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Highlights

- Method for evaluation of power system reliability if nuclear is replaced with wind power plants.
- Upgrade of the loss of load expectation method with consideration of the actual instead of the nominal power.
- Semi dynamic considerations of evaluations, which are performed for every hour of system operation instead of performing one run.
- Development of new models and application of real case studies.

Evaluation of the power system reliability if a nuclear power plant is replaced with wind power plants

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Abstract

The modern power systems include a larger number of more dispersed and smaller power generating sources, which are slowly replacing larger and more concentrated power sources. The objective of this paper is to analyse the replacement of nuclear power plant with wind power plants to compare both cases from the viewpoints of power system reliability. The load diagram and the variability of the power plants, whose power depend on the environmental parameters with the time is considered. This paper is focused on the loss of load expectation. The upgraded method considers plant power as a function of the time instead of its nominal power. Initial real power system model consists of twelve power plants including one nuclear power plant. This plant is then replaced by three wind power plants with their total power five times larger than the power of the nuclear power plant. A comparison of reliability in terms of comparing the loss of load expectation is performed using the real weather data for one calendar year. The results show that the replacement of the nuclear power plant with several wind power plants with wind power capacity five times larger than the nuclear power capacity causes a decrease of the power system reliability.

Key words

reliability, nuclear power plant, wind power, renewable, loss of load expectation

1 INTRODUCTION

The modern power systems include a larger number of more dispersed and smaller power generating sources, which are slowly replacing larger and more concentrated power sources [1]. Consequently, the power system operators deal with more dynamic conditions, larger number of parameters under investigation and more complex solutions requiring more complex models and new analyses. The capacity factors have been studied on real weather data for offshore wind power plants compared to onshore plants showing higher values for the offshore plants [2]. The reliability of equipment integrated in wind power plants has been studied identifying more and less reliable subassemblies [3]. In parallel, the analyses of faults in the more and more interconnected transmission power systems hae been conducted to asses the total energy not supplied, the total loss of power, the restoration time and several other power reliability indicators, because the power system is too complex that the reliability would be represented as one parameter [4]. Weather parameters have been studied to enable more certain predictions of available power from power technologies, which power is linked to the weather parameters [5]. Many similar analyses and trends pave the way of more and more wind power in power systems.

The objective of this paper is to analyse replacement of nuclear power plant with wind power plants in order to compare both cases from the viewpoint of power system reliability. The characteristics of the real power system needs to be considered including the features of the load diagram and the variability of the power of wind and hydro power plants, whose power depend on the environmental parameters.

Reliability of the power systems is a wide term and a large number of methods are developed, each of which represents the power system reliability from each side [6], [7], [8], [9]. They can be grouped into two main groups.

The first one deals with the power system as a static system where the term adequacy is considered as a measure of the static power system reliability. The method was developed to enable assessment of power system reserve keeping in mind the loss of load probability [10]. The common mechanisms of dependent failures were introduced to the method, which enabled consideration of events, which can cause the failures of more components due to the same root cause [11]. The method was improved to evaluate time dependent power system reserve considering timely changing daily power diagram with respect to desired level of system reliability [12]. The importance factors have been identified in order to distinguish more and less important power generation sources in the power system from the reliability point of view [13]. The data collection processes about the consumer oriented indices on the distribution power system were conducted in parallel to develop more indicators, each showing the power system reliability from another viewpoint [14].

The other group deals with the power system as a dynamic system where the term security is considered as a measure of the dynamic power system reliability [15]. The inertia in the power system is studied together with the frequency response in order to keep the power system stable [16]. And, the improved methods have been developed for simulations of power flows through the lines of the power system considering the system dynamics [17]. Both groups also represent the standpoint for a variety of simulation and optimisation methods which improve the power system planning processes and its operation. The method was developed to schedule the power from a variety of power plants in the power system considering the environmental characteristics and the availability of the power generators included [18].

The outline of the paper is the following. The section about methods describes the loss of load expectation as an existing method in theory and in terms of a simple example. Its upgrade is presented and the computer code, which is developed as a support, is described. The section 3 presents the models:

- the initial power system model with a nuclear power plant (no wind power considered),
- the power system model without the nuclear power plant and with three wind power plants:
  - the real weather data is used in the first case,
  - the random wind speed data is used in other cases, where the average of the random wind speed is notably higher then the average wind speed of the real weather data.

Section 4 gives the takeaway message.

2 METHODS

The focus of this paper is placed on the first of the two sets of methods for the evaluation of the power system reliability which considers the power system as a static one and thus excludes dynamic stability studies [7], [9], [10]. However, consideration of the actual instead of the nominal capacity of the intermittent power sources is considered in the paper, i.e. the capacity of the hydro power plants depending on the river flows, and, i.e. the capacity of the wind power plants depending on the wind speed. In more details, the capacity of the wind power plant (considering one unit only) depends on a number of parameters where the dominant one is the wind speed. The set of the most important parameters for assessing the capacity of the wind power plant at the future site includes the average wind speed in the certain time interval (e.g. 10 min), the maximal wind speed in this time interval, air density depending on pressure and moisture, the height of measurement and the height of the projected wind plant. The power of the existing power plant can be modelled according to the following equation.

$$P = \frac{1}{2} \cdot \eta \cdot \rho \cdot A \cdot v^3 \tag{1}$$

P - power (power of the wind power plant – one unit)

ρ - air density

A- area

v - wind speed

η - efficiency: $\eta = \eta_t \cdot c_p$

η_t – technical efficiency (technical efficiency is a function of rotation speed, power)

c_p – maksimum theoretical efficiency (Betz factor or Betz Lancaster factor); cp=16/27≈0.59

If the wind power plant consists of several units, the total plant power is the sum of powers of all the units. Normally, even when the different units are located close next to another, the wind speed mostly differs from one unit to another, because the wind speed is a location specific parameter.

The loss of load expectation (LOLE) is a method for determination of required reserves in the power system and for assessing the static reliability of power system evaluating the expected time duration when the power load is not being supplied with required power capacity [7], [8], [9], [10]. The method analyses the probabilities of states of power plants, which based on a model of daily, or monthly, or yearly load diagram determine the number of hours of expected power production capacity shortages during the period considered, e.g. one day, one month or one year, which is the most common period used.

The loss of load is specified whenever the power system load exceeds the available generating capacity of all the power plants within the specified state. The loss of load expectation expresses the value which represents the number of hours or days in a certain time period considered, when the load (i.e. power consumption) cannot be supplied. A similar method is loss of load probability (LOLP), which can be used in parallel, but with one difference. The loss of load probability expresses the value which represents the percentage in a certain time period considered, when the load (i.e. power consumption) cannot be supplied.

The general expected outcome of both methods is the determination of the required power reserve in the system in order for the reliability to stay at the required level. The targeted loss of load expectation is less than 10 hours per year in some country [28, 29] and varies also from 3 hours per year to 8 hours per year in some countries in Europe. On the other hand, the targeted loss of load expectation in USA is less than 0.1 day per year [30].

The power system generation planners can evaluate the generation system reliability and determine how much capacity is required to obtain the specified level of the loss of load expectation. As the power demand grows over time, additional generating units need to be introduced to the power system at least with such a capacity that the loss of load expectation does not exceed the required criterion. Actually, the initial objective of the method is more to determine the required reserve power in the system, rather than to evaluate its reliability. In this sense, the application of the method is performed in a way to determine the capacity of the wind power plants if the exchange for the existing nuclear power plants is considered.

2.1 Basic loss of load expectation

Figure 1 shows the graphical representation of parameters for determining the loss of load expectation on ordered load diagram [7], [8], [9], [10]. The points of load in certain time point are ordered by load in this load diagram, while normally observed load points in the load diagram are ordered by consecutive points in time (smaller load during the night and higher load during the day). The load of the power system is the sum of all the loads of the power system consumers considering the losses in the power system and its import and export. The installed power capacity is the sum of nominal power capacities of all power plants in the power system. The peak load is the highest power load in the power system. The reserve margin is the difference between the installed capacity and the peak load. The capacity in outage represents the sum of considered nominal power capacities of power plants, which are considered as unavailable in specific state. The capacity in operation represents the sum of considered power capacities of power plants, which are considered as available in specific state. The states, which are considered, are all possible states considering that each power plant can be either available or unavailable.

$$K = 2^n \qquad (2)$$

K – number of states

n – number of power plants in the system

The duration of the loss of capacity is the time interval, in which the capacity of power plants in operation of certain state does not reach the load.

Straightforward algorithms have been developed which consider states one after another considering the combinations of available and unavailable plants in terms of evaluating LOLE.

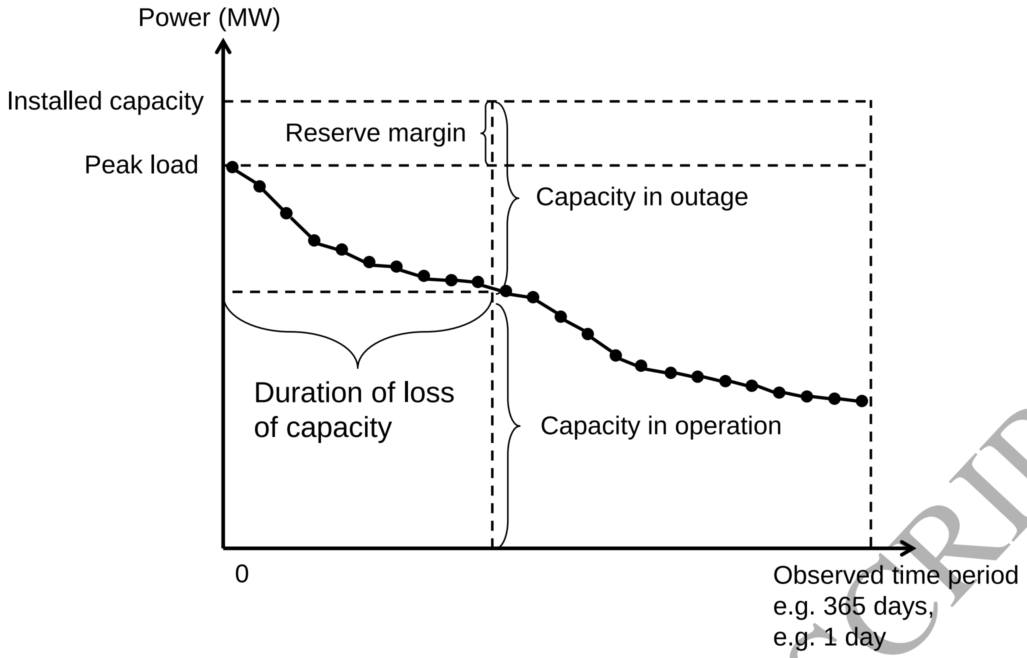

Figure 1: Graphical representation of parameters for determining the loss of load expectation

The equation for calculation of LOLE is the following.

$$LOLE = \sum_{k=1}^{K} p(k) \cdot t_{loss}(k) \tag{3}$$

k - index of considered state

K - number of states

p(k) - probability of state k

$t_{loss}(k)$ - time duration of loss of capacity of state k

The probability of state k is evaluated by the product of availabilities of plants which are available in this state k and unavailabilities of plants which are unavailable in this state k. Capacity table is the table which keeps the data about the state of the specific plants in each state and the resulted probability of that state.

$$p(k) = \prod_{r=1}^{n1} a(r) \cdot \prod_{s=1}^{n2} (1 - a(s)) \tag{4}$$

n1 - number of plants available for certain state

n2 - number of plants unavailable for certain state

a(r) - availability of plant r

a(s) - availability of plant s

1 - a(s) - unavailability of plant s (expressed as the complement of its availability)

a(r) = 1 - FOR(r) - availability of plant r is the complement of forced outage rate of plant r because forced outage rate can represent unavailability

FOR(r) – forced outage rate of plant r

The relation between the availability and forced outage rate is presented, because the forced outage rate is a well known term, which is normally available for most of the plants.

Table 1 shows simple example of determining LOLE for a daily load diagram which is flat at constant power of 20 MW through half of the day and 10 MW through the other half of the day.

Table 1: Example of the capacity table for three power plants

State k	Unit A 40 MW a(A)=0.9	Unit B 30 MW a(B)=0.95	Unit C 10 MW a(C)=0.96	Capacity lost (MW)	Capacity in service (MW)	Probability of each capacity state, p(k)	$t_{loss}(k)$ (h/d)	$p(k)^* t_{loss}(k)$ (h/d)
1	1	1	1	0	80	0.9·0.95·0.96=0.8208	0	0
2	1	1	0	10	70	0.90·0.95·0.04=0.0342	0	0
3	1	0	1	30	50	0.90·0.05·0.96=0.0432	0	0
4	0	1	1	40	40	0.10·0.95·0.96=0.0912	0	0
5	1	0	0	40	40	0.90·0.05·0.04=0.0018	0	0
6	0	1	0	50	30	0.10·0.95·0.04=0.0038	0	0
7	0	0	1	70	10	0.10·0.05·0.96=0.0048	12	0.0576
8	0	0	0	80	0	0.01·0.05·0.04=0.0002	24	0.0048
							LOLE(hours/day) =	0.0624

For state 1 (k=1) the units A, B and C are in operation. The power capacity of the power system is equal to 80 MW (in other words: the capacity of power plants in service is 80 MW). The power capacity of power plants which do not operate is 0 MW (the capacity lost is equal to 0 MW). The probability of state 1 is the product of plant unavailabilities (0.8208). All day the power capacity (80 MW) is larger than the load in the load diagram, so the time where this would not be true, is $t_{loss} = 0$. Consequently, state 1 does not contribute to LOLE. In state 7, only plant C is considered operable, so the power capacity of the power system is 10 MW and half of the day this is sufficient as the load is 10 MW, but half of the day the load is 20 MW and the power capacity is insufficient, thus $T_{loss} = 12$ hours.

The problem of the straightforward algorithms which consider all states one after another is a large increase of the model in terms of the increasing number of states with the increasing number of power plants considered.

Additionally, the recursive algorithms have been developed which combine states with the same power capacity in operation, and enable faster and more efficient consideration of large cases with more power plants in the power system [19], [20], [21], [22], [23]. The procedure for the evaluation of LOLE using the recursive algorithm is the following.

- Prepare COPT (Capacity Outage Probability Table) based on plants data.

The COPT contains all power capacities from 0 to the maximum system capacity, and every capacity is associated with its probability.

$$P_n(X) = P_{n-1}(X) * (1 - q_n) + P_{n-1}(X - C_n) * q_n \quad (5)$$

X - the capacity lost

$P_n(X)$ - the probability of the capacity lost X of the plant n

$P_{n-1}(X)$ - the probability of the capacity lost X of the plant n-1

q_n - the unavailability (or FOR) of the plant n

C_n - the capacity of plant n

- Analyze the load data, and put the results in the LPT (Load Probability Table).

The load data can be collected every hour throughout the year, so there can be 8760 data values (or some other time interval and time increment can be determined). These data values are sorted in descending order and converted to percentages. Every percentage represents a range of load, and the LPT contains the frequency of these ranges throughout the year.

- Merge COPT and LPT to get the SMST (System Margin Stable Table).

Based on the probability of every possible capacity and every possible load through the year, one can merge these probabilities to get the probability of every state. A state is given by the difference of a certain capacity and a certain load.

The cumulative probability of every possible state is obtained using the following equation.

$$P_{\mathrm{C}}(X_{\mathrm{K}}) = \sum_{j=0}^{N_{\mathrm{L}}} P_{\mathrm{N}}(X_{\mathrm{K}} - X_{\mathrm{J}}) * P_{\mathrm{L}}(X_{\mathrm{J}}) \tag{6}$$

$P_C(X_K)$ - the margin state cumulative probability of state K

X_K - the capacity of state K

N_L - the number of load (100)

$P_N(X_K\text{-}X_J)$ - the probability of the capacity based on the difference between the X_K capacity of state K and the load J

$P_L(X_J)$ - the probability of the load J

- Calculate LOLP and LOLE based on SMST.

The loss of load probability is given by the first negative margin state, which is the first state where the system does not provide enough power capacity to the load, because the difference between the capacity and the load is negative. Then, LOLE is evaluated out of LOLP.

The loss of load expectation can be calculated for each day, its mean value over certain time period (e.g. month or year) can be calculated.

$$LOLE_{h/d} = \frac{1}{z}\sum_{j=1}^{z} LOLE_{h/d}(j) \tag{7}$$

$LOLE_{h/d}$ - loss of load expectation (hours per day)

$LOLE_{h/d}(j)$ - loss of load expectation in day j (hours per day)

z - number of days considered

j - index of a day

Monthly LOLE can be expressed in hours per month (z=30 or z=31).

$$LOLE_{h/m} = \sum_{j=1}^{z} LOLE_{h/d}(j) \tag{8}$$

$LOLE_{h/m}$ - loss of load expectation (hours per month).

Yearly LOLE can be expressed in hours per year (z=365, or z=366).

$$LOLE_{h/y} = \sum_{j=1}^{z} LOLE_{h/d}(j) \tag{9}$$

$LOLE_{h/y}$ - loss of load expectation (hours per year).

2.2 Upgraded loss of load expectation

The original loss of load expectation considers constant power capacity of each power plant for the entire duration of the period observed and constant forced outage rate (or unavailability). It is also an improvement, which can be useful for effective load carrying capability evaluations [24], [25], [26].

The upgraded method enables FOR to be represented as a probability distribution instead of point value. Consequently, LOLE is not a point value but a probability distribution.

In addition, the upgraded method considers plant power capacity as a function of the time. If the flow of the river is smaller than nominal at certain time increment, then the power capacity of hydro power plant is smaller than nominal in this time increment. The same is with wind power plants, where the power capacity depends on the weather parameters such as wind speed, although some other parameters also impact the power, such as the moisture of air, pressure for wind power.

Due to variability of power capacity of renewable sources the power capacity from renewable sources lasts for certain time increment (e.g. ΔT), which can be one hour for example. At every ΔT (e.g. every hour) the LOLE is calculated considering the actual power capacity of renewable plants, even forced outage rate could vary in theory if there would be some indication that some power plant works more reliably at a certain power copacity than at another power capacity. One can calculate LOLE for each increment and its averate through the overall time interval considered.

$$LOLE = \frac{1}{z}\sum_{j=1}^{z} LOLE(j) \tag{10}$$

LOLE - loss of load expectation

LOLE(j) - loss of load expectation at j-th time increment ΔT

z - number of time increments ΔT

The ΔT in the current method is fixed to 1 hour, but this can easily be changed.

Consequently, the wind power capacity varies because of the stochastic wind speed variability. Some periods of higher average wind speed and some periods with lower average wind speed exist..

This opens the question of criteria: shall all the periods have the same average LOLE or can we allow periods with smaller LOLE and how much smaller LOLE can be tolerated and for how long. Further on, shall reserve power be the same through all the periods or can we tolerate smaller power reserve and for how long. The method can give a variety of results and can open discussions in the field of determining the proper reserve power in such a way that the reliability of the power system is not decreased.

2.3 Computer Code

Computer code has been developed which facilitates the evaluation of LOLE through the evaluation of all states of power system configuration one after another. As the number of states increases exponentially with the increase of the number of power plants in the system, such algorithm becomes less effective and even useless for larger systems.

Additionally, the recursive algorithm within the computer code has been developed for calculating LOLE which combines states with the same capacity in operation and which allows faster evaluation of a more complex power system consisting of more power plants.

In addition, the upgrade of the method has been developed in the computer code which allows the evaluation of LOLE every hour of the year considering the actual power capacity of the renewable power plants. The averages of a weekly or monthly LOLE can easily be evaluated.

3 ANALYSIS AND RESULTS

3.1 Power System Model

The data for the power system consists of the identification of each plant, its nominal power capacity (net electric power delivered to the power system), and its forced outage rate (or plant unavailability caused by unintentional causes). From this, the availability needs to be obtained for LOLE calculation. For the renewable sources such as hydro power plants, the functions of their power capacity versus time depend on the hourly river flow. The functions of power capacity versus time based on the hydrology data are prepared as part of the evaluation for the year 2016. Hydro pumping station operates in motor pumping state (180 MW) for approximately 8 hours per day in the period of low power demand and in turbine operating state (185 MW) for approximately 6 hours per day in the period of high power demand. It is assumed in the model that the hydro pumping station directly changes the daily load diagram.

Initial real power system consists of 12 power plants. 1 nuclear power plant, P_{NPP} = 696 MW net, FOR_{NPP}=0.01, 6 thermal power plants, P_{TPPi} = {544 MW, 345 MW, 275 MW, 84 MW, 124 MW, 350 MW} and FOR_{TPPi} = {0.080, 0.090, 0.090, 0.060, 0.060, 0.040}, 4 hydro power plants, P_{HPPi} = {590 MW, 321 MW, 118 MW, 156 MW}, FOR_{HPPi} = {0.01, 0.01, 0.01, 0.01} and 1 hydro pumping storage power plant (185 MW in turbine mode with a flow of 40m^3/s operating approximately 6 hours per day, 180 MW in pumping water motor mode with a flow 34 m^3/s operating approximately 8 hours per day).

3.1.1 Case with three wind power plants and real wind data

Then the initial model is changed. Nuclear power plant (696 MW) is replaced by three wind power plants (total 3480 MW in three plants with 1160 MW each). The approximate capacity factor of nuclear power is 0.92 in considered plant. The capacity factor of wind power is 0.2 in considered plants. The ratio between those two capacity factors suggests that the installed wind power needs to be for a factor of 4 to 5 times larger then the installed power of nuclear power plant in sense to deliver approximately the same electric energy. Factor of five is selected, so 696 MW of nuclear power is replaced with the total of 3480 MW of wind power. The real weather data for the year 2016 with the wind speed measurement at ten minute intervals in the region are considered for calculation of the wind power at each time point [27].

3.1.2 Cases with three wind power plants and random wind data

In addition, the random wind speed data in all time points was considered instead of the real wind measurements. The randomly selected wind speeds at specific time points are determined by developed random generator, which was modelled in a way that the wind speeds in average are notable larger than the average wind speeds of the real weather data. The consequent power of the wind power plants therefore gives relatively optimistic capacity factors of 0.3 in one case and 0.31 in another case. This means that the wind speed is distributed in a way that the average power from the wind power plants is 0.3 times its nominal power throughout the year (or 0.31 times its nominal power in another case). The actual weather data in the region show that the capacity factor for wind power is 0.2. Therefore, considering the capacity factor of 0.3 (or 0.31) would be highly optimistic in wind speed expectations through the year.

3.2 Analysis and results

The results for the initial model are the following. The loss of load expectation is calculated as 15.101 hours per year (0.0324 hours per day) as the average of a number of calculations, where the maximum loss of load expectation is 174.72 hours per year and the minimum LOLE is 0.00407 hours per year. The differences in performed calculations are due to the differences of hydro power plants, which are not assumed nominal all the time, but their power capacity depends on the incoming river flow throughout the year and changes respectively in the considered calculations. Figure 2 shows LOLE calculated for each day and its average through the year. Table 2 shows LOLE averages through the months of the year.

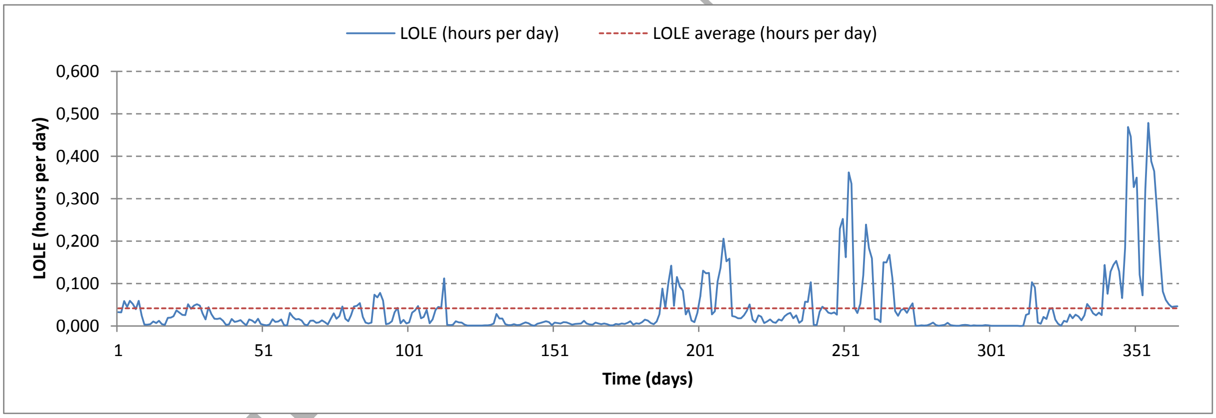

Figure 2: LOLE for the existing power system (with nuclear power plant)

3.2.1 Case with three wind power plants and real wind data

The replacement of a nuclear power plant with several wind power plants resulting in five times more power, gives significantly higher LOLE (63.605 hours per year as the average of a number of calculations, where maximum loss of load expectation is 2429 hours per year and minimum LOLE is negligible) reflecting notable reliability decrease. Such results are expected, because, if the wind blows there is a large reserve in the power system and its reliability is high and LOLE can be consequently negligible. In the case of lack of wind, there is less reserve, motably less than in the initial system with a stable power from the nuclear power plant and, consequently, the reliability of the system is decreased and LOLE is consequently increases. Figure 3 shows LOLE calculated for each day and its average throughout the year if nuclear power is replaced with wind power. Figure 4 shows real wind power plant data for the wind power plant named Wind1 (daily averages). More descriptive information on the wind speed as a source of power is shown on the next figure with monthly average values of wind speed. Figure 5 shows monthly averages of the wind speed, which indicate that in the months of January, September, and December, there is less wind than in other months. Consequently, the LOLE during these months can be significantly increased and the power system reliability is significantly decreased. Table 2 shows LOLE averages over the months of the year in addition to its yearly average. This information needs to be considered together with the changing power of hydro power plants, whose power depends mostly on the river flow.

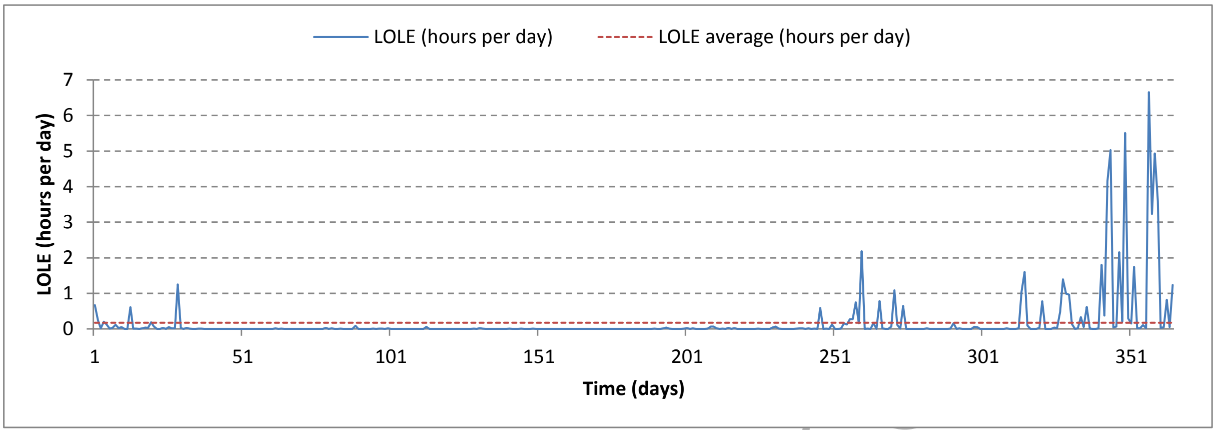

Figure 3: LOLE for the power system considering the replacement of the nuclear power plant (696 MW) with wind power plants (the total of 3480 MW in three plants with 1160 MW each), real weather data

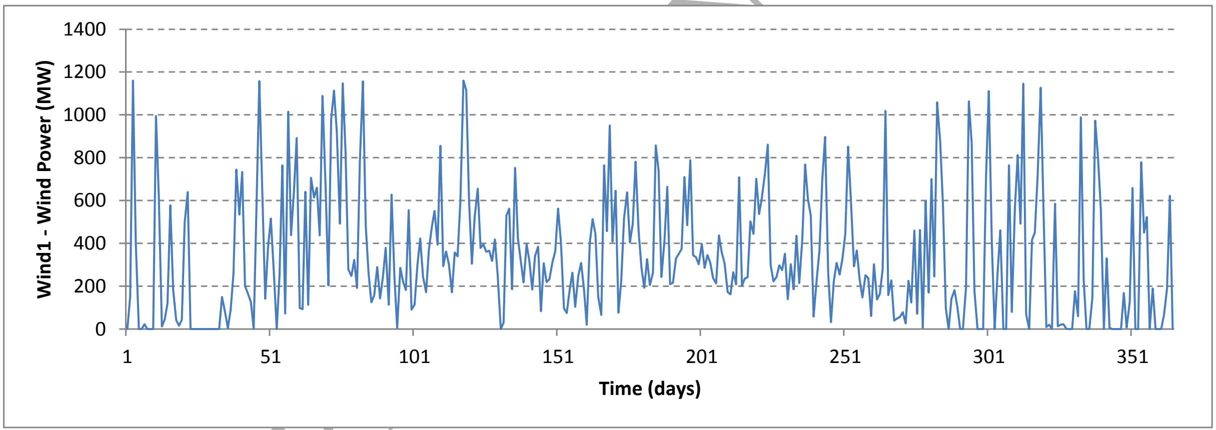

Figure 4: Real wind power plant data for the wind power plant named Wind1 (daily averages)

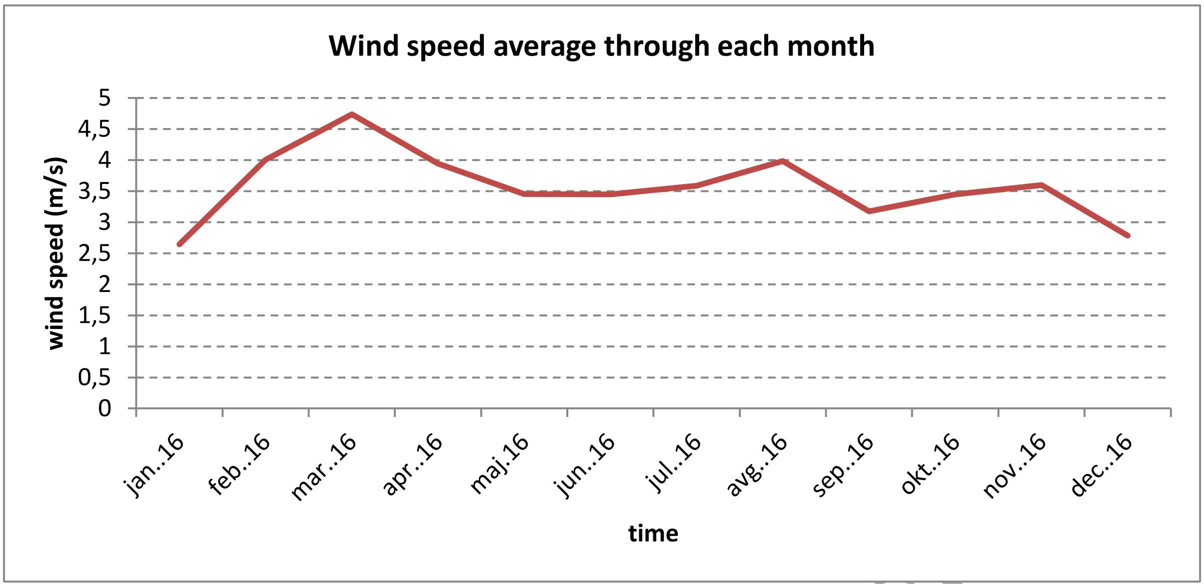

Figure 5: Real wind power plant data for the wind power plant named Wind1 (monthly averages)

Figure 6 shows the power capacity of the hydro power plants, which may indicate that at periods of low water flow and low wind speed the LOLE increases notably and the reliability of the power system decreases. The third and the fourth hydro power plant are both on the same river, so there is a large similarity regarding the function of power versus time (due to the similarity of the river flow).

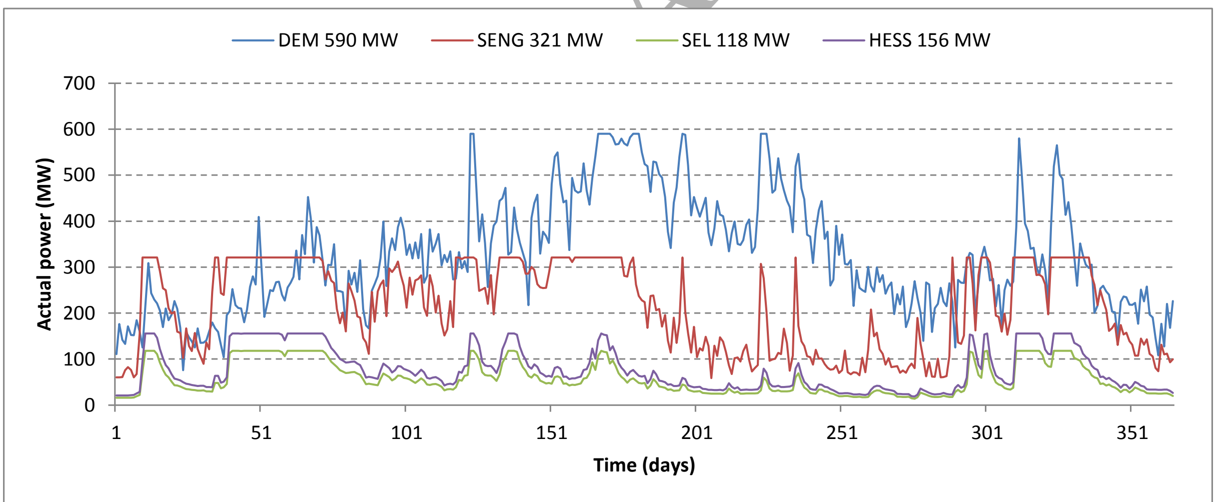

Figure 6: Hydro power plant (daily average power)

Figure 7 shows the power capacity of hydro power plants averaged by month to see why the system reliability is the largest in January, September, and December. Namely, in those months the river flows (and thus the power capacity of the hydro power plants) and the wind speed (and thus the power capacity of wind power plants) are the lowest (see Table 2).

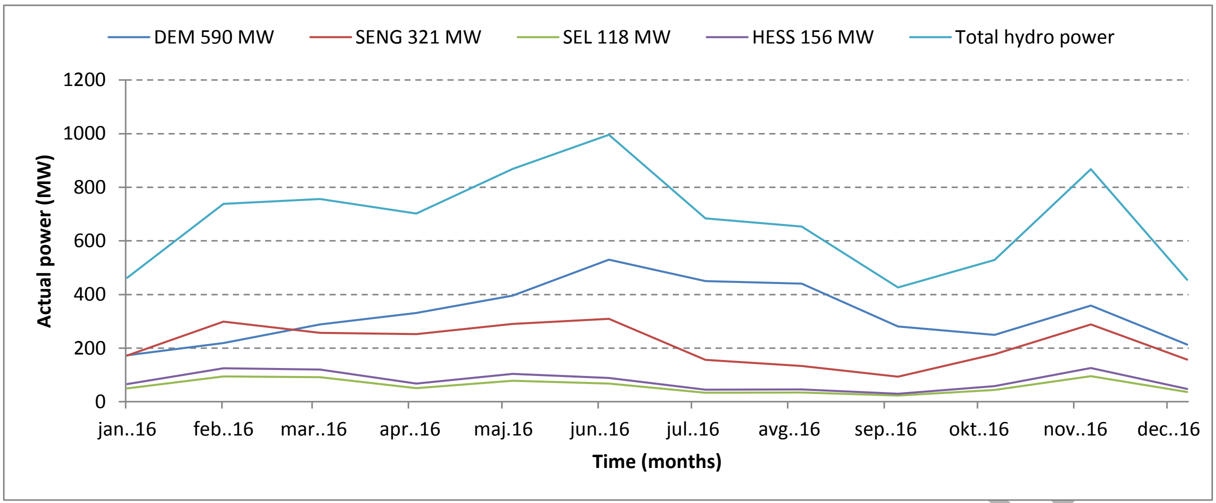

Figure 7: Hydro power plant (month average power)

3.2.2 Cases with three wind power plants and random wind data

Additionally, simulations were made with random weather concerning the wind power, where the average wind power is 30 % of the nominal power (and 31 %) which is very optimistically for our region. Figure 8 shows LOLE for the power system considering the replacement of the nuclear power plant (696 MW) with the wind power (the total 3480 MW in three plants with 1160 MW each), random weather data very optimistic with the wind power capacity factor 0.30 (CF=0.3). Figure 9 shows the respective wind power data.

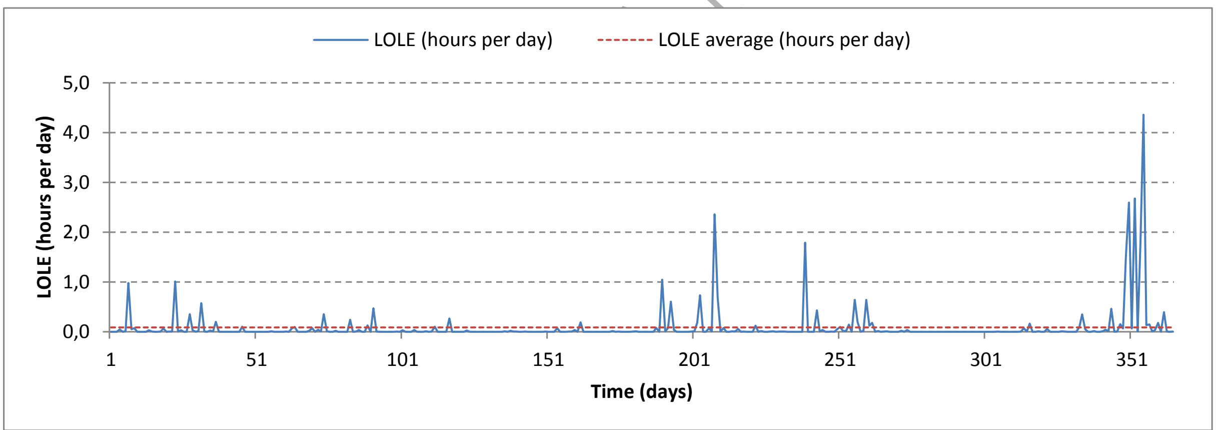

Figure 8: LOLE for the power system considering replacement of the nuclear power plant (696 MW) with the wind power plants (the total of 3480 MW in three plants with 1160 MW each), random weather data very optimistic with the capacity factor 0.30

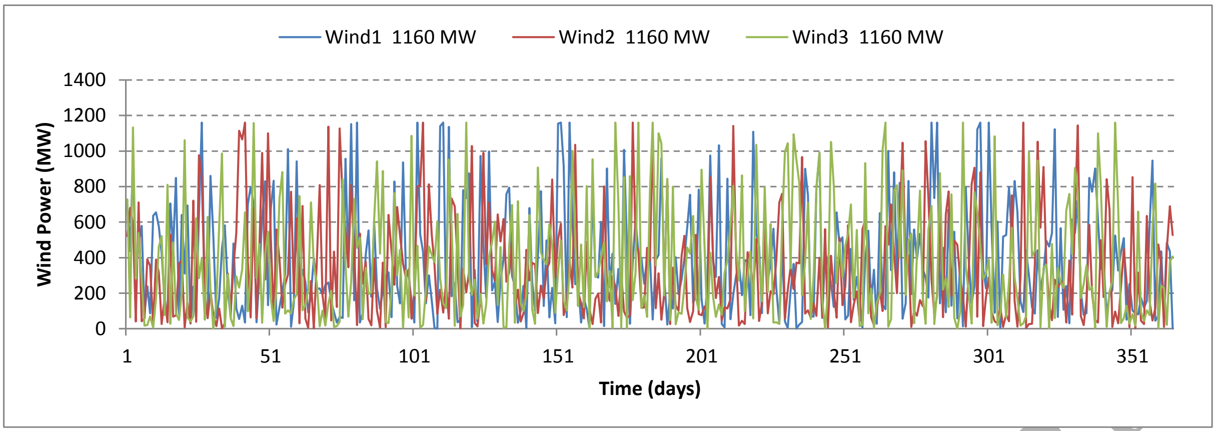

Figure 9: Superficial wind power plant data for the power system considering the replacement of the nuclear power plant with the wind power plants, random weather data very optimistic with capacity factor 0.30

Similarly, Figure 10 shows LOLE for even more optimistic random weather (CF=0.31). Figure 11 shows the related weather data.

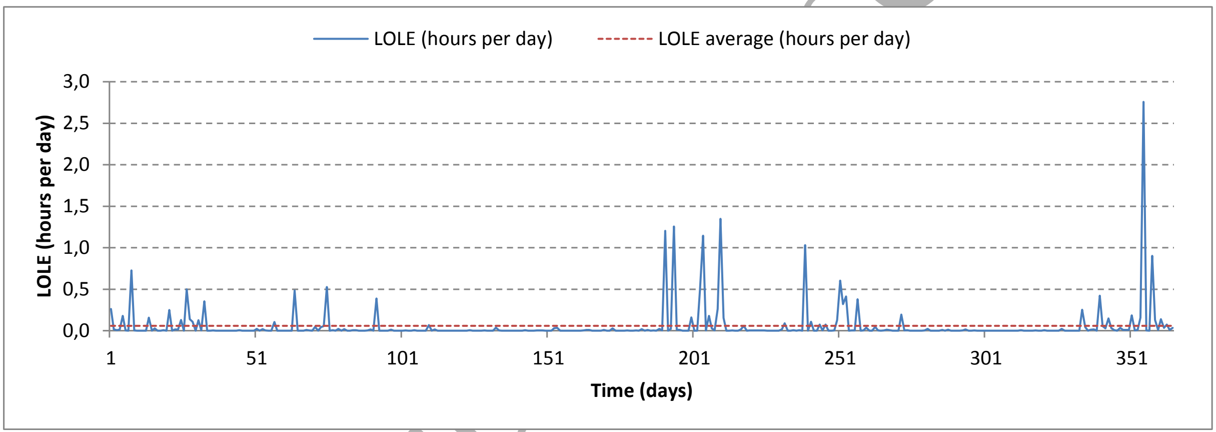

Figure 10: LOLE for power system considering replacement of nuclear power plant (696 MW) with wind power plants (the total of 3480 MW in three plants with 1160 MW each), random weather data very optimistic with the capacity factor 0.31

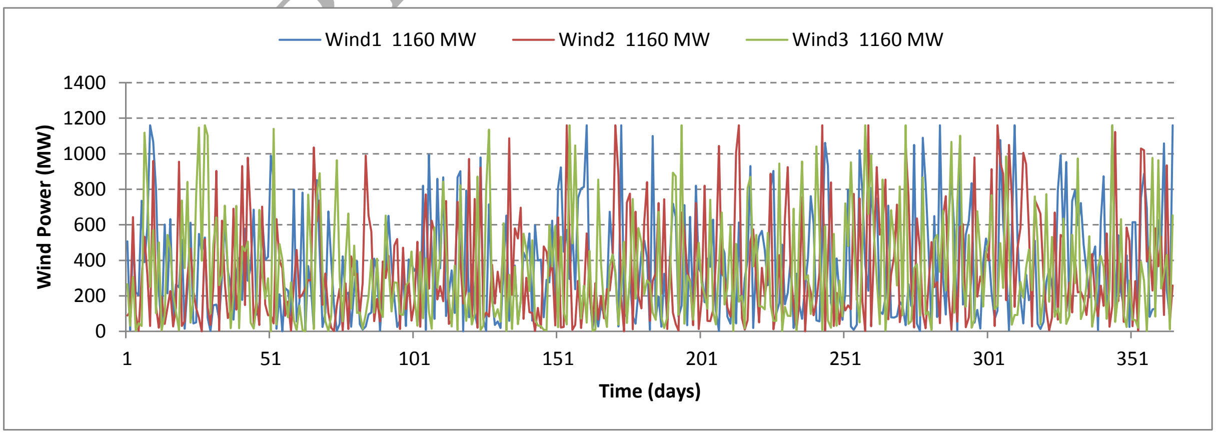

Figure 11: Superficial wind power plant data for the power system considering the replacement of thr nuclear power plant with the wind power plants, random weather data very optimistic with capacity factor 0.31

3.2.3 Comparison of the results

Table 2 shows the collected results, where reliability of the power system is the worse in December, because of low river flows and small amounts of wind power. Some storage or some additional reserve power is needed for this period so that the reliability is not significantly decreased.

Table 2: Collected results of LOLE (h/y)

	Yearly average LOLE (h/y)	Monthly average LOLE (h/y)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Initial power system (with nuclear power plant)	15.10	10.73	4.12	8.03	8.89	1.99	2.14	25.31	8.93	37.13	1.18	7.41	62.21
Nuclear replaced with wind - real wind data	63.61	45.25	0.83	2.04	1.37	0.64	0.11	3.16	3.03	86.24	11.38	91.13	506.27
Nuclear replaced with wind - random wind data 1 (CF=0.30)	32.44	32.08	12.15	13.22	11.22	1.05	4.24	68.44	29.26	30.69	0.49	9.48	173.43
Nuclear replaced with wind - random wind data 2 (CF=0.31)	32.26	11.51	7.32	29.70	11.94	7.81	2.20	62.07	22.89	38.99	4.27	16.88	165.33

The results show that the replacement of the nuclear power plant several wind power plants with wind power capacity five times larger than the nuclear power capacity causes decrease of power system reliability. The most important observation is the variability of reliability throughout months (or weeks, or days) which may direct the different amount of additional storage power in those periods. The storage of power can be achieved by the additional hydro pumping stations as the environmental friendly power storage, or other means of large power storage. One example of such storage are lifted heavy blocks of concrete, which can be gravity driven to release power and can store power by lifting heavy weight blocks of concrete. Storage of power or some additional power reserve needs to be considered together with the replacement of conventional with renewable power otherwise the costs of assuring the needed electric power may become extremely large in some periods, where weather does not allow a lot of production from renewable power. The issue is even more important, if the solar technologies are included, in spite of the fact that they are even more dispersed and connected mostly to the distribution systems on lower voltage levels. But the difference considering the summer and the winter and the day and the night need consideration of more dynamic analyses than was the case decades ago.

4 CONCLUSIONS

The objective of the work was to analyse the replacement of conventional power plant with weather dependent renewable power plants. In other words, the objective was to analyse the replacement of nuclear power plant with several wind power plants.

The methods of static power system reliability were considered and the loss of load expectation was selected for its improvement. The method was improved in order to allow the consideration of variability of power versus weather parameters in power plants considered. The computer code facilitating the evaluations was developed firstly using the straightforward algorithm and secondly using the recursive formulation for larger systems. Then the upgrade of the method was developed.

The difference between the original loss of load expectation method and the developed improvement is that originally the nominal power capacities of power plants have been considered for determining the capacity in outage and the capacity in operation, while the improved method considers the available power capacity due to the weather conditions (river flow, wind speed). The available power capacity can be equal or smaller to the nominal power capacity.

The real power system was selected and the real data related to the power plants in this power system were obtained. The timely functions of the hydro power plants were obtained from hydrology of rivers which is the data publicly available at the weather portal. Similarly, the wind speed and other parameters needed for evaluating the wind power are publicly available at the weather portal and those were used for the year 2016.

The evaluations have been performed for several cases with the common standpoint: the nuclear power plant with 696 MW was exchanged with three wind power plants in the total power of 3480 MW, which is five times larger than the original plant capacity.

The results show the decrease of the power system reliability in the case of mentioned exchange. The decrease of the power system reliability was observed throughout the increase of loss of load expectation both calculated on the real weather data and on the superficial random weather data notably optimistic in terms of producing more wind power as expected according to normal weather conditions.

The results indicate that the change where the conventional power plant is replaced with the weather dependent power plant needs to be accompanied with additional capacity of power storage or with additional reserve capacity if the reliability of the power system needs to be preserved. The required capacity of storage may depend on the period of the year, but the conservative approach requires the largest reserve that may be identified among all periods. The additional reserve capacity can mostly rely on gas power plants, where the storage of gas plays the role of the stored energy.

Further work may include consideration of the storage power in addition to assure the acceptable power system reliability and thus the acceptable loss of load expectation, its average throughout the year and its average over the time intervals within a year. This can include cost optimization by comparing different levels of new renewable power with different levels of the additional storage power. The effective load carrying capability and similar methods can serve as a standpoint.

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