System frequency regulation investigation in doubly fed induction generator (DFIG)

XUE YINGCHENG，TAI NENGLING，
Electrical Engineering Department
Shanghai Jiaotong University
DongChuan Load 800,Shanghai 200030
CHINA
Xyc_xyc_xyc@126.com

Abstract: -The conventional decoupling control in the variable-speed doubly fed wind turbines has little support to the system frequency. The characteristics of doubly fed induction generator (DFIG) wind turbines and conventional plant are compared. The contributions of DFIG to system inertial response and frequency regulation are investigated. The influence of auxiliary loop parameters on the inertial response is illustrated. The paper also introduces a novel algorithm to enhance the participation of DFIG in existing frequency regulation mechanisms. The proposed approach takes advantage of the fast response capability associated with DFIG. The control system consists of four functional modules, i.e. frequency control, rotational speed delay recovery, speed protection and coordination control with conventional generators. Simulation results show that the control strategy has a fast response speed to the transient frequency error. It proves that wind farms can participate in the system frequency regulation to a certain extent.

Key-Words: - DFIG，inertial response， wind turbine generators，Frequency regulation, power control

Project supported by the Shanghai “Phosphor” Science Foundation, China (07SG11); New Century Excellent Talents in University , China (NCET-08-0356)

1 Introduction

During the last decades, many large wind farms have already been installed so far and recently huge offshore wind farms have also been integrated in the power networks. With the ever-increasing development of wind power, the impacts on grid become more significant. The effect of wind generation on the system frequency regulation is one of the most problems.

First, the unpredictable and highly fluctuating wind generation can have consequences in terms of frequency "stability". As the wind penetration in a system increases, the randomness and fluctuation of wind power increase. The frequency variation of power system due to wind generator output fluctuations increases. Generally, wind parks are equipped with a frequency relay that disconnects the wind park after a frequency disturbance. When the wind power penetration of a grid is high, a massive wind farms disconnection can lead to power system oscillations [1].

Secondly, Modern wind farms are mostly equipped with Variable Speed Wind Turbines (VSWT)，variable speed turbine technologies use back to back power electronic converters for the grid connetion. The intermediate DC voltage bus creates an electrical decoupling between the machine and the grid. Therefore variations in grid frequency are not seen by the generator rotor and the power system apparent inertia decreases with increasing wind power penetration.

As the wind penetration in a system increases, wind generation displaces conventional generating units. In general, this leads to a reduction of the total system inertia. Consequently greater rates of frequency change will be observed in various system contingencies (e.g. generating unit loss) or sudden load variations.

If the operation of wind power could adhere to some operational functions that are similar to the conventional plants, and thus, reduce the impact of the wind penetration. Therefore ，the need to study the way in which wind units could participate in system frequency support strongly arises [2].

In recent years, some grid codes were established in some countries. These grid codes require wind farms to participate in frequency regulation. For example, Danish grid code asks all production units connected to transmission line, to contribute in system frequency control with a fast and rapid automatic power control [3].

The Great Britain (GB) Grid Code states that wind farms must provide balancing services that are originally supported from conventional plants, all wind farms must be capable of meeting the frequency response requirements of primary, secondary and high-frequency response [4]. When the frequency drops, say a frequency deviation of 0.5 Hz, the generator output power should increase by an amount equal to primary response, within the time period 0–10 s and be sustained for a further 20 s. The generators should maintain power output at the secondary response from 30 s to 30 min in order to stabilize the frequency. In the event of a frequency increase, the generator output power should decrease by an amount equal to high-frequency response within the time period 0–10 s.

Considering this problems, some researches have developed research regarding the possibility of using wind generators to contribute for primary frequency control [5]–[11]. There are three Methods to allows VSWT to participate effectively in system frequency regulation, the first is inertial control method, the second is power reserve control method, the third is the other method such as communication method etc.

The inertial control [6-7] uses the kinetic energy storage system (blade and machine inertia) to participate in primary frequency control. But releasing or storing kinetic energy can only be considered as a part of primary control. Indeed, the wind persistence being limited, this power reserve cannot be guaranteed further to short-term.

In order to perform permanent active power control, it is generally necessary to force the wind turbine to operate in a non-optimal power point. In [8], a strategy for primary frequency control has been developed. The wind generator operates according to a deloaded optimum power extraction curve in order to create a primary power reserve. This control strategy allows us to ensure a primary power reserve even when the wind turbine generator (WTG) works under rated power. However this strategy requires the wind speed measurement and a detailed model of the wind turbine[9-10].

[11] proposes a communication control strategy that use output electric power of conventional plant as VSWT reference power, so that VSWT injects an additional power, equal to Pload just after imbalanced. Output power is then decrease by suitable time constant.

This paper presents a new strategy that takes advantage of the fast response capability of VSWT ， The control system consists of four functional modules, i.e. frequency control, rotational speed delaying recovery, speed protection and coordination control with conventional generators. Simulation results show that the control strategy has a fast response speed to the transient frequency error. It proves that wind farms can participate in the system frequency regulation to a certain extent.

This paper is structured as following. Section I reviews the contribution to frequency control through variable speed wind turbine， Section II Compares the frequency response of VSWT and conventional plant. Section III describes new strategy to enable variable speed wind turbine primary regulation. In section IV the simulation and results are presented. Finally, conclusions and future work are given in Section VI..

2 Comparison of The Frequency Response of VSWT and Conventional Plant

Conventional generating plants use directly connected synchronous generators. This means that there is a coupling between the power system frequency and the electromagnetic torque (and the resulting electrical active power output) of the generators. When the power system frequency suddenly decreases the electrical active power suddenly and temporarily increases due to this coupling. This is known as the "natural" inertial response of the generator, and it contributes to frequency stabilization.

Classical VSWTs are characterized by lower inertia than classical power plants. Further, some VSWTs technologies use back-to-back power electronic converters for the grid connexion. The intermediate DC voltage bus creates an electrical decoupling between the machine and the grid. Therefore although wind turbines also have a significant amount of kinetic energy stored in the rotating mass of their blades Similar to conventional generators. This energy will not contribute to the inertia of the grid as the rotational speed is decoupled from the grid frequency by a power electronic converter. However through the addition of a control loop, VSWT can make the "hidden inertia" available to the grid. In this way, VSWT may be configured to emulate an inertial response similar to that of synchronous generation.

In fact, modern wind-turbine generators (WTGs) have inertia constants which are comparable to those of conventional turbine-alternators, In addition VSWTs can operate in a wide range of speed changes, The generator speed can drop to as low as 0.7 p.u. speed , while conventional unit speed can only drop to as low as 0.95 p.u. speed. Therefore from two installations of the same rating and the same inertial constant H, the variable speed wind turbines would have 4.12 times more kinetic energy than the conventional unit. This kinetic energy could be utilized to provide temporary primary frequency control support to the grid in the event of a load/generation mismatch. However, the power is limited by the operating conditions and the power rating of the VSWT.

Wind Turbines will normally operate to maximize their power output under all possible conditions. Hence they are not available to provide a sustained increase in power output and therefore participate in 'secondary response' services which conventional plants are able to do. However they can provide the two components of inertia and governor responses, which are present in primary response from existing synchronous plant as outlined below.

An important feature of VSWT is the possibility for their active and reactive power outputs to be controlled as required by system operators. They can increase their output power almost instantaneously. This is an important feature, although the steady-state active power delivered to the grid by a VSWT depends on the mechanical energy transferred from the wind, the electric power can be transiently controlled, to a certain extent, by resorting to the mechanical system kinetic energy. This is due to the capability of these machines to work at asynchronous speeds.

[12]Compares Frequency Response characteristics of Conventional Power Plant with Wind Power Plant by increasing the load of the power system, the conventional power plant acquire time (Response and Settling time of Mechanical power of Hydro, Thermal & Steam unit take 04-25 sec and 20-68 sec respectively to stabilize the system) to supply the demand power in order to balance the entire system. While the Response and settling time of Electrical Power of the wind turbine are 03 sec – 09 sec and 08 sec –38 sec respectively. Therefore, during this transition time power to the system can be supplied from the wind turbine to meet the raised power and to stabilize the frequency.

[13] States that the initial power surge of a hydro turbine is opposite to that desired. The initial opposite power surge lasts for 1–2 s depending on the water starting time and the load step. Because of this phenomenon, during a generation deficit situation, the decelerating power (energy) is higher for a hydro turbine compared to that of a steam turbine with/without the reheat. Due to these reasons, a fast short-term active power support from the wind turbine could be beneficial for a hydro dominated system in arresting the initial frequency fall, which corresponds to an improvement in the system temporary minimum frequency.

[14-15] Quantifies the capability of providing a short-term excess active power support of a commercial multi-megawatt VSWT, a GE 3.6MW model was used. It was found that the VSWT can provide an extra 0.1pu of active power for more than 10s quite easily without hitting the minimum speed limit, which is twice the Hydro- Qu é bec requirement.

[16] Studies the behavior and capability of VSWT for providing temporary active power overproduction. A 2MW VSWT-DFIG was investigated. It was found that it is possible to have an active power overproduction of 0.2 p.u. for at least 10 seconds, which could be useful for the grid operator for restoring a critical situation of grid frequency dip, especially in power systems with slow primary movers response or low inertia.

3 DFIG frequency control strategy

3.1 The problems of DFIG frequency controller design to be considered

Aiming at these problems above, based on the analysis of the frequency control characteristics, for DFIG frequency controller design, several issues should be considered as following:

1) The proposed approach should take advantage of the fast response capability associated with DFIG..

2) DFIG units should only respond to the dynamic frequency, while the steady-state frequency error, adjusted by the conventional unit.

3) When Frequency control is completed, the DFIG rotor should recovery to the optimal state with a faster speed, while minimize the impact of the frequency control.

4) The rapid, transient nature of DFIG should match with the delay, continuity nature of conventional units. The two properties should coordinate with each othe; each plays its respective advantage.

3.2 DFIG frequency control strategy

Through the above analysis of the Frequency control characteristics and the problems of DFIG frequency controller design to be considered, a new frequency control scheme shown in Figure 2.is Proposed.

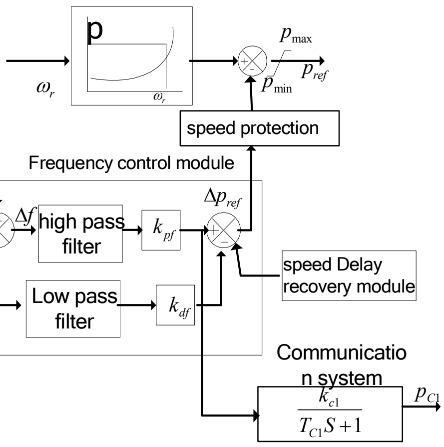


Fig.1. scheme for frequency control

In fig.1, the control system consists of four functional modules, i.e. frequency control, rotational speed delaying recovery, speed protection and coordination control with conventional generators.

3.2.1 Frequency control modules

To solve the problem described in Section 3.1.Frequency control module is proposed based on the frequency control in the literature [7], It retains the rapid response nature of the original controller, while a high-pass filter and a low pass filter are added.

Adding low pass filter results in two effects: first, there is a reduction in the rate of electromagnetic power (torque), and second, there is also a reduction in the magnitude of the peak power (torque). Therefore the filter can minimize the impact of this supplementary control on mechanical drive train loads, and frequency measurement noise does not cause problems. More details on this filter can be found in literatures [7].

The high-pass filter is behind the frequency deviation signal. It blocks the steady-state input signal of the frequency control module, and responds only to dynamic frequency deviation; So that a permanent frequency deviation has no effect on the control strategy.

The choice of K and T determines the magnitude and shape of additional signal. The greater K the longer response time, the more power output, but the time return to the steady state becomes longer. How to tune the K parameter becomes one of the issues to be studied.

If all the time constant K of large-scale wind farms are set to the same value, it may lead to some undesirable results. First, it may lead to overload of some units, while some units still have the power margin, and second, all the units follow the same recovery power curve decline .It is not conducive to system frequency adjustment. To avoid these situations, the time constant K of each wind turbine is set to different values for different operating conditions, operating conditions here is the speed range of the rotor.

3.2.2 Speed delay recovery module

Speed Delay recovery module is designed to help the rotor quickly return to optimal state. Control structure is shown in figure 2.The difference between measurement speed and reference speed is sent to PI controller. The output of PI controller multiplied by the proportion gain m. So that the power reference value can be adjust continuously, and wind turbine can finally get into optimal operating state.

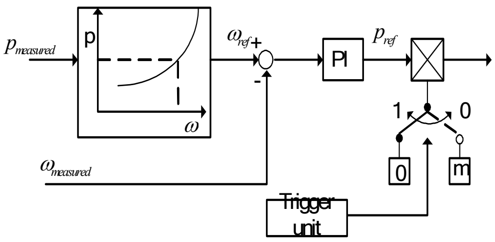


Fig.2 Structure of speed delay recovery module

The selection of reference values ω_{ref} is Mainly based on real-time measurement wind speed. The greatest available wind energy is calculated by the wind speed. And through the power - speed optimal curve, the optimal reference value of the rotor speed at given wind speed is obtained.

Delay is mainly to prevent the speed recovery form weakening the active power support. As shown in Figure 2 When the module does not work, the proportion gain is set to 0.After some delay t, trigger unit acts. The proportion gain becomes m. In order to reduce sudden jump of the reference value, m values uses the trapezoidal curve shown in Figure 3.

When the speed recovers, the trigger unit acts again. The proportion gain is set to 0,and speed recovery module is out of operation.

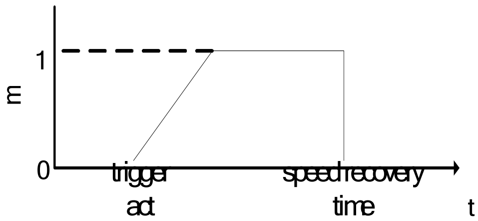


Fig.3 Value of proportion gains m

Delay time t is generally about 5 s ~ 30 s after the frequency control starts. For large wind farms, delay time t of all the units cannot be the same. When at the same time all the units have access to speed recovery mode, active power provided by the whole wind farms will greatly reduce. This may cause the second drop of the system frequency [15]. Therefore, we should first determine the delay time t of the No. 1 unit; the delay t of other units equals the delay time t of the previous unit plus additional delay Δt.

3.2.3 Coordinate control module

Coordinate control module mainly considers the rapid nature of wind turbine and sustainability of conventional units. When an unexpected demand increase, the active power generated by wind generators quickly increases to avoid the frequency fall. As this increased power can last just for a few seconds, conventional generators should eventually take charge of the increased demand by shifting their generation. But the fast increment in wind Generators output slows down to a certain extent the response of conventional generators. To avoid this undesirable effect, coordination between wind generators and a selected set of regulating conventional units is proposed. This is based on injecting the additional signal [17]:

$$p_{ci} = k_{ci} p_f^*$$

Where p_f^* is inertial control output power. The constant k_{ci} is the participation factor for each conventional generator supporting the wind generation. This set of constants must be computed in order to comply with:

$$\sum_i k_{ci} = 1$$

3.2.4 Speed protection module

When DFIG Participate in frequency control, Speed protection module can prevent the rotor speed from falling below the minimum value ω_{min}. When the rotational speed is lower than ω_{min}, the speed protection system acts, DFIG no longer participate in the system frequency control. ω_{min} is generally set to 0.7p.u.

4. Simulation

The power system consists of a number of generators and loads connected to a single bus bar, as depicted in Fig. 4. The generator groups G1(3 MVA)and G2(3 MVA) are conventional synchronous generator plants. The conventional generator is modeled as a synchronous generator equipped with standard IEEE governor and AVR. The generator group G3(4x1.5 MW) is simulated as a DFIG wind turbines with power electronic interfaces. Two-mass model of the mechanical shaft is also included. DFIG is equipped with a decoupled active (P) and reactive (Q) power controller in stator-flux oriented reference frame where d- and q-axis rotor currents regulate stator active and reactive power, respectively [6].

In the analysis presented in the sequel, constant wind speed is assumed (unless otherwise specified). The essential aerodynamics (curves) are incorporated in all studies.

To create variations of frequency, Generators /loads are connected or disconnected. Simulations are carried out with the help of Matlab/simulink® software.

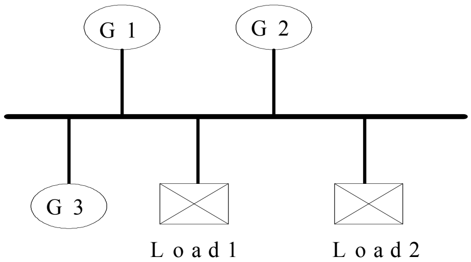
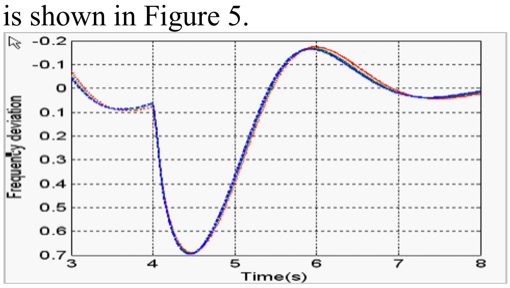


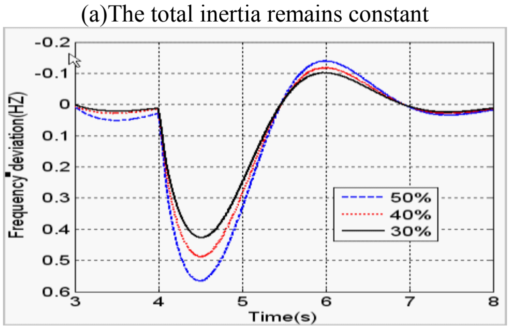
Fig.4 Simulated grid

4.1 Influence of DFIG penetration on frequency deviation

Two case studies are considered in order to illustrate the influence of different DFIG penetration on system frequency regulation. Initially DFIG supplies 30% of the load and the disturbance is 15% (3 MW) increase in load at t=4s. The system frequency of two cases is shown in Figure 5.



(a)The total inertia remains constant



(b)The total inertia is changed

Fig. 5. Influence of DFIG penetration on frequency deviation (Hz).

The first case is shown in Figure 5 (a). Total generation and the total synchronous generator inertia remain constant. The synchronous generator rating reduces in proportion with the increment of DFIG power.

The second case is shown in Figure 5 (b). Total generation remains constant. The total synchronous generator inertia is changed, double-fed generator replaces synchronous generator.

In Figure 5 (a), because the system inertia remains constant, with the increasing penetration of DFIG, the adjustment of DFIG penetration has little impact on the system frequency. System maximum frequency offset remains unchanged.

However if the rating of synchronous generator is reduced (to represent the replacement of DFIG), In Figure 5 (b), Case2, the system inertia is also reduced as DFIG penetration increases. System maximum frequency offset becomes larger.

The simulation results confirm that DFIG is inertia-less as opposed to synchronous generator whose connection to the grid intrinsically provides inertial contribution. Penetration of DFIG does not influence system frequency regulation at all unless it replaces conventional synchronous generator.

4.2 The influence of the double-fed generators inertial control on frequency response

When no additional inertia control is added to the power control loop, due to double-fed generator torque adjustment is very fast (about 10 milliseconds or so). Rotor mechanical speed is decoupled from system frequency. Frequency response is shown in Figure 6, the dashed line. This case double-fed generator showed no inertia (or less inertia).

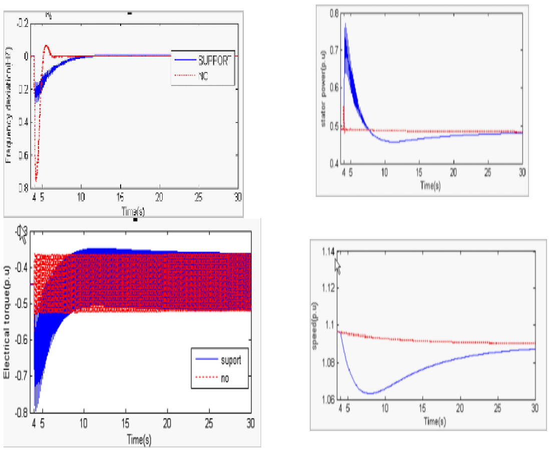


Fig. 6. Influence of inertia control (a) frequency variation. (b)the stator power (dashed)，(c) electrical torque (solid)，(d)speed

On the other hand, if additional inertia control is added to the power control loop, frequency response is shown in Figure 6, solid line. As the double-fed generator power can be transiently controlled, when the frequency decreases, the stator active power increases, electromagnetic torque increases. As the wind speed remains unchanged, pneumatic torque remains constant, the rotor decelerates. At this point, the double-fed generator shows inertia.

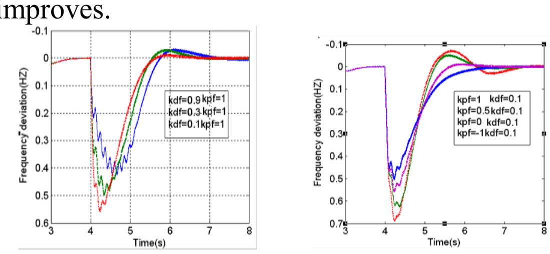
As can be observed In Fig. 6, without support from wind generation, the frequency response has an important drop. The inertial control reduces this frequency decrement and makes it slower, which is in accordance with the increased inertia this strategy brings about. However, oscillations arise.

If the frequency remains low, the electromagnetic torque (braking torque) is continually greater than pneumatic torque. wind turbine will stall. Therefore, in the power systems that frequency changes greatly such as micro-grid system, the stator output power should be carefully controlled (not cause wind turbine stall).

4.3 Influence of controller parameters

At t = 4 seconds , the load increase by 15% , system frequency drops until the automatic generation devices increase output power.

Frequency response for different values of K_{df} is shown in Figure 7 (a). It can be noticed that as K_{df} increases, equivalent inertia increases; rate of frequency change becomes small. The high-frequency oscillation is more and more relevant, but at the same time, the frequency regulation improves.



（a）frequency response in different K_{df} （b）frequency response in different K_{pf}

Fig. 7 Influence of controller Parameters on inertial response.

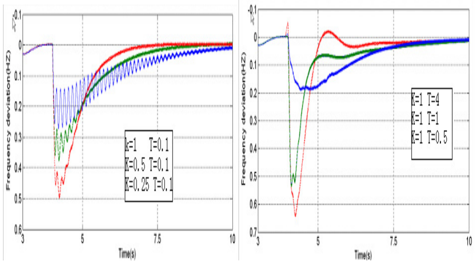
Frequency response for different value of K_{pf} is shown in Figure 7 (b). As K_{pf} increases, , the frequency regulation improves. Although Rate of frequency change decline is almost the same, at the same time, high-frequency oscillations become more and more apparent, the maximum frequency offset become small. The greater K_{pf}, the smaller the frequency offset. Therefore the overall system frequency response and operational robustness is improved.

4.4 Influence of filter parameters

To minimize the impact of the inertia control on mechanical drive chain, the frequency deviation shall be subject to high Pass Filter. filter transfer function is: $\frac{kS}{1+TS}$ .Suitable K, T can provide better frequency response and damping[18], In order not to introduce any artificial delays and attenuation, t value should be small, typically 0.1s [19]. K can be selected according to acceleration time constant

Frequency response for different values of K is shown in Figure 8 (a). It can be noticed that as K increases, the high-frequency oscillation is more and more relevant but, at the same time, the frequency regulation improves. The greater K the longer response time.

Frequency response for different values of T is shown in Figure 8 (b). It can be noticed that as T increases, equivalent inertia increases, rate of frequency change become small.



(a) frequency response for different k (b) frequency response for different T

Fig. 8. Influence of filter *Parameters* to inertia effect.

4.5 Comparison of Strategies

In the next simulations a sudden load increment of 15 %(3 MW) is considered. System frequency response of three conditions (the new method with coordination, the new method without coordination, no frequency support method) is shown in figure9. The solid line is frequency response of the new method with coordination. Dashed line is frequency response of the new method without coordination; dotted line is frequency response of no frequency support method. In absence of coordination the frequency drop is reduced by almost 40% compared with the case when no support from wind turbine generation is present. When the coordinating signal is considered, an improvement in the frequency support is obtained. This is achieved by making conventional generators aware that wind turbine generators are contributing transiently to the frequency regulation. The response of conventional generators is considerably slower than that of the wind turbine equivalent generation, which is only responsible for the quick power injection following the frequency perturbation, but it is helpful to provide frequency support at the end of the frequency transient.

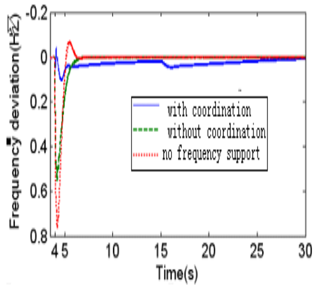


Fig.9. Comparison of different control methods.

Figure 10 is DFIG rotor speed recovery curve when the rotating speed recovery module is added. As can be observed from Figure 7, speed recovery module enables rotor speed to return to optimal state fasterly.

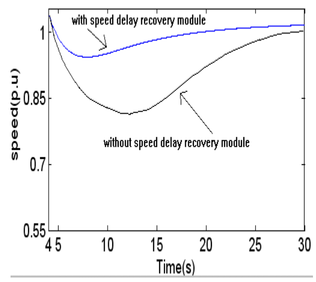


Fig.10 speed response of DFIG with speed delay recovery module

5 Conclusions and future work

The paper introduces a novel algorithm to enhance the participation of DFIG in existing frequency regulation mechanisms. The proposed approach takes advantage of the fast response capability associated with DFIG. The control system consists of four functional modules, i.e. frequency control, rotational speed delaying recovery, speed protection and coordination control with conventional generators. Simulation results show that wind farms can participate in the system frequency regulation to a certain extent.

Further work is required to establish the optimal timing of the kinetic energy discharge and the optimal profile of this power surge in coordination with the characteristics of conventional plants. And verify the existing simulations by laboratory based hardware simulation in future work.

A method of estimating the reserve from wind turbines 、its ratio to conventional generation reserves、and its economic issues have not yet been presented in the literature. This is a complex unit commitment problem, one however that will determine the extent to which frequency control by wind generation is economically viable for a power system.

Reference

[1] A. Causebrook, D. J. Atkinson, and A. G. Jack, Fault ride-through of large wind farms using series dynamic braking resistors (March 2007),IEEE Trans. Power Syst., vol. 22, No.3, pp. 966–975, Aug. 2007.

[2] European Wind Energy Association (EWEA), Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations, 2005. [Online]. Available: http://www.ewea.org/.

[3] Wind Turbines Connected to Grids With Voltages above 100 kV—Technical Regulation for the Properties and the Regulation of Wind Turbines, Elkraft System and Eltra Regulation, version TF 3.2.5, Dec 2004

[4] National Grid Company plc: The Grid Code, Issue 3, Revision 17, September 2006

[5]Grid Connection Regulations for High and Extra High voltage, E.ON Netz GmbH, 1 April 2006

[6] J. Ekanayake and N. Jenkins. Comparison of the Response of Doubly Fed and Fixed-Speed Induction Generator Wind Turbines to Changes in Network Frequency. IEEE Trans. Energy Conversion, Vol. 19, No. 4, pages 800–802, 2004.

[7] J. Morrenetal. Wind turbines emulating inertia and supporting primary frequency control，IEEE Trans. Power System. ， vol. 21， No. 1， pp.433-434，Feb.2006.

[8] G. Ramtharan, J.B. Ekanayake and N. Jenkins, Frequency support from doubly fed induction generator wind turbines, IET Renew. Power Generation. 2007, 1, (1), pp. 3–9.

[9] DE ALMEIDA R G, PECAS LOPES J A. Participation of doubly fed induction wind generators in system frequency regulation. IEEE Trans on Power Systems, 2007, 22 (3):944-950.

[10] REN L, CHIEN C, HUNG C M, et al. Dynamic reserve allocation for system contingency by DFIG wind farms. IEEE Trans on Power Systems, 2008, 23(2): 729-73

[11] Akbari M.; madani; Seyed M.; Participation of DFIG based wind turbines in improving short term frequency regulation, Electrical Engineering (ICEE), 2010 18th Iranian Conference on Digital Object Identifier: 2010 , Page(s): 874 – 879.

[12] Comparing and Evaluating Frequency Response characteristics of Conventional Power Plant with Wind Power Plant. http://webfiles.portal.chalmers.se/et/MSc/BhuiyanDinakarMSc.pdf.

[13] P. Kundur, Power System Stability and Control. New York: McGraw-Hill, 1993.

[14]NAYEEM, RAHMAT, ULLAH, Added Value for Network Operation. http://webfiles.portal.chalmers.se/et/PhD/UllahNayeemPhD.pdf

[15]N. R. Ullah, T. Thiringer, D. Karlsson,Temporary Primary Frequency Control Support by Variable Speed Wind Turbines –Potential and Applications, IEEE Trans.Power Systems, vol. 23, No.2, pp. 601-612,May 2008.

[16] Tarnowski G.C., Kjar P.C., Sorensen P.E., Ostergaard J., "Variable Speed Wind Turbines Capability for Temporary Over-Production,"Power & Energy Society General Meeting, 2009. PES '09. IEEE.

[17] MAURICIO J M, MARANO A, MEZ-EXP SITO A G,et al. Frequency regulation contribution through variable-speed wind energy conversion systems. IEEE Trans on Power Systems, 2009, 24(1): 173-179.

[18] O. Anaya-Lara， F. M. Hughes， N. Jenkins， and G. Strbac， Contribution of DFIG-based wind farms to power system short-term frequency regulation，IEE proceedings. Part C, Generation,

Transmission, and Distribution . vol. 153,no. 2, pp. 164–170, 2006.
[19]Chemmangot V. Nayar， Mochamad Ashari, W. W. L. Keerthipala, A grid-interactive photovoltaic uninterruptible power supply sys-tem using battery storage and a back up diesel generator, IEEE Transactions on Energy Conversion, Vol. 15, No. 3, pp.348-352, September 2000.