9th International Conference on Probabilistic Methods Applied to Power Systems
KTH, Stockholm, Sweden – June 11-15, 2006

Probabilistic Reliability Calculations for the Grid Connection of an Offshore Wind Farm

A. Underbrink, J. Hanson, A. Osterholt, W. Zimmermann, ABB AG, Mannheim, Germany

Abstract-- **Probabilistic reliability calculations are widely spread for the design of distribution networks.**

This paper deals with the application of probabilistic reliability calculations to assess the impact of the grid connection on the overall reliability of wind farm power production.

A characteristic of the grid connections of offshore wind farms is almost no redundancy. The main intention of the presented study is to evaluate the grid connection's influence on the wind power infeed into the public grid and to carry out weak-spot analyses revealing these components of the grid connection, which are decisive for reliability. Since some of the reliability input parameters are not known up to now and experience with offshore equipment is rare, a parameter study has been performed.

Index Terms-- **Offshore Wind Farm, Grid Connection, Reliability at PCC**

I. INTRODUCTION

Deregulation of energy markets has forced utilities to face new challenges and to evaluate the cost-benefit implications of providing an acceptable level of service. One of these new challenges is the permanently rising number of wind farm projects, especially at the German Sea coasts. For these projects in general a feasibility study has been carried out, with special focus on the aspect of reliability. The task has been defined as analyzing the impact of network components from the offshore site of the wind farm up to the Point of Common Coupling (PCC) at the onshore 400/150 kV substation.

This paper describes the model of the grid connection from the offshore platforms of wind turbines to the onshore 400/150 kV substation, that serves as the Point of Common Coupling (PCC). The method of reliability calculation is a well accepted network planning tool [1]. Besides its capability to predict the power supply reliability of consumers based on statistics of component outages and re-supply strategies, this study shall prove, whether probabilistic reliability calculations are suitable for the assessment of grid connections of wind farms, too.

The application of this methodology requires network calculation methods of high integrity. It has proven valuable for detailed quantitative reliability assessments in many studies and practical applications such as [2]-[4]. Reliability software is established since the early 80's and becomes more and more user friendly. The tool used for this study is NEPLAN® [5].

II. COMPUTATION OF GRID CONNECTION RELIABILITY

The question of interest of this study was: How is the power infeed at the PCC influenced by outages of wind turbines on the offshore platforms, the availability of wind in general, outages of submarine cables and of onshore components up to the 400/150 kV substation at the PCC. Any component has been assigned with reliability data. The stochastic wind characteristic has been modeled by a Generation Duration Curve (GDC). Thus the results show specific contributions of wind turbines as well as of failing grid connection equipment. The following sections describe general aspects of reliability calculations.

A. Methodology of probabilistic reliability calculation

The results of reliability calculations are only as good as the input data, i.e. the outage data of the electrical network equipment. In Germany the Association of German network operators "VDN-Berlin" provides a comprehensive and reliable pool for this purpose since 1994 [6]. Certainly, data describing the outages of offshore wind farm components are yet not available for a representative time range or amount of disturbances. Therefore this study mainly proves the general possibility to apply probabilistic reliability calculations on evaluations of wind farm grid connections. Any result should be considered only as a qualitative conclusion and further studies with the objective to provide quantitative results have to be conducted as soon as statistics of offshore wind farm components are available.

B. General course of calculation

The course of reliability calculation is shown in Fig. 1. The underlying methodology is of analytical manner based on expected values for failure rates, switching and repair times. For any relevant equipment outage the program performs a failure effect analysis. Firstly, all circuit breakers will trip with regard to the network protection concept. Afterwards the line and transformer loading will be checked by a load flow calculation. If overloads are detected, the tripping zone will be extended according to the overloaded equipment. Finally possible switching measures are checked to find an optimal strategy for the restoration of the power supply.

As a result, for each outage the affected power demand and duration for restoration of supply will be determined and contribute to the system reliability indices.

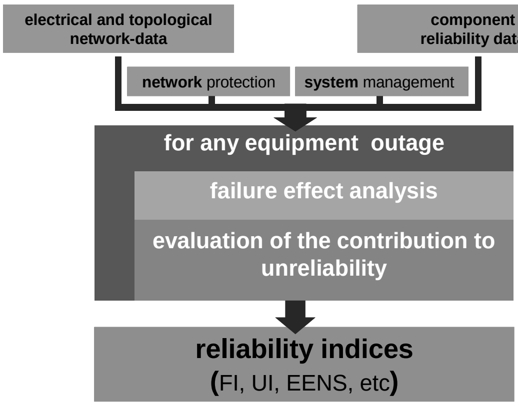

Fig. 1 Probabilistic reliability calculation

A model for the course of supply restoration after an outage is shown in Fig. 2. The failure effect analysis determines the duration of interrupted or reduced power supply on the consumption side

- after tripping of network protection
- after automatic load transfer
- after remote controlled switching measures (T_{rem})
- after local manual switching measures (T_{loc})
- after (provisional) repair

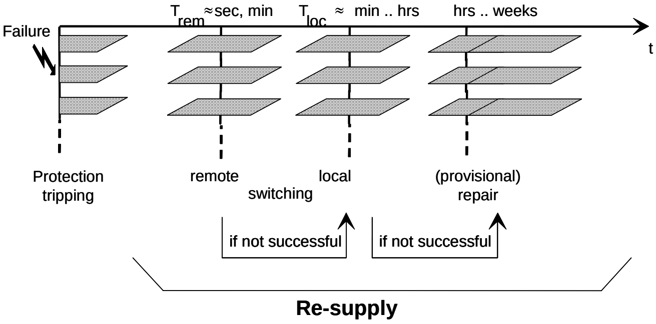

Fig. 2 Model for the course of supply restoration

C. *Failure modes*

The failure modes describe the different types of failures which are generally be considered for reliability calculation. Table I shows all possible failure modes.

TABLE I
FAILURE MODES

Failure	**Description**	**Data**
Independent failures of one or more elements (given stochastic overlapping)	Sudden occurrence of short-circuits on components during normal operation.	Separated in short and long duration outages: Frequency and duration, i.e. time until restoration of power supply can be achieved
Common-Mode-failure	Failures of several elements due to a common cause (e.g. on multiple cables)	Frequency and duration, i.e. time until restoration of power supply can be achieved On lines and cables the Common-Mode-length
Failure of the protection system	Loss of selectivity due to failing protection devices. This normally leads to extended failure-affected network areas.	Conditional probability of failing protection device
Protection over-function	Unwanted operation of the protection system in response to network problems	Conditional probability of failing protection device
Failures of several components	Due to multiple ground fault	Frequency and conditional probability of additional ground fault
Overlapping of the determined shutdown of one element (e.g. during maintenance) with the stochastic failure of a second element	The failure can also be associated with maintenance work (e.g. the result of operator error or damage caused by the maintenance work itself).	Frequency and duration, i.e. time until restoration of power supply can be achieved Earliest possible time to interrupt maintenance in emergency case (when maintained component needs to be reenergized)

III. DESCRIPTION OF WIND FARM AND GRID CONNECTION

A. *Electrical model*

The wind farm considered in this paper has the structure and data, depicted in Fig. 3. At the wind farm location a 33 kV network has been selected to interconnect the wind turbines. The structure divides 80 wind turbines in groups of 20 based on an open loop structure. The total 33 kV cable length is 65 km. Group interconnections deliver redundancy. At offshore location two 3-winding transformers (126 MVA) connect the wind farm to a 150 kV submarine cable jetted approx. 1 m under sea bed. The distance to shore is 45 km, which will be covered by a single 1200 mm^2 submarine cable. From that first substation, which provides compensation for the huge amount of reactive power demand of the submarine cable the produced power has to be transmitted to a 400/150 kV substation by three parallel 150 kV land cables.

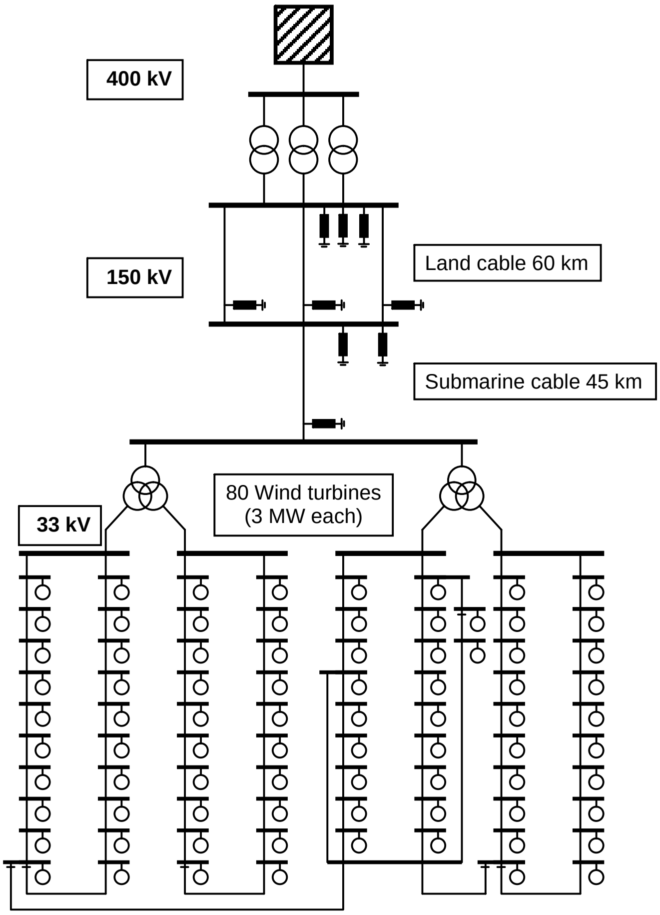

Fig. 3 Sketch of considered offshore wind farm

The onshore distance to the 400/150 kV substation is 60 km. This substation serves as the point of common coupling (PCC). At this point reliability results were calculated based on disturbances on the path from the offshore wind farm to the PCC.

B. *Reliability model*

As only little experience with the outage behavior of components under the severe environmental conditions at offshore sites is available to date, the input data for this study is mainly based on plausible assumptions. Table II shows the components outage data used for this study. Failure rates of components have been set to empirical data from German statistics (VDN-Berlin, 2004 statistic) assuming the same failure rates for offshore and onshore elements. The average repair time was set to 6 days for every offshore component.

TABLE II
EQUIPMENT OUTAGE DATA USED FOR THIS STUDY

Equipment	**Failure rate in 1/yr**	**Repair time in h**
Land Cable	0.00021 /km yr	120
Submarine Cable	0.00021 /km yr	144
Wind Turbine	1 /yr	144
All other offshore components	acc. to VDN-Berlin	144

IV. STUDY RESULTS

A. *Energy consumption and demand at PCC*

As described in section II. A. the applied analytical method for reliability calculations utilizes expected values for stochastic failure rates, switching and repair times. The availability of wind has a stochastic characteristic, too. In advance of the establishment of offshore wind farm projects, comprehensive studies about the wind speed at the planned location are carried out. Based on the specific relation between wind speed and power generation depending on the turbine type, an expected Generation Duration Curve (GDC) can be developed. So the randomness of wind power availability is considered by a distribution curve of expected wind production related to the duration. The GDC as shown in Fig. 4 is based on a reference wind profile and has been simplified by 4 steps. The GDC also considers downtimes of the wind farm due to maintenance work.

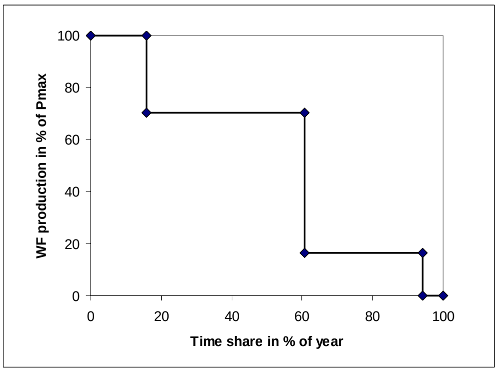

Fig. 4 Generation Duration Curve

B. *Reliability of grid connection*

Based on the GDC a theoretical yearly production of 1116 GWh could be delivered by the wind farm. The summarizing results from generation profile calculations and reliability analyses can be seen below in Table III.

TABLE III
ENERGY PRODUCTION OF WF AND SUPPLY RELIABILITY AT PCC

Index	**Value**	**Unit**	**Description**
TP	1116	GWh	Total production (w/o disturbances)
TS	1060	GWh	Total supply at PCC (w/o disturbances)
NL	56000	MWh	Network losses (w/o disturbances)
FI	13.1	1/yr	Frequency of reduced output at PCC
UI	78	d/yr	Unavailability of full output at PCC
EENS	9421	MWh	Expected energy not supplied at PCC
EAI	99.11	%	Energy availability at PCC

These results show, that less than 1 % of the possible energy supply at the PCC is lost due to disturbances of wind turbines or on the transmission path from the wind farm to the PCC. A relatively small portion when considering the calculated 5 % of network losses.

At the point of common coupling reliability figures as shown in Fig. 5 and Fig. 6 can be expected. Fig. 5 shows the frequency of disturbed energy supply from the wind farm. The resulting expected energy not delivered due to these disturbances is shown in Fig. 6.

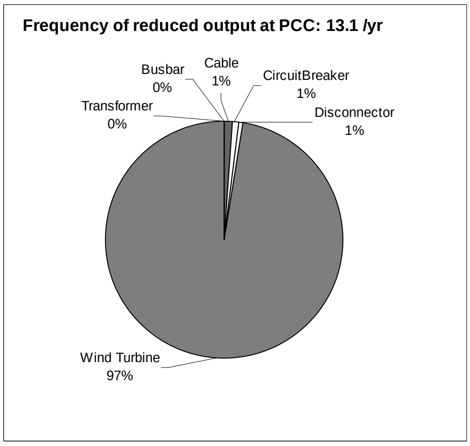

Fig. 5 Reliability at PCC – Frequency of Supply reduction

Evidently 97 % of the incidents, which lead to a reduction of power output at the PCC are caused by wind turbines. Certainly outages of wind turbines normally mean the loss of a single 3 MW unit, while other events like a failing submarine cable causes the loss of the entire wind farm with 240 MW generation. This effect becomes obvious, when considering the results, shown in Fig. 6.

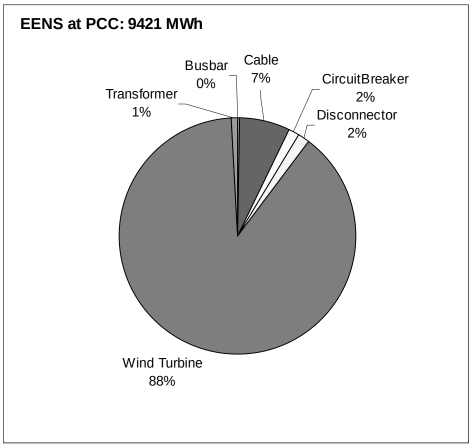

Fig. 6 Reliability at PCC – Expected energy not supplied

Again, the vast majority of disturbances of the EENS index is caused by the dominating weak-spot of the system, which can be identified as the wind turbines. Due to the high failure rate of wind turbines (more than 100 times higher than the submarine cable), they are causing the resulting EENS at the PCC. But a significant portion of energy not supplied can be assigned to the cables, in particular the single submarine cable.

Since these figures react very sensitive on amendments of the outage characteristic of offshore components as shown in Table II, an exemplary parameter study has been carried out.

C. Parameter variation

Due to the fact that no reliability input data is available for the wind turbines, a parameter variation is shown in Fig. 7 and Fig. 8, where the reliability at PCC is shown depending on various failure rates.

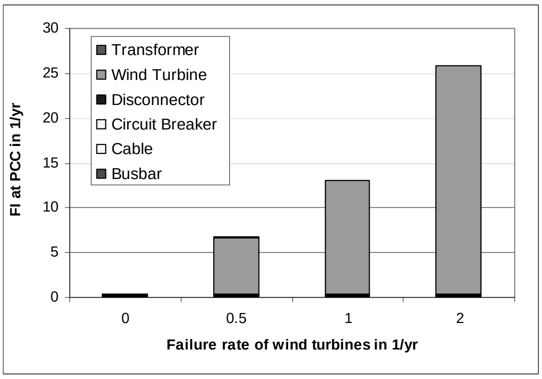

Fig. 7 FI at PCC depending on various failure rates of wind turbines

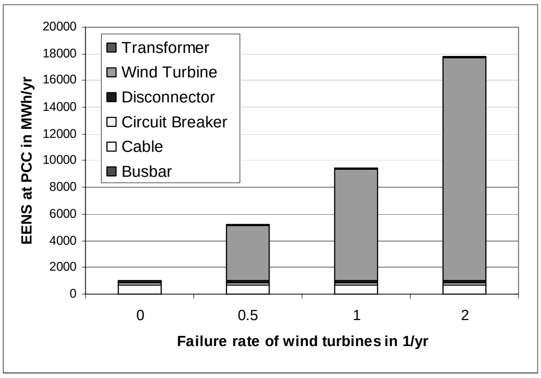

Fig. 8 EENS at PCC depending on various failure rates of wind turbines

Fig. 7 and Fig. 8 support the formerly grown findings, that the outage behavior of wind turbines dominate the reliability results at the PCC.

Another sensitive parameter is the repair time of the submarine cable, which only can be repaired under specific wind and wave conditions. With pessimistic assumptions it may take weeks or even months to repair the submarine cable. The influence of this parameter has been considered in Fig. 9.

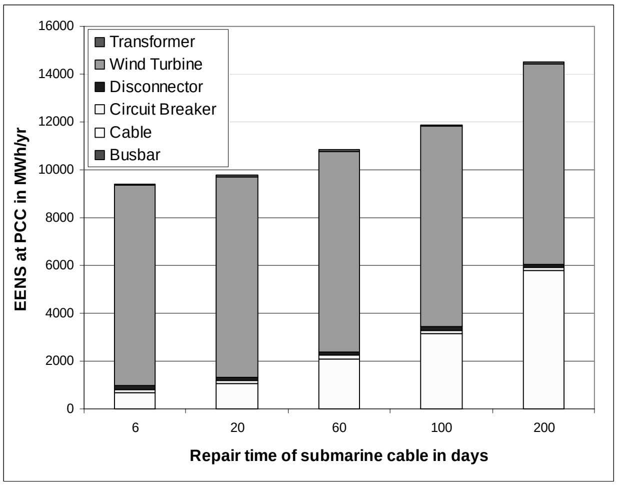

Fig. 9 EENS at PCC depending on various repair times of the submarine cable

By completely neglecting failures of wind turbines the impact of different network component types on the reliability at the PCC can be evaluated.

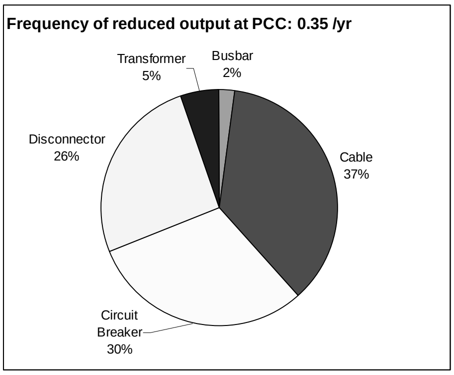

Fig. 10 FI at PCC without impact of wind turbines

Fig. 10 shows a typical distribution of component group contributions to system interruptions as one would expect in urban distribution systems. Nothing else could have been expected by utilizing the failure rates from [6]. Although the failure rate of cables is low, its impact becomes obvious, when considering Fig. 11.

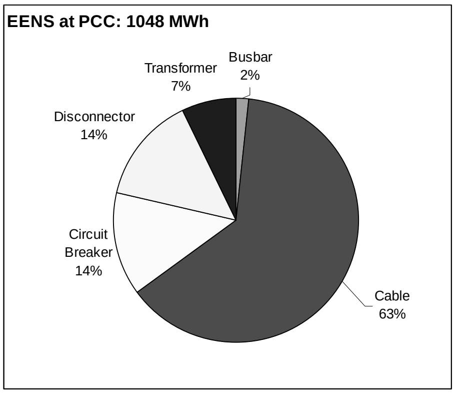

Fig. 11 EENS at PCC without impact of wind turbines

Due to the missing redundancy of the submarine cable the total cable contribution to the EENS index is 63 % when wind turbines are modeled to be ideal.

V. CONCLUSION

The application of probabilistic reliability calculation to support the assessment of wind farm grid connections has proven to be a sensible and useful tool. Although specific statistical data of wind farm components is not available to date, an adequate evaluation of the grid connection is possible. On the one hand, this study shows, that the dominant elements are the individual wind turbines. On the other hand, even with an extraordinary high failure rate of 2/yr (more than 200 times higher than the failure rate of the submarine cable), yet the EENS index of the offshore wind farm at the PCC is small compared to the production and losses of an ideal system. The main conclusion of this study is certainly, that the methodology can be applied to assess and evaluate reliability indices of wind farm grid connections. Furthermore, would investors strive for any improvement of reliability, effort should be focused to decrease failure rates and repair times of wind turbines. Even with a weak connection just by a single submarine cable, this obvious network weak-spot is not the driver of the expected energy not supplied to the PCC.

VI. REFERENCES

[1] R. Allan, R. Billinton, "Probabilistic Assessment of Power Systems", Proceedings of the IEEE, Vol. 88, No. 2, Febr. 2000, pp. 140 - 162

[2] A. Underbrink, "Risk analysis in distribution and transmission networks, 3rd IEE International Conference on Reliability of Transmission and Distribution Networks (RTDN 2005), Febr. 2005, London

[3] V. Kulkarni, A. Underbrink, "Reliability centered maintenance (RCM): Planning of maintenance programs", SWICON 2004, Nov. 2004, Bombay

[4] J. Backes, A. Osterholt, U. Prause, Zimmermann W., 2001, "Reliability Study for the Refurbishment of a HV/MV transformer Substation", CIRED 2003 16th International Conference & Exhibition on Electricity Distribution, Part 1, 3-14

[5] J. Backes, O. Schmitt, A. Underbrink, W. Zimmermann, "Reliability calculation – A method enters planning practice", Elektrizitätswirtschaft, 1998 (in German)

[6] www.vdn-berlin.de (Association of German network operators), "VDN-Disturbance and -Availability Statistic", July 2004

VII. BIOGRAPHIES

Andreas Underbrink was born in Münster in Germany, on May 16th, 1970. He graduated as Dipl.-Ing. from the Technical University (RWTH) Aachen, Germany.
His employment experience includes BET and ABB AG, where he has been working as a Network Planning Engineer since 1997.
His special field of interest covers studies related to power systems reliability. Furthermore he is an expert in Optimization of Maintenance Strategies.

Jutta Hanson was born in Vechta in Germany, on April 7th, 1967. She graduated as Dipl.-Ing. and got her PHD from the Technical University Darmstadt, Germany.
Her employment experience includes ABB AG, where she has been working since 1999. She is responsible for the Network Planning and System Studies Group Transmission and Industrial Systems.
Her special field of interest covers transmission and industrial network planning, system dynamics, connection of wind farms to the public grid and power electronic devices in electrical power systems.

André Osterholt was born in Lüdinghausen in Germany, on August 8, 1967. A. Osterholt graduated as Dipl.-Ing. at the Technical University (RWTH) Aachen. Since 1997 he is a staff member of the department „Electric System Consulting" of ABB AG, Mannheim, Germany.
As engineer his activities include study works and analyses of transmission and distribution networks. He has special knowledge and experience in transmission and distribution network analysis, distribution network restructuring and distribution network reliability evaluation.

Werner Zimmermann was born in Rottweil in Germany, on July 22, 1944. He graduated as Dipl.-Ing. from the Technical University Darmstadt, Germany.
His employment experience includes Brown Boveri and Cie. AG and ABB AG, where he has been working since 1971. He is responsible for Network Planning and System Studies.
His special field of interest covers transmission and distribution network planning, system dynamics and connection of power plants to the public grid