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Predictive power dispatch using imperfect generation forecasts of variable RES

Master Thesis
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Preface

This Master Thesis was conducted during the fall semester 2011 at the Power Laboratory Systems of ETH Zurich. The research topic proposed by the institute has always interested and fascinated me: Are our electricity grids and the power system as a whole ready to welcome the "Energiewende"? What are the most important aspects to consider when integrating high shares of renewable energy generation systems in a country’s portfolio? I often hear people complaining and say: “just put a solar panel on every roof, and we will be fine!” But is it really so easy? Is a 100% renewable energy grid feasible?

Of course this thesis cannot answer all of these questions and it does not dare to do so. However, it was a fantastic opportunity for me to investigate these interesting and more hidden aspects of the race towards a sustainable electric power supply. For this reason I would really like to thank my supervisor Andreas Ulbig for the exceptional support and the many, fruitful discussions. He was not only ready to help and assist in the research, but he kindly understood and adapted his requests to accommodate my work exigencies. Thank you again for the flexibility.

Other important people that I would like to thank are Prof. Göran Andersson, that not only supervised my thesis but thanks to his lectures awoke my interest in power systems. Stephan Koch, my second supervisor that I met only a few, but precious and productive, times. My fellow Master students Alejandro and Chris for the input and the moments together at the PSL student room. And finally my family that has always supported and helped me in every possible way.
Abstract

This thesis investigates the impact of high shares of variable renewable energy systems in an electricity grid regulated by a model predictive power dispatch controller. The main goal is to assess the variations in the operating reserve capacity in order to accommodate the stochastic variability of wind and solar generation plants. In order to achieve this result, a literature study for this particular field is presented and commented. This was necessary to frame the conditions and the aspects to consider in the modelling process: a concatenated MPC approach was chosen, divided in two different time-scale layers. In the first one, the power grid dispatch is created every hour in order to optimize the ecological usage of the storage in function to the two-day-ahead forecasts. In the second one, grid stability is ensured in face of the sudden changes in renewable power production. This implementation needed the development of a forecast generator tool completely scalable and adaptable for both solar and wind infeed.

Results indicates that the strongest impact take place when the shares of RES in the electricity grid are equal or under the total demand capacity. The regulation needs tend to stabilize and even decrease with larger shares because forecast errors cease to play a decisive role. This means that during the transition phase large investments in the grid are required to ensure stability of operation, while after the threshold of 100% of covered demand the control problematic almost disappear, reducing the effectiveness of the regulation means installed.
Kurzfassung


Die Ergebnisse zeigen, dass die stärksten Regulierungsmassnahmen zwischen 0% und 100% (Leistungsanteil an Kapazität von RES gegenüber gesamt Last) erforderlich sind. Danach wird die Beifussung der Prognosefehler verschwindend klein. Dies bedeutet, dass während der Übergangsphase (von 0% bis auf mehr als 100%) grosse Investitionen in die Netzregulierung nötig sind, um die Betriebssicherheit zu gewährleisten, während nach der 100%-Schwelle (RES globale maximale Leistung ist gleich größer wie den Last) die Kontrolle-Problematik fast verschwindet, so dass die Effektivität der angewendeten Regulierungsmassnahmen abnimmt.
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<td>RES</td>
<td>Renewable Energy Source</td>
</tr>
<tr>
<td>PSL</td>
<td>Power Systems Laboratory</td>
</tr>
<tr>
<td>ETH</td>
<td>Eidgenössische Technische Hochschule, Swiss Federal Institute of Technology</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
</tr>
<tr>
<td>FERC</td>
<td>Federal Energy Regulatory Commission</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>RMSE</td>
<td>Relative Mean Square Error</td>
</tr>
<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecast</td>
</tr>
<tr>
<td>GFS</td>
<td>Global Forecast System</td>
</tr>
<tr>
<td>DENA</td>
<td>Deutsche Energie Agentur, Germany Energy Agency</td>
</tr>
<tr>
<td>SOC</td>
<td>State-of-charge</td>
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Chapter 1

Introduction

The accuracy of forecasts for renewable energies systems of stochastic nature (mainly wind and solar PV) has received much attention in recent years because of the impact that fluctuating electricity generation plants have on power grid stability. The rapid increase and integration of these technologies in the production mix of different countries (e.g. Spain, Germany, Denmark), enforced by national policy and international protocols (Kyoto, Copenhagen) with the goal to reduce greenhouse gas emissions (GHG), raise the problem that the actual infrastructure is not prepared to manage this kind of variability and limited predictability. The main problem is the absence of an economically valid storage technology (one that can keep pace with the growth of renewable power systems) that could be used as a buffer to compensate and redistribute the fluctuating power of solar and wind generated power in-feed. This situation requires the grid operator to find other means to manage these sudden and unexpected changes: possible solutions are curtailments of RES power production or the use of dispatchable power plants able to react quickly, varying their load, in order to respond to the exigencies of the grid. The first option is clearly not desirable, because the final goal is to use as much electricity from renewable energy as possible and not to reduce it because the power systems cannot compensate for the variations. Hence a more intensive usage of fast power plant units for compensation purposes is required.

The first and more researched impact of solar and wind production regards mostly the primary control reserves, that react to sudden changes from the start of the instability till 15 minutes after, while the tertiary reserves, responsible for the stability of the grid after the secondary control regulation and until a new power dispatch is issued, were less influenced because of the scarce penetration of RES. The present thesis presents an analysis and an overview of the impact of high shares of RES in a power grid composed by control power plants and cheap, dynamically slow production facilities (e.g. nuclear, coal). The main intent is to investigate the impact of forecast
CHAPTER 1. INTRODUCTION

accuracy on the power dispatch problem and the regulating energy reserves. This requires the development of a forecasts generator tool for wind and solar energy systems, integrated in a concept of a cascaded model-predictive control scheme for the power system, modelled using the power node framework detailed in [1]. This model construction makes it possible to assess and evaluate the variations and the requirements of secondary and tertiary control reserves. As expected intuitively the necessary capacity requirements will augment as the RES share increases, but this variation is not linearly correlated with the accuracy of forecasts and assumes different values for the two examined renewable generation technologies.

1.1 Thesis structure

The structure of this thesis follows closely the actual time-order of the research activities taken during the course of the thesis. At first the problematic is analysed, framed and researched in a broad literature study. Most of the papers found, however, did not directly relate to the specific topic of this thesis and were mostly concerned with secondary capacity regulation and less with the interaction of dynamically slow power plants and the probabilistic change of wind and solar power production.

After this analysis the development of a forecast-generator tool for both wind and solar production is presented. To simulate the impact of stochastic variable power production the variability of the energy sources (hours of sunshine, wind) must be accounted for. Instead of choosing a reference model for forecasts, based on meteorological data, a more practical solution is chosen: a tool that starting from the effective production during the future horizon $H_{\text{future}}$ and a weight parameter $w_{\text{forecast}}$ can simulate an actual forecast, as if it were generated by a meteorological model. Since the analysis of the grid already requires the consumption and power production data distributed by the TSO’s and that the inclusion of the weighting factor $w_{\text{forecast}}$ can represent different degrees of precision, this promising concept has been able to provide an efficient and accurate solution for the generation of different forecasts for wind and solar generation.

The third chapter of the thesis consisted in the developing of a power grid model, composed by five different kinds of power plants: dynamically slow, dynamically fast (fossil fuel based), dynamically fast with storage (hydro power), based on stochastic volatile sources (wind, PV) and the grid load. During the research process more types of power plants were modelled and analysed, but in the end, to avoid an overly complex set of grid interactions, which not only lead to an increased computational time but can also make interpretation of the grid relationships much more difficult, only the mentioned five unit types were implemented.

The second differentiation of this power plants, the time scale in which they
can react and be dispatched, is integrated in the control structure, the fourth chapter of this thesis. The concept of cascaded model predictive controller, presented in [2], is modified so as to make a full representation of dynamically slow power plants possible. Briefly described, the first-layer MPC acts with a time step of an hour, preparing a power dispatch plan for the slower plants. This plan is then inflexibly applied and all the changes provoked by stochastic changes due to wind and solar production is compensated by the faster control power plants during a second-layer MPC dispatch. Every hour a new dispatch plan is generated based on the forecasts created with the developed tool, and the overall usage of power during this hour to stabilize the grid has proven itself to be a good approximation of tertiary energy reserves, as shown in the final chapters regarding results and conclusions.

1.2 Growth of RES shares in power production: an overview

The increasing concerns about climate change and pollution caused by extensive use of fossil fuels have not left the power electric systems untouched. In 2009 approximately 67% of all the electricity produced globally [4] was

![Figure 1.1: Wind power generation growth in Germany for the years 1990-2016 [3]](image)
generated using either gas, coal or oil. Since all the energy transformation processes linked to fossil fuel utilise combustion to retrieve the energy stored in the hydrocarbon molecules, carbon dioxide is generated in large quantities and inserted in the atmosphere. Several international committee and convention have engaged and sustained a climate discussion with several proposal and measure to restrain the greenhouse gases emission into the atmosphere. Several countries have decided to shift the electrical power generation network to a more sustainable one, facilitating the use of renewable energy systems, such as hydroelectric, wind turbines, solar photovoltaic or geothermal plants. The potentiality of hydroelectricity was early recognized and is nowadays widely adopted throughout the world power systems, letting only a small margin of optimization and growth constrained by different problematic, e.g. the construction of new dams in populated areas. Most of the transition of the electrical generation from fossil to renewable sources is today left to solar photovoltaic plants and wind turbines, that have proven to be the most successful and mature technologies at disposition. The increase and adoptions of these technologies in some countries in the last years has been dramatic: in Germany the combined power capacity of solar and wind plants has gone from about 6 GW in 2000 to roughly 53.9 GW in 2011, reaching 63% of the total load power requirement. On the other hand, only 12.5% of the total required energy came from these sources, since high fluctuations in the production impede a continuous generation of electricity. In People’s Republic of China the wind power generation went from a modest 1.26 GW in 2005 to an astonishing 62 GW in 2011, more or less 7% of total power production. But the increase of this volatile kind of generation and the lack of adequate storage technology require a deep analysis of all the consequences that the integration of wind and solar systems can cause to the existing power grid, built over years following a completely different concept, based on large power plants independent from the plant location and the source availability. The problems that can arise are various in degree and forms and are mostly related to the ancillary services provided by the responsible TSO’s of the different countries.

1.3 Impact of high shares of RES on ancillary services

1.3.1 Ancillary services: definitions
The ancillary services, as defined by the United States Federal Energy Regulatory Commission (FERC) (analysed in [5]), are those “necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.” It
identifies six major sectors:

- Scheduling and dispatch management
- Operating reserves
- Energy imbalance
- Real-power-loss replacement
- Voltage control
- Other minor services, like black start capability or time correction

For the purpose of this thesis the following assumptions and definitions related to the presented ancillary services are defined:

### 1.3.2 Scheduling and dispatch management

The scheduling and dispatch services are considered unaffected by the composition of the power grid: they only serve to determine the production portfolio in advance for different time periods (scheduling from a week ahead to few minutes before each hour) and are responsible for the grid stability and reliability. Although extremely important both strategically and technically, those services are not expensive (0.2 millicents/kWh), requiring only IT materials and room operators, are therefore considered to be not affected by an increase of the renewable energy shares.

### 1.3.3 Operating reserves

It stands for all the required reserves needed to ensure the grid stability controlled by the TSO’s. This is the field where this thesis investigates the dimension of the impact of high shares of renewable energy systems of stochastic nature. A more detailed approach and definition is discussed in Section 1.4.

### 1.3.4 Energy imbalances

Another service is the appropriate compensation for the unavoidable energy imbalance between control zones. Since it is impossible for every control zone to match exactly load and generation, the resulting difference stresses the rest of the system that must compensate for it, or in a second case, a stressed system is compensated by a favourable deviation inside a control zone. The TSO’s must keep track of the nature and consequences of these imbalances and provide adequate compensation/punishment. The modelling of zones interchanges is far too computationally time intensive: they could be represented by more power buses with random variations of
the load and a different energy production portfolio (reflecting the different geographical distribution of RES), but this level of precision exceeds the goals of this thesis and it is therefore decided to give more focus to a simpler system yet capable of run more efficiently and quickly, better suited for a Montecarlo methodology. An examination of possible Energy Imbalance Market implementations can be found in [6], focusing in cooperation and pooling of resources in case of high shares of wind production.

1.3.5 Real-power-loss replacement

The compensation of power losses caused by electricity transmission and distribution is another service provided by the TSO’s: although the impact of RES could be interesting to analyse in the contest of decentralised energy production and possible losses due to transportation from a favourable site (for wind, solar production) to the large consumer regions (cities, industries), this is not a topic of research of this thesis. Interesting considerations can be read in [7] or [8].

1.3.6 Voltage control and other minor services

High shares of RES in a power grid can easily generate large amount of fluctuating power in the critical nodes of the network. Voltage stability is therefore extremely important, achieved with an appropriate management of the reactive power. The representation of this kind of impact requires the modelling of complex network and nodal analysis, is therefore not indicated and not necessary for the purpose investigated in this thesis. However there are studies (e.g. [9]) that focuses for instance on the possibility for voltage control offered by Smart Grid and integrated RES.

1.4 Literature study on operating reserves

1.4.1 Definitions

As operating reserve is defined all the power capacity at disposition in a power system for regulating purpose and emergency supply in case of generation, line or load unit failure. The time reaction may vary from very short intervals (seconds) to longer ones (more minutes). Power systems operators all over the world may use different nomenclature and time-scale. In this thesis the following definitions (commonly used in Switzerland and Germany) are adopted, focusing on active power regulation:

- **Primary frequency control**: is the first power intervening for regulating purpose. Power plants automatically adapt and react to change
in frequency, thus providing the necessary balancing effect within seconds from the discrepancy between load demand and generation.

- **Secondary frequency control:** if the plants providing primary control cannot keep the frequency stable, other load following power plants, usually kept committed at a value beneath the maximum load, can shift their operating point and provide the necessary negative/positive power. The intervention of this power plants starts around 30 seconds after the primary control reserves have been fully exploited and lasts until they are replaced by the tertiary control reserve.

- **Tertiary frequency control:** this last step is left to back-up power plants that must be activated and are used to replace and unload the secondary control plants and allow them to go back to their normal operating point. This is important to ensure safety of operation, since to react to eventual other disturbances the tertiary control power plants are usually too slow and cannot help the secondary ones to stabilize the grid.

Figure 1.2 resumes time of intervention and typology of the different control power included under "operating reserves". After one hour of unstable operation a rescheduling of the largest, dynamically slower power plants can recreate an equilibrium condition and fully replace the secondary and tertiary power plants.

Figure 1.2: Activation time of Control Reserves after a fault

### 1.4.2 Literature overview

The main purpose of this thesis is the analysis of simplified power grids with high shares of RES with variable generation profile. The focus is on
the energy that must be provided from fast reacting power plants (e.g. gas or hydroelectric) in order to compensate for deviations from the forecast schedule. A second interesting result that can be achieved is the relationship between the control power plants and the slower ones, that can adjust their schedules only every hour. Most of the research in this field have as primary focus the impact of wind systems, since the unpredictability is present throughout the day, night included, where solar forecast is facilitated by the day-night cycle of the system. However, solar reacts extremely quickly to small variation in light intensity (for instance caused by passing clouds) and the importance of variability for system including high shares of solar plants is not to be dismissed if confronted to high shares of wind. Hannele Holttinen published different studies (e.g. [10]) focused on the impact of wind power on power systems. The most obvious advantage of including high shares of renewable energy systems in the power grid is the diminishing of the marginal operating costs of the power system (less fossil fuel is consumed); it remains to be analysed if this benefits are not shadowed by the efforts and the investments needed to ensure operation reliability. As Holttinen remarks, it is very difficult to assess properly the impact of wind technologies: for instance is not easy to compare different studies in different countries, because methodology, data and the whole geophysical conditions (location, wind distribution), nevertheless the grid infrastructure, are very different and can result in very contrasting outputs. Despite that, three recurrent situations emerge from the analysis of different studies:

- For an energy share of wind production of up to 20% of the total energy demand, an increase of the operating costs for balancing and regulation purposes of about 10% of the sell value of wind power are to be considered. The impact on the total capacity reserve differs greatly from study to study.

- There is a positive effect on balancing costs if the interconnection of different power grids for balancing purposes is allowed. With larger balancing area, the aggregating benefits for wind forecasts and the access to larger regulation reserves reduces the impact of wind power integration.

- An operating schedule for load following flexible power plant in a sub-hourly regime greatly increases the optimal usage of the regulating reserve, reducing the need for more control power plants.

These last two points are confirmed by another study focusing on the California Power Grid [11]. This last study considered the impact of up to 33% of renewable energy penetration in the actual Californian power grid. For instance the maximum area control error increased dramatically from +/- 100 MW to 3000 MW, while the necessary secondary control power
roughly doubled. The largest deviation were detected by the system during the morning and the evening, corresponding to the ramping of renewable energy system (solar ones) and the traditional load ramping for the peak at midday and the second intermediary peak in the evening. Among the many results an increase of the greenhouse gas emissions of the whole control system generation is observed, not only because the requirements change: the necessity of fast ramping requires most fossil-fuel based power plants to remain committed, running in sub-optimal condition.

Another North-American study [12] repeated the importance of balancing area cooperation and sub-hourly scheduling, though it insisted that since the largest deviation peaks, that would require a great increase in the control energy reserves, only occur 89 hours every year, and it raises the question if a demand-side response scheme for mitigating these deviations may be more cost-effective.

1.4.3 Conclusions

The considerations found in different studies are difficult to compare because assumptions, terminology and physical conditions are too different and make it impossible to find a common ground to fully evaluate the impact of renewable technologies on power grids and the ancillary services. A first step in the right direction would be the creation of standard terminology and sizing embracing ancillary services, balancing zones and control reserves. The impression is that every country/power system uses their own set of words and definitions, making it difficult to cross-results the different studies and analysis. However, the trends signalised in Section 1.4.2 will be integrated in the analysis and considerations of the results of this thesis.
Chapter 2

Forecasts generation tools

2.1 Introduction

An important part of this thesis consisted in the development of tools to generate realistic forecast profiles for wind and solar power generation. To obtain a solid and reliable tool the problem was approached from two different points, the first being a classical literature study while the second was the calculation of the precision of actual forecasting tools thanks to statistical analysis of the published data from different TSOs.

In this chapter the development of the tools will be described from both points of view, starting with solar and concluding with wind generation. It must be clear that the intention is to create reliable forecasts, not to analyse or evaluate different forecasting methods. What is necessary is a tool that can produce forecast profiles within an acceptable standard deviation error range. To do this, a "reverse engineering"-like approach is used: from the effective renewable production profile a forecast curve is built that respects the RMSE of actual forecasting models.

2.2 Solar forecasting precision

2.2.1 Literature research

The increasing integration of solar power production units in different countries (e.g. Germany or Spain) results in a boost of the research and the benchmarking of different numerical weather prediction models. In 2009 a combined study [13] of values from four different European regions with different climatic condition (Germany, Switzerland, Austria, Spain) were gathered and evaluated. Table 2.1 shows the different teams and their approach to the forecasting problem, including the utilised spatial and temporal resolution. All the approaches are based on a global prediction model (developed by, for example, the European Centre for Medium-Range Weather Forecast.
<table>
<thead>
<tr>
<th>Team</th>
<th>Approach</th>
<th>NWP Model, resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Oldenburg, Germany</td>
<td>Statistical Post-processing in combination with a clear sky model</td>
<td>ECMWF, 0.25° x 0.25°, 3 hours</td>
</tr>
<tr>
<td>Blue Sky, Austria</td>
<td>a) human cloud cover forecast (by meteorologists) and b) BLUE FORECAST, a statistical forecast tool</td>
<td>GFS, 1° x 1° and 0.5° x 0.5°, 3-6 hours</td>
</tr>
<tr>
<td>Meteocontrol, Germany</td>
<td>MOS (Model Output Statistics) by Metemedia GmbH</td>
<td>ECMWF, 0.25° x 0.25°, 3 hours</td>
</tr>
<tr>
<td>Ciemat, Spain</td>
<td>Bias correction</td>
<td>AEMet-HIRLAM, 0.1° x 0.1°, 1 hour</td>
</tr>
<tr>
<td>CENER, Spain</td>
<td>Post-processing based on learning machine models</td>
<td>Skiron/GFS, 0.1° x 0.1°, 1 hour</td>
</tr>
<tr>
<td>Meteotest, Switzerland</td>
<td>Direct model output of global irradiance</td>
<td>WRF/GFS, 5km x 5km, 1 hour</td>
</tr>
<tr>
<td>University of Jaen, Spain</td>
<td>Direct model output of global irradiance</td>
<td>WRF/GFS, 3km x 3km, 1 hour</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of research groups and forecast methods
(ECMWF) or the Global Forecast System (GFS)) and are then refined and scaled thanks to numerical operation to determine the forecast for a single region. A more detailed analysis of these methods and approaches is described in the quoted paper.

The main conclusion shown by this study is the importance of the climatic conditions: stations of Central European countries have relative RMSE ranges from 40% to 60% for a three-day forecast horizon, while in Spain the values vary from 20% to 35%. In a following study [14] realised by the same group, a more detailed analysis based on ECMWF forecasts and dedicated only to Germany has shown the great impact of aggregation. If the forecasts for one site could vary from a relative RMSE of 37% for the first day to 46% for the third day, the spatial averaging effects could highly improve the accuracy of the post-processing procedures, resulting in a RMSE of 13% for the first-day forecast of whole Germany.

### 2.2.2 Statistical analysis

![Figure 2.1: Average RMSE over time (in hours) of the 4 different TSOs in Germany and their aggregated value in 2011](image)

A second way to analyse the accuracy of modern solar power forecasting methods is to consider the results used in real world by private companies. However most of the time the power companies keep their analyses inside and do not publish the results, because of the obvious need to preserve secrecy over the concurring companies. The TSOs instead have to publish their estimation of the successive day. This data are usually distributed online at 8:00 of the preceding day and comprehend the forecast for the whole following day. That means that is possible to analyse the quality of
their models for the interval between +16 h and +40 h.

Figure 2.1 shows the average RMSE for all the German TSOs over a period of one year. Because the forecast are always published at the same time, it is possible to generate such graphics by simply comparing the effective production with forecasted quantity. The maximum inaccuracy in this case shows a RMSE of around 20%. This is in accord with the studies cited above and validates the important role played by aggregation: 50 Hertz manages a territory large almost the size of one third Germany, and together with the aggregated profile is the one with the best average RMSE.

2.3 Solar forecasts generation tool

2.3.1 Concept and assumptions

After the analysis presented in the previous sections it is possible to determine the expected progression between RMSE and the forecasting horizon. Diagram 2.2 approximates the variation by the actual weather forecast models: The goal of the tool is to obtain a similar behaviour for its forecasts. Since even with scarce solar intensity a minimal generation is always provided, and that the maximum power is obtainable only in summer days, the maximum forecast error for solar production after 2-3 days is limited to around 40%. Even without using weather prediction models a generic forecast of "60% of total installed power" with an expected error of +/- 40% will cover all the generation between 20% and 100%. This natural threshold is not present in wind generation, since it is almost entirely of stochastic nature, where solar production is linked to a non stochastic part (day-night
cycles). This pattern is shown in the above diagram by the 0% error region between the different daily peaks.

### 2.3.2 Realization

The important part of solar generation is the position of the peak, i.e. the moment with the maximal power generation. The developed tool analyses the profiles, seeks the effective peak for each day of the whole horizon and changes the position in accord to the RMSE illustrated above. That means that the peak has two degrees of freedom, horizontally in time (i.e. the hour in which take place) and vertically in amplitude (the intensity of direct radiation).

The first one is not only defined by the position of the sun over the horizon but from the cloud movement too. For the simulation in this thesis it is decided that the peak position can vary between 11:30 AM and 13:30 PM. The direct radiation influences the global solar production and it determines the vertical position: a deviation from the actual production is obtained thanks to a normal distribution respecting the results detailed in Section 2.2. Plot 2.3 shows one forecast generated with the tool and the related actual production.

### 2.3.3 Examples

![Figure 2.3: 4-day-ahead solar forecast.](image)

To verify that the generator tool obtains a RMSE distribution in line with the expectation defined in Figure 2.2 a Montecarlo approach is used. Thousands of forecasts were calculated and averaged. The results is shown
Figure 2.4: Montecarlo-generated RMSE variation.

in Fig. 2.4. The desired progression, from 0 to 40% as defined in Figure 2.2 is almost identical obtained. The forecast seem inaccurate for the first 20 hours, but the problem is that since the forecast is built around the position of the peak, an absolute error of 10% is easily reached during the morning hours due to the fast increasing output power. Real life observations confirm this tendency in having larger error during the increasing and decreasing hours of dawn and twilight. The presence of the irregular forecast profiles does not constitute a problem or a fault in the model of pattern in the daily cycle.

2.4 Wind forecasting precision

2.4.1 Literature research

While solar power generation follows a recognizable daily cycle, the same does not happen for wind power generation. It is however possible to notice a certain correlation between the histories of wind data and the developing of future wind pattern (i.e. auto-correlation property).

In [15] eleven state-of-the-art models, actively used in day-to-day operations, were tested and their performance assessed. Six different European stations, with very different geographical conditions, were chosen to evaluate the models: from the off-shore wind farm of Tuno Knob, Denmark, to the Alaiz wind farm in Pamplona, Spain, characterised by a very complicated morphology of the terrain.

The results show a varying error from 10% to 25% RMSE of the nominal power for the 12h horizon forecast, with the morphological conditions indi-
cated as the most important accuracy factor. The most precise model still displayed an average error of 5% for the 15 minutes ahead forecast: this fact must be taken in account during the modelling of the tool. Pinson and Madsen, in [16] proposed a regime-switching approach, in which they identified three different regimes (low power, average, high power production). These regions have different degrees of forecast accuracy, because it is possible to foresee, with a good degree of approximation, if in two days there will be strong or almost no wind. This causes an improvement of the forecast for the horizon +36-72 h. It is important to note that this improvement only takes place if there will actually be a low/high power production regime. During average power production the accuracy tends to decrease linearly.

2.4.2 Statistical analysis

Analogously in respect to what was done in Section 2.2.2, a statistical analysis of the data published by German’s TSOs is carried on. The results (plotted in Fig. 2.5) are in line with the assessment presented above and show a variation between 6% and 10%.

2.5 Wind forecasts generation tool

2.5.1 Concept and assumptions

After the analysis over the accuracy of the existing methods an ideal forecast precision curve is developed. Because of the discussion enlightened in
Figure 2.6: Desired accuracy progression. Above: normal production. Below: strong/low production regimes.

Section 2.4.1 two different curves are chosen: one for the situation where low or high power production is expected in the next two days, and a second for all the intermediate production profiles, where the accuracy is lower. Figure 2.6 shows the two profiles and the desired progression of the RMSE in function of the forecast horizon. Because of the ever-changing nature of wind fluctuations, a normal linear approximation is chosen. After a Monte-carlo validation the tool should then be able to reproduce an averaged curve between these two expected profiles.

2.5.2 Realization

Nowadays large and sudden changes on wind production are far more present than average production values: that means that forecasts tend to predict more accurately when wind production is in switching regime (it is easy to foresee if strong or weak wind is coming). It is rare that forecasts are wrong about an intensity switching: they tend to accumulate mistakes of future amplitudes of wind production (manifested by a gap between the expected and the end value). This means that the slope of the wind curve is decisive: if the wind power generation is increasing quickly, the slope tends to $+\infty$, while if it is ceasing it tends towards $-\infty$. This characteristic is used in this tool so that the varying value of the slope acts as a controller, increasing accuracy if the wind slope tend to positive (or negative) infinity: in this way the wind forecasts tend to foresee more accurately if low or high power regimes are approaching.

The first forecast curves using this methods are extremely noisy and saw-
toothed, but interpolation passages and the use of the \textit{smooth} operator adjust the end results, creating a realistic approximation of a forecast curve.

\subsection*{2.5.3 Examples}

Figure 2.7 shows a first example of a wind forecast generated by this tool. The created curve follow approximately the regime switches of the real wind power production, but it still has realistic behaviour when it comes to foresee average or constant wind power.

![Figure 2.7: 4-day-ahead wind forecast.](image-url)
A conclusive Monte Carlo routine test is run and the results are shown in Fig. 2.8 for different precision values. The expected curves (a mix of the two chosen progressions enlightened in 2.6) are obtained, so that a realistic stochastic variability of the used forecasts for wind profiles is ensured.

Figure 2.8: Monte Carlo test of the forecast generator tool
Chapter 3

Power System Model

3.1 Introduction

To model the power grid the power node framework described in [1] is used. This framework models all the participants in a power bus as nodes, represented by the general power node equation:

\[ C_i \dot{x}_i = \eta_{load,i} u_{load,i} - \eta_{gen,i}^{-1} u_{gen,i} + \xi_i - w_i - v_i \]  \hspace{1cm} (3.1)

The graphical representation shown in 3.1 could help to better outline the idea behind the single node equation. This approach is very simple: from

Figure 3.1: Representation of the single node equation as described in [1] an energy source or an energy demand (in the picture on the left side and...
marked as $\xi_i$ an electrical profile $u_{\text{load},i}$ or $u_{\text{gen},i}$ is derived (right side, usually specified as ‘grid side’). The efficiency term $\eta_i$ models all the energy dispersed by the conversion process, while the storage variable $x$ could represent the energy capacity $C$ stored in the node (if a buffer element is present). The loss terms $w$ and $v$ indicates respectively a curtailment of the source energy (or unserved load) or general storage losses.

The power flow direction and the dynamic behaviour of the storage are modelled through a series of constraints, and so is the grid model itself. The number and typology of power buses is namely defined with the bus balance equation, that says that in a power grid bus must always exist a power balance between load demand and generation:

$$\sum_{i=1}^{N} u_{\text{load},i} = \sum_{i=1}^{N} u_{\text{gen},i}. \quad (3.2)$$

Depending on the typology of the modelled power nodes the single variables in the equation may be controllable, observable, driven by external factors or simply not present. For example a classical load without buffer (e.g. a typical household) would have a storage capacity $C = 0$, while the external source $\xi_i$ could be constrained to follow a typical domestic load profile. On the other hand, if a power plant with unlimited fuel is modelled, the $u_{\text{gen},i}$ variable would be the constrained one (by the power grid balance equation), while $\xi_i$ would be left unconstrained.

With the use of different kind of constraints a good approximation of power nodes can be reached; however it is important to note that more constraints mean less degree of freedom for the optimization algorithm, hence resulting in possible infeasibility errors during the simulation. In the next sections the six most important power nodes for this thesis are thoroughly presented and explained, while at the end some of the unconventional investigated ones (not used in the case study) are briefly discussed.

### 3.2 Power Nodes

#### 3.2.1 Conventional Load

The first power node is an aggregated representation of all the loads of the demand grid. The power node equation is reduced to

$$u_{\text{load},1} \cdot \eta_{\text{load},1} = w_1 - \xi_1$$

where $\xi_1$ is the external demand and correspond to the load profile of the grid bus. In the case study presented and analysed in Chapter 5 the 2011 load profile for Germany is used. This means that in every step of the simulation the $\xi$ value will be constrained to be identical to the corresponding load profile step value. $w_1$ represents the curtailment option and is freely
controllable by the algorithm (unconstrained): hence a degree of freedom in adjusting the demand profile exists, such that \( u_{load} \) can meet the requirement of the balance grid Equation (3.2). Other constraints are resumed in Table 3.1. As already indicated in Figure 3.1 \( \xi \) and \( w \) in case of load are negative,

<table>
<thead>
<tr>
<th>Variable</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{load,1} )</td>
<td>( 0 &lt; u_1 &lt; u_{max,1} )</td>
</tr>
<tr>
<td>( w_1 )</td>
<td>( \xi_1 &lt; w_1 &lt; 0 )</td>
</tr>
<tr>
<td>( \xi_1 )</td>
<td>( \xi_1 = -1 \cdot \text{load}_{TSO}(t) )</td>
</tr>
</tbody>
</table>

Table 3.1: Constraints for conventional load power node.

while in respect to Equation 3.2 \( u_{load} \) is positive.

### 3.2.2 Wind generation power node

With the following equation

\[
u_{gen,2} \cdot \eta_{gen,2}^{-1} = \xi_2 - w_2
\]

it is possible to adequately model a generation plant with curtailment option. Since the equation itself is very similar for all types of generation (see conventional fossil generation below) the differentiation in dynamic behaviour is expressed through an appropriate set of constraints. In this case the external processes \( \xi_2 \) are constrained by the generation profile (the wind availability), similar to the conventional load. The curtailment term is inserted to prevent infeasibility during the solution of the algorithm. Other specific constraints are expressed in the table 3.2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{gen,2} )</td>
<td>( 0 &lt; u_2 &lt; u_{max,2} ) (</td>
</tr>
<tr>
<td>( w_2 )</td>
<td>( 0 &lt; w_2 &lt; \xi_2 )</td>
</tr>
<tr>
<td>( \xi_2 )</td>
<td>( \xi_2 = \text{wind}_{TSO}(t) )</td>
</tr>
</tbody>
</table>

Table 3.2: Constraints for wind generation load power node
3.2.3 Solar generation power node

The solar generation is modelled exactly like the wind one, since both are non-dispatchable external driven generation plants.

\[ u_{\text{gen},3} \cdot \eta_{\text{gen},3}^{-1} = \xi_3 - w_3 \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Constraints</th>
</tr>
</thead>
</table>
| \( u_{\text{gen},3} \) | \( 0 < u_3 < u_{\text{max},3} \)  
| | \( | u_3 | \leq u_{\text{max},3} \) |
| \( w_3 \) | \( 0 < w_3 < \xi_3 \) |
| \( \xi_3 \) | \( \xi_3 = \text{solar}_{\text{TSO}}(t) \) |

Table 3.3: Constraints for solar generation power node.

3.2.4 Pumped-hydro storage unit

To compensate for stochastic generation plants like wind or solar units, the integration of a buffer node is almost unavoidable. This node is therefore considered to be a control plant, meaning that it can effectively be deployed for regulating purposes in case of an unbalanced grid. With the following equation

\[ C_4 \cdot \dot{x}_4 + u_{\text{gen},4} \cdot \eta_{\text{gen},4}^{-1} - u_{\text{load},4} \cdot \eta_{\text{load},4} = 0 \]

a bi-directional storage system can be modelled. \( C_4 \) is the total storage capacity, while \( x_4 \) varies from 0 to 1 and represents the state-of-charge (SOC). This buffer has not an external source of energy, i.e. it can represent pumped water storage, where the influence of precipitations or seasonality is neglected. With the appropriate constraints this node can model an electro-chemical buffer, like a cluster of batteries.

Another very important constraint is the one preventing a contemporary usage of generation and loading capacities, so that the optimization algorithm does not utilize this process to waste energy through the different efficiencies by cycling pump/turbine systems: this behaviour is not used in real world operation and must be avoided. The problem posed by this constraint, expressed with the equation

\[ u_{\text{gen},4} \cdot u_{\text{load},4} = 0 \]

is of numerical nature. The introduction of a non-linearity in the equations requires a mixed-integer approach, with the utilisation of boolean variables.
as logic constraints. However, as outlined in [17], it is possible to avoid numerical problem and complications by omitting the constraints and carefully choose a cost set that avoids internal discharge/charge cycles. In this case the optimization problem remains quadratic, thus facilitating the implementation in MATLAB.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{gen,4}$</td>
<td>$0 &lt; u_4 &lt; u_{max,4}$&lt;br&gt;$</td>
</tr>
<tr>
<td>$u_{load,4}$</td>
<td>$-1 \cdot u_{max,4} &lt; u_{load,4} &lt; 0$&lt;br&gt;$</td>
</tr>
</tbody>
</table>

Table 3.4: Constraints for bi-directional storage power node.

### 3.2.5 Fossil-fuel based conventional plants

Traditional fossil fuel power plants can be modelled easily with the simplified equation

$$u_{gen,5} \cdot \eta_{gen,5}^{-1} = \xi_5.$$  

In this case there is no need for curtailment, since the fuel is supposed to be unlimited and always at disposition. This means that $\xi_5$ is not driven by an external profile, like for wind or solar, but instead represents the used fuel in generating $u_{load,5}$. This plant is fully dispatchable, but on the other hand is not considered a control power plant and thus cannot adapt its production to match an unbalanced grid. The slow dynamic is then reinforced by modelling a set of constraints that avoid abrupt changes in the power production, simulating an aggregation of different, dynamically slow power plants. Since the power node represents the aggregated power production from slow power plants, there is no particular need for a constraint for low regime production (e.g. nuclear plants do not work under 50% load, because of the intrinsic limit of the fission technology). The many different plants included (with different dynamics and different peak power) de facto eliminate this kind of constraint through aggregation.

In this case $\dot{u}$ is limited not to the maximum $u$ value, as the others, but instead is limited to a fixed $u_{max,5}$ value that represents the slow adaptation of this kind of power plants. For example in the case study analysed in this thesis this value is set to 5%, meaning that this power node can vary only with the 5% of the maximum power between each simulated step. This is consistent with real life measurement [3].
CHAPTER 3. POWER SYSTEM MODEL

### Variable Constraints

<table>
<thead>
<tr>
<th>Variable</th>
<th>Constraints</th>
</tr>
</thead>
</table>
| $u_{\text{gen},5}$ | $0 < u_5 < u_{\text{max},5}$  
|           | $|\dot{u}_5| \leq \dot{u}_{\text{max},5}$ |
| $\xi_5$  | unconstrained |

Table 3.5: Constraints for fossil-fuel based power node.

### 3.2.6 Fossil-fuel peak conventional plants

This power node is modelled almost exactly as the base one above. The difference, distinguished by the denomination ‘peak’, is that this node is used for regulatory purpose, compensating the grid balance when the combination of solar, wind, hydro pump and base power cannot satisfy the constrained conditions. Since these kind of plants can react very quickly to different loads, $\dot{u}$ can assume large values and do not need of a set of constraints.

\[
U_{\text{gen},6} \cdot \eta_{\text{gen},6}^{-1} = \xi_6
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Constraints</th>
</tr>
</thead>
</table>
| $u_{\text{gen},6}$ | $0 < u_6 < u_{\text{max},6}$  
|           | $|\dot{u}_6| \leq \dot{u}_{\text{max},6}$ |
| $\xi_6$  | unconstrained |

Table 3.6: Constraints for fossil-fuel peak power node.

### 3.2.7 Other power nodes

In the next sections a brief overview of other investigated power nodes is provided, although they were not used in the analysed case study. The main reasons for the exclusion were the complication of the interpretation of the results and the impact on the computational time.

#### Hydro seasonal storage

In the hydro seasonal storage no pumping option is modelled, since this power node deals with traditional dams and basins, that collect seasonal-dependant waters, like rains or snow melting.

\[
C \cdot \dot{x} + u_{\text{gen}} \cdot \eta_{\text{gen}}^{-1} = \xi
\]
CHAPTER 3. POWER SYSTEM MODEL

The in-feed of water is represented by the external profile $\xi$: it should take into account all the rain precipitation and seasonal effect. The best way to obtain this profile is to start from the power production seasonal profile for this kind of plants and trace back the feed-in profile. The storage variable $x$ must be constrained and should model the storage fill variation during the year. Since this variation is not only physical (overflow risk of basins) but an economical one too, the constraint limit should not be too harsh and should allow for some degree of freedom for the $x$ curve to follow the optimal cost configuration.

**Hydro run-of-river**

The hydroelectric power has almost the same conditions of wind and solar production facilities, containing a stochastic part represented by the river height difference before and after the turbines thus limiting the power output.

$$u_{gen} \cdot \eta_{gen}^{-1} = \xi - w$$

One example is during heavy precipitation, where river plants must let some water flow by and not in the turbines, to avoid complications and possible overflows. To obtain this $\xi$ profile the same method as in the above section about seasonal storage must be used by tracing back in-feed profiles by power production data. The curtailment option $w$ must be included to grant a degree of freedom more to the controller, so that it could privilege an alternative power source (e.g. solar generation) and let therefore water flowing by without generating power.

**Electrochemical storage**

Electrochemical storage, like batteries, can be efficiently modelled as the hydro pumped storage, with the same limitation and constraints.

$$C \cdot \dot{x} + u_{gen} \cdot \eta_{gen}^{-1} - u_{load} \cdot \eta_{load} = 0$$

One difference is the modelling of the capacity $C$: in this case, differently from water basins, the capacity of batteries can degrade with time and utilization. An appropriate model should account for this behaviour by decreasing $C$ with time.
Chapter 4

Model structure and control

4.1 Introduction

The integration of stochastic forecasts in a MPC oriented approach needs an appropriate definition of the controller structure, so that not only the grid balance is always respected, but that the impact of the power production deviations can be evaluated. The solution proposed in the following sections not only fulfills both the conditions, but it makes it possible to fully represent the interactions between a dynamically slow plant (i.e. plants that cannot provide any kind of power control but that must follow the production schedule) and a dynamically faster one (i.e. plants able to intervene and compensate fast power deviations of stochastic nature).

4.2 General structure of MPC and MATLAB implementation

In this section a brief overview of MPC is presented along with the chosen MATLAB implementation. A theoretical approach to the MPC algorithm and implementation in MATLAB is presented in [18].

In a few words, MPC is a controlling algorithm that tries to optimize the cost function of a system by means of model-based predictions of a system’s output relative to the control input. In order to work, a model of the system is absolutely necessary, and for this thesis the single bus power grid model presented in Chapter 3 will be used. The second important factor is the optimization cost function, usually of the form

\[ J = \sum_{i=1}^{N} w_{x_i} |r_i - x_i|_2 + \sum_{i=1}^{N} w_i \Delta |u_i|_2 \]

In the studied case \( |r_i - x_i|_2 \) represents the deviation of the grid output \( x \) from the desired value \( r \) while the second term \( \Delta |u_i|_2 \) is the cost associated
with the changing of the control input \( u \). Usually the optimization seeks the minimum of the cost function \( J \), with the weighting factors \( w \) as a means to tweak the behaviour in the desired way. The algorithm is fairly easy to describe:

- A possible control input vector \( u \), of the same size as the desired control horizon \( H \) (usually defined as \( N \) steps) is fed into the prediction model.
- The output vector \( x \), of the same size as \( u \), is calculated and compared against the desired value \( r \) for each step of the horizon length.
- The cost term \( J \) is calculated.

The optimization function then tries different input vectors \( u \) until \( J \) is minimized. The input vectors have to respect a subset of constraints that define the model, for example in the power grid case the power balance \( u_{\text{gen}} = u_{\text{load}} \). Then, after the optimal input vectors \( u \) is obtained, the control algorithm goes to the step \( n + 1 \) along the horizon and starts the calculations again, using therefore only the control information stored in \( u_1 \). This way to move along the horizon one step at a time is the reason why the MPC is also usually called receding horizon control.

There are different possibilities to implement an MPC control algorithm in MATLAB. This thesis is developed using the Yalmip toolbox for MATLAB, a free high-level modelling language that allows the user to concentrate on the model implementation and take care efficiently of all the low level modelling operations. More information are published on-line in [19]. The external numerical solver CPLEX of IBM is chosen for the actual computation tasks.

### 4.3 Nested MPCs

#### 4.3.1 The concept

The time series data used in this thesis have a time step of 15 minutes and are provided by the grid operators for wind and solar generation. As the main goal of this research is to evaluate the impact of stochastic variation for the technologies mentioned before, this time length is a good compromise between accuracy and velocity of the variation, i.e. the time step is large enough to avoid the simulation of the control action provided by the first and part of the second regulation power reserve but it is small enough to integrate a sudden change in wind or solar power generation.

Chart 1.2 in Chapter 1 shows the time scale of different implementation of regulation energy. After one hour of instability, compensated by the tertiary energy reserves, the dynamically slow power plant can finally react and automatically adjust to the necessity of the grid, compensating the power
deviations, and the TSOs can provide a new power production schedule, based on the last forecasts.

This procedure can be optimally simulated with the concept of concatenated MPCs, i.e. where the controlling of the grid does not exist in only one time-scale but it relies upon the implementation of different controllers acting for different horizon and activation step lengths. Diagram 4.1 presents a scheme to best represent this solution. The largest block in the middle is the first and more complex MPC that defines the control strategy (in this case is the production portfolio) every hour and that bases its decision upon the different forecasts for solar and power production. Because the time step of the data is 15 min. there will be 3 steps without an MPC intervention and in which the production portfolio will follow the defined schedule. The presence of high shares of wind and power generation, however, could cause a sudden change in power availability for which the control strategy is not prepared. The intervention of a second short-term MPC (represented by the lower central block) is necessary. The only purpose of this controller is to stabilize the grid and any variation of the control energy caused by the new MPC decisions from the scheduled one is considered to be part of the tertiary energy reserve, either the negative or the positive one. Every four steps, kept in balance by this short-term MPC, the production schedule is
renewed and changed by the long-term MPC. To resume, this controlling structure can be described as divided in two different layers: the first one, in which an MPC works with imperfect data and is responsible for the schedule of dynamically slow power plant (long-term MPC), and a second one, responsible for the balancing of the power equations and that reacts to the stochastic changes caused by wind and solar generation (short-term MPC).

4.3.2 A deeper insight: first layer MPC

The generation capabilities of power plants is modelled (in the Power Node framework) with the definition of appropriate constraints, as exposed in Chapter 3. To model a first layer MPC no particular constraint limitation is needed: every Power Node works as modelled, with the only difference that the feed-in information $\xi_i$ for wind and solar production, used to elaborate the controller, is generated utilizing a forecast of the tool shown in Chapter 2 and do not respect the future, real production. The MPC controller will therefore try to balance the power system equation every hour (4 algorithm steps) for the horizon $H_{\text{future}}$ in function of the forecasted generation. The consequent result of this procedure is a $N$-length schedule vector for all the dynamically slow power plants:

$$MPC_1(\xi_i, \text{forecast}) \rightarrow u_{\text{gen,slow}}$$

The $u_{\text{gen,slow}}$ power production vector is optimized using the merit-order distribution shown in figure 4.2. This distribution is chosen with marginal-cost in the same order of magnitude as the ones analysed in [17]. In this case they are heuristically modified so to respect the wanted ecological optimization of the grid, with the exceeding power from RES saved in the hydro-electrical storage. With perfect prediction the schedule of dynamically slow power plants will avoid the use of fast, fossil based control power plant. On the other hand, the hydroelectric power is only used if the prospect of an
exceeding production (from either wind or solar plants) has been forecasted. The dispatch solves therefore an ecological optimization, storing fluctuating RES energy for use in a latter moment. The simplest strategy is applied: when the forecasted energy production exceeds the demand, hydro-power is scheduled in order to empty the storage bassin and making it thus ready to absorb the forecasted energy surplus.

4.3.3 A deeper insight: second-layer MPC

The second-layer MPC works only in function of the stability of the grid. During step $n_1$ the first layer MPC manages the power grid equations and ensures stability, generating the dispatch vector $u_{gen,slow}$ of the slower plants. But from step $n_2$ to $n_4$ the actual RES production changes so that the power balance equation

$$u_{gen} = u_{load}$$

is no more respected, because $u_{gen,slow}$ of the dynamically slower plants is no more a freely adjustable quantity but is treated as constrained by the dispatch vector determined in $n_1$ by the first-layer MPC. This obliges the grid operator, simulated by the second-layer MPC, to reinstate the grid balance by either changing the production of dynamically fast control plants, curtailing the RES generation or by acting on the demand side. The differences, that arise after 15 minutes (in step $n_2$, $n_3$ and $n_4$) can be seen as the tertiary reserves activating and deploying in order to substitute the secondary control power plants and maintaining grid stability. Since the simulation models only one bus load, the results is the aggregated net usage of operating reserves.
Chapter 5

Simulations and Results

5.1 Case study

The first test with the chosen set of constraints and implementation resulted in a much higher computational time than other similar efforts [17]. The main difference was the dynamic constraints for the integration of imperfect forecasts and the modelling of dynamically slow power plants. More on this topic and possible solutions are discussed in the next chapter.

However this problematic directly affects the complexity of the chosen case study, forcing the simulation of a most general case study to evaluate the impact of stochastic deviations, instead of diversifying the different case studies representing countries scenarios and their foreseeable integration of RES. For the purpose and in respect to the time-plan of this thesis, however, the analysis of this general case is more than sufficient to evaluate the approach and the methods used and to cast a first impression of the overall impact of forecast precision on the integration of power plants with power sources with stochastic power in-feed profile.

The case study is then detailed respecting the following assumptions:

- A single bus containing 6 power nodes, presented in Chapter 3,
- An arbitrary peak load of 100 GW,
- A cost vector based on marginal cost models, but developed heuristically so to force a desired strategic behaviour (see in Chapter 4),
- A storage capacity of 10 hours at the rated power of 10% of the peak load.

Different RES integration scenarios are simulated, with wind and solar power capacities varying from 0 GW to 200 GW at a step of 50 GW. The length of the time-series data is chosen to be 180 days, starting from the 1st of February, with a time-step of 15 minutes. In this way it is possible to include winter and summer conditions, as well as the uncertainties of spring
weather. The chosen country is Germany, not only for the availability of the data but also because of the high presence of wind and solar generation, that can be used as comparison to assess the model. The horizon length for the first layer MPC is fixed to be 30 hours, while the horizon considered by the second layer MPC is only of minutes (one step ahead). Another changing factor is the precision of the forecast, that varies from perfect prediction (0% of today RMSE) to the actual forecasting precision (100% of today RMSE) with a 25% step. In this way the effectiveness and the impact of prediction precision can be evaluated together with other more punctual considerations.

The following nomenclature applies for the different cases analysed: for example the situation with 50% wind, 50% solar and 100% of today RMSE will be referred in this thesis as W50-S50-P100.

5.1.1 Dimensioning of the Power Nodes

Table 5.1.1 presents the different numerical values chosen for the constraints presented in Chapter 3. Both the fossil-fuelled base and peak power plants were set at 100 GW. Although this situation is very unlikely to happen in real world operations, it was necessary to quantify the real impact of RES integration. Since the merit-order cost vector is built in order to incentivize the use of wind or solar power, the different case scenario with different degree of RES penetration required that the base power plants could sustain the whole load without other intervention. On the other hand, it could have been possible to limit the fossil fuel peak resources and to compensate for required power by curtailing the load. Since this thesis is mostly interested in the amount of power and energy required for the control operation, and not by the actual consequences in grid reliability, it is easier to keep the fossil
fuel intervention unlimited so that all the tertiary energy requirements can be determined by combining hydro storage and fuel peak power intervention, thus making the interpretation of the results easier and less ambiguous.

Figure 5.1: 4 days results with perfect prediction

Figure 5.2: 4 days results with imperfect prediction
5.2 Results

Diagram 5.1 shows a 4-days snapshot of the typical plot result for a 200% solar and 200% wind penetration grid. The MPC-based optimization used perfect predictions. The load request is reported in the negative half of the y-axis with the grid demand coloured in violet while hydro negative power absorption (through water pumping for storage refilling purpose) is marked in blue. In the positive part of the y-axis the power producers and their participation is plotted: solar and wind are reported respectively in yellow and green, while the base power plants are marked as red and the peak ones in orange.

Comparing Plot 5.1 with Plot 5.2 reveals the work of the second-layer MPC in correcting the grid balance. The many small interventions of fossil fuel-based peak and hydro power plants in substitution to missing or exceeding power from dispatched power plants are essential to meet the load requests.

5.2.1 Model validation and assessment

The tertiary and secondary operating reserves for the year 2011 in Germany were +4606 MW and -4566 MW [20], corresponding to approximately +/- 5.7% of the peak load. As already reported as example in Section 1.2 the RES shares in Germany power production have known a great expansion over the last years, and at the end of 2010 accounted for 35% of the peak load in installed wind capacity and 21% in solar capacity.

Thanks to the results of the simulations W0-S0-P100, W0-S50-P100, W50-S0-P100 and W50-S50-P100 it is possible to approximate the regulating need of the grid by averaging the 50 largest power peaks. Interpolating for the point W35-S21-P100 (representing Germany RES integration as of end 2010) results in about 5% for both positive and negative integrated regulating capacity, also very similar to the real data of 5.7%. The discrepancy of 0.7% is in part the result of the inclusion of the secondary reserves and in part to the simplification adopted into the model. This is by no means an appropriate validation of the grid model and the double layer structure of the MPC controllers. Nevertheless, the numbers are in the same range and demonstrate that the used methodology can be employed in qualitative analysis of scenarios with different RES shares integration, while maintaining realistic outcomes.

5.2.2 Impact over tertiary regulation capacity

Figure 5.3 shows the negative peak control power distribution in % of maximum load power at actual forecast precision for all the simulated scenarios. For negative control requirement, the needed power reaches about 10% if either solar or wind production capacity has 100% or more integration (this
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Figure 5.3: Negative control power distribution with forecast accuracy at today’s error rate, average of the largest 50 peaks occurred in the analysed scenario.

For positive control power the peak is slightly higher, reaching 15%. This is due because the term “control power” refers only to hydro storage and fossil fuel peak power plants.

The color-scale of these plots is not an absolute reference: the lowest limit is coloured in blue (usually at 0 of the z-axis), while the maximum value shown on the z-axis corresponds to red. If two or more plots of one result exist for different combination of wind and PV in-feed, then only one color-scale (and therefore the same z-axis extension) is used for all the plots.

The curtailment of wind and solar production, although a powerful option for controlling the grid in case of impossibility to absorb all the energy produced, is not included in this definition. The main reason is that this thesis aims to evaluate the impact on the infrastructure outside wind and solar plants capabilities. In this case the results conclude that the major impact on the regulatory aspect of the grid is on the positive control power requirement (i.e., the demand load is higher than the production and power reserves must be deployed in order to keep the power balance). Excessive power production has the advantage that can always be curtailed (and thus avoiding the deployment of negative control power reserves), although of course this is not a desirable course of action.

The power magnitude frequency follows a normal distribution and shows (Plot 5.4) that the largest deviations occur only rarely: if the limit is set around 8 MW of deviation (also 8% of maximum peak load), larger events only occur for slightly more than 100 hours per year, up to almost 20 MW of required positive balancing power. This interesting result can be linked to the observations analysed in the literature overview (Section 1.4.2) and it raises the question if load management capability could really represent the most economic and effective solution for these sparse events.
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Figure 5.4: Positive/negative control power deployment during the simulation window, redistributed in descending order. Single scenario with 100% of load’s total power for both wind and solar in-feeds at today’s forecast accuracy.

5.2.3 Impact over tertiary regulation energy reserves

Another interesting consideration can be made over the total energy out-of-schedule compared to different RES shares integration and forecast precision. Analysing both the results for wind and solar it is possible to notice that for low integration (0-100%) the impact is approximately the same, while for larger power integration the required energy for solar remains stable. This is not the case for wind generation, where the total regulation energy needs never stops growing (Figures 5.5 and 5.6). The cause for this difference

Figure 5.5: Total percent of out-of-schedule energy over total load energy for the case with solar generation only.
lies in the day-night pattern of solar generation: while with integration of less than 100% of power production the uncertainty affects all the sunlight hours of the day, with more than 100% the solar panels can produce surplus energy almost every day and only negative regulation is needed, obtained by curtailment or storage filling. The significance of this consideration is that the necessity of regulating power decreases with large shares of RES. Of course the problem shifts then in the realm of economic feasibility: if not enough storage capacity is provided, the marginal cost of curtailed energy will make such large penetration not financially feasible.

On the other hand, while high concentration of solar power presents less out-of-schedule control energy, is it true that advancement in solar forecast technology are only useful for small shares: this fact, united with the existing benefit from aggregation of a large distribution of solar power plants makes the pursuing of new and better solar forecast methods less worthy than for wind forecast.

The presence of wind throughout the day and the great impact for large aggregation of wind production suggests a concentration of efforts in wind modelling and forecast methodology, instead of the solar one. This last one, even if more important, it remains manageable most of the time.

5.2.4 Impact over storage cycles and losses

One last interesting consideration is the impact on storage cycles and losses. The use of hydroelectric storage as control power increases regime switching (i.e. changing from charging to discharging) proportionally to the increase of the technology utilization. Analysing the numbers from Figures 5.7 and 5.8, and considering the perfect prediction scenario, it is possible to note
that with up to 200% of wind power (no solar), the regime switches are a little less than 5 per week. On the other hand, with 200% of solar and no wind generation, and still with perfect prediction, the regime switches average to almost 10 per week, doubling the numbers of the wind only generation. This is probably a consequence of the daily pattern of solar in-feed, that helps maximising the usage of storage possibilities. Wind generation, even at 200%, can incur in long period of time of low production, resulting in a difficult management of the stored energy. In addition to this effect there could be long periods of high production that could fill the storage and keep sustaining the demand without regulating plant (since is a perfect prediction scenario). The regularity of the "on/off" generation of solar technology always allows opportunities to fill or empty the storage basins.

The forecast precision plays in this case a decisive role in differentiating
the two technologies: with a forecast at today’s precision, wind generation results in a bigger number of regime switches: up to 20 per week, against the 14 of PV in-feed. The explanation is fairly simple: bad forecasts yield as consequence a larger usage of regulation energy. The absence of a relevant deterministic pattern in wind generation requires a 24-hours presence of control systems (whereas at night in solar only power systems is not necessary). This increases the intervention of the hydroelectric compensation. The same is not true for solar: the precision seems not to have a particular influence on the regime switches. As already stated in section 5.2.3 solar generation with more than 100% cause an impact on the control systems only at the beginning or at the end of the day.

These considerations find confirmation in the total lost energy during pump/-
generation cycles of the hydroelectric units, as shown in Figures 5.9 and 5.10. Solar seems again to be unaffected by the forecast precision, but it reaches an higher value than wind, that seem to cause less losses, even with bad forecasts. This may seem in contradiction with the number of regime switches, since those are higher for wind generation only. The difference is in the quantity of energy transmitted during the regime switches: the daily pattern of solar generation allows a large transfer of energy, emptying the basins at night and charging them full during the day. On the other hand wind generation may never reach full depletion or replenishment of the storage basins: the consequence is less energy lost, but united to an inefficient use of the storage capabilities of the power systems.
Chapter 6

Conclusion and outlook

6.1 Conclusion

In this final chapter the most interesting aspects of this thesis are resumed and discussed. The main goal of this thesis is the investigation of forecast accuracy and its impact on power system with high shares of renewable energy sources. To achieve this a model of a simplified power system is obtained using the Power Node framework in which the coexistence of the different power plants technologies is simulated via a cascading MPC approach. This methodology has proven itself as numerically solid and has realistic outputs, for instance if compared with Germany’s production and its tertiary power reserves. This simulation needed specific forecast generator tools in order to use the model predictive control strategy in the most realistic way. In many studies (e.g. [21]) the forecast accuracy for wind is just simulated through the variation of the RMSE for each forecast step: while in the average the results are correct, the resulting forecast profile is an extreme and not very realistic tooth-sawed curve. The solution proposed and developed for this thesis has the advantage to combine a variable RMSE with a realistic profile of the forecast curve (as seen on Plot 2.7). The control structure vector of the first layer MPC has therefore acted on realistic forecast vectors and its strategic choices yielded plausible behaviour, enhancing the correctness of the outputs of the simulation.

The major problem encountered during the development of this thesis was the implementation of the forecast as constraints in the Yalmip overhead. The generation of new forecasts for every step of the first layer MPC required the not-liner modification of the constraints (also of the $\xi_{i,n}$ values). The simulation for 180 days, 15 min step and with an horizon of 30 hours required approximately 10 hours to solve on a shared server. The implementation of the parallel computing option, with the contemporary execution of up to 5 jobs de-facto reduced the total computational time to a fifth. The origin of this problematic could probably be found in the implementation,
meaning that an alternative approach to the management of the constraints could result in an implicit treatment in Yalmip (thanks to the 'controller’ operator: see Yalmip documentation for more informations [19]), resulting in a simulation time of few minutes instead of hours. Unfortunately the recognition of this limit in the chosen implementation was discovered too late, when the results were already obtained. However, it could be of stimulus for future investigations.

The obtainable results with the analysed case study are numerous and with different importance. At first the impact of forecast accuracy on the average out-of-schedule required power is investigated. The results confirm the impression that only a small percentage of wrong forecasts have a dramatic impact on the regulating power, and that these events always happen, even with accurate and precise forecasts. The best possible solution, instead of increase control power capacity with reserves that would be rarely used, is the implementation of a load curtailment option that could supply the required power adaptation at a smaller investment cost. Good targets for this policy could be the interruption of electric car charging or the remote controlling of heating systems (as already explored in [17]).

Two other very interesting results regard the impact on the control energy reserves and the regime switching of the storage facilities. In this case the impact of forecast accuracy is diametrically opposite: while it helps reducing the energy used in regulating grid with high shares of wind energy, it has almost no impact in reducing regime switches of storage systems with solar generation only. Different is the discourse for wind generation, that always benefits of improvements in forecast accuracy.

But the very interesting consideration is that large shares of RES (more than 100%) needs less control energy because of the curtailment options: if during the day the load demand is constantly covered by RES, than the regulation is easily achieved with the curtailment of exceeding energy. In other words, large shares of RES can cause high stochastic fluctuation at today’s degree of accuracy, but on the other hand are easily manageable since potential in-feed energy surpluses can be directly curtailed. This obvious conclusion has no practical consequences, since high shares of RES do not necessarily mean a larger contribution to the total energy consumed in the grid: as explained in [17] and confirmed by this thesis, the percent of renewable energy tends to stabilize around 70-80% of the total needed energy, and this already with a grid composed by solar and wind power at 50% of the total load. But with this kind of penetration (both around 50% - 75%) the impact of forecast accuracy is not negligible, since there is no curtailment option as in the occasion of a superabundance of solar and wind power generation. It is therefore necessary to investigate the perfect equilibrium point between superabundance of RES energy (with the consequent reduction in regulation capacity) and storage management to avoid curtailment as much as possible.
Finally, a couple of words should be said on the intrinsic nature of both the investigated technologies. After the results of this thesis, solar technology results more reliable and apt to large penetration shares. The night/day pattern gives this kind of production a deterministic component that on the overall reduces the impact of wrong forecasts and the need for regulating capacity. Another advantage is that the aggregation effects greatly improve the production prediction making this technology a good candidate for larger distribution shares. For all these aspects, if the geographical and meteorological conditions of one country allows it, the development of solar production plants should be prioritised, since wind presents the larger hidden cost in terms of investments in control facilities and forecast modelling.

6.2 Outlook

The conclusions quoted above raise the following question: if the integrated renewable energy quote stops with a penetration of 75% of the peak power load, what are the best solutions to regulate and control the power system? Is it the enlargement of operating reserves followed by a load-side control capability? Or maybe the most economical solution is the expansion of RES units to more than 100% load, ensuring higher versatility and reliability of the power grid together with reduced control needs? These questions could be the topic of future work in the institute, exploring in further details the financial and economical impacts of solutions for these high shares of RES. The proposed thesis and tools make a solid point of start for the modelling of power grid under the influence of different degree of forecast precision, although the code and Yalmip implementation proposed here could be extended and a solution for reducing the still large computational effort should also be investigated.
Appendix A

Forecast Tools

A.1 Wind forecasts

Both forecasts tools have similar structure. They are programmed as m-function in MATLAB:

```matlab
%Wind forecast generator:
forecast = forecast_tool_wind(wind_coming,
wc_step,
nominal_power,
precision_degree)
```

Where the inputs and the output comprehend:

- `wind_coming` is the vector containing the effective production data for the investigated region/country.

- `wc_step` is the time-step of vector `wind_coming`, expressed in hour. In this case is equal to 0.25.

- `nominal_power` is the peak power of the wind production units. Necessary to understand if `wind_coming` is in the high- or low-regime production and to calculate the RMSE.

- `precision_degree`
is a number between $0...+\infty$, with 0 being a perfect forecast and “1” a forecast with the degree of accuracy as of 2010. For example $\text{precision\_degree} = 0.5$ will generate a forecast with half RMSE as forecasts generated in 2010. In the same way $\text{precision\_degree} = 2$ will generate a forecast with double RMSE as forecasts generated in 2010.

\text{forecast}

is a vector of the same size of \textit{wind\_coming} and containing the forecasted wind generation for the given period and precision degree.

### A.2 Solar forecasts

The tool for PV in-feed forecasts is called using:

```
% Solar forecast generator:
forecast = forecast_tool_solar(solar\_coming, sc\_step, nominal\_power, precision\_degree)
```

The inputs and output descriptions match exactly the ones of the wind forecast tool listed above.
Appendix B

Power Node model and implementation

B.1 Organization and structure

The structure is fairly simple: the launcher file allows to specify the most important parameters of the simulation. After these declarations, five different external function are called to complete the simulation. They are named:

- `create_folder`
- `import_profiles`
- `power_node_preparation`
- `model_construction`
- `power_node_simulation`

The Power Node model and simulation specifications are stored into the `Params` struct variable. This variable is cycled through the different steps of the modelling process, causing modification to the original structure, adding ramification and complexity. The analysis of the `Params` structure can be used to better explain the characteristics of the different functions:

```plaintext
% LAUNCHER: USER-DEFINED PART OF LAUNCHER FILE
%special continued
%Creation of Params struct, user-defined specifications:

% - Params.Sim (storing of information about the simulation: name, scenario, etc)
% - Params.Solver (specification for the solver, in this case CPLEX)
% - Params.TimeFrame (temporal specification: time-length,
```
APPENDIX B. POWER NODE MODEL AND IMPLEMENTATION

% time-step, first-layer MPC interval, etc)
% - Params.PowerNode (dimensioning of Power Nodes)

%END OF USER-DEFINED PART OF LAUNCHER FILE

%The following functions are then called:

Params = create_folder(Params);
Params.Profiles = import_profiles(Params);
Params.PowerNode = power_node_preparation(Params);
Params.Model = model_construction(Params);
Results = power_node_simulation(Params);

%END OF LAUNCHER FILE: Results and Params structs are saved in the
%right path. Evtl: plot of some results.

B.2 \textit{Params} variable description

- \textit{Params.Sim}
  - \textit{CreationFolder} Boolean variable to activate the creation of a
    new folder to store the results.
  - \textit{Stochastic} Boolean variable to activate the stochastic modus (vs
    a perfect forecast modus). Using stochastic modus with 0 RMSE
    as stochastic precision yields the same results as switching this
    variable off.
  - \textit{DirSaveRoot} Directory of the root folder where for every sce-
    nario a new folder is created.
  - \textit{Name} Specify the scenario and the folder name.
  - \textit{MkDirError} Boolean flag indicating error in creating a folder.
  - \textit{SaveFolderName} Complete name of results file.
  - \textit{DirSave} Complete path including file name.

- \textit{Params.Solver}
  - \textit{options} standard \textit{options struct} as generated by the command
    \textit{sdpsettings}.

- \textit{Params.TimeFrame}
  - \textit{StartDay} Starting day of the simulation (template ‘dd.mm.yyyy’).
  - \textit{NumberDays} Length of the simulation in days.
  - \textit{Step} Size of the time step of profile data in hour (e.g. 15 minutes
    = 0.25 h).
APPENDIX B. POWER NODE MODEL AND IMPLEMENTATION

- `.HoursHor` Length of MPC optimization horizon in hours.
- `.CallOpt` Calling step of the first-layer MPC (usually 1 hour).

- **`Params.Profiles`**
  - `.FcRange` Forecast range. Necessary because data profiles must be as long as `Params.TimeFrame.NumberDays + FcRange`.
  - `.TimeVector` Time vector (unit: days) used to plot data profiles.
  - `.Load` Load data profiles, e.g. EEX data.
  - `.Solar` PV in-feed data profiles, e.g. EEX data.
  - `.Wind` Wind power data profiles, e.g. EEX data.

- **`Params.PowerNode`**
  - To many objects to list: This struct contains all the different Power Nodes generated by this simulation. It includes equations and constrains as detailed in Chapter 3.

- **`Params.Model`**
  - To many objects to list: It contains all the algebraical aspects of the two MPC: cost matrix, signs matrix and so on.

### B.3 External functions description

- `create_folder`
  Function that using the user provided information (root directory, scenario, etc) creates the appropriate directory to store the results.

- `import_profiles`
  This function simply converts EEX data in usable vector for the simulation. If other data-set are used, it is necessary to develop and implement a new function that build the same data vector as this one.

- `power_node_preparation`
  It prepares equations and constraints of the Power Nodes using the informations provided by the user in the first half of the launcher file.

- `model_construction`
  Creates all the algebraic component of an MPC: cost matrix, signs vector, etc.

- `power_node_simulation`
  It runs the yalmip implementation of the MPC problem, solving it with the specified solver. It returns the `Results` struct, containing the input and state vectors $u$ and $x$. 
Bibliography


