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Integration of Wind Power in the Power System

PhD dissertation thesis booklet

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1 Introduction

The electric power industry is currently experiencing one of the largest transformations of its history. The structure and operational practices that have evolved over several decades are facing new challenges to meet. These expectations are multiple; the penetration of distributed generation, the ever stronger support of renewable energy sources and the dramatically accelerated development of communication technologies all contribute to the development of smart grids.

My work, presented in my PhD dissertation, represents only a small part of this very diverse and multidisciplinary scientific field. However, the integration of wind power has brought unprecedented challenges to the electric power industry, for which finding the solution has become a priority over the years. My research and publications, the results of which are summarized in this dissertation, are my contribution to this work.

2 Examination of the ramping events of wind power plants

In chapter 3 of my dissertation, examinations of the ramping events of wind power plants are presented. The presentation of the different definitions of ramping events is followed by the review of the literature related to the forecasting of such events. Typical forecasting methods and their potential errors are presented. I summarized the results of the international research that focuses on the effects on gradient capabilities of the power system caused by the increasing share of wind power. I emphasized those papers that are connected to my research the most; those that intend to use energy storage to maintain the gradient capabilities of the power system.

The production gradient of Hungarian wind power plants was examined using 1-minute data, while resizing the total installed wind capacity to different values. The resulting amount of control reserves was compared to the actual gradient capability of the Hungarian power system in the same period. The results clearly showed that significant deployment of new control reserve options is necessary in case that the amount of installed wind capacity is to increase.

The production gradient of wind power plants was examined using two different methods. The statistical analysis ignores the time data of the input, in contrast to the self-made computer simulation tool, where it is a priority. Both methods use the same input data: production of wind power plants and the downward and upward gradient control capability of the examined power system, but they are only suitable for examination after multistage processing.

The first step of this process is the calculation of the gradient values of wind power production ((2-1)), which are calculated as the difference of consecutive production values. The second step is to resize these gradient values, using the installed wind capacity at the time the data was recorded and the installed wind capacity we would like to examine. ((2-2))

(2-1)

$$IF\ \nexists\ P_{production_i} \rightarrow P_{wind\ gradient_i} = FALSE$$
$$IF\ \exists\ P_{production_i} \rightarrow P_{wind\ gradient_i} = P_{production_i} - P_{production_{i-1}}$$

(2-2)

$$IF\ P_{wind\ gradient_i} = FALSE \rightarrow P_{ex.wind\ gradient_i} = FALSE$$
$$IF\ P_{wind\ gradient_i} \neq FALSE \rightarrow P_{ex.wind\ gradient_i} = P_{wind\ gradient_i} \cdot \frac{P_{ex.nominal}}{P_{nominal}}$$

The gradient capability of the power system itself is usually not available – in this case it is calculated using the difference of the system load and the minimal and maximal values of available spinning reserves, divided by the selected time scale ((2-3)).

$$IF \nexists\ P_{spinning\ reserve_i} \rightarrow P_{control\ gradient_i} = FALSE$$

(2-3)

$$IF \exists\ P_{spinning\ reserve_i} \begin{cases} IF \nexists\ P_{system\ load_i} \rightarrow P_{control\ gradient_i} = FALSE \\ IF \exists\ P_{system\ load_i} \rightarrow P_{down.contr.gradient_i} = \dfrac{P_{system\ load_i} - P_{down.contr.reserve_i}}{15} \\ IF \exists\ P_{system\ load_i} \rightarrow P_{up.contr.gradient_i} = \dfrac{P_{up.contr.reserve_i} - P_{system\ load_i}}{15} \end{cases}$$

After the completion of (2-1), (2-2) and (2-3), rescaled wind power gradient and control gradient data are available, and may be used in the last step of the procession, when the so-called corrected wind power gradient values are calculated. The interpretation is illustrated by the example of downward gradient needs.

From the viewpoint of power system operation, the best case would be if production of wind power plants would be constant in time – similar to traditional power plant units. In reality this is not the case, of course, in some cases, for example, wind power production increases between two sample points so downward control is needed (assuming that the system load remains unchanged). The power system may handle this situation in three ways. If the downward gradient capability of the power system is greater than the demand of the wind power plant, operation of the energy storage is not necessary. If the demand exceeds the capabilities of the system, the energy storage shall help the system with power equal to the difference, so from the perspective of the energy storage, the production gradient of the wind power plants will be smaller than the actual value. In case there is no available gradient control reserve at all, the energy storage has to perform the operation, provided that it's power and energy allows it. The mathematical description of these rules is the following:

$$IF\ P_{wind\ gradient_i} = FALSE \rightarrow P_{corr.w.grad._i} = FALSE$$

(2-4)

$$IF \exists\ P_{w.grad._i} \begin{cases} IF\ P_{w.grad._i} > 0 \begin{cases} IF\ P_{down.contr.gradient_i} \leq 0 \rightarrow P_{corr.w.grad._i} = P_{w.grad._i} \\ IF\ P_{down.contr.gradient_i} > 0 \begin{cases} HA\ P_{down.contr.gradient_i} > P_{w.grad._i} \rightarrow P_{corr.w.grad._i} = \\ = 0 \\ HA\ P_{down.contr.gradient_i} \leq P_{w.grad._i} \rightarrow P_{corr.w.grad._i} = \\ = P_{w.grad._i} - P_{down.contr.gradient_i} \end{cases} \end{cases} \\ HA\ P_{w.grad._i} \leq 0 \rightarrow P_{corr.w.grad._i} = FALSE \end{cases}$$

The equations in case of upward regulation are similar to (2-4).

$$IF\ P_{wind\ gradient_i} = FALSE \rightarrow P_{corr.w.grad._i} = FALSE$$

(2-5)

$$IF \exists\ P_{w.grad._i} \begin{cases} IF\ P_{w.grad._i} < 0 \begin{cases} IF\ P_{up.contr.gradient_i} \leq 0 \rightarrow P_{corr.w.grad._i} = \left|P_{w.grad._i}\right| \\ IF\ P_{up.contr.gradient_i} > 0 \begin{cases} IF\ P_{up.contr.gradient_i} > \left|P_{w.grad._i}\right| \rightarrow P_{corr.w.grad._i} = \\ = 0 \\ IF\ P_{up.contr.gradient_i} \leq \left|P_{w.grad._i}\right| \rightarrow P_{corr.w.grad._i} = \\ = \left|P_{w.grad._i}\right| - P_{up.contr.gradient_i} \end{cases} \end{cases} \\ IF\ P_{w.grad._i} \geq 0 \rightarrow P_{corr.w.grad._i} = FALSE \end{cases}$$

During my research I determined different parameters that can be used for the sizing of an auxiliary energy storage unit; I analyzed the length and distribution of the downward and upward gradient operations performed by the energy storage, while the magnitude of the power gradient of each operation was also examined.

The operation of the different methods was demonstrated using the three year data of the Hungarian power system between 2009 and 2011 that are available on the website of MAVIR (MAVIR Hungarian Independent Transmission Operator Company Ltd.). Production data of the wind power plants was rescaled in 100 MW steps between 400 and 1 000 MW based on the actual installed capacity. The gradient capabilities of the power system were included in the examinations with their historical values, since the aim of the energy storage in my examinations is to provide auxiliary gradient capabilities to the actual power system. Concerning the results, downward and upward control reserves were analysed separately, and chapter 3.3.3. also demonstrated, what additional information is needed if we would like to serve both downward and upward control needs with the same energy storage unit.

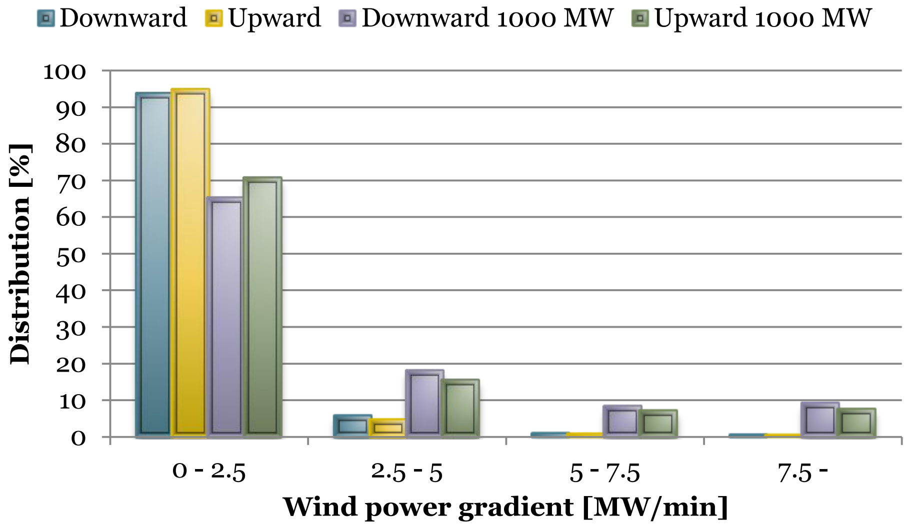

Fig. 2-1.: distribution of the gradients of Hungarian wind power plants during the examined period

Based on the results, the following conclusions may be drawn:

- In the Hungarian power system auxiliary gradient control reserves are needed mainly in case of downward control needs, upward capabilities are significantly greater.
- Increase of installed wind capacity increases the number and the cumulative length of the periods when auxiliary gradient control reserves are necessary. However, the rate of growth is different in case of the two control directions; the cumulative length of periods with auxiliary downward control needs increase by a factor of two, while a factor of three can be observed in the opposite direction.
- With the increase of the number of auxiliary gradient control operations the average length of such operation decreases. The primary reason for this phenomenon is that the occurring control reserve needs are typically shorter (1-2 minute), so the proportion of longer periods decreases.
- The magnitude of auxiliary downward control operations increases with the installed wind capacity, but in case of upward direction this growth stops in the range of 600-700 MW, and then declines. The reason for the phenomenon is again the increasing proportion of shorter operations, performed by the energy storage.
- Based on my examinations, an energy storage unit with a nominal power of at least 25 MW, capable of continuous operation at full power for 4 minutes (1,66 MWh) is necessary to provide auxiliary gradient control reserves for the Hungarian power system, assuming that the number and capacity of power plant units involved in control does not increase.

Based on the results of the research I formulated the following thesis:

First thesis:

I elaborated two different complementary methods that can be used to determine the parameters (power, energy) of a grid-connected energy storage unit that is capable of providing auxiliary gradient control reserves required by wind power *ramping events, assuming that the power system is partially or wholly not capable of such operation.*

First sub-thesis of the first thesis:

I elaborated a statistical analysis that ignores time data of the input data, thus always resulting the smallest parameters (power, energy) of an energy storage unit that is capable of serving the pre-defined proportion of gradient control reserve needs.

Second sub-thesis of the first thesis:

I elaborated a computer simulation tool that takes into consideration the time data of the input data, which may carry characteristic additional information on the source (wind power plant and power system) of the input data. The thus performed examination with good approximation would result an upper estimation on the parameters (power, energy) of an energy storage unit that is capable of serving the pre-defined proportion of gradient control reserve needs.

The presented two research methods may be used with arbitrary input data, provided that the pre-procession is performed. The methods are therefore, in case of any power system or sub-system, suitable to determine the parameters of a grid-connected energy storage unit that is capable of providing auxiliary gradient control reserve. The methods use only technical parameters, so the results are independent of the frequently changing financial parameters; however these results can be used without modification in a subsequent economical analysis.

Publications of the author, related to the research presented in chapter 3.: [S9], [S17-S18]

3 Examination of the scheduling errors of wind power plants

In chapter 4. of my dissertation, examinations of the forecast errors of wind power plants are presented. While giving a detailed overview of the field's literature, I present studies that examine the increasing amount of control reserve needs as a result of the increasing penetration of wind power. There are two possible solutions to mitigate such needs. Among them I only dealt with the wind power forecasting methods in passing, since my research focuses on the application of energy storage: what size of storage is needed to be operated in cooperation with the power system, to mitigate the scheduling errors of wind power plants. The latter application is also widely discussed in the literature: I presented a number of publications that are close to my work either in concept or in method. It is important, however, that while the majority of these examinations are based on the optimization of costs, my purpose was performing solely technical examinations. During the examination of the scheduling errors of Hungarian wind power plants I reviewed the forecasting systems used in recent years by MAVIR, and I also presented the amount of available control reserves in the Hungarian power system.

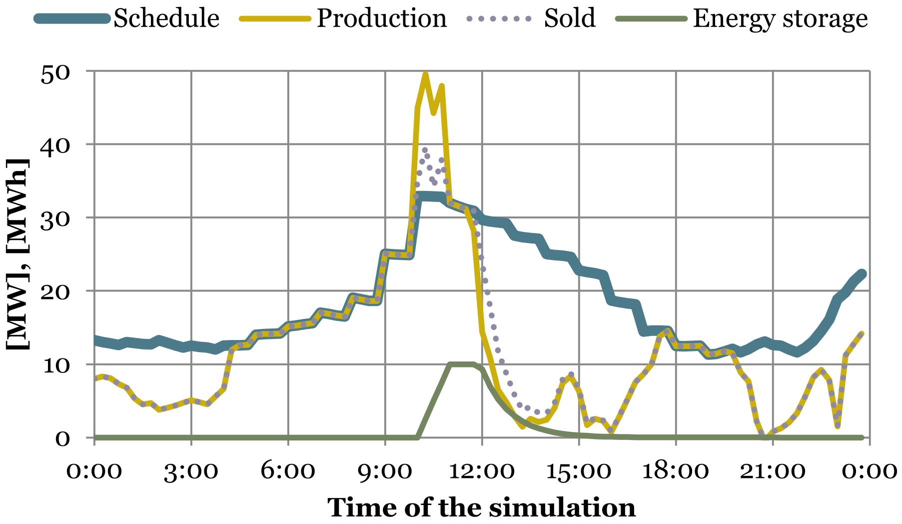

Fig. 3-1.: example of the operation of the computer simulation

For the examination of the amount of control needs imposed by wind power plants I used two methods, similar to that described in chapter 3. The input data for these methods are the schedules presented by the wind power plants, actual production values and the amount of downward and upward control reserves available in the power system.

The error of the schedule is calculated as the difference of available production and schedule values. ((3-1)) Error values have to be rescaled, using the installed wind capacity at the time the data was recorded and the installed wind capacity we would like to examine. ((3-2))

(3-1)

$$IF\ \nexists\ P_{schedule_i} \rightarrow P_{error_i} = FALSE$$
$$IF\ \exists\ P_{schedule_i} \begin{cases} IF\ \nexists\ P_{production_i} \rightarrow P_{error_i} = FALSE \\ IF\ \exists\ P_{production_i} \rightarrow P_{error_i} = P_{production_i} - P_{schedule_i} \end{cases}$$

(3-2)

$$IF\ P_{error_i} = FALSE \rightarrow P_{ex.error_i} = FALSE$$
$$IF\ P_{error_i} \neq FALSE \rightarrow P_{ex.error_i} = P_{error_i} \cdot \frac{P_{ex.nominal}}{P_{nominal}}$$

The amount of available downward and upward control reserves – in case they are not available in such form – are calculated as the difference of the system load of the examined power system and the minimal and maximal values of the available spinning reserves. ((3-3))

(3-3)

$$IF\ \nexists\ P_{spinning\ reserve_i} \rightarrow P_{contr.reserve_i} = FALSE$$
$$IF\ \exists\ P_{spinning\ reserve_i} \begin{cases} IF\ \nexists\ P_{system\ load_i} \rightarrow P_{contr.reserve_i} = FALSE \\ IF\ \exists\ P_{system\ load_i} \rightarrow P_{contr.reserve_i} = \left|P_{system\ load_i} - P_{spinning\ reserve_i}\right| \end{cases}$$

After the completion of (3-1), (3-2) and (3-3), rescaled schedule error and control reserve data are available, and may be used in the last step of the procession, when the so-called corrected wind production values are calculated. The interpretation is illustrated by the example of downward control needs.

The ideal case would be if the production of wind power plants would not differ from their schedule, since there would be no need for control. In reality, there are four possible outcomes. The first is that production of wind power plants does not exceed their schedule during the examined period, thus no need arises for downward control. In case such need arises, the next step is determined by the amount of available downward control reserve. If the amount of available reserve exceeds downward control needs, the power system is capable of performing the control operation without the help of the energy storage, so from the viewpoint of the storage, the error of the schedule is virtually zero. In case the amount of available reserves is not sufficient, part of the error of the schedule has to be equalized by the energy storage. This means that from the viewpoint of the storage the error of the schedule is equal to the difference of the actual error and the control performed by the power system. If there is no available control reserve at all, the energy storage has to perform the operation, provided that it's power and energy allows it. The mathematical description of these rules is the following:

$$IF\ P_{error_i} = FALSE \rightarrow P_{corr.production_i} = P_{schedule_i}$$

(3-4)

$$IF\ \exists\ P_{error_i} \begin{cases} IF\ P_{error_i} > 0 \begin{cases} IF\ P_{down.contr.reserve_i} \geq P_{error_i} \rightarrow P_{corr.production_i} = P_{schedule_i} \\ IF\ P_{down.contr.reserve_i} < P_{eltérés_i} \begin{cases} IF\ P_{down.contr.reserve_i} > 0 \rightarrow P_{corr.production_i} = \\ = P_{production_i} - P_{down.contr.reserve_i} \\ IF\ P_{down.contr.reserve_i} \leq 0 \rightarrow P_{corr.production_i} = \\ = P_{production_i} \end{cases} \end{cases} \\ IF\ P_{error_i} \leq 0 \rightarrow P_{corr.production_i} = P_{production_i} \end{cases}$$

The equations in case of upward regulation are similar to (3-4).

$$IF\ P_{error_i} = FALSE \rightarrow P_{corr.production_i} = P_{schedule_i}$$

(3-5)

$$IF\ \exists\ P_{error_i} \begin{cases} IF\ P_{error_i} \leq 0 \begin{cases} IF\ P_{up.contr.reserve_i} \geq P_{error_i} \rightarrow P_{corr.production_i} = P_{schedule_i} \\ IF\ P_{up.contr.reserve_i} < P_{error_i} \begin{cases} IF\ P_{up.contr.reserve_i} > 0 \rightarrow P_{corr.production_i} = \\ = P_{production_i} + P_{up.contr.reserve_i} \\ IF\ P_{up.contr.reserve_i} \leq 0 \rightarrow P_{corr.production_i} = \\ = P_{production_i} \end{cases} \end{cases} \\ IF\ P_{error_i} > 0 \rightarrow P_{corr.production_i} = P_{production_i} \end{cases}$$

During my research I determined different parameters that can be used for the sizing of an auxiliary energy storage unit; I analysed the length and distribution of the downward and upward control operations performed by the energy storage, while the magnitude of the power and energy of each operation was also examined.

The operation of the different methods was demonstrated using the two year data of the Hungarian power system that are available on the website of MAVIR. Schedule and production data of the wind power plants was rescaled in 100 MW steps between 400 and 1 000 MW based on the actual installed capacity. The control reserve capabilities of the power system were included in the examinations with their historical values, since the aim of the energy storage in my examinations is to provide auxiliary control capabilities to the actual power system. Concerning the results, downward and upward control reserves were analysed separately, and I also demonstrated, what additional information is needed if we would like to serve both downward and upward control needs with the same energy storage unit.

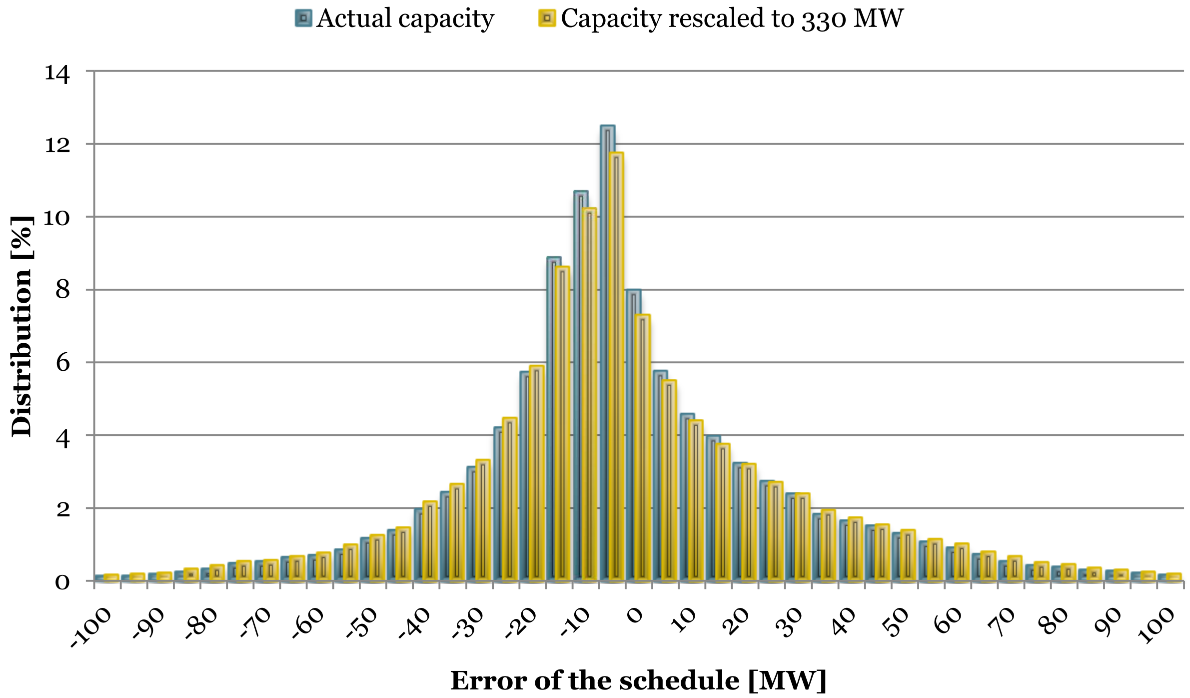

Fig. 3-2.: scheduling error of the Hungarian wind power plants during the examined period (2009-2011)

Based on the results, the following conclusions may be drawn:

- Downward control reserves of the Hungarian power system are significantly smaller than in the opposite direction.
- Increase of installed wind capacity increases the number and the cumulative length of the periods when auxiliary control reserves are necessary. The rate of growth is almost the same in both directions.
- The amount of auxiliary power increases with the installed wind capacity, but a difference between the two directions can be observed here, upward control needs are growing faster. In contrast, no significant difference can be observed in relation to the rate of growth in case of the auxiliary energy needs.
- All examined parameters show nearly linear dependence on installed wind capacity, therefore if the latter value is given as the proportion of the total installed capacity of the power system, parameters of the energy storage may be calculated easily. Based on the results of the statistical analysis, nominal power of such energy storage should be approximately 25% of the installed wind capacity, while the nominal energy of the storage should reach 25-45% of the capacity. The bigger range of the latter value is the result of the 1 000 MW scenario, where significant difference can be observed between downward and upward control needs.
- Subdivision and random alignment of the input data is a unique part of the research. It provides transition between statistical analysis and computer simulation by mitigating the disadvantages of the methods.

Based on the results of the research I formulated the following thesis:

Second thesis:

I elaborated two different complementary methods that can be used to determine the parameters (power, energy) of a grid-connected energy storage unit that is capable of providing auxiliary control reserves required by scheduling errors of *wind power plants, assuming that the power system is partially or wholly not capable of such operation.*

First sub-thesis of the second thesis:

I elaborated a statistical analysis that ignores time data of the input data, thus always resulting the smallest parameters (power, energy) of an energy storage unit that is capable of serving the pre-defined proportion of control reserve needs induced by the scheduling error of wind power plants.

Second sub-thesis of the second thesis:

I elaborated a computer simulation tool that takes into consideration the time data of the input data, which may carry characteristic additional information on the source (wind power plant and power system) of the input data. The thus performed examination with good approximation would result an upper estimation on the parameters (power, energy) of an energy storage unit that is capable of serving the pre-defined proportion of control reserve needs induced by the scheduling error of wind power plants.

Third sub-thesis of the second thesis:

I elaborated a method that is capable of the subdivision and random alignment of the input data. Performing examinations using these new input data provides a transition between statistical analysis and computer simulation by mitigating the disadvantages of the methods. The thus performed examination would result a realistic estimation on the parameters (power, energy) of an energy storage unit that is capable of serving the pre-defined proportion of control reserve needs induced by the scheduling error of wind power plants, assuming that the rate of subdivision is chosen properly.

The presented two research methods may be used with arbitrary input data, provided that the pre-procession is performed. The methods are therefore, in case of any power system or sub-system, suitable to determine the parameters of a grid-connected energy storage unit that is capable of providing auxiliary control reserve to mitigate the scheduling errors of wind power plants. Since both methods use only technical parameters, the results are independent of the frequently changing financial parameters, however these results can be used without modification in a subsequent economical analysis.

Publications of the author, related to the research presented in chapter 4.: [S1-S17]

4 Reduction of the amount of control reserves required by wind power plants

While in chapter 4 of my dissertation I presented the amount of control reserve needs induced by the scheduling error of wind power plants, in chapter 5 I proposed a possible method to decrease these needs. As review of the literature has shown, standpoint of the experts is not unequivocal, whether to serve the increased reserve needs or to try to decrease them as much as possible. Two possibilities of this decrease were presented. The first aims to alter the current method of control reserve planning by shifting the focus from deterministic methods, based on the power of the largest power plant unit, to stochastic methods that also include the scheduling error of wind power plants. The other possibility to decrease reserve needs is indirect and is based on financial motivation. All such process can be classified here that sanctions scheduling errors or motivates more accurate scheduling. In connection with this field, feed-in prices and penalty tariffs of obligatory electricity purchase systems of the EU were presented. The chapter also included the presentation of a simple method, capable of planning the amount of control reserve needs, which uses the empirical distribution of scheduling errors to calculate confidence levels of the forecast.

The Hungarian legislation system is often cited as the one that did not reach its goal. On one hand, scheduling accuracy of wind power plants falls short of similar data of foreign units; on the other hand, introduction of the penalty tariff did not prove to be effective to reverse the process. Trying to solve the twofold problem at once, in my dissertation I proposed a new obligatory electricity purchase and scheduling system, which allows the transmission system operator to decrease the amount of control reserves required by wind power plants.

The first element of the system I proposed is to replace the current, purely deterministic scheduling by a new method, which includes a range of uncertainty. This range may be selected by the wind power plant, defined as the proportion of the RMS error. ((4-1)) The other novelty of the system is to replace the current rewarding-penalizing tariff system with a differentially rewarding one that would use two tariffs, *Base* and *Bonus*. The operator of the wind power plant would receive *Base* tariff for the total amount of generated electricity, but the *Bonus* tariff that depends on the committed RMS error would only be paid if scheduling error would not exceed the committed error. ((4-2)) The two tariffs (*Base* and *Bonus*) would be chosen in order not to decrease the income of wind power plants compared to current levels, assuming ideal behaviour.

(4-1) $$P_{schedule_i} = P_{estimated\ production_i} \pm RMSE_{committed_i}$$

(4-2) $$IF\ P_{error_i} \leq RMSE_{committed_i} \rightarrow p = Base + Bonus\left(RMSE_{committed_i}\right)$$
$$IF\ P_{error_i} > RMSE_{committed_i} \rightarrow p = Base$$

The aim of the system is to financially reward those units that determine their scheduling error with the best accuracy, since from the viewpoint of the power system; neither larger nor smaller uncertainty range would help the proper determination of the amount of required control reserves. To control the amount of extra income that a wind power operator would benefit by committing its empirical RMS error that choosing a bigger range, I developed the so-called *Aimed revenue* function. ((4-3)) Nature of the function may be defined arbitrarily thus giving more freedom to legislation bodies. To satisfy the boundary conditions set by the previously introduced two tariffs and the *Aimed revenue* function, the RMS error dependent multiplier of the Bonus tariff has to be determined.

(4-3) $$R_{aim_i}\left(RMSE_{com.i}\right) = E_{inside}\left(RMSE_{com.i}\right) \cdot \left(Base + Bonus\left(RMSE_{com.i}\right)\right) + E_{outside}\left(RMSE_{com.i}\right) \cdot Base$$

By proper selection of the two tariffs it can be ensured that financial coverage is available in case scheduling error of wind power plants exceeds the committed uncertainty level, thus allowing the implementation of the previously presented control reserve planning method. The method is altered in a way to only obligate control reserves equal to the committed RMS error of wind power plants, which would result significantly smaller amounts.

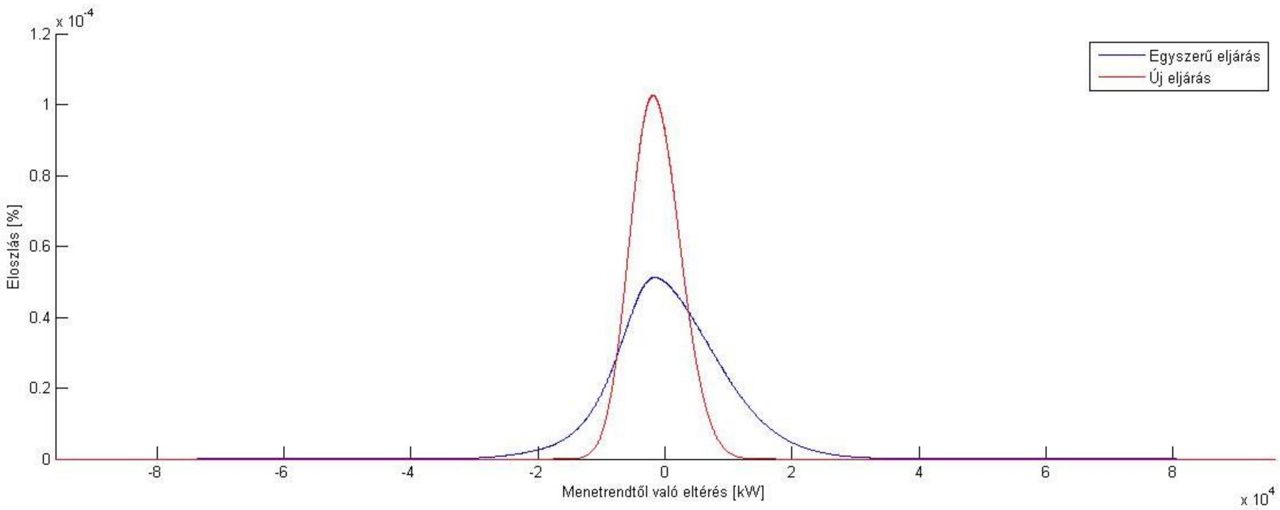

Fig. 4-1.: distribution of the cumulative scheduling error of wind power plants according to the existing (blue) and the proposed (red) method

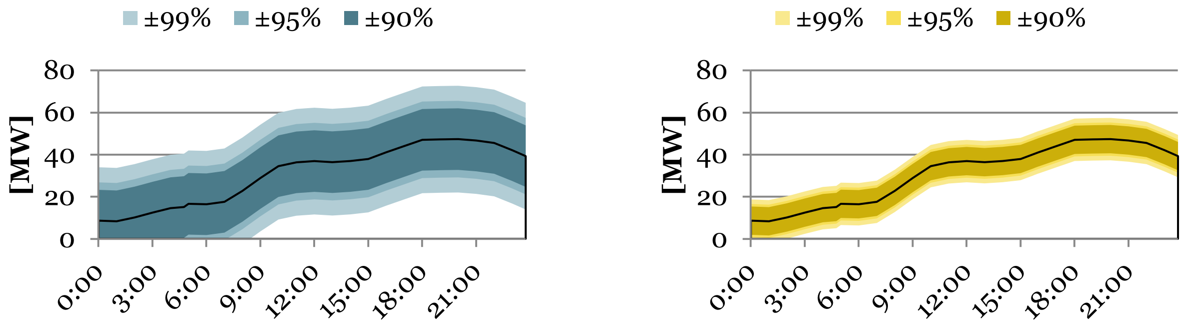

Fig. 4-2.: the schedule presented by the wind power plants and different uncertainty levels according to the existing (left) and the proposed (right) method

The operation of the method was demonstrated using actual schedule and production values of a wind power plant. The available 8-month data was divided to 4 periods with 2 month length, thus modelling four wind farms that have equal installed capacity but different scheduling error. By selecting a possible combination of *Base-Bonus* tariffs and using a self-defined *Aimed revenue* function, the amount of control reserve needs was calculated, which was 57% less than using the existing simple method. (Fig. 4-2.) Based on the results, the following conclusions may be drawn:

- Current Hungarian legislations do not include such financial pressure that would motivate wind power plants to improve their scheduling.
- The presented method modifies both the process of scheduling and tariffs of the obligatory electricity purchase system by replacing the purely deterministic scheduling by a new method including a range of uncertainty and replacing the current rewarding-penalizing tariff system with a differentially rewarding one.
- The proposed system does not originate substantive additional tasks to wind power plant operators. The income of the operators in the proposed system is also equal to the income with the present system, assuming that income is defined as the difference of feed-in tariffs received for produced energy and penalty tariffs.
- The proposed system would use groups that include wind farms with similar installed capacity, so it would not give an advantage to larger farms that may have smaller scheduling errors due to the portfolio effect.
- Besides creating the lacked motivation, the proposed system would give an opportunity to use less control reserve by taking into consideration the scheduling error of wind power plants.

- The proposed method may result different solutions that are alternatives to each other. Selecting the best of these can only be performed knowing the boundary conditions of the legislation system

Based on the results of the research I formulated the following thesis:

Third thesis:

I elaborated an obligatory electricity purchase and scheduling system that allows using less control reserve to mitigate the difference between the scheduled and the actual production of wind power plants. The two new elements of the system are the scheduling characterised by a level of uncertainty and the differentially rewarding tariff system, using two tariffs (Base and Bonus). Besides creating the lacked motivation for operators, with the conditions of the Bonus tariff, financial assets are available to cover the cost of the use of unforeseen control reserves.

Examination performed by using actual schedule and production data has shown that the proposed financial system motivates wind power plant operators to commit an uncertainty range as close to their actual scheduling error as possible and in case they exceed this range, by not receiving the *Bonus* tariff, financial assets are available to cover the cost of the use of unforeseen control reserves. The two effects jointly allows the transmission system operator to use less control reserve by taking into consideration the scheduling error of wind power plants.

Further development of the proposed system is possible if intra-day scheduling is introduced. In this case scheduling horizon may also be taken into account when defining the multiplier of *Bonus* tariff.

Publications of the author, related to the research presented in chapter 5.: [S1], [S5-S7], [S10-S14]

5 Publications of the author

[S1] Hartmann Bálint, „Szélerőmű rendszerintegrálásához szükséges tározókapacitás vizsgálata, különös tekintettel a mélyvölgy időszakra" (Investigation of a Storage Facility Needed for the System Integration of a Wind Generator, in Consideration of the Off-peak period), MSc Thesis, Budapest University of Technology and Economics, 2008

[S2] Bálint Hartmann, András Dán, „Harmonic Source Identification of a Distributed Generator, and Compensation of the Voltage Change Caused by Changing Generation", International Conference on Renewable Energies and Power Quality 2008 (ICREPQ 2008), Santander, Spain, 12-14 March, 2008, Paper 279

[S3] Bálint Hartmann, András Dán, „Investigation of a Storage Facility Needed for the System Integration of a Wind Generator", 31st World Energy Engineering Congress 2008 (WEEC 2008), Washington D.C., USA, 1-3 October, 2008, Paper 123

[S4] Hartmann Bálint, „Szélerőmű rendszerintegrálásához szükséges tározókapacitás vizsgálata" (Investigation of a Storage Facility Needed for the System Integration of a Wind Generator), Elektrotechnika, 2009, vol. 4., pp. 12-14.

[S5] Bálint Hartmann, Zsuzsa Csetvei, „Support Policies Regarding Wind Generation, and Use of Storage Technologies from the Viewpoint of the TSO", 9th International Conference on Heat Engines and Environmental Protection, Balatonfüred, Hungary, 25-27 May, 2009, Paper 3

[S6] Bálint Hartmann, Zsuzsa Csetvei, András Dán, „The Scheduling Methods of Wind Generator Production, and Use of Storage Technologies to Avoid Penalty Tariffs", 2nd International Youth Conference on Energetics 2009 (IYCE 2009), Budapest, Hungary, 4-6 June, 2009, Paper 415

[S7] Bálint Hartmann, András Dán, „Energy Storage in Connection With Wind Generation Production", IEEE Nordic Conference, R8 Power Chapters Leadership Workshop and IAS Technical Seminar on Wind Power Technologies, Stockholm, Sweden, 13-15 September, 2009, invited lecture

[S8] Bálint Hartmann, „Some Aspects of Distributed Generation – Voltage Drop and Energy Storage", IEEE PES Bucharest PowerTech 2009, Bucharest, Romania, 28 June – 2 July, 2009, Paper 41

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