HYBRID TECHNIQUE FOR WIND FARM PARTICIPATION IN FREQUENCY CONTROL"

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Abstract: *To increase the penetration of wind turbines, participation of latter in power system management is required, this work evaluate the participation of a wind farm in primary frequency regulation. To participate in primary frequency control, wind farms must have some power reserves; over-speeding technique is used to satisfy power reserve required by the network operator. Control strategy for a wind farms to participate in power system frequency regulation, based on a combination of inertial response and de-loading control is proposed. The wind farm detects the frequency changes and starts to participate in frequency regulation. The combined control scheme using both controllers is also developed. Simulation results are presented to demonstrate the frequency regulation capability and validate the effectiveness of the proposed strategy.*

Key words: *Frequency control, Over-speeding technique, Inertial response, PMSG.*

1. Introduction

In areas where the penetration of wind farms is quite high, system operators encounter frequency control problems [1]. For this reason requirements are set by system operators for grid integration of wind farms [2-4]. Power system frequency stability means the ability of a power system to maintain a stable frequency during a perturbation resulting of unbalance between production and demand. In the case of a loss of generator or an increase in energy demand, synchronous generators are able to provide reserve energy to stabilize the frequency of system [5, 6].

It is necessary that the wind farms behave like the conventional power generators units, ie, participation in frequency control. Wind farms often are composed of variable speed wind turbines with electronic power converters. Power electronics decouples the rotor inertia from the AC grid, and as a result the inertia of the power network is lowered. During the last years, studies have been oriented in the axis of frequency controller design for wind farms with variable speed wind turbines [7]. Several techniques that allow wind turbines to participate in frequency control can be found in the literature [8-14].They can be grouped into three categories (Fig.1): the kinetic energy utilization, de-loading control and use of storage equipment control. Research has been done to allow the wind turbines to inject their rotational kinetic energy into the grid during frequency variations [15]. Originally the inertial control is proposed in [16, 17], and then further studied in [18-20]. Virtual wind inertia is simulated to respond to frequency drops by using the kinetic energy stored in rotating masses of the wind turbine. Authors in [21] indicates that the wind turbine inertial response may be larger than that of synchronous generator for the same inertia value, the fact that large speed variations of variable wind speed turbine are acceptable which means having more kinetic energy which can be converted to electrical energy. As for the conventional generator, in order that wind turbines can ensure electrical grid stability, active power reserve has been obtained by forcing the wind turbine to operate out of their optimal point [22] through the pitch regulation or over speeding technique, in [23], both pitch regulation and inertial control schemes are exploited. In literature the mentioned techniques are used and combined technique between pitch control and inertial control is presented, the aim and the contribution of this paper is the use of combined technique for frequency regulation based on inertial control and rotor speed control strategy of a wind farm, connected to the network. Simulations are made for different system composition (different wind farm penetration rate). We can summarize the frequency control strategy in three groups, like shown in Fig.1.

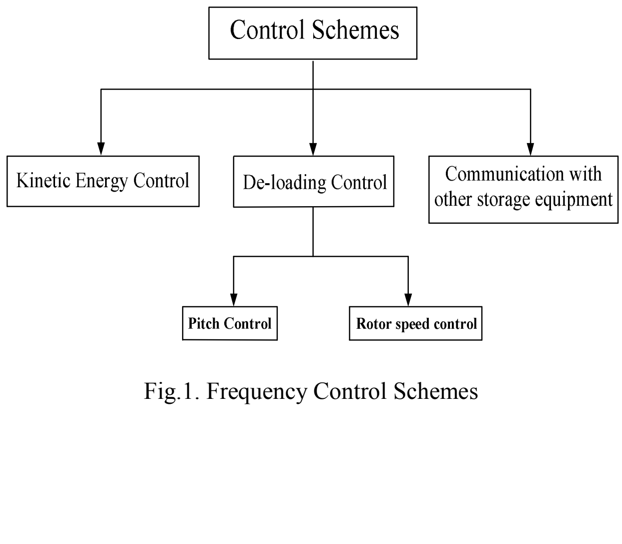

Fig.1. Frequency Control Schemes

2. State of the art on the frequency control

As previously indicated, frequency control can be grouped into three categories. Generally, the variable speed wind turbines are equipped with a controller to force them to operate at speeds that allow to maximize the power extracted from the wind, in that case the optimal aerodynamic power is calculated as:

$$P_{opt} = K_{Cp}\,(\beta) \times \Omega \qquad (1)$$

With Ω is the turbine speed and K_{Cp} is the optimal aerodynamic torque coefficient, which depends on the aerodynamics of the turbine and the pitch angle β. Fig.2 shows an example of the optimum power curve of wind turbine.

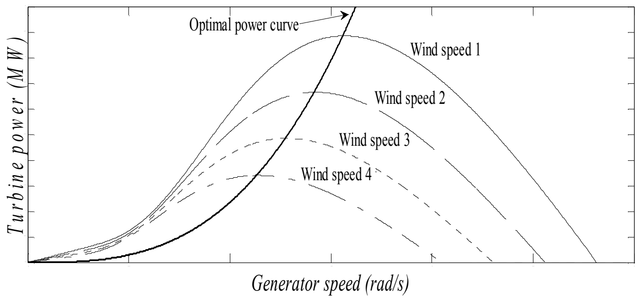

Fig.2. Power-speed curve for a range of wind speeds

But in the case where wind turbines participate in frequency regulation this control strategy is not applied, and wind turbines are required to have a reserve power. The easiest way for wind power to dispose of this reserve is to operate below capacity offered by wind speed. We can cite two methods that allow wind turbines to have a power reserve in order to participate in primary frequency control; these techniques are over speeding and pitching techniques of wind turbines.

2.1. Over speeding technique

It can only be used in variable speed wind turbine; the principle is illustrated in Fig. 3 and 4. If wind speed is considered constant and the pitch angle does not change, a requested amount of de-loading is achieved. Compared to the Maximum power point "*A*", the point "*B*" is achieved by increasing the rotor speed. In [24] a look-up table of de-loaded active power set points substitutes that of the maximum power tracking and achieves the required power. The technique requires wind speed measurement. In [25], for a DFIG, the maximum power tracking look-up table was replaced with a de-loading one as previously. However, wind speed measurement is not required. Although the strategy is accurate, for wind speed above rated, de-loading about 10% may need over speeding at 150% of the nominal rotor speed.

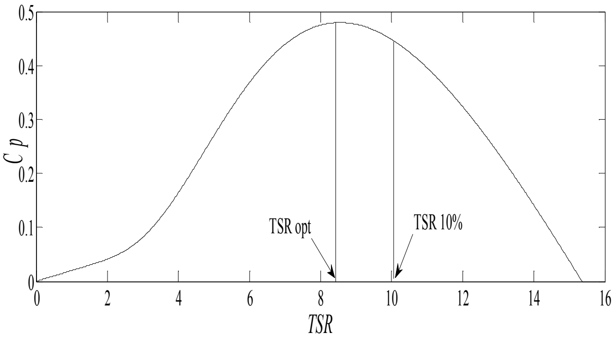

Fig.3. Principle of operation with reserve

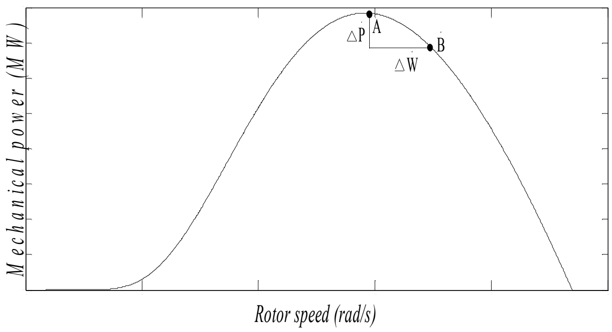

Fig.4. De-loading using Over-speeding method

That creates a burden on rotor power converters. In case of WTs equipped with a full-power converter (e.g. PMSG), over speeding does not cause the same effects. In [26], de-loading through over speeding for wind speeds above some certain value is discussed. Under speeding techniques are not preferably applicable, a deceleration of the rotor to reduce the active power output causes a transient increase in active power, due to the release of kinetic energy by the rotor, when moving from an under speed point to an optimal point, the rotor consumes transiently active power for acceleration.

2.2 Pitch control methods

It is based on the idea of performing a non optimal working point in the power rotor speed curve like shown in Fig.5. For a given wind speed, a requested amount of de-loading is achieved at an operating point corresponding to a greater pitch angle.

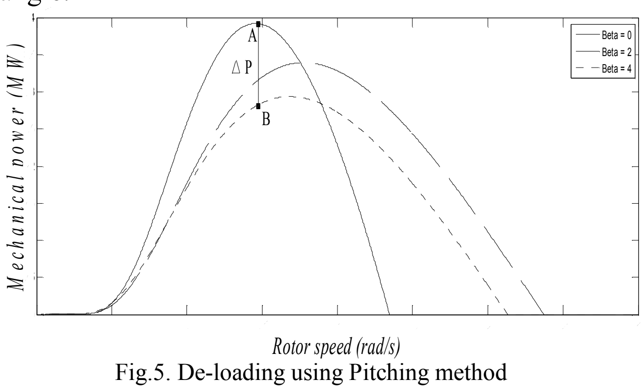

Fig.5. De-loading using Pitching method

The pitch angle controller was first suggested in [27] for de-loading of a wind turbine. In [28] the proposed pitch controlled de-loading is based on a look-up table for all operating regimes of the wind turbine. Inputs of the look-up table are the rotational speed of the wind turbine and the requested de-loading level. No wind speed measurement is required. This technique is slower in response compared to over speeding due to the pitch servo time delays. To address this issue, combination of the method presented in [29].

2.3 Kinetic energy control

This control tries to reduce imbalance between demand and generation power by activating kinetic energy stored in the rotating mass of blades and rotor. Study in [29] finds that this control method cannot be guaranteed and may cause overload of the machine when operating at high wind speeds. In [30] a primary frequency control loop is proposed, the output power is increased by releasing rotor kinetic energy when frequency mitigation is observed, but they didn't take the effect of wind speed into account. Different from traditional generators, the output power of wind turbines can be adjusted more rapidly, but it is limited by the amount of rotor kinetic energy that can be released. According to [31], typical wind turbine inertia constants are between 4 and 6 s. Using the fact that the rotor speed of variable speed wind turbines is not coupled to the grid frequency, the deceleration of the rotor can be chosen by the operator, this allows a compromise between the additionally power supplied and the duration. Generator speed of conventional synchronous generating units varies directly with frequency, i.e., for variations between *47.5* and *52.5 Hz* of frequency, generator speed stays between *0.95–1.05 pu*. However, the generator speed of wind turbines can vary down to *0.7 pu*. This means that wind turbines can use more than *4* times the capacity of regulation of the kinetic energy of conventional generating units [31]. After a drop in network frequency conventional power plants will immediately release energy from their rotating mass. The energy stored in this rotating mass is given by:

$$E= (0,5 \times J_m \times \Omega^2_m) \qquad (2)$$

Where J_m is the inertia moment of the machine in $kg.m^2$ and Ω_m is the speed of the wind turbine in *rad/s*. In electrical power engineering, inertia constant H is used, which is defined as:

$$H= (0,5 \times J_m \times \Omega^2_{Opt}) /S \qquad (3)$$

Where S is the nominal apparent power of the generator. The electrical torque controller is used to extract maximum power from the wind. A change in rotor speed Ω_m will cause a change in the torque set point. In order to integrate the inertial response, an additional term will be added to this torque set point. The principle is to take the derivative of the kinetic energy available at any speed Ω_m, the power that can be extracted from a rotating mass can be obtained as:

$$P= \frac{dE}{dt} = J_m \times \Omega_m \times \frac{d\Omega m}{dt} \qquad (4)$$

Substituting H for J_m, the following result is obtained:

$$\frac{P}{S}= 2 \times H \times \frac{\Omega m}{\Omega opt} \times \frac{d(\frac{\Omega m}{\Omega opt})}{dt} \qquad (5)$$

With P_{pu} and Ω_{pu} the per unit quantities of power and speed this can be written as:

$$P_{pu} = 2 \times H \times \Omega pu \times \frac{d\,\Omega pu}{dt} \qquad (6)$$

Fig.6 shows a schematic diagram of kinetic energy control according to the equation (6), it is noticed, about terms of Fig.6, that K_1 and K_2 are varied regarding the loading level of the wind turbine. It is done because inadequate parameters can cause unstable operation of the wind turbine.

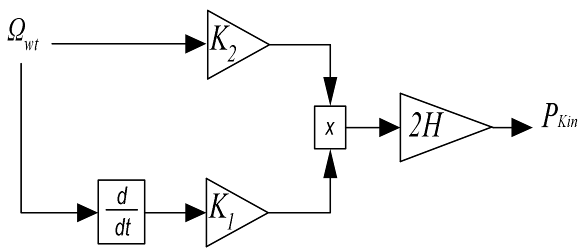

Fig.6. Schematic diagram of kinetic energy control

For example, the great value of proportional parameter K_2 under low wind speed can cause wind turbine to stall because of excessive extraction of kinetic energy [30]. It is important to note that P_{kin} is the quantity of additional wind power injected to the grid after a fault and is not necessarily equal to the natural inertia of turbine. Advantages and drawbacks of each technique are given in Table 1.

Table 1
Advantages and disadvantages of each method

	Kinetic energy control	Over speeding techniques	Pitching techniques
Advantages	• Very fast response. • Can be used for different wind speed.	• Very fast response. • Preferably applied to below rotor wind speed.	• No wind speed measurements are required. • Can be applied to above rated wind speed
Disadvantages	• Limited by the energy that it can release. • Must be used with other technical.	• Wind speed or rotor speed measurements are required. • Need of limitations of rate of change of torque cause of mechanical stress in the rotor shaft	• Larger time responses than other techniques due to pitch servo time delays. • Pitch angle regulation could affect fatigue life of the blades. • Excessive pitch control actions may lead to tear and wear on the mechanism.

3. Proposed control scheme

Regarding the contribution of this paper, this part presents the hybrid technique to enable the wind farm to participate in the frequency control. Generally, the variable speed wind turbines are equipped with a regulator to force them to operate at speeds that allow to maximize the power extracted from the wind, the output of the speed regulator determines the reference of the electromagnetic torque $T_{em\text{-}ref}$ of the machine, witch allow us to control the generator like shown in Fig.7:

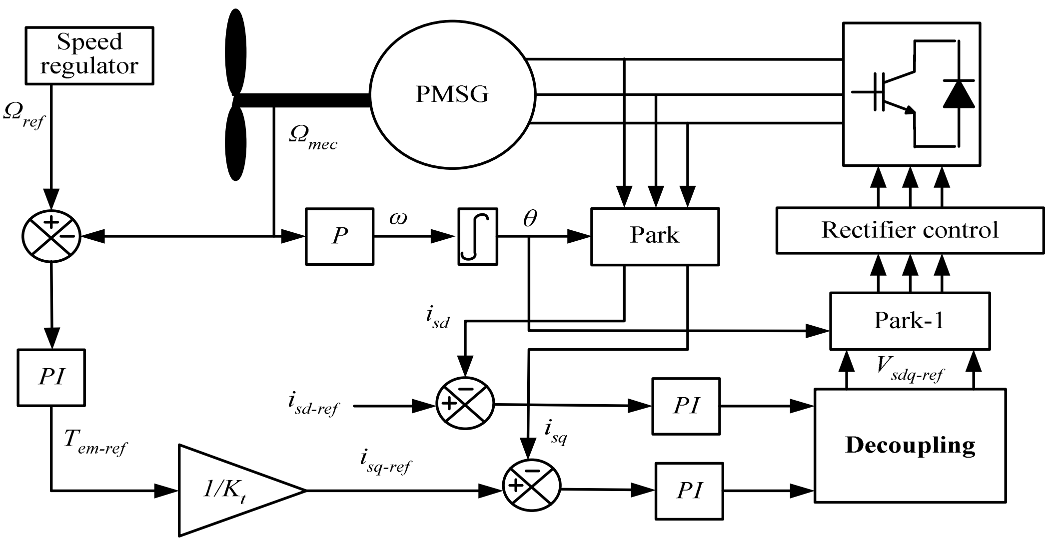

Fig.7. Vector control of the PMSG by using MPPT

In our case the speed regulator will be changed by a lookup table which allows us to determine the speed reference which ensures *10%* of reserve (over speeding technique). The control strategy of a wind generator is a combination of the over speeding and kinetic energy control, it consists in adjusting the torque reference as a function of the derivative of the grid frequency. When the grid frequency falls, the electromagnetic power set point increases, causing a deceleration of the rotor speed, which allow us extraction of the kinetic energy stored in rotating masses. The required power can therefore be released to the grid for dynamic frequency control support. Dead band (±0.02% of nominal frequency) is used to avoid the reaction of proposed strategy on very small frequency variations during normal operation of the power system.

Since the wind farm is decoupling from the grid, it will not be able to detect frequency disturbances, for this central control system is required as an intermediate between the system and wind farm like shown in Fig.8, and its role is to provide control signals in accordance with the rules established in the Grid Code.

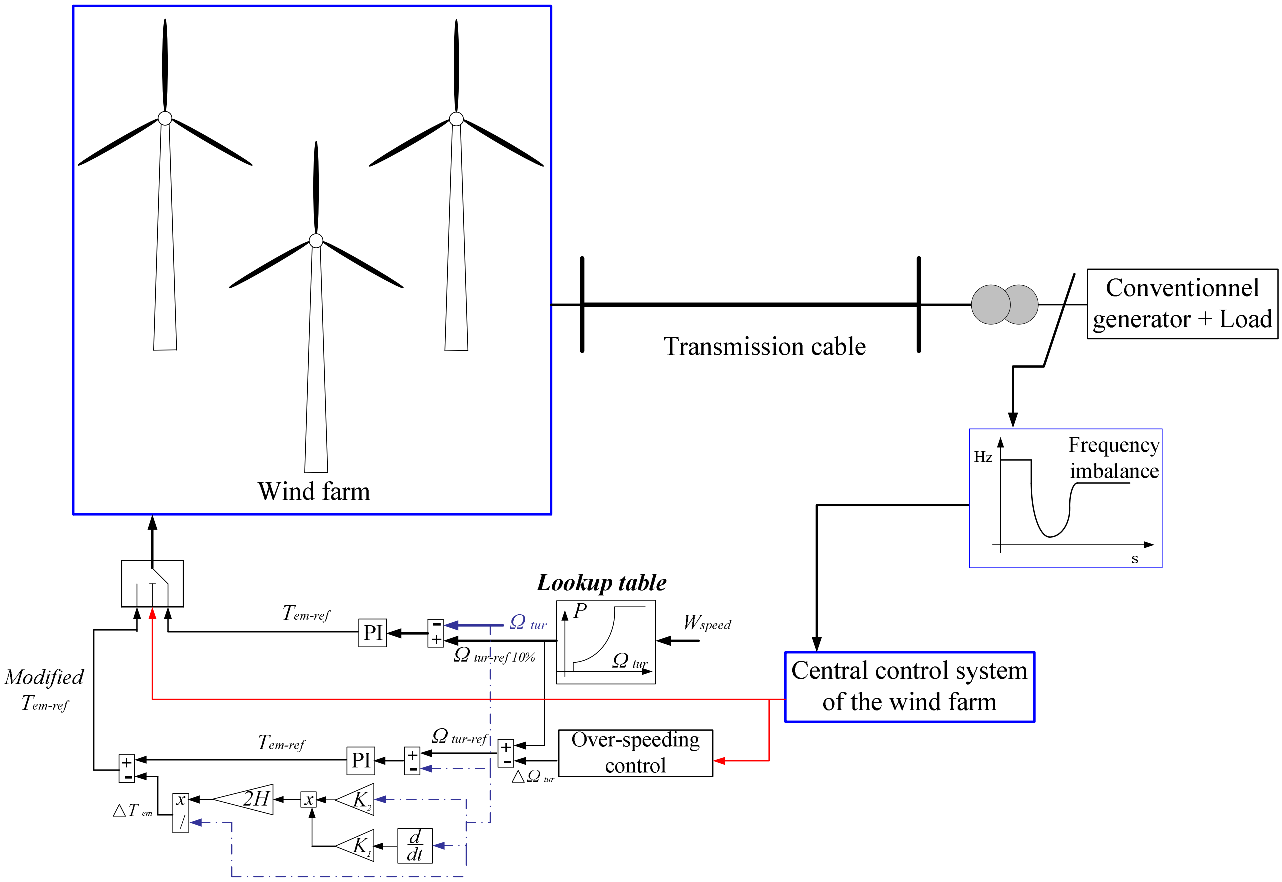

Fig.8. Explaining diagram of the system

When there is no disturbance in the frequency of the network, the wind farm work normally with over speeding mode (10% of reserve), the control of turbine give us the torques references of generators. When a disturbance is detected a signal is sent to turbines to decelerate (Reaching the maximum power point), a new torques references are calculated and an additional torque value is added (kinetic energy control), on the diagram it takes a negative value because the turbine decelerates (the derivative of a decreasing function is negative).

4. Study case presentation

As shown in Fig.9, our system is composed of a wind farm which consists of a permanent magnet synchronous generator (PMSG), conventional generating units coupled to a non reheat steam turbines and load. *5MW PMSGs* are used; the mathematical model and control strategies are widely developed in the literature. The model of *PMSG* based wind turbines, including the electrical and mechanical part, control of power converters and grid side control are detailed in [32, 36]. The electrical model of synchronous generator is detailed in [33], while the model of the steam turbine is explained in [34]. The power generation of the steam turbine is governed by a primary controller as detailed also in [34]. The output voltage is in the range of *3.3kV*, transformer is used to raise them to *33kV* "wind farm grid voltage", it is connected to the collector which serves as an intermediary between the wind farm and the electric power transmission station, and transformer is used to raise the voltage from *33kV* to *230kV*. On the other side, the output voltages of conventional generators are *18kV*; transformer is used to raise them to *63kV*. The same for the output voltages of power transmission station it is decrease from *230kV* to *63kV*.

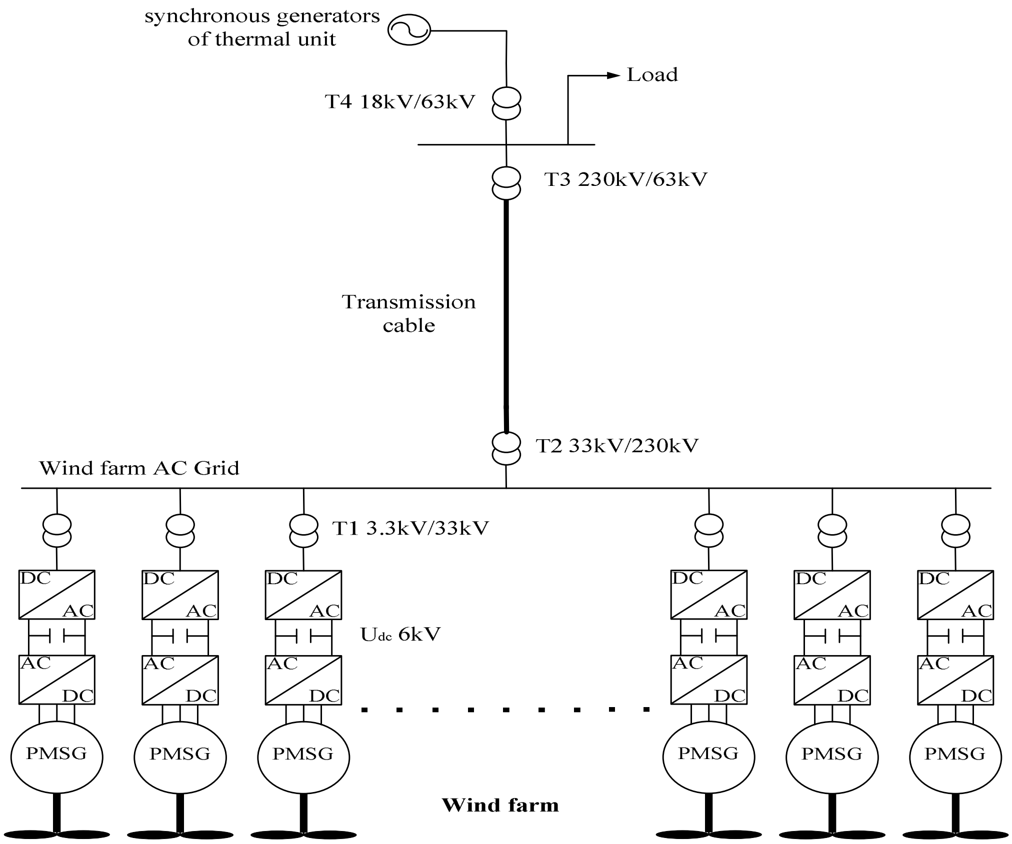

Fig.9. Global wind turbine system

5. Simulation results of global system and discussion

In this study, all system modelling and simulations are implemented on *Matlab Simulink.* Simulations are carried as shown in Fig.9. The generators are conventional synchronous generators with *IEEE* standard turbine-governor (*gov_IEEEG1*) and *IEEE* exciter (*avr_IEEET1*). Wind farm is represented by an aggregated model. Constant wind speed of *11.5m/s* is taken.

For the first part we'll study the Influence of wind power penetration, in this part, the wind farm doesn't participate in frequency control. We took a load of *1000MW* and at *t = 5s* a sudden increase of *20%* of the load is registered, four cases were taken

- Penetration rate of *0%* (*0* wind turbine and *10* conventional generators are used)
- Penetration rate of *10%* (*20* wind turbines and *9* conventional generators are used)
- Penetration rate of *20%* (*40* wind turbines and *8* conventional generators are used)
- Penetration rate of *30%* (*60* wind turbines and *7* conventional generators are used)

Fig.10 show us results of simulation, we can notice that whenever the penetration rate of the wind farm increases the frequency drop increases, hence the necessity of participation of wind farms in frequency control. For a penetration rate of *0%* the minimum frequency recorded is *48.826Hz* and stabilization frequency is *49.524Hz*, However, for a penetration rate of *30%*, minimum frequency recorded is *48.324Hz* and stabilization frequency is *49.320Hz*.

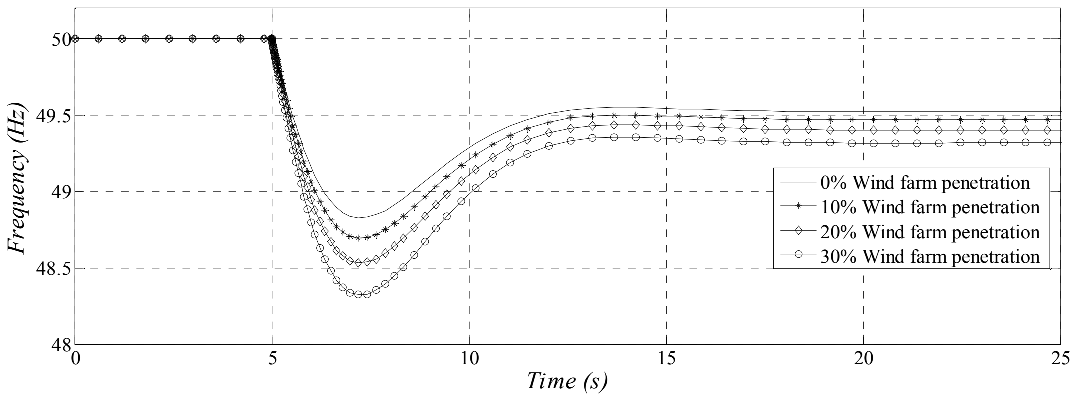

Fig.10. Simulation result Frequency response to an increase of load without wind farm participation

For the second part we'll study the Influence of over speeding technique, in this part, margin reserve of *10%* is taken to use it for participate in frequency control. We took a load of *1000MW* and at $t = 5s$ a sudden increase of *20%* of the load is registered; four cases were taken like the previous part. Fig.11 shows us the results of simulation, we can notice that whenever the penetration rate of the wind farm increases the frequency drop increases, but compared to the previous section, wind farm participation in frequency control limits the frequency droop and improves the stability of system (for a penetration rate of *30%* the minimum frequency recorded is *48.600Hz* and stabilization frequency is *49.445Hz*, instead of *48.324Hz* and *49.320Hz* respectively). It seems that improvement is minimal and negligible, but it allows us to keep more load and more households connect and feed by the network.

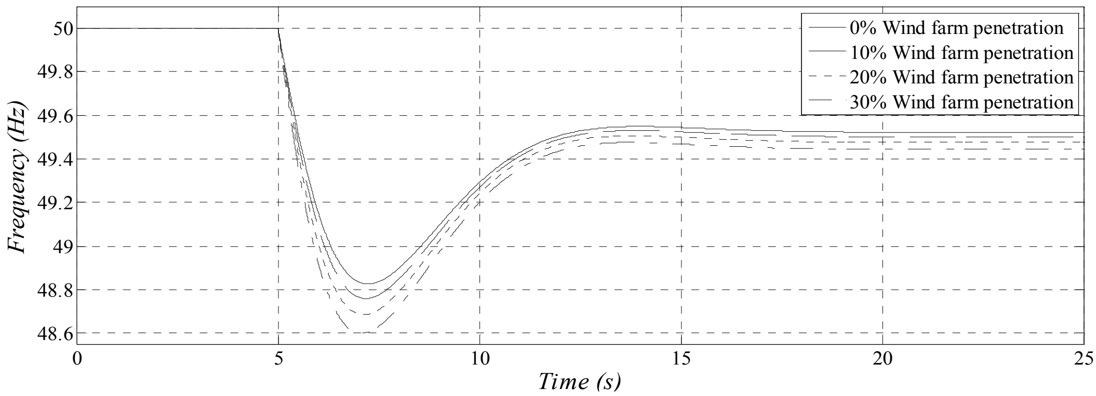

Fig.11. Frequency response to an increase of load with wind farm participation (over speeding technique)

For the third part we'll study the Influence of proposed technique, in this part, margin reserve of *10%* is taken to use it for participate in frequency control and proposed technique is used. We took a load of *1000MW* and at $t = 5s$ a sudden increase of *20%* of the load is registered; four cases were taken like the previous part. Fig.12 shows us results of simulation, we can notice that the technique proposed improve two things, first, rate of change of frequency (*ROCOF*) and second the frequency minimum, the proposed technique allows us to avoid a sudden drop in frequency by decreasing *ROCOF* whenever the rate of penetration of the wind farm is high, and this is due to the quick response of Kinetic energy control, the minimum frequency recorded is *48.732Hz* for a penetration rate of *30%* instead of *48.600Hz* and no change for the stabilization frequency because Kinetic energy control acts in the short term. Table 2 summarizes the simulation results obtained for the different techniques and for different rates of penetration (minimum frequency recorded and stabilization frequency).

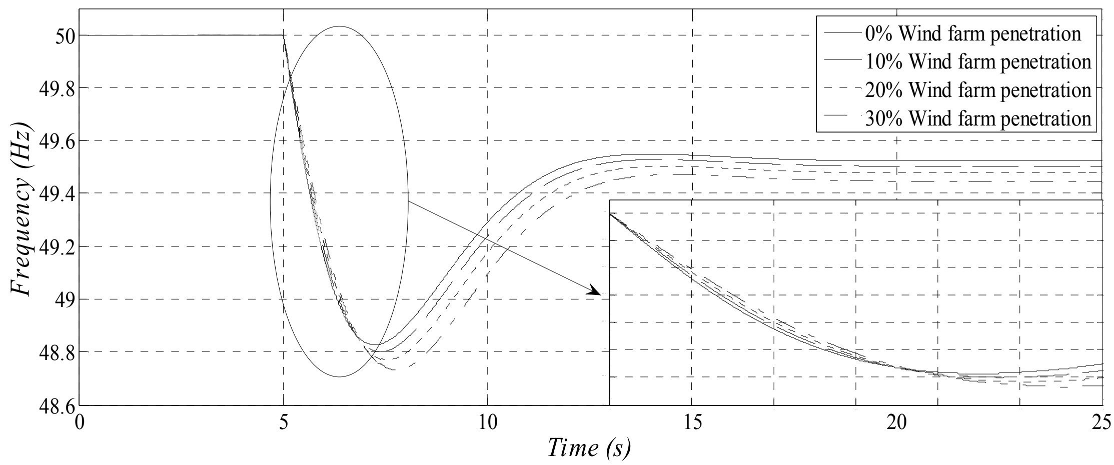

Fig.12. Frequency response to an increase of load with wind farm participation (proposed technique)

Table 2
Summaries of simulation results

Wind farm	Without participation		Over-speeding technique		Proposed technique	
penetration	Minimum frequency	Frequency stabilization	Minimum frequency	Frequency stabilization	Minimum frequency	Frequency stabilization
0%	48.826 Hz	49.524 Hz	48.823 Hz	49.524 Hz	48.827 Hz	49.524 Hz
10%	48.696 Hz	49.471 Hz	48.760 Hz	49.503 Hz	48.799 Hz	49.503 Hz
20%	48.533 Hz	49.405 Hz	48.685 Hz	49.477 Hz	48.770 Hz	49.477 Hz
30%	48.324 Hz	49.320 Hz	48.600 Hz	49.445 Hz	48.732 Hz	49.445 Hz

For the fourth part we will show the contribution of the proposed technique, the case of *30%* penetration rate was taken, We took a load of *1000MW* and at $t = 5s$ a sudden increase of *20%* of the load is registered; three scenarios were performed, first without wind farm participation, second margin reserve of *10%* is taken to use it for participate in frequency control with just over speeding control; third proposed technique is used. Fig.13 shows us results of simulation, we can notice that the technique proposed improve two things, first, rate of change of frequency (*ROCOF*) and second the frequency minimum, the proposed technique allows us to avoid a sudden drop in frequency by decreasing *ROCOF* due to the quick response of Kinetic energy control, and the minimum frequency recorded is improved.

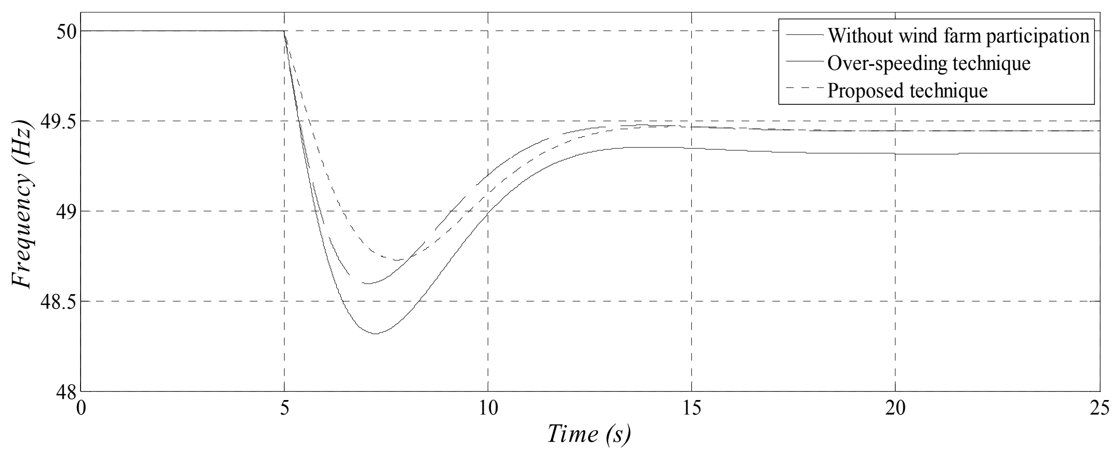

Fig.13. Frequency response to an increase of load (a) with wind farm participation (demonstration of the contribution of the proposed technique)

6. Conclusion

In this paper a new hybrid technique for participation of wind farm frequency regulation based on combining of kinetic energy control and over speeding control is presented, we began by presenting the state of the art on frequency control, than the proposed technique for frequency regulation after describing the overall system and study case presentation. Simulations were made to show the contribution and benefits of the proposed method, two advantages are to retain: the decrease of *RACOF* and the increase of the minimum recorded frequency. It is well to note that the drawback we can mention is the fact we do not use the maximum power of the wind farm for this use a storage system to participate in frequency control solution is a study in future works.

Appendix I. System parameter values

The characteristic parameters of the conventional power plant are extracted from [34] (in p.u. stator base): rated power 100 *MVA*, rated stator line to line voltage 18 *kV*, r_s= 0.0033, x_d=1.65, x_q=1.57, x_{ls}= 0.15, x'_d=x'_qd=0.275, T'_{d0}=6:5 *s*, T'_{q0}=1.25*s*. The parameters of its speed governor are [34] (in p.u. stator base): R=0.05, T_G=0.2 *s*. The parameter of the non-reheat turbine is [34]: T_{CH}=0.3*s*. The characteristic parameters of the PMSG are [35]: rated electrical power 5 *MW*, rated stator line to line voltage 3300 *V*, rated rotor speed 14.5 *rpm*, Rs=50*mΩ*, Ls=7.5*mH*, Pair of pole 60, Magnetic flux Ψ_f=28.6 *Wb*, inertia J_g= $2.10^5 kg.m^2$. The parameters of the turbine are: R=60*m*, inertia J_t= $30.10^6 kg.m^2$, $\lambda_{optimal}$ =8.5, $C_p(\lambda, \beta)_{max}$= 0,48. The parameters (in per unit) of the power transformers of the system are [33]: copper losses 0.1% of rated power, short-circuit voltage 0:15 pu, leakage reactance 0.1 pu. T1: 5*MVA* 3.3*kV*/33*kV*, WPP T2: 300*MVA* 33*kV*/230*kV*, T3: 300*MVA* 230*kV*/63*kV*; Conventional generating unit T4: 1000*MVA* 18*kV*/63*kV*. The parameters of the lines are: r= 0.0212*Ω/km*, x= 0.116*Ω/km* .

References

1. J. Brisebois and N. Aubut.: Wind farm inertia emulation to fulfill Hydro-Québec's specific need, in Proc. IEEE PES General Meeting, Jul. 2011, Detroit,MI, USA.

2. Francisco Díaz-González, Melanie Hau, Andreas Sumper, Oriol Gomis-Bellmunt.: Coordinated operation of wind turbines and flywheel storage for primary frequency control support. In Electrical Power and Energy Systems, No. 68, 2015, p: 313–326.

3. ENTSO-E. Entso-e network code for requirements for grid connection applicable to all generators. https://www.entsoe.eu/>.

4. Eirgrid Grid Code, Version 5.0, Eirgrid, 2012 [Online]. Available: http://www.eirgrid.com/operations/gridcode/

5. Pasala Gopi P. Linga Reddy. : Design of Robust Load Frequency Controller for Multi-Area Interconnected Power System Using SDO Software. In: Journal of Electrical Engineering, No 15 (4), 2015, p: 118-126.

6. Monika Jain Sushma Gupta Deepika Masand Shailendra Jain Gayatri Agnihotri. : Voltage and frequency regulation with synchronization of micro grid under islanding operation, In: Journal of Electrical Engineering, No 15 (2), 2015,p 186-195

7. Xue Yingcheng, Tai Nengling.: Review of contribution to frequency control through variable speed wind turbine, In: Renewable Energy, No 36, 2011, p: 1671-1677.

8. J. Morren, S. W. de Haan, W. L. Kling, and J. Ferreira.: Wind turbines emulating inertia and supporting primary frequency control, In: IEEE Trans Power System, No 2, 2006, p: 433–443.

9. J. Morren, J. Pierik, and S. W. de Haan.: Inertial response of variable speed wind turbines, In Electrical. Power System. Research, No 76, 2006, p: 980–987.

10. Mauricio, A. Marano, A. Gomez-Exposito, and J. L. M. Ramos.: Frequency regulation contribution through variable-speed wind energy conversion systems, In: IEEE Trans Power System, No 24, 2009, p: 173–180.

11. R. G. de Almeida and J. P. Lopes.: Participation of doubly fed induction wind generators in system frequency regulation, In IEEE Trans Power System, No 22, 2007, p: 944–950.

12. L. Wu and D. G. Infield.: Towards an assessment of power system frequency support from wind plant – Modeling aggregate inertial response, In IEEE Transaction Power System, No 28, 2013, p: 2283–2291.

13. K. Vidyanandan and N. Senroy.: Primary frequency regulation by de-loaded wind turbines using variable droop, In IEEE Trans Power System, No 28, 2013, p: 837–846.

14. M. N. Tandjaoui c. Benachaiba o. Abdelkhalek c. Banoudjafar.: Role of power electronics in grid integration of renewable energy systems, In Journal of Electrical Engineering, No 16 (1), 2016, p: 369-374

15. Conroy JF, Watson R.: Frequency response capability of full converter wind turbine generators in comparison to conventional generation, In IEEE Transactions on Power Systems, No 23, 2008, p: 649-656.

16. J. Morren, S. W. H. de Haan, and J. A. Ferreira.: Contribution of DG units to primary frequency control, In Proc. ICFPS, Amsterdam, The Netherlands, Nov. 2005.

17. J. Ekanayake and N. Jenkins.: Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency, In IEEE Trans. Energy Conversion, No 19, 2004, p: 800–802.

18. J. Morren, S.W.H. deHaan, W. L. Kling et, and J. A. Ferreira.: Wind turbines emulating inertia and supporting primary frequency control, In IEEE Trans Power System, No 21, 2006, p: 433–434.

19. G. Ramtharan, J. B. Ekanayake, and N. Jenkins.: Frequency support from doubly fed induction generator wind turbines, In IET Renewable Power Generation, No 1, 2007, p: 3–9.

20. D. Gautam, L. Goel, R. Ayyanar, V. Vittal, and T. Harbour.: Control strategy to mitigate the impact of

reduced inertia due to doubly fed induction generators on large power systems, In IEEE Transaction Power System, No 26, 2011, p: 214–224.

21. P. K. Keung, P. Li, H. Banakar, and B. T. Ooi.: Kinetic energy of wind-turbine generators for system frequency support, In IEEE Transaction Power System, No 24, 2009, p: 279–287.

22. Zhang ZS, Sun YZ, Lin J, et al.: Coordinated frequency regulation by doubly fed induction generator-based wind power plants. Renewable Power Generation, In IET, No 6, 2012, p:38-47.

23. H. T. Ma and B. H. Chowdhury.: Working towards frequency regulation with wind plants: combined control approaches, In IET Renewable Power Generation, No 4, 2010, p: 308–316.

24. Almeida RG, Castronuovo ED, Lopes JAP.: Optimum generation control in wind parcs when carrying out system operator requests, In IEEE Transactions on Power Systems, No 21(2), 2006, p:718-725.

25. Kanellos FD, Hatziargyriou ND.: Control of variable speed wind turbines in islanded mode of operation, In IEEE Transactions on Energy Conversion, No 23, 2008, p:535-543.

26. Courtecuisse V, Robyns B, Francois B, Petit M, Deuse J.: Variable speed wind generators participation in primary frequency control, In Wind Engineering, No 32, 2008, p: 299-318.

27. Holdsworth L, Ekanayake JB, Jenkins N.: Power system frequency response from fixed speed and doubly fed induction generator-based wind turbines, In Wind Energy, No7, 2004, p: 21-35.

28. Moutis P, Loukarakis E, Papathanasiou S, Hatziargyriou ND.: Primary load frequency control from pitch-controlled wind turbines, In 2009 IEEE power tech Bucharest: 1-7.

29. Durga Gautan, Lalit Goet.: Control strategy to mitigate the impact of reduced inertia due to doubly fed induction generation on large power systems, IEEE transactions on power systems, No 26, 2011, 9: 214-224.

30. Ayman Bakry Taha Attya, Thomas Hartkopf.: Control and quantification of kinetic energy released by wind farms during power system frequency drops, In IET Renewable Power Generation, No 7, 2013, p: 210 – 224.

31. Francisco Díaz-González, Melanie Hau, Andreas Sumper, Oriol Gomis-Bellmunt.: Participation of wind power plants in system frequency control: Review of grid code requirements and control methods, In Renewable and Sustainable Energy Reviews, No 34, 2014, p: 551–564.

32. Ali M. Eltamaly, Hassan M. Farh.: Maximum power extraction from wind energy system based on fuzzy logic control, In Electric Power Systems Research, No 97, 2013, p: 144– 150.

33. Ong C-M. Dynamic simulation of electric machinery using Matlab/Simulink. Prentice Hall PTR; 1997.

34. Kundur P. Power system stability and control. Mc Grau-Hill Inc.; 1993.

35. Pascal MONJEAN. : Optimisation de l’architecture et des flux énergétiques de centrales à énergies renouvelables offshore et onshore équipées de liaisons en continu“ doctoral thesis, 2012, l’École Nationale Supérieure d'Arts et Métiers. Paris.

36. Remli Aziz Aouzellag Djamal Ghedamsi Kaci. : Full electrical strategy control of wind energy conversion system based PMSG, In Journal of Electrical Engineering, No 13 (2), 2013,p 259-266.