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# Reliability Model of Large Offshore Wind Farms

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***Abstract*--For investors of wind farms projects, it is indispensable to get reliable prognosis of the expected energy produced per year, taking into account technical failures and the stochastic characteristic of the wind. This applies especially for offshore wind farms with higher installation costs and difficult maintenance conditions. The repair of components located on sea may take many days or even weeks because of limited access caused by bad weather conditions. Additionally, transmission system operators which are providing the point of common coupling (PCC) have to know the impact of the wind farm on the reliability of the grid.**

**In this paper a model for the probabilistic reliability calculation of the offshore wind farms as a whole and as a part of the entire system has been introduced.**

***Index Terms*--wind farm, reliability, model, offshore.**

## I. Introduction

THE targets for the reduction of greenhouse gas emissions among other measures that have been recently agreed by the EU require a consistent implementation of the planned or already approved offshore wind farms in the German North and Baltic Sea. The German Government is participating in the ambitious target by the year 2020 setting the share of renewable energy production to a minimum of 20% [1]. The largest contribution to this is planned with the use of wind farms. The 2020 target is app. 50 GW, thereof more than 20 GW offshore - Fig. 1.

The impact of this offshore development on the power system has already been analysed in [1]. The reinforcement of existing and building of new transmission capacities are proposed. Furthermore, the future role of the wind farm operators in the generation management becomes an object of discussion. Another important issue is the backup of the wind generation, i.e. in case of incorrect forecast or sudden changes of the wind power generation the secondary and minute power reserve have to cover missing power ("shadow" power plants).

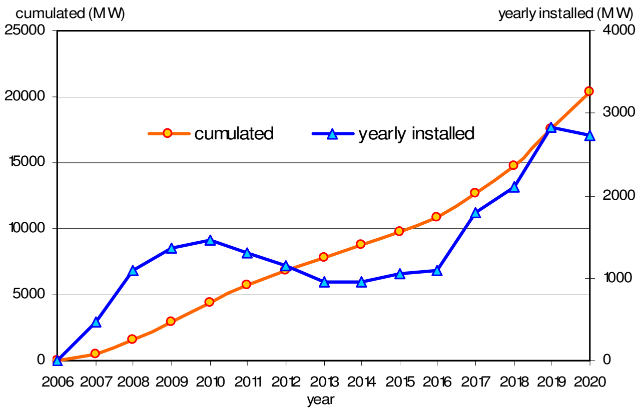


Fig. 1. Planned offshore wind power in Germany [1].

However, the issue of the power system reliability in case of increased wind power penetration (especially offshore) is only qualitatively evaluated. Therefore, the analytical reliability calculation for the evaluation of the impact of the offshore wind farms on the power system reliability is shown here. The modelling of the offshore wind farm, system, their equipment and their reliability parameters is made with the power system analysis software tool NEPLAN® [2]. The model is taking into account following parameters which are important for the reliability evaluation:

- wind farm location,
- single generator power and power of the entire wind farm,
- wind farm grid (radial/meshed),
- switchgear and protection concept,
- automation technology,
- selection of the PCC.

Both wind farm investors and transmission system operators have interest in a risk analysis of the wind farms. Therefore, the reliability data of the equipment is required. The NEPLAN® provides a module for the analytical calculation of the reliability values, which are based on the expected values of the component failure rates, their repair times and necessary duration of switching operation. According to the simulation of component failures (short circuit, malfunction, sequential failure, etc.), the analysis of the reaction of the protection

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equipment, fault isolation measures and the evaluation of re-supply measures follow. At any time point, the consequences on the entire power system supply are considered. As a result one or more loads (consumers) or generators can be disconnected from the system, respectively a part of them.

This approach enables also a principle evaluation of offshore wind farms beginning from a small to a large power plant. Both the internal wind farm grid as well as installed primary and secondary technique have an impact on reliability. For investors, it is important to obtain an optimal ratio between capital investment and expected returns. Low investment and operation costs can cause low level of reliability and, therewith, deficit of the energy. On the other hand, high investment costs provide high availability of the system, but they cause unattractive returns and long payback periods.

## II. Wind and Wind Power Characteristics

The expected produced energy of one wind farm is obtained when considering the wind characteristics of the location planned for building the wind farm. Beside the power curve of the used generators (usually only one type, i.e. only one power curve), the most influencing parameter is the average wind speed. According to these two parameters the theoretical expected annual energy ($E_{\text{thwf}}$) can be estimated. This value is a reference when considering possible interruptions caused by grid or equipment failure, forced disconnection etc. The ratio between theoretical energy and the expected energy not supplied ($EENS_{\text{wf}}$) gives the energy availability of the wind farm:

$$p_{wf} = \frac{E_{thwf} - EENS_{wf}}{E_{thwf}} \cdot 100\% \qquad (1)$$

This factor, which as already said depends mainly on the reliability of the wind farm, has a significant impact on the profitability and payback periods of investor capital, and therewith, on the decision of building the wind farm.

The measured values of the wind speed are being sorted in different clusters. In this case the clusters are being set to the changes of 1 m/s. According to the measured and in clusters sorted data, a discrete curve of the wind distribution is obtained (Fig. 2). The data are obtained from FINO measurement station, which is located in North Sea [3], and are giving values for the period 01.09.2003 - 01.01.2005.

It is obvious that the curve of the measured wind speed values has the shape of the Weibull distribution. The approximation with Weibull's distribution is also given in Fig. 2, giving a mean wind speed of 9,8 m/s with parameters A=11,1 m/s and k=2,16.

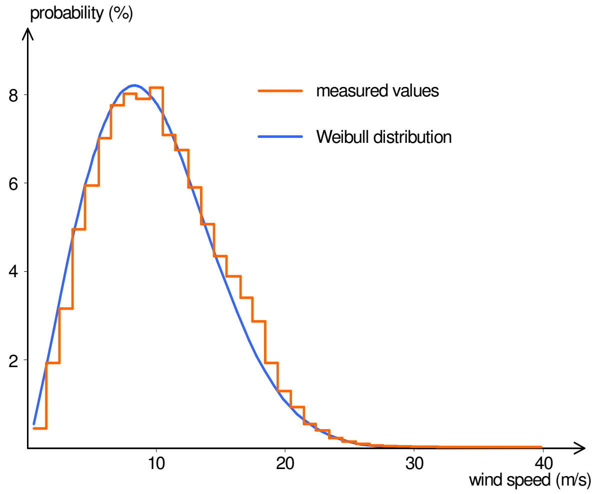


Fig. 2. Wind speed distribution at FINO measurement station.

For a given offshore wind farm example, wind generators of 5 MW rated power are considered. In Fig. 3 a typical power curve of such generator class is shown.

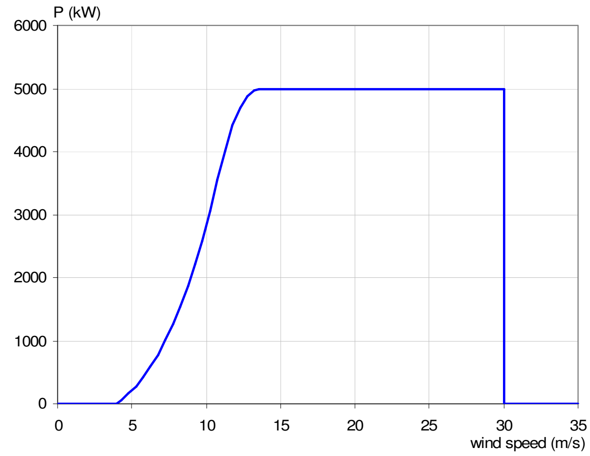


Fig. 3. Power curve of wind generator of 5MW class.

As it can be seen, the power curve consists of four characteristic operating regimes: standstill (the wind is too weak to start power generation), nonlinear power production (the power output is a cube function of the wind speed), rated power and standstill (the wind is too strong and the wind generator is disconnected). The wind speeds which characterise these regimes are:

- 4 m/s: cut-in wind speed,
- 13,5 m/s: rated wind speed,
- 30 m/s: cut-off wind speed.

The chosen generator/wind farm will supply the system with its rated power at wind speeds between 13,5 and 30 m/s. From Fig. 2 can be seen, that the density of the distribution function for this wind speed range is app. 30%. This means that the probability that the wind generator will operate with rated power is 30%. In other words, it can be expected that the wind generator will produce the rated power in over 2600 h/yr! On the other hand, the wind speeds smaller than 4 m/s occur in only 8% of cases. Thereat, in only 700 h/yr there will be no power production from the wind farm. This is clearly shown in Fig. 4, where the power duration curve of a chosen place has been presented.

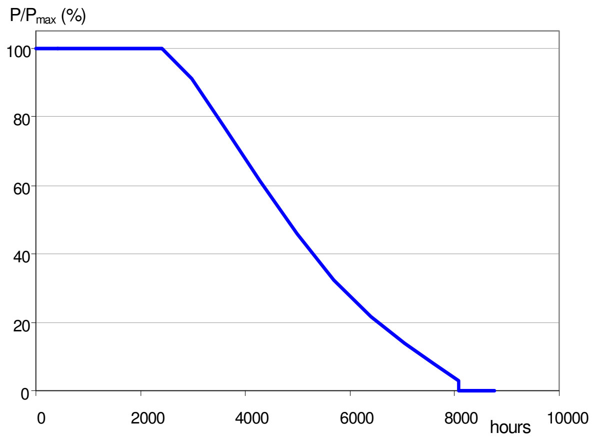


Fig. 4. Power duration curve.

In total, at the offshore place, where the measurements have been accomplished [3], the utilization time of app. 4600 h can be achieved. Therewith, it is to expect that the offshore wind farm much higher energy yield than onshore wind farm. However, this is only theoretical expected production. As already mentioned, the reliability of the wind farm and its equipment play very important role when calculating the energy supplied to the system.

As the switching and eventual re-supply measures after a failure may depend on the wind power generation, it is important to consider the various wind generation cases. This may provide much more accurate results especially when the system or the wind farm has some redundancy or reserve capacity. However, if all the possible cases have to be considered, it would result in an enormous computation time for simulation. That is why the power duration curve has been classified in several characteristic cases weighted with their occurrence probability. In this example four wind states have been chosen which represent all of possible cases.

The importance of reliability analysis becomes even more important when, beside already discussed stochastic characteristic of the wind and thereat power output, the behaviour of the wind farm equipment (components like: cable, wind generators, cable, transformers...) is also taken into account. Therefore, the risk analysis for the investment in the offshore wind farms must include the reliability analysis too. In the following, a model which makes the reliability analysis of a wind farm will be presented.

## III. Wind Farm Model

One of the premises when modelling an offshore wind farm was that the entire produced power from the wind farm can be injected into the system, i.e. there is no congestion. The possible need for the extension of the transmission grid of the system was here not discussed. In Fig. 5 the analysed offshore wind farm is presented.

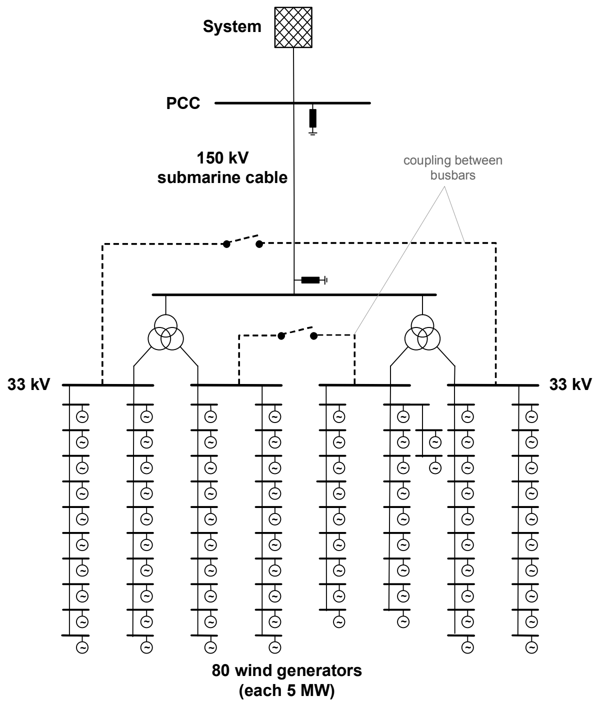


Fig. 5. Analysed wind farm.

The wind farm has 80 generators (each 5 MW) making a total of 400 MW rated power. They are grouped in 8 clusters. The MV/LV transformers are stepping up the voltage at 33 kV. The clusters are connected to the offshore platform on the 4 busbars with 33 kV submarine cables. At the offshore platform there are also two three winding step up HV/MV transformers 33/150 kV (each 200 MVA). They are connected to the system with a 150 kV submarine cable.

Due to new application area (offshore) and lack of the experience regarding the behaviour of wind farm components, the input data necessary for the reliability calculation were taken from the official VDN (Association of German system operators) statistics [4] - Table I.

TABLE I
Reliability Data of Wind Farm Components [4]

| component | Stochastic failure rate (1/yr or 1/km) | Deterministic disconnection (1/yr) | Repair time (h) |
|---|---|---|---|
| MV cable (XLPE) | 0,001266 | 0,0064 | 144 |
| MV/LV Transformer | 0,007712 | 0 | 144 |
| HV/MV Transformer | 0,006 | 0,35 | 144 |
| Circuit breaker | 0,000823 | 0,2 | 144 |
| Switch | 0,000524 | 0,2 | 144 |
| Wind generator | 2 | - | 144 |

The repair time was estimated uniformly to 6 days (144 h). Due to lack of experience in offshore conditions and accordingly shortage in adequate database, these plausible data for the wind farm components have been used. It can be recommended to review these values after getting data based on the experience from the operational behaviour of the equipment in the offshore conditions.

## IV. Results of the Wind Farm Reliability Calculation

### A. *Reliability Calculations*

The component's stochastic behaviour is under the cited reasonable assumptions determined by the homogeneous Markov two-state model, which has been used for these calculations. That implies first of all that each component is either fully functional or out of order, whereas changes of state are due to the failure or repair of one component. Moreover, a Markov process supposes that the given current state of the system, the future evolution of the system is independent of its history. The probability of a transition from one of these two states to the other state, for example the failure rate $Z_B$ to $Z_A$, is given from the transition rate, in this case $\alpha_{A,B}$ (Fig. 6).

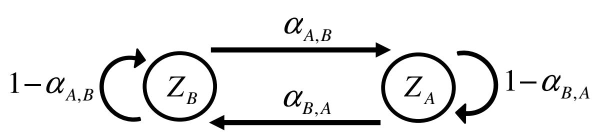


Fig. 6. The principle of Markov process.

It can be supposed that the distribution of the functionality of the components is exponential, because, according to the statistics, this represents a very good approximation for most of the system components. For an exponential distribution the probability that the life time $T$ of the component is smaller than $t$ is:

$$P(T \le t) = \begin{cases} 1 - e^{\lambda t} , & t \ge 0 \\ 0 , & t < 0 \end{cases} \qquad (2)$$

In the case of an exponential distribution it can be shown that the transition rates are constant or time homogeneous. Therefore, if the parameter of this distribution is $\lambda$, than is the failure rate constant and equal to $\lambda$.

The calculation in the simulation software, which determines the probability of each failure, is based on this model. As it is very difficult to compute all of the failure states of the system, only the single-component and the multi-component failures with the highest probabilities are simulated. In fact, failures that involve many components have much bigger effects in (n-1) secure systems, even if their probability is significantly smaller.

The most important parameters that can be determined as result of the reliability calculation are the interruption frequency $H$ [1/yr], the non-availability $Q$ [min/yr], and the EENS (expected energy not supplied) [MWh/yr].

### B. *Results for an Offshore Wind Farm*

An overview of the general calculation results of the wind farm: total production, grid losses, and EENS (due to unavailability of the equipment), is shown in Table II

TABLE II
Calculation Results of the Wind Farm Model

| | |
|---|---|
| Theoretical available energy | 1872 GWh/yr |
| Energy supplied to the PCC (without disturbances) | 1757 GWh/yr |
| Grid losses | 115 GWh/yr |
| EENS | 7,26 GWh/yr |
| Availability | 99,6 % |

The results show that around 0,4% of the theoretically available energy will not be supplied into the grid due to the failures in the wind farm. With announced feed-in tariffs in a range of 13-15 c€/kWh from offshore wind farm (amendment to the actual renewable energy act [5]), this amounts the financial loss of app. 1 Million € per year.

With the help of a weak point analysis it can be shown, that the wind generators represent the main cause for the unavailability - Fig. 7.

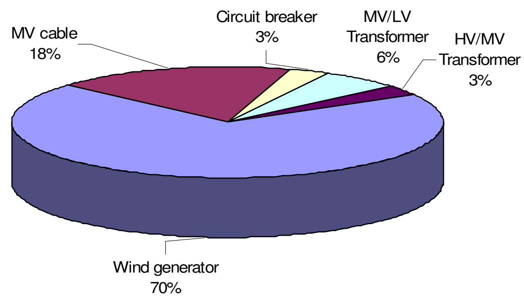


Fig. 7. The impact of wind farm components on the EENS.

However, as shown in Fig. 7, the network structure and secondary protection are not to neglect. The high proportion of medium voltage cables of 18% is the result of the radial network structure.

On the example of three different internal grid alternatives, the impact of the protection scheme and automation technology will be investigated. To eliminate their impact, in following analyses the wind generator were not included. Three variants have been analysed:

1. basic variant - only switches have been used for the MV cable feeders,
2. variant CB - same as 1, but equipped with additional circuit breakers (Fig. 8),
3. variant WCO - same as 1, but without coupling between main busbars at the offshore platform (see Fig. 5).

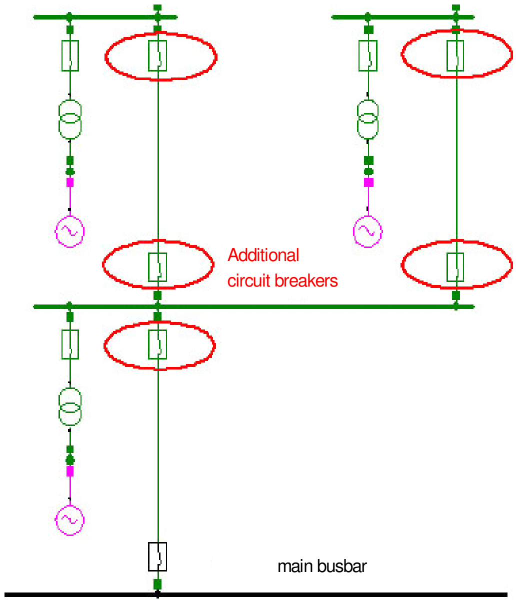


Fig. 8. Variant CB - additional circuit breakers in cable feeders.

In Fig. 9 the results of expected energy not supplied (EENS) for all three variants are presented.

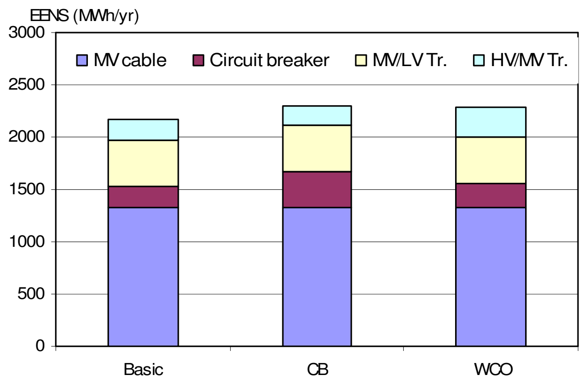


Fig. 9. The comparison of EENS for all three variants.

It is clear that neither the addition of circuit breakers (CB) nor the additional coupling between main busbars (basic) are making significant improvements in the reliability of the wind farm. As a consequence it can be concluded that the protection, additional switchgear equipment or automation level have only a small impact on the EENS. This impact can not justify the costs of the investment for this additional equipment. Furthermore, for the risk analysis of investors the focus should be made on the wind generators and their failure rate, maintenance etc., because they have the biggest impact on the EENS. This is also a conclusion made in [6].

## V. Wind Farm Connected to one Power System

From the point of view of transmission system operator, which has to integrate the power from the offshore wind farm, there are other conclusion when considering the connection of a wind power:

- a significant contribution to the secure power in the transmission system is not expected (only 6% of installed wind power),
- in order to reduce the risks of secure power supply, the participation of the wind farms in the generation management is required.

At the example of one real European transmission grid the quantitative effect of connecting a 400 MW wind farm on the reliability of 400/220 kV system was investigated - Fig. 10. The wind farm can cover (at its rated power) 20 % of the peak load of the system (2000 MW). The analysed PCC of the wind farm is shown in Fig. 10. This is chosen in such a way to supply the local peaks and be able to inject its power in 400 kV grid.

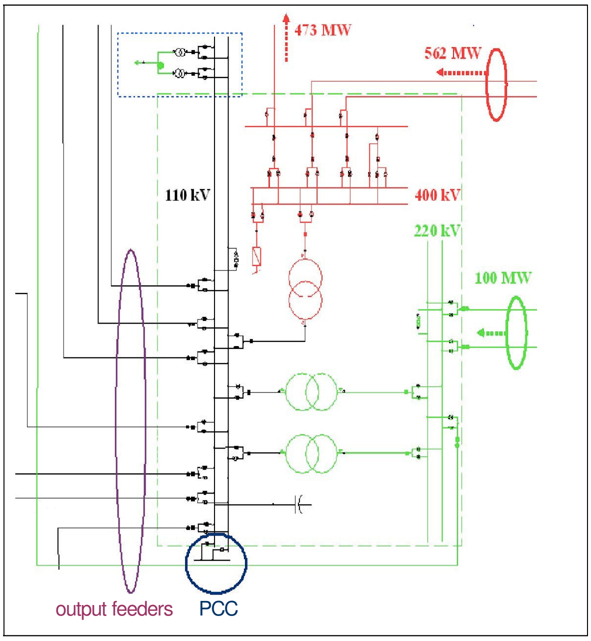


Fig. 10. PCC of the wind farm with load flows.

In the reliability calculation typical power duration curve (Fig. 4) and typical transmission load curve analysis are used and combined. The results show that the impact of the wind farm on the failure frequency of the entire system can be neglected. Namely, only 2% of the expected failures can be avoided by the connection of the wind farms. This coincides with the estimation in [1] which also supposes almost no change in the system reliability. However, in order to get an overall picture of the wind farm impact on the reliability, an insight on the changes of the unavailability and EENS index has to be made. Due to the connection of the wind farm the unavailability decreases by 5%. The reason for it is that the wind farm is taking over a part of the load of the highly stressed 400 kV line (see Fig. 10). The wind farm can under sufficient good wind conditions partially or even fully compensate its failure and therewith, increase the total system availability. In Fig. 11 the changes of the EENS with and without wind farm for every wind farm component and in total is presented.

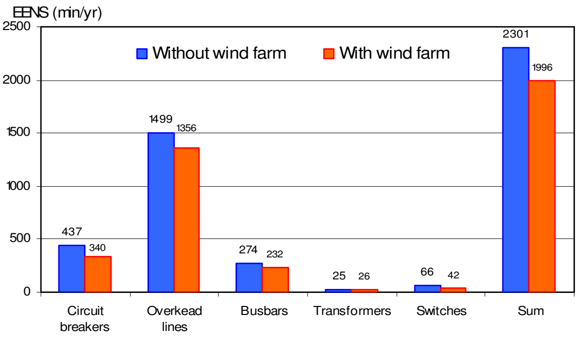


Fig. 11. EENS with and without wind farm – components and summarised.

With the commissioning of the wind farm, the EENS reduces 13% (~300 MWh/yr) for the entire system, whereas the choice of the PCC plays a decisive role. This shows that despite the little advantage for system security in the transmission system, a positive influence on the EENS caused by the faults can be achieved. The model described here enables the quantification of the effects of the wind farm on the entire power system reliability.

## VI. Conclusion

To estimate the investment risks and EENS due to unavailability of the wind farm components, the reliability analysis of the planned offshore wind farm projects in the North and Baltic Sea are from very big importance. The results presented here show that the behaviour of the wind generators has the largest impact on the availability of the wind farm, i.e. they are causing the largest part of the EENS. Effective measures to minimize risk the failure rate and the maintenance of the wind generators would significantly decrease the investment risks. Much smaller, but still quantifiable influence (developed model calculates their share in entire wind farm) have the grid structure, protection scheme and automation technique.

For the transmission system operators the location of PCC can be of decisive importance. With the application of the model, the impact of the wind farm connected at selected PCC on the availability and EENS of the entire system can be calculated. With careful selection of the PCC the reliability of the system can be increased. This can be quantified by the use of the model presented in this paper.

## References

[1] German Energy Agency (dena), “Integration into the national grid of onshore and offshore wind energy generated in Germany by the year 2020”, Berlin, Germany, 2005
[2] NEPLAN®, *Power System Analysis - Manual*, www.abb.de/neplan
[3] FINO – *Offshore research platform in the North Sea – measurement database*, November 2007
[4] Association of German System Operators, *Failure and availability statistics in German transmission networks*, Berlin, Germany, 2004,
[5] German Ministry for the Environment, Nature Conservation and Nuclear Safety, *Renewable Energy Sources Act*, Germany, 2006
[6] A. Underbrink, J. Hanson, A. Osterholt and W. Zimmermann, “Probabilistic Reliability Calculations for the Grid Connection of an Offshore Wind Farm”, 9th International Conference on Probabilistic Methods Applied to Power Systems PMAPS 2006, Stockholm, Sweden, June 2006