Probabilistic Transmission Network Planning Based on Risk Criteria

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Abstract:
The proposed methodology introduces the risk concept, which takes into consideration the probability of the occurrence of different operating states, the probability of the outage of system elements, and the impact such outages would have on the electric power system (EPS). The impact on the EPS is assessed on the basis of a new indicator called Impact on the Grid (IOG), which takes into consideration all overloads caused by the outage of a particular element. The new methodology, based on a risk index, demonstrates the reliability of the EPS and provides background and arguments, useful for transmission system operators (TSOs) taking decisions regarding new investments on the TN. The new methodology also contributes multi-selection criteria for determining priorities among individual investments, based on investment costs and on maintaining a sufficient level of reliability.

1. Introduction

When planning a transmission network, a TSO uses the deterministic N-1 criterion, according to which an outage of any network element should not cause any overloading of system elements, any voltage violation, any interruption of electricity supply, any system instability and/or any cascading outages [1]. This traditional approach does not take into consideration the probability of various operating states, and also does not consider the probability of outages of individual network elements and the impact of these outages on the EPS. Instead, it is based on the "worst case scenario" [2], [3], [4], [5] which is a very conservative approach. Specifically, the operating state that reflects the "worst case scenario" might be an operating state with such a low probability of occurrence that it could be disregarded. And conversely, the N-1 deterministic criterion disregards operating states with a higher probability of occurrence. In addition to this, the traditional network development approach only provides very general information regarding whether or not the security criterion is fulfilled, while more detailed network security analysis is rather challenging to achieve (it is difficult to compare two outages with the same degree of probability of occurrence, but with different impacts on the transmission network) [6], [7]. Analysis based on the deterministic criterion usually leads to over-dimensioning and excessive investment into the TN [2], [8], which results in higher tariffs for consumers.

Alternatively, probabilistic criteria and criteria for assessing reliability take into consideration the stochastic nature of the EPS and address a large number of operating states, including their probability of occurrence. Furthermore, on the basis of past states, the probabilistic methods enable the modelling of future states [2], [3], [6]. Well-known methods such as Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Unserved Energy (EUE), when used as risk criteria, integrate the probability of outage and its impact on the network, which is reflected as a loss of load [6]. Up to now, many different methods using approaches based on risk evaluation have been applied [6], [8-16], but they have mainly assessed reliability on the basis of one indicator. Either on the basis of overload caused by an outage of an element [10], on the basis of voltage violations and angular stability [16], or on the basis of load outage [8], [13], [14], [15]. The methodology presented in [9] combines various problems in the network into one indicator. A criterion that reflects combined problems in the network is called "per cent of security/reliability" and expresses system reliability as a percentage; 100 % reflects a totally reliable system and 0 % a completely unreliable system. This criterion only combines a number of individual violations, and fails to reflect the individual size of each violation (if an outage of an element leads to three overloads below 120 % of thermal capacity, such an outage is less important than an outage which causes three overloads greater than 120 %). However, in [11] a different alternative solution for transmission expansion planning, which accounts for various risk factors, has been analyzed in order to illustrate how to include risk analysis in the transmission network planning process.

This paper presents a new transmission network development methodology, which is based on the risk criterion that combines a variety of restrictions in the transmission network under one single indicator, and which represents the appropriateness of reliability of the electric power system (EPS). The new methodology for the planning of the TN takes into consideration the probability of individual operating states as well as the probability of the outage of individual network elements and the impact of this on the network. The impact on the network is presented with a new indicator called Impact on the Grid (IOG), which represents all violations [1] on the network (both the size and number of violations) caused by the outage of an element (such as overloading, voltage violations, interruption of electric power supply of substations and generation downtimes) in an appropriately weighted manner. The advantage of this methodology is that it enables multi-scenario selection and can be applied to any future year. A further important advantage is its capability of comparing the reliability of two different operating states or network configurations in a relatively simple way. At the same time, it will be a great help to TSOs prioritizing investments into the TN, as it will enable the optimization of investment costs in new TN elements while maintaining a sufficient level of reliability.

The new methodology has been applied and tested on the Slovenian EPS. Specifically, analyses have been carried out on the 110 kV network of the Primorska region, and the results presented here. Comparisons with the traditional N-1 deterministic method have also been calculated, and the results compared, both technically and financially, with the approved ten-year development plan of the Republic of Slovenia [17].

The remainder of the paper consists of Chapter 2, which presents the methodology and algorithm of the calculations and a description of the operation; Chapter 3, which presents the test model of a part of Slovenia's 110 kV network, a presentation of the results of the calculations, and a comparative analysis; and Chapter 4, which provides conclusions and findings, and the main contributions of this paper.

2. Stochastic formulation and algorithm

In the context of electric system reliability, risk is the likelihood that an operating event will reduce the reliability of the EPS to the point that the consequences are unacceptable [7]. A TSO cannot prevent all events from happening but it plans and operates the EPS in such a way that, if and when such events occur, their effects are manageable and consequences acceptable [7].

In Figure 1, the risk concept is presented. The green area represents a low probability of occurrence with acceptable consequences to the EPS. In this area, outages of elements impacting the grid do not represent a major threat to the reliable operation of the EPS, and can be managed in real time operation. Therefore, the risk of such outages is acceptable and additional investment into grid reinforcement aimed at minimising it is not necessary. The yellow area represents a medium level of risk. In this area, outages are divided between outages with high probability and low impact on the grid (which can lead to minor operating problems, but can be controlled in real time operation and will, in most cases, not impact the reliability of the EPS), and outages with low probability and high impact which can lead to unacceptable consequences, such as blackouts. As it is economically impossible to construct an electric system robust enough to be unaffected by extremely unlikely and extremely severe events [7], TSOs accept some risk of those kinds of outages. For these outages (yellow area top left corner) TSOs prepare detailed analyses and concrete defence plans in order to minimize the consequences to the EPS as far as possible. New investments in this area are questionable, as they can lead to over dimension of the TN and, as such, are not economically justified. The red area represents a high level of risk. Outages in this area can seriously threaten the reliability of the EPS, so measures and new investments into the EPS are of high priority. According to the basic principles of asset management, the goal in the decision process is to either eliminate likely events with unacceptable consequences (in the red field on Figure 1), or else reduce their impact and/or probability to a sufficient degree that they are shifted out of the red field. For all outages of elements, which have impact on the grid, in the red area we have to plan new investments in the grid.

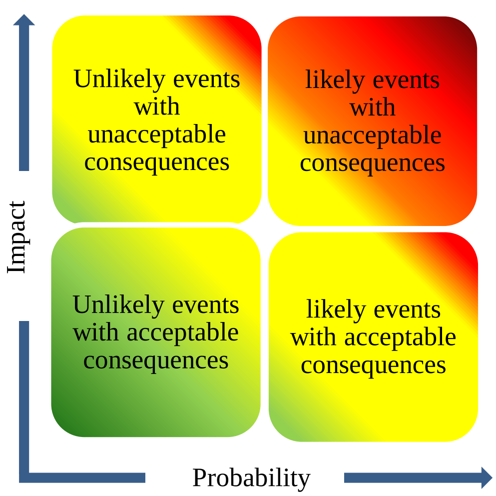


Fig.1: *Risk concept [7]*

To assess the risk-based reliability of the EPS, the probability of the occurrence of an operating state and the consequence on the EPS resulting from such an operating state [7], [13] should be analyzed. The potential risk (PR) to the EPS, on the basis of which we will assess reliability, can be written as:

$$PR_i(OS_i) = P(OS_i) \cdot IOG_i(OS_i), \tag{1}$$

where:
OS_i: is the operating state i,
$PR_i(OS_i)$: is the potential risk of operating state i,
$P(OS_i)$: is the probability of the occurrence of operating state i,
$IOG_i(OS_i)$: is the impact on the grid resulting from operating state i

The probability of an operating state is defined as the product of the probability of the system state, which refers to load [8], generation probability and outage probability [18], [19] of an individual element:

$$P\,(OS_i) = P_k(O)\cdot P(g_i)\cdot P(b_i), \tag{2}$$

where:
$P_k(O)$ is the probability of outage of a system element
$P(b_i)$ is the probability of occurrence of system load i
$P(g_i)$ is the probability of occurrence of generation i

In order to determine the probability of a future operating state (load and generation), on the basis of statistical processing and load forecasts, we initially carried out a probability histogram of future system loads, which was divided into individual load intervals, with a generation histogram carried out for each load interval. The probability of the outage of an individual system element has been determined by historical observation of the outages of generators, power lines (single, double), transformers and substations, and was calculated as follows [18], [19]:

$$P_k(O) = \frac{h_k \cdot t_k}{8760}, \tag{3}$$

where:
$P_k(O)$ is the probability of an outage of a system element k
h_k is system element k outage frequency in occurrences per year
t_k is system element k outage duration in hours
k different system elements

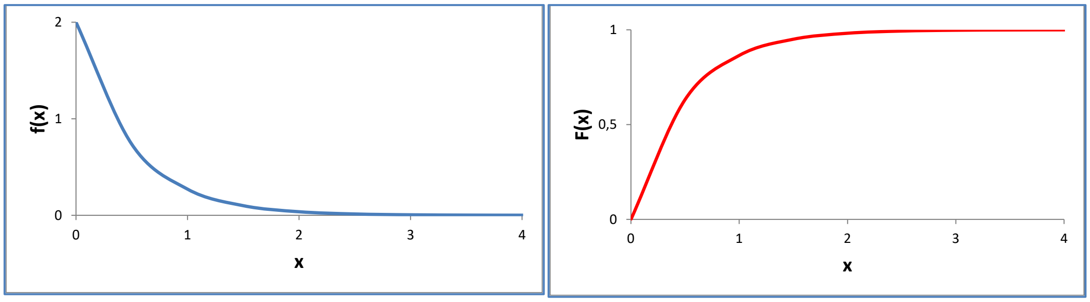
In order to incorporate all problems caused by an individual outage into a single indicator, an equation (6) can be used to calculate the impact on the grid (IOG). The basis for writing the IOG function was the exponential distribution function [19], one of the most important distribution functions used for reliability calculations, with which the probability density and its cumulative distribution function can be written as:

$$\mathrm{f(x)} = \begin{cases} \lambda e^{-\lambda x}, & x \geq 0 \\ 0, & x < 0, \end{cases} \tag{4}$$

$$F(\mathrm{x}) = \begin{cases} 1 - e^{-\lambda x}, & x \geq 0 \\ 0, & x < 0, \end{cases} \tag{5}$$

Where;
$\lambda > 0$ is the parameter of the distribution,
x random variable x

Figure 2 shows the exponential distribution function for both the probability density function (Subfigure a) and cumulative distribution function (Subfigure b).



a   b

Fig.2: *Exponential distribution function*
a Probability density function (λ = 2)
b Cumulative distribution function (λ = 2)

The cumulative distribution function has been used to write IOG as follows:

$$IOG_i = 1 - e^{-2\cdot(\alpha \cdot PE_i + \beta \cdot UN_i + \gamma \cdot Pbg_i)} \tag{6}$$

Where:

$$PE_i = \sum_{j=1}^{n} \left(\frac{PE_{\text{overloadi, } j}}{PE_{\max}} - 1 \right) \tag{7}$$

$$UN_i = \sum_{k=1}^{m} \left(\frac{U_{\text{limitmaxi, k}}}{U_{\text{nominalmax}}} - 1 \right) + \sum_{k=1}^{m} \left(1 - \frac{U_{\text{limitmini, k}}}{U_{\text{nominalmin}}} \right) \tag{8}$$

$$Pbg_i = \sum_{l=1}^{o} \left(\frac{P_{bi,l}}{P_{bk}} \right) + \sum_{l=1}^{o} \left(\frac{P_{gi,l}}{P_{g\max}} \right) \tag{9}$$

IOG_i	is the impact on the grid in operating state i
PE_i	is the impact on the element in operating state i
$PE_{overload,\ i}$	is the overloaded element in operating state i [%]
PE_{max}	is the maximum permitted load on the element [%]
UN_i	is the impact on the node voltage in operating state i
$U_{limitmax,i}$	is the voltage in operating state i, beyond the upper permitted limit [%]
$U_{nominalmax}$	is the maximum permitted voltage [%]
$U_{limitmin,i}$	is the voltage in operating state i, beyond the lower permitted limit [%]
$U_{nominalmin}$	is the minimum permitted voltage [%]
Pbg_i	is the impact on loss of load and loss of generation in operating state i
P_{bi}	is the loss of load in operating state i [%]
P_{bk}	is the peak active load in the observed year [%]
P_{gi}	is an outage of generation in operating state i [%]
P_{gmax}	is the maximum generation [%]
n	is the number of overloaded elements in operating state i
m	is the number of node voltage violations in operating state i
o	is the number of load and generation loss in operating state i
α,β,γ	are coefficients

Security parameters, defined as PE_i, UN_i and Pbg_i represent the impact of different components and have a major impact on the exponential distribution function used in the IOG. This means that the higher the impacts of different components in the system are, the closer the results of IOG are to 1. As such, the value 1 represents the maximum impact on the grid, and the value 0 represents the minimum impact on the grid. The influence of components on the IOG are plainly shown in Figure 2, Subfigure b, where the random variable x represents the sum of the security parameters PE_i, UN_i and Pbg_i.

The distribution parameter λ was set based on an experiment using test simulations carried out on the RBTS (Roy Billinton Test System). We followed the principles from the transmission system standards [1],[7],[18], where different security limits for low and high probability elements, as well as the cascade event probability, are considered. If the overloading of an element is below 120 % the probability of tripping and cascading is lower than if the overloading of an element is above 120 %. The parameter λ was selected based on the experiment and the test calculations: $\lambda = 2$.

By setting one or more of the coefficients α, β and γ in equation (6) to 0, we can exclude selected security parameters (PE_i, UN_i and Pbg_i) from the calculation. Normally all security parameters are included in calculations, so all coefficients were set to 1. As such, the equation represents the impact on the grid in a manner which accounts for element overloads, voltage violations, loss of load, and loss of generation, as well as the number of individual overloads resulting from element outage. If we present the results of calculations solely on the basis of IOG, we already obtain an overview of individual outages which can be compared to each other very easily. Therefore we can identify which outages are less important from the operating point of view and which outages are extremely important and require follow-up actions.

Impact on the grid (IOG) (for $\alpha = 1$, $\beta = 0$, $\gamma = 0$) is calculated when the thermal load of an element is exceeded, as the ratio of overload on the element and its thermal load. If the results of IOG are compared to traditional N-1 criterion all values higher than 0 mean that the N-1 criterion is not fulfilled. Additionally, as presented in Figure 3, all overloads are included in the calculations.

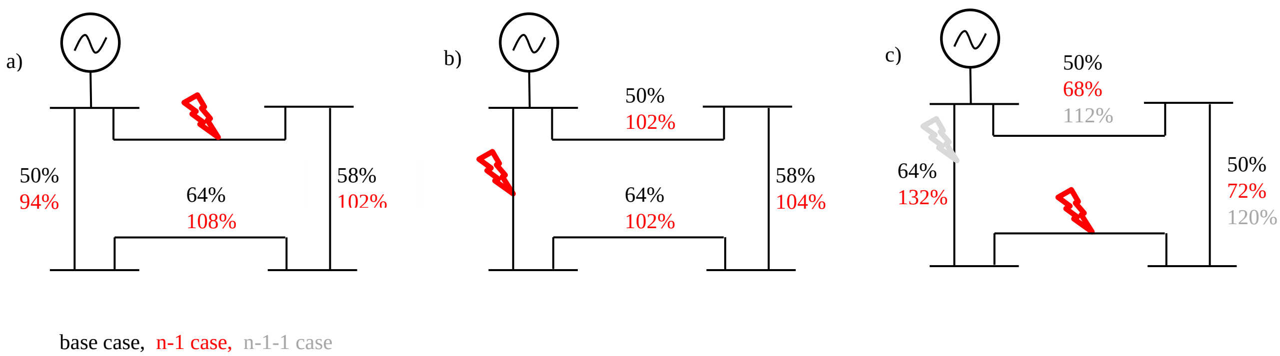


Fig.3: *example*

As shown in Figure 3, example a) the outage of the line (red arrow) causes overloads on two lines (PE = 0.1), while the outage in example b) causes overloads on three lines (PE = 0.08). In example c) n-1 of the line causes activation of line protection and additional line tripped out (grey arrow), causing overloads on the remaining two lines (PE=0.72). From Figure 3 we can see that in all cases N-1 criteria is not fulfilled, but the outage in example a) is more important than the outage in example b). The outage in example c) causes cascade tripping and loss of substation, and is therefore the most important.

Where IOG occurs in the area of likely events with unacceptable consequences, it is required to either eliminate likely events with unacceptable consequences (in the red field on Figure 1), or else reduce their impact and/or probability to a sufficient degree that they are shifted out of the red field. For all outages of elements, which have impact on the grid, in the red area we have to plan new investments in the grid. We can define the area covered in the decision making process using level of operating risk (SOT). The level of operating risk (SOT) can be set either to cover likely events with unacceptable consequences (red field on Figure 1); to cover likely events with unacceptable consequences, unlikely events with unacceptable consequences and likely events with acceptable consequences (red and yellow field on Figure 1); or to cover all events in the EPS, including unlikely events with acceptable consequences (this represents the traditional N-1 criterion). According to the asset management principle the main goal is to cover all likely events with unacceptable consequences (red field in Figure 1). Therefore the level of operational risk was set as a linear function:

$$SOT = -10 \cdot P(OS_i) + 1.2 \quad (10)$$

Based on PR and IOG calculations, additional criteria have been introduced; the sum of all potential risks (SPR) and the sum of all violations where IOG exceeds the level of operating risk (NPR). The first represents the sum of all PR_i and is expressed as one percentage value, and the other represents the sum of all violations exceeding the level of operating risk in the observed period:

$$SPR = \sum_{i=1}^{s} PR_i(OS_i), \quad (11)$$

where:
SPR is the sum of all potential risks
s is the number of all analyzed operating states
$PR_i(OS_i)$ is the potential risk in operating state i

$$NPR = \sum_{i=1}^{s}(y_i)\,, \tag{12}$$

where:
NPR is the sum of IOG where the level of operating risk is exceeded
s is the number of all analyzed operating states

$$y_i = \begin{cases} 1, & |IOG_i \geq SOT \\ 0, & |IOG_i < SOT \end{cases}$$

The calculation of new investments is carried out using the following steps (Figure 4). Step one refers to the selection of the future year and preparing the operating state using the Monte Carlo (MC) method [19], [20]. This is followed by a Power Flow (PF) calculation based on the Newton-Raphson algorithm. We then carry out an N-1 power flow analysis for all defined outages. In this respect the N-1 analysis is carried out for all elements in the system, N-2 analysis is carried out for all double-circuit elements and for all randomly selected elements in the system. If overloading occurs which could lead to cascade tripping, protection activation or automatic tripping device (ATD) activation, then the calculation is repeated without the faulty elements. After power flow calculations and both N-1 and N-1-1 security analyses are carried out, the outage assessments are complete. If element overload, voltage violation, loss of consumption or loss of generation occurs in the grid, PR is duly calculated.

The results obtained take into account the probability of the occurrence of an individual operational state, and an outage probability, along with a measure of its impact on the grid. Possible impact measures include the extent and number of overloads to individual grid elements, voltage violations and loss of supply of an individual load or loss of generation units. In the calculation process, cascade tripping is also considered in N-1-1 analysis. Every operating state where the IOG exceeds the level of operating risk (IOG > SOT) requires new investment. Transmission system planners working according to various societal, environmental, technical and economic assessments define different alternatives, which are then verified using the proposed methodology, and the best one is used in the transmission network development plan. In this way, an expert can make a comprehensive analysis of the state of the grid, and include required investments in development plans, as well as defining the degree of priority among existing individual investments.

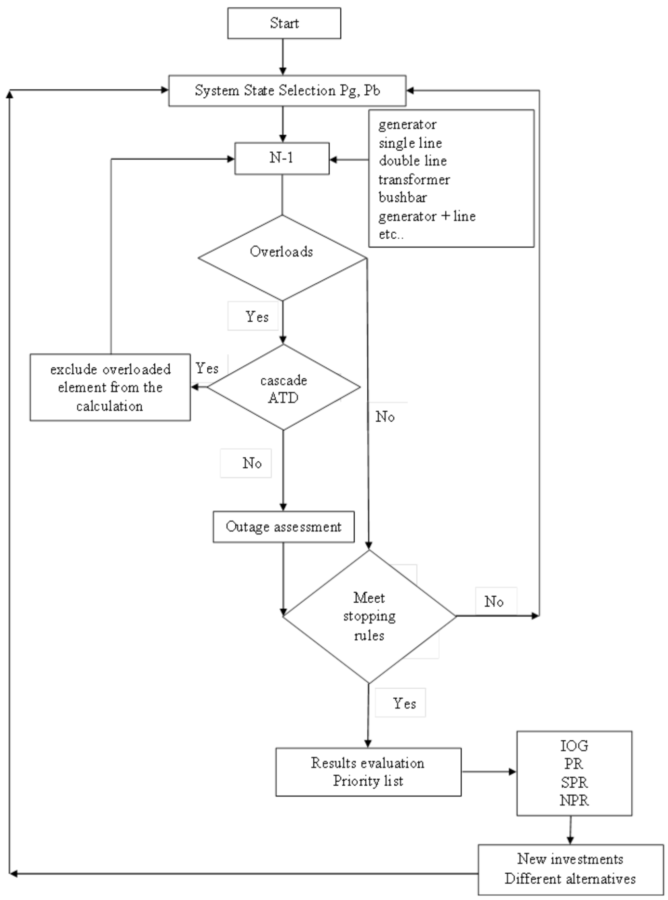


Fig.4: *System Development Flowchart*

3. Case Study

As a test model for examining the efficiency of the algorithm, we used a part of the Slovenia's 110 kV grid, which is a reflection of the real state and is presented in Figure 5. The model operates on the 110 kV network and has one feeding point in the main 110/220/400 kV substation at Divača, through one 400/110 kV and two 220/110 kV transformers. The model has 26 substations on 110 kV, 5 of them in the planning phase. The peak load is 283 MW. Load forecast until 2020 is based on an average 1.5 % growth of power and energy consumption per year. The installed production of the model is 314 MW, divided into 5 hydro generation units (Doblar = 70 MW, Plave1 = 15 MW, Plave2 = 17 MW, Solkan = 32 MW, Avce = 180 MW), the largest of which enables both turbine and pumping regime. Higher consumption and a new production unit (HE Učja) demand construction of new substations (Učja, Žaga, Kobarid, Izola) and grid extensions of the EPS. These connections are vital, otherwise new substations cannot be connected to the EPS and will not be the subject of evaluation. In accordance with the TN development plan [17], it is required to complete the elements detailed below (indicated by dotted lines in Figure 5) by 2020. On the basis of a deterministic approach, these elements represent a technically and economically optimal selection of elements in the TN. However, in this case study they will be reviewed and evaluated with the new algorithm:

1. 2x110 kV Sežana-Vrtojba transmission line (0.88 MEUR)
2. 400/110 kV Divača TR (4.63 MEUR)
3. 400/110 kV Avče substation (15 MEUR)
4. Upgrade of 110 kV Pivka–Ilirska Bistrica transmission line to 2 x 110 kV (2.5 MEUR)
5. Upgrade of 110 kV Divača–Koper transmission line to 2 x 110 kV (7.5 MEUR)

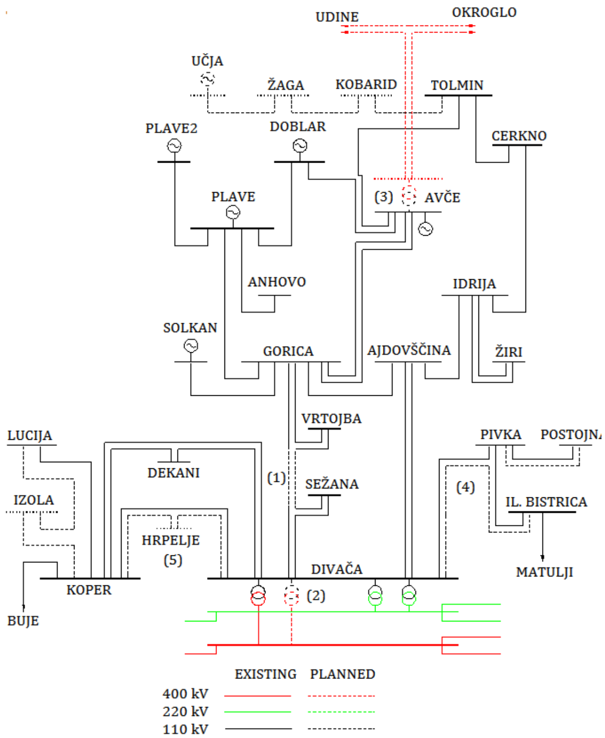


Fig. 25. *Model of grid and required development candidates by 2020 [17]*

Figure 6 shows the risks chart, which indicates the dependence of the impact on the grid IOG, caused by an individual element outage in relation to the probability of occurrence of operating states. As can be seen from Figure 6, the most critical outage is that of the 110 kV N-G-AJD line, where a high number of analyzed operating states appears in the red field. This field represents an area of high probability of the occurrence of the operating state combined with a non-acceptable impact on the grid [7], so all violations appearing in this field must be eliminated as soon as possible.

As can be seen from Figure 6, the level of operating risk (SOT) is exceeded only in the event of an outage of the 110 kV Nova Gorica–Ajdovščina line, which indicates the need for new investment. All other operational risks, which are below the acceptable level of operational risk (SOT), are managed in real time operation.

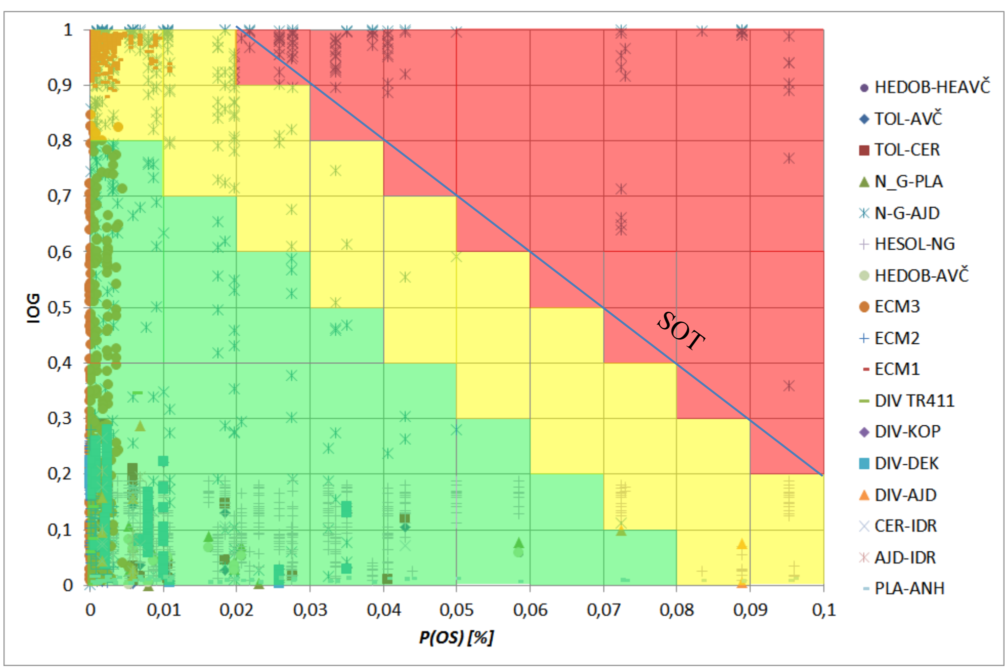


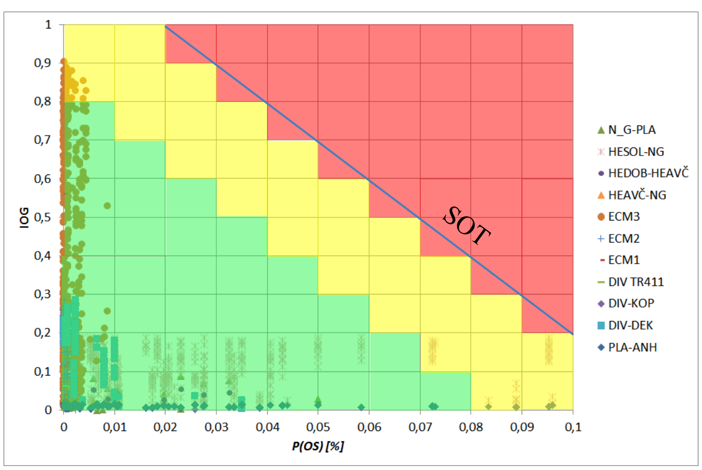
Fig.6. *Impacts on the grid (IOG)*

The results of calculations for each individual outage causing overload or problems in the grid, are displayed in more detail in Table 1.

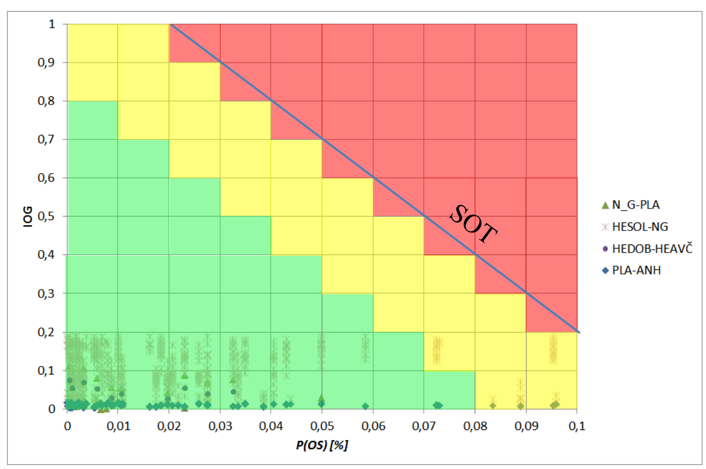
Table 1 results of calculations without investments

OUTAGE	No. of violations [%]	SPR [%]	NPR
AJD-IDR	1.29	0.00	0
CER-IDR	1.86	0.01	0
DIV-AJD1	1.43	0.02	0
DIV-DEK	15.14	0.06	0
DIV-KOP1	15.14	0.06	0
DIV-TR411	0.71	0.00	0
ECM 1	99.71	1.17	0
ECM 2	15.14	0.01	0
ECM 3	40.00	0.11	0
HEDOB-HEAVC	2.14	0.01	0
HESOL-N_G	100.00	1.40	0
N_G-AJD	65.00	6.16	91
N_G-HEPLA	2.29	0.01	0
TOL-CER	3.71	0.02	0
TOL-HEAVC	2.86	0.01	0
PLA-ANH	100.00	0.13	0

As can be seen from a more detailed analysis of the results of the calculations (see Table 1 above), outages of the 2 x 110 kV Divača–Ajdovščina (ECM 1), 110 kV Plave HPP–Anhovo and 110 kV Solkan–Nova Gorica lines result in violations in almost all discussed operating states, and outages of the 110 kV Nova Gorica–Ajdovščina and 2 x 110 kV Nova Gorica-Avče (ECM 3) lines cause violations in 65 % and 40 % of them respectively. Upon examining SPR, which represents the sum of all potential risks of individual operating states, it is clear that the most problematic outage is the outage of the 110 kV Nova Gorica–Ajdovščina line, which represents SPR of 6.16 %. From the point of view of SPR, outages of the 110 kV HESOL-N_G and ECM1 lines also stand out. Upon examining the results that exceed the SOT, in accordance with the NPR criterion (which expresses the sum of all violations), it is clear that the SOT is exceeded only in the outage of the 110 kV N_G-AJD line, so in order to remedy system violations by 2020 it is urgently necessary to eliminate the problems caused by the mentioned outage. In accordance with [17], the proposed solution for remediation of the problems mentioned above is investment in the 2 x 110 kV Sežana-Vrtojba. The proposed developmental solution was also examined in accordance with the new indicators of grid reliability, and the results of that examination are displayed in Figure 7.



a



b

Fig. 3. Impact on the grid (IOG)
a Results of calculations (IOG) with new investment the 2 x 110 kV Vrtojba – Sežana line included in the grid
b Results of calculations (IOG) with all investments *[17]* included in the grid

As can be seen from Figure 7, Subfigure a, with the completion of investment into the 2 x 110 kV Vrtojba–Sežana line, we have duly eliminated all outages of elements causing bigger impacts on the grid (as shown in the red field in Figure 6). With the completion of all investments according to [17], shown in Subfigure b, the results are even better, as there are no element outages in the area of low probability and high impact on the grid (upper left yellow field).

Detailed results of the calculations for each individual outage causing overload or problems in the new configuration of the grid (including both the investment in the 2 x 110 kV Vrtojba–Sežana transmission line, and all other investments in accordance with [17]), are displayed in Table 2.

Table 2 results of calculations accounting for the 2 x 110 kV Vrtojba–Sežana line, and all other investments in accordance with [17]

OUTAGE	No. of violations [%]	SPR [%]	NPR	No. of violations [%]	SPR [%]	NPR
AJD-IDR	0.00	0.00	0	0.00	0.00	0
CER-IDR	0.00	0.00	0	0.00	0.00	0
DIV-AJD1	0.00	0.00	0	0.00	0.00	0
DIV-DEK	15.14	0.05	0	0.00	0.00	0
DIV-KOP1	15.14	0.05	0	0.00	0.00	0
DIV-TR411	0.57	0.00	0	0.00	0.00	0
ECM 1	1.86	0.00	0	0.00	0.00	0
ECM 2	15.14	0.00	0	0.00	0.00	0
ECM 3	37.00	0.24	0	0.00	0.00	0
HEDOB-HEAVC	1.71	0.01	0	1.71	0.01	0
HESOL-N_G	100.00	1.40	0	100.00	1.40	0
N_G-AJD	0.00	0.00	0	0.00	0.00	0
N_G-HEPLA	3.43	0.01	0	3.43	0.01	0
TOL-CER	0.00	0.00	0	0.00	0.00	0
TOL-HEAVC	0.00	0.00	0	0.00	0.00	0
PLA-ANH	100.00	0.13	0	100.00	0.13	0

On the basis of a more detailed analysis and comparison of the results presented in tables 1 and 2 it is clear that, due to radial connection outages of the 110 kV Plave HPP–Anhovo and 110 kV Solkan–Nova Gorica lines still cause problems in all operating states. While problems caused by outage of the 2 x 110 kV Nova Gorica-Avče (ECM 3) line, decrease from 40% to 37 % with investment in the 2 x 110 kV Vrtojba–Sežana line, and totally disappear where all investments are included. As can be seen from the results, with new investment we managed to eliminate all problems caused by the outage of the key 110 kV Nova Gorica–Ajdovščina line.

After reviewing the results following the NPR criterion, it is clear that the level of operating risk has not been exceeded in any case, which means that with only the investment in the 2 x 110 kV Vrtojba–Sežana line we have already met all the criteria of safe and reliable operation. Therefore, according to the new criteria, it is only necessary to complete the aforementioned investment in the 2 x 110 kV Sežana-Vrtojba transmission line.

As can be seen from Table 2 and Figure 9, the main effect on SPR is on the 2 x 110 kV Sežana-Vrtojba line, the SPR of which is reduced from 9.18% to 1.89%. Neither the new investment in the 400/110 TR at the Divača substation or the upgrade of the 110 kV Pivka Ilirska Bistrica line to a double transmission line have any effect on SPR. While the upgrade of the 110 kV Divača–Koper line to a double transmission line reduces SPR by 0.1 %. Investment in the 400/110 kV Avče substation reduces SPR by 0.24 %. The results regarding the 2 x 110 kV Vrtojba–Sežana transmission line (SPR= 1.89 %) and all investments in accordance with [17] (SPR = 1.55 %) show that with the completion of all new investments, system reliability increases by 0.34 % SPR. To achieve higher reliability of the EPS (SPR down from 1.89 % to 1.55 %), the investment cost increases from 0.88 MEUR to 30.5 MEUR, and these additional, unnecessary costs will increase tariffs for customers.

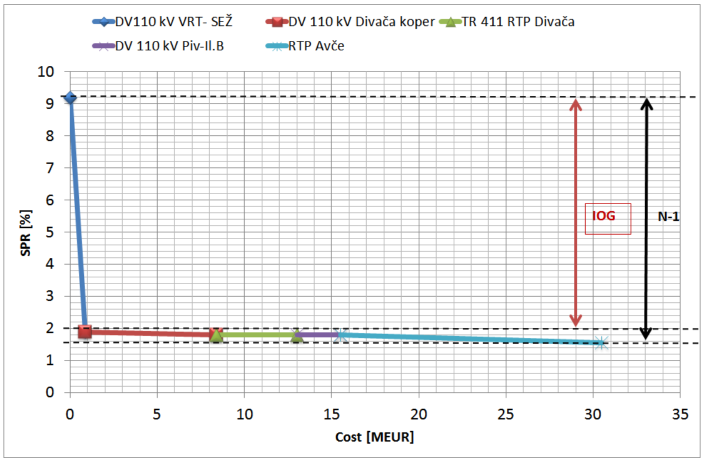


Fig. 4. *SPR dependence of investments cost*

This new methodology is also reflected in the costs for the system operator, and consequently in consumer tariffs too. Using the new algorithm, the cost of investment for the system operator is smaller and in the future period amounts to only 2.8 % of the cost of the original development plan. On the basis of the new algorithm, which observes the probability of the occurrence of various operating states and includes a certain level of risk, we achieve sufficient reliability and a positive impact on the network charge for all network users (Figure 9).

4. Conclusions

This paper introduces a grid planning procedure based on a new methodology in which the risk level is set in advance, and which accounts for the probability of the occurrence of an individual operating state, as well as for the probability of an outage of an individual element and the impact of that outage element on the system. Within the methodology we also developed a new indicator, called IOG, which combines all problems caused by an outage into a single indicator. This new methodology for planning the grid enables optimal investments in the transmission network, while retaining the appropriate level of reliability.

With this new approach, the system operator will invest in the transmission network only if an acceptable level of operating risk is exceeded, while all other potential risks will be accepted and managed in real time operation.

The methodology quantifies network security using IOG and PR, and can also provide a supplement to existing verified methods, serving as a tool for determining priorities among investments in the transmission network.

5. References

[1] UCTE OH Policy 3, ˈOperational Securityˈ, https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/Operation_Handbook/Policy_3_final.pdf, March 2009, pp. 1-12

[2] Li, W., Choundhury, P.,: ˈProbabilistic planning of transmission systems: Why, How and Actual Exampleˈ IEEE Power and Energy Society General Meeting, August 2008, pp. 1-4

[3] Buygi, M., O., Shanechi, H., M., Balzer, G., Shahidehpour, M.,: ˈTransmission Planning Approaches in Restructured Power Systemsˈ IEEE, Power Tech Conference Proceedings, Bologna, Italy, June 2003, pp. 1-2

[4] Billinton, R., Mo, R.,: ˈDeterministic/probabilistic contingency evaluation in composite generation and transmission systemˈ IEEE Power Engineering Society General Meeting, Denver, Colorado, June 2004, pp 1-6

[5] Yunting, S., Hailei, H., Dongxia, Z., Jianbo, G.: ˈProbabilistic Security Evaluation of Bulk Power System Considering Cascading Outagesˈ IEEE Power System Technology, Internal Conference on Power System Technology, 1, October 2006, pp 1-2

[6] Setreus, J., Arnborg, S., Eriksson, R., Bertling, L.: ˈComponents´ Impact on Critical Transfer Section for Risk Based

Transmission System Planning' IEEE Power Tech Conference, Bucharest, Romania, June 2009, pp. 1-8

[7] NERC, 'Reliability Concepts', NERC, December, 2007, pp. 11-49.

[8] Chowdhury, A., A., Koval, D., O.: 'Probabilistic Assessment of Transmission System Reliability Performance' IEEE Power Engineering Society General Meeting, October 2006, pp.1-6

[9] Markov, Y., V., Moharari, N., S.: 'A Generalized Power System Reliability and Security Index', IEEE Power Tech Conference, Budapest, Hungary, August 1999, pp 1-6

[10] Markov, Y., V., Hardiman, R., C.: 'On Risk-based Indices for Transmission System' IEEE Power Engineering Society General Meeting, July 2003, pp. 671-678

[11] Varadan, S., Mittelstad, W., A., Aggarwal, R., K., VanZandt, V., Silverstein, B.: 'Transmission Planning Risk Assessment' IEEE Power and Energy Society General Meeting, July 2008, pp. 1-6

[12] LiSon H., SuBae, I., Hoon, D., Kim, J.,O.: 'Determine of transmission expansion planning using risk-benefit and well-being method 'IEEE Transmission & Distribution Conference & Exposition, October 2009, pp. 1-6

[13] Song, S., H., Lee, S., H., Oh, T., K., Jinsu Lee, J.: 'Risk-based Contingency Analysis for Transmission and Substation Planning' IEEE Transmission and Distribution conference, Asia, 2009, pp. 1-4.

[14] Qin, C., Liu Y., Z., Zhou, B., Jin, X., Chen, J.: 'BTRANS, A tool for Transmission Network Risk Assessment' IEEE Innovative Smart Grid Technologies 2012, pp. 1-4.

[15] Papic, M., Ciniglio, O.: 'Prevention of NERC C3 Category Outages in Idaho Power´s Network: Risk Based Methodology and Practical Application' IEEE Power and Energy Society General Meeting (PES), July 2013, pp. 1-4

[16] Awater, P., Alvarez, R., Belting, J., Moser, A.: 'Probabilistic Assessment of Grid Security for Different Scenarios of Power System Development' IEEE Energy Conference (ENERGYCON), Dubrovnik, Croatia, May 2014, pp. 536-542

[17] ELES, 'Ten year development plan from 2009 till 2018' ELES, 2009, pp 61-90.

[18] Chowdhury, A., A., Koval, D., O.: 'Deregulated transmission system reliability planning criteria based on historical equipment performance data' IEEE Industrial and Commercial Power Systems Technical Conference, Clearwater Beach, Florida, February 2001, pp. 55-56

[19] Li, W.,: 'Probabilistic Transmission System Planning' (IEEE Press, New York, 2011)

[20] Billinton R., Allan, R., N.: 'Reliability Evaluation of Power Systems '(Plenum press, New York and London, 1984, 2nd edn. 1996)