Improving Frequency Stability with Inertial and Primary Frequency Response via DFIG Wind Turbines equipped with Energy Storage System

Christos Nikolakakos*, Umer Mushtaq†, Peter Palensky‡ and Miloš Cvetković§
Intelligent Electrical Power Grids (IEPG), TU Delft
the Netherlands
Email: *ch.nikolakakos@gmail.com, †U.Mushtaq@tudelft.nl, ‡P.Palensky@tudelft.nl, §M.Cvetkovic@tudelft.nl

***Abstract*—Renewable Energy Sources (RES), and especially wind turbines (WT) as the most mature technology, will provide a large share of energy generation in a future sustainable power system. This development introduces several challenges that need to be addressed in order to ensure a safe transition away from the fossil-fuel based generation. One of the segments where RES will have a major impact is ancillary services, such as frequency support. Until now, RES (Wind & Solar) did not participate at frequency regulation of the system, which will change as their numbers in the grid increase. The contribution of this paper is the investigation of the system impact of wind generation, when wind turbines are equipped with a control system that provides frequency related ancillary services. More specifically, we analyze primary frequency response and inertial response in the case when Doubly Fed Induction Generator (DFIG) wind turbines are equipped with Energy Storage Systems (ESS). The results are presented for different levels of RES penetration and different levels of ESS deployment.**

***Index Terms*—Renewable Energy Sources, Ancillary Services, Wind Turbines, DFIG, Real-Time Simulation .**

I. Introduction

Nowadays, global warming is becoming a concerning issue for the international community. As it is known, CO_2 emissions are responsible for a high rate of greenhouse gases, one of the main global warming causes. In order to limit this effect, many countries have decided to restrict their emissions by a significant percentage. A drastic measure to deteriorate global warming is the de-carbonization of the energy sector, which is responsible for a significant part of the emissions mentioned above [1]. To this end, traditional fossil-fuel generators are gradually decommissioned, and Renewable Energy Sources (RES) take their place. Wind Energy becomes one of the most popular power sources among other RES [2]. In fact, Wind Energy is the most used RES (excluding hydro), with its capacity, rapidly increasing globally during the last decades. This happens due to the fact that wind energy has high reserve, almost zero carbon footprint and does not contribute greenhouse emissions. Moreover its the most mature technology amongst its competitors [3]. The importance of RES and especially wind, leads to the need of researching the impact that this penetration is going to have to the existing utility grid and finding ways to make the transition to a RES-based generation system feasible by ensuring grid's stability.

Frequency is one of the most important parameters of the grid that defines its stability. As a result it has to be maintained into specific limits that are defined by each country's grid code [4]. The de-carbonization of the electric energy by increasing renewable penetration can violate the grid codes and endanger this stability if it is not done in a proper fashion. The substitution of traditional Synchronous Generators (SGs) with power electronic interfaced RES creates several problems that need to be addressed for a smooth and secure transition. This assumption is not valid for RES which, as mentioned before, are interfaced with the existing utility grid with power electronic devices. This means that RES generators and specifically wind turbines (WTs), cannot inherently support the grid's frequency. This situation, in a future scenario with high wind penetration, is going to make frequency volatile. Except for frequency, rate of change of frequency (RoCoF) is another important index that needs to be considered. During the previous years, when generation was provided mostly by SGs with inherent inertia, RoCoF had minor significance, since the inertia inherently limited this rate of change when power imbalance occurred. Yet, in a future system with high RES penetration, due to decreased system's inertia, RoCoF values will increase, which endangers the stable operation of the system. SGs, due to their inherent mechanical limitations are stressed from high RoCoF values triggering protection and leading to further outages [5].

The main contribution of this paper is the demonstration of the capability of Doubly Fed Induction Generator-based (DFIG) WTs to support the system's frequency when they are equipped with Energy Storage System (ESS) and appropriate control strategy. Moreover, it is also showed that increasing the penetration of this type of WT does not have a negative impact on frequency response. In contrast, it is also possible to achieve better performance than when the system is operated only with SG.

The paper is further organized in three subsections. The first one explains the rationale behind the control strategy for frequency support, the following one demonstrates several results for various test cases while the last one presents the conclusions.

II. Inertia support and Primary Frequency control by Type-3 Wind Turbines

The variable speed WTs , which hold the lion's share of the wind turbine market, lack or have highly limited inertial response capability and are not widely used for frequency control [6]. The traditional approach, demanded from wind turbines, is to only inject their maximum power to the grid, without participating in the ancillary services market. This approach creates serious drawbacks when wind penetration rises [7]. In order to ensure that the power network will operate in a reliable, secure and economical manner, it is required to maintain system's frequency close to the nominal value, within the desired range during its operation. Since wind penetration is gradually increasing and traditional synchronous generators are decommissioned, WTs will need to provide frequency regulation capabilities to the grid [8].

A. Inertial Response

In a power system, during steady-state operation, power generation is always equal to power demand, including grid losses. During a load or generation change event, the kinetic energy which is stored in the rotating masses of machines that are connected to the system is going to change. This means frequency will fluctuate.
The frequency change is calculated by Equation (1) [9]:

$$\frac{dE_{kin}}{dt} \approx J \cdot f_0 \cdot \frac{df}{dt} \approx P_{gen} - P_{demand} \tag{1}$$

where :

- E_{kin} : Kinetic energy stored in the generators and motors shaft [J]
- f : System frequency [Hz]
- f_0 : System's nominal frequency [Hz]
- J : Total System Inertia [kgm^2]

Since generators cannot change their active power output ($\mathrm{P_{gen}}$) instantly, the variation of frequency is mitigated by the system's kinetic energy release from its inertia. That is the inertial response which tries to stabilize the system's frequency after a disturbance. This response is an inherent feature of synchronous generators and happens immediately when there is a disturbance in the grid. Some seconds after the disturbance, primary frequency control, which is explained in the following section, is activated in order to eliminate the remnant frequency deviation.

From the Equation (1), it can be concluded that reduced J, due to decommissioning of traditional SG and increased penetration of RES, will have an impact on frequency excursions. A system with a high inertia value has a higher frequency nadir during load increases and lower RoCoF.

Therefore, it is important to achieve a similar behavior between SGs and RES, in terms of inertial response, to ensure system's frequency stability in a RES dominated grid [1]. This feature, known as synthetic inertia, has been thoroughly examined in literature [9, 11-14]. In order to enhance wind turbine capability of providing inertia response, this paper exploits the capability of connecting an ESS at the DC link of the Back-to-Back inverter topology, which allows the optimal operation of WT for the whole range of its operation.

B. Primary Frequency Control

During the past, frequency control was mainly provided by large conventional units, depending on the type of the activated reserves. The increasing RES penetration in the generation mix, replacing those sources, reduces the frequency control capability in the system [1]. Under those circumstances, RES are ideal candidates to provide primary frequency response, since they can offer faster ramp rates and flexibility due to the fact that their are interfaced with the main grid with power electronics. Thus, proper control strategies are necessary in order to ensure normal operation of the system [1].

In order to be capable of providing primary frequency response, variable speed WT are operated in a lower power point than their optimal. The difference between their optimal and the operational point can be used as an emergency reserve in case of frequency deviation. There are three types of deloaded control in literature [9,10,11]:

a) "Balanced" control: This control scheme is reserving a constant percentage of WT's rated power as a reserve.

b) "Delta" control: This control scheme, is reserving a percentage of WT's maximum active power output.

c) "Fixed Reserve" control: This control scheme is reserving a fixed amount of active power to provide as a reserve in case of a disturbance.

The mathematical formulation of this control is described in the equation. This paper proposes a modified "Fixed Reserve" control, by utilizing the ESS installed in the WT. The main difference with the traditional approach is that WT can operate at its optimal point, since reserve is provided by the ESS installed at the DC Link of the Back-to-Back inverters.

C. Inertial Response and Primary Frequency Control proposed approach

In order to provide inertial support and primary frequency support to the grid, while operating the turbine at its optimal point an ESS is integrated inside the inverter topology. To control the injection of the ESS it is necessary to implement a Bidirectional DC-DC Converter, in order to provide support in both under-frequency and over-frequency incidents. With this setup, ESS provides the active power needed, instead of the turbine shaft. The control system to provide inertial response and primary frequency control this kind of operation is consisted of two controls integrated under one system, as shown in Figure 1.

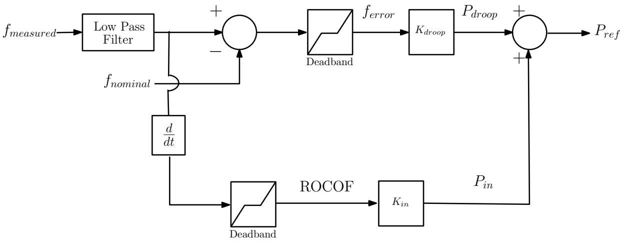

Fig. 1: Proposed integrated frequency control.

This control scheme can be expressed mathematically with Equation 2:

$$P_{ref} = (f_{measured} - f_{nominal}) \cdot K_{droop} + \frac{df}{dt} \cdot K_{in} \qquad (2)$$

With:

$$-f_{deadband} \leq (f_{measured} - f_{nominal}) \leq f_{deadband}$$

$$-df_{deadband} \leq \frac{df}{dt} \leq df_{deadband}$$

The first part is used for providing Primary Frequency Control by adjusting the injected power according to the frequency deviation. The second part is providing synthetic inertia, by adjusting the injected power according to RoCoF. The main difference between this strategy with the aforementioned ones, is the fact that the power needed to provide those ancillary services are not held as a reserve from the WT power capability, but they are provided by the ESS which is installed inside the WT. This is beneficial, since WT can always provide their maximum power to the system.

D. Topology

In order to provide the aforementioned ancillary services to the grid, while DFIG provides its maximal power output, it is necessary modify the DFIG topology. Specifically, a new connection of an Energy Storage System ESS with the DC Link is introduced. A bidirectional DC-DC converter is required to interface the ESS with DC Link and control the injected power. A bidirectional topology is proposed, so ESS can be involved both in under-frequency and over-frequency situations and provide frequency support to the grid. With this proposed topology and the appropriate control system, it is possible to operate the WT in its optimal power output. When frequency support is needed, ESS is activated with the proper control of the Bidirectional DC-DC converter and injects the necessary extra power.

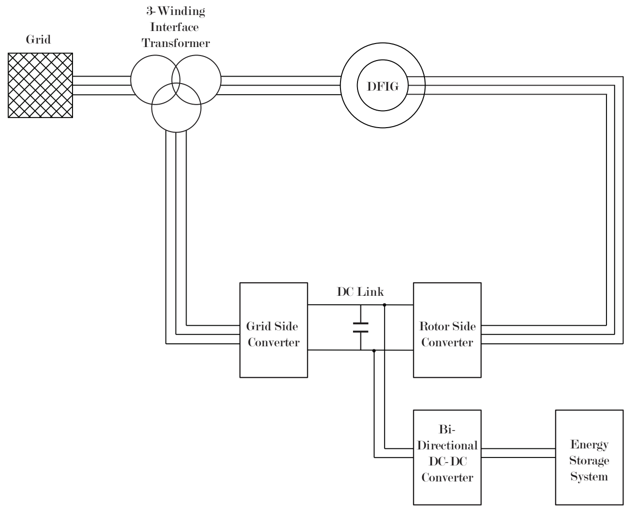

Fig. 2: DFIG topology with integrated ESS at the DC Link.

III. Simulation and Results

For all the following simulations, IEEE 14-Bus System was used as a benchmark, since it is suitable for frequency studies. In order to assess the impact of WT penetration to system's frequency behavior, one of the two SGs was substituted with a DFIG with ESS model, specifically the generator located at Bus 2. The following results show frequency response during a load increase for different penetration levels and different proportions with WTs equipped with ESS and the proposed control system. The system was modeled in RSCAD and the following results were obtained with real-time simulations using RTDS.

A. Inertial Response and Primary Frequency Control proposed approach

In this subsection, the system's frequency behaviour is examined, and a comparison between traditional primary frequency control with the proposed integrated frequency controller is going to be demonstrated. In order to get a frequency deviation at the grid, a load step increase of 10 MW at Bus 9, with a total load of 285MW, is introduced at the first second of the simulation. The Wind Penetration at this case is 15% (in terms of active power) and all WTs are equipped with ESS. Frequency and RoCoF responses are shown in the following figures and table. From Figures 3 and 4 it is clear that Primary Frequency Control has an impact on system's frequency nadir, by decreasing it, compared to the base case where WTs do not participate in frequency regulation. Furthermore, it slightly enhances the response of the system by reducing RoCoF immediately after the disturbance. The integrated control strategy, on the other hand, is improving both primary frequency and inertial response. This can be validated since both Nadir and RoCoF are improved compared to the previous controller.

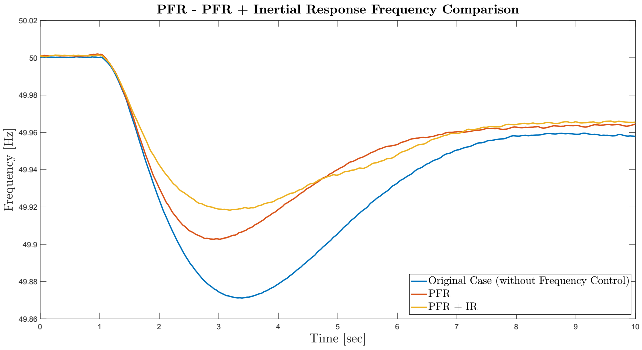

Fig. 3: Frequency Comparison between Primary Frequency Response (PFR) and proposed Integrated Control.

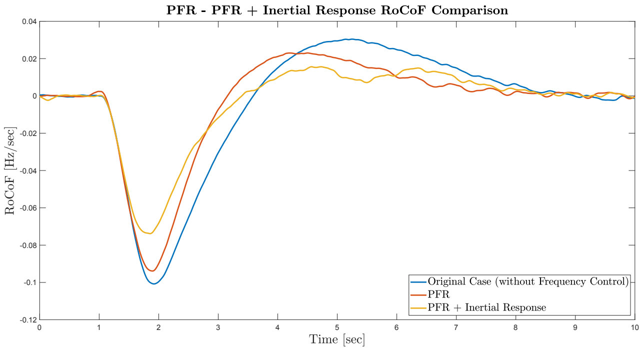

Fig. 4: RoCoF Comparison between PFR and proposed Integrated Control.

B. Frequency Comparison for different proportion of WTs equipped with ESS

In this section, a comparative frequency behaviour study for different percentage of WTs equipped with ESS and the proposed control strategy is going to be demonstrated. This study is capable of highlighting proposed control strategy's impact and its ability to mitigate frequency fluctuations even if it is partially implemented. For the following simulation, Wind Penetration is 15% of total system generation.

Furthermore, this analysis can provide information about the reserve power needed from ESS in order to achieve an operation similar to the synchronous system's (without any RES, only with SGs). From Figures 5, 6 and Table I it can be observed that, when 50% of farm's WTs are equipped with ESS and the proposed control scheme, frequency's nadir and maximum rate of change are similar to those of the base case, when system operates only with SGs. For a higher rate of the proposed system implementation, frequency becomes more stable than the synchronous system, since power reserve from ESS increases. This is an important feature of the enhanced system, which can be exploited in order to achieve better performance and simultaneously reduce WTs costs.

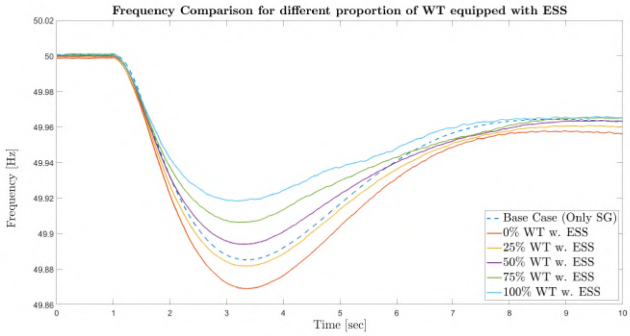

Fig. 5: Frequency Comparison for different percentage of WT equipped with ESS.

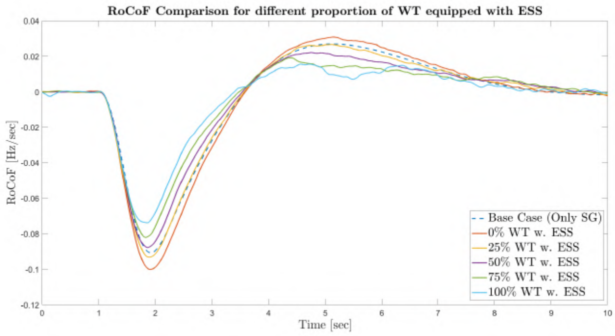

Fig. 6: RoCoF Comparison for different percentage of WT equipped with ESS.

TABLE I: Frequency and RoCoF comparison for different percentage of WTs equipped with ESS.

% ESS	Nadir [Hz]	Max.RoCoF [Hz/sec]
Base Case (Only SGs)	49.8853	-0.0906
0 %	49.8691	-0.1000
25 %	49.8812	-0.0931
50 %	49.8941	-0.0878
75 %	49.9064	-0.0820
100 %	49.9171	-0.0783

C. Frequency Comparison for different Wind Penetration Levels

As mentioned before, a serious drawback of RES penetration is that system's inertia decreases; thus the grid is more vulnerable to large frequency deviations. This leads to lower frequency nadirs and higher RoCoF, which stresses the existing synchronous generators and endangers the stability of the system. In this subsection, the system's frequency response to a load increase of 20 MW at Bus 3, for different penetration levels (in terms of active power) is examined. It has to be noted that, for each level, all WTs are considered to be equipped with ESS and the proposed integrated control system. The findings of those simulations are shown in Figures 7, 8. From the results, it is notable that, while penetration increases, frequency has enhanced performance, since nadir is increased and maximum RoCoF decreases. This is contrary to the system's behaviour when WTs are integrated without control to the grid. Figures 7, 8 and Table II clearly show that frequency nadir and maximum RoCoF are significantly improving as penetration increases. This is a consequence of adding a small ESS (in this case, 5% of DFIG's output).

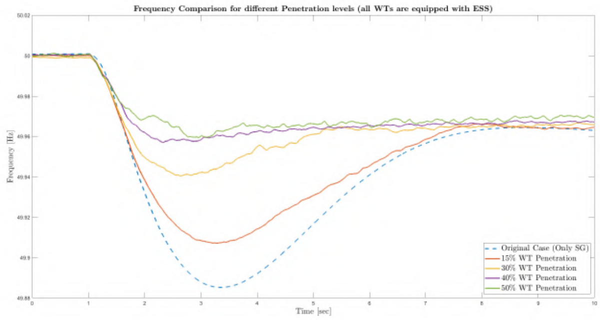

Fig. 7: Frequency Comparison for different levels of Wind Penetration.

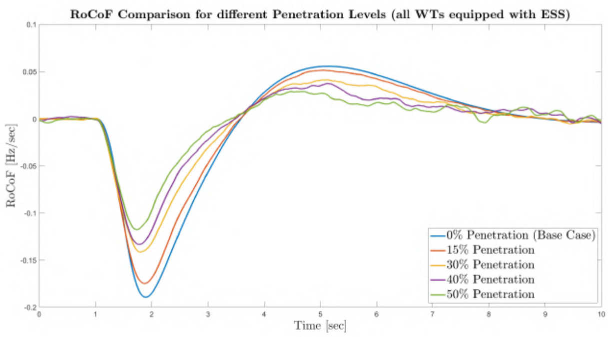

Fig. 8: RoCoF Comparison for different levels of Wind Penetration.

TABLE II: Frequency and RoCoF comparison for different Wind Penetration Levels.

Wind Penetration Level	Nadir [Hz]	Max.RoCoF [Hz/sec]
Base Case (Only SGs)	49.7615	-0.1895
15 %	49.7830	-0.1751
30 %	49.8308	-0.1416
40 %	49.8551	-0.1334
50 %	49.8742	-0.1180

IV. Conclusions

As stated in introduction, one of the most significant drawbacks which do not allow high penetration of RES to the existing grid, is their lack of inertia. Thus, when their penetration increases, system becomes more susceptible to frequency disturbances. This paper demonstrates that, a proper control strategy with an ESS can reduce this problem. From those results, it can be concluded that the proposed topology combined with the integrated controller strategy for frequency support has the potential to enhance nadir and RoCoF indices while penetration increases. This is caused by the addition of an extra energy storage at the WT, which for the aforementioned simulations was rated as 5% of the total DFIG rated power. This fact provides excellent flexibility and enables the higher penetration of wind energy to the existing grid without causing any risks since frequency stability is ensured. Moreover, another useful feature of the proposed system can be deduced. It is observed, from the simulation results, that it is possible to achieve better performance than the one when the system is based on Synchronous Generators. This fact can leverage wind energy integration to the existing grid and reduce the CO_2 emissions.

Acknowledgments

This work is in part supported by the European Union, Horizon 2020 project EASYRES, grant agreement: 764090.

References

[1] J. Essletzbichler. Renewable Energy Technology and Path Creation: A Multi-scalar Approach to Energy Transition in the UK. European Planning Studies, 20(5):791–816, 2012.

[2] S.M Muyeen. Wind Energy Conversion Systems: Technology and Trends. Springer, 2012.

[3] D. Xu, F. Blaabjerg, W. Chen, and N. Zhu. Advanced Control of Doubly Fed Induction Generator for Wind Power Systems. John Wiley Sons, 2018.

[4] E. Nycanderand and L. Söder. Review of European Grid Codes for Wind Farms and Their Implications for Wind Power Curtailments. In 17th International Wind Integration Workshop Stockholm Sweden, 2018.

[5] ENTSO-E. Rate of change of frequency (ROCOF) withstand capability. ENTSO-E guidance document for national implementation for network codes on grid connection. Technical report, March 2017.

[6] M. Pacesila, S.G Burcea, and S.E. Colesca. Analysis of renewable energies in European Union. Renewable and Sustainable Energy Reviews, 56:156–170, 2016.

[7] J. Van de Vyver, J. De Kooning, B. Meersman, L. Vandevelde, and T. L Vandoorn. Droop Control as an Alternative Inertial Response Strategy for the Synthetic Inertia on Wind Turbines. IEEE Transactions on Power Systems, 31(2):1129–1138, 2016.

[8] K. Oureilidis, K.- N. Malamaki, K. Gallos, A. Tsitsimelis, C. Dikaiakos, S. Gkavanoudis, M. Cvetkovic, J. Mauricio, J. Ortega, J. Ramos, G. Papaioannou, and C. Demoulias, Charis. (2020). Ancillary Services Market Design in Distribution Networks: Review and Identification of Barriers. Energies. 13. 917.

[9] W. Ziping, G. Wenzhong, G. Tianqi, Y. Weihang, H. Zhang, Y. Shijie, and W. Xiao. State-of-the-art review on frequency response of wind power plants in power systems. Journal of Modern Power Systems and Clean Energy, 6(1):1–16, 2018.

[10] F. Blaabjerg and K. Ma. Wind Energy Systems. Proceedings of the IEEE, 105(11):2116–2131, Nov 2017. ISSN 0018-9219.

[11] A. Žertek, G. Verbič, and M. Pantoš. A Novel Strategy for Variable-Speed Wind Turbines' Participation in Primary Frequency Control. IEEE Transactions on sustainable energy, 3(4):791–799, 2012.

[12] A. Žertek, G. Verbič, and M. Pantoš. Optimised control approach for frequency-control contribution of variable speed wind turbines. IET Renewable Power Generation, 6(1):17–23, 2012.

[13] L. Chang-Chien, C. Hung, and Y. Yin. Dynamic reserve allocation for system contingency by DFIG wind farms. IEEE Transactions on Power Systems, 23(2):729–736, 2008.

[14] J.P Lopes and R. Almeida. Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation. IEEE Transactions on Power Systems, 22 (3):944–950, 2007.