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Participation of Wind Generation in Balancing Reserve Markets

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In my younger and more vulnerable years my father gave me some advice that I've been turning over in my mind ever since. "Whenever you feel like criticizing one", he told me, "just remember that all the people in this world haven't had the advantages that you've had."

The Great Gatsby, F. Scott Fitzgerald, 1925

Abstract

In order to increase the amount of renewable energy generation in the electrical grids and at the same time keep the existing power quality and safety of supply, it is mandatory that these energy sources not only deliver energy, but also perform ancillary services. Consequently the wind, solar, water and biomass units should be able to supply frequency containment, restoration and replacement reserve services.

The installed capacity of wind generators has risen in recent years, which means that increasingly larger shares of electricity will be supplied by these sources. During off-peak hours this will lead to situations where wind generators become the main electricity supplier. Therefore, wind farms should be encouraged to participate in balance markets so that the system's stability does not become threatened.

In this dissertation, it is analysed the possibility and the impact of Wind Farms in participating in the electrical energy market and in the replacement reserve market.

This work starts with an investigation, on the existing literature, with regard to the physical feasibility of wind farms to provide active power control. Afterwards it is delineated different forecasting tools: of wind power production, of regulation's direction and needed power and of balance market prices. This literature review is compulsory for a better understanding of the problem of bidding in balance markets.

Subsequently it is formulated the decision problem to define the offers of a wind farm. Then a decision support model, based on probabilistic forecasts of: wind generation, balance market prices and regulation's direction, for the offering of control reserve provision is presented. Different decision strategies were implemented, and from the comparison of them conclusions were made.

Resumo

Tendo em vista o aumento da potência instalada de fontes de energia renovável nas redes elétricas e mantendo, ao mesmo tempo, o mesmo nível de qualidade e segurança de fornecimento de energia é imperativo que este tipo de fontes de energia não só forneçam energia, mas também que facultem serviços auxiliares ao sistema elétrico. Consequentemente as unidades eólicas, solares, hídricas e de biomassa deverão fornecer serviços de reserva primária, secundária e terciária.

Nos últimos anos a capacidade instalada em geradores eólicos tem vindo a aumentar, o que implica que maiores percentagens de energia sejam fornecidas por este tipo de máquinas. Fora das horas de pico irão ocorrer situações em que os geradores eólicos serão os maiores fornecedores de energia dos sistemas. Sendo assim, os produtores de energia eólica devem ser encorajados a participar nos mercados de balanço de forma que a estabilidade do sistema não seja posta em risco.

Nesta dissertação analisa-se a possibilidade e o respetivo impacto de os parques eólicos participarem no mercado de energia elétrica e no mercado de reserva terciária.

Neste trabalho começa-se por investigar, na literatura existente, a viabilidade física de os parques eólicos controlarem a potência ativa que fornecem ao sistema. Posteriormente são analisadas diferentes ferramentas de previsão de produção eólica, do sentido e da potência da regulação necessária e dos preços dos mercados de balanço. Este estudo do estado da arte é indispensável para que se compreenda melhor o problema da licitação em mercados de balanço.

Posteriormente, é formulado o problema de decisão que define as ofertas da produção eólica. Em seguida, um modelo de apoio à decisão, com base em previsões probabilísticas: de geração de energia eólica, dos preços do mercado de balanço e do sentido da regulação, para a participação da produção eólica na reserva de balanço é apresentado. No final são implementadas diferentes estratégias de decisão, comparam-se e retiram-se conclusões.

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I would like to start by thanking my supervisor Ricardo Bessa for his patience and guidance during my internship. His expertise made this work possible.

Moreover, I would like to thank my other supervisor Prof. Manuel Matos whose feedbacks and recommendations were extremely helpful.

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Being this work a conclusion of a 5 years cycle spent at FEUP, I would also like to express my gratitude to all my colleagues and friends, especially Filipe, Bruno, Pedro T., Eduardo, Pedro C. and Rui.

Finally, I would like to thank my closest friends Diana and Ricardo for their support and motivation throughout all the ups and downs.

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Abbreviations and Symbols

List of abbreviations

AAP	Available Active Power
CVaR	Conditional Value at Risk
DA	Day-ahead
DFIG	Doubly-Fed Induction Generator
EPSO	Evolutionary Particle Swarm Optimization
EU	European Union
FCR	Frequency Containment Reserves
FEUP	Faculdade de Engenharia da Universidade do Porto
FRR	Frequency Restoration Reserves
G7	Group of 7
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
KDF	Kernel Density Forecast
LMPs	Locational Marginal Prices
MEU	Maximization of the Expected Utility
MIBEL	Mercado Ibérico de Energia Elétrica
NWPs	Numerical Weather Prediction Models
NWS	Nacelle Anemometer Wind Speed
RES	Renewable Energy Sources
RNS	Reserve not supplied
RR	Replacement Reserves
SARIMA	Seasonal Autoregressive Integrated Moving Average
SCADA	Supervision Control and Data Acquisition
SVM	Support Vector Machine
TSO	Transmission System Operator
WF	Wind Farm
WPP	Wind Power Plant

WT	Wind Turbine

List of symbols

RS_A	Remuneration scheme A
RS_B	Remuneration scheme B
t	Hour of the day
$\hat{p}_t$	DA Electrical Energy Market Price Forecast for hour *t*
$\hat{p}_t^{up}$	DA Balancing Upward Reserve Price Forecast for hour *t*
$\hat{p}_t^{down}$	DA Balancing Downward Reserve Price Forecast for hour *t*
τ_t^{up}	Probability of DA balancing reserve being in upwards direction at hour *t*
τ_t^{down}	Probability of DA balancing reserve being in downwards direction at hour *t*
$\widehat{W_t}$	Wind Power Forecast for hour *t*
W_t^B	DA Electrical Energy Market bid for hour *t*
W_t^{B+}	DA Upwards Reserve bid for hour *t*
W_t^{B-}	DA Downwards Reserve bid for hour *t*
ρ	Penalization coefficient for upward reserve not supplied
RNS_t^{up}	Penalization for upward reserve not supplied at hour *t*
RNS_t^{down}	Penalization for downward reserve not supplied at hour *t*
$R_t^{surplus\_up}$	Payment for extra upward reserve delivery at hour *t*
$R_t^{surplus\_down}$	Payment for extra downward reserve delivery at hour *t*
$\widehat{W_t}^{oc}$	Maximum forecasted power production during hour *t*
W_t^{oc}	Energy delivered in a given scenario at hour *t*
W_t^{oc+}	Upward reserve delivered in a given scenario at hour *t*
W_t^{oc-}	Downward reserve delivered in a given scenario at hour *t*
R_t^{up*}	Direction of the upward balancing reserve at hour *t*
R_t^{down*}	Direction of the downward balancing reserve at hour *t*
W_{inst}	Installed power in wind farm(s)
$E(R)$	Mean revenue
$\hat{E}(R)$	Estimation of the mean revenue
$V(E)$	Variance of the mean revenue
$V\left(\hat{E}(R)\right)$	Estimation of the variance of the mean revenue
N	Dimension of the sample
β	Monte Carlo's coefficient of variation
$u(z)$	Expected utility function
max_{ep}	Maximum expected profit
min_{ep}	Minimum expected profit

α	Coefficient to model different attitudes towards risk
$C(R)$	Conditional value at risk function
$CVaR_{5\%}(R)$	Conditional value at risk 5% from distribution of results of revenues

Chapter 1

Introduction

1.1 - Background

In recent years efforts have been made in order to decrease the greenhouse gases emissions. The “20-20-20” target, a directive from the European Union (EU), is an example of that. The EU set three key objectives for the year 2020 [36]:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU’s energy efficiency.

More recently, on June 2015, the G7 leaders have agreed to cut greenhouse gases by phasing out the use of fossil fuels by the end of the century. They agreed on reducing the global greenhouse gas emissions at the upper end of a range of 40% to 70% by 2050, using 2010 as baseline [37].

Phasing out the use of fossil fuels involves installing renewable energy sources (RES). Therefore, the electricity market will have, necessarily, to adapt to this new paradigm. Moreover, the ancillary services provided by the conventional generators will have to be gradually provided by the RES.

Nowadays, wind power generation is remunerated with a feed-in fixed tariff scheme. The trend in some countries (e.g., Spain, Denmark and Germany) is to promote the participation of wind generation directly in the electricity market, in some cases with a premium tariff on the top of the market price. In Portugal the wind power producers establish contracts with a market player called EDP Serviço Universal.

These contracts were helpful to subsidise investments in this type of RES, while the technology was taking the first steps in its evolution and was extremely expensive. However, being now available in the market a more mature and cheaper technology, which is capable of providing certain ancillary services, and considering the necessity of phasing out conventional generators, it is expected that, in a near future, feed-in tariffs will end.

This dissertation provides a possible methodology which would enable wind power producers to actively participate in balancing reserve markets. As a result, a tool for creating bids both for the day-ahead electrical energy market and for the balancing reserve market is provided.

1.2 - Motivation

Since the last few years wind energy is not only increasing its installed capacity, but it is also starting to replace conventional generation in some countries. This leads to high levels of wind power penetration during certain periods of the day. This is already happening in Portugal, as it can be observed in Figure 1.1. For instance, during this specific day, of the current year, between 2 and 5 o'clock in the morning the consumption's needs were fulfilled by the "Special Regime Production" units (in green).

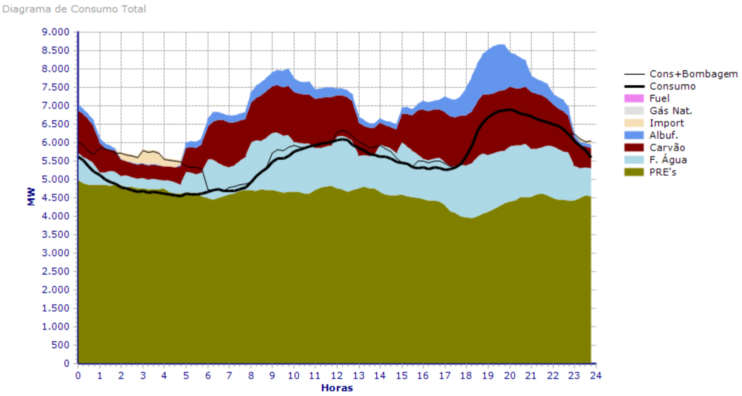

Figure 1.1 - Renewable energies penetration in Portugal during February 17th 2015 (REN). [1]

As it can be observed in Figure 1.2 the "Special Regime Production" is mainly from Wind sources (Eólica, in light green).

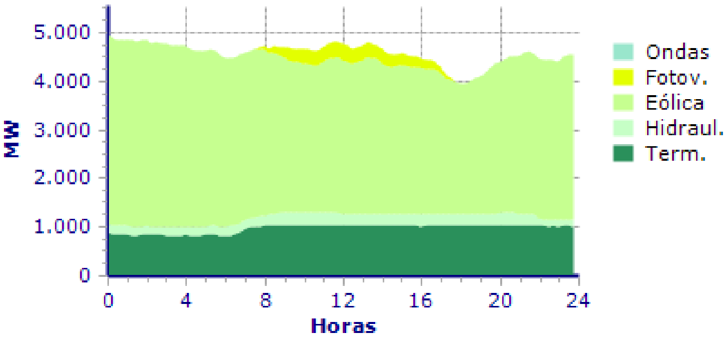

Figure 1.2 - Wind power penetration in Portugal during February 17th 2015 (REN). [1]

With this increasing installation of renewable energy sources, the energy system in Europe is changing towards a more decentralized and intermittent power production. The main challenge here is to substitute fossil fuel fired power plants by wind turbines and other renewable energy sources (RES), but then it would be necessary that these RES were able to provide ancillary services to the grid, that nowadays are secured by conventional power sources.

As it is going to be described in this work, real tests have shown that it is possible, for wind generators, to provide active power control, and therefore control the system's frequency, one of the most important ancillary services.

In order to keep today's quality of supply and stability of the power system, wind power will need to become an active market participant. Consequently it is going to be required new regulatory and technical conditions for involving wind energy into the provision of quality supply.

To conclude, it is expected that in a near future Wind Producers will be required to participate in reserve markets. Therefore the motivation of this work is to give them the needed tools to decide which is going to be their bid for the balancing markets where they are participating and for the electrical energy market.

1.3 - Assumptions

In this work wind power producers will be considered to deliver only Replacement Reserves (RR). In this document the Frequency Containment Reserve (FCR) and the Frequency Restoration Reserve (FRR) will not be studied as an ancillary service provided by wind generators. It is also considered that wind generators also participate in the day-ahead Electrical Energy Market. Therefore, it will be considered that wind producers are allowed to bid in day-ahead electrical energy markets and in balancing reserve markets. In this dissertation, intraday markets will not be considered due to its inherent complexity.

Furthermore, it is assumed that the wind power farm used to develop the decision problem is a price-taker, therefore it will not have an influence in the making of the price of the day-ahead electrical energy market.

In this work, as it will be later explained, two ways of defining the revenue of a given bid are studied. One of them sets the "true" wind power generation as baseline for downward reserve. This could be done if the market player had access to the wind velocity verified in the wind farm.

Lastly, when the possible scenarios are calculated it is taken for granted that when the maximum available production, for a given hour, is higher than the day-ahead electrical energy bid, for that same hour, the producer is always capable of limiting its production to a value equal to the energy bid.

1.4 - Document structure

The present work is structured as follows:

Chapter 2: in this chapter a review of the state of the art is made. Here the main subjects related to the wind participation in the balancing reserve markets are studied. The most relevant ones are the technical capabilities of wind generators to vary their production, the forecasting tools that can be used in order to predict not only power productions, but also market prices and the direction of the needed regulation.

Chapter 3: the methodology of this work is shown in this chapter. The problem is described and a mathematic formulation is explained. Lastly, three decision strategies are defined, these will be later used to elucidate how the proneness towards risk of a decision maker can be simulated. In this work a Matlab algorithm was implemented considering what was defined in the mathematic formulation from this chapter.

Chapter 4: the results obtained when there was no uncertainty in the power forecast and when the probabilities of the direction of each reserve were known and given as input to the Matlab algorithm, are analysed in this chapter. These analysis enable a full understanding of the formulated problem, more specifically, the difference between the two cases that are studied becomes more intelligible.

Chapter 5: in this chapter the results obtained when the Matlab algorithm was run, considering the uncertainty of the power forecast, of the reserve direction and of the three market prices, which are the day-ahead electrical energy market and the upward and downward balancing reserve market prices, are shown. These results were tested with real power production and real prices verified in that specific day and hour.

Chapter 6: in this last chapter, not only the conclusions of this thesis are summarised, but also some suggestions of possible future developments are made.

This document concludes with the glossary and the bibliography.

Chapter 2

State of the art

The participation of wind power producers in balancing reserve markets is the subject of our study. Therefore the state of the art in this field was investigated and the main conclusions are presented in this chapter.

In order to involve wind power producers in this type of electricity market it is indispensable that the wind generators have the physical capacity to vary, in both upward and downward direction, their power output between zero and a maximum production which is dependent from the wind velocity at the time. Therefore, in this chapter the main studies found related to this technical capability are shown.

Moreover, there are a number of forecasting tools that are needed to be used in order to create an offer for the day-ahead electrical energy and balancing reserve markets. Several studies concerning different forecasting tools were consulted and their conclusions are brought to light in this chapter.

A subject that is of crucial importance in order to incite the participation of wind power producers is the electricity market design, which means how the market should pay for the ancillary services provided by this renewable sources of energy.

Under current market regulations up-regulation provided by wind farms is not profitable because it induces large opportunity losses [2], since the wind farms must be scheduled to be down regulated. On the other hand, down-regulation do not lead to such losses, in this case the farm can be operating normally and at given point it is requested to reduce its production to a given set point.

Wind power is considerably different from other power technologies and integrating large amounts of this source of energy in the existing power system turns out to be a challenging action, requiring innovative approaches to keep the sustainability of the power system operation [3]. The power production of wind farms is time variant, which means its production, at a given time, depends on the wind speeds at that moment. While the conventional power plants can be considered time invariant.

The main goal of this dissertation is to propose a solution that would enable the wind farm producer do decide whether if he should bid for up or down (or both) regulation markets, not only considering the power forecast for a given period of time, but also, the probability in which way regulation is going to be required during the same period and the market price that paid for the energy and for the reserves in each direction.

2.1 - Technical capabilities

In order to being able to deliver frequency support to the system, wind farms must be capable of controlling their active power output. Following what is stated in [4] the most common available methods for active power control are:

- Active Power Delta Control Mode;
- Active Power Limitation Control Mode;
- Active Power Gradient Control Mode;

The first one, which is sometimes referred as *spinning reserve*, is also known as *Delta Production Constraint*, this type of control implies that the Wind Power Plant (WPP) has the ability to reduce its power output by a desired power offset percentage value compared to the possible production under the present wind speed, creating this way a power output reserve.

The second control type is also known as *Absolute Production Constraint,* this one limits the power output of the WPP to a given set point. This one is usually used in order to avoid overloading the grid.

The last one is also known as *Power Gradient Constraint* and through this control it is possible to limit the maximum speed at which the power output of a WPP changes, independently from wind speed variations.

All modern Wind Turbines (WT), specifically: variable speed, doubly-fed asynchronous generators with rotor-side converter and variable speed generators with full converter interface, are able to control their active power output. These machines are equipped with blade pitch control. These WT technology represents the greater part of the installed power in Europe [4]. However, it is said in the same research that there are some WT, operating nowadays in Europe that cannot actively control their power output. These ones are estimated to represent less than 20% of the installed power.

The author adds that modern WT only take 6 to 10 seconds of maximum response time when going from the lowest power level to full rated power, and it is said that from responses given by manufacturers the response times for up- and downward regulation are between 1-2 seconds to 4-6 seconds. The author concludes, this section, by saying that active power control is generally available and very fast ramp rate control can be achieved.

In [9] a method on how wind power plants can control their power production is presented. Here, the authors propose a novel control strategy for active power reserve provision of doubly fed induction generator wind turbines.

The report [10] declares that the main obstacles towards turning wind power into an active player in the markets for ancillary services are cost driven. Nowadays, participating in these markets lead to high opportunity costs related to not producing at a high and fix subsidy regime. The same report adds that it is a fundamentally political decision to incentivise renewable power production, especially wind power, participation in markets for ancillary services.

2.2 - Proof of frequency control provision with wind farms

In [6] the authors state that in Germany, nowadays, the proof of frequency control provision is done by comparing the planned power production with the real power production, the difference between the two must equal the amount of contracted frequency control power. This technique works perfectly with conventional power plants where the power production can be planned. For variable producers, as wind farms or photovoltaics this cannot be applied. For them there are two possibilities: one is to reduce their planned power production, and this is done by increasing the probability of reaching it; the other possibility is to combine storage with the wind farm, this last solution was studied in [8].

On one hand, the authors from [6] concluded that the first option is neither ecologic nor economic, as at a low security level of 90% a great amount of energy is lost. On the other hand, accordingly to [8] nowadays, considering the market conditions, it does not make sense to provide tertiary control with a regenerative virtual power plant, with a considerable amount of wind energy, not even with biogas plants and a pump storage plant balancing the fluctuations of the wind power production.

As the last two solutions had disadvantages the authors from [5] and [6] developed a new proof. This one is done by comparing the available active power (AAP) with the real power production. The AAP is the same power that would have been produced if the wind farm has not been curtailed. AAP provides relevant information in case of: provision of control reserve, or down-regulation due to negative prices at the spot market and congestions management [11].

In [11], five different methods for the estimation of the AAP were defined and compared. The five studied methods were the following:

- Last Measured Value;
- Adjusted Power Curve;
- Site-specific Power Curve;
- Reference Wind Turbine;
- Physical model;

A full description of each method can be found in [11]. For now it should be noted that accordingly to this paper the best method to estimate the AAP of a wind farm is the *physical model*. This technique of estimating the AAP tries to reproduce the physical effects, within the wind farm, that influence the Nacelle anemometer Wind Speed (NWS) measurement, which are: the rotor's wake effect[1] and the wake effect caused by other wind turbines. Basically, the authors implemented a NWS correction using historical time series of measured NWS and produced power of wind turbines. Moreover, the method requires some static data: hub heights, rotor diameters, wind turbine's positions and power curves.

2.3 - Forecasting

a. Wind Power

Wind power forecasting is a subject that has already been studied extensively. The tools created to predict the wind generation are particularly helpful for a secure and economic management of a power system [16].

There is a wide range of methods to forecast wind power. For instance, in [17] a Kernel Density Forecast (KDF) is used. The KDF provides predictions in the form of probability density functions. In other papers adapted resampling [19] [18]and spline quantile regression [20] were used.

Accordingly to [18] there are two typical approaches for wind power forecasting: a *statistical* approach and a *physical* one. In the first method numerical weather predictions and past observations are used in order to estimate the future production. Whereas, the second type of models include the process of conversion from global to local wind and then to wind power.

The authors from [21] used an advanced wind power forecasting system which had input data from different sources, including: SCADA data (i.e. active power generated), local meteorological measurements, numerical weather prediction models (NWPs) and additional characteristics of the nearby terrain topography and the wind power plants. In the same paper, the authors state that, typically, forecasting systems produce predictions for a time horizon between 1 hour and 2-3 days ahead in time and add that, generally speaking, the forecasting error increases with the forecast horizon, therefore the closer one gets to the time of delivery the better are the forecasts of the wind production.

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[1] Wake effect – "*Occurs between commercial upwind turbines and downwind turbines. Upwind turbines create wind wakes that impact the natural wind flow to adjacent downwind turbines, causing the downwind turbines to experience diminished energy production and, in some cases, increased mechanical loads.*" taken from [12].

In recent years the accuracy of forecasts have improved considerably, accordingly [14]. Furthermore, the German DENA II study, [15], predicts that a minimum improvement of ~40% on the mean absolute error of forecasts will be possible by 2020.

b. Day-ahead prices

In [22] a complete review on the state of the art of electricity prices forecasting is done. The author from this work introduces the subject by saying that, nowadays, power portfolio managers are particularly interested in price forecasts from a few hours ahead up to a few months ahead, because, on the corporate level, price forecasts have become indispensable as an input of an energy company's decision-making mechanism. Price forecasts with reasonable accuracies allow market participants to adjust their bidding strategies or their consumption or production schedule in order to maximise profits or reduce risk in day-ahead trading.

As system operators require advance notice in order to verify if the schedule is feasible and transmission constraints are not violated the 'spot market' is typically a day-ahead market where continuous trading is not allowed [22][21].

The author from [22] proposes five groups of models for classification of the forecast models used in the literature. And they are:

- Multi-agent models.
- Fundamental (structural) methods.
- Reduced-form (quantitative, stochastic) models.
- Statistical (econometric, technical analysis) approaches.
- Computational intelligence techniques.

But it is also stated that there are other models that result from the combination of two or more of the mentioned models, these one are called *hybrid* solutions.

In [23] and [24] the authors employed an uncertainty model that consisted in the use of a Seasonal Autoregressive Integrated Moving Average (SARIMA) and then the errors of SARIMA are tested to find a Generalized Autoregressive Conditional Heteroskedasticity[2] model (GARCH) behaviour. Using past data, they applied a price forecasting model and generated scenarios, which represented the prices uncertainties.

In [17] it was used a naïve model to project day-ahead (DA) locational marginal prices (LMPs), here, they were assumed to be Gaussian. The model created correlates the mean and variance calculated from the most recent four weeks data with the price for each hour of the next day.

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[2] Heteroskedasticity – In statistics is a collection of random variables where there are sub-populations that have different variances or any other measure of statistical dispersion from others. [25]

c. Regulation direction

As it is stated in [28] anticipating the regulation direction requires predicting if upward or downward balancing reserve is going to be needed in each time interval of the next hours.

In [26] the forecast of regulation's direction is studied using classification models. A logistic regression model, which included a trading schedule, was used. Although when it was applied to the data set the resulting hit rate was 61.1% and 58.6% for the down and up regulation respectively. Without the trading schedule, results were not as successful. Afterwards a sliding window version of the logistic regression model was attempted as well. In this case the hit rate improved considerably, 67.8% and 69.2% for the down and up regulation respectively.

In the same work, the author also tried to make the regulation's direction prediction using a Support Vector Machine (SVM). While logistic regression models assume that classes are linearly separated and non-overlapping, on the contrary SVM do not assume that. As this assumption is not valid in the regulation direction, SVMs are expected to work better in this specific case. Accordingly to [26] SVMs handle this type of classes by mapping them into a high dimensional space.

The author created, again, two models one static version and a sliding window version, but this time using SVMs. The static version of the SVM accomplished a hit rate that was slightly worse than the static version of the logistic regression model. Nevertheless, the sliding window version had a hit rate that was quite better than the hit rate from the logistic regression. In this case the SVM model had a hit rate of 75.5% for the down regulation and 76.4% for the up regulation. It is important to note that this last results were from a model that included the trading schedule.

In [28] the author plotted the autocorrelation time series of secondary and balancing reserve direction, and concluded that forecasts could not be calculated using past values of the time series as the autocorrelation for secondary reserve was very low. On the other hand, the autocorrelation plot for balancing reserve presented higher autocorrelation values, which suggested that past values of the time series had relevant information to forecast the next values. The author opted to forecast the regulation's direction using a Generalized Linear Model (GLM) with the response variable following a binominal distribution.

d. Balance prices

As it is referred in [27], when studying electricity balancing markets there are two options to be considered. The market can either be:

- a one-price balancing market;
- a two-price (or dual-price) settlement for imbalances;

On one hand, in the first type of market the price paid by the TSO for downward and upward regulation is the same. On the other, the DA price is applied to unwanted deviations in the opposite direction to the system's imbalance, while the marginal price at the balancing stage is applied to all the other deviations.

Accordingly to [28], in most markets the reserve bids consist in a quantity (in MW) and a price for dispatched energy (in €/MWh). Moreover, the price for upward reserve is usually greater or equal to the energy price, while the downward reserve price is lower or equal. In this work, [28], the price was forecasted using a Holt-Winters algorithm for irregular time series.

In this work it will be implemented a two-price balancing market, as this is the employed system at the Iberian market (MIBEL).

Accordingly to [26] it is not possible to treat balance prices as a time series, due to the fact that regulation in each direction occurs only for some hours and the time between observations varies. With this statement the author concludes that separated modelling of regulation prices, conditioned on the occurrence of regulation in that direction, is needed. Therefore, before predicting the regulation price it is necessary to predict if the regulation is going to be needed and if that is the case, in which direction. In his master thesis, [26], the author made the balance price predictions using a quantile regression.

2.4 - Bidding in control reserve markets

In [7] the author describes briefly the regulation market. There it is said that this specific market is managed by the TSO and its goal is to ensure a real-time balance between load and generation. The general principles of the settlement mechanism for imbalance prices are the same throughout countries. Firstly if production is equal to consumption no regulation is needed. Then there are two other possibilities: generation does not meet load either because the latter is bigger than the former and in that case the production is not sufficient to meet the load, or the production exceeds the consumption. In the first scenario an up-regulation is needed and for that reason it is necessary to increase generation or decrease consumption. In the second one a down-regulation is necessary to balance the electrical system and as a consequence generation needs to be curtailed or alternatively consumption is increased or the excess energy is sold to neighbouring countries. This last possibility of balancing the system is only possible if there are good interconnections between countries. In [7] the authors mention that at the same time it may be necessary an up-regulation in an area and a down-regulation in another, due to the physical limitation of connections between areas of the overall power system. This leads to high variability and hard predictability of imbalance prices. The author concludes by saying that the production or curtailment costs, a premium for readiness and a way to discourage power producers to plan imbalances should be considered when defining imbalance prices.

Accordingly to [5] when bidding on control reserve markets the wind park operator must calculate an offer based on a defined security level for the forecast. This prediction is estimated by means of probabilistic forecasts and defines the amount of capacity that can be delivered at a certain time. The authors of [5] and [6] opted for a statistical approach for the estimation of the different security levels of the probabilistic forecast and used the n-dimensional Gaussian kernel density estimation to do so. This method allows to include pre-errors into the calculation, which means that errors between forecast and feed-in that have already been identified are used for the improvement of the method. Although this technique, owing to the large lead-time of day-ahead forecasts, is only effective for intraday forecast. Using this method the authors concluded that at times of low wind power predictions the power that could not be offered due to forecast uncertainty was considerably high compared to times with high wind power predictions. Consequently, in order to be more efficient it would be better to offer control reserve at times of high wind power forecasts. Moreover, as shown by [5], lower security levels may put at risk system's stability as the forecasted value is higher than the actual feed-in.

2.5 - Current grid connection requirements in Europe

When wind generators started to be installed they were considered to be non-controllable energy sources and their production was completely dependent on the unstable and unpredictable weather conditions, [3].

Traditionally RES, and particularly wind generation, have been thought to not being capable of actively providing ancillary services. Mechanisms which support the integration of RES did not consider this possibility often. However, nowadays the feed-in tariff schemes are sometimes compatible with other remuneration concepts. In general, present mechanisms incentivize the production of as much energy as possible, regardless of the regulation needs of the TSOs [38].

During the last years, as the wind power penetration has increased drastically and turbine manufacturers have developed new technologies capable of controlling active and reactive power productions from wind farms, some technical requirements started to be included into grid codes.

In Europe the current requirements with regard to active power control are [3]:

- Controllability and control range;
- Ramping and limitation;
- Control modes;
- Reduction due to over frequency and reduction for protection schemes;
- Frequency control;

These requirements are specific to each country, but there are some that are compulsory all over the EU, accordingly to [38] primary reserve provision is one example of an obligatory service for all participating generators.

In Spain, the system operator can require wind farms to set a reference active power. This set-point can be in all the feasible active power range until the maximum active power available, which depends directly on the wind speed available at the time. In Denmark, this set-point is only required to be in between 20 and 100% of the rated power [3].

In what concerns the ramping and limitation, in most countries the ramping control of active power must be possible [3].

In case of a transmission congestion TSOs are generally authorized to curtail wind generation, however depending on the country this energy curtailment might be or not compensated. In Spain, producers under feed-in tariffs are not compensated, while in Germany the opposite scenario might be verified [38].

Energy curtailments can also occur when the frequency of the system drops below a given value or in other circumstances if an over frequency is detected, in Spain these limits are 48 and 51 Hz, respectively [3].

2.6 - Differences in the Market design

a. Current situation

In Portugal and Spain the MIBEL is the day-ahead market where agents submit their bids using physical unit bidding for each hour of the next day.

Nowadays, as mentioned before, frequency containment reserve provision is mandatory for all participating generators. On the other hand, Replacement Reserves, also known as tertiary reserve, are not compulsory. In the Iberian market the allocation of this kind of reserve, (the latter) is done by a continuous auction where all generation and pumping units are obliged to offer their available capacity, which have not been offered on previous markets. These RR bids are sent at 23h00 from the day-ahead and can be updated until 25 minutes before the beginning of the delivery hour. The bids can be activated until 15 minutes before the delivery period, or in case the bid is allocated in the same hourly period of the delivery they can be activated during the delivery period. RR bids are selected by economic merit order, without causing technical constraints, and comprise quantity (MW) and hourly price (€/MWh). The availability to provide RR is not payed. Furthermore, the costs of the provision of RR are covered by generation and demand units that have deviated from their programmes, except from exports and pumping consumption [38].

In Portugal and Spain, intermittent renewable generation have two possible support schemes that they can choose:

- a regulated tariff, which varies depending on the periods they generate;

- participate in the market and therefore, selling the energy at the hourly market price, but they receive a plus premium, with upper and lower limits for the sum of the reference market price and the reference premium;

In both cases, in case of program deviations, a penalty must be paid for the balancing energy needed to counteract their deviation.

b. New market settlement

In [28] a description of a possible market settlement phase for the energy and balancing reserve bids is done. In this PhD thesis, the author proposed methodologies for the participation of an electric vehicles' aggregator in the electricity market.

Likewise it is done in this work, the aggregator (here the wind power producer) offered energy and balancing reserve bids. While in this work upward reserve consists in increasing the power production of a WF, in [28] upward reserve was delivered by the demand side and, consequently, consisted in reducing the consumption. Furthermore, here a downward reserve bid consists in a power production reduction.

As highlighted in [28] and [39], a payment for consumption reduction of a load faces a problem, which is how to measure this reduction compared to the consumption level in the absence of a payment. If the reduction is measured by calculating the difference between the energy bid and the consumption bid verified, it can lead to exaggerated energy bids when the aggregator forecasts a high probability for upward reserve. Inflated energy bids result in increased consumption reductions. This can be a serious problem, in this case of demand response, system operators would continue to undermine faith in its reliability [39].

This problem is also verified in the delivery of downward reserve by wind power producers. Here if the producer forecasts a high probability of downward reserve, it might induce him to gamble, and therefore, make a high energy bid. If the reserve is actually used it will lead to a very high profit, if the reserve is not used, then the producer will incur in a penalization.

In [28] a baseline which places a limit on the paid upward reserve is introduced. In his work, Bessa defined it as the minimum between the maximum charging power and the residual charging requirement at the same time interval.

The way that RR are paid is also covered in [28], this work follows what was done in the mentioned PhD thesis.

This could be implemented in a market which would incite the penetration of intermittent RES.

Chapter 3

Methodology

3.1 - Problem Formulation

The aim of this problem is to maximize the revenue of wind power producers. Therefore the goal is to sell the energy produced while minimizing penalties. To accomplish this the producer will have to decide, considering a certain level of risk, what he is going to offer in the DA electrical energy market and in the DA balancing reserve market. Hence, one can conclude that the variables calculated (outputs) from the problem will be:

- Energy bid for DA electrical energy market (W_t^B);
- Power bid for DA upward balancing reserve market (W_t^{B+});
- Power bid for DA downward balancing reserve market (W_t^{B-});

The price offered in the DA electrical energy market will be 0€/MWh, at all times. This is only possible because these producers do not have fuel costs (being the wind the source of energy). Consequently they are capable of offering this marginal price. The advantage of bidding such low price is that it increases expressively the probability of the offer to be accepted. On the other hand, if the power system has a meaningful penetration of producers which marginal costs is also zero, the demand might be satisfied, at times, only by these low marginal energy price producers, subsequently the spot price becomes 0€/MWh. Which means that all the power producers will not be paid for producing electricity.

In some countries negative prices are accepted as bids in spot markets. In this work this option will not be considered as this is the case of the Iberian market (MIBEL). Negative prices, mean that producers are willing to pay to produce electrical energy as this is less expensive than turning off and on a power plant, for instance.

It is going to be considered, in this work, that the offers for upward and downward reserves are always accepted in the balancing reserve market.

In order to calculate the above mentioned variables one needs as input variables, the following ones:

- Hourly wind power production forecast and its probability;
- Hourly forecast of the probability of the direction of the balance reserve (up or down);
- Hourly forecasts of prices of:
    - Day-ahead electrical energy market;
    - Upward reserve from day-ahead balancing reserve market;
    - Downward reserve from day-ahead balancing reserve market;

As the decision problem is the main objective of this work the forecasts of power quantities and prices will be considered as random variables, i.e., probability distributions with mean and variances comparable to real data.

The price bid for the upward reserve will be low enough to be accepted in the DA electrical energy market. As mentioned before, in (1.3) it is assumed that the wind farm is a price-taker. On the other hand, the price bid for the DA balancing downward reserve will be lower than the price from the DA electrical energy market. Both prices are random variables created with the mean and variance, of each hour, from real values.

Given these inputs it becomes possible to create hourly bids where different probabilities of power forecasts and the direction of the reserve are considered. In the end, given the propensity towards risk of the decision maker a bid for each market will be made. Each bid involves defining a power quantity and a price, however as mentioned before only the quantity will be calculated as the bid is considered to be accepted at all times.

The input variables for this problem are:

- $\hat{p}_t - DA\ electrical\ energy\ market\ price\ forecast\ for\ each\ hour\ t;$
- $\hat{p}_t^{up} - DA\ balancing\ upward\ reserve\ price\ forecast\ for\ each\ hour\ t;$
- $\hat{p}_t^{down} - DA\ balancing\ downward\ reserve\ price\ forecast\ for\ each\ hour\ t;$
- $\tau_t^{up} -\ probability\ of\ DA\ balancing\ reserve\ at\ hour\ t\ being\ in\ upwards\ direction;$
- $\tau_t^{down} - probability\ of\ DA\ balancing\ reserve\ at\ hour\ t\ being\ in\ downwards\ direction;$
- $\widehat{W}_t - wind\ power\ forecast\ for\ each\ hour\ t;$

Notice that (t) is the hour of the day, therefore this variable varies between 1 and 24.

The objective for the wind power producer is to find the most adequate DA bids (W_t^B,W_t^{B+}, W_t^{B-}) depending on the decision criterion adopted. Therefore, it is possible to implement different objective functions for this problem. Likewise it was done in [17], here three different objective functions are tested: an expected profit function, a maximization of the expected utility (MEU) and one conditional value at risk (CVaR), this topic will be further developed in section 3.7.

In order to calculate the expected revenue, the profit from selling energy in the DA electrical energy market and from selling upward and downward reserve in the DA balancing reserve market must be calculated. Although, this three parcels are not enough to calculate the expected profit, unfortunately, there are also penalizations that must be included.

The penalizations occur when the contracted energy or reserve power is not delivered, for instance when a pre-contracted upward reserve is requested to a wind farm and the producer cannot deliver it because he has no, or enough, margin to increase its production as he was supposed to. This usually happens due to forecast errors, in this case producers are misled into offering a greater quantity than what they are actually capable of delivering. Other reason for being penalized is when the decision maker is prone to risk, this way the decisions made can incur in great penalizations, in the worst case scenarios. The same might happen when delivering the contracted energy in the spot market and downward reserve.

Another parcel that will have a negative effect on the total expected revenue is the cost of having made a bid for upward reserve for a given hour of the day, and during that hour the TSO ends up not asking for upward reserve from producers, although this one was not directly considered in the mathematic formulation of the problem.

Wind power producers must operate in a lower operating point in order to save some power margin that enables an increase of generated power to deliver upward reserve. Consequently whenever they leave a margin and the TSO does not ask for that power, producers end up “spilling” energy. Once again this might happen due to forecasting errors, here, when predicting the reserve´s direction.

Afterwards the mathematic formulation of the problem will be shown.

3.2 - Mathematic Formulation

Given the power forecast distribution ($\widehat{W_t}$), the probability of the needed reserve, and the prices of each market, for each hour of the day three bids are created.

The expected revenue from participating in the DA electrical energy market and in the DA balancing reserve market can be decomposed in, as mentioned before, four major parts: profit from selling energy in the DA electrical energy market (equation 1), profit from selling upward and downward reserve in the DA balancing reserve market (equations 2, 3, 6 and 7) and penalizations (equations 4, 5, 8 and 9). In order to estimate the revenue one must sum these six parcels.

Selling the contracted power at the DA electrical energy market:

$$W_t^B \cdot \hat{p}_t \tag{1}$$

Selling the contracted upward reserve:

$$W_t^{B+}.\hat{p}_t^{up} \tag{2}$$

Selling the contracted downward reserve:

$$-W_t^{B-}.\hat{p}_t^{down} \tag{3}$$

Penalizations are proportional to the difference between the contracted energy at the day before and the actual electrical energy delivered (4). Moreover, as far as energy penalizations are concerned, when there are differences between the contracted electrical energy and the energy delivered one must consider that if the imbalance provides an "additional reserve" that helps solving the system deviation, it should not be penalized. Which means that if, for instance, the energy delivered at a given hour is smaller than the contracted energy and during that hour downward reserve is needed, the producer will not be penalized for not delivering it.

In order to calculate these penalizations, there are some variables that must be introduced at this point: R_t^{down*} and R_t^{up*} are the directions of the balancing reserve at each hour of the day. These two variables are binary and follow a binominal distribution with their parameters equal to the probability of the reserve being necessary in each way, τ_t^{down} and τ_t^{up} respectively.

Variables marked with "^{oc}" are the outcomes, for instance: W_t^{oc} is the delivered energy in a given scenario at hour t, this variable will depend on the randomly selected value from the power forecast and on the Remuneration Scheme in study (A or B). This will be further explained on section 3.5.

$$Energy\ penalty = \begin{cases} 0, & if\ W_t^{oc} = W_t^B \\ -|W_t^B - W_t^{oc}|.\hat{p}_t^{up}, & if\ W_t^{oc} < W_t^B\ AND\ R_t^{down*} = 0 \end{cases} \tag{4}$$

Like it can be observed in equation 4, when there is a lack of delivered energy and downward reserve is not necessary the producer will have to pay for this difference at the upward reserve price. Since there will be a lack of energy in the power system, it will be necessary that some other market players increase their power production, therefore they will be paid a certain amount equal to what the faulty producer paid as penalization for not delivering the total quantity of electrical energy.

One should notice that: scenarios with energy deliveries bigger than the corresponding energy bids were considered to be non-existent, since it was assumed that the wind farm producer was capable of restricting its production to a given set point, leaving a margin to increase its power production.

There will also be penalizations, due to reserves not supplied (RNS), these can be in both directions, upwards or downwards.

Although, penalizations for not delivering the offered reserves are both penalized, one should notice that the way these penalizations are calculated differ from each other. The reason for this to happen has mainly to do with the prices that are paid for each reserve. Like it was mentioned before, upward reserve has higher prices than the spot market price and downward reserves are paid at a lower price than the spot market.

When the bid for upward reserve is not met, due to a lack of production, the penalization is calculated applying equation 5:

$$RNS_t^{up} = -(W_t^{B+} - W_t^{oc+}).\hat{p}_t^{up}.R_t^{up*}.\rho \tag{5}$$

Likewise it was done in [28], here ρ (from equation 5) is equal to one. Having this coefficient with this value means that, if the wind power producer does not deliver at least 50% of the contracted upward reserve, he will incur in a penalization which will be greater than the profit from selling part of the contracted reserve.

On the other hand, it might happen, at times, reserves surpluses, once again this can happen in both directions. If it is a downward reserve surplus, this extra is paid at the electrical energy market price, following equation 6:

$$R_t^{surplus\_down} = -(W_t^{oc-} - W_t^{B-}).\hat{p}_t.R_t^{down*} \tag{6}$$

If the delivered extra reserve is in the opposite direction the difference is also paid at the spot market, like it is shown in equation 7:

$$R_t^{surplus\_up} = (W_t^{oc+} - W_t^{B+}).\hat{p}_t.R_t^{up*} \tag{7}$$

As mentioned before, there are two different remuneration schemes that were studied. One of the differences, between them, is in the way that penalizations for downward reserve are calculated when the downward reserve outcome (W_t^{oc-}) is higher than the bid (W_t^{B-}) for the same hour. In remuneration scheme (A), when W_t^{oc-} is higher than W_t^{B-} this means that the producer will be penalized for not delivering the reserve that was contracted and will also pay the downward reserve surplus (6).

$$RNS_t^{down} = -W_t^{B-}.(\hat{p}_t - \hat{p}_t^{down}).R_t^{down*} \tag{8}$$

In remuneration scheme (B), when W_t^{oc-} is higher than W_t^{B-} the market player will assume that the reserve was fully delivered and it was also delivered an extra downward reserve.

Finally in both remuneration schemes, when W_t^{oc-} is smaller than W_t^{B-} the penalization for not fully delivering downward reserve is calculated following equation 9:

$$RNS_t^{down} = -(W_t^{B-} - W_t^{oc-}).(\hat{p}_t - \hat{p}_t^{down}).R_t^{down*} \tag{9}$$

One should take notice that upward and downward penalizations and profits from selling extra reserves will only be enabled when R_t^{up*} and R_t^{down*}, respectively, are equal to one. Whenever upwards or downwards reserve are not necessary, in a given tested scenario, there should be no penalty for differences in the contracted and available reserves.

The revenue, $R(W_t^{oc}, W_t^{oc+}, W_t^{oc-})$ from selling electricity at a given hour t will be:

$$\begin{aligned} R(W_t^{oc}, W_t^{oc+}, W_t^{oc-}) = (W_t^{B}.\hat{p}_t) + (R_t^{up*}.W_t^{oc+}.\hat{p}_t^{up}) - (R_t^{down*}.W_t^{oc-}.\hat{p}_t^{down}) - \\ -f(W_t^{oc}, W_t^{B}, R_t^{down*}) - RNS_t^{down} - RNS_t^{up} + R_t^{surplus_{up}} + R_t^{surplus\_down} \end{aligned} \tag{10}$$

Where $f(W_t^{oc}, W_t^{B}, R_t^{down*})$ is defined as the energy penalty was in equation (4).

c. Problem Constraints

The problem constraints are defined hereafter.

Firstly, no matter the hour of the day, the sum of upward reserve and DA electrical energy market bids must be lower or equal to the installed power (W_{inst}) of the wind farm(s) that the market participant is bidding for.

$$W_t^B + W_t^{B+} \leq W_{inst} \quad with\ t \in [1; 2; \dots; 24] \tag{11}$$

Secondly, the power bid for downward reserve must be lower or equal to the bid for the DA electrical energy market because that should be the maximum reduction of power production that could be verified at each hour of the day.

$$W_t^{B-} \leq W_t^B\ with\ t \in [1; 2; \dots; 24] \tag{12}$$

Thirdly, as mentioned before, it is assumed that this market does not accept negative bids, therefore all prices must be equal or greater than zero €/MWh.

$$\hat{p}_t^{down} \geq 0 \quad with\ t \in [1; 2; \dots; 24] \tag{13}$$

$$\hat{p}_t^{up} \geq 0 \quad with\ t \in [1; 2; \dots; 24] \tag{14}$$

$$\hat{p}_t \geq 0 \quad with\ t \in [1; 2; \dots; 24] \tag{15}$$

Lastly, all power bids must be equal or greater than zero MW.

$$W_t^B \geq 0 \quad with\ t \in [1; 2; \dots; 24] \tag{16}$$

$$W_t^{B+} \geq 0 \quad with\ t \in [1; 2; \dots; 24] \tag{17}$$

$$W_t^{B-} \geq 0 \quad with\ t \in [1; 2; \dots; 24] \tag{18}$$

3.3 - Solving the stochastic problem

Likewise it was done in [32], here a Monte Carlo Simulation will be used. Using this tool one can characterize the probabilistic behaviour of the problem.

The Monte Carlo model is generally used to create a representative sample of the behaviour of a system by randomly creating and analysing possible outcomes. Afterwards it is possible to calculate the mean value of results or other parameters like the standard deviation for instance, and, consequently, one can deduce the behaviour of the global system based on the behaviour of the sample [33].

For each hour, a series of possible outcomes (scenarios) for: the actual wind power production, market prices and reserves necessity are generated. With these possible outcomes one can evaluate how the different bids perform, due to the possibility to calculate the penalizations that might occur as a consequence of differences in the contracted and delivered energy and reserves. Their performance will help the market player to make a decision.

Each scenario is made of a vector **x** = [$\widehat{W}_t^{\,oc}$, R_t^{up*}, R_t^{down*}, $\hat{p}_t$, $\hat{p}_t^{up}$, $\hat{p}_t^{down}$], the probability of occurrence of each element (**i**) of **x** is known, p($\mathbf{x}_i$). Given the probabilities of each element, it is assumed that it is possible to know the probability of each scenario p(**x**). As the occurrence of each element of **x** is probabilistically independent from each other, p(**x**) is given by the product between all p($\mathbf{x}_i$).

The maximization of the function $R(W_t^B, W_t^{B+}, W_t^{B-})$, will be the test function for this Monte Carlo simulation. If all the possible scenarios and all the possible combinations of states were considered, it would be possible to calculate the real expected value, $E(R)$, of the test function. Although, only a finite number of scenarios will be tested, therefore it can only be determined an estimation of $E(R)$, $\hat{E}(R)$.

In the Monte Carlo method $E(R)$ is estimated by randomly selecting N possible scenarios:

$$\hat{E}(R) = \frac{1}{N}\sum_{i=1}^{N} R(x_i) \tag{19}$$

As in any other sampling process the mean value form the sample is distributed around the "real" value in such a way that the uncertainty of the estimation can be represented by a variance $V\left(\hat{E}(R)\right)$.

$$V\left(\hat{E}(R)\right) = \frac{V(E)}{N} \tag{20}$$

Where $V(E)$ is the real variance of $E(R)$. As this value is not known, it is usually used an unbiased estimator given by:

$$\hat{V}(E) = \frac{1}{N-1}\sum_{i=1}^{N}\left[R(x_i) - \hat{E}(R)\right]^2 \tag{21}$$

From the last expression one can deduce that the uncertainty in the estimation is inversely proportional to the dimension of the sample N. It is usual to define a convergence criterion for the Monte Carlo Simulation as a coefficient of variation:

$$\beta^2 = \frac{V\left(\hat{E}(R)\right)}{\hat{E}(R)^2} \tag{22}$$

Or in terms of the standard deviation $\sigma\left(\hat{E}(R)\right)$:

$$\beta = \frac{\sigma\left(\hat{E}(R)\right)}{\hat{E}(R)} \tag{23}$$

The simulation ends when this coefficient is lower than a pre-established threshold or when the loop runs 100.000 times.

3.4 - Analysing different rules for generating outcomes

In order to create the different scenarios, two possibilities were considered. One where the market player set the "true" wind power generation as baseline for downward reserve. Therefore he would have access to the values of the wind velocity during that hour, which would enable the market player to estimate the power that could be actually delivered. From now on these case will be referred as: remuneration scheme A (RS_A).

The other possibility considered was the one where the market player considered the accepted energy offer as baseline for downward reserve. From now on these case will be referred as: remuneration scheme B (RS_B).

These two possibilities interfere in the way which each scenario, created for testing an offer, is shaped and more specifically in the way that the revenue of each offer is calculated. While on RS_A the market player has more information about what is happening in the wind farm, it is possible to estimate how much downward reserve is being delivered, for instance, in RS_B the market player has little information and might be misled into thinking that a certain quantity of reserve is being delivered, when, what is in fact happening is that, there is not enough wind to produce more electricity.

One should notice that in both remuneration schemes the rule adopted defines that given a certain power quantity as outcome, the energy bid is the first to be met, then the remaining power, if there is any, will be for upward reserve. When the randomly generated number from the probability distribution of power forecast is equal or greater than the energy bid the downward reserve is always available for delivery. Other possibilities of distributing the randomly generated value through W_t^{oc}, W_t^{oc+} and W_t^{oc-} were examined and are explained hereafter.

Considering the example:

- $W_t^B = 50\ MWh$
- $W_t^{B+} = 10\ MW$
- $W_t^{B-} = 10\ MW$

This means that the producer is offering to deliver 50MW during hour t and is volunteering to reduce, if necessary and during hour t, his production from 50MW to 40MW, and if upward reserve is needed he is agreeing to increase his production from 50MW to 60MW.

If $\widehat{W}_t^{oc}$ happens to be bigger than 60MW the producer will be available to deliver more than 60MW, if upward reserve is demanded by the system, and will not be penalized for delivering more than what was negotiated before. However, like it was mentioned before, the surplus will not be paid at the upward reserve price but rather at the electrical energy market price. In this scenario the revenue is calculated following equation 24.

$$\begin{aligned} &R(W_t^B, W_t^{B+}, W_t^{B-}) = \\ &= (W_t^B +. \hat{p}_t) + \left(R_t^{up*}. W_t^{B+}. \hat{p}_t^{up}\right) + R_t^{surplus\_up} - (R_t^{down*}. W_t^{B-}. \hat{p}_t^{down}) \end{aligned} \tag{24}$$

As penalties are proportional to the difference between the outcome and the offer, when creating the outcomes the adopted rule tries to minimize this difference. Moreover, as upward and downward reserve offers consist in increasing or decreasing the delivered power from the value of the electrical energy offer to another value and not increasing or decreasing a given amount irrespectively of the power that was being delivered, the implemented algorithm starts by trying to meet the requested energy bid.

3.5 - Creating different scenarios for testing the bids

In both remuneration schemes the program starts by generating randomly a number from the probability distribution of power forecast, defining $\widehat{W_t}^{oc}$, as the maximum value of power production during that hour. Then the values of W_t^{oc}, W_t^{oc+} and W_t^{oc-} are calculated following two different reasonings:

- In RS$_A$:
    - If $\widehat{W_t}^{oc}$ is bigger than the bid for the DAEEM (W_t^B) then: W_t^{oc} is equal to the bid W_t^B, otherwise W_t^{oc} assumes the value of $\widehat{W_t}^{oc}$;
    - In case W_t^{oc} is equal to W_t^B, then W_t^{oc+} will be equal to difference between $\widehat{W_t}^{oc}$ and W_t^B; and W_t^{oc-} will be equal to the bid W_t^{B-}.
    - If W_t^{oc} is smaller than the difference between W_t^B and W_t^{B-} then there is no upward reserve and W_t^{oc-} will be equal to difference between W_t^B and W_t^{oc}.
    - Lastly if W_t^{oc} is equal or bigger than the difference between W_t^B and W_t^{B-} then: the value of W_t^{oc-} will be the difference between W_t^{oc} and $(W_t^B - W_t^{B-})$ and W_t^{oc+} will be zero.

Hereafter some illustrative examples of what occurs in RS$_A$, depending on the randomly selected value from the power forecast, will be presented to clearly explain what happens in each scenario.

Considering that the three day-ahead bids, for hour t, were:

- $W_t^B = 50\ MWh$
- $W_t^{B+} = 10\ MW$
- $W_t^{B-} = 10\ MW$

Knowing the bids one must evaluate them, calculating the revenue, but to do so several production outcomes are tested.

Following what was stated before if the randomly selected number from the probability distribution of power forecast was:

- $\widehat{W_t}^{oc} = 65\ MW \ => \begin{cases} W_t^{oc} = 50\ MWh \\ W_t^{oc+} = 15\ MW \\ W_t^{oc-} = 10\ MW \end{cases}$
- $\widehat{W_t}^{oc} = 60\ MW \ => \begin{cases} W_t^{oc} = 50\ MWh \\ W_t^{oc+} = 10\ MW \\ W_t^{oc-} = 10\ MW \end{cases}$
- $\widehat{W_t}^{oc} = 55\ MW \ => \begin{cases} W_t^{oc} = 50\ MWh \\ W_t^{oc+} = 5\ MW \\ W_t^{oc-} = 10\ MW \end{cases}$

- $\widehat{W}_t^{\ oc} = 50\, MW \ \ => \begin{cases} W_t^{oc} = 50\, MWh \\ W_t^{oc+} = 0\, MW \\ W_t^{oc-} = 10\, MW \end{cases}$
- $\widehat{W}_t^{\ oc} = 45\, MW \ \ => \begin{cases} W_t^{oc} = 45\, MWh \\ W_t^{oc+} = 0\, MW \\ W_t^{oc-} = 5\, MW \end{cases}$
- $\widehat{W}_t^{\ oc} = 30\, MW \ \ => \begin{cases} W_t^{oc} = 30\, MWh \\ W_t^{oc+} = 0\, MW \\ W_t^{oc-} = 20\, MW \end{cases}$

These variables W_t^{oc}, W_t^{oc+} and W_t^{oc-} are the ones used to calculate the revenue in each scenario.

Now RS_B will be further explained and likewise it was done for RS_A several examples will be presented.

- In RS_B the outcomes depend directly on the necessity for downward reserve:
    - If R_t^{down*} is equal to one, independently of the maximum possible production, at the time, the market player will assume that the energy bid is possible to be delivered and the production is being reduced because the power producer decided to. Therefore, W_t^{oc} will be equal to W_t^B.
    - On the other hand, if R_t^{down*} is equal to zero there are two possibilities: if W_t^B is higher than $\widehat{W}_t^{\ oc}$, then W_t^{oc} will be equal to $\widehat{W}_t^{\ oc}$; if W_t^B is equal or smaller than $\widehat{W}_t^{\ oc}$, then W_t^{oc} will be equal to W_t^B;
    - If W_t^B is smaller than $\widehat{W}_t^{\ oc}$, then W_t^{oc+} will be equal to the difference between $\widehat{W}_t^{\ oc}$ and W_t^B; otherwise W_t^{oc+} will be equal to zero.
    - If $\widehat{W}_t^{\ oc}$ is equal or higher than the difference between W_t^B and W_t^{B-}, then W_t^{oc-} will be equal to W_t^{B-}; otherwise it will be equal to the difference between W_t^B and $\widehat{W}_t^{\ oc}$.

From the above, one can conclude that when downward reserve is needed the market player might be led into thinking that the downward reserve delivered is greater than what it actually is.

In order to calculate the revenue for each scenario, one must consider that the only information available to the market player, in this remuneration scheme, is the accepted energy offer and the delivered power. So when calculating the revenue, the direction of the needed reserve will have an important influence in the totalling. In this RS_B offering downward reserve can be more profitable than in RS_A, but only if the reserve is actually needed.

The bids for the day ahead electrical energy market and for the day ahead balancing reserve market are the same used in the first example.

If downward reserve is needed then:

- $\widehat{W}_t^{\ oc} = 45\, MW \ \ => \begin{cases} W_t^{oc} = 50\, MWh \\ W_t^{oc+} = 0\, MW \\ W_t^{oc-} = \ 10\, MW \end{cases}$

- $$\widehat{W_t}^{oc} = 40\,MW \;=>\begin{cases} W_t^{oc} = 50\,MWh \\ W_t^{oc+} = 0\,MW \\ W_t^{oc-} = 10\,MW \end{cases}$$
- $$\widehat{W_t}^{oc} = 30\,MW \;=>\begin{cases} W_t^{oc} = 50\,MWh \\ W_t^{oc+} = 0\,MW \\ W_t^{oc-} = 20\,MW \end{cases}$$

On the other hand, if there is no need for downward reserve, then:

- $$\widehat{W_t}^{oc} = 45\,MW \;=>\begin{cases} W_t^{oc} = 45\,MWh \\ W_t^{oc+} = 0\,MW \\ W_t^{oc-} = 10\,MW \end{cases}$$
- $$\widehat{W_t}^{oc} = 40\,MW \;=>\begin{cases} W_t^{oc} = 40\,MWh \\ W_t^{oc+} = 0\,MW \\ W_t^{oc-} = 10\,MW \end{cases}$$
- $$\widehat{W_t}^{oc} = 30\,MW \;=>\begin{cases} W_t^{oc} = 30\,MWh \\ W_t^{oc+} = 0\,MW \\ W_t^{oc-} = 20\,MW \end{cases}$$

Examples of $\widehat{W_t}^{oc}$ equal or bigger than W_t^B were not presented this time as they would be equal to the ones from RS_A.

In scenarios that lead to downward reserve outcomes bigger than the bid for downward reserve of the day before (W_t^{B-}) the revenue is calculated following this equation:

$$\begin{gathered} R(W_t^B, W_t^{B+}, W_t^{B-}) = \\ = (W_t^B.\hat{p}_t) + \left(R_t^{up*}.W_t^{B+}.\hat{p}_t^{up}\right) - f(W_t^{oc}, W_t^B, R_t^{down*}) - \left((W_t^{oc-} - W_t^{B-}).\hat{p}_t.R_t^{down*}\right) \\ - \\ -(W_t^{B-}.\hat{p}_t^{down}.R_t^{down*}) \end{gathered} \tag{25}$$

Equation 25 could also be written in a shorter version:

$$\begin{gathered} R(W_t^B, W_t^{B+}, W_t^{B-}) = \\ = (W_t^B.\hat{p}_t) + \left(R_t^{up*}.W_t^{B+}.\hat{p}_t^{up}\right) - f(W_t^{oc}, W_t^B, R_t^{down*}) - R_t^{surplus_{down}} \\ -(W_t^{B-}.\hat{p}_t^{down}.R_t^{down*}) \end{gathered} \tag{26}$$

Finally there is still a possible scenario that should be highlighted and it consists in the possibility of the producer offering 0MWh for the day-ahead Electrical Energy Market and 0MW for the balancing reserve market (in both upward and downward directions) for a given hour. Then, on the following day, if during that hour the available production happens to be bigger than what was offered, this energy would only be produced if it happened that during that hour upward reserve was necessary, and if so the producer would be paid the DAEEM price multiplied by the available quantity. Otherwise a set point of no production would be given to the generators.

3.6 - Using EPSO

The program created uses an Evolutionary Particle Swarm Optimization (EPSO) algorithm, which was created by INESC Porto, in order to define what is the best solution, for a given hour, depending on the adaptation function.

Firstly a population of particles is created given the size of the population as input to a function. Afterwards, the EPSO algorithm evaluates each particle and evolve the swarm in the direction of the best solution.

In order to evaluate each bid a Monte Carlo simulation is used. Each bid is tested for a series of scenarios (as explained before at least 100.000) and the mean revenue of each particle is calculated. The particles that lead to the best mean revenues will be the ones to lead the swarm to the optimum value.

The EPSO algorithm is widely explained in [34], further explanations of the used algorithm can be found there. Although, here might be relevant to explain briefly the working principle of this algorithm.

Each particle comprises three bids: a bid for the electrical energy market (W_t^B), a bid for upward reserve for the balancing reserve market (W_t^{B+}) and a third bid for downward reserve for the balancing reserve market (W_t^{B-}). There are also the strategic parameters that also describe each particle. These strategic parameters are: inertia, memory and cooperation vectors. The first one pushes the particle to a direction identical to the one that the particle had been following. The memory vector pushes the particle to the direction where the best solution, found by the particle during its life time, was. Lastly, the third vector attracts the particle to the location where the best solution, found by the swarm, was.

The EPSO algorithm starts by copying (or cloning) the particles. After that each clone suffers a mutation in their strategic parameters. The next step is reproduction: each particle generates a descendent following a given movement equation. Afterwards is time for evaluation: each descendent is assessed concerning its adaptation. The last step is selection: the best particle of each group of descendants, of each particle from the past generation, is selected to create a new generation.

3.7 - Other Decision Strategies

The first decision strategy implemented consisted in calculating the expected profit of each bid, then the EPSO algorithm defined the best bids as being the ones which led to the maximum values of mean revenue. Therefore, this first implemented algorithm tried to maximize the following function:

$$F(R) = \max \hat{E}(R) \tag{27}$$

This specific adaptation function leads to risk neutral solutions and it is called an expected revenue function.

As mentioned before, in this work, other decision strategies are tested and their results are compared, a maximization of the expected utility (MEU) and one conditional value at risk (CVaR) are implemented.

a. Maximization of the expected utility

The utility function implemented in this dissertation is expressed in equation 28.

$$u(z) = \frac{1}{1-e^{\alpha}} \times \left[1 - e^{\frac{\alpha\times(z-min_{ep})}{max_{ep}-min_{ep}}}\right], \qquad u(z) \in [0,1] \tag{28}$$

This utility function was also used in [35], however in this work the parameters α, z, max_{ep} and min_{ep} have different values since they are specific to each problem. The max_{ep} and min_{ep} constants are the bounds of the function. Thanks to α modelling different attitudes towards risk from the decision maker is possible. In equation 28, z is the revenue which is calculated following equation 10.

In this work the value of max_{ep} was defined as being 90 and min_{ep} as -40, these values are the maximum and minimum expected profit, respectively. These two values were defined after running the program several times and concluding that in most of them the revenue was rarely higher than 90 nor smaller than -40 almost always. Calculating the exact values of maximum and minimum revenues would turn out to be impossible, since the value of the revenue depends not only on the necessity of upward and/or downward reserve, but also on the randomly selected value of the power forecast and on the randomly generated values of prices, which are dependent on the mean and variance of the prices of each hour of the day.

Moreover, α is defined by the decision maker. When α is negative the decision maker is considered to be averse to risk, on the other hand if α is positive the decision maker is considered to be prone to risk. Furthermore, the greater the absolute value of α is, the stronger is the attitude of the decision maker.

On one hand, prone attitudes towards risk are expected to favour very profitable scenarios with low probability of occurrence. On the other, an averse attitude towards risk from the decision maker, makes him prefer scenarios where the probability of a certain profit is higher.

The utility function was implemented in the program. This time the EPSO algorithm looks for the offer which leads to the maximization of the mean of results from equation 28.

b. CVaR$_{5\%}$

Likewise it was done in [17] here a Conditional Value at Risk was also implemented. The Value at Risk (VaR) is a financial measure created to quantify the exposure to risk of a portfolio of a company [32].

The result, for each hour, of the CVaR is calculated determining firstly the Value at Risk of 5% (VaR$_{5\%}$) from the distribution of results from the Monte Carlo. The VaR$_{5\%}$ is the maximal expected revenue with a probability of 5%. Afterwards the mean of results which revenue is smaller than the VaR$_{5\%}$ is calculated, and this way the conditional value at risk is calculated.

The used equation can be found in [17], equation number (9) and (10) from the mentioned paper.

The objective function will be the maximization of the sum between the mean revenue and the product between ω and the conditional value at risk. In this function ω will be a coefficient which assumes values between 0 and 1. Here, bigger values of ω reflect in more averse decisions towards risk.

$$C(R) = max\{\hat{E}(R) + \omega \times CVaR_{5\%}(R)\}, \ \omega \in [0,1] \tag{29}$$

In equation 29 the $\text{CVaR}_{5\%}$ $\left(C(R)\right)$ is presented. In this equation $\hat{E}(R)$ is the mean of the distribution of results from the Monte Carlo. This time the EPSO algorithm looks for the offer which leads to the maximization of equation 29.

This function will describe the decisions of a decision maker averse to risk when ω is bigger than zero, and when ω is equal to zero the decisions will be risk neutral.

Chapter 4

Output Analysis

4.1 - Assessing results

In order to validate the correctness of the code, part of the uncertainty of the problem was set aside, otherwise it would be difficult to verify if the outcome, the three bids for each hour, was reasonable.

Therefore the algorithm was run giving as input the exact prices of the DA Electrical Energy Market and of the DA Balancing Reserve Market. Furthermore, there was no error in the power forecast, given that, it was always considered the same power (0.42 p.u.), as outcome, when the scenarios of the Monte Carlo were created. The only uncertainty that had an influence on the result was the probability of the reserves being necessary in each direction.

Before verifying the algorithms of both remuneration schemes the results from "limit" scenarios, where the probability of the reserves being needed in one of each direction were either 0 or 1, were calculated given the problem formulation.

For instance, in both RS$_A$ and RS$_B$ if $\tau_t^{up} = 1$ and $\tau_t^{down} = 0$ it was expected that no matter the proneness or aversion towards risk, from the decision maker, the energy offer would be zero or very close to zero, the upward reserve offer would be equal to the maximum power forecasted and the downward reserve can take any value equal or smaller than the energy offer (given that it is still bigger than zero), since it will not influence the result.

In Figure 4.1, the results obtained for RS$_A$ using the $CVaR_{5\%}$ and having $\tau_t^{up} = 1$ and $\tau_t^{down} = 0$ are shown. Like it was expected the available power (0.42 p.u.) was offered as upward reserve, leaving no margin for an energy offer and consequently having the downward reserve offer equal to zero.

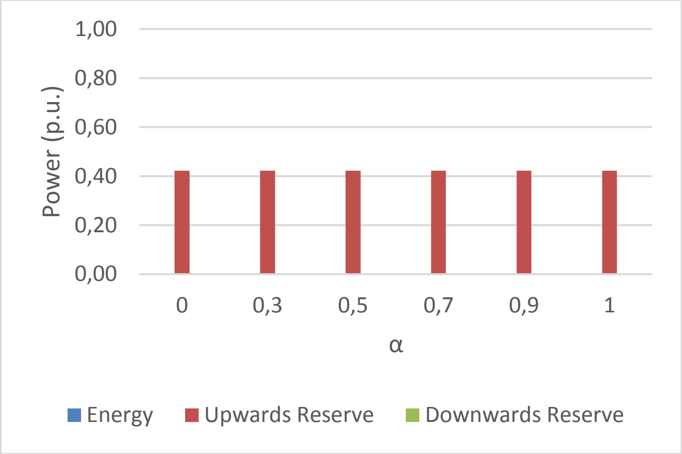

Figure 4.1 - RS$_A$ - CVaR$_{5\%}$ with $\boldsymbol{\tau_t^{up} = 1}$ and $\boldsymbol{\tau_t^{down} = 0}$.

Another test that was carried out was setting τ_t^{up} and τ_t^{down} equal to zero, and in both remunerations schemes it was expected that the energy bid would be equal or close to the power forecast and since the reserve bids would not influence the result, they could take any value. The results for this test were considered to be not as relevant as the others tests so the results were not included here in a figure. However, it should be mentioned that: the reserve bids assumed the values of the first particle of the EPSO which had an energy bid equal to the power forecast.

These last two tests were also verified for RS$_B$. As the results were the same there was no need to add the outcomes here. As τ_t^{down} was considered equal to zero in both tests, the mean revenue from the best particles was the same, approximately 25.31€. On the other hand, when $\tau_t^{down} = 0$ and $\tau_t^{up} = 1$ the mean profit was 33.75€. In order to confirm this profit, one only needs to do the following calculations:

$$R\left(\tau_t^{up} = 0, \tau_t^{down} = 0\right) = 0.4218 \times 60 = 25.31€ \tag{30}$$

$$R\left(\tau_t^{up} = 1, \tau_t^{down} = 0\right) = 0.4218 \times 80 = 33.75 \tag{31}$$

In both remuneration schemes, τ_t^{down} has a big influence in the results, when this probability is set to 1, and given that $\tau_t^{up} = 0$, the offers for upward reserve are equal to zero, and the energy bids are equal to 1, no matter the power forecast, this can be verified in Figures 4.2 and 4.3.

In this case the energy offer is set to the installed power since the producer knows for sure that downward reserve is going to be needed. Knowing that beforehand allows the producer to make such offer. When the time, for the energy delivery, comes the producer will deliver the amount of energy that is available at the time. This amount of energy will most likely be smaller than the installed power and as this deviation in the contracted energy and the delivered energy has the same direction of the system imbalance, the producer will not be penalized.

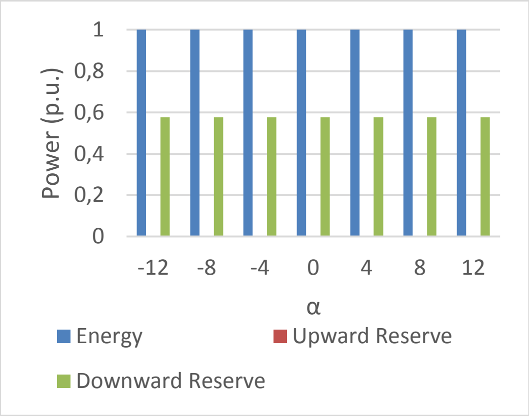

Figure 4.2 - RS$_A$ - Maximization of the expected utility with $\tau_t^{up} = 0$ and $\tau_t^{down} = 1$.

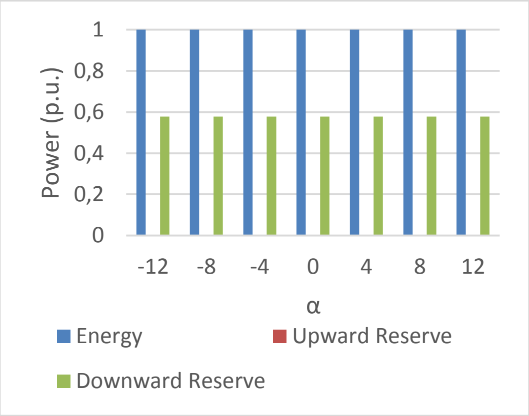

Figure 4.3 - RS$_B$ - Maximization of the expected utility with $\tau_t^{up} = 0$ and $\tau_t^{down} = 1$.

At first glance, the results shown in Figures 4.2 and 4.3 might seem alike, however there is a slight difference in the downward reserve bids. [3]

In RS$_A$, the difference between the energy and the downward reserve bids does not need to be exactly the forecasted power, although it must be a value very close to it, in order to have a maximum revenue. In this RS$_A$, small differences in the downward reserve bid lead to minor differences in the revenue, as it can be concluded from Table 4.1.

On the other hand, in RS$_B$ the producer offers to reduce his production from the installed capacity to the forecasted production. In this RS$_B$, if the difference between the energy and the downward reserve bid is a value higher than the power forecast, the revenue decreases more than in RS$_A$, see Table 4.1.

Table 4.1 - Differences in revenue for the same bids and real maximum production in RS$_A$ and RS$_B$.

Real Maximum Production (p.u.)	Bid			RS$_A$ Revenue (€)	RS$_B$ Revenue (€)
	Energy (p.u.)	Upward Reserve (p.u.)	Downward Reserve (p.u.)		
0.5	1	0	0.48	34.8	54
0.5	1	0	0.5	35	55
0.5	1	0	0.52	34.8	54.8

One should notice that in RS$_A$ the market player would be able to estimate how much power the producer could deliver (the “true” wind power generation), and would verify that the offered downward reserve could not be supplied, due to a lack of wind, and consequently would penalize the producer. Moreover, as the difference between the energy bid and the production would have the same direction of the system imbalance, there would not be any penalization in what concerns the energy delivery.

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[3] Notice that in this Figure and in the next figures, where results from the expected utility function are shown, the offers for α equal to zero were obtained running the program with the expected revenue function and not with the expected utility function.

The main difference between the two remuneration schemes can be detected in the mean revenue from the best particle, see Table 4.2.

Table 4.2 - Mean revenue from the best particle in RS$_A$ and RS$_B$, when $\boldsymbol{\tau_t^{up}} = \mathbf{0}$ and $\boldsymbol{\tau_t^{down}} = \mathbf{1}$.

	RS$_A$	**RS$_B$**
Mean Revenue from best particle (€)	31.08	54.21

The revenue from the best particle is calculated hereafter, in order to fully understand the difference in the revenue calculation.

The revenue in RS$_A$ is calculated following equations 32 and 33:

$$RNS_t^{down}(RS_A) = (0.578 - 0.00089) \times (60 - 10) \times 1 = 28.85€ \tag{32}$$

$$R(RS_A) = 0.999 \times 60 - RNS_t^{down} - (0.00089 \times 10 \times 1) = 31.08€ \tag{33}$$

In RS$_B$ the revenue is calculate following equations 34:

$$R(RS_B) = 0.999 \times 60 - (0.578 \times 10 \times 1) = 54.16€ \tag{34}$$

Comparing equations 33 and 34 it becomes clear that in RS$_B$ the market player assumes that the reserve is being fully delivered, and therefore does not penalize the producer for not completely delivering the contracted downward reserve.

Another test that was carried out evaluated the correctness of the implemented functions. Figures 4.4 and 4.5 show the results obtained when the probabilities τ_t^{up} and τ_t^{down} were set to 0.8 and 0, respectively.

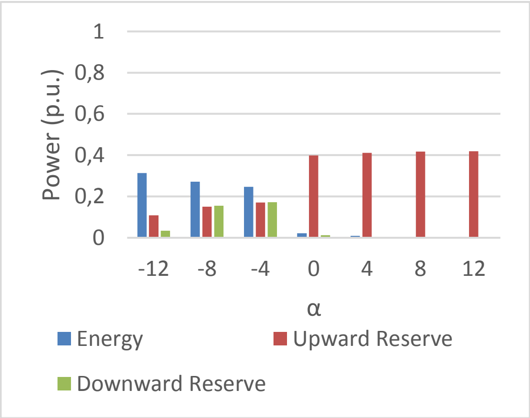

Figure 4.4 - RS$_A$ - Maximization of the expected utility with $\boldsymbol{\tau_t^{up}} = \mathbf{0.8}$ and $\boldsymbol{\tau_t^{down}} = \mathbf{0}$.

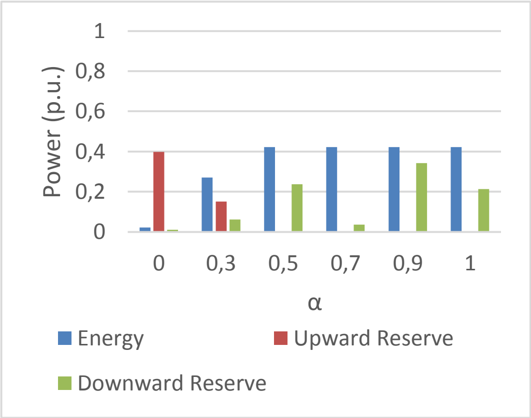

Figure 4.5 - RS$_A$ - CVaR$_{5\%}$ with $\boldsymbol{\tau_t^{up}} = \mathbf{0.8}$ and $\boldsymbol{\tau_t^{down}} = \mathbf{0}$.

In the maximization of the expected utility, like it was mentioned before, when α assumes higher values the decisions are more susceptible to risk which means that the energy bids are reduced and the upwards reserve bids are increased. In Figure 4.4 the proneness towards risk can be clearly recognized.

On the other hand, with the CVaR$_{5\%}$ one can only get decisions that are neutral (ω=0) or averse (ω>0) to risk. Comparing Figures 4.4 and 4.5 one can notice that the bids for ω and α equal to 0 are equal and that the bids averse to risk (α<0) in Figure 4.4 are similar to the bids where ω is higher than zero (Figure 4.5).

One of the last tests that were done consisted in evaluating how the program performed in both remuneration schemes when neither τ_t^{up} nor τ_t^{down} were equal to zero.

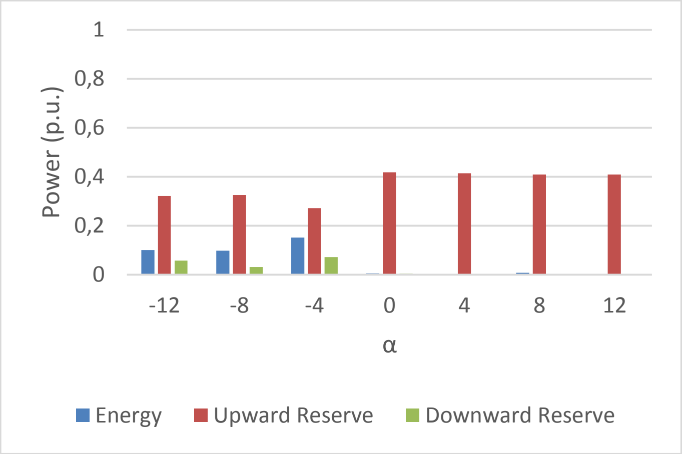

Figure 4.6 - RS_A - Maximization of the expected utility with $\boldsymbol{\tau_t^{up} = 0.8}$ and $\boldsymbol{\tau_t^{down} = 0.2}$.

In Figure 4.6 it can be observed that when the decision maker is averse to risk (α<0) the sum of the energy and the upward reserve bids are close to the maximum production (0,42p.u.). For values of α greater than 0 the decisions are more prone to risk, therefore the decision maker opts to reduce its energy bid and leaves all his available production for upward reserve, as it can be seen in Figure 4.6.

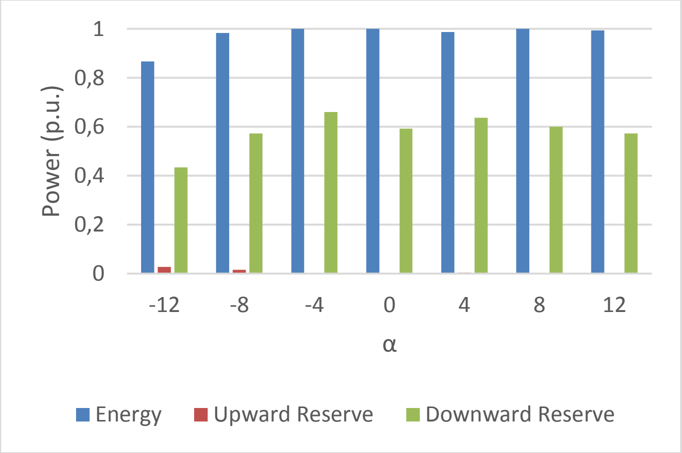

Figure 4.7 - RS$_A$ - Maximization of the expected utility with $\boldsymbol{\tau_t^{up} = 0.2}$ and $\boldsymbol{\tau_t^{down} = 0.8}$.

In Figure 4.7 it can be witnessed offers that are clearly more averse to risk than others, the decision makers behind these offers, the ones where α is smaller than -4, are more cautious and do not offer the installed power as energy bid. This option for not bidding the installed power results from giving more importance to scenarios where downward reserve was not necessary and the energy bid was very high, which led to high penalizations, which ultimately reflects an averse attitude towards risk.

Chapter 5

Case Study

5.1 - Data description

In this chapter an assessment of the offers obtained in both Remuneration Schemes A and B for the three different objective functions is done. To do so, the created Matlab algorithm was run solving at each time the problem for the same hour, but with one of the two adaptation functions. In order to obtain a risk neutral solution, the adaptation function that was used was the one which considered the $CVaR_{5\%}$ where ω (from equation 29) was set to 0. Setting ω to 0 is the same as running the algorithm with the expected revenue (equation 27) function.

The created algorithm used data provided by two entities. On one hand, the wind power forecasts were provided by INESC TEC, and the available period was since July 2009 until June 2012. On the other hand, the values used to calculate the mean and variance of prices and the probability of the direction of the needed reserve, during each hour, were from the same time period of the power forecasts, and were downloaded from [31].

The wind power forecasts also included the real available production verified during each hour. These values were used in order to calculate the revenue that each bid would have allowed. This calculation was also dependent on the market prices which were obtained in [31].

5.2 - Assessing results

The first adaptation function, which was tested, was the maximization of the expected utility (MEU) equation (28). It was run with different values of α in order to model different attitudes towards risk.

The second and last implemented algorithm tried to maximize equation (27), the $CVaR_{5\%}$. The program was run with several values of ω, once more, in order to test different attitudes towards risk.

The offers for 2 hours of the available data were calculated. They were: hour 1 from 3rd July 2009 and hour 18 from 9th July 2009. The first tested hour corresponds to an hour where upward reserve was not necessary and downward reserve was used. This hour was selected to be tested as the difference between the DA electrical energy market price and the price payed for downward reserve was small. The consequences in the calculation, of the real revenue, due to this difference, between the two prices, will be studied in this chapter. On the other hand, in the second tested hour upward reserve was used and the referred difference between the two prices was significantly higher than in the other test.

Subsequently, it was necessary to evaluate the program's performance. So, having the values from the real prices and from the electric power production verified at each hour it was possible to calculate the revenue given the power offers for the electrical energy market and for the balancing reserve market, that the program created.

The remuneration schemes were implemented in two Excel sheets so that given the above mentioned inputs the worksheet was able to calculate the revenue for each hour. The results for the two tested hours for each RS_A and RS_B are going to be presented hereafter.

Table 5.1 - Real revenue calculation for RS_A, using the $CVaR_{5\%}$ and MEU (03/07/2009 – 01h00).

								Offer			
Adaptation Function	**ω (CVaR5%) α (MEU)**	**Upward Reserve**	**Upward Reserve Price (€/MWh)**	**Downward Reserve**	**Downward Reserve Price (€/MWh)**	**Energy Market Price (€/MWh)**	**Maximum Power Production (p.u.)**	**Energy (p.u.)**	**Upward Reserve (p.u.)**	**Downward Reserve (p.u.)**	**Revenue (€)**
$CVaR_{5\%}$	0	0	0	1	23.49	36.3	0.12	1.00	0.00	0.86	24.52
	0.3							0.09	0.00	0.00	3.26
	0.5							0.08	0.00	0.00	2.87
	0.7							0.06	0.00	0.00	2.29
	0.9							0.04	0.00	0.00	1.42
	1							0.02	0.00	0.00	0.57
MEU	-12	0	0	1	23.49	36.3	0.12	0.28	0.00	0.20	7.34
	-8							0.37	0.00	0.30	8.98
	-4							0.64	0.00	0.52	16.40
	4							1.00	0.00	0.86	24.54
	8							1.00	0.00	0.86	25.01
	12							1.00	0.00	0.88	24.78

Table 5.2 - Real revenue calculation for RS_B, using the $CVaR_{5\%}$ and MEU (03/07/2009 – 01h00).

								Offer			
Adaptation Function	**ω (CVaR5%) α (MEU)**	**Upward Reserve**	**Upward Reserve Price (€/MWh)**	**Downward Reserve**	**Downward Reserve Price (€/MWh)**	**Energy Market Price (€/MWh)**	**Maximum Power Production (p.u.)**	**Energy (p.u.)**	**Upward Reserve (p.u.)**	**Downward Reserve (p.u.)**	**Revenue (€)**
$CVaR_{5\%}$	0	0	0	1	23.49	36.3	0.12	0.99	0.00	0.88	15.36
	0.3							0.09	0.00	0.00	3.28
	0.5							0.09	0.00	0.00	3.17
	0.7							0.08	0.00	0.00	2.99
	0.9							0.06	0.00	0.00	2.14
	1							0.04	0.00	0.00	1.56
MEU	-12	0	0	1	23.49	36.3	0.12	0.34	0.00	0.23	6.73
	-8							0.42	0.00	0.34	7.36
	-4							0.63	0.00	0.59	8.97
	4							0.99	0.00	0.88	14.69
	8							1.00	0.00	0.92	15.33
	12							1.00	0.00	0.86	14.90

The values from tables 5.1 and 5.2 were calculated using the equations presented and explained in Chapter 3, from this thesis.

From tables 5.1 and 5.2 one can notice that the more prone to risk the decisions are, the higher are the energy bids. As mentioned before riskier decisions can be simulated through increasing the α coefficient in the maximization of the expected utility function.

Although, downward reserve was necessary during this first hour from the third day of July 2009, in RS_A the market player will limit the profit of the wind power producer, because he can estimate the real power production. Therefore, he will conclude that the offered energy bids and respective downward reserves would not be possible to be delivered. So, he will penalize the downward reserve not supplied, which can be calculated using equation 9, presented here once again:

$$RNS_t^{down} = (W_t^{B-} - W_t^{oc-}).(\hat{p}_t - \hat{p}_t^{down}).R_t^{down*} \tag{9}$$

On the other hand, in RS_B, the downward reserve is thought to be always supplied and at times there is even a surplus of delivery. In such cases the payment of this surplus is calculated following equation 6, presented here once again:

$$R_t^{surplus\_down} = -(W_t^{oc-} - W_t^{B-}).\hat{p}_t.R_t^{down*} \tag{6}$$

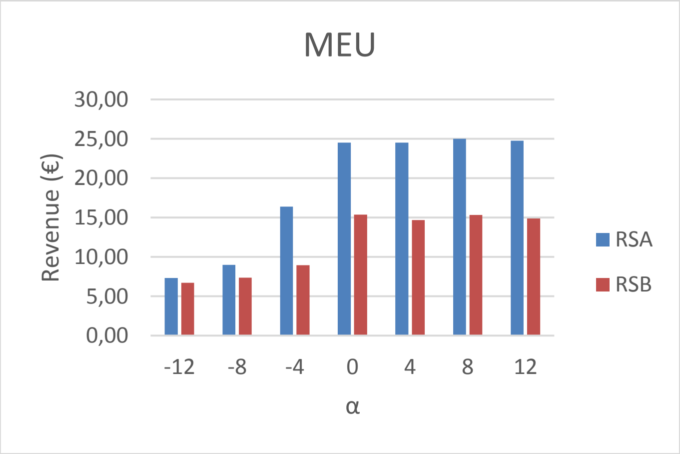

Figure 5.1 - Real revenue obtained for each remuneration scheme, with the MEU (03/07/2009 – 01h00).

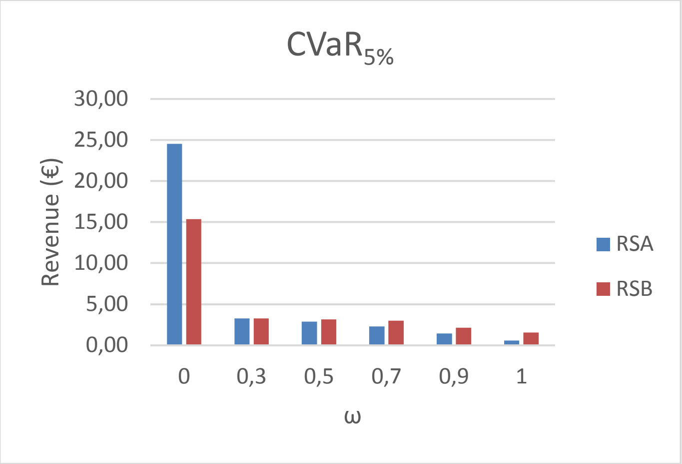

Figure 5.2 - Real revenue obtained for each remuneration scheme, with the $\text{CVaR}_{5\%}$ (03/07/2009 – 01h00).

Differing from what had happened in tests done before, and explained in the last chapter, here, the revenues obtained in RS_A were higher than the ones from RS_B when the energy bids were close to the installed power (1 p.u.).

The reason for this to happen has to do with the prices of the DA electrical energy market and of the downward reserve market. While in the tests done in the 4th chapter the prices were 60€/MWh and 10€/MWh, for the DA electrical energy and balancing reserve markets, respectively, during this hour the real market prices were 36.30€/MWh and 23.49€/MWh, as it can be observed in tables 5.1 and 5.2.

As the penalization for not supplying downward reserve is proportional to the difference between DA electrical energy and downward reserve prices: the higher this difference is the higher the penalization is. If the difference between this two prices is small, it might happen that not delivering the offered downward reserve turns out to be less penalizing than the profit due to the delivery of part or all the offered reserve (equation 3), since the price paid for the downward reserve is higher than the difference between the two mentioned prices.

$$-W_t^{B-}.\hat{p}_t^{down} \tag{3}$$

In this first hour of the third day of July 2009 the difference between the two market prices was: 12.81€, which is the price that the power producer will have to pay during that hour for each MWh of downward reserve energy not delivered. On the other hand, if he actually delivers part or all the offered downward reserve he will incur in a revenue reduction of 23.49€ for every MWh of downward reserve supplied.

In order to confirm that RS_B would be more profitable when the difference between the DA electrical energy price and the downward reserve balancing market price was higher than the downward reserve balancing market price, which means: $(\hat{p}_t - \hat{p}_t^{down} > \hat{p}_t^{down})$, an hour where this actually happened was selected. As the last tested hour did not include the necessity for upward reserve, this was also taken into consideration.

The real data was analysed and an hour where this two prerequisites were met was found. The selected day and hour was: 9th July 2009, 18h00.

The algorithm was asked to create bids for this specific day and hour. Once more, both remuneration schemes were run and for each one of them different aversions to risk were simulated. The results obtained are presented hereafter.

Table 5.3 - Real revenue calculation for RS$_A$, using the CVaR$_{5\%}$ and MEU (09/07/2009 – 18h00).

								Offer			
Adaptation Function	**ω (CVaR5%) α (MEU)**	**Upward Reserve**	**Upward Reserve Price (€/MWh)**	**Downward Reserve**	**Downward Reserve Price (€/MWh)**	**Energy Market Price (€/MWh)**	**Maximum Power Production (p.u.)**	**Energy (p.u.)**	**Upward Reserve (p.u.)**	**Downward Reserve (p.u.)**	**Revenue (€)**
CVaR$_{5\%}$	0	1	45.74	1	1.52	38.45	0.266	1.00	0.00	0.55	-22.41
	0.3							0.79	0.00	0.39	-13.19
	0.5							0.47	0.00	0.07	0.85
	0.7							0.50	0.01	0.09	-0.89
	0.9							0.38	0.00	0.08	4.95
	1							0.41	0.00	0.10	3.75
MEU	-12	1	45.74	1	1.52	38.45	0.266	0.51	0.00	0.15	-1.06
	-8							0.59	0.00	0.27	-4.27
	-4							0.85	0.01	0.47	-16.09
	4							1.00	0.00	0.55	11.06
	8							0.99	0.00	0.55	-22.28
	12							0.02	0.79	0.00	-12.87

Table 5.4 - Real revenue calculation for RS_B, using the $CVaR_{5\%}$ and MEU (09/07/2009 – 18h00).

								Offer			
Adaptation Function	**ω (CVaR5%) α (MEU)**	**Upward Reserve**	**Upward Reserve Price (€/MWh)**	**Downward Reserve**	**Downward Reserve Price (€/MWh)**	**Energy Market Price (€/MWh)**	**Maximum Power Production (p.u.)**	**Energy (p.u.)**	**Upward Reserve (p.u.)**	**Downward Reserve (p.u.)**	**Revenue (€)**
$CVaR_{5\%}$	0	1	45.74	1	1.52	38.45	0.266	1.00	0.00	0.73	30.87
	0.3							0.54	0.00	0.28	15.13
	0.5							0.48	0.00	0.21	13.73
	0.7							0.43	0.00	0.04	11.63
	0.9							0.39	0.00	0.11	14.30
	1							0.34	0.00	0.04	11.54
MEU	-12	1	45.74	1	1.52	38.45	0.266	0.66	0.01	0.24	18.88
	-8							0.90	0.01	0.41	24.92
	-4							1.00	0.00	0.58	31.82
	4							0.94	0.00	0.38	24.21
	8							0.94	0.00	0.34	22.81
	12							0.02	0.66	0.00	-7.04

As expected, the revenue in this tested hour was always higher in RS_B than in RS_A. The explanation for this is in the electrical energy and downward reserve price registered during this hour. In tables 5.3 and 5.4 one can observe that during this hour the referred prices were 38.45€/MWh and 1.52€/MWh.

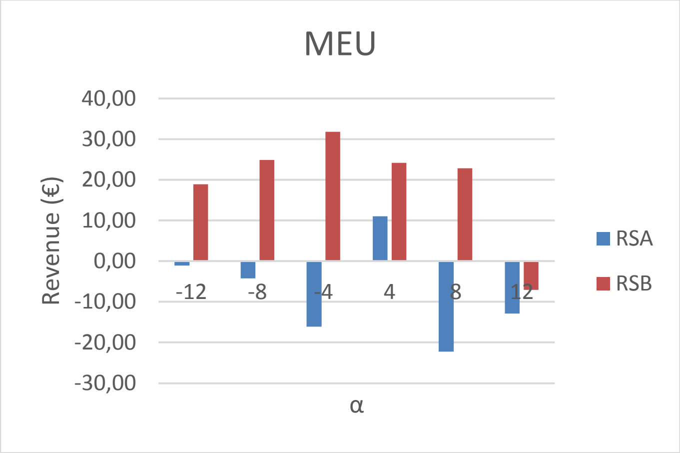

Figure 5.3 - Real revenue obtained for each remuneration scheme, with the MEU (09/07/2009 – 01h00).

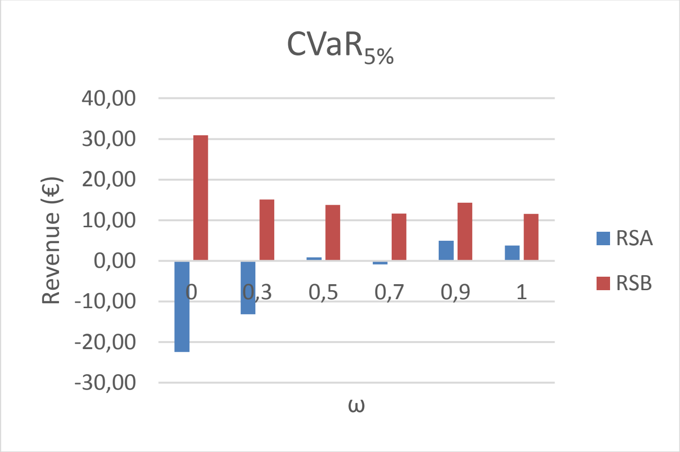

Figure 5.4 - Real revenue obtained for each remuneration scheme, with the $CVaR_{5\%}$ (09/07/2009 – 01h00).

Analysing figures 5.3 and 5.4 one can observe that in RS_A there were offers which penalizations were so high that if the decision maker opted to select one of them, he would incur in high losses. He would even have to pay for his delivered energy, which is the worst case scenario.

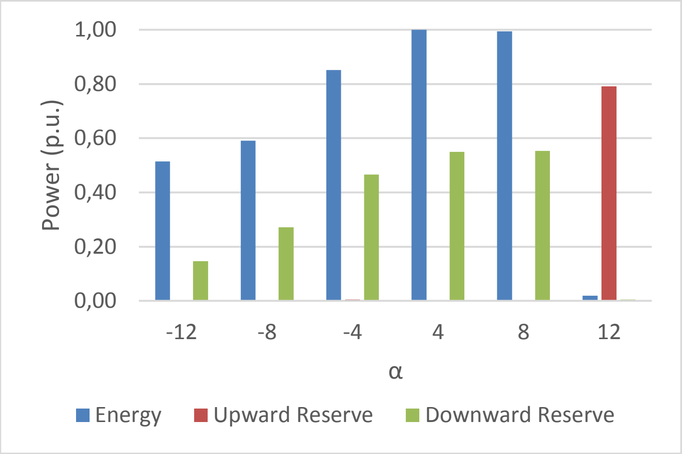

Figure 5.5 - Obtained offers for - RS$_A$ - Maximization of the expected utility (09/07/2009 - 01h00).

An interesting outcome that can be noticed in Figure 5.5 is that, when a very prone to risk decision maker is simulated (α=12), he opts to offer only upward reserve and no energy or downward reserve are bided. This outcome is also verified in the other remuneration scheme, which can be confirmed in Table 5.4. Although, in both remuneration schemes as the delivered upward reserve is smaller than 50% of the offered upward reserve, he incurs in a penalization that is higher than the income from selling part of the reserve.

The upward resereve not supplied can be calculated following, equation (5) presented before:

$$RNS_t^{up} = (W_t^{B+} - W_t^{oc+}).\hat{p}_t^{up}.R_t^{up*}.\rho \tag{5}$$

$$RNS_t^{up} = (0.791 - 0.247) \times 45.74 \times 1 \times 1 = 24.89\ € \tag{35}$$

The reserve supplied is paid following equation 36:

$$Reserve\ Supplied_t^{up} = (0.266 - 0.02) \times 45.74 \times 1 = 11.25\ € \tag{36}$$

As it can be seen in equations 35 and 36 the profit form selling part of the upward reserve is smaller than the penalty for not delivering the offered upward reserve.

Applying and adapting to this offer, equation (10) which gives us the revenue:

$$\begin{aligned} R(W_t^{oc}, W_t^{oc+}, W_t^{oc-}) = (W_t^{B}.\hat{p}_t) + (R_t^{up*}.W_t^{oc+}.\hat{p}_t^{up}) - (R_t^{down*}.W_t^{oc-}.\hat{p}_t^{down}) - \\ - f(W_t^{oc}, W_t^{B}, R_t^{down*}) - RNS_t^{down} - RNS_t^{up} + R_t^{surplus_{up}} + R_t^{surplus\_down} \end{aligned} \tag{10}$$

$$R(RS_A) = 0.02 \times 38.45 + Reserve\ Supplied_t^{up} - RNS_t^{up} = -12.87\ € \tag{37}$$

Chapter 6

Conclusions and Future Work

The main goal of this work was to propose a model to enable wind power producers to participate not only in the DA electrical energy market, but also in the balancing reserve markets, and to test it in a case study.

In order to fulfil this goal a research on what have been done before in this field of study was done, the problem was explained and a mathematic formulation was presented. Two possible ways of defining the revenue of a market player were defined, through two different remuneration schemes. Afterwards a Matlab algorithm was implemented. This algorithm used an Evolutionary Particle Swarm Optimization (EPSO) program, which was created by INESC TEC and was adapted to this problem. Moreover, inside the EPSO, a Monte Carlo simulation was implemented so that each created bid, which was a particle from the EPSO, could be tested against a series of possible scenarios. The results obtained were presented here and explained.

From the study done it was possible to conclude that risk proneness generally leads to high energy and downward reserve bids, given that the probability of downward reserve being needed was also high. The problem of inflated energy bids was dealt with in the proposed "RS_A". Here the profit from selling downward reserve was limited, since it was considered that at the time of the payment the market player would have access to the information about the weather conditions felt in the wind farm during the production time. Having access to this, the market player could accurately estimate the maximum power production, and therefore, he would only pay for what could be actually delivered.

Moreover, from the same study one can conclude that the prices verified at the time of delivery have a significant influence on the profit of the wind power producer. In this work it was considered that these prices followed a normal distribution, with a mean and a variance which were calculated from the available historical data. A possible solution, which could be a future development of what has been done here, would be to integrate a price forecasting tool. This way the number of possible outcomes would be considerably limited and the mean revenue of each bid would be more accurate. Another possible improvement would be to incorporate in the model another forecasting tool, however this one would be to determine more accurately the direction of the needed reserve at each hour.

In this work scenarios where for some technical reason it is not possible to reduce the power production, which means that the energy bid might not be met or the downward reserve cannot be activated, were not considered and perhaps they should be in an extended version of this work, since technical failures are likely to occur.

Furthermore, alternative market rules could be implemented. The wind power producers would benefit from a model which created bids closer to the expected wind power generation. If a considerable number of market players offered very high energy bids and ended up not being able to deliver them, due to a lack of primary energy source (wind), the system would end up needing upward reserve which would turn out to be very expensive.

Finally, a further development of this work could be a comparison between the cost of the electricity in a power system where the replacement reserve services were mainly provided by wind power sources, which would only be possible if an high integration of this sources of energy was verified, and the cost of the electricity in a common system where these ancillary services are mainly provided by conventional generators.

Glossary

Balancing market – this market have been the only one to provide reserve and response operations. System operators resort to these markets in order to contract reserve and response capacity provided by generators which can be called upon on short notice to balance the system. In recent years newly installed wind power and renewable sources of energy in general have provoked additional demand for reserve and response operations, due to forecast errors. [14]

Frequency Containment Reserve – used to be called primary reserve. This reserve maintains the operational reliability of the synchronous area by stabilizing the system's frequency, in an acceptable stationary value, different from the nominal one, in the time-frame of seconds. FCR depends on reserve providing units along with the physical stabilizing effect from all connected rotating machines. It is a decentralized, automatic and fast-action function. Generators delivering FCR adjust their power output as a consequence of the system deviation, balancing generation and load. [28]

Frequency Restoration Reserve – used to be called secondary reserve. This reserve restores frequency to the nominal value in the time frame defined within the restoration area. This reserve also restores power balance to the scheduled value. Typically this type of reserves have an activation time that go up to 15 minutes. This is accomplished by releasing system wide activated frequency containment reserves, which is usually activated centrally and can be activated manually or automatically. [30]

Replacement Reserve – used to be called tertiary reserve. This type of reserve is characterized for being an operating reserve which is used to restore the required level of operating reserves so that if another imbalance occurs no harm is done to the system because it was prepared for it. The activation time of this kind of reserve can vary between 15 minutes and hours depending on the country. [30]

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