An Econometric Model of the Regulating Power Price for Interconnected Power Systems: the case of the Nord Pool Market

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***Abstract*—Transmission System Operators (TSOs) deploy frequency control reserves and regulating power to maintain the load-generation balance in real-time operation of power systems. In the Nordic countries, the TSOs buy regulating power from the Nord Pool regulating power market. In this paper, we developed a tool to quantify the price of regulating power as a function of both economic parameters such as spot (day-ahead) market price, and technical factors representing the current state of the system. First, the Nord Pool is considered as a single bidding area and an aggregated regulating power price is obtained, proving the validity of a simple non-linear algebraic model, when there is no influence of interconnections with neighboring areas. Then, we developed a case study for the West Denmark area, to demonstrate that for complex systems, where there is possibility of trade with other areas and there is high penetration of intermittent generation (e.g., wind power), this simple formulation is no longer valid. Finally, to solve this inconsistency, an improved model is here proposed by considering the effect of interconnections through two scenarios: one for unconstrained trade through the interconnections with neighbouring areas, and the second one where at least one of the interconnecting lines is congested. In addition, the wind penetration level is included as a parameter the non-linear algebraic model.**

***Index Terms*—Regulating power price, Nord Pool, Wind penetration, Interconnected market.**

I. Introduction

Transmission System Operators (TSOs) deploy frequency control reserves and regulating power to maintain the load-generation balance in real-time operation of power systems. This reserve is normally allocated in specific electricity markets where regulating power is traded, possibly between neighbor countries, as is the case in the Nord Pool area [1].

Although relevant research effort has been devoted to identifying tools to schedule power system operations and reserve provision [2]- [3], and regulating power market analysis [4]-[5], only a few econometric studies evaluate which factors affect the regulating power price. Moreover, performed studies such as [6] and [7], do not consider the current state of complex power systems, being highly interconnected and dependent on intermittent generation.

Thus, the purpose of this work is to develop a tool to quantify the price of regulating power as a function of both economic parameters such as price of energy in spot (day-ahead) market, and technical factors representing the current state of the system.

In addition, the proposed method is designed to support the identification and analysis of the driving patterns affecting the regulating power price.

In this paper, the following two case studies are developed in the context of the Nord Pool market because it offers the exchange of regulating power among the areas and its market data are publicly available.

First, the Nord Pool is considered as a single bidding area and an aggregated regulating power price is obtained, proving the validity of a simple model such as the Skytte model [6], when there is no influence of interconnections with neighboring areas. Through the second case study for the West Denmark area, it was found that for complex systems, where there is possibility of trade with other areas and there is high penetration of intermittent Renewable Energy Sources - RES (e.g., wind power), this simple formulation is no longer valid.

To solve this inconsistency, an improved model is here proposed by considering the effect of interconnections through two scenarios: one for unconstrained trade through the interconnections with neighbouring areas, and the second one where at least one of the interconnecting lines is congested. In addition, the wind penetration level is included as a parameter.

For both cases, it is found that market competition (a non-congested system) smooths the effect of other parameters such as the direction of the demand and the wind penetration level have over the regulating power price. As a result, the obtained model provides a good tool to quantify the price of regulating power as a function of the state of the system and different economic parameters.

The rest of this paper is organized as follows. Sections II describes the context of the Nordic regulating power market. The developed case studies and used data set are presented in section III. The methodologies and analysis are presented in section IV. In section V, the obtained numerical results are discussed. Finally, conclusions are presented in section VI.

II. The Nordic Regulating Power Market

The Nordic electricity market is one of the first deregulated markets in the sector in the 1990s. Norway was the first country to deregulate its power exchange, followed by Sweden, Finland and Denmark. Nowadays, each of the participating countries are divided in bidding areas, that will have different prices of electricity if congestions occur in the interconnecting lines.

The Nordic electricity market is composed of three markets, namely, spot (day-ahead), intraday, and regulating power market. The spot and the intraday markets deal with energy trading between the producers and consumers. Following these two markets, the TSO of each country, buys regulating power (in both upward and downward directions) in order to maintain the load-generation balance.

In case of deficit in production or excess in consumption, the TSOs buy upward regulating power. Producers and consumers could provide upward regulating power by increasing their production or decreasing their consumption, respectively.

In case of surplus of production or deficit in consumption, the TSOs buy downward regulating power. Producers and consumers could provide downward regulating power by decreasing their production or increasing their consumption, respectively.

The bids in the regulating power market are placed separately for up and down regulation. After the clearing of the market, a price is obtained for each type of regulation. National TSOs submit the collected bids in the area to the Nord Pool, where they are ranked by merit order according to price. At the same time, all the TSOs submit the demand for regulating power from the areas of their supervision. If imbalances go in opposite direction in different areas and sufficient transmission capacity exists, they are evened out and thus do not affect the regulating power price. Afterwards, the bids with the lowest price (for up regulation) and with the highest price (for down regulation) are activated, until the demand is satisfied [1].

The direction of the regulation is calculated globally at the Nord Pool level as the addition of the bidding areas demands. The net aggregated demand will determine the direction of the regulation, which will define the dominating price.

All the activated bids will receive the price of the highest activated bid, in the case of upward regulation, and they will pay the price of the lowest one in the case of downward regulation. Like the day-ahead and the intraday markets, bids might be bypassed in case of congestion in the interconnecting lines.

III. Case Studies and Data Set

The work developed in this paper uses the following two case studies:

- Case 1: the aggregated Nordic Case;
- Case 2: The DK West Case.

We use case 1 to check the validity of proposed models in a simple market situation. In this respect, the Nord Pool area (considering all the bidding areas) is examined to build a lumped model based in the Skytte methodology [6].

Afterwards, we use case 2 to evaluate the performance of proposed models in a more complex situation including high penetration of intermittent RES and possibility of exchange of regulating power with neighbouring areas. In this respect, West Denmark area (DK West) is selected for Case 2, due to the high penetration of wind production (51% in 2015 and 2016 [8]) and its participation in the spot and regulating power markets in the Nord Pool area.

The time series used in this study, correspond to data from the Nord Pool [9] and the Energinet (TSO of Denmark) [8] ranging from January 2015 to December 2016. To build the models, the spot prices and volumes, the regulating power prices for up and down regulation and the activated regulating power for all the bidding areas in the Nord Pool are used. In addition, regarding the DK West area, the wind generation volumes in the spot market and the demand for regulating power are considered to build the model. The prices in the series are given in EUR/MWh and the volumes of energy in MWh, with a time resolution of 1 hour.

Python and Matlab are used for processing of the data, and building and fitting of the models. From the original data set, the outliers (i.e., the 2% most extreme values of demand for regulating power) were eliminated. Since the model is not expected to be used for time series forecasting, there were no replacements made of the eliminated values.

In case 1, the spot and regulating power prices are aggregated as a weighted average based on the volumes traded in the markets at different area as formulated in (1) and (2), respectively.

$$SP^{\text{agg}} = \frac{\sum_{a\in\mathcal{A}} SP_a \cdot D_a}{\sum_{a\in A} D_a} \tag{1}$$

$$PR^{\text{agg}} = \frac{\sum_{a\in\mathcal{A}} RP_a \cdot DR_a}{\sum_{a\in A} DR_a} \tag{2}$$

SP^{agg} and PR^{agg}, are the aggregated spot and regulating power price, respectively. SP_a and PR_a, are the spot and regulating power price at area a, respectively. D_a and DR_a present demands of area a, in spot and regulating power markets, respectively. $\mathcal{A}$ is the set of all bidding areas in the Nord Pool.

the demand for regulating power is obtained as the addition of the activated regulation (supply of regulating power) in each of the bidding areas. It is assumed that the aggregated Nord Pool area has no external interconnection. For that reason, the activated regulation within the aggregated Nord Pool area will be exclusively used to satisfy the demand for regulation and therefore both quantities are equal.

For the DK West case, the data for the spot and regulating power prices is available. However, the available published data [8] of demand for regulation in the regulating power market, does not necessarily correspond to the actual needs for regulation within DK West. Indeed, as of June 2008, imbalances have been allowed to even each other out if the imbalances within the DK West area are in the opposite direction of those in DK East, Sweden or Norway, and capacity exists through the interconnecting lines. Based on this fact, results regarding the quality of fitting of the models are expected to be less accurate in the DK West case compare to those of Aggregated Nordic Case. In consequence, further analysis have been developed for the second case study. Parameters such as the intraday market price, the forecasting errors for consumption and wind production, the wind penetration level and the state of the interconnections with the DK West region have been analyzed, as possible parameters to be considered in the model.

IV. Methodology and Analysis

To obtain the regulating power price for Case 1 and Case 2, a multiple regression model is developed using Matlab. The regression model is given in terms of a non-linear function in which each of the input parameters have an associated coefficient, which will be determined based on the input data.

The formulation introduced in [6] is chosen as point of departure, and applied to both case studies. This way, the regulating power price is first explained through a regression model as a combination of the spot price, the volume and direction of the demand for regulation (upward or downward regulating power) and the premium for readiness for providing regulation services (defined by a constant term plus a term dependent on the spot price).

$$PR(SP, DR) = \varphi \cdot SP + 1_{(DR<0)} \cdot [\lambda \cdot SP + \mu \cdot DR + \eta] + 1_{(DR>0)} \cdot [\alpha \cdot SP + \gamma \cdot DR + \beta] \quad (3)$$

where SP is the spot price, DR is the demand for regulating power and φ, λ, μ, η, α, γ, and β are the coefficients of the model.

The initial model includes two indicator functions ($1_{(DR<0)}$, $1_{(DR>0)}$), that are used to distinguish cases with up and down regulation, in order to identify if the direction of the regulation has an important effect over the regulating power price. This will be the case if the value of the coefficients within the brackets (3) are significantly different. The coefficients μ and γ are interpreted as the marginal regulating power prices per unit of regulated power. The other coefficients in the brackets are used to magnify the premium for readiness in the regulation price, which is represented by a constant term (i.e., η and β) and a term directly related to the spot price (i.e., λ and α).

A. Wind production in the DK West area

The high unpredictability of wind is expected to result in an important correlation between the regulating power price in the area and the wind penetration level (share of wind power production in the generation mix).

Through a correlation analysis, using data from 2015 and 2016 [8], the correlation coefficient for the wind penetration level and the regulating power price was of -0.48, and of -0.53 with the spot price. The wind penetration level thus plays an important role in both markets.

The higher the wind penetration level, the smaller will be the spot price since cheaper generation will be activated to cover the demand in the spot market.

On the other hand, the activation of cheaper generation to cover imbalances could explain the negative relationship between wind penetration and the price of upward regulating power. Regarding the downward regulation, there might be higher needs for downward regulating power when there is high level of wind penetration.

Based on the results of this analysis, the wind penetration level is considered as an input parameter in the DK West model.

B. State of the interconnections

The Nord Pool spot (day-ahead), intraday and regulating power markets are structured as wholesale markets. All players in the market place their bids and offers in terms of quantity and volume. Then, the inverse supply and demand curves are computed, classifying the supply bids from the cheapest to the most expensive, and the demand offers in descendent price order. From the intersection of both curves, the market price is obtained, which represents the optimal solution for the market.

However, the obtained price and the scheduled production might not be feasible, since congestion can occur in the interconnecting lines, and as a result, a re-dispatch of the generation is required. This will result in different prices in areas where the interconnecting lines are congested.

The state of the interconnections plays an important role in defining the price of regulating power in an area, and is thus included in the developed models.

DK West is connected to DK East, Norway, Sweden and Germany. Since the analysis in this study, seeks to quantify the effect of the line congestion on the price levels in the regulating power market, only the interconnections to the Nord Pool areas (i.e., DK West to DK East, Norway, and Sweden) are considered.

The state of the interconnections is identified based on the difference in the price of regulating power between areas. Whenever there is a congestion in an interconnecting line, a price difference appears between areas. This information is used to build an indicator function.

The DK West regulation price has been compared to the one of Eastern Denmark, Norway and Sweden, which are the three regions to which DK West is interconnected. For the three of them, it was checked whether the up and down regulating prices were equal in the interconnected areas every hour.

Figure 1 shows the percentages of congestions between DK West and its neighboring areas computed based on price data of 2015 and 2016.Individually, each of the interconnections is congested around 30-40% of the time, while 56% of the times at least one of the interconnections is congested.

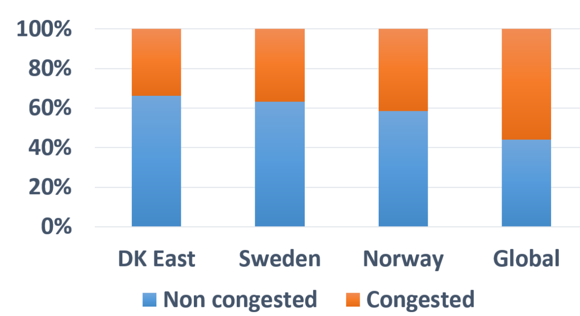

Figure 1: Congestion analysis: Percentage of the time (hourly basis) in 2015 and 2016 where the interconnections between DK West and neighboring areas were congested

V. Results and discussion

A. Case 1: the aggregated Nordic Case

For the Nord Pool area, we adapted the Skytte model [6] to obtain an aggregated regulating power price as a function of the spot price, regulating power volumes and the dominating direction of the regulation. We fitted the model with an R^2 of 0.925, which provides a good value if compared to the original Skytte results. Table I shows the following statistical characteristics of the estimated coefficients:

- Estimate:the value of estimated coefficient;
- SE: the standard error of the estimated coefficient;
- p-value: the probability value (asymptotic significance) of the estimated coefficient;
- tStat: The ratio of the departure of the estimated value of the coefficient from its hypothesized value to its standard error.

	Estimate	SE	tStat	p-value
φ	1	0.001715	583.1	0
λ	-0.057901	0.0051379	-11.269	2.97E-29
μ	0.0044049	0.00010904	40.396	0
η	-1.4523	0.1346	-10.79	5.69E-27
α	-0.059739	0.0057919	-10.314	8.45E-25
γ	0.0042649	0.00016813	25.368	5.18E-137
β	3.0284	0.15204	19.918	2.36E-86

Table I: Estimated coefficients for case 1

All the p-values of the different estimated parameters are zero or close to zero, being all significant to the model. The R^2 value obtained (0.929) is lower than in the original Skytte model (0.998). Note that the built model in Case 1, uses as an input an aggregated area while the Skytte model focuses only on the Norway area, which can explain why the obtained R^2 is slightly lower. Using the obtained coefficients, the regression model results is presented in (4).

$$\begin{aligned} &PR(SP, DR) = SP \\ &+ 1_{(DR<0)} \cdot [-0.0579 \cdot SP + 0.0044 \cdot DR - 1.4523] \\ &+ 1_{(DR>0)} \cdot [-0.0597 \cdot SP + 0.0043 \cdot DR + 3.0284] \end{aligned} \tag{4}$$

First, it can be observed that the coefficient φ is estimated to be equal to 1. Therefore, the estimated regulating power price is equal to the spot price whenever there is no demand for regulation. Results are as expected considering how the price is formed in the regulating power market, as the intersection between the supply and demand, with reference to spot price.

Second, contrary to the Skytte results, the use of the indicator function is not clearly justified for the adapted model, since the coefficients between brackets are in the same range of values. In consequence, for the proposed model, the direction of the regulation does not play an important role in determining the regulating power price.

Third, the premiums for readiness for upward and downward regulation, are seen to be very similar in terms of the correlation with the spot price, but still relevant in determining the regulating power price, since their associated p-values are close to 0.

In summary, although the Skytte model has proven to be well adapted to the current situation in the whole Aggregated Nordic Case, the implications of the results are significantly different.

B. case 1: The DK West Case

By applying the Skytte formulation to the DK West case, we observed that the R^2 value is 0.776 and the p-values associated to the individual parameters are above 5%, and thus non-significant to the model. The results obtained prove that such a simple formulation is not valid to capture the variability of complex power systems.

Therefore, new models have to be proposed in order to represent the current state of the system. Through the analysis in section IV, it is found that the wind penetration level and the state of the interconnections could be of important influence in defining the regulating power price.

First, the impact of the wind penetration level in the model is evaluated. This provided better results in terms of the significance of the individual parameters (all p-vales <5%), and a slightly higher R^2 (0.803 vs 0.776).

In addition, following the results of the carried out analysis, it seems relevant to consider the congestions in the lines as a factor of influence in the model. This is modeled considering two data sets for the two possible states of the system, as explained in section IV-B; 1) the system is not congested, and 2) at least one of the interconnecting lines between DK West and it's neighboring areas is congested.

First, the wind penetration level is considered to improve the model. However, it is found that the coefficients in the premium for readiness for upward and downward regulation related to the spot price (p-values for λ and α >5%) are not relevant for the model.

To solve this, the identified low significance parameters are eliminated. In consequence, the final formulation of the model for both the congested and non-congested system, including wind penetration level, is as equation (5).

$$\begin{aligned} PR(SP, DR, W) = \varphi \cdot SP + \delta \cdot W& \\ + 1_{(DR<0)} \cdot [\mu \cdot DR + \eta]& \\ + 1_{(DR>0)} \cdot [\gamma \cdot DR + \beta]& \end{aligned} \tag{5}$$

Here, the premium for readiness from the original Skytte model consists of a single constant term (η for downward and β for upward regulation).

Tables II and III present the obtained parameters for the congested and non-congested cases, respectively.

	Estimate	SE	tStat	p-value
φ	0.88857	0.0074978	118.51	0
μ	0.0081852	0.00077389	10.577	5.54E-26
η	0.82395	0.31268	2.6351	0.0084256
γ	0.0052408	0.00051428	10.19	3.02E-24
β	4.9256	0.3039	16.208	3.29E-58
δ	-1.1541	0.25684	-4.4934	7.10E-06

Table II: Parameters for the congested scenario

The R^2 value for the model of congested scenario is slightly lower than the original case (0.744 vs 0.776). However, the parameters of the model are significant and the model is valid. When the system is congested, complexities appear, due to the congestion, affecting market competition. Moreover, for this congested model, there are multiple scenarios considered,

	Estimate	SE	tStat	p-value
φ	0.93074	0.0055568	167.5	0
μ	0.0041372	0.00041847	9.8866	6.83E-23
η	-0.62827	0.18	-3.4904	0.00048546
γ	0.0031514	0.00032026	9.84	1.08E-22
β	2.8384	0.17814	15.934	3.96E-56
δ	-0.82663	0.15186	-5.4434	5.41E-08

Table III: Parameters for the non-congested scenario

as all the possible combinations of congestion in the interconnecting lines are considered Future work should focus on analyzing the effect of congestion individually.

It can be observed that the p-values for all the coefficients are low ($<5\%$), being all the parameters significant to the model. Regarding the non-congested scenario, the model has an R^2 value of 0.864, which represents an important improvement compared to the original results. Moreover, it is higher than the ones obtained in the literature [10].

In consequence, separation of congested and non-congested scenarios is justified, since the obtained values are proven to be better than the ones from the original model.

Moreover, the hypothesis of this study has been satisfied, and the adaptation to the current state of the system by considering the state of the interconnections and the wind penetration level do improve the results and the fitting when based in complex power systems.

The following equations show the obtained model for both the congested and non-congested scenarios:

$$\begin{aligned} PR_{congested}(SP, DR, W) = 0.8886 \cdot SP - 1.1541 \cdot W \\ +1_{(DR<0)} \cdot [0.0082 \cdot DR + 0.8239] \\ +1_{(DR>0)} \cdot [0.0052 \cdot DR + 4.9256] \end{aligned} \quad (6)$$

$$\begin{aligned} PR_{non-congested}(SP, DR, W) = 0.9307 \cdot SP - 0.8266 \cdot W \\ +1_{(DR<0)} \cdot [0.0041 \cdot DR - 0.6283] \\ +1_{(DR>0)} \cdot [0.0032 \cdot DR + 2.8384] \end{aligned} \quad (7)$$

Referring to these results, the wind penetration level has a more important effect over the regulating power price when the system is congested. In a congested system, the imbalances produced by the wind forecast error have to be solved within the area. Therefore, the correlation between wind penetration level and regulating power price is higher.

In non-congested cases, cheaper regulating power could be provided from the neighboring areas to cover the demand for regulation caused by high wind penetration level. As a result the correlation between wind penetration level and the price of regulating power is lower. Finally, in the case of a congested system, there is a clear asymmetry between the influence of demands for upward and downward regulation, again showing how market competition is important, in order to smooth the impact of other parameters on the regulating power price.

VI. Conclusions

In this paper, we first analyzed whether a data-driven non-linear algebraic model from the existing literature (i.e., Skyttes model) can provide good estimates of the regulating power price in the nowadays market context. The estimation performance of Skyttes model was tested considering two case studies derived from the Nord Pool regulating power market: a lumped model of the whole market (Case 1) and a single market area (Case 2). Case 1 was selected because Skyttes model was originally developed for a closed market area, where Case 1 is to evaluate the impact of a large proportion of production from intermittent generation (i.e., wind power) on the price of regulating power.

Validation results shown that, in Case 1, Skyttes model can describe regulating power price behavior quite accurately, with an R^2 value of 0.929. As far as the second case is concerned, estimation performance was worse than the first, with an R^2 value of 0.776 and non-significant individual parameters. In this case, it was shown that accounting for wind penetration level and interconnecting line congestion was conducive to a better performance. It is worth noting that in Case 2, estimation performance was tested under the assumption that the price of regulating power in a single area refers to the demand of regulating power for that same area.

In view of this considerations, whereas Case 2 analysis should be reconsidered with an updated data set and current results should be used with caution, the lumped analysis in Case 1 showed that the underlying mechanism at the base of Skyttes model can be still applied to estimate the regulating power price.

In this respect, an improved non-linear algebraic model with respect to Skytte's model, is proposed in this paper for estimating the regulating power price considering the current state of complex power systems. This model can be used in various techno-economic studies. For instance, the proposed model is expected to be useful to assess whether investing in a certain storage technology (e.g., batteries) within the current markets framework can be cost effective.

References

[1] C. Bang, F. Fock, and M. Togeby, “The existing nordic regulating power market,” *Ea Energy Analysis*, 2012.

[2] A. Ahmadi-Khatir, M. Bozorg, and R. Cherkaoui, “Probabilistic spinning reserve provision model in multi-control zone power system,” *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2819–2829, 2013.

[3] M. Bozorg, A. Ahmadi-Khatir, and R. Cherkaoui, “Developing offer curves for an electric railway company in reserve markets based on robust energy and reserve scheduling,” *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 2609–2620, 2016.

[4] S. Jaehnert and G. Doorman, “Modelling an integrated northern european regulating power market based on a common day-ahead market,” in *Proc. of IAEE International Conference, Rio de Janeiro*, 2010.

[5] S. Jaehnert and G. L. Doorman, “Assessing the benefits of regulating power market integration in northern europe,” *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 70–79, 2012.

[6] K. Skytte, “The regulating power market on the nordic power exchange nord pool: an econometric analysis,” *Energy Economics*, vol. 21, no. 4, pp. 295–308, 1999.

[7] S. Jaehnert, H. Farahmand, and G. L. Doorman, “Modelling of prices using the volume in the norwegian regulating power market,” in *PowerTech, 2009 IEEE Bucharest*. IEEE, 2009, pp. 1–7.

[8] Danish power market data. Energinet.dk. [Online]. Available: http://www.energinet.dk/en/el/engrosmarked/udtraek-af-markedsdata/Sider/default.aspx

[9] Nord pool spot power market data. Nord Pool Spot. [Online]. Available: http://www.nordpoolspot.com/Market-data1/

[10] I. Ilieva and T. F. Bolkesjø, “An econometric analysis of the regulation power market at the nordic power exchange,” *Energy Procedia*, vol. 58, pp. 58–64, 2014.