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Analysis of the Impact of Wind Power Participating in Both Energy and Ancillary Services Markets – The Danish Case

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Abstract—**The impact of a high penetration of wind power generation in power systems motivates need for an assessment of its interaction with electricity markets. With the continuous evolution of wind turbines technology, wind farms have today the ability to provide certain ancillary services with appropriate levels of security and reliability. The participation of wind farms in ancillary service markets ought to rely on market designs and offering strategies that satisfy power system needs, as well as their operating characteristics. Here we evaluate the system impact of different offering strategies that wind farms employ on energy and ancillary service market. Already proposed Proportional Wind Reserve Strategy (PWRS) and a Continuous Wind Reserve Strategy (CWRS) are used to determine the amount of available power for ancillary services. A case study based on real and recent data for Denmark allows evaluating impact on market prices, wind farms' revenue, as well as impact on power system reliability.**

I. INTRODUCTION

Wind power generation is one of the most important energy resources in the Danish power system. According to Energinet.dk (the Transmission System Operator-TSO), in December 2013 wind generation supplied, on average, 54.8% of the total electrical energy consumption. In particular on December 1st, wind turbines supplied all Danish power demand, while also exporting 36% of its power generation [1].

Following the Danish energy roadmap [2], such situations with very high wind generation will be common in the near future. In order to ensure an adequate system reliability level, new mechanisms for ancillary service provision should be thought of and implemented [3]. These should additionally consider the use of wind generation, not only to supply energy, but also to provide services necessary to support power system operation. The new generation of wind generators has the ability to provide different types of services, for instance those related to frequency and voltage control. Current wind turbines and wind farms controller systems have the capability (*i*) to alter active power injection in a few seconds, (*ii*) to respond to reactive power demands in less than 1 second, (*iii*) to support voltage levels, and (*iv*) to provide kinetic energy (virtual inertia) [4-7].

To use wind generation to support power system operation, new business models are required, also softening some of the rules imposed by system operators on wind generation units [8]. From the point of view of wind generators' owners, the participation in ancillary services market represents a new business opportunity [9]. Each wind farm should design its best bidding strategy, by determining both the amount of energy to offer through the day-ahead energy market, and the energy/capacity to bid in ancillary service markets [10]. However, the participation in ancillary service markets also represents a big challenge for wind power generation due to the high confidence level required for the delivery of market products: they cannot fail to deliver these services. In many electricity markets, failure to deliver may result in market exclusion. To face these concerns, adequate offering strategies and new market designs should be developed in order to accommodate the ability of wind turbines to provide ancillary services, while taking into account the intermittent behaviour of the wind.

In this scope, the work presents a study focusing on the participation of wind power generation in current energy and ancillary services market models. Two different offering strategies for ancillary services are implemented, considering a fix amount of power and a fix generation percentage. The study is performed from a system perspective and is based on real Danish market prices (DK1 and DK2 areas from Nord Pool), wind generation forecasts and wind power generation outcomes for these areas. These strategies are developed based on predicted wind generation, while they are validated based on the incomes obtained from actual wind generation and settlement prices used by the Danish TSO. Based on these results, it is clear that the participation of wind generation in both energy and ancillary services market may lead to an increase in day-ahead market prices. Moreover, new market designs are required to improve the economic efficiency of energy and ancillary service co-optimization. Market players would then revisit their offering strategies considering these new market rules and the new energy mix with high penetration of renewable energy sources.

The paper is structured as following: Section II presents the detailed formulation of offering strategies and market design for wind power participation in energy and ancillary services market. Section III describes our empirical investigation based on the Danish case-study, from both economical and operations perspectives. Finally, Section IV gathers the most important conclusions and discussion.

II. WIND POWER PARTICIPATION IN ELECTRICITY MARKETS

A. *Energy and ancillary services market*

The increasing penetration of wind power generation in power systems means that theses generating units play a more active role in the wholesale market [11]. Currently in Denmark it provides on average 33.2% of the total generation to supply system demand [1]. It is scheduled through participation in wholesale electricity markets. In Nordic countries wholesale electricity exchange is managed by Nord Pool. In Denmark wind power generation owners are remunerated by the electricity price in the market plus a fixed premium, supported by all final consumers [12]. Thus, wind power bids are usually submitted into the wholesale electricity market with zero or negative prices [13].

The TSO also operates a market for reserve capacity and regulating power which are the ancillary services that are needed to ensure stability in power system operation. Nowadays, wind power generation has the ability to provide different types of ancillary services such as frequency and voltage control. Thus, wind farms are able to participate in primary reserve with the ability to quickly change injection of active power and to provide kinetic energy (virtual inertia). Furthermore, wind farms have the ability to control reactive power and respond to reactive power needs in less than 1 second, as well as the ability to provide service of fault ride through capabilities [4].

Traditionally, there are different ancillary services market designs which are adapted to support the system needs of a specified country/region [14]. However, these markets are not designed to integrate wind generators considering their limitations. Although current technology of wind turbines being capable to provide such services, wind turbines still suffer from the intermittent behaviour of their power generation. Thus, in order to integrate wind power generation into ancillary services markets, emphasis ought to be placed on adequate offering strategies and market mechanisms, eventually permitting to s maintain suitable levels of power system security and reliability [8].

B. *Offering strategies*

Future participation of wind farms in ancillary services market will lead to the development of strategies and mechanism to improve the revenue of wind power producers, as well as the social welfare. On the other hand, wind farms should consider several strategies on simultaneous participation in energy and ancillary services market. Thus, simultaneous participation of wind farms on energy and ancillary services markets can be done splitting the maximum level of forecast wind power by energy and ancillary services. For that purpose it is considered two different bidding strategies of wind farms participation in energy and ancillary services markets [15], Proportional wind Reserve Strategy (PWRS) and Constant Wind Reserve Strategy (CWRS), as shown in Fig. 1.

PWRS consists in a proportional curtailment of the wind generation forecast to establish as power reserve, where

$$P_{AS} = (1-\alpha)P_{Energy} \tag{1}$$

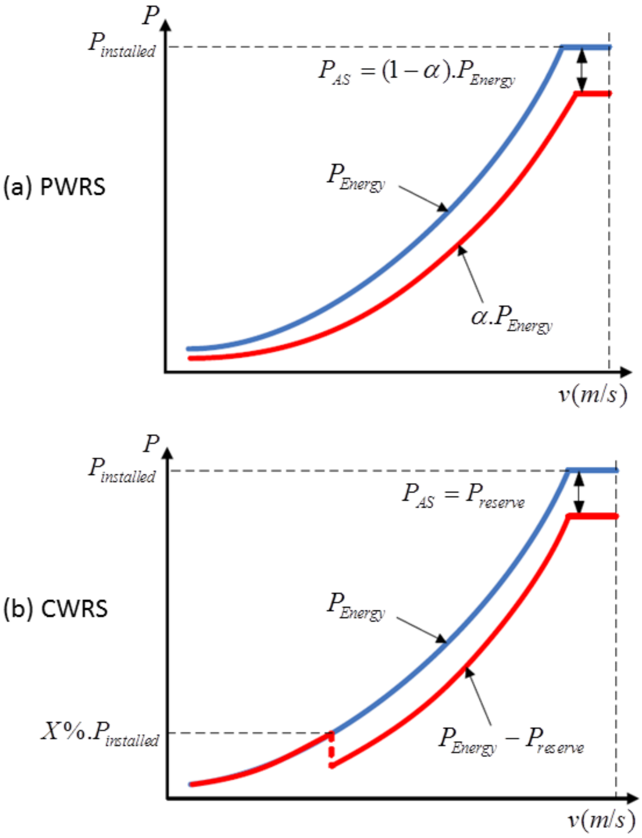

Figure 1. PWRS and CWRS bidding strategies operation (reproduced from [15] with permission).

The parameter α is used to determine the amount of power that is submitted to both markets and can be set between 0 (total curtailment) and 1 (no reserve). Current wind farms technology are able to maintain specified percentage of the available power (forecast) to provide primary reserve service [16].

In contrast, CWRS is based on a constant curtailment of power over a certain output level,

$$P_{AS} = P_{reserve}, \qquad P_{Energy} > X\%P_{installed} \tag{2}$$

where $X\%$ is the percentage of the installed wind power. However, the intermittency of wind power may lead to some discontinuities in the reserve power. In cases where forecast wind power is closer to the limit where wind farms start providing ancillary services, small real power deviations may lead to wind farms providing a fixed reserve power or not providing, in short periods. This implies a bigger difficulty for TSO to maintain stable supply of ancillary services.

C. *Strategies evaluation model*

The use of strategies for participation of wind power generation in energy and ancillary services market should be evaluated from a system perspective in order to optimize its global benefit in the market.

In this scope, the scheme shown in Fig. 2 is proposed to determine the remuneration that global wind power generation may obtain from both energy and ancillary service markets.

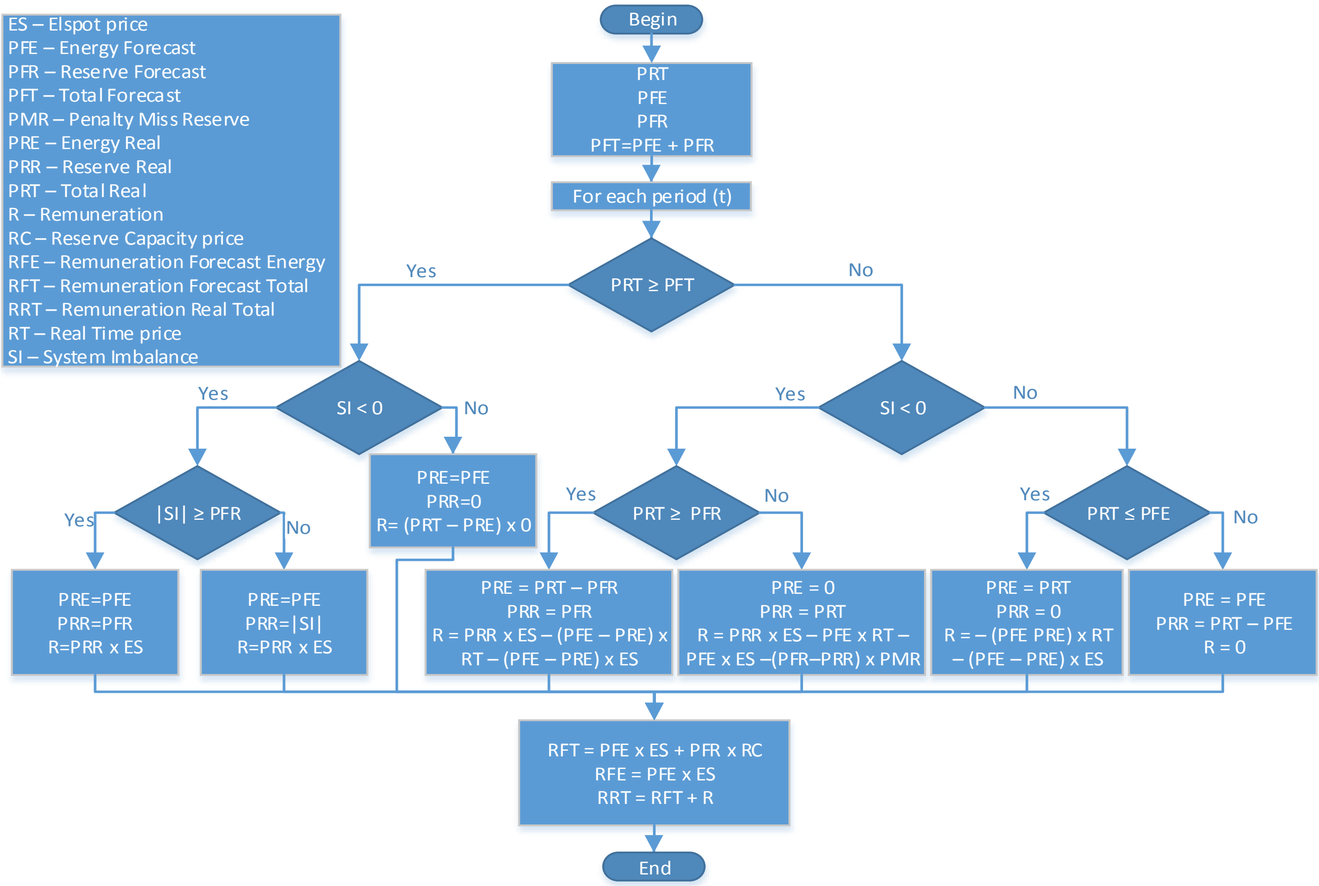

Figure 2. Strategy evaluation diagram.

The diagram is based on several inputs necessary to determine the remuneration which wind farms can get through participation in these markets. One particular aspect that should be taken into account during the wind remuneration determination is the system needs for up and down reserves. These needs correspond to the expected power imbalance in the power system. Since 2013 in Denmark, the TSO (Energinet.dk) starts providing data regarding power system imbalance, due to a restructuring of the Danish power system [17]. However, this data does not provide power imbalance for each region of the country, which is essential to know what reserve contribution may wind farms provide in its zone. In order to fulfil this gap, a simple approach is used for determination of system imbalance. The imbalance of the system $SI_{(t)}$ may be based on

$$SI_{(t)} = \Delta P_{Schedule(t)} + \Delta P_{Demand(t)} + \Delta P_{Wind(t)} \tag{3}$$

where the schedule deviation $\Delta P_{Schedule(t)}$ is determined by the difference between power of physical exchange $P_{Physical\_exchange(t)}$ and the power scheduled $P_{Scheduled\_trade(t)}$ in the market,

$$\Delta P_{Schedule(t)} = P_{Physical\_exchange(t)} - P_{Scheduled\_trade(t)} \tag{4}$$

Besides, demand deviation $\Delta P_{Demand(t)}$ may be determined by the difference between real consumption $P^{real}_{Demand(t)}$ and forecast demand $P^{forecast}_{Demand(t)}$,

$$\Delta P_{Schedule(t)} = P^{real}_{Demand(t)} - P^{forecast}_{Demand(t)} \tag{5}$$

Finally, the difference between observed and forecast wind power generation yields the wind imbalance

$$\Delta P_{Wind(t)} = P^{real}_{Wind(t)} - P^{forecast}_{Wind(t)} \tag{6}$$

Based on system imbalance and offering strategies for wind power generation, the total remuneration (described in Fig. 2) is determined, while taking into account all the possible operation contexts.

III. Case Study

An empirical investigation for the evaluation of the participation of wind power generation in energy and ancillary services market is carried out here. It is divided into two subsections – the case study characterization and the results analysis.

A. *Case-study Characterization*

The case study is focused on the Danish power system and the Nordic electricity market. The Danish power system is divided into two regions (West and East). Thus, wind participation in energy and ancillary services markets should be evaluated for each region of the system. In order to perform the analysis of wind power generation in energy and ancillary service markets, several data inputs are used. All data is for the period between January 1, 2012 and February 9, 2013. Data regarding physical exchange on transmissions lines, schedule trade on transmissions lines, real demand of the system, and balancing price are provided by Energinet.dk [17]. On the other hand, demand forecasts, wind power forecasts, and Elspot prices are provided by Nord Pool Spot. Observed wind power data is provided by Enfor A/S. In order to penalize the failure of wind power generation to provide contracted ancillary services, a simple penalty is used. It is assumed to be 20% of the price for balancing power – up and down regulation – for the specified time interval. This penalty it is also used to determine the Value Of Lost Load (VOLL) that wind farms induce on the power system.

B. Results

1) Wind Deviation

The difference between predicted and observed wind power generation for the last five days of the evaluation period, considering step time every 15 minutes for west region of Denmark is depicted in Fig. 3. One can see that power measurements tend to match quite well the forecasts. The root-mean-square error (RMSE) for that period is of 98 MW.

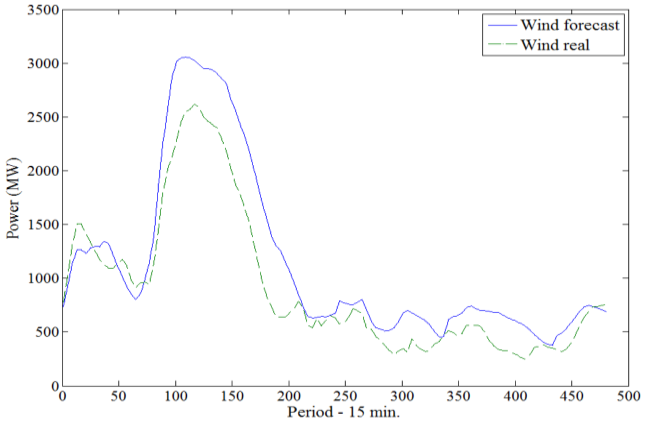

Figure 3. Example episode with wind power forecasts and obeservations.

The wind deviation is determined based on the difference between predicted and observed wind power generation. In turn, system imbalance is calculated partially based on wind deviation. In this way, there is a relationship between wind deviation and system imbalance. The wind deviation and system imbalance for the last five days of the range for the west region of Denmark is shown in Fig. 4. Negative power values of system imbalance correspond to upward regulation power needed to balance the power system. On the other hand, downward regulation is related to positive values for system imbalance.

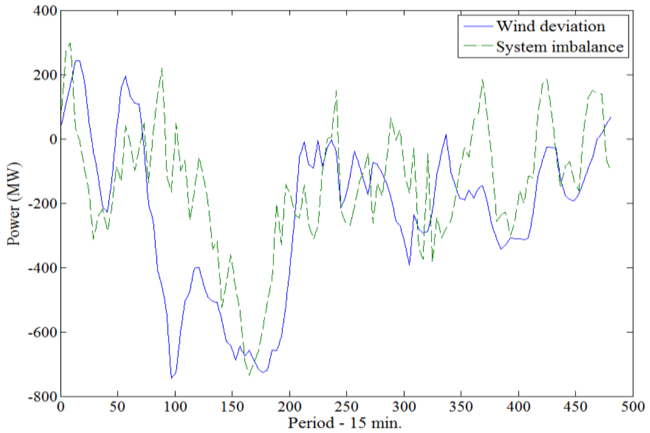

Figure 4. Impact of wind deviation on system imbalance.

From Fig. 4 it is possible to understand that the wind deviation has a substantial impact on system imbalance. In general, the system imbalance curve follows the wind deviation, which means that wind farms are responsible for a substantial part of the overall system imbalance. However, there are also several periods in Fig. 4 where is possible to identify that wind deviation has a positive impact and actually supporting system balancing. During such periods participation in reserve provision could be beneficial to wind farm operators.

2) Strategies evaluation

A sensitivity analysis for the evaluation of offering strategies for different regions of Denmark is presented. The participation of wind farms in ancillary service markets strategies leads to different prices in day-ahead energy market. Thus, new market prices for each region and strategy should be determined. For this purpose a linear regression between predicted wind power penetration and day-ahead price is obtained, in a spirit similar to [18]. Fig. 5 comprises the basis for determining price changes based on day-ahead prices for each region and the relationship between wind power and demand forecasts. In addition, the scale of day-ahead prices is in percentage for a better understanding of the impact that wind participation in ancillary services may have on day-ahead price. Price changes are then determined for each region and for the various potential offering strategies of wind power producers.

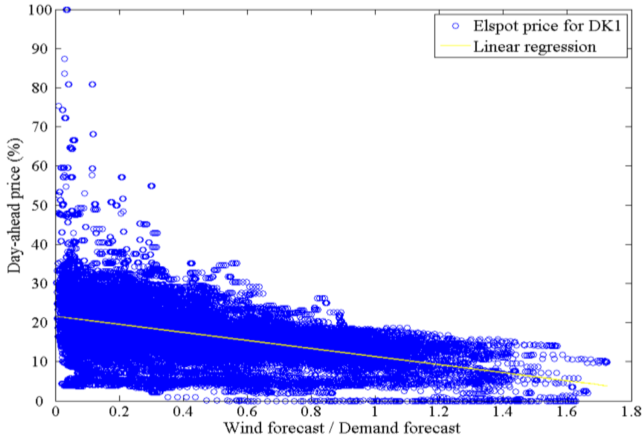

Figure 5. Impact of wind penetration on day-ahead price (DK1).

As an example, Fig. 6 depicts the evolution of new market prices if wind power offers ancillary services following the so-called PWRS strategy in DK1, with various values for α, controlling the balance between energy and service provision. These price curves are for the last 5 days of the evaluation period.

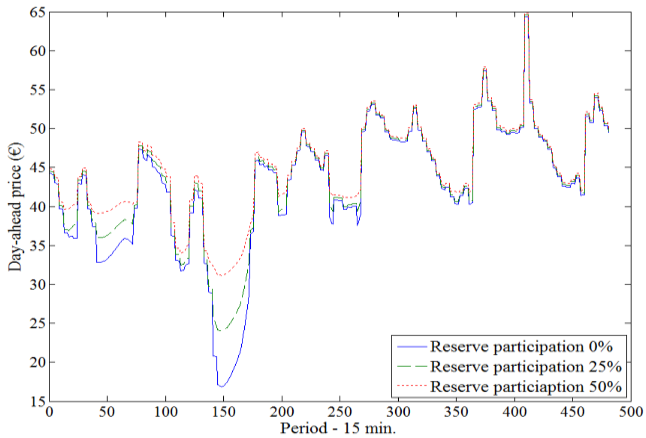

Figure 6. Day-ahead price considering PWRS strategy (DK1).

One can see that active participation of wind farms in ancillary service markets may result in higher prices on day-ahead energy markets. This is due to the fact that usually wind farms offer all energy they expect to produce at a very low marginal cost. If participating in ancillary service markets, the amount of energy offered in the day-ahead market is necessary less, hence requiring more expensive generators to be dispatch in order to supply demand, eventually resulting in a higher day-ahead price. However, the difference between new day-ahead prices for each amount of wind participation in ancillary services market is not very high. This might also be due to the simplicity of the model (linear regression only) used to perform the determination of new market prices.

Fig. 7 shows the benefits that total wind power generation would obtain from participating in ancillary service markets with each type of strategy, from a system perspective. Benefits are determined based on the calculation method presented in the strategy evaluation diagram (Fig. 2). One can see that both strategies for ancillary service market participation bring additional revenues to wind power producers overall, in comparison with the case of providing energy only. It is also possible to identify that the benefits from employing a PWRS strategy tends to increase when the participation in reserve market is increased. On the other hand, the CWRS strategy yields a different behaviour. Minimum step point of reserve participation has minimum amount of remuneration. This value starts increasing until reserve participation about 35%, which yields the maximum revenues (about 27% more than without reserve participation) that this strategy may achieve. Above this level of participation, the amount of remuneration tends to decrease, slightly.

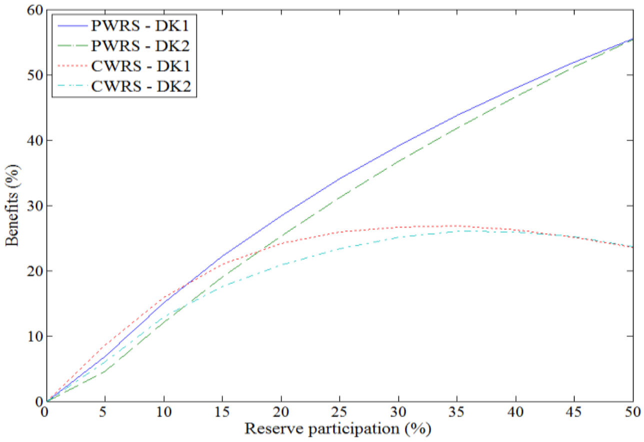

Figure 7. Remuneration comparison by strategy and region.

The fact that the limited predictability of wind power generation could result in failure to provide energy and/or ancillary services motivates the need to evaluate what impact wind power generation deviation may have from both technical and economic system perspectives. In this way, Fig. 8 illustrates the percentage of time that wind power generation are not available to support part/completely its energy and ancillary service schedules. This frequency of failing to provide services is determined based on the calculation method in Fig. 2. The two strategies have different impact on availability of the overall wind power generation to provide services. In general it is clear that ancillary services participation leads to a decrease in the probability of wind power generation to fail on its energy schedule. However, for PWRS it is possible to understand that as long as reserve participation increase, the percentage of time where system wind power generation will be not suitable to provide the service is lower. Furthermore, the maximum reserve participation for DK1 results in the lower time of failure for providing the services. Thus, a highly balanced participation of wind power generation in energy and ancillary service market results in a lower time of failure to provide all services. In this way, from the TSO standpoint high participation of wind power generation in ancillary services through PWRS strategy might improve the reliability of the power system.

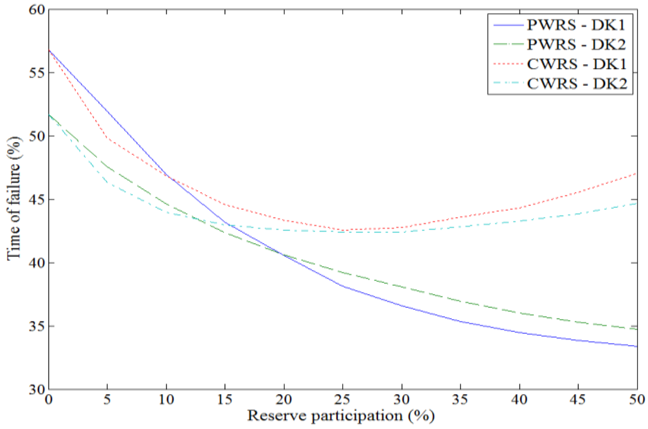

Figure 8. Failures of wind power generation in providing services for strategy and region.

Regarding the CWRS strategy, the best reserve participation level, from a TSO standpoint focusing on minimum failure to deliver, is at 25%, then resulting in not providing partly/fully the services 45% of the time. This strategy assumes a constant level of power participation, which depending on the availability of wind power generation may lead to more failures in providing ancillary services.

Fig. 9 depicts the VOLL associated to the amount of power that it is not provided by wind farms as scheduled in its forecast. This index is used in order to evaluate the amount of money that could be paid to demand when generators could not meet demand. VOLL is determined based on the amount of power that is not provided to the system multiplied by a high cost for lost load. The amount of power is calculated based on Fig. 2, while the cost for lost load is established as 20% of the price for balancing power.

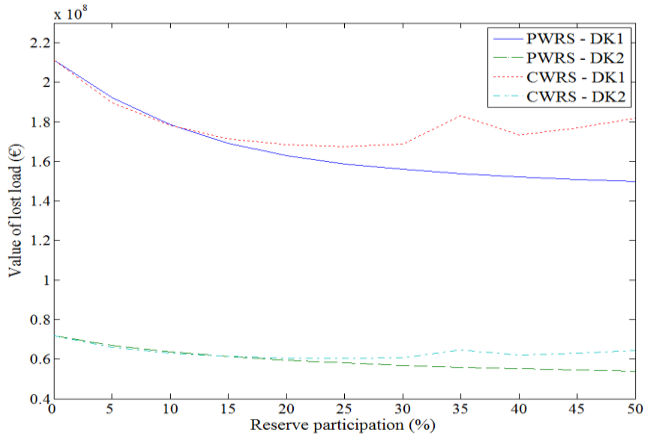

Figure 9. Value of lost load evaluation.

System imbalance results have impact on VOLL results. In certain periods participation of wind power producers in reserve could be useful to decrease the amount of lost load. Considering high participation of wind farms in ancillary services, and when real wind power generation is lower than the forecast hence requiring up-regulation, the amount of power scheduled for ancillary services may be used by wind farms to fulfil the difference between forecast and real wind power for energy market. This event takes place 23.4% of times over our evaluation period.

IV. CONCLUSIONS AND DISCUSSION

The increasing and important penetration of wind power generation in power systems leads to the design and development of strategies and market mechanisms to integrate this energy resource in both energy and ancillary service markets. This issue has been the focus of the present work, where we implemented and evaluated offering strategies for wind farms participation in these two markets. The main motivation behind this work is to argue for the need to verify whether wind power participation in ancillary service markets may really support power system operations, or not. Similarly, the system impact and potential economic benefits are to be thoroughly evaluated. While wind power producers are commonly participating in energy markets directly based on forecasts, it is also crucial for them to assess if there may be additional benefits from participation in ancillary service provision. For these reasons, several issues deserve to be further considered. On one hand, new market mechanisms for integration of wind power producers in ancillary services should be considered. As wind power generation is intermittent, even though it could quickly respond to system imbalances, flexible market mechanisms accommodating wind power producers could be proposed, accounting for the potential impact of limited predictability. On the other hand, wind turbines technology allows wind power participation to provide certain ancillary services either, e.g., in terms of frequency and voltage control, with fast response. But, it may not be suitable for all types of ancillary services. Besides these technical difficulties, wind power producers should design and develop offering strategies jointly considering energy and ancillary service markets, which may be rather complex.

In this context, we looked at two straightforward strategies, already proposed in the literature. The PWRS strategy reserves a percentage of the power expected from the forecasts. In contrast the CWRS strategy reserves a constant part of predicted wind power generation, for ancillary service provision. In general and from a system perspective, the PWRS strategy yields more benefits to wind power producers than the CWRS strategy. On average, PWRS results in about 34.5% more benefit than without strategy and 10.7% more benefit than CWRS strategy. From the TSO's point of view, PWRS presents better results than CWRS for medium and high participation in ancillary service markets. Furthermore, both strategies are better than wind not offering services, in terms of frequency of time failing to provide energy and ancillary services. Both offering strategies may then result in more benefits to all wind power generation, without causing more trouble to the TSO.

Besides the main message, this work has allowed to reach a number of practical conclusions from the evaluation of offering strategies for wind power producers. The most important are that: (*i*) the strategies results strongly depends on the system imbalance, (*ii*) there is a need for flexible mechanisms allowing wind generation to participate in ancillary service markets, and (*iii*) joint offering strategies should be further developed. The results support our expectations such that the participation of wind power generation on energy and ancillary service markets ensures more benefit for all wind power generation on the system. On the other hand, it is confirmed that wind power providing ancillary services support power system reliability. Future work will concentrate on the development of flexible market mechanisms for wind participation in ancillary services, and on more detailed case-studies e.g. based on IEEE cases systems, to better analyse direct and indirect effects of wind participation in both energy ancillary service markets through their technical capabilities and strategic behaviour.

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REFERENCES

[1] Energinet.dk. (2014). *2013 was a record-setting year for Danish wind power*. Available: http://www.energinet.dk/EN/El/Nyheder/Sider/2013-var-et-rekordaar-for-dansk-vindkraft.aspx

[2] Danish Government, "Energy Strategy 2050 - from coal, oil and gas to green energy," *DEA - Danish Energy Agency,* 2011.

[3] H. Lund, et al., "System and market integration of wind power in Denmark," *Energy Strategy Reviews,* vol. 1, pp. 143-156, 2013.

[4] E. Ela, B. Kirby, N. Navid, and J. C. Smith, "Effective ancillary services market designs on high wind power penetration systems," in Power and Energy Society General Meeting, 2012 IEEE, 2012, pp. 1-8.

[5] D. Nock, V. Krishnan, and J. D. McCalley, "Dispatching intermittent wind resources for ancillary services via wind control and its impact on power system economics," *Renewable Energy,* vol. 71, pp. 396-400, 2014.

[6] G. Michalke and A. D. Hansen, "Grid support capabilities of wind turbines," in *Handbook of Wind Power Systems*, Springer, Ed., ed, 2014, pp. 569-590.

[7] L. Zeni, et al., "Virtual inertia for variable speed wind turbines," *Wind Energy,* vol. 16, pp. 1225-1239, 2013.

[8] P. Sorknæs, A. N. Andersen, J. Tang, and S. Strøm, "Market integration of wind power in electricity system balancing," *Energy Strategy Reviews,* vol. 1, pp. 174-180, 2013.

[9] Z.-S. Zhang, Y.-Z. Sun, and L. Cheng, "Potential of trading wind power as regulation services in the California short-term electricity market," *Energy Policy,* vol. 59, pp. 885-897, 2013.

[10] M. Vilim and A. Botterud, "Wind power bidding in electricity markets with high wind penetration," *Applied Energy,* vol. 118, pp. 141-155, 2014.

[11] M. Silva, H. Morais, T. Sousa, and Z. Vale, "Energy resources management in three distinct time horizons considering a large variation in wind power," in EWEA Annual Event 2013 (EWEA 2013), Vienna, Austria, 2013.

[12] S. Krohn, P. E. Morthorst, and S. Awerbuch, "The Economics of Wind Energy," *EWEA - European Wind Energy Association,* 2009.

[13] Energinet.dk, "Wind power to combat climate change - How to integrate wind energy into the power system," Energinet.dk, 2009.

[14] ENTSO-E, "2013 Survey on Ancillary Services Procurement and Balancing market Design," *Ancillary Services Working Group,* 2014.

[15] Y. Wang, "Evaluation de la Performance des Réglages de Fréquence des Eoliennes à l'Echelle du Système Electrique : Application à un Cas Insulaire," Ecole Centrale de Lille, L2EP, [in french], 2012.

[16] Y. Wang, X. Guillaud, J. Duval, and B. François, "Enhanced design of a deloaded wind turbine controller for frequency regulation participation," in 9th International Workshop on large-scale Integration of Wind Power into Power Systems, Québec city, Canada, 2010.

[17] Energinet.dk. (2014). *Download of market data*. Available: http://www.energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

[18] T. Jónsson, P. Pinson, and H. Madsen, "On the market impact of wind energy forecasts," *Energy Economics,* vol. 32, pp. 313-320, 2010.