer remains constant. In addition, as shown in Figure 11, power spectral density of the voltage signal in figure10 is calculated in the two conditions. Compared with the delay time of 10ms, the frequency components of 38Hz, 62Hz, 78Hz and 95Hz and other harmonic components are introduced in the voltage signal when the delay time is 20ms, making the voltage is no longer sinusoidal even during the no-fault.



(a) The voltage curve of no additional feedback (phase A)



(b) The voltage curve of additional feedback (phase A)

Figure 8. Influence of reactive power centralized control on the bus voltage during the grid fault

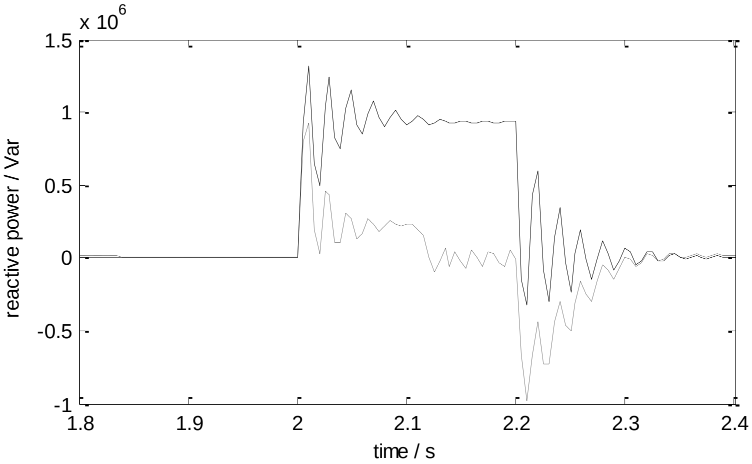
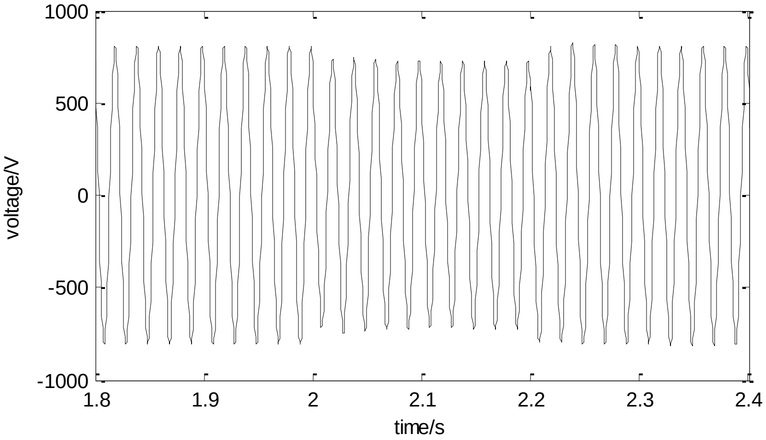
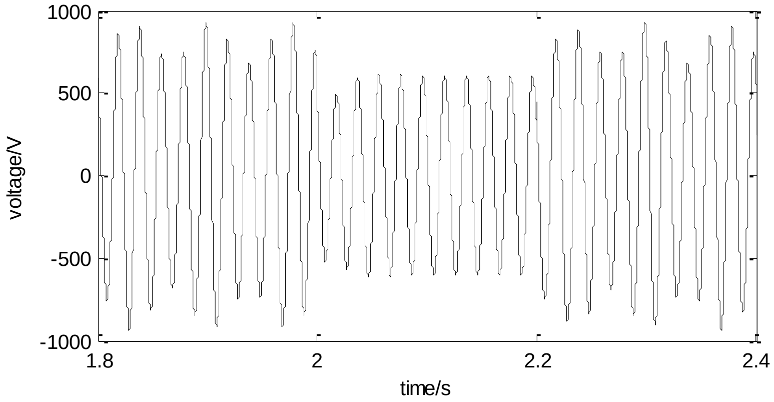


Figure 9. Influence of reactive power centralized control on reactive power during the grid fault

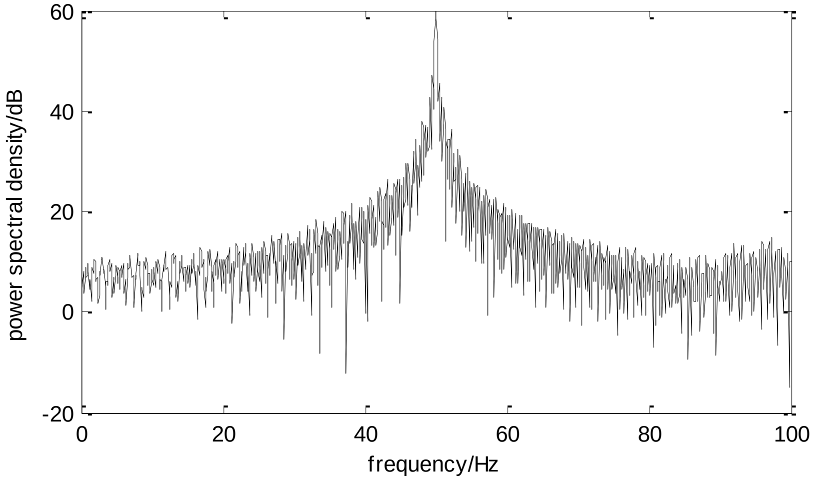


(a) The voltage curve based on the condition 1 (delay for 10 ms)

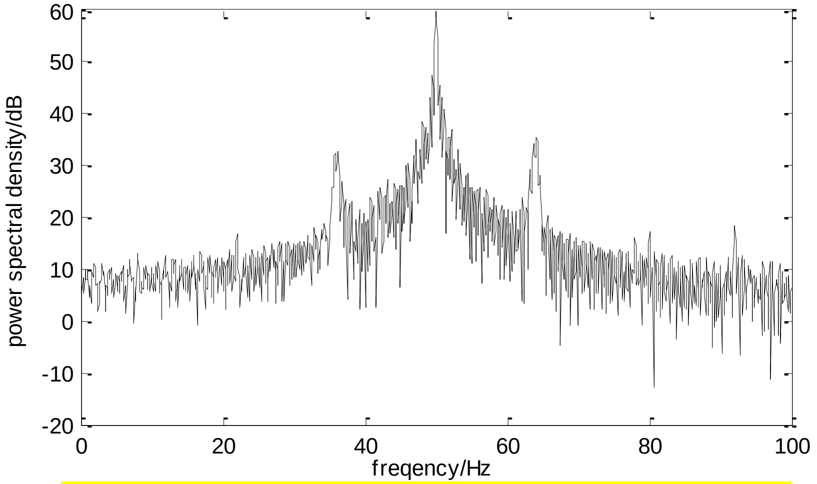


(b) The voltage curve based on condition 2 (delay for 20 ms)

Figure 10. Influence of communication delay on centralized control



(a) The power spectral density curve based on condition 1 (delay for 10 ms)

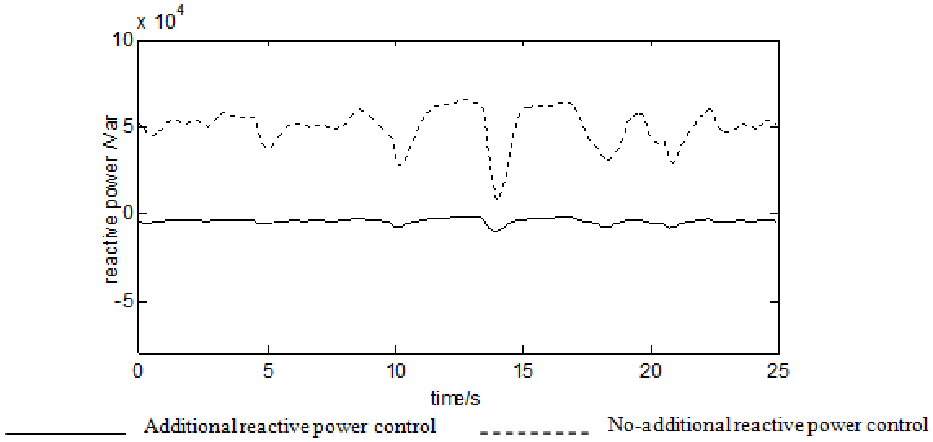


(b) The power spectral density curve based on condition 2 (delay for 20 ms)

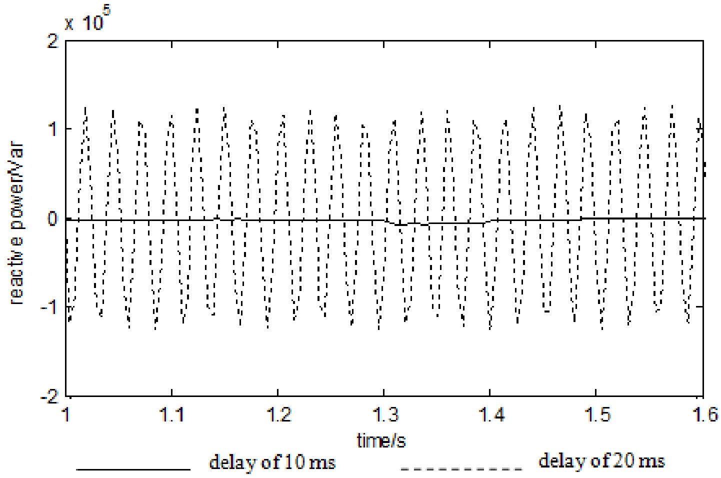
Figure 11. Influence of communication delay on signal frequency components

5.2. The Influence of Centralized Control on Reactive Power during Wind Speed Fluctuation

To verify the centralized control method is effective during the wind speed fluctuation, the wind speed is simulated with basic wind, random wind and gradient wind, where the basic wind speed is 7m/s. In general, the active power output of WTG varies with the changing of wind speed, and also the reactive power consumed by the transmission lines and the transformers changes accordingly. Thus, this variation is bound to lead the common bus voltage to fluctuate. When the communication delays are ignored, Figure12 (a) compares the reactive power output of the wind farm employing centralized control strategy with not employing it. With wind speed fluctuating, reactive power is regulated from given value 50000var to -1000var depending on the action of additional controller. Meanwhile, this regulation also effectively stabilizes the reactive fluctuation influenced by wind speed to achieve the goal of constant bus voltage. When all of the WTGs in the wind farm are equipped with the additional controller, Figure12 (b) compares the reactive power output of the wind farm based on the two conditions as Section 5.1. It is thus clear that the reactive power do not vary significantly when delay is 10ms. It should also be noticed that the variation do make the reactive power seriously oscillatory when the delay is 20ms.



(a) Comparison between additional control and no-additional control



(b) Comparison between the delay of 10ms and the delay of 20ms

Figure12. influence of additional control on reactive power during wind fluctuation

6. Conclusion

This paper presents the centralized control strategy for the wind farm which is combined traditional autonomous control strategy and additional control strategy of WTG. Meanwhile, the test system is simulated and analyzed to prove the availability of the centralized control strategy, revealing the influence of communication delay on the effect of the centralized control based on the conditions of the gird fault and wind fluctuation respectively and getting the following conclusions:

1) If the grid voltage drops by 40% because of grid fault, the control scheme put forward in this study can make the wind farm bus voltage drop by no more than 10%. This control scheme effectively improves the wind farm fault ride-through capability.

2) Centralized reactive power control can effectively regulate reactive power output during wind speed fluctuation so as to stabilize the bus voltage.

3) Different communication delay times can result in different influence on control effect. Communication delay times do lead to the introduction of voltage harmonic component. When the delay exceeds a certain range the controller will make failure.

Acknowledgements

The authors gratefully acknowledge the support of the National Natural Science Fund of China (51267003), and Social Development Research Project of Guizhou Province, China (SY[2011]3081)).

References

[1] M. Kayikçi and J. V. Milanovic, “Reactive power control strategies for DFIG-based plants”, IEEE Trans. Energy Conver, vol. 2, no. 22, **(2007).**

[2] B. K. Ranjan and W. Gao, “A novel controller design for grid-side converter of doubly fed induction generator for wind power interface: An experimental investigation. Electric Power Components and Systems, vol. 14, no. 38, **(2010).**

[3] P. S. Flannery and G. Venkataramanan, “A Fault Tolerant Doubly Fed Induction Generator Wind Turbine Using a Parallel Grid Side Rectifier and Series Grid Side Converter. IEEE Trans. on Power Elecronics, vol. 3, no. 23, **(2008).**

[4] C. Mengzeng and C. Xu, “Reactive power generation and optimization during a power system fault in wind power turbines having a DFIG and crowbar circuit”, Wind Engineering, vol. 2, no. 35, **(2011).**

[5] Meegahapola, L. Gunaruwan, T. Flynn and Damian, “ Decoupled-DFIG fault ride-through strategy for enhanced stability performance during grid faults”, IEEE Transactions on Sustainable Energy, vol. 3, no. 1, **(2010).**

[6] S. Tohidi, H. Oraee, M. R. olghadri, S. Shao and P. Tavner, “Analysis and enhancement of low-voltage ride-through capability of brushless doubly fed induction generator”, IEEE Trans. on Industrial Electronics, vol. 3, no. 60, **(2013).**

[7] F. Lima, D. A. Kleber, J. Dantas and B. Luz, “Reactive power control of DFIG-based wind turbine during voltage sag”, 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, Canada, (**2012**) October 25-28,

[8] Mohammed and G. Joos, “Optimal tracking secondary voltage control for the DFIG wind turbines and compensator devices”, Electric Power Systems Research, vol. 12, no. 79, (**2009**).

[9] L. Meegahapola, T. Littler and S. Perera, “Capability curve based enhanced reactive power control strategy for stability enhancement and network voltage management”, Electrical Power and Energy Systems, vol. 4, no. 52, (**2013**).

[10] E. G. Shehata, “Active and reactive power control of doubly fed induction generators for wind energy generation under unbalanced grid voltage conditions”, Electric Power Components and Systems, vol. 6, no. 41, (2013).

[11] K. Vinothkumar and M. P. Selvan, “Novel scheme for enhancement of fault ride- through capability of doubly fed induction generator based wind farms”, Energy Conversion and Management, vol. 7, no. 52, (**2011**).

[12] Z. Peng, H. Yikang and S. Dan, “Improved direct power control of a DFIG-based wind turbine during network unbalance”, IEEE Trans. on Power Electronics, vol. 11, no. 24, (**2009**).

[13] H. D. Anca, M. Gabriele, P. Srensen, T. Lund and F. Ioy, “Co-ordinated voltage control of DFIG wind turbines in uninterrupted operation during grid faults”, Wind Energy, vol. 1, no. 10, (**2007**).

[14]W. Li, and T. Dinh-Nhon, “Stability enhancement of a power system with a PMSG-based and a DFIG-based offshore wind farm using a SVC with an adaptive-network-based fuzzy inference system”, IEEE Trans. on Industrial Electronics, vol. 7, no. 60, (**2013**).

[15] Z. Xueguang, W. Pan, Y. Liu and D. Xu, “Improved grid voltage control strategy for wind frams with dfigs connected to distribution networks”, Journal of Power Electronics, vol. 3, no. 12, (**2012).**

[APPENDIX]

1.5 MW DFIG parameters:
Rated stator voltage: 0.69 kV;
Rated ro-tor voltage: 1863 V;
Rated apparent power: 1667 kVA;
Rated speed:1800 rpm;
No. pole pairs: 2;
Stator resistance: 0.008Ω ;
Stator inductance: 15.86mH;
Rotor resistance: 0.0188Ω ;
Rotor inductance: 16.2mH;
Mutual inductance: 15.66mH;
Generator inertia: 75 kg m^2;
Turbine inertia: 4,052,442 kg m^2;
Shaft stiffness: 83,000,000 Nm/rad.

Authors

Zhuo Chen

She received the B.S.degree in 2002 in applied electronic and the M.S degree in 2005 in power electronic and power transmission from Guizhou University, Guiyang, China. She is currently working toward the Ph.D degree in electrical engineering from Guizhou University.From 2008-2010, she was an Associate Professor with the Electrical Engineering Department at Guizhou University.

Zhenghang Hao

He received the B.S.degree in 1993 in applied physics from Zhengzhou University, China. He also received the M.S. degree in 2000 in electrical engineering from Guizhou University of Technology, Guiyang, China, and the Ph.D degree in 2008 in electrical engineering from Tianjin University, Tianjin, China.

Shuijie Qin

She received the B.S.degree and the M.S degree in precision instrument from Tsinghua University, Beijing, China, in 1985 and 1989, respectively. She also received the Ph.D degree in 2002 in nano electro-mechanical systems from Chinese University of Hong Kong, Hong Kong, China. Since 2002, Dr. Qin has been the director of the key Laboratory for Photoelectric Technology and Application.