New stochastic methodology for the estimation of the Wind Power impact on the Belgian High Voltage grid

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Abstract

The aim of the proposed stochastic methodology is to study and analyze the response of the Belgian HV-grid to the injection of a high wind power input. Factors such as the season of the year, the time of day, the installed power or the geographical spread of wind turbines are studied as well as the way they influence the power output and how to handle this behaviour for the benefit of the grid. The power flows in every line, the possible overloads, the most critical cases were reflected, and corresponding conclusions are drawn.

Keywords: Wind Power, Overloads, Grid Stability, Methodology.

1 Introduction

The introduction of wind power entails relevant questions such as the (re)distribution of the power flow over the existing grid, the control of the reactive power in the wind farms or the availability of the wind power production. In order to find out the optimal way to introduce more wind power into the Belgian grid, certain aspects of the grid operation must be analyzed.

More productive wind turbine technologies have been designed. More accurate and powerful tools for weather forecast are being developed. More efficient maintenance systems are being studied. New wind farms are planned. To know in advance the future behaviour of the wind park and the grid, as well as the response of the power lines becomes a key need now.

The aim of this methodology is to study and analyze the response of the Belgian grid to the injection of an increased level of wind power input. Based on wind measurement data from various sites in Belgium, factors such as the season of the year, the time of day, the installed power or the geographical spread of wind turbines

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are studied as well as the way they influence the power output and how to handle this behaviour in the grid benefit. The power flows in every line, the possible overloads, the most critical cases were reflected, and the corresponding conclusions are drawn.

It can be found that 56% of high loadings appear in power lines with less than or equal to 70 kV, while 13% appear in 150 kV lines, 6% in 230 kV lines and 25% in 400 kV lines. Most of the lines that should be reinforced are not the highest-level power lines, although some of the heavier lines (400 kV) should be reinforced as well. In a layout which takes into account the windiest sites in Belgium as well as the offshore wind power, the values for mean wind inputs reveal an assured and safe production, as they do not reach a maximum. This layout represents a good resume of the actual scene and seems to be the best solution for the Belgian grid.

The drawn conclusions involve the guidelines for an optimal introduction of wind power in Belgium.

2 Simulation parameters

In order to analyze the impact of additional wind power on the grid, some basic parameters are needed. One change in one parameter selected will lead to a different behaviour of the whole system. A study of the sensitivity of the results for some parameters is one of the aims of this research. Information can be extracted about which states of the system are most interesting, most productive or even most dangerous.

2.1 Seasonal variation of wind power production

The experience with analysis of wind speed data reflects that there is a clear seasonal periodicity in the wind behaviour. As a consequence, a long-term variable wind power production is obtained. Measures of wind speed were taken in the three different periods of the year: spring / autumn, summer and winter. In autumn and spring the wind speeds and gusts are very similar, from now on both seasons will be considered together. According to the measured wind speeds, the highest values can be found in the winter and the lowest values during the summer.

Electricity consumption is generally higher in winter than in summer (although consumption in summer is increasing due to the increased use of air conditioning and cooling systems). As also noticed by the Danish Wind Industry Association [1], wind power matches this seasonal variation of consumption, providing more power in winter and autumn than in summer and spring.

2.2 Diurnal variation of wind power production

There are many factors that influence wind behaviour, some of them being the land profile, the proximity of the sea, the height of the site, and the atmospheric conditions. One of these atmospheric conditions is the sunshine. The heat of the sun makes the warmth change constantly, and this difference in the air temperature changes the density of the air mass, and causes movement, translating into wind speed.

During the day wind has the influence of the sun. The wind starts blowing in the morning usually and will go on normally until the end of the day. The highest wind speeds can be found in the afternoon, and the lowest in the early morning or in the last hours of sun. During the night no influence from the sun is received, the temperatures decrease, be it quite smoothly. The changes in the temperature are very slight and slow. This justifies the winds being calmer and a not so high wind production registered. A very regular pattern is extracted for the wind speeds at night, with lower values than in the daytime.

2.3 Total installed power

The total installed power gives a notion of the amount of wind power available for each simulation. The injected power will be a variable fraction of this total installed power, the variation depending on the influence of the rest of the parameters (e.g. season, time of the day…). The values selected in order to obtain representative and clear results are 100 MW, 200 MW and 300 MW of total installed power across the Belgian grid.

100 MW of total installed power represents a broad outline of the recent state of the Belgian grid. By the end of 2004, 95 MW of wind power were installed in the whole country. By the end of 2010, the Thornton Bank project will have implemented from a minimum of 216 MW to a maximum of 300 MW of offshore wind power [2]. Added to the existing 95 MW, it will come up to a total of 311 MW to 395 MW of installed wind power in Belgium. Therefore, the proposed values for total installed power intend to simulate the progression towards the integration of the project.

2.4 Geographical spread of wind turbines

The geographical spread of wind turbines means the particular layout of the wind turbines all over the country. According to the wind turbines spread, a different state of the grid will result. Some distribution could lead to overloads or grid congestions, so every particular scenario must be analyzed. Many layouts can be designed for each purpose. For this project, the four most representative scenarios are adopted from [3] and showed in *Figure 1*:

Scenario 1 All wind power evenly distributed evenly all over Belgium
Scenario 2 Wind power concentrated onshore in the windiest regions
Scenario 3 Only offshore wind farms, no wind power onshore
Scenario 4 Offshore wind farms and wind power onshore, concentrated in the windiest regions.

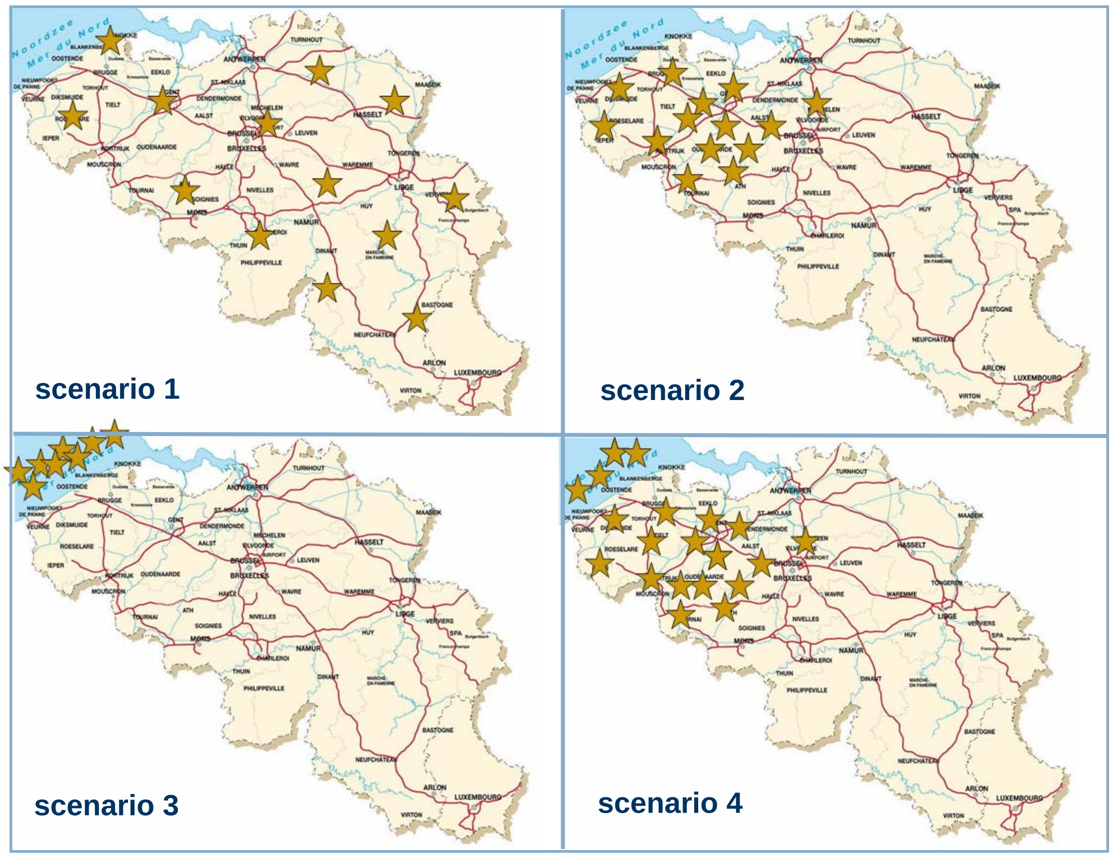

Figure 1. Layout of the different scenarios [3][4].

The **first scenario** is unrealistic, but considered here as the theoretical limit case. The whole wind power production being equally distributed in each point of the grid is unfeasible, as each part of the country has different wind speeds, and therefore, different wind potential. This scenario is interesting in order to analyze the most regular situation of the wind power production, and it is useful to compare this case to the other scenarios.

The **second scenario** concentrates the wind power just onshore and in the windiest regions of Belgium, which are West- and East-Flanders. This situation is more realistic, although it does not take into account the offshore power. It is useful to separately study the onshore case in a rather simplified manner.

The **third scenario** is designed to study the offshore wind power (as the second scenario is just for the onshore wind power), simplified as well. It studies the case as if the only wind power injected was just coming from offshore wind farms.

The **fourth scenario** is the most realistic, although it simplifies the Belgian wind power production to just some offshore wind farms and all the wind power onshore concentrated in the windiest regions. This layout intends to reflect the most logical display of the wind power over the country, and is expected to be a highly productive layout. This scenario is very useful as it shows a simplified version of the expected situation of the Belgian wind power production.

3 Methodology

3.1 Inputs

The variables the algorithm receives in order to obtain the desired results can be listed as follows:

Current simulation parameters	*Grid data*	*Wind data*
Season	Grid areas	Wind power curve
Daytime	Base MVA	Measured wind speeds
Total installed power	Nodes	
Scenario	Power lines	
Number of simulations	Generators	
Fluctuation parameter	Generators' costs	
Other internal options	Total demand	
	Load profile	

Table 1. Algorithm inputs

3.2 Algorithm

The selected parameters (season, daytime, scenario, installed power) will determine some characteristics of the simulations, but some other variables will be derived from the random nature of the wind phenomena that also plays an important role during the process of the data.

The algorithm studies a given distribution of wind speeds and, by following the model of Markov chains, obtains a particular generated series of wind speeds [5]. The introduction of a Markov model gives the random character to the simulation, resulting in a different series of wind speeds every time. Then it calculates the transformation of the wind speeds into wind power by means of a multi-turbine power curve [6]. With the injected power in each specific node, the power flows all over the Belgian grid are calculated. The results are the loadings of every power line in time.

The proposed algorithm involves these initial data (inputs) and by means of mathematical calculations, returns the final results (outputs). The software tool used was Matlab, for its relative simplicity and the possibility of getting advantage of Matpower [7], a useful tool to calculate power flows in the grid.

3.3 Outputs

The main outputs that the algorithm returns are listed as follows:

Current simulation parameters	*Grid data*	*Wind data*
Markov matrix	Nodes state	Power from the wind
Output from the multi-turbine curve	Power lines loading	Generated wind speeds
Total power output	Injected power	Wind mean speeds
Other internal results		Wind standard deviation

Table 2. Algorithm outputs

3.4 Structure of the algorithm

The steps that the algorithm follows and the way the data interact in order to achieve the final power flows in the grid, as well as the inputs and outputs of the program are shown in *Figure 1*. The most interesting variable in order to analyze the grid behaviour is active power flow. The study of reactive power, node voltage and some other phenomena related to AC power flows is not useful for this project and only DC load flow will be taken into account.

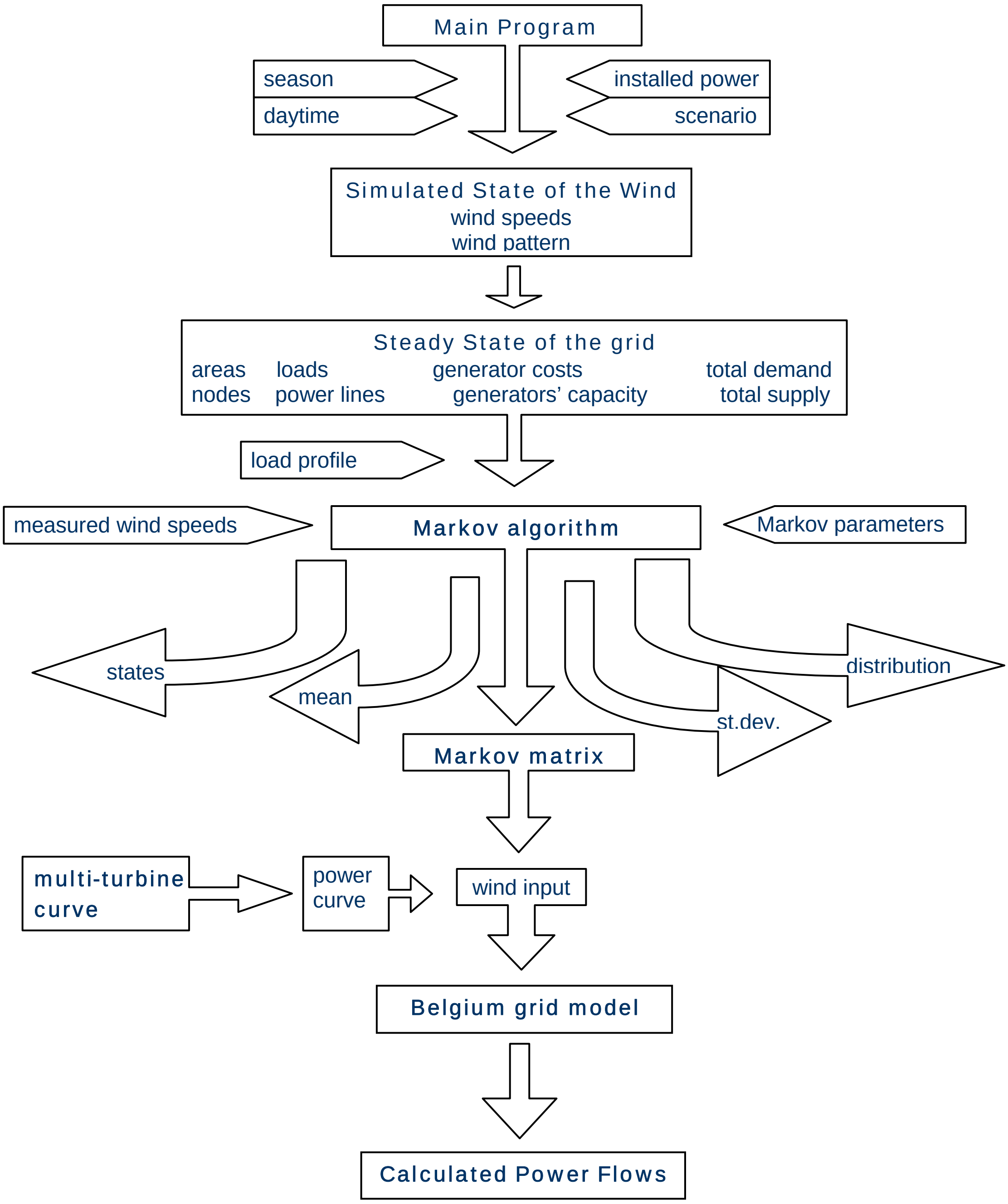

Figure 2. Structure of the algorithm

4 Results

The proposed algorithm returns the power flows in the lines of the Belgian grid in time for each simulation. This results in the analysis of a large amount of data. In order to obtain useful and clear results, some aspects are studied separately:

- Mean wind inputs in the Belgian wind park simulated
- Highest loadings in the power lines according to each parameter
- Most affected power lines (weakest lines of the grid)

4.1 Mean wind inputs in the grid

The mean wind input is used to represent the amount of wind power that is injected in every case. Minimum and maximum wind speeds are useful for the study of the turbines' specific restrictions, but the mean wind input is more useful to compare the different steady states of the grid for each case, from a static perspective of the grid. Dynamic behaviour is out of the scope in this study.

The mean wind input is related to the mean active power produced by the Belgian wind park that is injected into the grid. This is the importance of wind input.. As a representative example, the mean wind inputs for scenario 3 with respect to the rest of parameters are shown in *Table 3*.

	Autumn / Spring		**Summer**		**Winter**	
	Day	Night	Day	Night	Day	Night
100 MW	34,70MW	34,63 MW	35,79 MW	37,76 MW	32,70 MW	30,84 MW
200 MW	71,58 MW	75,51 MW	71,78 MW	66,08 MW	65,61 MW	66,67 MW
300 MW	107,67 MW	108,19 MW	103,89 MW	102,56 MW	106,70 MW	100,76 MW

Table 3. Mean wind inputs for scenario 3

4.2 Highest loadings in the power lines

Taking into account the rated power for every single power line and the highest loading observed for that line, a percentage of maximal loading is obtained for every single line. This means the higher loading a power line can reach by the injection of wind power, according to its rated power. As an example, *Table 4* shows the highest loading percentages in the grid in the season of autumn / spring, as well as characteristics of those power lines where the highest loading was found (name of the nodes that the line connects and type of line defined by its voltage). The results are sorted by the rest of the parameters: daytime, installed power and scenario for an easier comparison of the obtained values.

	Day			Night		
	100 MW					
Scenario 1	Tongeren - Voroux	70 kV	103,25%	Heimolen - Rodenhuize	150 kV	79,34%
Scenario 2	Tongeren - Voroux	70 kV	103,27%	Heimolen - Rodenhuize	150 kV	79;50%
Scenario 3	Tongeren - Voroux	70 kV	103,26%	Heimolen - Rodenhuize	150 kV	79,57%
Scenario 4	Tongeren - Voroux	70 kV	103,26%	Heimolen - Rodenhuize	150 kV	79,51%
	200 MW					
Scenario 1	Tongeren - Voroux	70 kV	103,20%	Heimolen - Rodenhuize	150 kV	79,31%
Scenario 2	Tongeren - Voroux	70 kV	103,24%	Heimolen - Rodenhuize	150 kV	79,64%
Scenario 3	Tongeren - Voroux	70 kV	103,17%	Heimolen - Rodenhuize	150 kV	79,97%
Scenario 4	Tongeren - Voroux	70 kV	103,24%	Heimolen - Rodenhuize	150 kV	79,76%
	300 MW					
Scenario 1	Tongeren - Voroux	70 kV	103,17%	Heimolen - Rodenhuize	150 kV	79,31%
Scenario 2	Tongeren - Voroux	70 kV	103,24%	Heimolen - Rodenhuize	150 kV	79,75%
Scenario 3	Tongeren - Voroux	70 kV	103,25%	Heimolen - Rodenhuize	150 kV	79,69%
Scenario 4	Tongeren - Voroux	70 kV	103,20%	Heimolen - Rodenhuize	150 kV	79,88%

Table 4. Highest loadings in the season of autumn / spring

4.3 Critical power lines

In order to find the most affected power lines, a comparison is made between the loading of each line with and without the injection of the generated wind input. The reason is that only by showing the total loading of the lines after the injection of wind power does not give a comparative result, due to the different rating of each type of power line. In that case the weakness of the lines showed could be just caused by the own characteristics of the grid, and not just by the wind power injected. Therefore, the study of the increase in the loading is useful to find the critical power lines in the grid.

Table 5 reflects the increase in the power flow for the most affected lines in the case of scenario 3, according to the rest of parameters.

Scenario 3		
Power line	Rated voltage	Power flow addition
Beveren - Koksijde	150 kV	79,11 MW
Gramme - StAmand	400 kV	67,70 MW
Mercator - Rodenhuize	400 kV	63,24 MW
Brugge - EekloNoord	150 kV	59,78 MW
EekloNoord - EekloNoord	150 kV	59,61 MW
EekloNoord - Zomergem	400 kV	59,61 MW
EekloNoord - Maldegem	150 kV	58,32 MW
Herderen - Zutendaal	400 kV	56,78 MW
Courcelles - StAmand	400 kV	55,83 MW
Gramme - Hermalle	400 kV	53,17 MW
Hermalle - Herderen	400 kV	53,17 MW
BlauweToren - Zeebrugge	150 kV	50,48 MW

Table 5. Most affected power lines in the case of scenario 3

5 Conclusions

5.1 Mean wind inputs in the grid

According to the obtained values of mean wind input, it can be extracted that the mean wind input never gets to reach the total installed power. As an example, the mean wind input, calculated for scenario 3, represents around 35% of the total installed power**.** This fact can be explained by two main reasons, one of them being the impossibility of having the maximum wind speed allowed for each turbine blowing in every single point of the country. The second reason is the use of the multi-turbine curve approach [6], which reflects the behaviour of a group of wind turbines in the same area. A multi-turbine curve presents a more limited range of wind speeds providing the rated power, as it is shown in *Figure 3* [6].

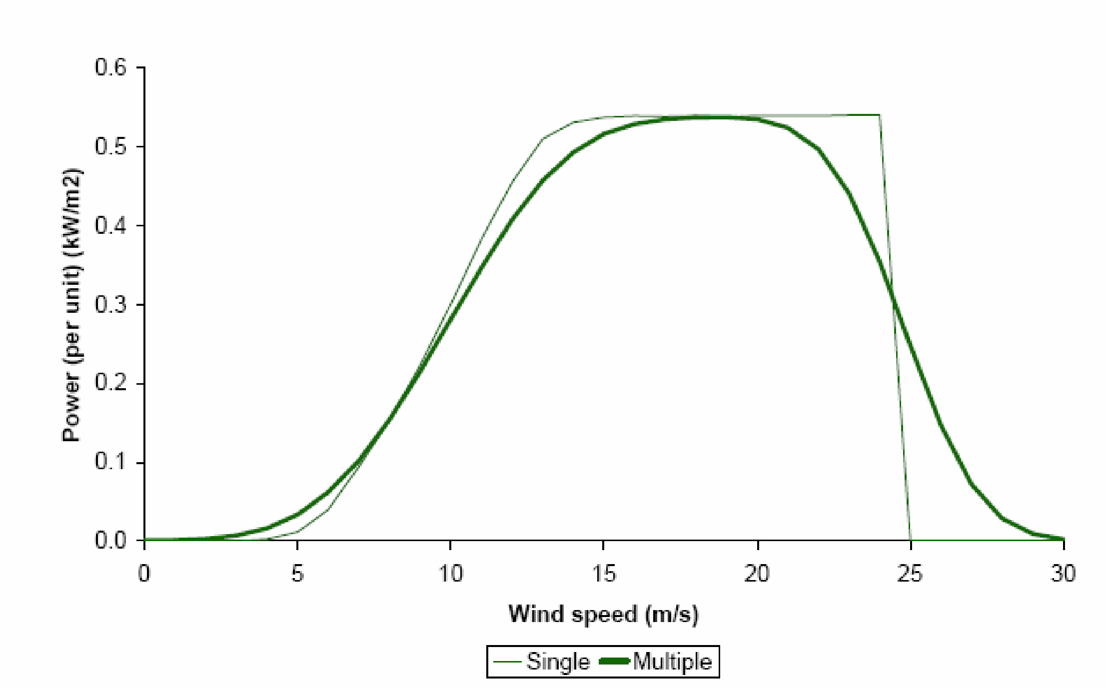

Figure 3. Single and Multi-turbine power curve.

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The highest mean wind inputs are found for the season of autumn / spring, being the following values for the seasons of winter and summer. In autumn, winds are usually strong and regular, while in the winter, winds tend to be irregular, strong gusts can be found combined with periods of no wind. In summer, winds tend to blow slower and longer periods with no wind at all are found.

5.2 Highest loadings in the power lines

As it was mentioned above, some power lines present the same loading percentage for the different amounts of installed power simulated. The loading is high in every case, but the same value for 100 MW, 200 MW and 300 MW. This fact reflects that the loading of these lines is not affected by the amount of installed wind power. The listed lines are just weak parts of the grid that should be reinforced in any case.

56% of high loadings appear in power lines with less than or equal to 70 kV, while 13% appear in 150 kV lines, 6% in 230 kV lines and 25% in 400 kV lines. Most of the lines that should be reinforced are not the highest-level power lines, although some of the major lines (400 kV) should be reinforced as well.

According to the seasonal parameter, In the seasons of autumn and spring, the heaviest loaded lines are Tongeren – Voroux, with an **overload** of 103% and Heimolen – Rodenhuize, which is not overloaded, but presents a load of 79% constantly. In the summer no overloads are found**.**

According to the diurnal parameter, the lines reach a more severe load during the day than during the night, as it was expected, due to the diurnal periodicity of the wind and the influence of the increase of the demand during the day.

5.3 Critical power lines

The obtained loading values show always the same group of power lines presenting a higher loading. In *Table 6* these lines prone to the highest loadings are listed, as well as their rated voltage:

Line	*Rated voltage*
Herderen – Zutendaal	400 kV
Zutendaal – Maasbracht	400 kV
Hermalle - Herderen	400 kV
Gramme - Hermalle	400 kV
Marcourt - Rimiere	230 kV
Heimolen - Rodenhuize	150 kV
Massenhoven - Meerhout	150 kV
Herbaimont - Villeroux	70 kV
Aubange - Moustier	70 kV
Aubange - Villeroux	70 kV
Tongeren - VorouxLezLiers	70 kV
Marcourt - Villeroux	70 kV
BoisdeVillers - Yvoir	70 kV
Dorinne - Yvoir	70 kV
Forrieres SNCB - Herbaimont	70 kV
Aubange - Heinsch	70 kV

Table 6. Highest loading power lines sorted by rated voltage

The highest effect of wind power injection is found in the line of Beveren – Koksijde. The power flow varies almost 80 MW in this power line when comparing scenario 3 with a situation with no wind power injected. A layout of the most affected lines is presented over a simplified map of the Belgian power grid in *Figure 4*.

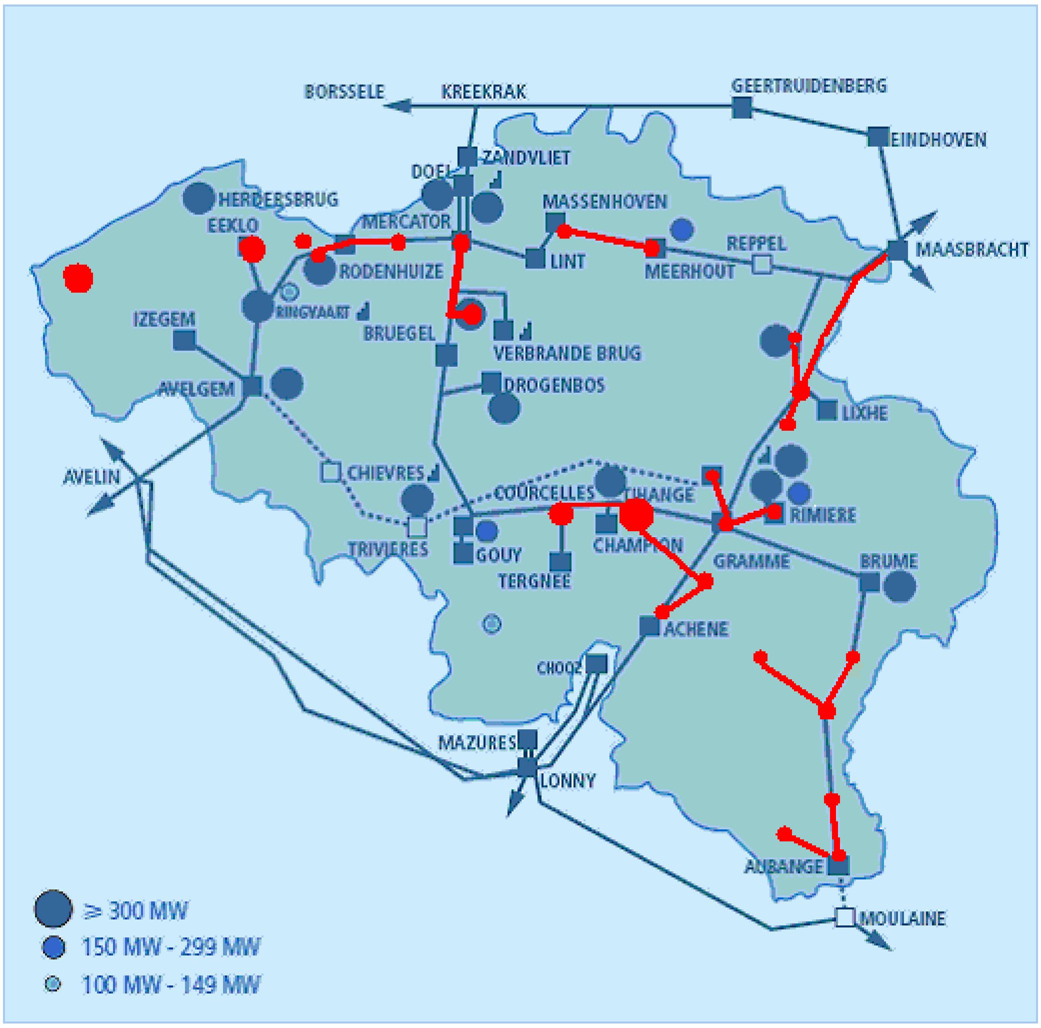

Figure 4. Critical nodes and power lines obtained for the Belgian high voltage grid.

For **scenario 1**, only two power lines achieve a high power flow increasing, This is explained by scenario 1 being the most regular layout, the injection of wind power according to this layout causes the lowest power flow increase in the lines. The power input is equally distributed all over the grid. The highest increase is almost 69 MW for the line Gramme – St Amand.

For **scenario 2**, a higher number of lines spread all over the country become affected. This scenario represents the wind power concentrated in the onshore windiest sites of Belgium. This layout is less spread than scenario 1 and therefore causes higher number of higher loads all over the country, as expected. Even though, increasing the number of power lines affected, does not entail the increasing of the amount of power. As an example, the highest increase is 67 MW in the line Gramme – St Amand.

For **scenario 3**, a higher number of lines are affected, besides the lines showed for scenario 2. Scenario 3 presents all the wind power injected in the offshore wind farms. This results in a high loading in the lines that connect the offshore wind power with the grid. Indeed, these results confirm the expectations, as all the affected power lines involve nodes highly connected to the offshore wind power. The highest value is an increase of 79 MW for Beveren – Koksijde power line. In order to easily locate the nodes on the map, *Figure 5* shows the location of some of these affected sites next to the coast line.

Figure 5. Location of some of the affected nodes (underlined).

For **scenario 4**, the affected lines are the same as for scenario 2, and the increases are similar, although higher for scenario 4. The reason is that scenario 4 reflects all the wind power injected in the windiest sites of Belgium and in the offshore wind farms. This layout is quite similar to scenario 2 as the number of offshore sites is low. The highest increase appears in the line of Gramme – St Amand with almost 68 MW.

From the obtained results can be extracted that in the ideal scenario with an even distribution of wind power, less overloads occur in the power lines, even though, the wind input is also lower, and so is the power output. With scenarios concentrated in the windiest sites the wind input is much higher, and so is the power output, with the drawback of the capacity of the existing power lines, which should be undoubtedly reinforced in case of a planned increase in the Belgian wind park. This paper presented a methodology to systematically study these effects.

6 References

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