The Need for Additional Inertia in the European Power System until 2050 and the Contribution of Wind Power

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Abstract – **In future years, a considerable share of conventional power plants in the European power system is expected to be replaced by solar and wind power, which may require additional inertia support for frequency control. Motivated by that, this paper quantifies the need for inertia in the future European power system until 2050. This paper also investigates the potential role of wind power as a provider of that by emulated inertia. The European power system of the EU-28 countries has been clustered to the four synchronous grids, UCTE, Nordic, UK and Baltic. A total of twelve different scenarios, developed by others, are considered, regarding the future energy mix in the EU. For each of these scenarios the worst case is examined. Production units are dispatched according to their sustainability which is coherent with the minimum natural contribution of inertia, in descending order. The available power output for all types of production is equal to the corresponding installed capacities, while a sudden disconnection of the largest production unit of the dispatched types is considered. Simulation results show that in most cases there will be a need for additional inertia and wind power could fully cover the additional inertia requirement up to 66.4% on the UCTE grid and for 98.3%, 92.4% and 99.1% on the Nordic, UK and Baltic grids, respectively.**

Keywords –**Emulated inertia, European power system, frequency response, inertia support, Wind power.**

I. Introduction

For 2050, leaders of the European Union and the G8 announced the objective to reduce greenhouse gas emissions to at least 80% percent below 1990 levels if other parts of the world initiate similar efforts. The European power sector would need to contribute even more than other sectors to these targets and reduce its greenhouse gas emissions to more than 95% percent below 1990 levels [1]. In order to achieve these goals, a considerable amount of Renewable Energy Sources (RES) should replace the conventional power plants.

Among RES, wind represents a significant amount. With a total net installed capacity of 168.7 GW, wind already today remains the second largest form of installed power generation capacity in Europe, closely approaching gas installations [2]. However, this growth in the installed power generation capacity in wind and the subsequent reduction of the conventional power plants (i.e. thermal production units) has already raised serious concerns about frequency regulation and stability problems when faults occur in the system [3]-[4]. Synchronous generators of thermal units help the power system to resist changes in its frequency. Synchronously connected rotating masses contribute to this resistance with their inertia, releasing their kinetic energy into the grid if needed to preserve the frequency. Nevertheless, wind power plants comprise of generating units with a power electronic converter interface to the power system. These converters are most often controlled in such a way that operation of the generating plants is isolated from the system frequency, thus they are not able to offer natural inertia, resulting in a system inertia reduction.

Significant research has been carried out to investigate the impact of reduced system inertia on frequency disturbances and the capability of modern wind power plants to provide emulated inertia to the grid. Authors in [5] have examined the impacts of emulated inertia, provided by wind turbine generators (WTG), on the frequency response. The results have shown that deployment of emulated inertia response could improve (increase) frequency nadir when a fault occurs in the power system. In [6] the expected system's changes on inertia in 2020 and 2025 have been estimated, showing that the future reduction of the Nordic Power System's kinetic energy could cause larger frequency deviations from the nominal value (50 Hz).

The aim of this paper is to quantify the maximum requirement for inertia in the European power system up to 2050 and to investigate the potential of wind power as a provider of emulated inertia.

Twelve different scenarios of future electricity production mix in Europe, by three different providers, are considered. In the study it is assumed that the future response time of the European grid should match with the current one and the frequency must not deviate more than 1% of the nominal value (50 Hz). For each scenario the frequency deviation is examined in the worst case. The units are considered to dispatch according to their sustainability, which was in a high degree coherent with the minimum natural contribution of the inertia, in descending order and the available power output for all types of production is equal to the corresponding installed capacities. A sudden disconnection of the largest production unit of the dispatched types is considered. The need for additional inertia to keep the frequency response stable and within its limits is found for all scenarios and afterwards the

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contribution of wind power on this additional need for inertia is calculated.

The rest of the paper is organized as follows: Section II presents briefly the related theory of power systems inertia and the emulated inertia of wind turbines. In Section III the case study is described and in Section IV the relevant results are presented and discussed. Finally, conclusions are drawn in Section V.

II. Theoretical Background

A. Inertia in Power Systems

The dynamic behavior of a synchronous turbine-generator i can be described using the motion equation as defined in (1).

$$H_i \frac{df_i}{dt} = \frac{f_n^{\,2}}{2S_{ni}\,f_i}(P_{mi} - P_{ei}) \tag{1}$$

where H_i is the inertia constant of the turbine-generator i and is given by (2).

$$H_i = \frac{1}{2}\frac{J_i \omega_n^{\,2}}{S_n} \tag{2}$$

In the above formulas, f_i is the frequency, P_{mi} is the mechanical power of the turbine, S_{ni} is the rated power, P_{ei} is the electrical power of generator i, f_n (ω_n) is the nominal frequency (rotational speed) and J_i is the moment of inertia of the generator-turbine.

Real power systems consist of a large number of production units, hence it is common for stability studies to use a reference transformation called the Center of Inertia (COI), where all generators of the system are represented by one theoretical equivalent generator rotating with ω_{COI} speed. For a power system consisting of N generators, the motion equation is expressed by (3) [7].

$$H_{sys}\frac{df_{COI}}{dt} = \frac{f_n}{2\sum_{i=1}^{N} S_{ni}}\Delta P \tag{3}$$

where H_{sys} is the total inertia of the power system and is defined as:

$$H_{sys} = \frac{\sum_{i=1}^{N} S_{ni} H_i}{\sum_{i=1}^{N} S_{ni}} \tag{4}$$

B. Emulated Inertia of Wind Turbines

The conversion of aerodynamic input power to output electrical power in variable speed wind turbines (VSWTs) is governed by the controller of the machine side converter. This controller varies the generator's real power output independently from any other parameters, including the input power to the generator by the turbine. Any difference between the input power and the output power is added on to the kinetic energy storage of the rotor, varying the rotor speed.

To support inertia emulation, the controller governing the generator power output needs to adopt a different control philosophy. Since a VSWT distributes power based on the reference power level dynamically set in its controller, a sudden increase in power output only needs a corresponding adaptation in the power set point. The wind turbine would extract kinetic energy from its rotor and deliver to the power system, similar to a synchronous generator responding to a system frequency disturbance [8].

III. Case Study setup

The European Power System of the EU-28 countries has been clustered to the four synchronous grids, UCTE, Nordic, UK and Baltic. Notice that the Ireland synchronous grid is not included in the simulation results. Each of these is simulated utilizing the model developed in [6] which is shown in Fig.1. The power system model is based on a system with hydro power as main frequency regulation. Authors in [6] tuned the model's parameters relying on historical measurements of Nordic grid's frequency response. In our case study it is assumed that in the future all the four synchronous grids would have the same frequency response with Nordic's current one, therefore the values of the parameters are the same. In Fig. 1, H_{tot_sim} is system's inertia and ΔP is the power of the considered disconnected unit. The considered scenarios have been obtained from three different providers, the European Commission, the McKinsey & Company and the DNV-GL [1], [9] and [10].

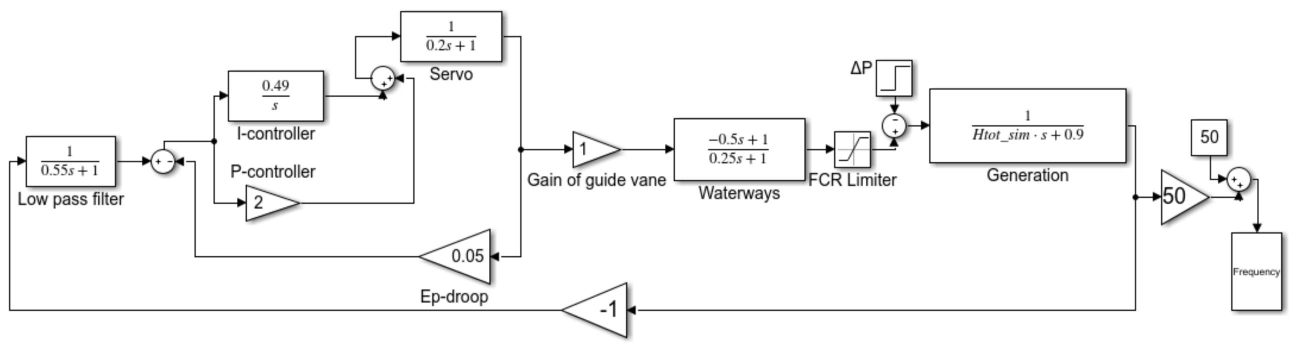

Figure 1. European power system Simulink model

TABLE I. SCENARIOS INSTALLED CAPACITIES IN GW

Provider of Scenario	Name	Time Horizon	Solar	Wind	Bio-mass	Hydro	Nuclear	Gas	Fossil	Total
EU	EU2030	2030	180.9	255.4	53.3	133.2	109.9	208.4	116.1	1057
	EU2050	2050	294.7	367.6	57.3	142	92.8	269.5	55.5	1279
McKinsey	Green	2050	330.1	647.1	56.4	214.8	79.4	Inc. in Fossil	190.4	2000
	Clean	2050	67.4	404.4	43	214.8	290.2	Inc. in Fossil	217.6	1237
DNV-GL	1	2030	188	470	78	120	91	92	50	1089
	1-DG	2030	376	405	78	120	91	91	56	1217
	1a	2030	229	526	83	121	91	102	46	1198
	1a-DG	2030	450	451	83	121	91	106	50	1352
	1b	2030	161	439	78	120	91	77	53	1019
	1b-DG	2030	332	381	78	120	91	78	57	1137
	2	2030	131	393	77	119	105	143	38	1006
	3	2030	94	325	74	118	102	78	117	908

The twelve scenarios are selected for comparison reasons and to also give a possibility to study the different combinations of production units and different total size of the system. In Table I the installed capacities per type of production of the EU-28 countries are illustrated for each scenario separately.

The hourly consumption time series has been obtained from the ENTSO-E [11] for the year 2017 and afterwards was scaled up according to the total annual production of each scenario and for each synchronous grid. Moreover, the proportions of the annual consumption and the installed capacities per type of production of each considered synchronous grid in the total European Power System have been obtained from [9].

The frequency response in the grids is simulated for the whole year, after a disconnection of the largest dispatched production unit for each grid, which are illustrated in Fig. 2 [11]. The requirement for additional inertia to maintain the frequency stable and within the acceptable limits, as set by the ENTSO-E (i.e. 49.5-50.5 Hz), is found for all synchronous grids and each scenario. In Table II the considered inertia constants for the production units are presented, where 0 is considered for wind since it has no natural contribution. The available power output for all types of production is equal to the corresponding installed capacities and they are dispatched according to their

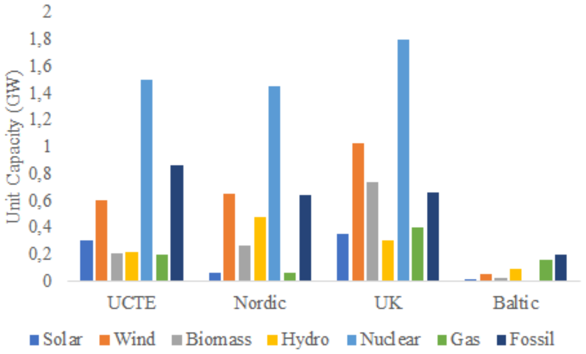

Figure 2. Largest production units

TABLE II.

Type of electricity production	Inertia constant H (s)
Nuclear	6,4
Hydro	3,4
Thermal	2,7
Wind	0 - 6
Solar	0

sustainability. Afterwards, the percentage of the additional inertia which wind power could provide to the grid is calculated. As it was mentioned above, wind turbines can provide emulated inertia to the grid through the power converters they are connected to, utilizing appropriate control schemes. According to [12]-[14] typical values of the inertia constant H for variable speed wind turbines are between 2-6 s. However, if only a part of the wind turbines is utilized for support also lower levels of contributions can be achieved on a system level. Our study is based on these values (0-6 s) to estimate the proportion of wind power contribution on the total additional inertia requirement.

IV. RESULTS AND DISCUSSIONS

A. *Requirement for Additional Inertia until 2050*

In Fig.3(a) UCTE's minimum and maximum requirements for additional inertia for all the considered scenarios are presented. As it can be observed, in all scenarios the maximum need for inertia is around 1.3 s, while the minimum value varies between 0 and 1.2 s depending on the scenario. The UCTE grid is the largest synchronous grid in Europe, therefore a loss of a production unit (e.g. a 600 MW wind farm in our study) corresponds only to 0.3% of the projected UCTE's minimum load.

Nordic grid's maximum additional need for inertia varies between the values 2.5 and 7.4 s, depending on scenarios and the minimum requirement is almost zero in all scenarios, as it can be seen in Fig. 3(b). The requirement for inertia in the Nordic grid is considerably higher compared with the UCTE. This can be interpreted by the fact that a disconnection of the largest wind farm in Nordic countries with a total capacity of 650 MW, corresponds to around 2.5-3% of the total Nordic grid's expected future minimum load.

In the UK grid the maximum additional requirement for inertia ranges between the values 3.3 and 8.4 s and the minimum requirement between 0 and 1.2 s, as are illustrated in Fig. 3(c). The largest wind farm in the UK grid has an installed capacity of 1.026 GW, corresponding around to 2.8-3.2% of the total expected minimum load.

Finally, Fig. 3(d) depicts the maximum and minimum additional need for inertia in the Baltic synchronous grid. The maximum need varies between the values 1.5 and 5.7 s and the minimum between the values 0 and 1 s. The projected wind and solar penetration in Baltic countries for the coming years is moderated, thus the conventional plants could provide a part of the need for inertia. The largest

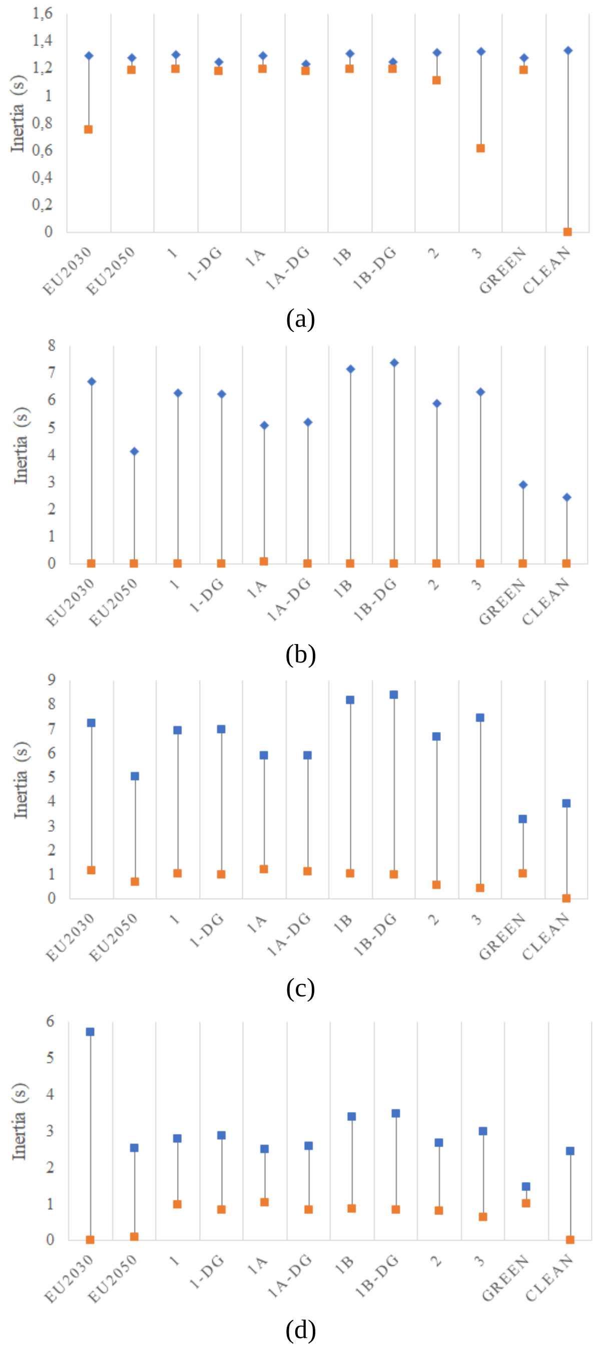

Figure 3. Requirement for additional inertia in the (a) UCTE, (b) Nordic, (c) UK and (d) Baltic synchronous grids.

Figure 4. Wind power contribution on inertia support for the (a) UCTE, (b) Nordic, (c) UK and (d) Baltic synchronous grids.

wind farm in Baltic countries with total capacity of 50 MW, corresponds to around 1.5-2.1% of the projected total future minimum load.

B. *Wind Power Contribution on Inertia Support*

As it can be observed in Fig. 4(a) wind power could fully cover the requirement for inertia in the UCTE grid up to 66.4% among all the scenarios. In scenarios with more solar installed capacities and less annual generation (1-DG, 1a-DG, 1b-DG) full inertia support is almost impossible. This can be interpreted by the fact that UCTE's installed solar and wind capacities correspond approximately to 95.8% and 80.32%, respectively, of the total installed solar and wind power capacities of EU-28 countries, thus when the considered solar production covers the demand wind power in not dispatched.

It can be concluded from Fig. 4(b) and Fig. 4(c) that in the Nordic and UK grids full inertia support is possible for up to 98.3%, 92.4%, respectively. In the Nordic grid the installed solar and wind power capacities represent 0.33% and 5.9% correspondingly, of the total installed capacities of EU-28 countries, while in the UK grid the proportions of solar and wind power capacities of the total are 3.83% and 12.84%, respectively. Consequently, in most cases wind power sources are dispatched and could offer emulated inertia into the grids [9].

In the Baltic grid wind power could provide full inertia support up to 99.1%. The solar and wind power installed capacities correspond to 0.04% and 0.94% of the total. As it was mentioned before the projected wind and solar penetration in the Baltic countries is limited, thence conventional plants are dispatched and cover partially the need for inertia.

C. Competition of other Inertia Providers

Following, wind power is compared qualitatively with different inertia providers to find the most preferred option. The considered alternative options in our study are batteries (Lead Acid, Li-Ion, Sodium Sulphur), supercapacitors, flywheel storage, dispatch of conventional power production and HVDC-links between adjacent synchronous grids.

Authors in [15] have found that flywheel storage is the least costly solution for inertia support among batteries and supercapacitors. However, the employment cost of wind turbines for inertia support is negligible, since overrating the converter is not necessary [8], thus flywheel storage could satisfy the requirement for inertia as a second choice.

The dispatch of conventional power plants could provide the necessary inertia to the grid, nevertheless it may carry environmental risks. On the one hand, focusing on the future European power system presented previously, inertia support through HVDC-links would be derived mostly from wind turbines, as in all the four considered synchronous grids the projected power production from conventional power plants is limited. On the other hand, transferring power from one synchronous grid to another could export the problems in the neighbour grids. In addition, HVDC-links are available only in a few points which lower the availability of this option.

V. CONCLUSIONS

In this paper the need for inertia IN the European power systems was quantified and the potential of the wind power as emulated inertia provider was investigated.

The case study results demonstrate that the maximum requirement for additional inertia in the UCTE is limited and has the value of about 1.3 s. For the Nordic and UK grids the maximum need is higher, since they are weaker grids comparing to the UCTE and range between 2.5-7.4 s and 3.3-8.4 s, respectively. Baltic’s maximum requirement varies between 1.5 and 5.7 s. Furthermore, it is shown that wind power may fully cover the additional inertia requirements for up to 66.4% on UCTE grid and for 98.3%, 92.4% and 99.1% on Nordic, UK and Baltic grids, respectively. Qualitative comparison of different inertia providers indicates that wind power is one of the most promising solution for emulated inertia among the other alternatives such as batteries (Lead Acid, Li-Ion, Sodium Sulphur), supercapacitors, flywheel storage, dispatch of conventional power production and HVDC-links between adjacent synchronous grids.

REFERENCES

[1] McKinsey&Company, Transformation of Europe´s power system until 2050, for Germany, Electric Power and Natural Gas Practice, October 2010, McKinsey & Company Inc. [Online]. https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/epng/pdfs/transformation_of_europes_power_system.ashx [Accessed: June 26. 2018]

[2] Wind Europe, ‘Wind in power 2017 Annual combined onshore and offshore wind energy statistics’ [Online]. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2017.pdf

[3] R. Doherty, A. Mullane, G. Nolan, D. J. Burke, A. Bryson, and M. O'Malley, "An Assessment of the Impact of Wind Generation on System Frequency Control," *Power Systems, IEEE Transactions on,* vol. 25, no. 1, pp. 452-460, Feb. 2010.

[4] W. Ye, G. Delille, H. Bayem, X. Guillaud, and B. Francois, "High Wind Power Penetration in Isolated Power Systems — Assessment of Wind Inertial and Primary Frequency Responses," *Power Systems, IEEE Transactions on*, vol. 28, no. 3, pp. 2412-2420, Aug. 2013.

[5] L. Ruttledge, D. Flynn, "Emulated Inertial Response from Wind Turbines: Gain Scheduling and Resource Coordination, " *Power Systems, IEEE Transactions on*, vol. 31, no. 5, pp. 3747-3755, sept. 2016.

[6] Erik Ørum, Mikko Kuivaniemi, Minna Laasonen, Alf Ivar Bruseth, Erik Alexander Jansson, Anders Danell, Katherine Elkington, Niklas Modig, "ENTSOE Report: Future system inertia", [Online]. https://docstore.entsoe.eu/Documents/Publications/SOC/Nordic/Nordic_report_Future_System_Inertia.pdf

[7] J. Machowski, J. Bialek, and J. Bumby, "Power System Dynamics, Stability and Control 2nd Edition," John Wiley&Sons, Ltd., 2008.

[8] A. Wickramasinghe, L. Meegahapola, A. P. Agalgaonkar, S. Perera, "Design considerations for inertia emulating controllers used in variable speed wind turbines, *" IEEE PES General Meeting,* Oct. 2014

[9] European Commission, "EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050", 2016, [Online]. https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf

[10] DNV-GL, Integration of Renewable Energy in Europe, ENER/C1/427-2010, Bonn, 2014. [Online]. https://www.dnvgl.com/publications/integration-of-renewable-energy-in-europe-103268

[11] ENTSO-E. (2017) ENTSO-E transparency platform. [Online]. Available:https://transparency.entsoe.eu/

[12] M. Persson, P. Chen, "Frequency control by variable speed wind turbines in islanded power systems with various generation mix," *IET Renewable Power Generation*, vol. 11, no. 8, pp. 1101-1109, July 2017

[13] Wind power in power systems //Edited by Thomas Ackermann// John Wiley&Sons, Ltd., 2005. – 691 p.

[14] J. Morren, Sjoerd W. H. de Haan, Wil L. Kling, J. A. Ferreira, "Wind Turbines Emulating Inertia and Supporting Primary Frequency Control," *Power Systems, IEEE Transactions on*, vol. 21, no.8, pp. 433-434, Feb. 2006

[15] H. Thiesen, C. Jauch, A. Gloe, "Design of a System Substituting Today’s Inherent Inertia in the European Continental Synchronous Area," *Energies*, vol. 9, pp. 1-12, July 2016