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EVALUATION OF THE IMPORTANCE FACTORS OF THE POWER PLANTS WITHIN THE POWER SYSTEM RELIABILITY EVALUATION

OCENA WSPÓŁCZYNNIKÓW WAŻNOŚCI ELEKTROWNI W RAMACH OCENY NIEZAWODNOŚCI SYSTEMU ELEKTROENERGETYCZNEGO

The objective of the paper is to develop the reliability importance factors which could identify the plants, which more or less contribute to the increased or decreased power system reliability. One group of importance factors could identify the plants, which with their increased availability would notably increase the power system reliability The other group of the importance factors could identify the plants, which with their reduced availability would notably reduce the power system reliability. The importance factors have been developed. An example of regional power system was considered for the case study. The results identify the power plants which are more susceptible to increase of the loss of load expectation and thus to decreasing of the power system reliability, if their availability is reduced. Similarly, the results identify the power plants which are more susceptible to decreasing of the loss of load expectation and thus to increase of the power system reliability, if their availability is increased. The lists of important factors can serve as a standpoint for inclusion of the power system reliability role within the power system to the planning activities. The lists of importance factors can represent the standpoint for the power system operator to reward the improvement of the power plant availability or to penalize the reduced power plant availability.

Keywords: *power plant, reliability, importance, loss of load expectation, network.*

Celem artykułu jest opracowanie współczynników ważności niezawodności, pozwalających identyfikować elektrownie, które w mniejszym lub większym stopniu przyczyniają się do zwiększenia lub zmniejszenia niezawodności systemu elektroenergetycznego. Opracowano dwie grupy takich współczynników: jedne – służące do identyfikacji elektrowni, które przy zwiększonej gotowości mogą znacznie zwiększać niezawodność systemu elektroenergetycznego, i drugie – do identyfikacji tych elektrowni, których zmniejszona gotowość może znacznie zmniejszać niezawodność sieci elektroenergetycznej. Jako studium przypadku rozważano przykład regionalnego systemu elektroenergetycznego. Wyniki pozwalają na wskazanie elektrowni, które są bardziej podatne na zwiększenie oczekiwanego czasu deficytu mocy (niepokrycia zapotrzebowania), a tym samym mogą bardziej przyczyniać się do zmniejszenia niezawodności systemu elektroenergetycznego, w przypadku spadku ich gotowości. Podobnie, uzyskane wyniki pozwalają ustalić, dla których elektrowni prawdopodobieństwo zmniejszenia oczekiwanego czasu deficytu mocy jest większe, a tym samym, które elektrownie mogą bardziej przyczyniać się do zwiększenia niezawodności systemu elektroenergetycznego, gdy zwiększy się ich gotowość. Listy współczynników ważności mogą służyć jako punkt odniesienia dla działań planistycznych, a także jako podstawa dla operatora systemu elektroenergetycznego do nagradzania poprawy gotowości elektrowni lub penalizacji jej spadku.

Słowa kluczowe: *elektrownia, niezawodność, ważność, oczekiwany czas niepokrycia zapotrzebowania, sieć.*

1. Introduction

The power system planning is performed considering the parameters related to the investment costs of power plants, considering the parameters related to the operational costs, considering the parameters, which penalise the impact to the environment, but the reliability of the power plants is not normally considered. The idea of the paper is to make a contribution, to rank the power plants in the power system in a way to consider their impact to the reliability of the power system. The classical method of loss of load expectation is selected as the starting point for the development of reliability importance factors, which would rank the power plants according to their reliability performance in the power system [3, 9].

The objective of the paper is to develop the reliability importance factors for the power plants in the power system based on evaluation of the loss of load expectation. One group of the importance factors could identify the plants, which increased availability would notably or significantly increase the power system reliability. Similarly, the other group of the importance factors could identify the plants, which reduced availability would notably or significantly reduce the power system reliability.

State of the art regarding the power systems reliability includes a large number of important methods and studies [2, 5, 8]. Much less has been written regarding the importance factors, although some papers exist in the field [9, 10]. However, they are not based on the loss of load expectation, which is one of the most widely used methods for adequacy evaluation, i. e. determining the reserve power for the static power system reliability evaluation [3, 5-7, 9, 15, 18]. Section 2 gives the overview of existing methods and newly developed importance factors. Section 3 gives the results of the case study showing the values of newly developed importance factors on selected cases. Section 4 gives conclusions.

2. Methods

2.1. The LOLE method

The focus of the paper is placed to the static methods aiming at power system adequacy [2, 3, 8, 9]. The loss of load expectation

(LOLE) is a standardised method for determination of the power system reserve in order that the power system reliability does not fall below the required reliability level.

LOLE represent the number of hours in a year (other units are possible), in which the power consumption could not be covered by the available power plants. Many states are considered. Each state expresses a configuration of the power system related to information that some power plants are available and some are unavailable at certain moment. The states are related to the load diagram. The load diagram is a diagram, which represent the hourly distributed load of all the consumers, which needs to be supplied [2, 3, 8, 9].

Figure 1 shows the parameters for evaluation of the LOLE on an example load diagram. The example load diagram is not ordered by the actual daily time, but the time points are followed by the decreasing capacity, as it is needed for evaluation of LOLE.

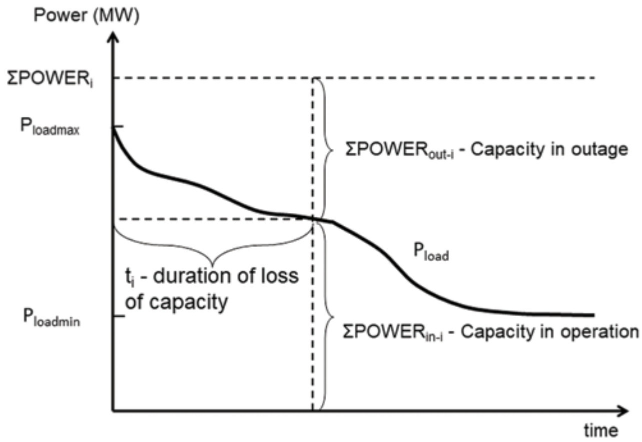

Fig. 1. Graphical representation for determining the loss of load expectation

The equation for calculation of LOLE:

$$LOLE = \sum_{i=1}^{ii} p_i \cdot t_i \tag{1}$$

$$t_i = time \qquad where \qquad P_{load} > \sum POWER_{in-i} \tag{2}$$

i – index of considered state

p_i – probability of state i

t_i – duration of loss of capacity of state i, the time interval, in which the capacity of power plants in operation does not reach the power of load

ii – the number of states

$ii = 2^n$

n – number of power plants in the system

P_{load} – power system load with its minimal value $P_{loadmin}$ and its maximal value - $P_{loadmax}$

$POWER_{in-i}$ – the sum of powers of the power plants, which are assumed available in state i

$POWER_{out-i}$ – the sum of powers of the power plants, which are assumed unavailable in state i

Probability of state i is evaluated as a product of availabilities and unavailabilities of plants assumed available or unavailable in this state. Thus, the states differ among each other by considering different sets of available and unavailable plants. In the case of one plant: it can be available or unavailable. In the case of two plants, we have four states: both available, both unavailable, first available and second unavailable, first unavailable and second available.

$$p(i) = \prod_{r=1}^{n1} a(r) \cdot \prod_{s=1}^{n2} (1 - a(s)) \tag{3}$$

n1 – number of plants available for certain state

n2 – number of plants unavailable for certain state

n=n1+n2

a(r) – availability of plant r (unavailability is expressed as u(r)=1-a(r) is its complement, or availability is expressed with forced outage rate (FOR) as a(r)=1-FOR(r), because forced outage rate can represent unavailability, u(r)= FOR(r))

a(s) – availability of plant s

The number of states and thus the time of evaluation increases significantly with the increase of number of power plants considered. Therefore, recursive algorithms have been developed, which does not go state by state when evaluating the LOLE, but they build the evaluation by adding the plants one by one to the evaluation [15, 18, 29, 31, 32].

Table 1 shows a small example of a power system including the data and the results, which give LOLE. The load diagram has the maximum power of 40 MW and the minimal power of 10 MW and in between it is linear. Figure 2 shows the load diagram.

Explanation of the table says that the first line shows state 1 and all three units in operation. Their total unavailable power is 0 MW and the total available power is 80 MW. The product of plant availabilities gives the probability of the state 0.8208. Their power is all the time larger than the load, so the time duration of loss of capacity is 0. The subsequent lines follow the described method. Figure 2 shows that 8 hours are such, where capacity service of 30 MW is smaller than the load.

Table 1. Example of 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	8	0.0304
7	0	0	1	70	10	0.10·0.05·0.96=0.0048	24	0.1152
8	0	0	0	80	0	0.01·0.05·0.04=0.0002	24	0.0048
						LOLE (hours/day) =		0.1504

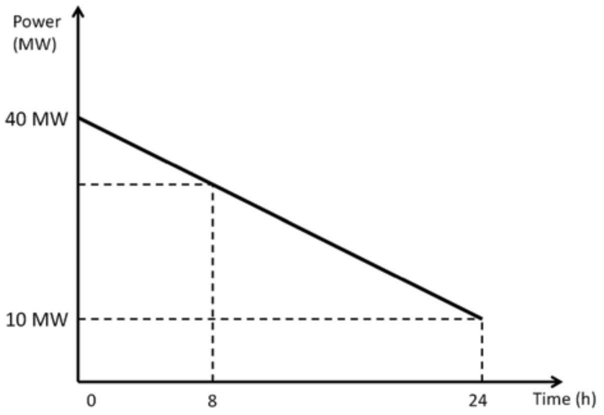

Fig. 2.Load diagram for a small example system

2.2. The improved LOLE method

The improved loss of load expectation method has been developed keeping in mind that the power plants, which rely on environmental conditions cannot have the nominal power available all the time [1, 4, 11, 13-14, 16]. Their power changes with regard to the related parameters such as river flow in the case of hydro power plants, wind speed in the case of wind power plants and sun irradiance in the case of the solar power plants [5, 6, 8]. Please note, that the listed factors are only representative for each plant. In reality, much more factors are involved in mathematical models, where the power of the specific plant is expressed based on influencing factors such as pressure, temperature and humidity for example. Figure 3 shows graphical representation of parameters for determining the improved LOLE. The figure shows that the overall considered time interval (usually a day or a year) is divided to 6 time windows for the figure being indicative. In reality, the considered time windows are cut to 1 hour windows even to time windows of shorter time durations.

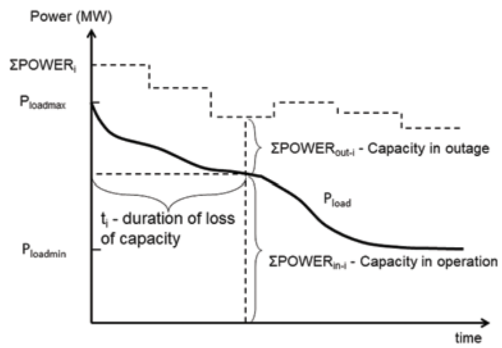

Fig. 3. Graphical representation of parameters for determining improved loss of load expectation

Evaluation of the loss of load expectation is calculated for each time window, its mean value over all time windows can give the average:

$$LOLE = \frac{i}{z}\sum_{j=1}^{z} LOLE_j \tag{4}$$

$LOLE_j$ – loss of load expectation in time window j (hours per day)
LOLE – loss of load expectation (hours per day)
z = number of time windows considered
j = index of a time window

2.3. Importance factors

The importance factors: RIF (risk increase factor) and RDF (risk decrease factor) have been originally developed for expressing the importance of different safety equipment in the safety and reliability analyses [9, 33]. Some other importance factors and their variants followed [10, 12, 20]. RIF was initially named as risk achievement worth (RAW). RDF was initially named as risk reduction worth (RRW).

The equation for calculation of RAW is the following:

$$RAW_a = \frac{P_s\left(P_a = 1\right)}{P_s} \tag{5}$$

RAW_a – risk achievement worth for failure of component A modeled in event a,
$P_s(P_a=1)$ – system failure probability when failure probability of component A modeled in event a is set to 1,
P_s – system failure probability.

The equation for calculation of RRW is the following:

$$RRW_a = \frac{P_s}{P_s\left(P_a = 0\right)} \tag{6}$$

RRW_a – risk reduction worth for failure of component A modeled in event a,
$P_s(P_a=0)$ – system failure probability when failure probability of component A modeled in event a is set to 0,
P_s – system failure probability.

2.4. New importance factors

The importance factors are factors, which based on some determined sensitivity analyses determine the impact of a certain parameter to the calculated result. They help ranking the components of the system based on the selected parameters.

The following importance factors have been developed for ranking of the power generating plants in the power system in sense to judge their role in contributing to the static system reliability and in sense to judge their role in contributing to the determining the power reserve needed for assuring power system reliability.

LOLE absolute increase factor for power plant i shows how much LOLE is increased in the case if the power plant i would become totally unavailable (its availability becomes 0, a(i)=0):

$$\mathrm{LOLE}_{\mathrm{abs-increase-i}} = \frac{LOLE_{a(i)=0}}{LOLE} \tag{7}$$

LOLE absolute decrease factor for power plant i shows how much LOLE is decreased in the case if the power plant i would become totally available (its availability becomes 1, a(i)=1):

$$\mathrm{LOLE}_{\mathrm{abs-decrease-i}} = \frac{LOLE}{LOLE_{a(i)=1}} \tag{8}$$

LOLE – loss of load expectation for the power system considering the number of power plants in the system and considering the load diagram
$LOLE_{abs\text{-}increase\text{-}i}$ – LOLE absolute increase factor for the power plant i
$LOLE_{abs\text{-}decrease\text{-}i}$ – LOLE absolute decrease factor for the power plant i
$LOLE_{a(i)=0}$ – LOLE if availability of the power plant i equals to 0
$LOLE_{a(i)=1}$ – LOLE if availability of the power plant i equals to 1

When LOLE is increased in the power system, this means more hours per year without power supply, and it is related with decrease of the power system reliability. Plants with high $LOLE_{abs\text{-}increase}$ are important in the power system in order to maintain them and monitor their availability in order not to become unavailable. Reduction of their availability affects the system reliability in a large extent.

Plants with high $LOLE_{abs\text{-}decrease}$ are important in the power system for its reliability improvement. Their improved availability in a large extent causes LOLE decrease and thus the power reliability increase.

Those two importance factors: $LOLE_{abs\text{-}increase\text{-}i}$ and $LOLE_{abs\text{-}decrease}$ can be considered as static, similarly as it is LOLE in section 2.1.

When considering different $LOLE_j$ in different time windows (see eq. 4 in section 2.2), one has to develop also importance factors for each time window: $LOLE_{abs\text{-}increase\text{-}i\text{-}j}$ and $LOLE_{abs\text{-}decrease\text{-}i\text{-}j}$.

Each of the the time windows with specific power system conditions need to be considered separately for better representation of the system behavior. In addition the average can be calculated as for LOLE in eq. 4.

The different LOLE absolute increase factors for the time windows can give also their mean value and show the change of this factor at different time windows of the power system. Similarly, the different LOLE absolute decrease factors for the time windows can give their mean value and show the change of this factor at different time windows of the power system:

$$\mathrm{LOLE}_{abs-increase-i-mean} = \frac{1}{jj}\sum_{j=1}^{jj}\mathrm{LOLE}_{abs-increase-i-j} = \frac{1}{jj}\sum_{j=1}^{jj}\frac{LOLE_{j\_a(i)=0}}{LOLE_j} \quad (9)$$

$$\mathrm{LOLE}_{abs-decrease-i-mean} = \frac{1}{jj}\sum_{j=1}^{jj}\mathrm{LOLE}_{abs-decrease-i-j} = \frac{1}{jj}\sum_{j=1}^{jj}\frac{LOLE_j}{LOLE_{j\_a(i)=1}} \quad (10)$$

$LOLE_{abs\text{-}increase\text{-}i\text{-}mean}$ – mean LOLE absolute increase factor for the power plant i

$LOLE_{abs\text{-}decrease\text{-}i\text{-}mean}$ – mean LOLE absolute decrease factor for the power plant i

$LOLE_{abs\text{-}increase\text{-}i\ \text{-}j}$– LOLE absolute increase factor for the power plant i in time window j

$LOLE_{abs\text{-}decrease\text{-}i\text{-}j}$ – LOLE absolute decrease factor for the power plant i in time window j

$LOLE_{j\_a(i)=0}$ – LOLE in the time interval j if availability of the power plant i equals to 0

$LOLE_{j\_a(i)=1}$ – LOLE in the time interval j if availability of the power plant i equals to 1

$LOLE_j$ – loss of load expectation for the power system in the time interval j

3. Analyses and Results

3.1. Models

Several power system models were used for application of the developed models. The verification of the algorithm for LOLE was performed for reliability test system.

An example of regional power system was considered for the case study. The selected regional system includes nuclear power plant, thermal power plants, hydro power plants and wind power plant. Table 2 shows the characteristics of the regional power system, which are needed for the evaluation of LOLE and the importance factors.

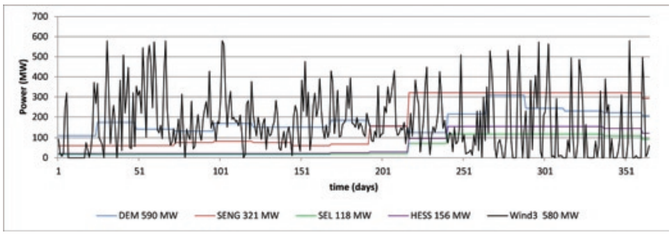

Fig. 4. The timely curves of the power of the power plants in the power system, which are subjected to the power system changes versus time

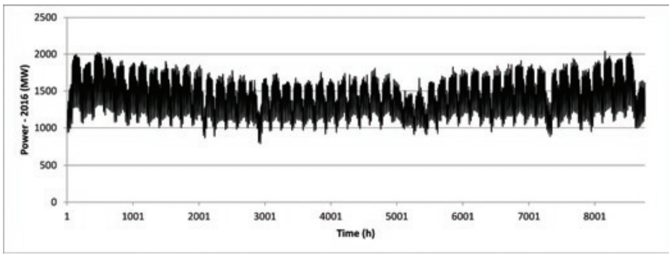

Fig. 5 The power consumption in the power system in the year 2016

Table 2. Characteristics of the regional power system

Plant Identification (includes nominal power)	Plant Type	Forced outage rate (FOR); unavailability	1-FOR; availability
NEK 696 MW	Nuclear	0.01	0.99
TEŠ6 544 MW	Thermal (coal)	0.08	0.92
TEŠ5 345 MW	Thermal (coal)	0.09	0.91
TEŠ4 275 MW	Thermal (coal)	0.09	0.91
TEŠplin 84 MW	Thermal (gas)	0.06	0.94
TETOL 124 MW	Thermal (coal)	0.06	0.94
TEB 350 MW	Thermal (gas)	0.04	0.96
DEM 590 MW	Hydro	0.01	0.99
SENG 321 MW	Hydro	0.01	0.99
SEL 118 MW	Hydro	0.01	0.99
HESS 156 MW	Hydro	0.01	0.99
Biomass 442 MW	Biomass	0.01	0.99
Wind 580 MW	Wind	0.01	0.99

Figure 4 shows the power plants, which are subjected to the power changes due to the weather parameters such as hydro power, which depends on the river flow and wind power, which depends on the wind speed.

Figure 5 shows the power consumption in the power system in the year 2016 including the losses at the transmission and distribution.

3.2. Analyses and results

LOLE was calculated for the example regional power system. Actually, LOLE was calculated in every time window (every day), considering the actual power plant power at each time window related to the actual weather parameters (river flow, wind speed) instead of considering the nominal power through all the evaluation.

Table 3 shows the calculated average importance factors for the regional power system. Figure 6 shows the LOLE absolute increase factors for the plants in the example power system. Figure 7 shows the LOLE absolute decrease factors for the plants in the example power system.

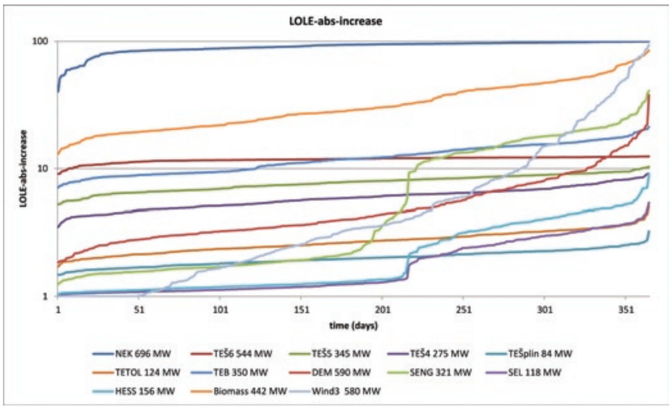

Fig. 6. The LOLE absolute increase factors for the plants in the example power system

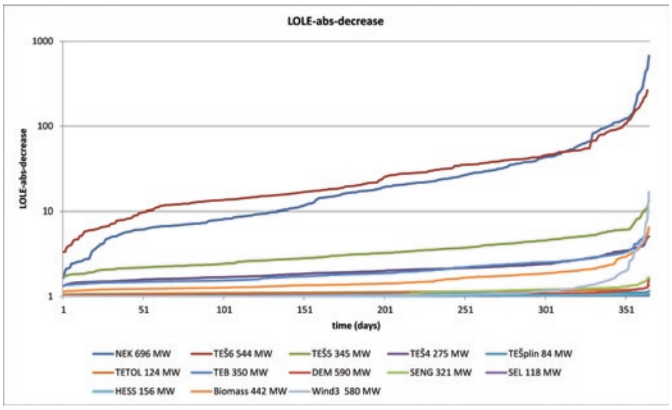

Fig. 7. The LOLE absolute decrease factors for the plants in the example power system

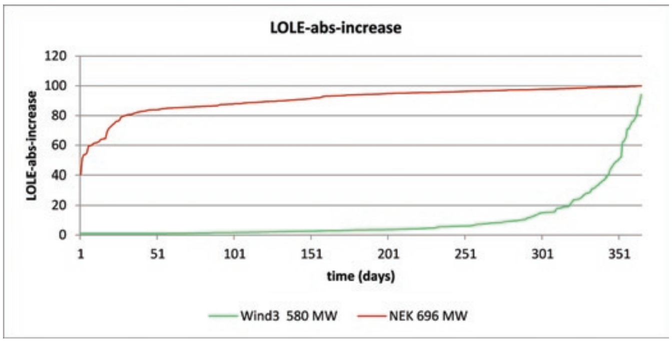

Fig. 8. The LOLE absolute increase factors for the plants in the example power system – nuclear versus wind

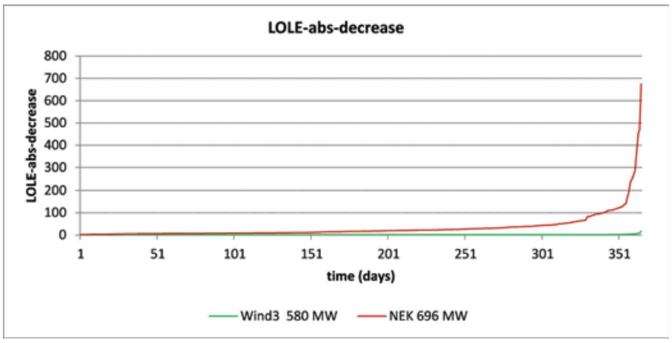

Fig. 9. The LOLE absolute decrease factors for the plants in the example power system – nuclear versus wind

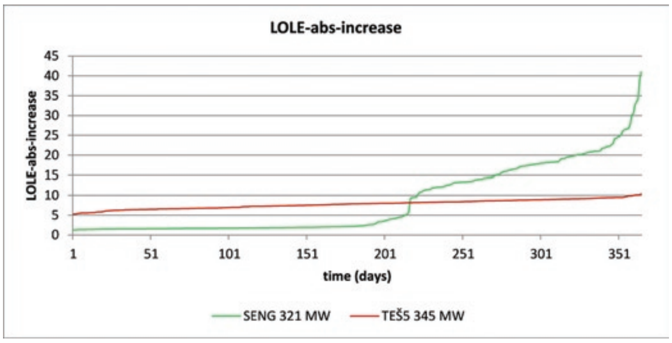

Fig. 10. The LOLE absolute increase factors for the plants in the example power system – thermal versus hydro

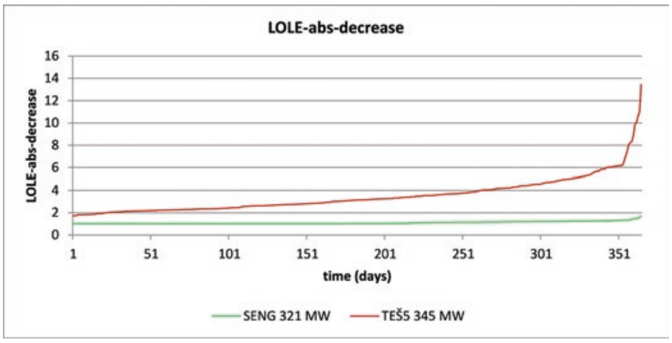

Fig. 11. The LOLE absolute decrease factors for the plants in the example power system – thermal versus hydro

Table 3. Average importance factors for the regional power system

Plant Identification (includes nominal power)	Forced outage rate (FOR)	$LOLE_{abs\text{-}increase\text{-}mean}$	$LOLE_{abs\text{-}decrease\text{-}mean}$
NEK 696 MW	0.01	90.76	33.66
TEŠ6 544 MW	0.08	11.80	32.15
TEŠ5 345 MW	0.09	7.79	3.50
TEŠ4 275 MW	0.09	5.95	2.08
TEŠgas 84 MW	0.06	2.00	1.06
TETOL 124 MW	0.06	2.72	1.12
TEB 350 MW	0.04	12.29	2.04
DEM 590 MW	0.01	5.64	1.05
SENG 321 MW	0.01	8.41	1.09
SEL 118 MW	0.01	1.86	1.00
HESS 156 MW	0.01	2.34	1.01
Biomass1 442 MW	0.01	33.49	1.61
Wind1 580 MW	0.01	9.66	1.23

Figure 8 shows the comparison the nuclear power and wind power related to the LOLE absolute increase factors. Figure 9 shows the comparison the nuclear power and wind power related to the LOLE absolute decrease factors.

Figure 10 shows the comparison the hydro power and thermal power related to the LOLE absolute increase factors. Figure 11 shows the comparison the hydro power and thermal power related to the LOLE absolute increase factors.

The results show that the power plants which can in the largest extent contribute to the decrease of the power system reliability (if their availability is reduced) are the nuclear (NEK), the thermal (TEŠ6 and TEB) and the biomass (Biomass1) power plants. Those plants availability need to be kept at the current level, otherwise the reliability of power system can be largely reduced (i.e. LOLE largely increased).

The results show that the power plants which can in the largest extent contribute to the increase of the power system reliability (if their availability is improved) are the nuclear (NEK) and the thermal (TEŠ6) power plants. All others can contribute to better power system reliability in much smaller extent. Those two plants need to be mostly credited for the good power system reliability. The system reliability measured by LOLE is 0.43 hours per year (average through all time windows).

The results can represent the standpoint for planning of future power systems. Normally, the optimisation of the levelised costs of electricity include the investment costs, the operational costs the impact to the environment, but no contribution to the reliability of power system. Application of this method could mean the standpoint for inclusion of the power system reliability role within the power system to the planning activities in order that some renewable plants are not favorited too much.

4. Conclusion

The objective related to development of the reliability importance factors for power plants in the system has been reached. New reliability importance factors have been developed. Their application on the real regional power system example was demonstrated. The results identify the most important plants in terms of mean LOLE absolute increase factor and thus decreasing the power system reliability. Similarly, the results identify the most important plants in terms of mean LOLE absolute decrease factor and thus increasing the power system reliability.

The lists of important factors can serve as a standpoint for inclusion of the power system reliability role within the power system to the planning activities.

The lists of importance factors can represent the standpoint for the power system operator to reward the improvement of the power plant availability or to penalize the reduced power plant availability.

Further work can be directed to develop the quantitative specifications of the importance factors for the power system planning and to develop the quantitative criteria for rewarding the availability improvement at each plant and the criteria for penalising the availability reduction at each plant.

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